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How, where, and when to charge electric vehicles – net-zero energy system implications and policy recommendations

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Abstract

A coordinated Charging Infrastructure (CI) strategy could accelerate the adoption of Battery Electric Vehicles (BEVs). Policymakers need to understand the tradeoffs between several types of CI developments. To support decision-makers, we apply the Swiss TIMES Energy system Model, which we extended with heterogeneous consumer segments with four trip types and several CI options. The novelty of this work lies in the interplay of such method advancements, representing BEV charging options with various CI types that can be accessed based on their location type at an hourly intraday temporal resolution. In explorative scenario analyses, we evaluate the effects of CI on car fleet deployment and their energy system implications in achieving net-zero CO_2 emissions in Switzerland by 2050. Our analysis shows that the BEV share makes up 39%–77% of the fleet by 2050, and each BEV needs about 5 kW total charging capacity, split into 1.6–2.6 BEVs per private charger and 18–25 BEVs per public charger. Providing overnight charging access through private home chargers or public chargers in residential areas facilitates a 12%–20% increased BEV penetration compared to the reference scenario. For consumers without private home charging, improved public CI in non-residential areas increases BEV uptake by 24%. While low-power slow CI is cost-effective at home, high-power fast CI in commercial areas supports integration of solar PV. We highlight the need for coordinated CI policies and provide a variety of policy options based on our analysis and international insights.

Abbreviations

BEV	Battery Electric Vehicle
CA	Charger Accessibility [%]
CAP	Capacity (cars: [Million]; Batteries: [GW])
CCS	Carbon Dioxide Capture and Storage
CI	Charging Infrastructure
ESOM	Energy System Optimization Model
E	Electricity Flow [TWh]
EU	European Union
EV	Electric Vehicle (BEV + PHEV)
FCEV	Fuel Cell Electric Vehicle (powered with hydrogen)
HC	Home Charging

ICEV	Internal Combustion Engine Vehicle
MTMC	Swiss Mobility and Transport Microcensus
COMM	Public charger in commercial locations
PC	Public Charging
PRIV	Private home charger
PHEV	Plugin Hybrid Electric Vehicle
pkm	Passenger kilometer
RAPID	Rapid public charger
RESID	Public charger in residential area close to home
RQ	Research Question
SP	Survival Probability [%]
STEM	Swiss TIMES Energy system Model
TIMES	The Integrated MARKAL-EFOM System
vkm	Vehicle kilometer
Indices	
α	Share of EVs at the location of the respective charger type [%]
β	Share of EVs parking on a parking spot with a charger [%]
γ	share of EVs that are plugged into the charger when parking at a parking spot with a charger [%]
c	consumer segment
θ	vkm share of trips with BEVs that exceed a threshold and need rapid charging [%]
Bat	Battery
i	type of electric car (BEV/PHEV)
j	engine size category of the car
m	long-distance trip type
t	time
ts	timeslice
v	vintage year
x	charger type

1. Introduction

1.1. Background and research focus

Electric Vehicles[5,6] (EVs) powered with low-carbon electricity are indispensable to transforming the transportation sector towards reaching ambitious climate targets [1, 2]. To accelerate EV uptake, Charging Infrastructure (CI) at convenient locations for consumers is critical [1–3].

In Switzerland, the electric car (EV) share in 2022 was 3.7%, including Battery Electric Vehicles (BEVs) and Plugin Hybrid Electric Vehicles (PHEVs) [4]. Nonetheless, the EV stock increased rapidly as 24% of newly sold cars were electric [5]. While a holistic CI buildup is important [1], Switzerland pursues a principle of individual measures based on voluntariness and self-initiative of different stakeholders [6]. The Swiss government steps with this as a facilitator between the stakeholders, but it remains unclear if this bottom-up initiative approach overcomes existing challenges for efficient CI integration into the energy system [6]. Switzerland's available Public Charging (PC) infrastructure currently accounts for 8 BEVs per charger, outpacing most European countries [7]. Challenges are faced due to the lack of access to overnight charging at home for those who do not own a parking lot, i.e., those who rent or lease a parking lot [8] or use public parking lots near home (primarily on-street parking) [9]. Such challenges are particularly relevant for Switzerland due to its high share of (renting) tenants (58% compared to 31% in the European Union (EU)) [10] and its low private garage ownership rate [8]. Specifically, tenants in Switzerland have limited rights to install a private charger in a rented private parking lot

[5] This work focuses on cars. Therefore, we use the terms 'vehicles' and 'cars' synonymously.

[6] The term 'Electric Vehicles' (EVs) refers to Battery Electric Vehicles (BEVs) and Plugin Hybrid Electric Vehicles (PHEVs). Fuel Cell Electric Vehicles (FCEVs) that are powered with hydrogen are treated separately and are consistently referred to as FCEVs.

[11–13]. Further, street-parking lots in residential areas currently have minimal CI, which complicates overnight charging for tenants [8].

CI of different charging powers and at diverse locations have distinctive use cases for meeting consumers' charging needs, such as slow/fast charging at the workplace, overnight charging at home, and rapid charging to cover long-distance trips [14]. To enable future EV deployment, providing CI options that suit the needs and locations of consumers is essential. Policymakers and investors are interested in understanding these needs for accelerating BEV uptake and decarbonizing the Swiss energy system cost-effectively [15, 16].

1.2. Literature overview: charging infrastructure in energy models

Energy System Optimization Models (ESOMs) combine a systemic perspective of the energy system with highly detailed techno-economic technology specifications, allowing them to simulate possible future energy- and CO_2-emission pathways in a cost-optimizing framework [17–19]. They are important tools for supporting decision-makers in evaluating energy transition pathways [18, 19]. However, a detailed integration of CI options into ESOMs has only insufficiently been considered, despite its importance for BEV uptake. This section summarizes literature on integrating specific CI aspects in ESOMs that we will tackle.

Various CI options should be considered to reflect distinguishing charging use cases depending on the chargers' location (but many ESOMs even lack explicit modeling of EVs in the first place). For instance, Zheng *et al* [20] distinguish between slow and fast chargers. Though Tsiropoulos *et al* [21] include various public CI options with different power outputs (fast versus slow charging), their analysis does not cover private home chargers and the mapping of car location types with accessible charger options. A recent study [22] links several CI options to different charging needs at certain charging locations, i.e., private CI at home and work locations and publicly accessible CI at commercial locations and for fast charging. While they apply an agent-based model that reflects consumers' CI usage choices, the study is limited in assessing electricity supply constraints or broader cross-sectoral energy systemic impacts [22]. However, these are common limitations in many agent-based models [18]. Gupta *et al* [23] apply a geographic information system based model in which they distinguish private chargers with various rated powers and public chargers with 22 kW rated power to determine the impacts of EV charging on the electricity grid until 2050. Rinaldi *et al* [24] consider different consumer segments and various CI options but fix their shares by charger capacity and assume a fixed hourly charging profile for a week, in contrast to our approach that determines the charging profiles endogenously based on the accessibility to different CI options.

The availability of different CI options to different consumer types (e.g., homeowners versus tenants) for accessing them is another aspect lacking in current ESOMs. While recent research focused on considering consumer segments in ESOMs [25–31], they did not assess the consumers' CI accessibility nor focused on EV charging in the first place.

Charging flexibility/patterns are rarely considered [32], but exceptions are, for instance, Cao *et al* [33], who compare uncontrolled and smart charging impacts on the household power demand profile. Heinisch *et al* [34] and Gunkel *et al* [35] each compare three different charging strategies. Di Somma *et al* [36] ensure that EVs always contain enough electricity to cover the upcoming trip. Schröder *et al* [37] reflect probability distributions of arrival time and remaining charge in batteries to assess their influences on the EV charging load demand. Wei *et al* [38] consider a probability distribution for the charging duration at commercial and residential chargers, and they require that the BEV battery is charged to at least 90% before any trip. Though such studies look at EV charging patterns, they often lack consideration of the need for various CI options and the consumers' location-specific usage and accessibility to a certain CI option.

The need for rapid charging on long-distance trips is a commonly discussed topic [39]. In ESOMs, however, this issue is underrepresented. Despite various works that integrated different trip-distance types in ESOMs [40–42], their focus is on modal shifts instead of assessing or considering the need for rapid charging on long trips. Furthermore, we could not find research with ESOMs that focuses on the broader energy systemic impacts of utilizing different CI options. We try to address the outlined limitations.

1.3. Research gap and current work

Despite many studies on EV charging, their focus is often limited to the transport sector, as outlined in section 1.2. A gap remains in assessing cross-sectoral implications of EV charging at the energy system level. This would allow considering intraday[7] and seasonal supply and demand variations. Further, existing ESOMs lack features to assess impacts of charging at different location types or by differing consumer segments (who have access to HC or rely on PC).

[7] For instance, electricity supply in a net-zero future could largely come from solar energy throughout daytime, but BEVs are mostly connected to chargers throughout the night.

Considering the interest of policymakers and investors and the reviewed literature in section 1.2, this paper aims to answer three Research Questions (*RQ1—RQ3*) in achieving a net-zero Swiss energy system by 2050:

RQ1. Quantitative: what are the effects of different CI options on BEV charging and car fleet deployment?

RQ2. Quantitative: which major systemic impacts in the energy system are triggered by different CI options?

RQ3. Qualitative: what can we learn for policy recommendations to support CI for an effective BEV rollout?

In answering these questions, we apply a technology-rich, cost-optimization model—the Swiss TIMES Energy systems Model (STEM) [43]—in an explorative scenario framework. The novelty of our work lies in the methodological advancements that represent EV charging options with various CIs based on their location type[8] at an hourly intraday temporal resolution [44, 45]. The CI is characterized by its techno-economic and spatiotemporal dimensions, its accessibility to different consumer segments, depending on the cars' location and trip type, and the need for enabling long-distance trips with BEVs. Unlike other existing studies on CI development [21, 22, 33, 34, 36], another strength of this work lies in linking the demand-side enhancements and their integration into the broader energy system (STEM) with high temporal resolution. This ensures a time-dependent link of the electricity demands to energy supply, conversion, and storage, which is relevant with increasing renewable energy supply. In STEM, we implement several CI options for cars, while other transportation modes have a generic CI [45]. Thus, in answering the above research questions, the analytical results focus on the car fleet deployment, development and usage of CI, and the cross-sectoral implications for the energy system.

Overall, this work's methodological novelties allow for overcoming the shortages of the often simplified representation of CI options in previous studies. Applying this advanced method in STEM allows for determining the feedback effects of CI accessibility and availability on the costs associated with providing electricity and other energy sources. These cost changes, in turn, influence the composition of the vehicle fleet and how mobility demand is fulfilled. Furthermore, the presence of electric vehicles impacts the cost-optimal technology mix across the entire energy system, including electricity supply, energy conversion, and the need for low-carbon technologies in other sectors.

2. Methodology

We apply the STEM (section 2.1), the scope of which has been extended for this work with an enhanced transportation module (section 2.2). A comprehensive overview of underlying data and assumptions of the modeling framework is presented in section 2.3. Section 2.4 provides an overview of the applied scenarios.

2.1. The Swiss TIMES energy systems model (STEM)

STEM is a technology-rich bottom-up cost-optimization model that applies the TIMES (The Integrated MARKAL-EFOM System) modeling framework [43, 46]. STEM has an hourly intraday resolution of three typical days in four seasons [43]. STEM's techno-economic richness allows making endogenous investment decisions to provide possible cost-optimal future pathways until 2050, considering technical and policy constraints. The energy supply-, conversion-, and demand (transport, residential, industry, services) sectors are coupled and exhibit strong interdependencies. It is a well-documented model with all inputs and data assumptions available [43–45, 47–49]. STEM's transportation module includes all main passenger and freight transportation modes. For each transport mode, annual driving demand trajectories are based on socio-economic trends [49, 50]. Those demands and the hourly driving patterns are exogenously defined [49, 51–53] and calibrated for each consumer segment and trip type (figure C1 in Appendix B.3) [54]. Each vehicle technology (appendix a) is characterized by capital costs, operation and maintenance costs, annual mileage, lifetime, fuel efficiency, and more [54, 55]. Future car ownership is based on population development and car ownership rate [56]. While this publication focuses on cars and their respective CI, the model considers various technology options for each transport mode, which can also be electrified [45].

We developed an extended STEM passenger transportation module. Reflecting the IEA's statement that 'location and accessibility define the potential use cases '[57] of CI, figure 1 shows how we mapped heterogeneous consumer segments (appendix B.1) and travel demands differentiating by trip distances (appendix B.2) with locations of different CI options (section 2.2), while considering endogenous intraday utilization and time-dependent CI accessibility (with hourly resolution). These enhancements enable distinguishing vehicle investment decisions with a focus on the relevance of CI options. Some enhancements were previously outlined in a project report [15].

[8] The model includes proxies for different types of locations (at home, commercial location, on/off road, on long-distance trip) to link the car's charging to a certain CI option, but does not reflect precise GIS-based locations.

