





## An assessment of energy system transformation pathways to achieve net-zero carbon dioxide emissions in Switzerland

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Switzerland has one of the lowest carbon intensities among industrialised countries. However, its transition to net-zero carbon dioxide emissions is complicated by limited domestic mitigation options, which tend to increase costs, raise energy security concerns, and trigger socio-economic barriers in policy implementation. Research on these issues is relevant to the societal and political debates on energy transition worldwide. Here we apply a well-established techno-economic energy systems model and highlight the challenges of the Swiss energy transition under different technical, socio-economic, and geopolitical contexts. We suggest feasible technical solutions based on low-carbon technologies, efficiency, and flexibility. We find that import independency and net-zero emissions by 2050 require an additional cumulative discounted investment, compared to a business-as-usual scenario, of 300 billion CHF<sub>2019</sub> in energy efficiency, negative emissions and renewable technologies. The average per capita costs of net-zero emissions are 320–1390 CHF<sub>2019</sub>/yr. from 2020 to 2050, depending on exploited domestic mitigation options, integration into international energy markets, and energy security ambition.

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Switzerland submitted its formal climate plan months before the Paris Agreement<sup>1</sup> and was among the first countries that met the “midnight survival deadline”<sup>2,3</sup>. The Swiss long-term climate strategy<sup>4</sup> aims at net-zero greenhouse gas (GHG) emissions in 2050, with an intermediate target of a 50% reduction in 2030 from the 1990 levels. Both targets are to be achieved using Internationally Transferred Mitigation Options (ITMOs). The domestic mitigation effort in 2030 should reach at least 37.5% GHG emissions reduction from the 1990 levels—the amount of ITMOs needed to achieve the 2050 target is currently unspecified.

However, the Swiss voters rejected key measures included in the amended CO<sub>2</sub> Act in June 2021. The Swiss direct democracy revealed major societal concerns on energy transition’s feasibility and costs, which are also concealed in many countries worldwide<sup>5</sup>. The rejection of the amended CO<sub>2</sub> Act has roots in the many challenges Switzerland faces in achieving its pledges.

First, the Swiss energy strategy<sup>6</sup> aims to gradually phase out existing nuclear power (safety is the sole criterion for the phase-out time) that supplies 36% of the electricity today. This entails an energy security challenge<sup>7</sup>, also confronted by many countries aiming at decommissioning strategic energy supply assets<sup>8</sup>.

Second, Switzerland starts from a low-carbon baseline—the country is at the Top-5 of the energy transition index<sup>9</sup>. It needs to maintain its carbon-free electricity supply and make progress in decarbonising industry, buildings and transport<sup>4</sup> that have less clear emissions reduction trajectories than the energy transformation sector<sup>10</sup>.

Third, Switzerland has limited domestic renewable resources<sup>11</sup> and depends on imported energy carriers that risk the security of supply. Solar photovoltaics have the largest potential for further development, albeit at low irradiation levels. Hydropower has little room for expansion. Low wind speeds, natural landscape preservation, and population density challenge wind power. Wood, which is important in the global decarbonisation pathways<sup>12,13</sup>, is confronted by forest management and preservation<sup>14</sup>. Biogas faces high costs and complex logistics due to the many small farms<sup>15</sup>.

Fourth, domestic CO<sub>2</sub> capture and storage are surrounded by large geological uncertainties<sup>16</sup>. Switzerland should connect to international CO<sub>2</sub> transport networks and storage sites<sup>17</sup>, competing for access with other European countries. Moreover, there is some social resistance to onshore domestic CO<sub>2</sub> sequestration in Switzerland<sup>16</sup>, a phenomenon attributable to the unfamiliarity of the population with CO<sub>2</sub> capture, storage and utilisation projects.

Fifth, the population increase in Switzerland for the next 30 years is projected to be 20%—one of the highest in Europe<sup>18</sup>. Without strong efficiency measures, energy security and emissions mitigation goals are at risk.

Switzerland needs robust, feasible solutions for its energy transition. Identifying these solutions requires frameworks that reflect societal, political and technical realities and not overly abstract models<sup>19</sup>. Such a framework is the Swiss TIMES Energy systems Model (STEM)<sup>20</sup>, with rich techno-economic details and sectoral interdependencies supported by state-of-the-art technology assessment<sup>21</sup>. While TIMES-based frameworks are widely used for assessing decarbonisation pathways<sup>22–24</sup>, STEM includes unique features identified as important in literature when assessing the energy transition<sup>19</sup>: long-time horizon, high temporal resolution, consumer segmentation, grids topology, unit commitment, energy and ancillary services markets, demand shifts, variability of renewables representation, age structures of assets, endogenous load and demand curves.

The work described in this study was performed within the Scenarios and Modelling Joint Activity (see “Methods” and Note

#2 in the Supplementary Information) of eight large collaborative energy research programmes of major Swiss universities, the Swiss Competence Centres for Energy Research (SCCERs), during 2013–2020<sup>25</sup>. Each SCCER programme promoted collaboration across different disciplines and dealt with a particular challenge of the Swiss energy transition: decarbonisation of buildings, decarbonisation of industry, decarbonisation of mobility, electricity supply and grid infrastructure, electricity and heat storage, biomass potential for energy uses, society. The Joint Activity Scenarios and Modelling (JASM) combined the modelling capabilities of all eight SCCERs to develop a set of scenarios for the transition of the Swiss energy system towards net-zero emissions by 2050. In JASM, STEM was coupled with several sector-specific models, e.g., for buildings, grids and industry.

The analysis with STEM in JASM fills the research gap in scenarios assessing net-zero emissions for Switzerland. So far, only the pledges made in 2015 of reducing emissions by 70–85% in 2050 from 1990 levels<sup>26</sup> were assessed, including energy system transformation<sup>27</sup>, economic implications<sup>28,29</sup>, social perceptions<sup>30</sup>, the need for system flexibility<sup>31</sup>, and the role of transport<sup>32</sup>, domestic biomass resources<sup>33</sup> and efficiency<sup>34</sup>. A few studies have assessed a net-zero Swiss energy system by 2050 but focused on the electricity sector<sup>35</sup> or neglected transition effects<sup>36,37</sup>. These studies overestimate technology deployment rates and underestimate costs. The Swiss Federal Office of Energy produced the “Energy Perspectives 2050+”<sup>38</sup> to assess net-zero emissions pathways for Switzerland. Still, the employed framework is commercial with little transparency and weak in representing sector coupling and interdependencies. Recently, a quantitative scenario analysis towards net-zero emissions in Switzerland was published by the Swiss Association of Electricity Enterprises (VSE)<sup>39</sup>. The study uses results from Energy Perspectives 2050+ as inputs for the energy demand and assesses the energy supply sectors configuration at snapshot years. A qualitative scenario analysis on net-zero emissions pathways in Switzerland is also available in the literature, providing a scenario framework for assessing the co-evolution of society and decarbonised energy systems<sup>40</sup>.

Our work contributes to the literature by quantifying energy system transformation pathways reflecting different contextual factors and transition lock-ins. It informs on future energy system configurations and is addressed mainly to decision-makers and the general public. The analysis of this paper results from alternative pathways regarding the deployment of renewable energy, the level of energy security, the degree of market integration and the speed of the technical progress in energy technologies. It suggests technically feasible solutions, although we should acknowledge that these could entail political and societal challenges regarding their implementation that are not addressed in this work.

We find that achieving net-zero CO<sub>2</sub> emissions by 2050 requires scaling up renewable energy technologies. The installed capacity of solar PV needs to double almost every decade from now to 2050. Wind energy deployment needs to accelerate in Switzerland at unprecedented rates to contribute to the winter electricity supply. Failing to deploy domestic renewable energy sources puts energy security at risk. Electrification of final energy consumption needs to reach 50% in 2050 (from 28% in 2050), but the electricity consumption per capita is slightly reduced from today by employing energy savings practices. Hydrogen penetrates industry and mobility sectors and it is used directly or indirectly via synthetic fuels in 2050. Carbon capture and bioenergy play an important role in reaching deep decarbonisation. About 9 Mt CO<sub>2</sub> are captured in 2050, with half of them from negative emissions technologies. Overall, a cost-efficient deep decarbonisation of the Swiss energy system requires all options to be on the table. The increase in energy system cost to achieve a

carbon-free energy system depends on resource availability and exploitation, social acceptance of new technologies, technology progress and innovation, and integration of local, national and global energy markets. According to the analysis with STEM of seven contrasted scenarios with different socio-economic, technical and geopolitical contexts (see section “A suite of contrasted net-zero scenarios”), the average increase in per capita energy system cost is between 320 and 1390 CHF<sub>2019</sub> per year compared to a Baseline scenario.

## Results and discussion

**A suite of contrasted net-zero scenarios.** We define several net-zero scenarios to address the role of resource availability, technological progress, energy market integration and social acceptance (Table 1). They benchmarked against a business-as-usual trajectory. All scenarios consider 60 years lifetime for nuclear power plants and share the same macroeconomic and demographic assumptions<sup>41</sup>. The GDP increases by 1.2% p.a. from 2020 to 2050, and the population grows from 8.7 million today to 10.4 million in 2050. Resource potentials<sup>41,42</sup> and technical progress assumptions<sup>11,41,42</sup> vary consistently across the scenarios.

Overarching features of STEM are given in the “Methods” section in the subsection entitled “The Swiss TIMES Energy Systems Model (STEM)” and in Supplementary Information Note 1. The links of STEM with the other sectoral models in SCCER JASM, which provided direct or indirect (in the form of side-constraints) input to STEM regarding technical and societal barriers in the deployment of energy technologies and infrastructures are described in Supplementary Information Note 2.

More details on the scenario definition are also given in the “Methods” section and specifically in the “Scenario design” subsection. The main assumptions of the assessed scenarios are described in Supplementary Information Note 3 and provided in Supplementary Data 1.

The following sections discuss results and provide insights from the net-zero scenarios. Additional results from the scenario analysis are given in Supplementary Information Note 5. A detailed comparison of all scenarios is provided in Supplementary Information Note 7. In addition, a comparison between the net-zero scenarios of this study and those from the Swiss Federal Office of Energy (the “Energy Perspectives 2050+” study<sup>38</sup>) is presented in Supplementary Information Note 6. At the same time, an additional variant of CLI, which assumes 50 years lifetime for the existing Swiss nuclear plants, is discussed in Supplementary Material Note 8. Extensive result tables from all seven scenarios assessed are available in Supplementary Data 2. Finally, all codes and data needed to reproduce the charts shown in Figs. 1–6, which are discussed in the next sections, are provided in Supplementary Data 3.

**Per capita final energy consumption in 2050 is similar to today’s world average.** In realising the net-zero emissions target, Switzerland moves towards a “2000 Watt” society<sup>43</sup>. This implies a per capita final energy consumption of around 50 GJ/yr. in 2050 compared to 109 GJ/yr. in 2000 in the CLI scenario—exceeding the –54% target in the Swiss energy strategy 2018<sup>6</sup>. The buildings and transport sectors bear the most efficiency improvement efforts (Fig. 1). On average, the space heating energy consumption across all buildings reduces from 87 kWh/sqm (2010–2020 average) to 45 kWh/sqm in 2050. Renovation rates of the existing residential buildings accelerate from 0.9% p.a. in 2020 to 1.7% p.a. on average for 2020–2050, and the adoption of the MINERGIE® standards<sup>44</sup> amplifies.

As electrification of the space heating is probably irrealisable for all buildings<sup>45</sup>, wood/biogas and district heating warrant

further consideration and double their share in 2050 from today. Transport calls for a portfolio of drivetrains. Its transition is characterised by (a) the period until 2030 with many options competing; (b) the period 2030–2040 with rapid penetration of electric vehicles; and (c) the period 2040–2050 with the dawn of fuel cell drivetrains for large vehicles and long-distance transport.

Achieving net-zero and minimising import dependency (SECUR scenario) requires bringing forward the energy efficiency efforts observed in the CLI scenario by a decade. In SECUR, the per capita final energy consumption drops to 45 GJ in 2050. As low electricity imports in winter challenge electro-mobility, uptake of fuel cell vehicles is the highest in SECUR—powered via domestic green hydrogen.