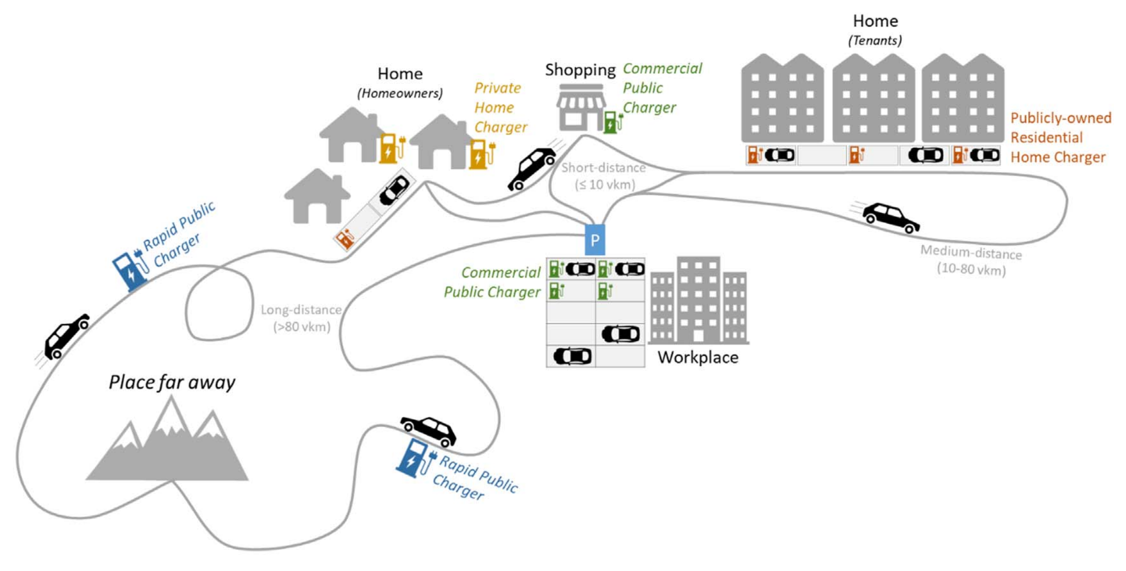

Figure 1. Schematic visualization of integrated approach of consumer segments, trip types, and charging infrastructure options.

2.2. Charging infrastructure enhancements in STEM

The CI for cars has been further developed to reflect consumers' charging options. Table 1 presents four CI options, each distinguished by their location and accessibility to consumers: PRIVate home chargers (PRIV), RESIDential public chargers close to home (RESID), COMMercial public chargers (COMM), and RAPID public chargers (RAPID).

The different CIs are mapped to the consumer segments (appendix B.1), trip distances (appendix B.2), and Vehicle-to-Grid (V2G) options, as illustrated in figure 2. While the charger accessibility concept is outlined in section 2.2.1, the method advancement to capture the need for rapid charging of BEVs on long-distance trips is presented in appendix B.3.1.

2.2.1. Charger accessibility

To ensure that cars are charged only during off-road times and via the charger type *x* that is available at a given time *t* at the location of the car, we map such aspects. We define for each charger type *x* the Charger Accessibility ($CA^{x}_{ts,i,j,c}$) [%]. This parameter is defined as the maximum number of EVs ($CAP^{EV}_{i,j,c}$) that can be charged in charger type *x* at a given time *t* of the day. Index *i* refers to the type of electric car (BEV or PHEV), index *j* indicates the engine size category of the car (appendix A), and index *c* refers to the individual consumer segment (appendix B). $CA^{x}_{ts,i,j,c}$ is defined as a function of the maximum electricity flow *E* [PJ] from the charger to the EVs batteries ($CAP^{Bat}_{i,j,c}$) at time *t* of a day, as shown in equation (1).

$$E^{x}_{ts,i,j,c}(t) \leqslant \frac{CAP^{Bat}_{i,j,c} * \left(\frac{t}{8760}\right)_{ts}}{\frac{CAP^{Bat}_{i,j,c}}{CAP^{EV}_{i,j,c}}} * CA^{x}_{i,j,c}(t) \tag{1}$$

with

$$CA^{x}_{i,j,c}(t) = \alpha^{x}_{i,j,c}(t) * \beta^{x}_{i,j,c} * \gamma^{x}_{i,j,c} \tag{2}$$

where $\alpha^{x}_{i,j,c}$, $\beta^{x}_{i,j,c}$ and $\gamma^{x}_{i,j,c}$, of charger type *x* (table 1) are described in table 2.

2.3. General data and assumptions on electric vehicle charging infrastructure

Since tenants in Switzerland have few individual rights to install PRIV chargers [11], the reference scenario assumes tenants have no access to PRIVs. They rely on public CI (RESID, COMM, and RAPID), whereas homeowners can charge at PRIV and all public CI. For homeowners[9], we assume that PRIVs are available for 70% of their BEVs and 20% of their PHEVs for the base year. Since RESID chargers are—to our best knowledge—limited in Switzerland to few pilot projects [63], we do not allocate the existing CI to this category. Public chargers with rated power of 43 kW and above are modeled as RAPID, while those with less than 43 kW as

[9] In 2020, 75% of all EVs in Switzerland are owned by homeowners [54].

Table 1. Overview of charging infrastructure options.

Charger type	Charger short name	Ownership (for investment)	Location	Modeled rated power [kW][a]	Accessibility	User profile
PRIVate home charger	PRIV	Private	*At home*: private parking lot	7 kW (3–10 kW)	*Can* be installed and used by consumers who park their car at home in a private parking lot.	Typically used for HC on a private parking lot [14]. They benefit from long car parking durations during nighttime.
RESIDential public charger	RESID	Public	*At home*: residential area (e.g., on-street charger)	22 kW (11–42 kW)	*Can* be used by consumers who park at home in a public parking lot (e.g., on-street parking).	Typically used for HC when PRIV chargers cannot be accessed [14]. They benefit from long car parking durations during nighttime.
COMMercial public charger	COMM	Public[b]	*Away from home*: commercial parking lots (e.g., at work[b], supermarkets, train stations)	22 kW (11–42 kW)	*Can* be used when the car is parked in public parking lots in commercial areas away from home	Mostly used during the duration of the respective activity of the car user [14].
RAPID public charger	RAPID	Public	*Away from home*: on highways and in commercial parking lots	150 kW (43–360 kW[c])	*Must* be used to cover long-distance trips. *Can* also compete with COMMs on public parking lots in commercial areas.	Mainly used for a recharge in a short time during a short break on a long-distance trip [14]. Compared to the other CI options, they are often provided on highways and are mostly occupied only during the actual charging duration [58, 59].

[a] The modeled rated power for each CI option is set based on a combination of the power of common CI that belongs into the range and reflects approximately an average value of the represented range. The values in the parenthesis indicate the commonly used real-world rated power range of the respective charger type [60].

[b] In the modeling context, this work combines chargers located at workplace locations (which are, in reality, not always publicly accessible or owned by the public) and chargers located at other (public) locations where cars are commonly parked when being away from home. This is because a certain charger's ownership is irrelevant from the modeling perspective. For the model, it is more relevant at which times consumers can access a certain charger type and with which rated power the EV is being charged, leading to an aggregated number of chargers on a national level.

[c] While CI with more than 100 kW is becoming increasingly common nowadays [61], novel car CI can provide up to 360 kW [62].

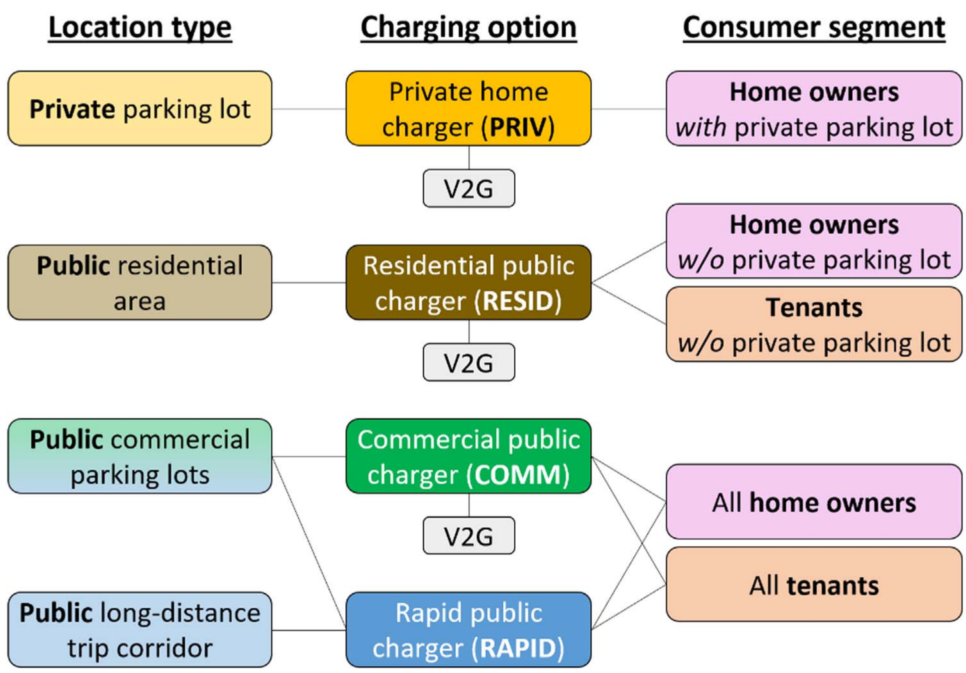

Figure 2. Mapping of charging infrastructure options with location types and consumer segments. All chargers are accessible between any trips at their respective location. Additionally, RAPID is also accessible during long-distance trip corridors.

COMM (see table 1). Since PHEVs do not rely on rapid charging on long-distance trips, we assume that only BEVs are charged at RAPID CI. The BEV battery range threshold (equation (3)) that requires rapid charging on long-distance trips is 70% of the battery range.

STEM implicitly reflects a cost-efficient smart charging approach that balances the endogenously calculated electricity price and demand for EV charging at any time. Techno-economic parameters are included for all charger types, e.g., capital costs (one charging point per charger/pedestal) [64] and Operation and Maintenance (O&M) costs [65] are outlined in appendix B.3. Annual utilization rates (intraday utilization is endogeneous) are estimated from existing CI, i.e., number of sessions per day, kWh charged per charging session, and connection duration per charging session [58, 66–68]. As CIs are emerging technologies, there is no historic data on their technical lifetime under real-world conditions [21, 69]. As RAPID chargers can be more durable than other CI options, we assume a technical lifetime of 20 years for PRIV, RESID, and COMM and 40 years for RAPID.

The home parking situation pre-determines if consumers could potentially access at home a PRIV on their private parking lot or rely on RESID. For cars of homeowners and tenants, we assume that 90% and 30% can park at home in a private parking lot, respectively. Table 2 summarizes the reference scenario values for the CA equation (equation (2)).

2.4. Scenario overview

We adopted two existing [45, 49] baseline scenarios to reflect potential transition pathways containing energy and climate policies for the Swiss energy system according to a *Business-As-Usual (BAU Ref)* and a *Net-Zero Carbon (NZC Ref)* reference approach. The latter aims to achieve net-zero CO_2 emissions by 2050. Both scenarios are described in Panos *et al* [49] and Kannan *et al* [45]; a summary is provided in appendix D.

The remaining scenarios, summarized in table 3, respect the energy and climate policies framework of *NZC Ref*. To assess potential impacts of CI policies, we evaluate the model's sensitivity regarding key parameters by simulating optimistic (OPTI) and conservative (CONS) scenario variations. The Public Charging *(PC)* scenarios explore the effects of high (*PC OPTI*) and low (*PC CONS*) accessibility of public CI away from home (COMM and RAPID). The high and low parameters reflect the potential for the density of such chargers, as their current deployment is still at an early stage. Due to the adjusted accessibility of such public CI, the need for rapid charging on long-distance trips is adjusted accordingly. In the *PRIVate HC for TENants (PRIV-TEN)* scenario, tenants with a rented private parking lot can install PRIV. This reflects building regulations from Norway [72], a forerunner country for EV adoption, and contrasts with the current Swiss regulations where only the building owner can make such a decision. The *RESIDential HC (RESID)* scenarios assess the effect of RESID accessibility, as the availability of public chargers in residential areas (RESIDs) is currently limited. Thus, it is challenging for tenants to charge their BEVs overnight. The optimistic scenario (*RESID OPTI*) provides improved overnight

Table 2. Assumptions for the charging accessibility factors (reference scenario).[a]

Factor	PRIV	RESID	COMM	RAPID
$\beta^{x}_{i,j,c}$: Share of EVs parking at charging spot when parking	BEV: 80% PHEV: 50%	BEV: 80% PHEV: 50%	BEV: 17%[b] PHEV: 17%[b]	BEV: 17%[b] PHEV: 17%[b]
$\gamma^{x}_{i,j,c}$: Share of EVs parking at charging spots that are plugged in	BEV: 40% [70] PHEV: 80%[c]	BEV: 40% [70] PHEV: 80%[c]	BEV: 80% PHEV:100%	BEV: 80% PHEV:100%
$\alpha^{x}_{i,j,c}(t)$: Hourly location profile	Accessible when car is parked at home [54]	Accessible when car is parked at home [54]	Accessible when car is parked away from home (e.g., at work, shopping, leisure, train station) [54]	Accessible when car is parked away from home (e.g., at work, shopping, leisure, train station) [54]

[a] As EV users have been special user groups to date, i.e., early adopters, data for the 'average' user are hardly accessible from the literature yet. This and the general lack of data for the required factors made us assume parametric values based on expert judgment.

[b] Calculated based on Swiss public chargers [61, 71], the number of EVs [4], and the car location profile in figure B3 [54].

[c] This assumes that PRIV owners would charge a PHEV more frequently than a BEV due to PHEVs limited electric range.

Table 3. Scenario overview.

Scenario abbreviation	Scenario description	Adjusted model parameters (reflecting possible effects from policy instruments)				Systemic climate framework
		Charger Accessibility (CA) (equations (1) and (2))	Rapid charging threshold on long-distance trips (equation (3))	PRIV access for tenants	Available chargers	(see [45])
BAU Ref	Business-as-usual reference	Baseline (section 2.3)	Baseline (section 2.3)	No	All	**BAU**
NZC Ref	Net-Zero CO_2 reference	Baseline	Baseline	No	All	**NZC**
PC OPTI	OPTImistic PC access away from home	• **COMM: +25%** • **RAPID: +25%**	+10%	No	All	NZC
PC CONS	CONServative PC access away from home	• **COMM: −25%** • **RAPID: −25%**	−10%	No	All	NZC
PRIV-TEN	PRIVate HC enabled for TENants	Baseline	Baseline	**Yes**	All	NZC
RESID OPTI	OPTImistic RESIDential PC	• **RESID: +25%**	Baseline	No	All	NZC
RESID CONS	CONServative RESIDential PC	• **RESID: −25%**	Baseline	No	All	NZC
RESID ZERO	ZERO uptake of RESIDential PC	Baseline	Baseline	No	**No RESID**	NZC

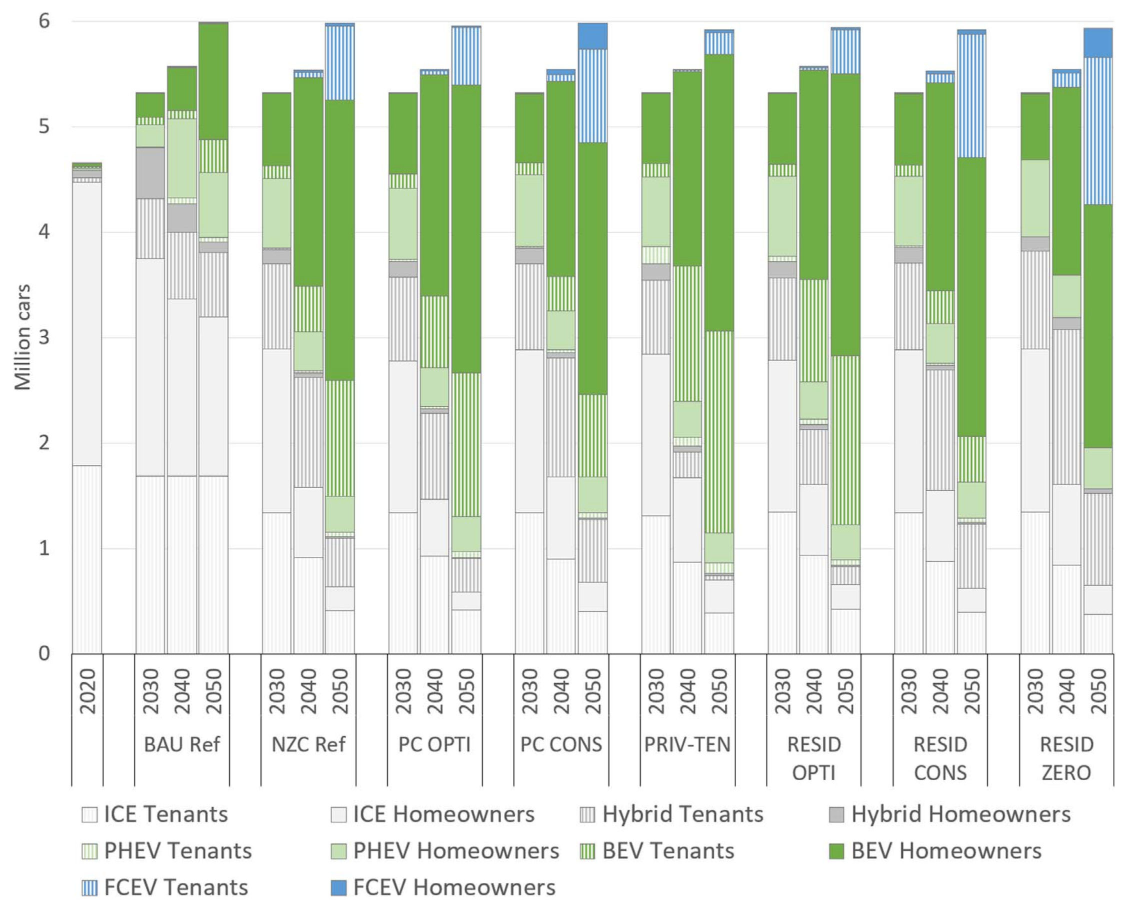

Figure 3. Development of the Swiss car fleet trajectory between 2020 and 2050 distinguished by tenants and homeowners. Car fleet percentages in the main text for tenants and homeowners typically relate to the entire car fleet of tenants (100%) and homeowners (100%), respectively.

charging options to consumers without a private parking lot. *RESID ZERO* assumes that RESID CI is not deployed, as is currently the case.

3. Results and discussion

In this section, we present results and discuss the analytical insights from the perspective of EV uptake and their charging implications (section 3.1) and broader energy system impacts (section 3.2) to answer research questions *RQ1* and *RQ2*, respectively. Section 3.3 elaborates on *RQ3* by interpreting the individual scenario results as effects of policies to derive learnings for CI policies. Finally, section 3.4 discusses the applied methodology and its limitations and suggests future work. Though we included a *BAU Ref* scenario, it only showcases the comparable technological shift to achieve the net-zero goal. Therefore, result values are compared to the *NZC Ref* scenario in 2050 unless stated otherwise.

3.1. What is the impact of different CI options on the charging and car fleet deployment? (*RQ1*)

In the reference scenario (*NZC Ref*), the BEV share in the total car fleet is 64%, while the BEV share for tenants is just 40% (figure 3) because of a lack of overnight charging options. In other words, of the 3.8 million BEVs in 2050, only 1.2 million BEVs are owned by tenants, even though they represent most of the population. Instead, the tenant segment opts for more hydrogen fuel cell cars due to the lack of home-charging infrastructure. In this reference scenario, about 6.6 TWh electricity is used in EVs via a total number of 1.8 million chargers (table 4). This reflects an average total charger capacity of 4.6 kW per BEV and a total number of 1.6 million private home chargers (PRIV) and 169 thousand public chargers.

The comparison of *BAU Ref* and *NZC Ref* shows that the uptake of EVs is primarily driven by the need for decarbonization in *NZC Ref*, but takes to some extent also place in the cost-driven *BAU Ref*. The quick battery technology advancements in terms of driving range and cost reduction throughout the last years are expected to continue in the future [2, 73], reducing the barriers of range limitations [74] and high capital costs [73] for BEV

Table 4. Charging infrastructure deployment (number of chargers[a]) by scenario.

Scenario	PRIV @ 7kW per charger			RESID @ 22kW per charger			COMM @ 22 kW per charger			RAPID @ 150 kW per charger		
	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050
BAU Ref	165,000	506,000	772,000	6,000	11,000	26,000	7,000	3,000	5,000	2,000	2,000	6,000
NZC Ref	705,000	1,403,000	1,637,000	17,000	48,000	113,000	7,000	26,000	39,000	4,000	11,000	17,000
PC OPTI	758,000	1,445,000	1,583,000	19,000	72,000	144,000	14,000	43,000	47,000	6,000	16,000	23,000
PC CONS	704,000	1,336,000	1,499,000	17,000	39,000	82,000	7,000	15,000	24,000	3,000	7,000	11,000
PRIV-TEN	746,000	1,601,000	2,031,000	23,000	118,000	152,000	8,000	30,000	29,000	4,000	15,000	21,000
RESID OPTI	737,000	1,389,000	1,623,000	22,000	127,000	194,000	8,000	31,000	29,000	4,000	14,000	20,000
RESID CONS	699,000	1,392,000	1,626,000	14,000	33,000	40,000	10,000	24,000	25,000	4,000	10,000	14,000
RESID ZERO	684,000	1,282,000	1,439,000	0	0	0	12,000	27,000	27,000	3,000	8,000	10,000

[a] The total installed CI capacity in GW is shown in figure E1 (appendix).

deployment, as reflected in its uptake in *BAU Ref*. Since the model considers advanced driving ranges and efficiencies in future vehicles (compare with Kannan *et al* [45]), the need for rapid charging on long-distance trips reduces throughout the time horizon, being increasingly substituted by options for slower overnight charging and daytime-charging at home.

While this study goes beyond previous studies in the Swiss context by better reflecting the CI accessibility for various consumers and trip types [75] and assessing the implications in the detailed context of the entire national energy system [23, 76], the vehicle fleet deployment trajectories follow similar trends. In line with the findings of the reference scenario in the Swiss energy perspectives [77] and the net-zero scenario by de Haan *et al* [78], we find that PHEVs are an intermediate technology while a more profound shift from Internal Combustion Engine Vehicles (ICEVs) towards BEVs and an uptake of FCEVs from 2040 onwards, occurs as a cost-efficient solution. Like the Swiss energy perspectives [77], we find that ICEVs are not entirely phased out by 2050 since their complete phase-out would entail additional 11 billion CHF cumulative systemic costs between 2024 and 2050 (section 3.1.4). This contrasts with Panos *et al* [75], where the net-zero reference scenario contains a 2050 car fleet consisting only of EVs (BEVs, PHEVs, and FCEVs) since they do not consider the distinctive consumer-, time- and location-type-dependent accessibility of various CI options. Another Swiss study determined the future car fleet in a behavioral-driven Agent-Based Model (ABM) [79] and found that for 2050 a BEV-share of 83% and ICEV-share of 16%. In contrast, we find that an FCEV uptake after 2040 enables a reduction in systemic costs due to cost advantages for their integration into the future energy system if consumers lack overnight charging access (figure 3).

3.1.1. Importance of overnight charging options (PRIV and RESID)

From figure 3, we can infer that consumers with access to PRIV chargers (homeowners) have higher EV (BEV + PHEV) adoption rates (94% in *NZC Ref*) than tenants (42%). Generally, this trend can be observed in all scenarios. Allowing tenants to invest in PRIV chargers (*PRIV-TEN* scenario) increases EV uptake among tenants to 76% (72% BEV and 4% PHEV). Under such circumstances, the EV share in the Swiss car fleet increases to 83% (70% in *NZC Ref*), and the BEV part increases from 64% (*NZC Ref*) to 77% (*PRIV-TEN*). Further, in *PRIV-TEN*, 33% and 48% of the electricity drawn by tenants (100%: 3.4 TWh) takes place at PRIVs and RESIDs, which are located close to the consumers' homes, respectively. Therefore, legislative changes that provide rights for tenants to install a charger could facilitate achieving net-zero emissions more cost-effectively.

The *RESID OPTI* scenario shows the importance of high RESID accessibility for consumers without PRIV access, as such chargers enable them to charge overnight at road side parking. This supports the BEV uptake particularly for tenants (figure 3: 60% in *RESID OPTI* versus 40% in *NZC Ref*) but remains less effective for tenants' BEV uptake than making private charging accessible to them (figure 3: 72% in *PRIV-TEN*). The number of RESID chargers increases by 72% to 194 thousand chargers compared to 113 thousand RESID chargers in *NZC Ref* (table 4). On the contrary, with a more conservative RESID accessibility (*RESID CONS*), BEVs lose relevance for tenants (figure 3: 16% versus 40%) as they have fewer overnight charging possibilities. Instead, tenants buy more hybrid cars in the mid-term (2030 and 2040) and shift toward FCEVs in 2050 (44% versus 26%). When RESID chargers are not deployed (*RESID ZERO*), it is not cost-efficient for consumers without any overnight charging access to adopt BEVs or PHEVs. Instead, such consumers deploy more hybrid vehicles until 2040, followed by a strong shift toward FCEVs (figure 3: 53% in 2050). Though we modeled CI in detail, hydrogen fueling stations are still aggregated. However, we assume the deployment of hydrogen infrastructure can be more centralized and market-driven compared to the more consumer-driven CI.

The importance of overnight charging options is underpinned by additional sensitivity analyses[10], showing that net-zero can generally not be achieved when overnight charging options (PRIV and RESID) are unavailable. It could be argued that consumers can adjust their traveling preferences and plan for an extra stopover at public or rapid charging locations. However, we assume that such a change in personal travel patterns would induce a barrier for consumers to purchase BEVs in the first place, and such an analysis is beyond the scope of this work.

3.1.2. Relevance of charging options away from home (COMM and RAPID)

The *PC OPTI* and *PC CONS* scenarios emphasize the relevance of public CI away from home (COMM and RAPID) for the BEV uptake of tenants when they cannot access PRIV chargers and no particularly positive RESID accessibility is assumed. While in *PC OPTI* the additional accessibility of COMM and RAPID chargers leads to a BEV share for tenants of 51%, this share shrinks in *PC CONS* to 29%, compared to 40% in *NZC Ref* (figure 3). The number of COMM and RAPID chargers increases in *PC OPTI* by 20% to 47.000 and 36% to 23,000, compared to NZC Ref, respectively (table 4).