Failing to accelerate renewable deployment (ANTI scenario) necessitates improvements in energy efficiency at the levels of SECUR. Heating and mobility are not decarbonised in 2050. Reliance on bioenergy with CO<sub>2</sub> Capture and Sequestration (CCS) increases by shifting wood from end-use to energy conversion (by 2050, 49% of bioenergy in ANTI is used in electricity and hydrogen production vs 44% in CLI, and only 35% today—Fig. 2).

**Electricity consumption exceeds oil and gas together for the first time in history by 2040, but zero-carbon molecules are needed.** Invariably across all scenarios, electrification of final energy reaches 50% in 2050 compared to 28% today. Efficiency gains in stationary sectors maintain electricity consumption at today’s levels. However, transport alone increases electricity demand by 10 TWh/yr. in 2050 from today (Fig. 2).

Domestically produced hydrogen is of growing importance. While hydrogen first enters industry by 2030, the automotive applications lead to improvements in fuel cells that spill over to other applications and carry forward infrastructure development. Next to transport, new uses of hydrogen in district heating supply occur by 2040, driven by fuel cell CHP micro-grids that help avoid high upfront costs of cogeneration in buildings (Fig. 2). Hydrogen also becomes important when targeting energy security and reduction of import dependency. Domestic e-fuel synthesis from green hydrogen via high-temperature electrolysis compensates for the curtailed imports (SECUR scenario). However, limited deployment of renewables delays hydrogen penetration by a decade (ANTI scenario), jeopardising the decarbonisation of sectors requiring zero-carbon molecules and necessitating increased energy efficiency measures and imports.

Domestic bioenergy use doubles in 2050 from today, requiring full mobilisation of waste, manure and forest wood resources. Compared to today, there is a shift in bioenergy use and uptake from end-uses to energy conversion sectors. This shift starts to be more pronounced after 2030 (Fig. 2) as biogenic CHPs penetrate district heating, wood with CCS for electricity and hydrogen production delivers negative emissions, and swarms of load-following biogenic CHPs provide flexibility for better integration of solar PV and wind<sup>33</sup> technology. For heat supply, pellets replace wood chips and firewood due to their higher energy density, efficiency, and easier distribution.

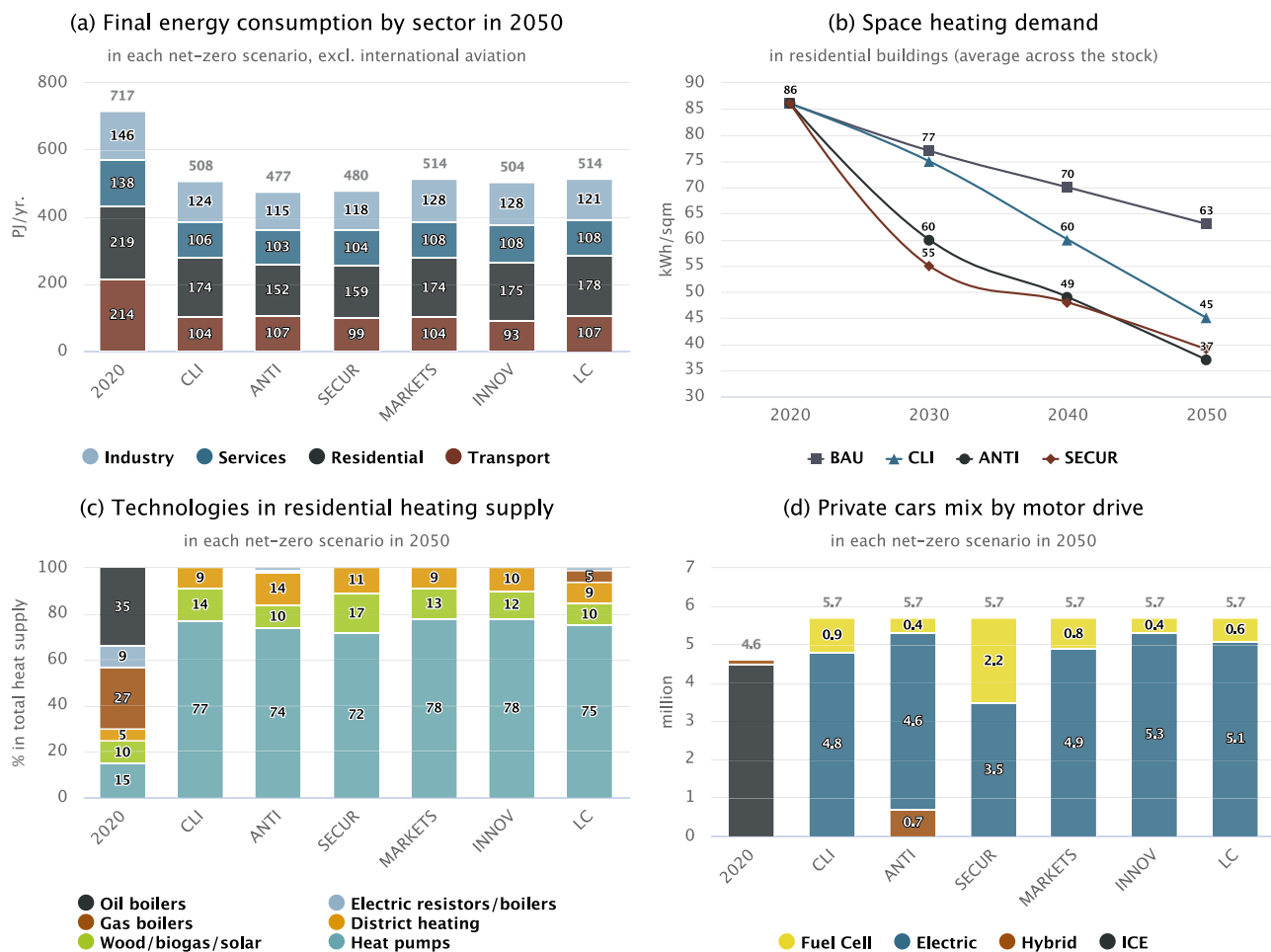
However, the decarbonisation of transport requires imported biogenic and synthetic electricity-based liquid fuels (short: e-fuels). These are also indispensable in the SECUR scenario (Fig. 3), signalling that import independence across the entire energy system is a formidable task.

**A carbon-free electricity supply requires doubling wind and solar production in each decade from today to 2050.** A carbon-free electricity supply after a nuclear phase-out requires an unprecedented deployment of solar and wind power (Fig. 3). At a

**Table 1 Outline of the net-zero CO<sub>2</sub> emissions scenarios and the business-as-usual scenario for Switzerland.**

Scenario	Sectoral policies	Social acceptance of new renewables	Swiss-EU energy market integration	Progress in low-carbon and clean technologies
CLI (similar to the amended CO <sub>2</sub> Act 2021)	Strengthening of efficiency and emissions standards in buildings, appliances and vehicles; Strengthening of CO <sub>2</sub> taxes and Emissions Trading Scheme	Solar PV is highly accepted, while wind turbines are accepted if “not visible from the “balconies”	Assuming full implementation of the energy agreements with the EU	Baseline (median progress)
ANTI (low mobilisation of the population towards climate change mitigation policies)	Continuation of current efficiency and emissions standards in buildings, appliances and vehicles; No strengthening of CO <sub>2</sub> taxes and of the Emissions Trading Scheme after 2025	Lower than today, reflecting lower tolerance for landscape changes and failure to accelerate licensing and permitting procedures	Lower than today due to the failure of agreements between Switzerland and the EU (also with other world regions)	Lower than today, reflecting fragmented worldwide climate policies that hamper R&D expenditures
SECUR (energy security by minimising total annual net imports across all energy carriers)	As in CLI	The population is willing to pay for increased security and exploit all domestic renewable resources at their fullest potential aiming at self-sufficiency	Switzerland is to be as close as possible to self-sufficiency on annual net imports by 2050, while for 2030, net imports are halved from today.	Baseline (median progress)
MARKETS (high integration of Switzerland in international markets and good availability of zero-carbon fuels)	As in CLI	Higher than today for wind turbines and new development of bioenergy projects (wood, manure)	Increased integration, reinforcement of grids, cross-border capacities and corridors	Baseline (median progress)
INNOV (derives from MARKETS and assumes accelerated innovation in clean energy technologies)	As in CLI	Higher than today for wind and bioenergy projects (wood, manure)	Increased integration, reinforcement of grids, cross-border capacities and corridors	Higher than baseline, reflecting coordinated worldwide climate policies that foster R&D expenditures
LC (least-cost trajectory variant of CLI)	None—let the optimiser decide the sectoral mitigation efforts	Solar PV is highly accepted, while wind turbines are accepted if not visible from the “balconies”	Assuming full implementation of the energy agreements with the EU	Baseline (median progress)
BAU (business-as-usual)	Continuation of energy policies and carbon taxes of 2020, but no explicit CO <sub>2</sub> or other targets	Solar PV is highly accepted; wind turbines are accepted if not visible from the “balconies”	Assuming full implementation of the energy agreements with the EU	Baseline (median progress)

All the net-zero scenarios viz. CLI, ANTI, MARKETS, INNOV and LC target to reduce 45% of the CO<sub>2</sub> emissions from the Swiss energy system and industrial processes, excluding international aviation, in 2030 from 1990 levels. The 2030 target is equivalent to at least 37.5% GHG emissions reduction in 2030 from 1990 levels. The SECUR scenario goes further in the mitigation effort by achieving 53% CO<sub>2</sub> emissions reduction in 2030 from 1990. All the net-zero scenarios achieve zero CO<sub>2</sub> emissions in 2050. The business-as-usual scenario does not include energy efficiency, renewable production or climate targets. An additional sensitivity analysis of CLI, which assumes 50 years lifetime for the existing Swiss nuclear power plants, is discussed in Supplementary Note 8. A more detailed description of the scenarios is provided in the “Methods” section.



**Fig. 1 Main developments in end-use sectors in the net-zero scenarios.** Panel (a) shows the final energy consumption by sector in each net-zero CO<sub>2</sub> emissions scenario, excluding consumption in international aviation. Panel (b) displays the average demand for space heating in terms of kWh per square metre across all residential buildings in Switzerland for the BAU, CLI, ANTI and SECUR scenarios. Panel (c) provides the contribution of the different heating technologies in the residential heating supply in the different scenarios for the year 2020 and 2050. The bold numbers at the top of each bar denote the total of the quantities shown in the bar. As shown in the figure, residential and transport sectors bear most of the energy transition effort. The transition requires an accelerated build-up of electric heating and mobility. The share of heat pumps in 2030 in the CLI scenario rises to 35%, before reaching 77% in 2050. In SECUR, heat pumps supply 45% of the space heating demand in 2030 to cope with the reduction of imported gas to half of today’s quantities, and their share reaches 72% in 2050. In transport, the share of electric cars in 2030 must be at least 25% of the total car stock across all scenarios, while by 2050 eight every ten cars in Switzerland run with electricity.

minimum, non-hydro renewable electricity would need to compensate for today’s nuclear electricity (ANTI scenario). By 2050, the electricity sector delivers 2 Mt CO<sub>2</sub>/yr. negative emissions via CCS deployment at 50% of the waste incineration plants and additional investment in 300 MW of large-scale wood-based electricity generation with CCS.