On the contrary, homeowners (i.e., consumers with access to private overnight chargers at home) do not show a substantially increased BEV uptake (figure 3) because they can charge sufficiently via PRIV and thus rely

[10] Any additional sensitivity analyses assume that the remaining CI options have the same values like in *NZC Ref*.

Table 5. Key result indicators for the charging infrastructure deployment by scenario.

Scenario	Total charging capacity [kW] per BEV			#BEVs per private charger (PRIV)			#BEVs per public charger (RESID + COMM + RAPID)		
	2030	2040	2050	2030	2040	2050	2030	2040	2050
BAU Ref	5.8	8.6	5.0	1.8	1.0	1.8	20.5	30.1	38.5
NZC Ref	7.5	5.4	4.6	1.1	1.7	2.3	28.7	28.2	22.3
PC OPTI	7.6	5.4	4.6	1.2	1.9	2.6	23.7	21.3	19.1
PC CONS	7.7	5.4	4.5	1.1	1.6	2.1	28.1	35.2	27.2
PRIV-TEN	8.2	5.3	4.7	1.1	2.0	2.2	22.6	19.3	22.5
RESID OPTI	8.2	5.1	4.5	1.1	2.1	2.6	22.8	17.3	17.6
RESID CONS	7.7	5.5	4.8	1.1	1.6	1.9	28.6	34.2	39.1
RESID ZERO	8.9	6.0	5.3	0.9	1.4	1.6	42.6	51.1	62.0

only to a lesser extent on public CI. This is in line with another recent Swiss study [22], which considers more behavioral aspects in a transport-focused ABM but lacks the systemic integration (see section 1.2) that the buildup of RAPIDs and slow CI on rented private parking lots and parking lots of commuters is essential for EV uptake. Further, our findings are supported by Tsiropulos *et al* [21], who found that the deployment of RAPIDs is important for near-term EV uptake as they reduce potential charging times away from home. Therefore, targeted policies for installing different CI options at various locations is essential to accelerate BEV uptake and meet individual consumer needs.

Since the *RESID ZERO* scenario (tenants have neither access to PRIV nor RESID) does not show uptake of BEVs for tenants, it raises the question of why such consumers do not still get BEVs and use public CI away from home. From additional sensitivity analyses, we found that relying solely on public CI located away from home (i.e., COMM and RAPID) is insufficient to adopt BEVs because consumers get to park (charge) for a very limited duration at public CI away from home. Instead, tenants deploy 1.47 million hybrid cars by 2040 (60% of tenant's fleet) before strongly shifting to 1.39 million FCEVs (53%) in 2050. Moreover, consumers may have anxiety about the charging station being occupied. Nevertheless, we quantified the need for public CI away from home to let BEVs enter the fleet of those consumers without any access to PRIV and RESID. We find that the accessibility (equation (2)) of the remaining chargers (COMM and RAPID) needs to be two times higher than in *NZC Ref* so that it would become cost-efficient for tenants to deploy some BEVs by 2050. In such a case, those BEVs strongly rely on daytime charging, leading to a 56% higher electricity demand peak for charging over midday, compared to *NZC Ref*. As this would impose higher challenges on the electricity grid, it underpins the importance of overnight charging options.

3.1.3. Number of charging points

The number of charging stations per CI category is outlined in table 4. Our analysis of key charging result indicators in table 5 shows that each BEV needs about 5 kW total charging capacity, including private home chargers and public chargers. We find a split of 1.6–2.6 BEVs per private charger and 18–62 BEVs per public charger.

For publicly available CI, the European Union proposed a recommendation of 1 kW per BEV and 0.66 kW per PHEV [80]. The *NZC Ref* scenario achieves to exceed this recommendation by 47% (5.9 GW public CI for 3.8 million BEVs and 0.4 million PHEVs). Scenarios with more optimistic CI accessibility outperform the target by 49%–77% despite their higher EV adoption rates (+77% in *PC OPTI*: 7.7 GW public CI, 4.1 million BEVs, 0.4 million PHEVs; +49% in *PRIV-TEN*: 7.1 GW public CI, 4.5 million BEVs, 0.4 million PHEVs; +73% in *RESID OPTI*: 7.1 GW public CI, 4.3 million BEVs, 0.4 million PHEVs). Also the scenarios with more conservative CI accessibility still outperform the recommended number of chargers by 5%–15% (+15% in *PC CONS*: 3.9 GW public CI, 3.2 million BEVs, 0.4 million PHEVs; +5% in *RESID CONS*: 3.5 GW public CI, 3.1 million BEVs, 0.4 million PHEVs). The recommended number of chargers is only missed if no residential chargers are deployed (−18% in *RESID ZERO*: 2.1 GW public CI, 2.3 million BEVs, 0.4 million PHEVs). According to our results, the EU recommendation on public CI is rather too conservative for achieving BEV uptake cost-efficiently, i.e., stronger BEV penetration can be achieved with more public CI than the EU recommendation. However, it is worth noting that workplace chargers are considered public chargers in our modeling context, while the EU recommendation does not cover them for publicly available CI. Still, our results align with a review of the EU proposal, which suggests that more public CI capacity than recommended is particularly important to accelerate BEV uptake when BEV market shares are still low [81]. Furthermore, our results indicate that the number of

BEVs per public charger decreases when the number of BEVs owned by consumers without private charging access increases, which is the case when charging options in residential areas are improved (compare figure 3 and table 4). This is in line with international observations showing that in countries with widespread options for charging at home or in the residential neighbourhood more EVs are deployed per public charger(e.g., Norway, which is a forerunner country in terms of EV uptake, with one public charger per 29 EVs and the United States with one public charger per 18 EVs) [1].

The deployment of 1.4 to 2.0 million private home chargers (PRIVs) reflect 87%–97% of all chargers (table 4). The number of public chargers (RESID, COMM, and RAPID) varies between 37,000 to 243,000, from which 35,000 to 70,000 are in public locations away from home (COMM and RAPID) (table 4). While COMM chargers in this study combine chargers at workplaces, which are not necessarily publicly accessible, and chargers at other commercial public locations, it is noteworthy that Hardman *et al* [14] found that chargers at work are more important than chargers in public locations. RESIDs make up a relatively large part of the public chargers, as the model favors using them for overnight charging over using COMMs and RAPIDs for daytime charging (still, daytime charging also takes place, as not every parking lot is equipped with a charger and to cover long distances). The large variation of RESID chargers (0–194,000) mainly depends on their availability and accessibility. The relatively high rated power of RAPIDs is why almost as much electricity is drawn from them (1.1 TWh in NZC Ref) as from RESIDs (1.3 TWh), despite its much lower number of chargers. The rapid charging required in 2050 to cover long-distance trips (equation (3)) equates to around 5% of the total charging at locations away from home. Considering the 65 fueling stations currently located on Swiss highways[11] (with approximately 6 pumps each) [82], this indicates that each fuel station would need between 16 to 60 rapid charging points, depending on the scenario.

3.1.4. Net-zero can be achieved with various vehicle fleet deployment trajectories

It becomes apparent that the interplay between BEVs (with a fleet share of 39%–77% in figure 3) and FCEVs (4%–28%) depends on the cost-efficient integration of CI options into the energy system. While a net-zero energy system is achieved in all scenarios by 2050, the results show that the 2050 car fleet still contains conventional ICEVs (9%–12%) and hybrid cars (1%–15%), which are partially driven with zero-carbon fuels. In additional sensitivity analyses, we evaluated the idea of banning ICEVs and hybrids by 2050 and found that such a solution is possible for the model but does not come into play in a cost-minimal scenario. Specifically, while the reduced tailpipe CO_2 emissions in the transport sector allow non-transport sectors to avoid expensive CO_2 mitigation measures that reduce their costs by 14 billion CHF cumulatively from 2024 to 2050, the increased capital costs for cars raise the transport sector's cumulative costs by 25 billion CHF, leading to a cumulative cost overshoot of 11 billion CHF when ICEVsand hybrids must completely phase out compared to NZC Ref. Furthermore, such a ban would let consumers with overnight charging access deploy more BEVs, and others would deploy more FCEVs.

3.2. Which major systemic impacts in the energy system are triggered by differing CI options? (*RQ2*)

The different CI options lead to varying car fleet compositions, which is closely linked to other cross-sectoral implications for the cost-optimal energy system. We especially observe cross-sectoral impacts on energy storage capacities, the energy conversion and storage sectors, and the deployment of needed energy supply technologies to meet the demand.

3.2.1. Higher electrification shares drive down the car fleet's fuel consumption

The fuel consumption of the Swiss car fleet (figure 4) reflects the varying car technologies across the scenarios (figure 3). Compared to the car fuel consumption of 145 PJ in 2020, the BAU Ref reaches 75 PJ by 2050 due to high vehicle efficiency. Alternative fuels in the net-zero scenarios further decrease the fuel consumption to 47–57 PJ The car fuel consumption is lower with stronger BEV uptake (47 PJ when overnight charging prevails for homeowners and tenants) and higher with more hybrids and FCEVs (57 or 54 PJ when overnight charging is only possible for homeowners or when public CI is limited, respectively).

3.2.2. FCEV deployment requires more CO_2 mitigation measures in other energy sectors than BEV uptake

Generally, trade-offs between hydrogen-fueled FCEVs and electricity-powered BEVs and PHEVs should be considered in the long term when FCEVs become increasingly cost-competitive. Hydrogen can be more easily and efficiently stored than electricity over longer time horizons, providing an advantage in integrating FCEVs in a future energy system that contains high renewable electricity shares, which supply can fluctuate across seasons and days [83, 84]. Moreover, FCEVs could cover trips with longer distances with reduced need for refueling breaks than BEVs [24]. However, converting electricity into hydrogen is less efficient when the produced

[11] In total, Switzerland has 3,325 fuel stations [82].

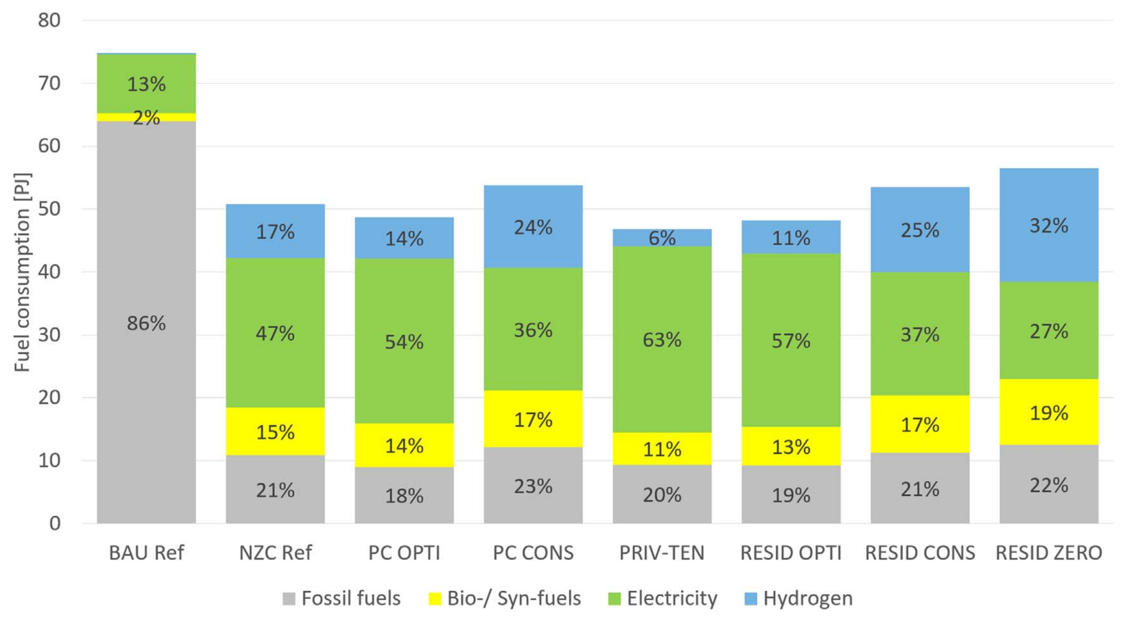

Figure 4. Total fuel consumption (in PJ) of the Swiss car fleet in 2050 by scenario.

electricity can power BEVs/PHEVs without long storage periods [84]. Moreover, hydrogen requires deploying costly supply chain infrastructure for its compression, distribution, storage, and dispersion [2, 85]. Furthermore, while hydrogen supply is limited, various energy sectors require hydrogen to decarbonize, e.g., to provide high-temperature heat in industry or fuel for heavy-freight and long-haul transportation, making electricity under current conditions more viable for cars.