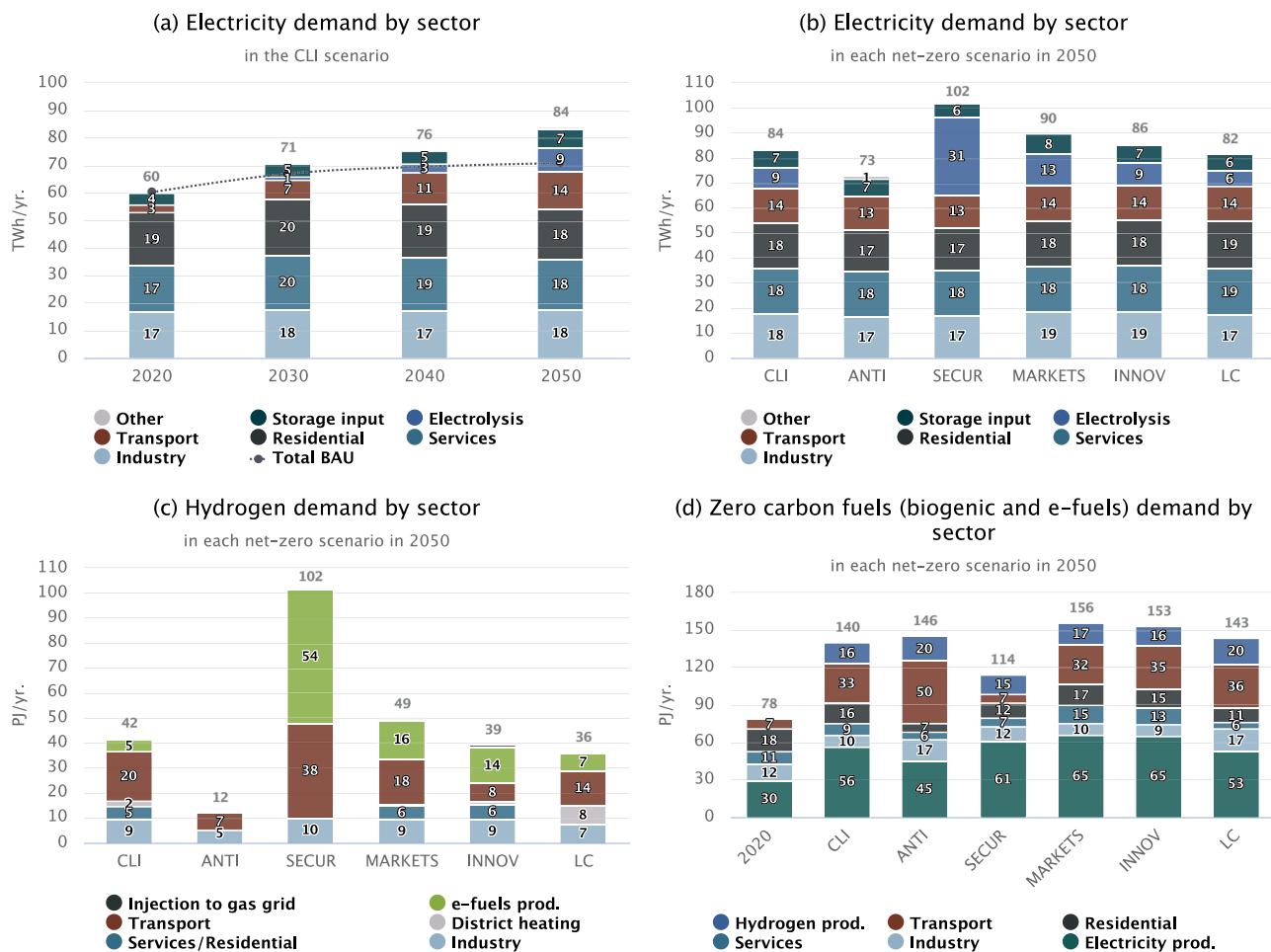
Regarding domestic hydrogen production, electrolysis is the main option until 2040. While electrolysis could cover all hydrogen needs, it is costly to integrate it into the energy system at a large scale. Thus, a cost-effective mix to supply high hydrogen demands beyond 2040 includes green and blue hydrogen. Wood gasification with CCS occurs in all scenarios, delivering 1.6 Mt CO<sub>2</sub>/yr. negative emissions in 2050, but it is challenged by limited wood resources and the availability of adequate CO<sub>2</sub> transport and storage infrastructure, like all CCS technology.

In the SECUR scenario, electrolysis becomes a major option to meet high domestic needs for hydrogen and fuel synthesis that compensate for oil and gas imports curtailment. Wood gasification cannot be further scaled up due to resource limits and competition from other sectors. Hence, high-temperature electrolysis is deployed to fill the supply gap. In 2050, 31 TWh/yr. of

electricity are consumed to produce 26 TWh of hydrogen—of which more than 50% is directed to fuel synthesis (Supplementary Information Note 7). Still, the domestic supply of e-fuels is insufficient to cover the transport demand. Imports of e-fuels from renewable-based hydrogen occur in all scenarios, with a maximum of 58 PJ/yr. in ANTI and a minimum of 11 PJ/yr. in SECUR (close to today’s levels of imported biofuels). The analysis from SECUR and ANTI scenarios clearly shows that failing to deploy domestic renewables puts energy security at risk.

**A reliable low-carbon energy system requires coordinated flexibility from all its actors.** In achieving the net-zero target, a suite of flexible options need to be deployed: energy storage, Power-to-X (PtX), demand-side response (DSR) in heating and electric loads, grid-to-vehicle (G2V) and vehicle-to-grid (V2G) services in transport (Fig. 4).

Pump hydrostorage of 4.5 GW with around 520 GWh storage capacity balances the high-voltage grid. It is complemented with 2.1 GW batteries providing 11.5 GWh storage at the medium- and low-voltage grid. Smart G2V absorbs excess electricity, with a maximum charging requirement of 6 GW on a summer Sunday



**Fig. 2 Electricity and hydrogen demand by sector and demand for biogenic and synthetic zero-carbon fuels by sector (electricity storage refers to stationary storage).** Panel (a) shows the electricity demand by sector in the CLI scenario, while the dotted line represents the total electricity demand in the BAU scenario. Panel (b) compares the electricity demand by sector in 2050 across all the net-zero CO<sub>2</sub> emissions scenarios assessed in the study. Panel (c) displays the hydrogen consumption by sector, including the hydrogen directly injected into the natural gas grid. Finally, panel (d) shows the consumption of the zero-carbon fuels, of biogenic or synthetic source, by sector in the different net-zero scenarios assessed in the study. The bold numbers at the top of each bar denote the total of the quantities shown in the bar.

at noon—on average, 75% of the EVs are charged at this time. V2G schemes could provide 2 GW<sub>p</sub> in spring and summer evenings if EVs have been charged with low-cost electricity. In 2050, the contribution of V2G is around 1 TWh/yr., with 13% of the EVs participating in this scheme. DSR enables intra-day shifts of electricity loads of 620 MW<sub>p</sub> in buildings and 110 MW<sub>p</sub> in industry, in line with estimated Swiss potentials<sup>46</sup>.

Thermal storage gains interest due to the increased coupling of electricity and heat systems. About 35 GWh of storage (of which 70% is low temperature) at weekly and daily time scales are needed in 2050 in CLI. Embedded thermal storage in heat pumps and water heaters enable intra-day shifts of 3 TWh/yr. of electricity used for heating in buildings in 2050, decoupling the time of heat provision from electricity consumption.

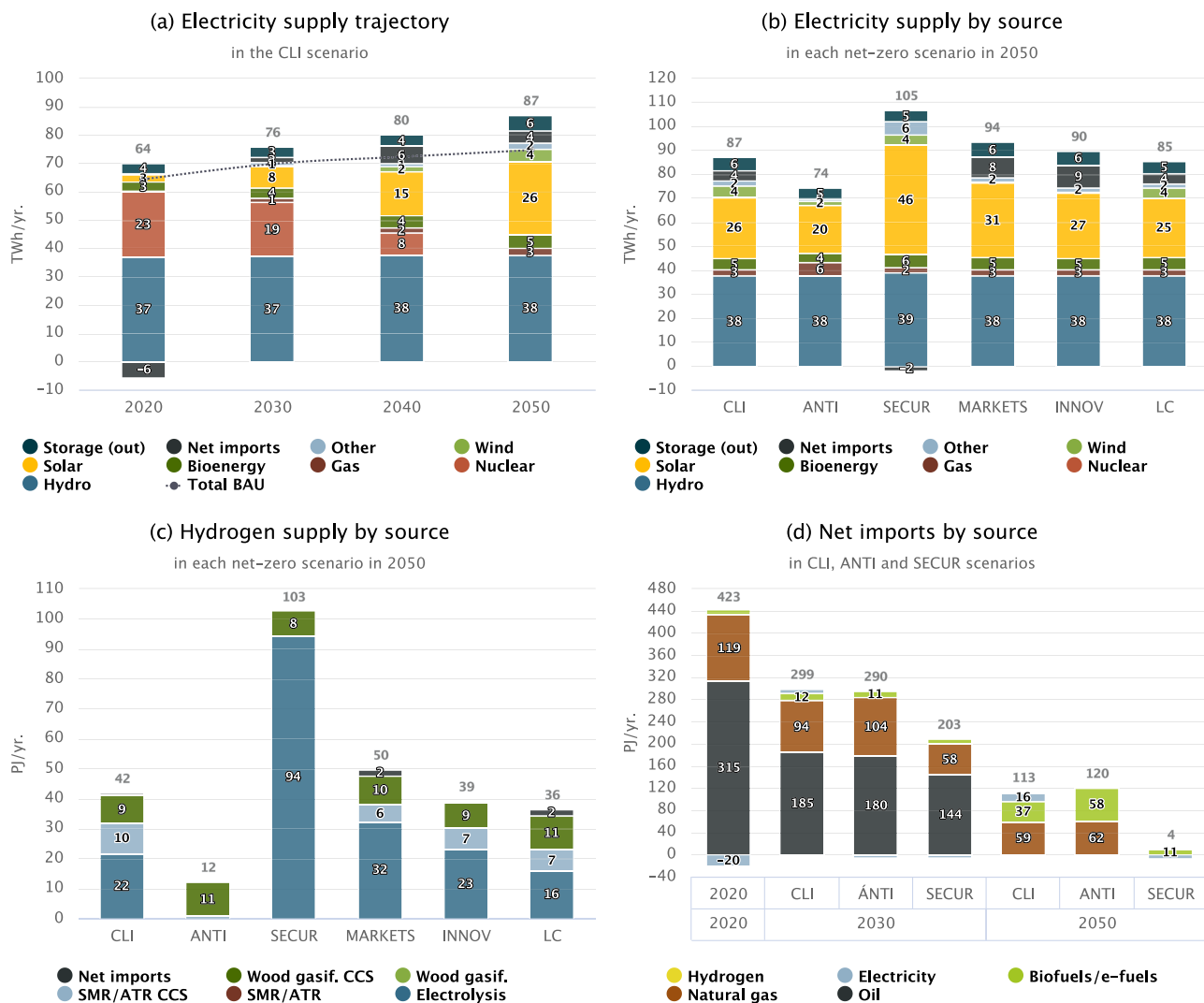
The seasonal balancing of the energy system is achieved via electricity imports, Power-to-X, and thermal storage. Electricity imports emerge in all scenarios in winter in 2050, ranging from 3 TWh/yr. (in SECUR) to 8 TWh/yr. (in MARKETS/INNOV), which are similar to BAU (7 TWh/yr. in 2050) and the winter imports observed for Switzerland in the past decade<sup>47</sup>. P2X contributes to seasonal balancing via hydrogen or synthetic fuels storage of up to 2 TWh/yr. in 2050. About 1.4 TWh/yr. seasonal thermal storage is also deployed as local or virtual community grid storage.

The need for secondary operating reserve (aFRR+) increase by 44% in 2050 from today's levels. On average, hydropower provides 75% of the aFRR+ demand, aggregated distributed units (CHPs, batteries, heat pumps) 20%, and electric vehicles 5%.

**Without CO<sub>2</sub> capture and negative emissions, the net-zero target cannot be achieved.** The net-zero scenarios require 370 Mt additional cumulative CO<sub>2</sub> reductions from 2020 to 2050 relative to the emissions trajectory of the BAU scenario. While system-wide net zero CO<sub>2</sub> emissions are achieved, industry emissions remain in 2050. These are offset via CO<sub>2</sub> capture in electricity and hydrogen production (Fig. 5).

CO<sub>2</sub> capture emerges from 2040 and amounts to about 9 Mt CO<sub>2</sub>/yr. in 2050. SECUR has the lowest amount of captured CO<sub>2</sub> as the goal for zero import dependency also implies the elimination of imported fossil fuels. In contrast, LC has the highest amounts of captured CO<sub>2</sub> because hard-to-abate emissions from buildings that have limited mitigation options are offset via CCS. On average, across all scenarios, about half of the captured CO<sub>2</sub> in 2050 is from negative emission technologies, viz. BECCS and DACCS (Fig. 5).

Based on the current estimates that the domestic CO<sub>2</sub> sequestration potential in Switzerland is 50 Mt CO<sub>2</sub><sup>48</sup>, regulations and policy agreements are necessary to access European

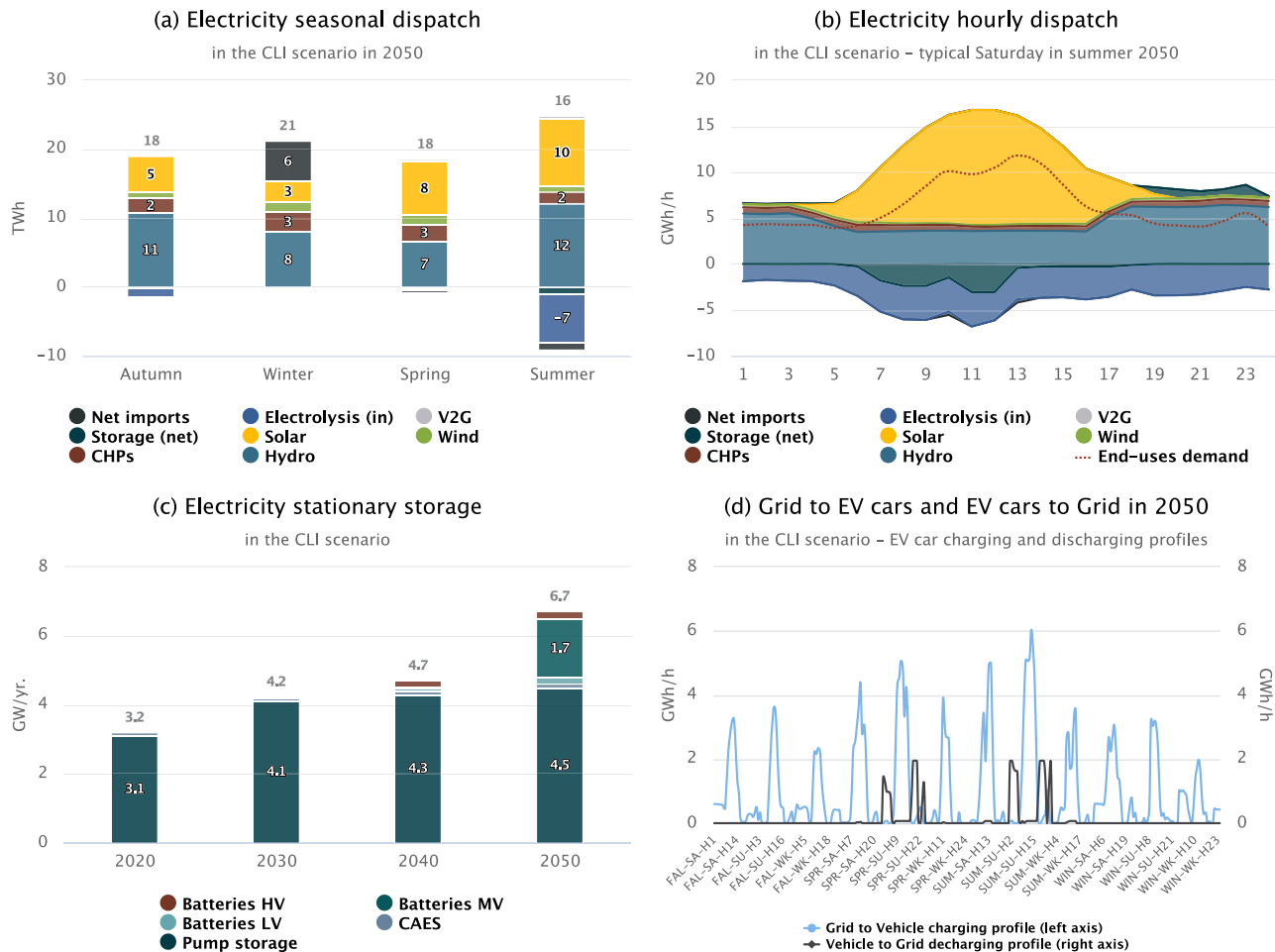


**Fig. 3 Energy supply development related to electricity and hydrogen production.** Panel (a) displays the electricity supply by major source in the CLI scenario from 2020 to 2050 and compares it with the total electricity supply in BAU. Panel (b) focuses on the electricity supply by major source for the different net-zero CO<sub>2</sub> emissions scenarios in 2050. Panel (c) presents the hydrogen supply by major technology in the different net-zero CO<sub>2</sub> emissions scenarios in 2050. Panel (d) shows the net imports by major energy source in the CLI, ANTI and SECUR scenarios—the net imports of the MARKETS, INNOV and LC scenarios are similar to the ones in CLI and, therefore, are not shown in the figure and the reader is directed to Supplementary Data 2 for these imports. The bold numbers at the top of each bar denote the total of the quantities shown in the bar. The net imports in MARKETS, INNOV and LC are quite similar to CLI and they are not shown in the figure. For the net imports in MARKETS, INNOV and LC please see Supplementary Information Note 7). In SECUR, gas imports in 2030 are reduced to half from today’s levels towards complete import independency by 2050. Achieving energy security and net-zero emissions goals would require almost two times the deployment of renewable energy that is seen in CLI to produce synthetic e-gases. Still, clean molecules must be imported to decarbonise the transport sector in Switzerland.

infrastructures for transferring and storing CO<sub>2</sub> outside Switzerland<sup>49</sup>.

**Four pillars for deep decarbonisation in Switzerland.** The analysis highlights four pillars for deep decarbonisation in Switzerland. First, to unlock domestic renewable potentials for solar PV and bioenergy whilst maintaining at least the current levels of hydropower. Second, to foster energy and emissions markets integration by fortifying the availability of imported zero-carbon fuels and securing access to international CO<sub>2</sub> storage sites, e.g., in the North Sea. Third, to scale up technology innovation and improve emerging technologies. Finally, the fourth pillar is lifting socio-economic barriers related to the storage of captured CO<sub>2</sub> and creating public awareness to accept the domestic deployment of negative emissions technologies.

Today, the average energy system cost per capita, as the model calculates, is around 3200 CHF<sub>2019</sub> per year. The BAU scenario, which reduces the CO<sub>2</sub> emissions by 42% in 2050 from 1990 levels, entails an increase to about 5700 CHF<sub>2019</sub> in 2030 and 7000 CHF<sub>2019</sub> in 2050. These costs relate to the maintenance and replacement of existing infrastructure and investments in new technologies (also to cope with the nuclear phase-out). As the BAU scenario does not include decarbonisation targets, it can be argued that these costs reflect the increase in the system cost to supply the future energy service demands by accounting for the ageing and phase-out of the existing assets. In CLI, the per capita energy system cost rises to around 5900 CHF<sub>2019</sub> in 2030 and 8500 CHF<sub>2019</sub> in 2050. Hence, the increase in energy system cost due to the decarbonisation of the Swiss energy system starts at about 200 CHF<sub>2019</sub>/capita and reaches 1500 CHF<sub>2019</sub>/capita in 2050.



**Fig. 4 Dispatch of power plants and deployment of electricity storage and flexibility options.** Panel (a) shows the seasonal electricity dispatch in the CLI scenario for 2050. Panel (b) displays the electricity hourly dispatch in the CLI scenario for a typical Saturday in summer 2050, with the x-axis denoting the hours within the typical Saturday. Panel (c) presents the uptake of the electricity storage from 2020 to 2050. Finally, panel (d) shows the electricity profile across the typical days and hours of STEM for charging the electric cars (on the left axis) and the profile of the electricity that is feedback to the grid from the electric cars (on the right axis). The bold numbers at the top of each bar denote the total of the quantities shown in the bar. The electricity dispatch is given in seasonal and hourly scales. The latter refer to the typical hours and days in STEM. STEM identifies four seasons (FAL- autumn, WIN- winter, SPR- spring, SUM- summer) and three typical days in a season (SA- Saturday, SU- Sunday, WK- working day) with hourly resolution (H1-H24 hours in a day). For the different types of battery storage the following abbreviations are used: HV High Voltage, MV Medium Voltage, and LV Low Voltage. Pump storage capacities in 2030 include Nant de Drance (900 MW at generator) that came online in 2022 and Ritom II (120 MW at generator) plants that is expected to be online by 2025. The flexibility provided by the transport sector is via smart charging and vehicle-to-grid schemes in the CLI scenario. The charging and vehicle-to-grid profiles are given for each typical day and hour in STEM.

The SECUR scenario entails an energy system cost per capita increase of 6500 CHF<sub>2019</sub> in 2030 and 9600 CHF<sub>2019</sub> in 2050. In ANTI, the limited deployment of domestic renewables induces an additional per capita cost of 6200 CHF<sub>2019</sub> in 2030 and 10700 CHF<sub>2019</sub> in 2050 (Fig. 6). Hence, the cost of achieving net-zero CO<sub>2</sub> emissions by 2050 is about 1000–3700 CHF<sub>2019</sub> above the BAU per capita cost in 2050.

The difference in the energy system cost between the net-zero scenarios and BAU shows a shift from low capital expenditure (CAPEX) and high operational expenditure (OPEX) in BAU to high CAPEX and low OPEX. Transport and residential sectors bear the highest policy costs. However, there are cost savings from reduced imports of fossil fuels (Fig. 6). The cumulative discounted energy system costs from 2020 to 2050 increase by 4–19% of the BAU costs to net-zero CO<sub>2</sub> emissions. ANTI and SECUR display the highest costs, while MARKETS and INNOV are the lowest. This shows that citizen mobilisation and national and international policy co-design are important for the energy transition. Across all scenarios, the cumulative discounted per

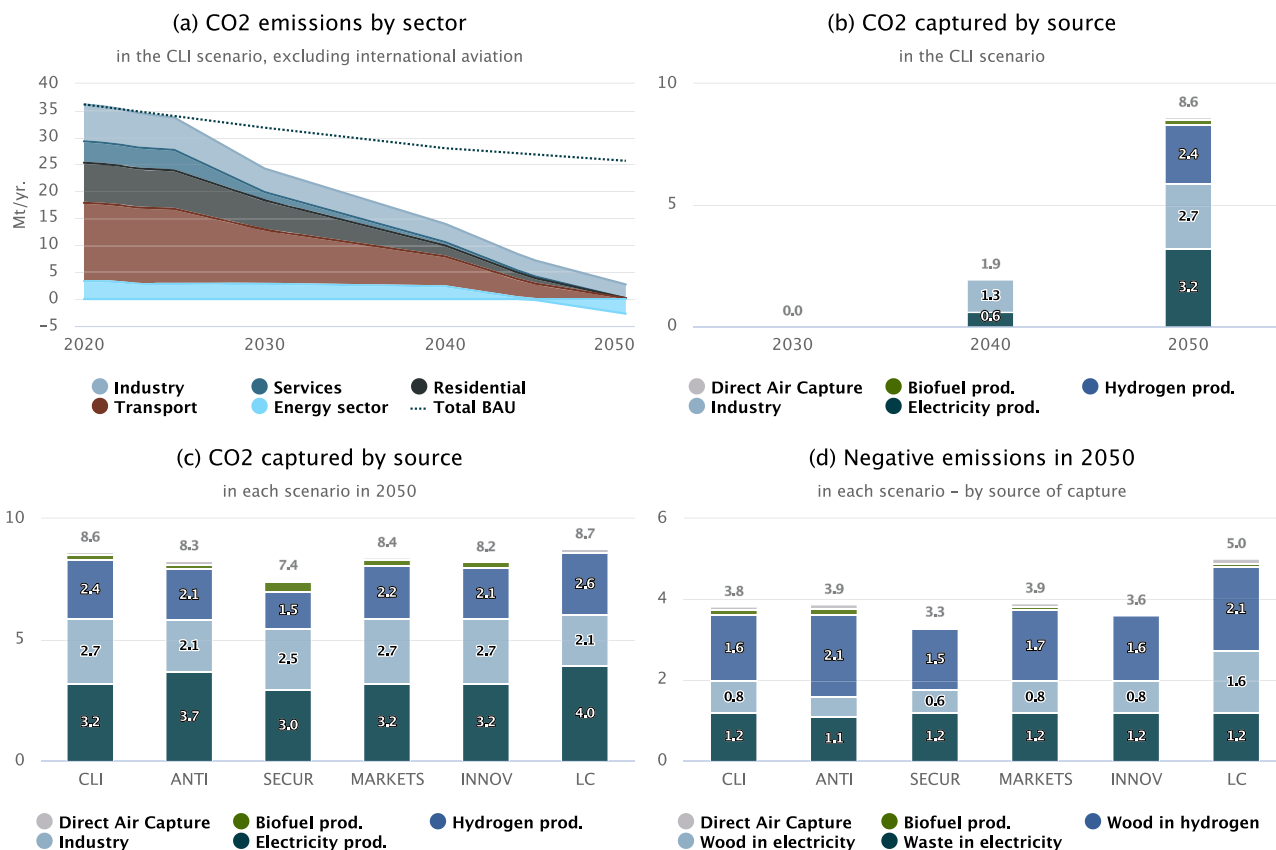
capita policy cost to achieve net-zero emissions from 2020 to 2050 varies between 5800 and 25400 CHF<sub>2019</sub> discounted at 2.5% (or, on average, 320–1390 CHF<sub>2019</sub>/yr. and per capita, undiscounted).