Like the car fuel consumption, figure 5 elucidates that tailpipe CO_2 emissions in the transport sector are lower in scenarios where more BEVs are deployed and higher in scenarios where more hybrids and FCEVs are deployed. Thus, a stronger BEV uptake reduces the need for CO_2 mitigation measures in other energy sectors (figure 5). Cross-sectoral implications are particularly observed for the electricity supply and energy conversion sector. In electricity supply, up to 4% more (+0.2 Mt_{CO2}) and down to 6% less (−0.3 Mt_{CO2}) CO_2 is produced, compared to *NZC Ref*. This is due to more or less electricity from gas when more BEVs or FCEVs enter the fleet, respectively. In energy conversion, CO_2 emissions rise by up to 190% (+0.6 Mt_{CO2}) and decrease by down to 90% (−0.3 Mt_{CO2}), which can be largely attributed to the amount of hydrogen produced via steam methane reforming (figure 6). However, most of such emissions are captured because the additional electricity from gas and the hydrogen supply via steam methane reforming are both equipped with Carbon Dioxide Capture and Storage (CCS). Moreover, when more FCEVs (and fewer BEVs) enter due to limited overnight charging options, more direct air capture—a relatively expensive CO_2 mitigation measure—needs to be deployed to capture up to 0.3 Mt_{CO2} (81% more than in *NZC Ref*). Across all energy sectors (not only those shown in figure 5), a total of 10 to 11 Mt_{CO2} is captured in 2050. In a sensitivity analysis scenario where ICEVs must entirely phase out by 2050 and are therefore substituted by more BEVs and FCEVs, we find reduced transport tailpipe emissions by 0.6 Mt_{CO2} in 2050. These emission reductions allow relaxing other CO_2 mitigation measures, which is found by a lesser use of CCS in bio-/synfuel production (0.2 Mt_{CO2} less are captured, mainly due to reduced bio-/synfuel demand for powering cars) and in direct air capturing (0.1 Mt_{CO2} less are captured).

3.2.3. While BEV uptake induces more power-to-X for seasonal energy shifts, FCEV uptake comes with increased hydrogen production

Higher BEV shares do require more electricity in winter. However, net-zero futures contain high shares of electricity from solar PV (28% in *NZC Ref* 2050), leading to oversupply in summer and limited supply in winter. This requires a seasonal shift by converting electricity into hydrogen via power-to-X technologies in summer, storing this in additional seasonal hydrogen storage capacities, and using the hydrogen in winter/spring to close the energy supply gap. With high BEV shares, up to 4.2 PJ hydrogen is shifted from summer to winter. With low BEV shares, less seasonal shifting (3.8 PJ) occurs.

Furthermore, stronger implementation of overnight charging requires that electricity is consumed during nighttime. Besides using stored electricity from the daytime, this provides an option to use electricity generated throughout the night, such as at hydro dams, running rivers, and wind. This relaxes the energy system by reducing competition with other energy sectors that can then utilize solar PV during their daytime operations.

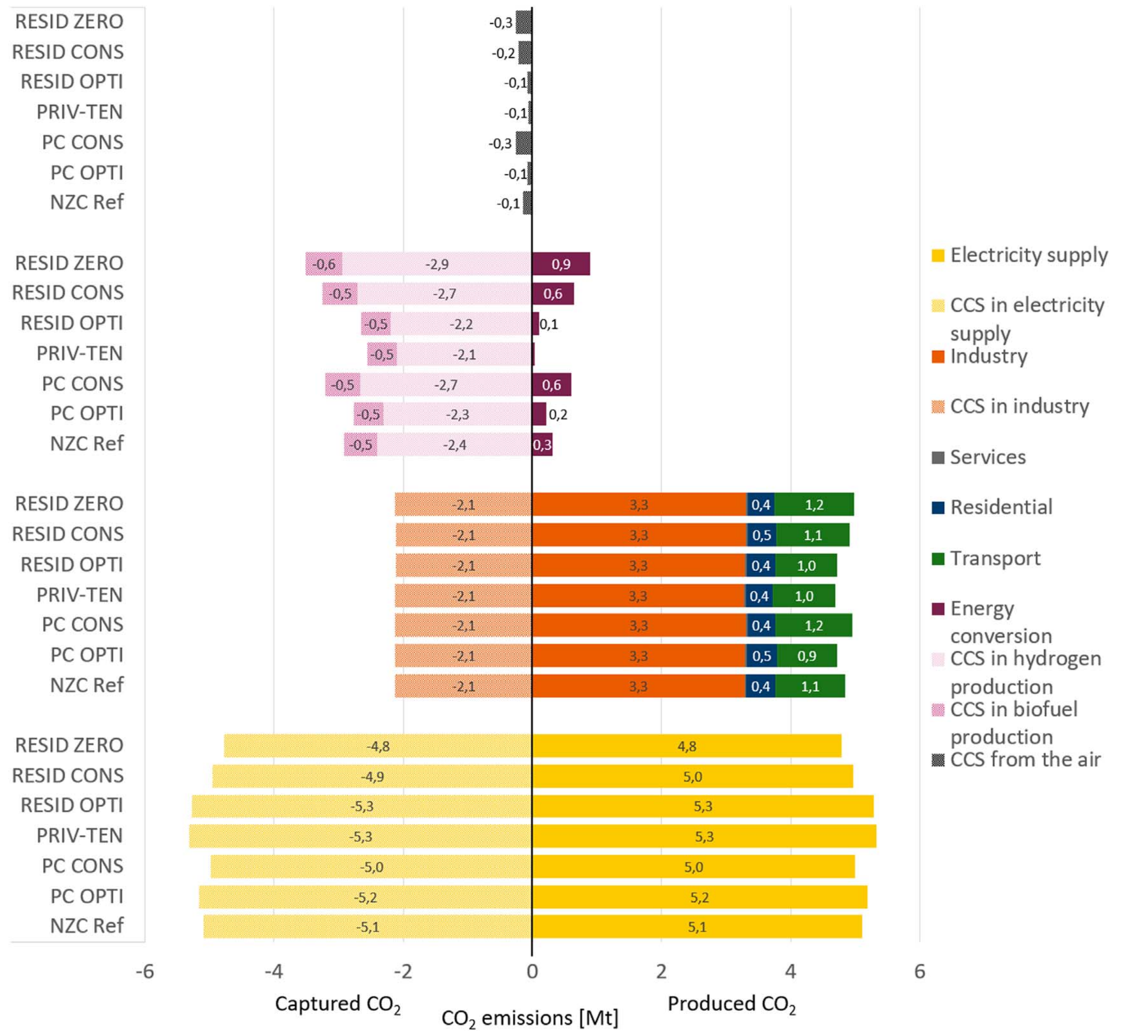

Figure 5. Sector-specific produced and captured CO_2 emissions by scenario. While each scenario achieves system-wide net-zero CO_2 in 2050 (all scenario-specific bars sum up to zero), this graph visualizes the sector-specific variations. The right-hand-side presents produced CO_2 emissions, and the left-hand-side shows captured CO_2 emissions via CCS technologies. The transport emissions refer to the sector's tailpipe emissions, e.g., when cars operated with bio-/synfuels would have net-zero CO_2 emissions, their positive tailpipe emissions are represented in the transport sector while their negative emissions from producing bio-/synfuels are captured as negative emissions in the energy conversion sector. The *BAU Ref* scenario is excluded for improved readability.

To power the car fleets with the highest FCEV share (*RESID ZERO*) instead of highest BEV share (*PRIV-TEN*), the energy system's final hydrogen consumption delta accounts for 21.9 PJ , which is attributed to a 0.1 PJ reduction each in the industry and service sector and a 22.2 PJ increase in the transport sector (+15.3 PJ for cars, +1.0 PJ for busses, +5.9 PJ for trucks). Figure 6 shows that the additional hydrogen is primarily produced via steam methane reforming with CCS and electrolysis. Additional hydrogen demand induces inefficiencies in the energy system due to additional conversions (electricity into hydrogen compared to direct use of electricity in EVs). Consequentially, this makes electricity more expensive, which impacts the supply and demand side. On the supply side, more renewable energy is needed, requiring a more flexible energy system for its integration into the power system. On the demand side, additional energy saving measures in the demand sectors are triggered, such as more efficient heat pumps and improved building insulation measures.

3.3. Policy recommendations to support CI for an effective EV rollout (*RQ3*)

From the above parametric scenarios on the accessibility of different CI options, we try to draw policy insights for an effective EV rollout. We focus on BEV uptake, as this leads to a more immediate reduction in CO_2 emissions, as opposed to FCEVs, which will later become market-ready and oppose higher stress levels in the energy system.

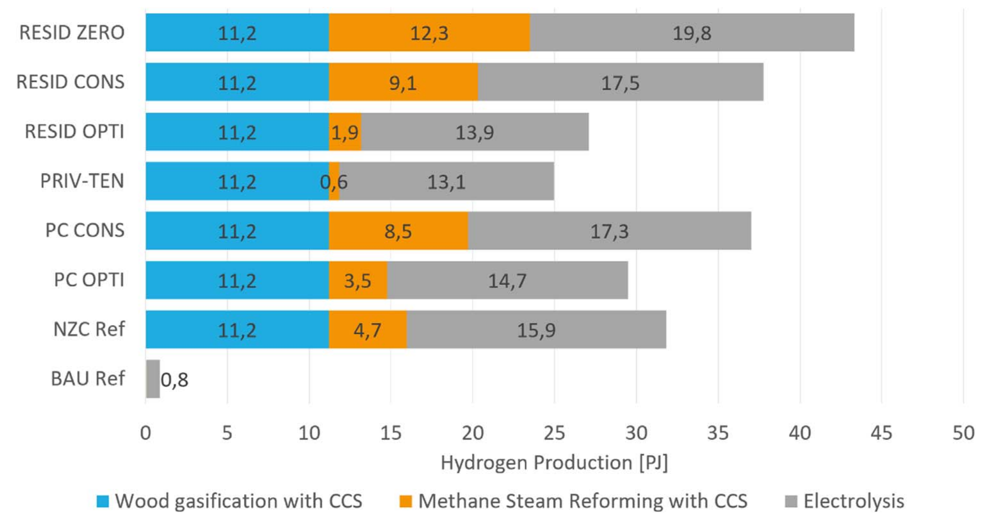

Figure 6. Hydrogen production in 2050 by scenario.

3.3.1. Overnight charging options as key enablers for BEV uptake

Any hindrance to overnight charging options reduces the overall BEV share in the Swiss car fleet from 64% to 39%–52% in 2050. In such scenarios, tenants opt for hybrid cars in the short-term and FCEVs in the long-term, which undermines the decarbonization effects. On the contrary, BEV uptake is strongest when overnight charging options are available by making PRIV chargers available to tenants (*PRIV-TEN*: 77% in 2050) or by assuming optimistic accessibility of public chargers in residential areas (*RESID OPTI*: 72%). Further, using BEVs makes the energy system more efficient due to fewer conversion losses than FCEVs. Therefore, policies could address legal implications that provide improved overnight charging options. These should distinguish between consumers with a privately rented parking lot and those who park at home in a public parking spot:

1. **Tenants with private rented parking lots:** policies could either mandate landlords to install CI or allow tenants to install PRIV CI. Many such policies are widely discussed and already applied in other countries. Norway, a forerunner country for BEV deployment, and German regulations provide tenants the right to install a PRIV in their rented parking lot [72, 86]. For instance, the city of Oslo implemented a mandate that calls for private charging options on at least 50% of the parking lots in new buildings [72]. However, we suggest that such a mandate should cover existing and new buildings. If it were limited to new houses or houses being renovated, it would take several decades until sufficient PRIV CI is installed. In countries with higher EV shares, PRIV is provided in all parking spaces of new buildings, even without regulations, as landlords recognize the increased parking lot value generated by CI [72]. In Switzerland, building owners show increasing awareness of such advantages to increase their property value, which is a promising indicator for a future with easier PRIV access for tenants [72, 87].
2. **Consumers parking at home on a public parking spot:** policies could adjust urban planning regulations to require a certain number of RESID charging spots, depending on local conditions, such as the private parking lot ownership rate. While local governments in Switzerland are typically in charge of such regulations, national subsidies could help incentivize the installment of such CI on a regional level. Residential roadside CI could either be classical chargers or innovative approaches like in London, where existing street light infrastructure is upgraded with charging options [88]. An alternative to residential roadside chargers are EV neighborhood hubs, whose installment a German state (Baden-Wuerttemberg) recently agreed to subsidize [89]. Such hubs could save space and enable more CI options at home for those without PRIV [90].

3.3.2. Charging options at commercial locations should be complemented by chargers in residential areas

Additional charging possibilities at public locations away from home (*PC OPTI*: increased CI accessibility for COMM and RAPID) can increase the share of BEV to 69% in 2050 (figure 3). This effect comes with a 20% increased amount of electricity charged through COMM and 36% through RAPID, respectively. Further, it is accompanied by 28% higher PC in residential areas (RESID). For policymakers, this underlines the complementary nature of different CI options to achieve cost-efficient integration of BEVs into the energy system, demonstrating the importance of a strategic CI concept.

To facilitate CI at commercial locations, the varying parking behaviors and charging use cases at different location types should be considered:

1. **Mandates for workplaces and commercial buildings:** A mandate for employers to offer charging options could make BEVs more attractive for those who cannot charge at home, as real-world data from other countries show that charging takes primarily place at home and work [72]. Similar to a residential building regulation (section 3.3.1), CI deployment could be mandated for commercial buildings (e.g., shopping centers, hotels, and restaurants). This would be a particularly important measure for consumers who cannot charge at home or work. Further, this could provide business model opportunities via additional revenue streams through payment schemes or attracting customers through free charging [91].
2. **CI deployment in rural areas:** Demand-driven approaches for CI buildup led many countries to a CI concentration in urban areas, while rural areas were neglected [86]. Swiss policymakers should avoid such a situation. Actually, public chargers in rural areas can be an important driver to keep up the EV sales momentum, as the availability and visibility of public chargers are an important BEV purchase determinant when BEVs are not common yet [1, 79]. For instance, the United States announced an action plan that dedicates $2.5 billion to support rural charging and CI accessibility in disadvantaged communities [92].