**Conclusions**

Despite the limited domestic resources and the population growth of at least 20% projected for the next 30 years, it is technically feasible for Switzerland to achieve net-zero CO<sub>2</sub> emissions, even within the context of increased energy security and import independence. Table 2 summarises key energy transition enablers for which societal, market or technical barriers must be removed to avoid financial burdens.

The energy system transformation requires decisive actions in each sector to reduce uncertainty in investors and society. Energy transition policies must account for systemic interdependencies. For example, imposing emissions standards in buildings and vehicles could create cost-inefficiencies if the potential of other sectors to mitigate at a lower cost is neglected. Or, implementing





**Fig. 5 CO<sub>2</sub> emissions trajectory for net-zero and CO<sub>2</sub> captured.** Panel (a) shows the CO<sub>2</sub> emissions by sector excluding the emissions from international aviation, which are not part of the climate change mitigation target of Switzerland. Panel (b) shows the CO<sub>2</sub> captured in industry, electricity production, hydrogen production, biofuel production, and direct air capture. Panel (c) compares the amounts of the captured CO<sub>2</sub> by source across the net-zero emissions scenarios assessed in the study. Finally, panel (d) provides insights into the required negative emissions needed in each net-zero emissions scenario from direct air capture and CO<sub>2</sub> capture from bioenergy for electricity, hydrogen and biofuel production. The bold numbers at the top of each bar denote the total of the quantities shown in the bar.

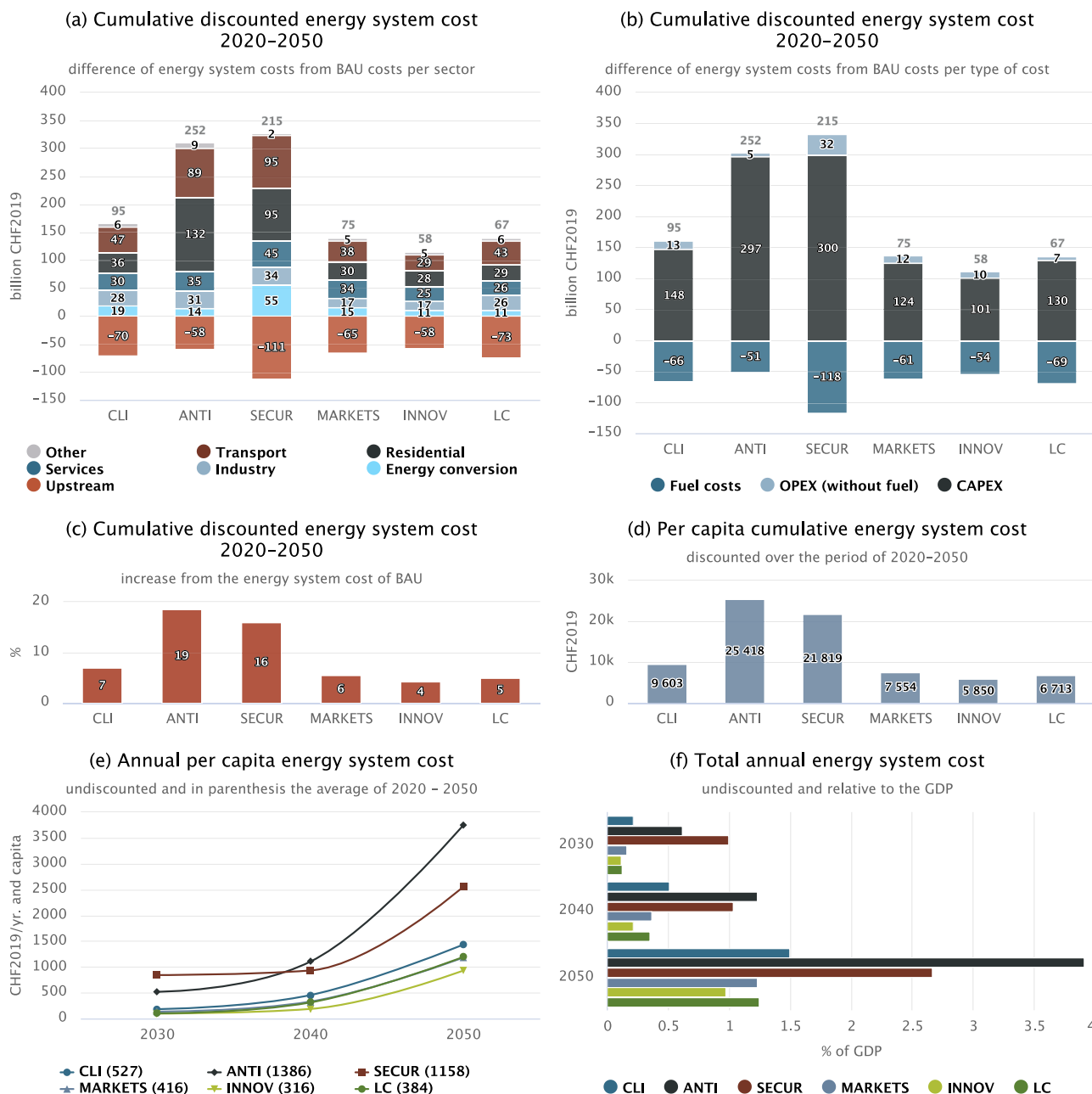
technology bans too early could increase energy bills for consumers. Even the most well-designed policies become expensive if citizens do not accept them or inefficiencies from non-energy sectors persist (e.g., lengthy licensing procedures). The analysis finds a sweet-point in policy implementation between the CLI scenario, which includes several sectoral policies and the LC scenario, which follows a cost-optimal trajectory. Moreover, fostering technology innovation (INNOV scenario) and integration into international energy markets (MARKETS scenario) reduces costs to 60% of CLI's costs.

Decarbonisation of residential heat entails Herculean efforts<sup>50,51</sup>. Carbon and energy performance requirements, mandates for solar energy in buildings and incentives for renewable and district heating could help reduce emissions, but they would need to be complemented with cost- and benefit-sharing between energy companies, tenants and landlords in order to improve the attractiveness of renovations, accelerate smart technologies, and lift the split of incentives barrier. To avoid jeopardising industry's competitiveness, market designs for low-carbon intensity products, industrial symbiosis<sup>52</sup>, technology standards, voluntary agreements, and timely replacement of ageing infrastructure with low-carbon alternatives can form a possible portfolio of policy options. Decarbonisation enablers in transport include clean vehicles, incentives for new infrastructure, increased digitalisation to support demand management, automated and connected mobility, and efficient multi-modality. Biofuels and e-fuels are part of the solution only when considering land-use and carbon sources needed for their

production<sup>53</sup>. Strengthening and expanding the emissions trading scheme to new sectors (buildings, transport, and small industries) could accelerate the energy transition and mitigate financial burdens from evasive taxation. The shift of electricity production to lower grid levels will require closer cooperation between System Operators and participation for storage and flexible consumers in energy and ancillary services markets. Energy security calls for support to technologies that can contribute to winter electricity supply, such as alpine PV, wind, geothermal, storage and demand-side response. To realise the deployment of these technologies, simplifying the permitting procedures for new renewable projects is required next to financial incentives. As the energy transition requires every domestic renewable kWh of energy, it is also necessary to lift financial and logistic obstacles in biogas production from manure and pursue balanced forest wood management by considering non-energetic uses and eco-services<sup>14</sup>.

Hydrogen deployment requires strong climate policy signals to mitigate investment risks. Pilot projects for negative emissions technologies can confirm their potential and gradually expand their deployment. The energy transition is costly without closer integration with the EU energy, carbon markets, and infrastructure.

However, the solutions found at the national level need to align with energy supply and demand options at the Cantonal or municipalities levels, as Swiss policy-making procedures are highly decentralised. The energy transition implications to all sustainability dimensions must be further assessed and



**Fig. 6 Cost of the Swiss energy system to reach net-zero CO<sub>2</sub> emissions in 2050.** Panel (a) shows the difference in cumulative discounted energy system costs by sector between each net-zero CO<sub>2</sub> emissions scenario and the BAU scenario—the applied social discount rate is 2.5%. Panel (b) presents the difference in the cumulative discounted energy system costs by type of expenditure between each net-zero CO<sub>2</sub> emissions scenario and the BAU scenario. Panel (c) displays the increase in the cumulative energy system cost in each scenario compared to the energy system cost of the BAU scenario. Panel (d) shows the per capita discounted cumulative energy system cost in each net-zero scenario, while panel (e) displays the exponential evolution of the annual per capita energy system cost in each scenario (with the average undiscounted per capita energy system cost from 2020 to 2050 given in the parenthesis). Finally, panel (f) shows the undiscounted annual energy system cost as percentage of the gross domestic product in Switzerland. The bold numbers at the top of each bar denote the total of the quantities shown in the bar. The reported costs are calculated by taking the difference between the energy system cost of the net-zero and BAU scenarios, i.e. the reported costs for the climate change mitigation scenarios come on top of the BAU costs. The costs in the end-use sectors refer to investment and operating costs for: demand and energy conservation technologies, on-site energy supply and storage technologies (e.g., CHPs, solar PV, batteries, thermal storage) and distribution infrastructure. The costs in the energy conversion sector refer to investment and operating costs for: power plants (other than on-site CHPs and solar PV in end-use sectors), utility-scale storage for energy carriers and heat, hydrogen and biofuel production, and transmission infrastructure. The upstream sector costs include purchases and sales related to the cross-border trade and investment and operation costs of cross-border infrastructure. In MARKETS and INNOV, the costs are benchmarked with variants of BAU having the same energy markets integration and technological progress as in MARKETS and INNOV. Comparing MARKETS with the original BAU results in a policy cost of 6 billion CHF<sub>2019</sub> instead of the 75 billion CHF<sub>2019</sub> shown in the figure. The policy cost of INNOV, when comparing it with the original BAU scenario, is -17 billion CHF<sub>2019</sub> instead of 58 billion CHF<sub>2019</sub>. The social discount rate used in the cost calculations is 2.5%. It should be noted that the increase in the energy system cost is affected (a) by the emissions reductions in BAU, (b) by the choice of the social discount rate, and (c) by the market conditions and technical progress assumed in each net-zero scenario compared to BAU.