3.3.3. More power is not always better

The ideal charging power depends on the time of the day when such chargers are typically used:

1. **CI primarily used overnight (PRIV and RESID):** our results show that 70% of the EVs with overnight charging access are recharged on an average night. Further, the results infer that integrating charging stations with lower rated power (7 kW instead of 22 kW) into the energy system is sufficient and more cost-effective due to long parking durations and lower capital costs. With overnight CI, smart/coordinated charging can smoothen electricity demand peaks. The importance of smart charging has also been recognized by the European Commission, which recently proposed ensuring smart charging for a more flexible energy system [93, 94].
2. **CI primarily used throughout the day (RAPID and COMM):** we found that charging stations in commercial locations are more cost-effective with higher rated power, i.e., RAPID (150 kW) instead of COMM (22 kW). Besides allowing more efficient usage of renewable solar energy throughout daytime, they also enable quicker recharging, reducing potential waiting times, a key perceived barrier for consumers to adopt EVs [95–97]. However, it could be argued that the RAPID CI capacity should be partially substituted by deploying more COMM CI, each with lower rated power, to deploy more charging points with denser distribution and reduce undesirable waiting times [98] when the number of cars outweighs the charging points. Thus, there are tradeoffs between a limited number of higher rated power CI and more CI with lower rated power. Dedicated agent-based transport- and traffic-models can help make choices depending on local conditions [99–104].

3.4. Limitations and future work

This analysis provides meaningful insights into the cost-optimal integration of different CI options into the Swiss energy system from a technological perspective. However, we do not consider consumers' (potentially changing) behavior regarding charging preferences and vehicle choices. Instead, this work focuses on assessing the cost-optimal integration of BEVs depending on the time- and consumer-specific availability of various CI types based on current car usage patterns. Future work could merge our methodological CI enhancements with recent method enhancements representing specific behavioral consumer mobility choices in ESOMs [105, 106].

STEM is an energy system model that optimizes costs from a social planner perspective. However, consumers see and react based on market prices. To reflect consumers' price sensitivity, the system's electricity costs could be substituted with the actual prices consumers experience for charging. Other model types could be more suited to represent prices and individual consumer decision-making [107, 108]. However, implementing this in a large-scale ESOM like STEM requires a consistent shift from system costs to consumer prices across all energy system sectors. Moreover, to ensure consistency with other energy sectors represented in STEM, the transport sector is calibrated for 2010, 2015, and 2020 despite the sector's fast development (see appendix C).

The CI options in STEM are mapped to cars' aggregated locations (e.g., at home and work) based on Swiss mobility survey data [54]. The modeling framework is limited by considering each CI option as an aggregated capacity instead of as individual charging points at specific locations. Thus, the CI options represent country-wide charging nodes but are not allocated to GIS-based locations. Agent-based transport simulation models with a finer geographical resolution [109–112] and dedicated EV charging models [113] could be better suited for a detailed assessment of the ideal type and number of charging points needed at certain locations. However, such models typically lack in assessing cross-sectoral impacts and have other disadvantages [114]. In ESOMs, such detailed assessments could be considered via model coupling [115–117], but such approaches can be challenging [105]. For future work with ESOMs, we suggest improving the model's spatial disaggregation [118] and distinguishing COMM chargers by typical parking/charging duration. For instance, a distinction between chargers at (semi-public) workplace locations and other public locations should be considered (compare with table 1).

While our results show stronger EV uptake potential when PRIV becomes available to tenants, such future development remains uncertain. The method applied in this work is limited by assuming that PRIV will become 'fully' available or will not be available. This approach could be more nuanced by reflecting, for instance, that some tenants get access to PRIV due to the landlord's decision.

The results do not provide forecasts of the future but rather potential future pathways that achieve a cost-optimal net-zero energy system. The CI assumptions are subject to uncertainties regarding current and future mobility and charging behavior [119], as assessed by extended sensitivity analyses (section 3.1). When EVs become more mainstream, data availability and robustness should increase, allowing to determine such factors better. However, with the sensitivity analyses performed, we showed a range of future trajectories—still, the reality could be somewhere in between. Furthermore, fixed transport demand trajectories have been applied in this work. Price-elastic demands, as well as wider socioeconomic trends[12] influencing travel demands, could be assessed in future work.

Future work could link the residential and transport sector in the model to determine the different availabilities of local low-carbon electricity for optimizing EV charging. Moreover, while we assume more centralized and market-driven hydrogen fueling stations, such infrastructure could be modeled more explicitly. Lastly, the costs of the provided policy suggestions were not assessed, but future work could apply these policies in STEM to assess systemic cost implications.

4. Conclusion

We assessed the role of different CI options for cost-efficiently integrating BEVs into the energy system by assessing potential long-term system-wide net-zero pathways in the Swiss TIMES energy system model (STEM). The interplay between the demand-side advancements in STEM considers an hourly intraday time resolution. This provides an important step towards improving the temporal resolution of CI options and their flexibility in ESOMs, which is gaining increasing attention from the modeling community [21, 22]. In addition, the charging considers a spatial proxy by mapping the CI options to cars' location types and trip categories. This allowed us to demonstrate systemic implications and required CO_2 mitigation measures for other energy sectors. The insights from our scenario analysis led to valuable recommendations for policymakers. As the Swiss energy system is techno-economically closely embedded in Europe, results from our work can also provide indications for other countries.

The provision of overnight charging (PRIV and RESID) is most conducive for integrating BEVs into the energy system due to long parking durations that allow avoiding electricity demand peaks by utilizing controlled charging. When increased overnight charging is achieved by making PRIV chargers available to tenants, 4.54 million BEVs and 0.39 million PHEVs, and 2.2 million overnight chargers (2.0 million PRIV and 152 thousand RESID) are deployed. When more overnight charging is achieved through high RESID accessibility, 4.28 million BEVs and 0.38 million PHEVs enter the fleet, requiring 1.6 million PRIV and 194 thousand RESID overnight chargers. Adjusting building- or urban planning regulations could help achieve this. Further, we found that CI with lower rated power is sufficient and more cost-effective for overnight/home charging.

PC options away from home (COMM and RAPID) support the BEV rollout by making their adoption cost-effective for consumers who cover long-distance trips or cannot charge (overnight) at home. CI with higher rated power is cost-advantageous for this, as faster charging throughout the day allows more efficient use of renewable energy from photovoltaics. The system deploys 11,000 to 23,000 RAPIDs by 2050, and each BEV uses them annually for 1.5–2.5 hours on average. Still, policymakers should consider tradeoffs between this cost-effective solution and providing more charging spots (each with lower power) to ensure sufficient charging spots at peak demand times. Further, increased CI accessibility away from home leads not only to more BEVs (+9%) and usage of such CI (+35%) but, in turn, also to more PC at home (+28%) to utilize long parking durations. Therefore, overnight charging options should be accompanied by sufficient CI in commercial locations and on highways. However, this work is limited regarding location-specific CI allocation, and spatially more detailed models could help provide such insights.

[12] For instance, carsharing, increased remote work and leisure trips, more centralized or decentralized automated driving leading to higher productivity and fewer time restrictions for traveling, and trends towards pedestrianizing and car reduction in inner cities.

The methodological enhancements of this work allowed a higher level of consumer-specific EV charging details that reflect various types of locations. Thereby, improved charging flexibility was achieved compared to previous approaches used in ESOMs. Considering who can charge when, where, and at what type of CI enabled a close link with available energy supply options by daytime and season, which becomes increasingly important in a future net-zero energy system. This enabled novel and advanced analyses of CI options within the energy system. The methodology can serve as a basis for other ESOMs, which typically represent the transportation sector at a more aggregated level. Future work should distinguish commercial chargers at locations with shorter and longer parking duration, e.g., workplace chargers, and it could aim at linking the residential and transport sector to determine the availability of local low-carbon electricity for EV charging.

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Data availability statement

The data cannot be made publicly available upon publication because they contain commercially sensitive information. The data that support the findings of this study are available upon reasonable request from the authors. https://data.sccer-jasm.ch/.

Contributions

Sandro Luh: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - Original Draft, Visualization, Project administration. **Ramachandran Kannan:** Conceptualization, Resources, Writing – Review & Editing, Supervision, Funding acquisition. **Russell McKenna:** Conceptualization, Writing – Review & Editing. **Thomas J. Schmidt:** Writing – Review & Editing, Supervision. **Tom Kober:** Conceptualization, Resources, Writing – Review & Editing, Supervision, Funding acquisition.

Appendix A

A.1 Techno-economic parameters of cars in STEM

Analog to the STEM model with one homogeneous consumer, each of the eight consumer segments can invest in four car size categories, each with eleven car types varying by drivetrain and fuel (table A1). Appendix B.3 provides more details on such investment options.

Table A1. Overview of techno-economic parameters for cars the model can invest in. Data source: [55, 120][a,b].

Car size by engine power[c]	Drivetrain	Fuel	Capital cost [CHF] 2030	Capital cost [CHF] 2050	Fixed O&M cost [CHF] 2030	Fixed O&M cost [CHF] 2050	Efficiency [vkm/MJ] 2030	Efficiency [vkm/MJ] 2050
<60 kW	ICEV	Gasoline	100%	100%	100%	100%	100%	155%
		Diesel	113%	112%	100%	100%	105%	154%
		Natural Gas	107%	97%	100%	100%	97%	154%
	Mild hybrid	Gasoline	103%	100%	100%	100%	102%	155%
		Diesel	115%	112%	100%	100%	108%	155%
	Hybrid	Gasoline	110%	105%	100%	100%	148%	179%
		Diesel	110%	105%	100%	100%	148%	179%
	PHEV	Electricity + Gasoline	114%	110%	100%	100%	156%	262%
		Electricity + Diesel	114%	110%	100%	100%	158%	263%
	Battery	Electricity	126%	112%	83%	83%	304%	369%
	Fuel Cell	Hydrogen	150%	118%	87%	83%	184%	234%
60–100 kW	ICEV	Gasoline	195%	196%	260%	260%	81%	129%
		Diesel	219%	217%	260%	260%	85%	128%
		Natural Gas	208%	189%	260%	260%	78%	128%
	Mild hybrid	Gasoline	200%	196%	260%	260%	83%	129%
		Diesel	222%	217%	260%	260%	87%	129%
	Hybrid	Gasoline	213%	204%	260%	260%	122%	149%
		Diesel	213%	204%	260%	260%	122%	149%
	PHEV	Electricity + Gasoline	217%	210%	260%	260%	133%	227%
		Electricity + Diesel	216%	210%	260%	260%	135%	228%
	Battery	Electricity	241%	217%	217%	217%	246%	301%
	Fuel Cell	Hydrogen	286%	228%	225%	217%	150%	192%
101–140 kW	ICEV	Gasoline	248%	249%	368%	368%	75%	121%
		Diesel	278%	275%	368%	368%	79%	120%
		Natural Gas	247%	224%	342%	342%	75%	123%
	Mild hybrid	Gasoline	254%	249%	368%	368%	77%	121%
		Diesel	282%	274%	368%	368%	81%	120%
	Hybrid	Gasoline	297%	284%	406%	406%	110%	135%
		Diesel	297%	284%	406%	406%	110%	134%
	PHEV	Electricity + Gasoline	276%	268%	368%	368%	133%	226%
		Electricity + Diesel	276%	268%	368%	368%	134%	227%
	Battery	Electricity	319%	289%	323%	323%	224%	276%
	Fuel Cell	Hydrogen	366%	292%	318%	306%	139%	179%
>140 kW	ICEV	Gasoline	208%	209%	273%	273%	76%	119%
		Diesel	264%	261%	312%	312%	75%	113%
		Natural Gas	206%	188%	254%	254%	75%	122%
	Mild hybrid	Gasoline	213%	209%	273%	273%	78%	120%
		Diesel	267%	261%	312%	312%	77%	113%
	Hybrid	Gasoline	256%	246%	312%	312%	109%	131%
		Diesel	256%	247%	312%	312%	109%	131%
	PHEV	Electricity + Gasoline	262%	255%	312%	312%	124%	208%
		Electricity + Diesel	261%	255%	312%	312%	125%	209%
	Battery	Electricity	292%	268%	273%	273%	217%	263%
	Fuel Cell	Hydrogen	302%	243%	236%	228%	140%	178%

[a] All values have been scaled in relation to the baseline year (2020) data of the ICEV gasoline car with an engine power of less than 60 kW.
[b] In addition to 2030 and 2050, exact values are available for the model's milestone years in 2020 and 2040. Values between and beyond the milestone years have been linear interpolated and forward extrapolated, respectively.
[c] 1 kW = 1.341 horsepower.

Appendix B. Methodological advancements in STEM

The STEM advancements regarding consumer segments and trip types are relevant due to their interplay with the CI options. Further, they increase the model's level of detail.

B.1. Consumer segmentation

Eight consumer segments are implemented in STEM's passenger transportation module. Inspired by previous studies [26–28], they distinguish socio-demographic and socio-economic parameters within the population to reflect varying mobility demands, driving patterns, and EV charging options with a higher level of detail. Table B1 outlines the characteristics of each consumer segment.

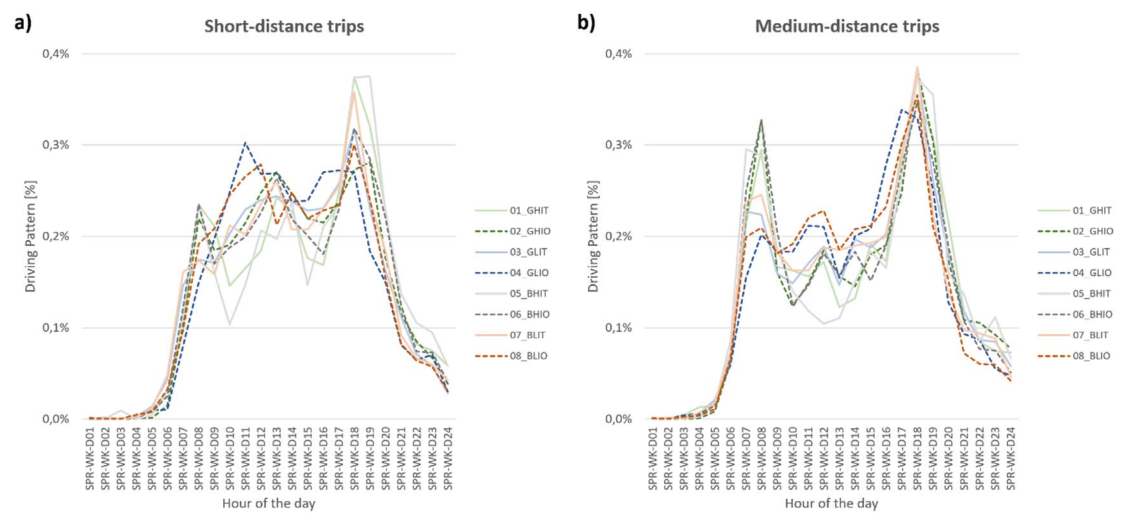

Figure B1. Consumer- and trip-specific driving patterns with hourly resolution. The driving patterns for each consumer segment and trip type are determined based on the Swiss MTMC 2015 survey with 57,000 respondents [54]. The graphs show exemplary driving patterns on a spring weekday of a) short-distance trips and b) medium-distance trips. For each consumer-trip combination, the percentage sums to 100% when considering all weekdays and seasons, i.e., the annual demand.

Table B1. Summary of consumer segment parameters[a].

#	Abbreviation	Public transport connectivity at the place of living (G/L)[b]	Household income (HI/LI)[c]	Household ownership type (T/O)
1	GHIT	Good	High Income (>10,000 CHF)	Tenant
2	GHIO	Good	High Income (>10,000 CHF)	Owner
3	GLIT	Good	Low Income (<=10,000 CHF)	Tenant
4	GLIO	Good	Low Income (<=10,000 CHF)	Owner
5	LHIT	Limited	High Income (>10,000 CHF)	Tenant
6	LHIO	Limited	High Income (>10,000 CHF)	Owner
7	LLIT	Limited	Low Income (<=10,000 CHF)	Tenant
8	LLIO	Limited	Low Income (<=10,000 CHF)	Owner

[a] The data for defining and calibrating the consumer segments were acquired via the Swiss Mobility and Transport Microcensus 2015 [54].
[b] The public transport connectivity at the place of living is determined based on the public transport quality classes calculated by the Swiss Federal Office for Spatial Development (ARE) [121]: 'good' reflects the ARE ratings A, B, and C; 'limited' reflects the ARE ratings D, and 'none'.
[c] The cut between 'high' and 'low' household income at 10,000 CHF reflects the rounded average gross household income in Switzerland in 2015–2017, which is 9,951 CHF [122]

B.2. Trip types

To reflect that BEVs require rapid charging on long-distance trips, we split each consumer segment's mobility demand across four trip types in STEM. Regarding the trip distance, we distinguish short-distance trips (<10 km), medium-distance trips (10–80 km), and long-distance trips (>80 km), according to a 2015 Swiss mobility survey [54]. The long-distance trips further distinguish between those where the starting point and destination are in a high-agglomerated area (lower threshold for consumers' need for rapid charging) and those where starting point or destination is in a low-agglomerated area or outside the agglomeration (higher threshold). Furthermore, figure B1 shows exemplary hourly car driving demand patterns that differentiate each consumer segment and trip type.

B.3. Charging infrastructure

The specific capital costs, specific fixed Operation and Maintenance (O&M) costs, and the technical lifetime of each charging infrastructure option are outlined in table B2.

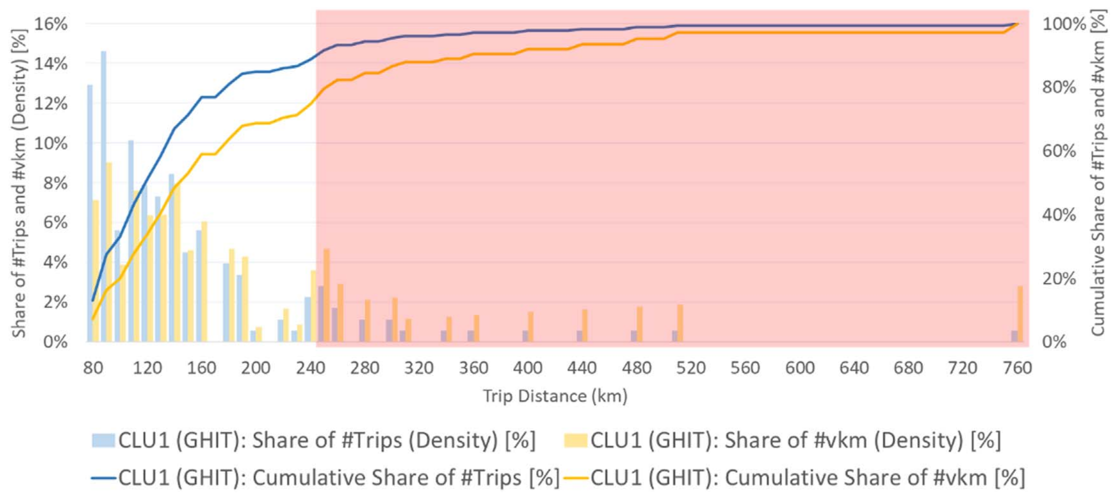

Figure B2. Exemplary histogram of long-distance car trips of consumer segment GHIT in 2015. The red area visualizes the trip distances that exceed 70% of the battery range of a medium-sized BEV in 2030 (344 vkm * 70% = 241 vkm). Thus, 9% of the long-distance trips (blue line) require rapid charging, translating to 29% of the long-distance vkm (yellow line). Data source: [54].

Table B2. Overview of charging infrastructure options.

Charger type	Charger short name	Specific capital costs[a] (hardware + installation) [64] [CHF/kW]	Specific fixed O&M costs [65] [CHF/kW]	Technical lifetime [years]
PRIVate home charger	PRIV	2020: 767 2030: 566 2040: 417 2050: 308	7	20
RESIDential public charger	RESID	2020: 789 2030: 582 2040: 429 2050: 317	91	20
COMMercial public charger	COMM	2020: 789 2030: 582 2040: 429 2050: 317	91	20
RAPID public charger	RAPID	2020: 561 2030: 414 2040: 305 2050: 225	13	40

[a] The charger hardware costs assume a 3% annual decline rate for future years [64]. Further, the hardware costs assume one charging point per charger/pedestal [64].

B.3.1. Need for rapid charging of BEVs on long-distance trips. BEV's need for rapid charging on long-distance trips[13] is based on when the electricity consumption of such trips exceeds a defined threshold of the car battery's maximum distance range (figure B2). The electricity flow E of RAPIDs in timeslice ts must exceed $1/k$th of the electricity consumed on such trips in the previous k hours. This endogenizes that rapid charging must occur at times when long-distance trips are being made. For each vintage year v, engine power category j, and consumer segment c, the vkm share of such trips with BEVs that exceed the threshold and therefore need rapid charging is represented as $\theta_{v,j,c}$.

$$E^{RPC}_{ts,v,k,j,m,c} \geqslant \theta_{v,j,c} {}^{*} \tau_{m,c,v,j} {}^{*} \frac{1}{k} \sum_{ts-1}^{ts-k} pkm_{\,j,c,t,v,m} \tag{3}$$

[13] As PHEVs do not rely on electric charging, the need for rapid charging on long-distance trips is only implemented for BEVs.

with

$$\tau_{m,c,v,j} = \frac{1}{OR_{m,c} {}^{*} Eff_{v,j}} \quad (4)$$

to account for conversion from *pkm* to the electricity consumed on such trips. The latter formula considers the Occupancy Rate (*OR*) of each long-distance trip type *m* (trips in non-agglomerated versus agglomerated areas) and the fuel efficiency *Eff* of BEVs. Consumers' risk-taking willingness can be accounted for by adjusting the threshold at which rapid recharging is necessary. To achieve time consistency between rapid charging and long-distance trips, we assume k = 5 in equation (3).

B.3.2. Supplementary figure for the charger accessibility methodology.

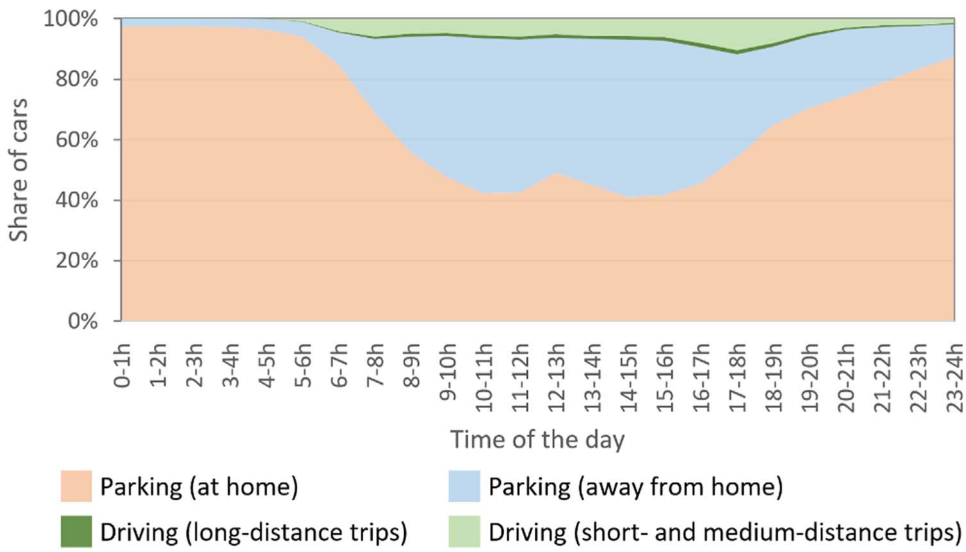

Figure B3. Car location profiles on an average day in Switzerland. The profiles are assumed to remain constant in future periods. Data source: [54].

Appendix C

C.1. STEM car transport calibration

The car transport sector has developed fast in recent years concerning an increasing deployment of EVs and respective CI. The car fleet in Switzerland in 2022 consists of 91% ICEVs (4.3 million), 5% Hybrids (220,000), 2% BEVs (111,000), and 1% PHEVs (64,000) [4]. Whereas the number of EVs is still relatively low, their sales shares have increased rapidly in recent years, reaching 25% in 2022 [5]. At the time of writing, the number of public chargers in Switzerland is 14,830 (see figure C2) [61]. For modeling purposes, the car transport sector had to be calibrated for 2020 to ensure consistency with the remaining sectors of the energy system covered in STEM.

With the new consumer segments, the mobility sector as a whole and each consumer segment are calibrated to 2010, 2015, and 2020 vehicle stocks, annually driven vehicle-km (vkm) and passenger-km (pkm), and fuel consumption [4, 54, 123, 124]. Each consumer segment is characterized by its individual average annual driving distance, hourly demand patterns, hourly car locations, car occupancy rates, and vehicle fuel efficiencies of the existing fleet.

The existing Swiss car stock is distinguished for each consumer segment across five drivetrain-fuel combinations, i.e., ICEV powered by gasoline, diesel and natural gas, BEVs, and hybrid gasoline cars. Within each consumer segment, each of those vehicles is calibrated separately: the fuel efficiencies of ICEV gasoline and ICEV diesel cars are estimated for each consumer group according to the Swiss Mobility and Transport Microcensus (MTMC) 2015 [54]. To achieve robust data for ICEV natural gas, BEVs, and hybrid gasoline cars, their fuel efficiencies are based on data from the entire MTMC 2015 (instead of differentiation across the consumer segments) due to their limited data sample within separate consumer segments [54]. Table C1 shows the model's calibrated vehicle fleet results in 2020 by consumer segment.