**Table 2 Main enablers of the Swiss energy transition (see also Supplementary Information Note 5 for additional results).**

Energy transition enabler	Underlying sector
Increase share of electricity in final demand by accelerating electrification of heating and mobility	<ul style="list-style-type: none"> <li>●Electricity share in final energy to 50% by 2050, compared to 28% in 2020</li> <li>●Heat pumps to supply 35% of the space and water heating demand in buildings in 2030 and at least 75% by 2050, from 12% in 2020</li> <li>●Electric cars to account for 38% of sales by 2030 and 83% of car stock by 2050</li> </ul>
Achieve efficiency gains in end-use sectors, also in electricity consumption	<ul style="list-style-type: none"> <li>●Final energy consumption per capita (excluding international aviation) to be reduced by 17% in 2030 and 55% in 2050 compared to 2000 levels</li> <li>●Increase house renovation rate from 0.9% in 2020 to 1.9% in 2050</li> <li>●Electricity consumption per capita to reduce to 6500 kWh in 2050 from 6670 kWh in 2019, or at least –10% from 2000 levels, despite increased electrification of the energy demand</li> </ul>
Maintain carbon-free electricity supply even after the nuclear phase-out	<ul style="list-style-type: none"> <li>●Electricity supply increases by at least 20 TWh in 2050 from 2020 levels</li> <li>●Solar PV capacity increases from 3 GW in 2020 to 27 GW in 2050</li> <li>●Hydropower to be maintained at least at 37.4 TWh/yr. from 2030 onwards</li> </ul>
Deploy coordinated flexibility options across all energy sectors and across different time scales for integrating high shares of renewables	<p>For example, in the CLI scenario:</p> <ul style="list-style-type: none"> <li>●Pump hydro storage of 4.5 GW by 2050, with a storage capacity of at least 520 GWh</li> <li>●Battery storage at 2.1 GW by 2050, with an energy storage capacity of 11.5 GWh</li> <li>●Thermal storage additions of 5.8 GW by 2050, with 35 GWh energy storage capacity</li> <li>●Seasonal thermal storage output at 1.4 TWh by 2050</li> <li>●Seasonal PtX storage output reaching 1.6 TWh by 2050</li> <li>●620 MW intraday load shifts from electric appliances in buildings by 2050</li> <li>●Secondary positive reserve demand +45% in 2050 from 2020</li> <li>●6 GW peak charging power for electric cars by 2050 (grid-to-vehicle)</li> <li>●2 GW peak electricity power from electric cars by 2050 (vehicle-to-grid)</li> </ul>
Lift socio-economic barriers in domestic new renewables potential, e.g., wind, manure and wood	<ul style="list-style-type: none"> <li>●Deployment of Solar PV to be doubled every decade (see also above)</li> <li>●Biogas production from manure at 2.5 TWh in 2050 versus less than one TWh in 2020</li> <li>●Wind electricity of 2 TWh in 2040 and (at least) 4.3 TWh in 2050, from 146 GWh in 2020</li> </ul>
Deploy domestic green hydrogen production for decarbonisation and seasonal balancing	<ul style="list-style-type: none"> <li>●Domestic hydrogen production increase to 11-14 TWh/yr. in 2050</li> <li>●If self-sufficiency is a priority, at least 30 TWh/yr. of hydrogen are needed to feed domestic e-fuel synthesis in 2050 (SECUR scenario)</li> <li>●Green hydrogen accounts for more than three-quarters of the production; blue H<sub>2</sub> from natural gas steam reforming to supply the demand in seasons with low solar irradiation</li> </ul>
Foster integration of Swiss and international energy markets for electricity, biofuels/e-fuels imports	<ul style="list-style-type: none"> <li>●Electricity imports in winter increase to 5.8–7.9 TWh in 2050 from the historical (2010-2020) average of 3.5 TWh</li> <li>●Biofuels/e-fuels imports increase to 38–58 PJ/yr. in 2050 from 7 PJ/yr. in 2020</li> <li>●At a minimum, electricity imports in winter are 3 TWh and biofuel/e-fuels imports are 11 PJ in 2050</li> </ul>
Deploy carbon capture and negative emissions technologies	<ul style="list-style-type: none"> <li>●7.4–8.7 Mt CO<sub>2</sub>/yr. need to be captured and sequestered to ensure carbon neutrality in the energy system by 2050</li> <li>●3–5 Mt CO<sub>2</sub>/yr. negative emissions by 2050 are required via bioenergy with CCS in electricity and hydrogen production and Direct Air Capture with CCS</li> </ul>
Secure access to European (or international) CO <sub>2</sub> storage sites	<ul style="list-style-type: none"> <li>●Domestic sequestration of CO<sub>2</sub> is 2.1 Mt/yr. in 2050, due to geological uncertainties</li> <li>●At least 5–8 Mt CO<sub>2</sub> need to be sequestered in sites outside Switzerland, if not offset with other measures, e.g., international emissions credits, and only from the energy system</li> </ul>
Avoidance of energy imports as far as possible with deployment of domestic renewable energy sources and energy efficiency	<p>In SECUR scenario (with priority to self-sufficiency):</p> <ul style="list-style-type: none"> <li>●By 2030 around 14 TWh from solar PV, increasing to 46 TWh by 2050</li> <li>●Domestic hydrogen production to cover 90% of the otherwise imported gas fuels by 2050</li> <li>●Compared to the CLI scenario that achieves net-zero with imports:                         <ul style="list-style-type: none"> <li>○ Heat-saving measures in buildings need to be further improved by 13 to 26% by 2050</li> <li>○ Accelerate deployment of heat pumps in buildings by 10 years</li> <li>○ Accelerate deployment of district heating based on large-scale heat pumps by +50%</li> </ul> </li> </ul>

emphasised. Quantifying external costs for cost-benefit analysis and Multi-Criteria Decision Analysis, including environmental and social aspects of the energy transition, while accounting for different stakeholder preferences, are currently pursued within an integrated framework including STEM. Another development in progress with STEM is to lift the limitation of exogenous lifestyle changes and sustainable and circular economy and improve the representation of consumer energy behaviour and social acceptance of new technologies by pursuing closer collaboration with scholars from Social Sciences and Humanities. Finally, the need to account for the co-evolution of energy, economy, environment and social systems is not fully accounted for in our analysis as the employed framework is a partial equilibrium bottom-up techno-economic model. To this end, more collaborative and interdisciplinary research is needed, including the fields of energy systems analysis, economics, social sciences and humanities, and political sciences, to address this limitation in our work.

## Methods

**The Swiss TIMES energy systems model (STEM).** The Swiss TIMES Energy Systems Model (STEM)<sup>20</sup> is based on The Integrated MARKAL-EFOM System (TIMES) framework developed by the International Energy Agency's Energy System Technologies Analysis Program (IEA-ETSAP)<sup>54</sup>. STEM is a partial equilibrium framework representing the entire energy system, from an engineering techno-economic perspective, with a full range of energy processes, including exploitation, conversion, transmission, distribution, storage, and energy end-use. As STEM is a bottom-up technology-rich model, it does not explicitly include broader socio-technical or political perspectives of the energy system and energy transition<sup>55</sup>. The model consists of the following sectors of the energy system:

- Upstream sector, including the production and extraction of resources, energy imports and exports
- Conversion sector that includes electricity and heat production, hydrogen production, production of biofuels and e-fuels
- Final energy consumption sectors, including industry, services, residential, transport and agriculture
- CO<sub>2</sub> capture, sequestration and utilisation sectors

STEM aims to supply energy services at a minimum energy system cost by simultaneously making energy technology investments and operating decisions to reach a demand-supply equilibrium state. The equilibrium found by STEM has the property that the total surplus is maximised. STEM has a long-term horizon. This analysis focuses on the developments until 2050, with reporting years 2020, 2030, 2040 and 2050. We apply a 2.5% social discount rate and technology-specific interest rates of up to 5.5%, depending on the sector and technologies. In each year, 288 operating hours are considered, representing four seasons, three average days per season (*viz.* working day, Saturday and Sunday), with 24 h resolution.

For each energy service demand sector and energy use, the model considers hourly profiles, which are given exogenously<sup>20</sup>, but the hourly energy consumption needed to meet the hourly energy service demand is fully endogenous<sup>56</sup>. Based on construction year and size, different residential building classes are distinguished. The transport sector includes passenger and freight transport, with different modes and many types of vehicles for each mode. Stock-based material flow analysis approach for the evolution of building stock<sup>45</sup>, discrete choice methods for appliances, Gompertz functions for car ownership, etc., are used to project energy service demands for the subsectors according to the scenarios' macroeconomic and demographic developments. Climate change impacts on heating and cooling demands, as well as on energy resources (e.g., water), are explicitly accounted for based on the climate scenarios that are consistent with the energy scenarios<sup>41</sup>.

STEM includes options for producing synthetic fuels, and it explicitly represents the storage, transport and distribution required for the secondary energy carriers. A particular emphasis was given to the electricity sector to address systems with high shares of variable renewable energy. Four electricity grid transmission and distribution levels are represented, from very high to low voltage<sup>33</sup>. STEM includes direct current (DC) power flow model modelling of the electricity transmission grid with 15 nodes and 319 bi-directional lines<sup>57,58</sup>. Technical operating constraints for the hydrothermal power plants are approximated via a continuous relaxation of the unit commitment problem<sup>59</sup>. They include ramping rates, minimum stable operating levels, part-load efficiency losses, minimum online and offline times and start-up costs. While it is unsuitable for analysing actual system operation, it is valuable for including short-term decisions in long-term planning. The energy supply and use assets can be retired before the end of their technical lifetime when they have higher fixed or operating costs than the investment cost of new alternatives<sup>60</sup>.

While energy service demands are determined exogenously based on macroeconomic and demographic developments, the model endogenously considers energy savings measures for each end-use to reduce energy consumption.

These include the switch to a more efficient technology or another energy carrier like electricity, building renovations (walls, windows, floors, roof), adopting waste heat recovery practices, optimisation of motor drive operations and other industrial equipment, investments in specific industrial processes and measures that reduce consumption, and many others. Supplementary Information Note 1 elaborates a list of the technical measures in the model that characterises the demand reduction in our modelling framework. The costs for deploying such measures are fully accounted for in the objective function when minimising the total energy system cost.

Though STEM includes many technical and policy measures, changes in consumer behaviour or lifestyles, such as lowering indoor temperatures, are not considered because of the lack of reliable costs associated with the shift in consumer behaviour (e.g., discomfort costs). STEM is a bottom-up techno-economic partial equilibrium modelling framework. In this regard, consumer behaviour and acceptance of new technologies (in the meaning of openness or willingness to invest) is approximated by side constraints regarding the deployment level of these technologies or the access to the remaining exploitable and sustainable renewable energy potential.

STEM endogenously accounts for the stochastic variation of renewable energy availability, demand, and the residual load curve<sup>61</sup>. Besides energy markets, the requirements for primary and secondary operating reserves are endogenously modelled with explicit representation of ancillary services markets<sup>62</sup>. Hence, STEM includes both market- and technical-based flexibility mechanisms. For example, STEM represents energy storage, demand-side management schemes in the end-use sectors, grid-to-vehicle and vehicle-to-grid services from electric vehicles and detailed Power-to-X pathways<sup>31</sup>. The energy storage options are at different time scales and sizes, ranging from daily storage options to weekly and seasonal storage options<sup>31</sup>. In addition, we distinguish between centralised and large-scale storage (e.g. pumped hydro and large stationary batteries) and distributed storage (e.g. batteries and heat storage). The demand-side management schemes enable the shifting of electricity loads related to heating, cooking, washing, etc., also based on discomfort costs, shifting windows, and maximum load constraints derived from Swiss consumer surveys<sup>63–65</sup> and international studies<sup>66,67</sup>.

The cross-border electricity trade in STEM is modelled through exogenous hourly electricity import price profiles. These profiles are based on interfacing STEM with complicated electricity systems and grid simulation models for the transmission grid of Switzerland and Europe, assuming European developments align with the ENTSO-E TYNDP scenarios<sup>41</sup>. Additionally, trade patterns concerning the potential of Switzerland to export excess electricity to the neighbouring countries are considered, which result from transmission grid reliability constraints and other power plant dispatching constraints in Switzerland and its neighbours.

Regarding modelling the district heating infrastructure, we apply an approach that considers the aggregate of the corresponding network infrastructure, distinguishing between existing and newly built equipment. When a pipeline comes to the end of its life, it can be replaced with a new investment or refurbished. In this regard, STEM does not allow disinvestments in the district heating network. However, the model ensures that the overall annualised investment and operating, and maintenance costs of the district heating infrastructure are covered in each year of the projection period. The connections to district heating of existing buildings<sup>68</sup> are explicitly modelled in STEM. When existing buildings are demolished, their connections can be used by new buildings built in the same locations. The development of the building stock is based on a detailed dynamic stock model. The model was developed in cooperation with our partners in this project from the University of Geneva<sup>45</sup>. New buildings can also require new district heating connections, depending on the overall energy system cost minimisation. When the new connections exceed the current capacity of the process, then a new investment is made. The overall district heating potential is limited in the model at around 18 TWh/yr.<sup>69</sup>

Particular emphasis has been given to STEM for modelling battery electric vehicles. The charging and discharging profiles of electric vehicles are endogenously determined in STEM. We distinguish four consumer segments with different driving profiles and, consequently, charging and discharging needs. For each consumer segment, there is also a set of constraints to guarantee that the electric vehicle cannot be used if there is not enough energy in the battery to perform the requested trip at a given time. With the consumer segmentation and the set of constraints for having enough energy in the battery to complete the car trips, we try to improve the realism of the resulting charging and discharging profiles. The modelling of electric vehicles in STEM allows each vehicle's battery to provide electricity back to the grid (at a cost reflecting the necessary electronic equipment to achieve the reverse electricity flow). Thus, the estimation of the number of electric cars participating in vehicle-to-grid schemes is calculated from the model results. It is based on the driving, charging and discharging profiles of the different consumer segments, the amount of electricity these segments give to the grid, and the total number of cars in each segment—all these aspects are endogenously determined by STEM based on the mobility energy service demands<sup>32</sup>.

The emissions included in STEM are CO<sub>2</sub> from fuel combustion and CO<sub>2</sub> from the cement production process, which are generated by decomposing raw materials. The model does not include the CO<sub>2</sub> emissions from international aviation and navigation in the overall mitigation target since these are not included

in the Swiss National Determined Contribution and are not part of the Paris Agreement of 2015. STEM also does not calculate other non-CO<sub>2</sub> Kyoto GHGs related to the following sectors: from agriculture related to livestock, manure management, agricultural soils, liming, and urea applications; from the waste sector on solid waste disposal, biological treatment of solid waste, incineration and open burning of waste (other than the waste consumption for cogeneration of electricity and heat) and shredding; from fire damages; from land use, land use change and forestry.

STEM lacks endogenous mitigation options and technologies for non-CO<sub>2</sub> GHG emissions. Marginal Abatement Cost Curves (MACCs) can approximate emissions reductions from N<sub>2</sub>O, CH<sub>4</sub>, SF<sub>6</sub>, etc., but these would need to be exogenously calculated based on complementary modelling frameworks and studies. In the context of the present study, performed within the project Swiss Competence Centre for Energy Research Joint Scenario and Modelling (SCCER JASM), such complementary modelling competencies to provide STEM with these MACCs were not available. Hence, we focused on the transformation of energy systems to achieve net-zero CO<sub>2</sub> emissions. This implies that the remaining non-CO<sub>2</sub> emissions in 2050, around 5.7 Mt CO<sub>2</sub>-eq if the targets for reducing the non-CO<sub>2</sub> GHG stated in the Long-Term Climate Strategy of Switzerland<sup>4</sup> are met, should be compensated abroad in our analysis, as noted in the Swiss National Determined Contribution<sup>26</sup>.

Most of the 5.7 Mt CO<sub>2</sub>-eq that remain in 2050 and compensated abroad are emitted from the agriculture sector. This sector does not have mitigation options in STEM other than those for emissions from fuel combustion. Agriculture accounted for about 14% of the total GHG emissions in Switzerland in 2019, and in the Long-Term Climate Strategy of Switzerland the sector accounts for more than 95% of the remaining GHG emissions in 2050. We include the CO<sub>2</sub> emissions from fuel combustion in agriculture (about 10% of the total emissions from agriculture) but not the non-CO<sub>2</sub> GHG that are predominately related to biological and biophysical processes and come from diffuse sources or sources that fluctuate in terms of time and space. The complexity of the Swiss agriculture sector, with many small farms and various business operations, challenges the development of generally applicable mitigation measures—an argument also noted in the Long-Term Climate Strategy of Switzerland<sup>4</sup>. Given that more data and research is needed for identifying mitigation options for the GHG emissions from agriculture, and given that the Swiss climate change mitigation policy relies on the use of Internationally Transferred Mitigation Options for offsetting these emissions, we opted to exclude non-CO<sub>2</sub> emissions in our analysis. However, in an ongoing project, we have established collaborations with researchers from the agriculture and forestry sectors to assess potential mitigation options for the sector.

Finally, CO<sub>2</sub> domestic and cross-border pipelines are also considered for transferring captured emissions. As stated above, additional details about the structure and features of STEM are provided in Supplementary Information Note 1.

**Scenario design.** The scenario analysis was performed within the Swiss Competence Centre for Energy Research (SCCER) Joint Activity Scenarios and Modelling (JASM)<sup>70</sup> by using the Swiss TIMES energy systems model (STEM) of Paul Scherrer Institute. The SCCER energy programme<sup>25</sup> is a collection of eight university-networked research activities in Switzerland from 2013 to 2020 on energy efficiency, energy grids, electricity supply, economy, society, energy behaviour, mobility and biomass resources and technologies. It was funded by Inno-Suisse, aiming to provide solutions to the technical, social and political challenges of the Swiss energy transition. In JASM, modelling teams from the eight SCCERs worked together to analyse the technical feasibility of energy transformation pathways to net-zero. This approach is different from other efforts to define long-term energy strategy for Switzerland, as it is based on the combined output of the Swiss energy systems research community. In JASM, a framework that soft-links various energy systems and sectoral technical-economic models from the project partners was developed. All models used a consistent set of drivers and scenario definitions<sup>41</sup>, derived from the Swiss Administrative Federal Offices.

In the context of the SCCER JASM, STEM is enhanced via the collaboration with the other modelling teams regarding renewable potentials, import prices, the potential for domestic sequestration of CO<sub>2</sub>, cross-border trade infrastructure, characterisation of electricity, hydrogen, biofuel and synthetic fuel production technologies, the definition of end-use technologies such as boilers, appliances and vehicles, climate change impacts on energy demand and energy resources (e.g. water), and side-constraints reflecting consumer energy behaviour and social acceptance. The links between STEM and the rest of the sectoral models and approaches employed in SCCER JASM are detailed in Supplementary Information Note 2.

STEM explores possible energy futures based on contrasted scenarios. Unlike forecasts, scenarios do not presuppose knowledge of the main drivers of the energy system. Instead, they consist of a set of coherent assumptions about the future trajectories of these drivers, leading to a cohesive organisation of the energy system under study. A scenario builder carefully tests the hypotheses for internal consistency. A scenario definition requires at least four inputs: energy service demands, resources and potentials, policy settings, description and availability of technologies.

In developing the SCCER JASM scenarios, we examined two key methodologies:<sup>71</sup> (a) using input from knowledge carriers such as scientific experts

or stakeholders; (b) using intuitive logics (IL) or scenario axes. We also considered using the newly developed Cross Impact Balance (CIB) approach<sup>71</sup> that enables the traceability and reproducibility of scenarios' construction processes. At the same time, CIB can lead to scenarios with better consistency and more complete assumption sets than the two traditional approaches mentioned before. However, CIB was evaluated as unattractive to our exercise because of the considerable time and human resources required (which were unavailable to us) and the quality risks associated with its use by non-experienced teams in this method.

Therefore, in the SCCER JASM study, we based the scenario design process on our expertise with the scenario development methods we followed for the World Energy Council (WEC) scenarios<sup>72</sup>. The WEC methodology combines developing scenarios using three axes, the so-called energy trilemma, which refers to a balance between affordability, sustainability and security in energy system transformation<sup>73</sup>, and stakeholder expertise<sup>73</sup>. In SCCER JASM, the scenario axes were based on research and policy questions in Switzerland within the active discourse from 2017 to 2020, which was the timeframe within which the current exercise was performed. These mostly referred to the technical feasibility of transforming the Swiss energy system to a carbon-free energy supply and use and its economic implications regarding energy system costs and required investments in energy infrastructure. The technical feasibility of the presented pathways does not directly imply social, economic, or political feasibility.

Thus, the scenarios aim at exploring technically plausible pathways for reaching carbon neutrality by 2050 by adopting socio-economic drivers from Swiss Administrative and Federal Offices<sup>41</sup>. It should be noted that the assessed pathways presented in this study are only a subset of all the possible future energy system developments, and they are neither mutually exclusive nor forecasts. The main scenario axes used in their construction are: (a) technology development; (b) market integration; (c) security of energy supply. The first axis relates to sustainability, as new and immature technologies are needed in a decarbonised energy system. The second axis relates to market integration and trade of energy carriers, and emissions permits can reduce the mitigation costs. The third axis relates to the security of energy supply, which applies to different time and spatial scales, i.e., from hourly to annual and from local to global.

The *BAU scenario* extrapolates the energy consumption trends and energy policies in place for the future. It tries to answer the research question, "where does Switzerland land in terms of CO<sub>2</sub> emissions in 2050 if we continue the business-as-usual practices?". The scenario reflects the energy and climate policy instruments currently in force but not measures under discussion and not included in the energy and climate Swiss legislation until 2019. Table 3 shows the major energy and climate policies implemented in the Baseline scenario.

The *CLI scenario* assumes that the world gradually shifts to implement green economy strategies. Most governments agree on driving environmental sustainability through related policies and practices. Emissions trading markets are globally introduced, and many international governments support standards and protocols to improve energy efficiency and adopt circular economy practices. Society has become aware of the challenges related to climate change mitigation and embraces cleaner and smarter lifestyles than in the BAU scenario. Shifts in energy consumer behaviour towards energy efficiency gradually developed in CLI from 2020 onwards. Thus, energy demand is reduced in the end-use sectors as more energy-sufficient lifestyles are developed. In this scenario, due to the global cooperation and effort in mitigating climate change, Internationally Transferred Mitigation Options (ITMOs) are available for Switzerland at competitive prices, which help the country compensate for a part of the domestic emissions abroad. Besides, CO<sub>2</sub> grids are developed, connecting the European countries, and regulations enabling carbon emissions transportation for sequestration abroad are enacted after 2030.

Until 2030 the energy sector in Switzerland is regulated through taxes, feed-in tariffs, capital subsidies and state-funded building renovation programmes to encourage clean energy solutions. Switzerland implements climate change mitigation policies to achieve emissions cuts by 2030, many of which are described in the revised CO<sub>2</sub> Act<sup>74</sup>. A key subset of these policies is provided in Table 4.

Besides the core net-zero scenario, i.e. CLI, four additional scenarios are defined that are aimed at providing insights into the following questions related to energy transition towards net-zero CO<sub>2</sub> emissions: (a) what if the renewable expansion is not realised due to low population mobilisation (scenario ANTI); (b) what if the current bilateral energy agreements between Switzerland and the EU fail (ANTI and SECUR); (c) can Switzerland achieve the net-zero ambition by merely relying on domestic resources (SECUR); (d) what are the benefits for the energy transition cost, if increased integration between Swiss and international markets is achieved (MARKETS); (e) how the speed of the transition and its cost is affected by high innovation in low-carbon and clean technologies (INNOV); (f) which sectoral policies are incompatible with a least-cost trajectory to net-zero (LC). The design of these scenarios ensures comparability with CLI, and to some extent, among themselves.