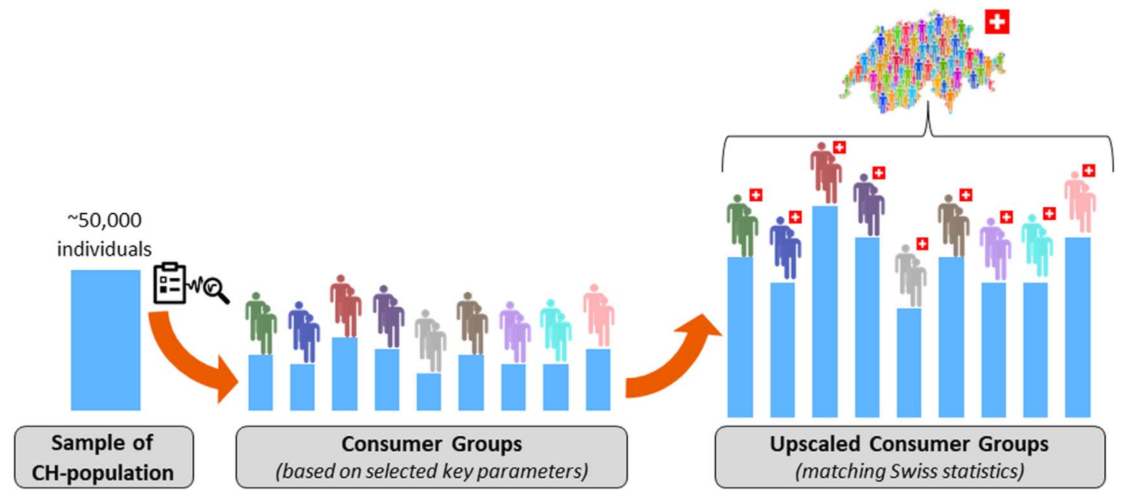

Figure C1. Calibration of the consumer segments.

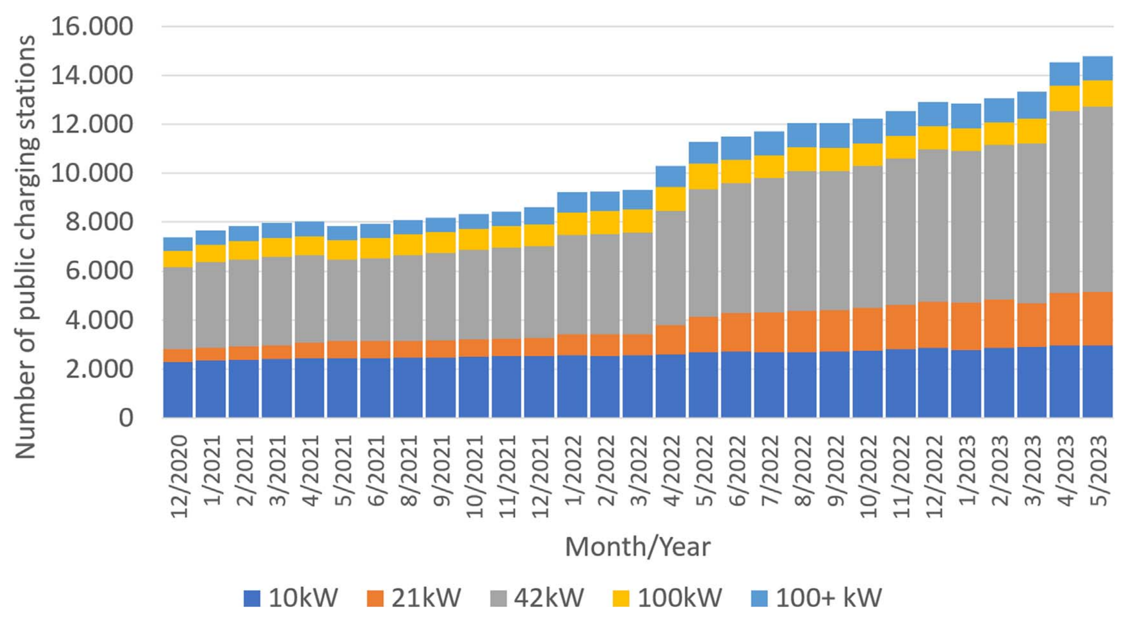

Figure C2. Past monthly development of the number of public charging stations by rated power in Switzerland. (**Data source:** [61]).

Table C1. Calibrated vehicle fleet results in 2020 by consumer segment.

Category	Vehicle type	GHIT	GHIO	GLIT	GLIO	LHIT	LHIO	LLIT	LLIO	Total
Car stock [million]	ICEV Gasoline	0.23	0.32	0.57	0.38	0.12	0.50	0.32	0.65	3.09
	ICEV Diesel	0.12	0.16	0.23	0.14	0.07	0.27	0.13	0.27	1.38
	ICEV Natural Gas	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
	BEV	0.01	0.01	0.00	0.00	0.00	0.01	0.00	0.01	0.04
	Hybrid Gasoline	0.01	0.02	0.02	0.02	0.01	0.02	0.00	0.03	0.13
Activity [vkm]	ICEV Gasoline	2.81	2.97	7.10	3.32	1.60	4.98	4.61	6.45	33.84
	ICEV Diesel	2.23	2.42	4.39	2.05	1.39	4.53	2.87	4.13	24.00
	ICEV Natural Gas	0.02	0.02	0.03	0.02	0.01	0.05	0.02	0.03	0.20
	BEV	0.09	0.06	0.00	0.01	0.00	0.12	0.02	0.08	0.39
	Hybrid Gasoline	0.15	0.28	0.32	0.18	0.12	0.33	0.09	0.33	1.78

New vehicles can penetrate the market from 2020 onwards. It is assumed that the economic value of a car is fully depreciated after ten years (economic lifetime). Analog to the STEM model with one homogeneous consumer, each of the eight consumer segments can invest in a variety of 44 car types, varying by drivetrain, fuel, and engine power (table A1). Across the consumer segments, the techno-economic parameters are adjusted to reflect technical car characteristics. For instance, the annual driving range varies across consumer segments and engine power categories, based on historical data [54], influencing annual Fixed Operation & Maintenance (O&M) costs. Also, the occupancy rate varies across trip types and consumer segments based on historical data [54]. For each consumer group and vehicle size, the values of each consumer segment are calibrated towards their annual driving distance data reported in MCMT 2015 [54]. Table A1 (Appendix) presents an overview of the possible car investment options. Appendix B provides more details on the mobility demands that steer each consumer segment's investment and usage decisions.

Car investments must meet certain conditions, derived by Panos *et al* [49], that we have adjusted to reflect the eight consumer segments instead of one homogenous consumer. Such conditions include limited growth and decay rates for vehicle technologies to reflect realistic market diffusions. Further, the maximum total car stock follows a trajectory based on the expected Swiss population development and the number of cars per capita, according to [56]. Finally, the engine power distribution across the four categories (appendix a) must reflect the data derived from MTMC 2015 [54] for each consumer segment. To account for varying preferences in the future, such shares are increasingly relaxed over time.

The number of existing publicly available charging stations in Switzerland in terms of their rated power is presented in figure C2. Based on the available data, existing public CI capacity has been calibrated for 2010 to 2020 [61, 71]. As data availability of private CI is lacking, such calibration is based on assumptions (section 2.3).

Appendix D

D.1. Systemic assumptions for the reference scenarios

Table D1 presents the systemic assumptions for the BAU Ref and NZC Ref scenarios. According to Kannan *et al*, BAU Ref 'is a business as usual scenario. We assume continuation of already decided energy policies in 2019. Neither any targets, for example, renewables deployment or vehicle emission standards, nor climate mitigation goals are imposed. Nevertheless, we assume progressive developments in vehicle (and energy supply) technologies in terms of cost reduction and efficiency improvements […].' [45]. Further, the NZC Ref scenario 'aims at achieving a net-zero CO_2 emission in the Swiss energy system and industrial processes by 2050. Up to 2030, the emission targets follow the trajectory sets under the Swiss CO_2 law […]. Between 2030 and 2050, the

Table D1. Systemic assumptions for the BAU and NZC reference scenarios (adopted from [45, 49]). Adapted from [45] John Wiley & Sons. © 2022 The Authors. Futures & Foresight Science published by John Wiley & Sons Ltd.

Key assumptions	BAU Ref	NZC Ref
Demands	Socio-economic demand drivers similar to the Swiss energy strategy 2050 plus (BFE, 2021). No new nuclear power plants and existing plants are phased out after a 60-year operational lifetime.	
Building emissions standards	No specific targets	12 kg-CO_2/m^2 in 2030 and beyond for the existing buildings. New buildings 0 kg-CO_2/m^2 from 2030 and beyond.
Vehicle CO_2 emissions standards	No specific targets	Cars: 105 g-CO_2/km in 2020 & 65 g-CO_2/km in 2030 and beyond. LGV: 160 g-CO_2/km in 2020 & 110 g-CO_2/km in 2030 and beyond. HGV: 680 g-CO_2/km in 2020 & 475 g-CO_2/km in 2030 and beyond. Coach buses: 820 g-CO_2/km in 2020 & 575 g-CO_2/km in 2030 and beyond. City buses: 1160 g-CO_2/km in 2020 & 810 g-CO_2/km in 2030 and beyond.
CO_2 emissions reduction target	No specific targets	Up to 2030, the emission targets sets under the Swiss CO_2 law (BAFU, 2020). By 2050, achieve a net-zero emission in energy system.[a]
Fossil fuel prices	No specific targets	IEA's Sustainable Development Scenario prices (IEA, 2020).
Transport fuel tax	No specific targets	Current climate levy and fuel taxes are for diesel and gasoline. For new transport fuels (electricity/hydrogen), a mineral oil tax equivalent to gasoline is applied.

[a] Only from CO_2 emissions from fuel combustion and industrial processes. We exclude international aviation and agriculture. Between 2030 and 2050, the CO_2 cap is linearly applied.

CO_2 cap is linearly applied to reach the net-zero goal by 2050. We implement most of the proposed policy measures such as building energy efficiency standards, vehicle CO_2 emissions standards till 2030 as in the Swiss energy strategy […] and revised CO_2 Law […]. The model has the option to import zero-carbon fuels (e.g., biodiesel and hydrogen) and electricity. The climate change impacts on heating/cooling demand and hydropower generation are also included in this scenario […]. We assumed no new electric grid expansion other than planned by the Swiss transmission grid operator […].' [45].

Appendix E

E.1. Supplementary results

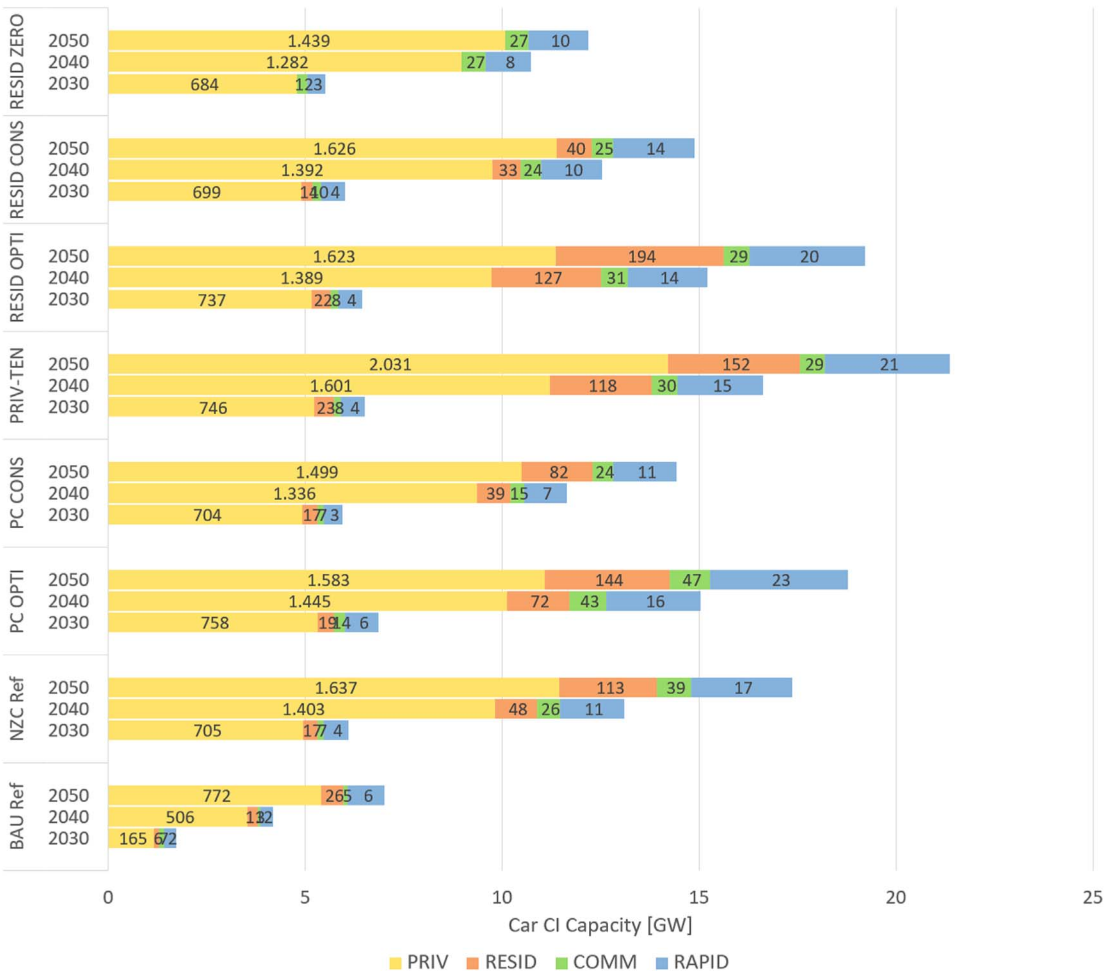

Figure E1. Number of chargers and charging infrastructure capacity by charger option, year, and scenario. While the *x*-axis reflects the CI capacity in GW, the bars' numbers refer to the number of chargers in thousands.

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