The *ANTI scenario* assumes an international context with low cooperation in mitigating climate change. Due to the fragmented climate policies worldwide, R&D expenditures in low-carbon technologies are stagnated. There is limited technological progress, and, as a result, both consumers and utilities are faced with high upfront capital costs when adopting low-carbon solutions for energy supply

**Table 3 Major energy and climate policies implemented in the BAU scenario for Switzerland.**

Sector	Major policies implemented
Nuclear in electricity generation	60 years lifetime of existing nuclear power plants, no new nuclear power plants
Sectors participating in the Emissions Trading Scheme (ETS)	Coupled with the EU-ETS and follows an annual linear emissions reduction factor of 2.2%
Sectors outside the ETS	CO <sub>2</sub> tax in heating fuels at 120 CHF/tCO <sub>2</sub> from 2022
Aviation	Voluntary emissions reduction agreements in industries not covered by the ETS sectors
Residential and services sector—energy efficiency	As in the EU: Intra-EEA flights in ETS until 2024, but no aviation in ETS from 2025 Buildings Programme subsidies for efficiency and heating equipment substitution Tax incentives for building renovation Ecodesign and Eco-labelling regulations for appliances
Renewable electricity supply	Feed-in tariffs and investment grants for renewable technologies until 2030, as in the current Energy Supply Law (EnG) Lead-in times of renewable projects as of today
Road transport	Emissions standards of the average of the new vehicles registrations: 118 grCO <sub>2</sub> /km for cars, 147 grCO <sub>2</sub> /km for light duty vehicles based on the WLTP cycle Distance-related heavy vehicle fees (LSVA) and lump-sum heavy vehicle charges (PSVA) Mineral oil taxation Tax incentives for alternative vehicles (depending on Canton) that phased-out after 2030
Internal energy market and infrastructure	Electricity grid expansion according to the Swissgrid 2025 Network Plans <sup>76</sup> and expansion of the NTCs according to the ENTSO-E TYNDP plan of 2018 <sup>77</sup> Electricity grid expansion according to the Swissgrid 2025 Network Plans <sup>76</sup> and expansion of the NTCs according to the ENTSO-E TYNDP plan of 2018 <sup>77</sup>

and use. The integration of the Swiss and international energy markets is weaker in ANTI than in CLI, which hinders the availability of imported zero-carbon fuels and energy carriers, including electricity. However, environmental sensitivity still develops at local scales, and climate change mitigation goals are not abandoned. Communities seek to build a more sustainable future locally, and consumers rely on best-fit local solutions for energy supply and demand that maximise local benefits. They increasingly desire products and energy services customised for local contexts, which implies a high willingness to pay for these products. Individualistic lifestyles emerge with uneven energy efficiency and equipment replacement efforts between different consumer groups. A decentralised energy supply supports the development of local energy networks, accelerated building renovations to minimise import dependency at the community level, and widespread e-mobility and intelligent mobility. Local self-sufficiency becomes a priority in the ANTI scenario, which could often conflict with nationally-wide energy and climate targets. There is limited tolerance from society regarding landscape changes for implementing renewable and other low-carbon projects that do not directly benefit the local communities. In this context, we argue that the focus in ANTI is more on adaptation than mitigation, as capital-intensive projects for reducing the carbon footprint of the Swiss energy system are postponed to the future. Regarding implemented sectoral climate policies, the ANTI scenario extrapolates the BAU policies.

The *SECUR scenario* assumes that the world gravitates toward a multi-polar order, weakening the international governance systems. As a result, economic volatility increases and international trade agreements are not fully implemented due to rising nationalist policies that make export-oriented growth less critical as a financial strategy. Most countries use whatever capabilities they have to achieve national-wide security in energy supply. Due to weakened international structures, access to energy resources becomes complicated, and import duties increase energy import prices. The shift in priority from environmental sustainability to energy supply security triggers conflicting objectives, but the overall global climate change mitigation targets are not abandoned. Switzerland relies upon its domestic energy resources, including hydropower and other renewable energy sources. The Swiss society is keener in the *SECUR scenario* than in CLI in fully exploiting sustainable domestic renewable resources to reduce the carbon intensity of the energy system. In *SECUR*, there is a higher social acceptance than in CLI in implementing projects based on new renewable energy forms such as bioenergy, geothermal and solar. Priority for consumers and utilities in *SECUR* is the secure and reliable operation of the Swiss energy system, given the weak integration of Swiss and international energy markets. The reduction of the overall import dependency in future is a priority. Domestic grid reinforcement is highly acceptable in *SECUR* and desirable to mitigate congestion for a secure and reliable grid operation. In terms of implemented sectoral policies, the *SECUR scenario* includes the ones of CLI. The *SECUR scenario* relaxes the domestic sustainable exploitable renewable energy potentials to their maximum values in the literature. It additionally imposes a constraint on annual net imports of all energy carriers to be as close as possible to zero without deviating from the net-zero CO<sub>2</sub> emissions target in 2050. The right-hand side of the constraint is found by continuously tightening the constraint and keeping the feasibility of the climate target.

The *MARKETS scenario* is a variant of CLI, which assumes higher global cooperation and integration of the Swiss and international energy markets beyond

the levels considered in the core scenarios. Therefore, the *MARKETS* variant allows increased availability of imported biofuels, synthetic e-fuels, hydrogen and electricity. Priority in *MARKETS* is decarbonisation through affordable energy, which is also achieved via the development of local energy markets and intelligent prosumage schemes in coordination with national energy markets. As a result, technologies enabling sector coupling, prosumers and storages, demand-side management and vehicle-to-grid enjoy economies of scale, and their costs are lower than in the core scenarios. In supporting domestic and national markets integration, grid congestion is eliminated to a large extent by reinforcing domestic grids. With the focus on new business models based on renewable energy and P2X pathways, the social acceptance for using domestic renewable energy resources is higher than in the core scenarios and similar to the levels in *SECUR*. All policies included in the CLI scenario are also implemented in *MARKETS*.

The *INNOV scenario* is a variant of *MARKETS*. It assumes the same developments as *MARKETS* regarding integrating local, national and international energy markets and that a global effort exists to mitigate climate change and achieve the Paris Agreements. Closer international coordination is assumed concerning implementing climate change policies worldwide and reducing the costs of low-carbon technologies in energy supply and demand via increased R&D expenditures worldwide. Circular economy policies and schemes emerge globally, and there is a high level of material efficiency that results in lower energy conservation and renovation costs compared to the core scenarios. Moreover, in the context of a global joint effort to reduce GHG emissions, consumers also have high social acceptance for new technologies. Thus, the costs of clean and low-carbon technologies, such as renewable technologies, alternative vehicles and CCS, and energy supply and demand efficiency measures are lower in this variant than in the core scenarios. As *INNOV* builds on *MARKETS*, grid reinforcement and high availability of imported zero-carbon fuels and energy carriers are also assumed in this variant.

The *LC scenario* is another variant of CLI in which we sought the cost-optimal emissions reduction trajectory by excluding the sectoral policies in CLI (see Table 3 and “Table 4”). The *LC scenario* is regarded as the *Least Cost* solution and used as a benchmark to identify sectoral policies in CLI that could potentially entail high costs for energy consumers. The only constraints given to the *LC scenario* are the resource potentials, which are set to the levels of CLI, and the overarching CO<sub>2</sub> emissions reduction targets for 2030 and 2050.

The scenario design and quantification are based on systematic and informed research regarding alternative pathways and their costs. The derived paths are realistic and technically feasible under the evolving uncertainty of technical progress, resources, societal structures, national and international energy policies and markets.

All scenario assumptions used as input to the model are given in Supplementary Information Note 3 and Supplementary Data 1 with the key scenario parameters accompanying this manuscript. Further comparisons of the scenario results are provided in Supplementary Information Note 7. Detailed results are given in Supplementary Data 2 with energy balance tables for each scenario.

It should be noted that quantifying the scenarios by STEM assumes rational agents. In this regard, many of the policy interventions included in the scenarios are of financial nature. Moreover, aspects regarding lifestyle changes and sustainable and circular economy can only be given exogenously to our framework

**Table 4 Major policies implement in the CLI scenario in Switzerland.**

Sector	Major policies implemented
Nuclear in electricity generation	60 years lifetime of existing nuclear power plants, no new nuclear power plants
Sectors participating in the Emissions Trading Scheme (ETS)	Coupled with the EU-ETS, with an annual linear reduction factor of 2.2% until 2030, 2.6% until 2040 and 2.8% until 2050
Sectors outside the ETS	CO <sub>2</sub> tax in heating fuels at 120 CHF/tCO <sub>2</sub> from 2022, increasing to 210 CHF/tCO <sub>2</sub> in 2030
Aviation	Voluntary emissions reduction agreements in industries not covered by the ETS sectors Intra-EEA flights in ETS Emissions from international aviation should be linearly reduced to 0 Mt CO <sub>2</sub> from 2030 to 2050 CO <sub>2</sub> tax per passenger will go from 30 CHF in 2025 to a maximum of 120 CHF by 2030
Residential and services sectors—energy efficiency	Buildings Programme subsidies for efficiency and heating equipment substitution Tax incentives for building renovation Ecodesign and Eco-labelling regulations for appliances New buildings constructed with the new MINERGIE standards <sup>44</sup> New buildings constructed with the new MINERGIE standards <sup>44</sup>
Residential and services sectors—emissions reductions	Emissions regulations standards for residential buildings: –Existing buildings 20 kgCO <sub>2</sub> /sqm in 2025, reduced every five years by 5 kgCO <sub>2</sub> , to reach 0 kgCO <sub>2</sub> /sqm in 2050 –New buildings: 0 kgCO <sub>2</sub> /sqm from 2030 Emissions standards for commercial buildings: –Existing buildings 12 kgCO <sub>2</sub> /sqm in 2030, 4 kgCO <sub>2</sub> /sqm in 2040 and 0 kgCO <sub>2</sub> /sqm in 2050 –New buildings: 0 kgCO <sub>2</sub> /sqm from 2030
Renewable electricity supply	Feed-in tariffs and investment grants for renewable technologies until 2030, as in the current Energy Supply Law (EnG) Non-hydro renewable targets in the electricity supply: 11.4 TWh/yr in 2030, 24.2 TWh in 2050 Hydropower supply at least 37.4 TWh in 2035, excluding pump storage Regulations halving the lead-in times of renewable projects in 2030
Road transport	Emissions standards for the average of the registrations based on the WLTP cycle: –Cars: 118 grCO <sub>2</sub> /km for cars in 2021, 95 grCO <sub>2</sub> /km for the period 2020-24, 65 grCO <sub>2</sub> /km in 2030, 16 grCO <sub>2</sub> /km in 2050 –Light duty vehicles registrations: 147 grCO <sub>2</sub> /km for the period 2020-24, 110 grCO <sub>2</sub> /km in 2030, 60 grCO <sub>2</sub> /km in 2050 –Heavy duty trucks registrations: 475 grCO <sub>2</sub> /km in 2030, 330 grCO <sub>2</sub> /km in 2050 –Coaches registrations: 575 grCO <sub>2</sub> /km in 2030, 400 grCO <sub>2</sub> /km in 2030 Distance-related heavy vehicle fees (LSVA) and lump-sum heavy vehicle charges (PSVA) Mineral oil taxation Tax incentives for alternative vehicles (depending on Canton) that phased-out after 2030 Subsidies for investment in charging infrastructures up to 30% of the capital Compensation levy of fossil liquids: 1.5 Rp/litre in 2025 to be increased to 5 Rp/litre in 2030 and beyond
Internal energy market policies and infrastructure	Electricity grid expansion according to the Swissgrid 2025 Network Plans <sup>76</sup> and expansion of the NTCs according to the ENTSO-E TYNDP plan of 2018 <sup>77</sup> Electricity grid expansion according to the Swissgrid 2025 Network Plans <sup>76</sup> and expansion of the NTCs according to the ENTSO-E TYNDP plan of 2018 <sup>77</sup>
Climate Fund—cross-sectoral financing of subsidies	One-third of the revenues from the CO <sub>2</sub> tax in heating sectors, or a maximum of 450 million CHF per year, and a maximum of half of the revenues from the CO <sub>2</sub> tax in flights are used to finance subsidies and financial incentives in the buildings sector, industry and electric vehicles charging infrastructure.

as part of a coherent storyline. An endogenous assessment of these aspects is beyond the scope of this paper as STEM needs further development to capture them. It is a limitation of our work, which we aim to address in future research with stronger collaboration with scholars from the social sciences and humanities fields.

Finally, the assessed scenarios did not include aggressive energy demand reductions in their hypotheses. While aspects of efficient lifestyles and circular economy are included in the scenarios, including ambitious energy savings due to lifestyle changes and beyond the levels achieved with technical measures needs extensive assessment of the energy saving potential that can be achieved with such changes. Such estimates are not yet available for Switzerland in a format that quantitative energy systems models like STEM can use. Thus, to avoid creating a paper exercise by arbitrarily changing the energy demand levels due to lifestyle changes, we opted for the scenario definitions to follow a conservative approach. Still, such a conservative approach is not necessarily out of context, given the uncertainty surrounding the energy demand development and associated with the future lifestyle changes affecting energy consumption behaviour and patterns. We aim to collaborate closely with the social sciences community in Switzerland to identify potential energy demand reductions associated with changes in energy consumption behaviour for the future years. Nevertheless, we should note that the model result regarding the need for accelerating renewable energy and introducing negative emissions technologies to meet the net-zero CO<sub>2</sub> emissions target is

robust, as a recent study that assumed ambitious demand reductions due to lifestyle changes at global scales shows<sup>75</sup>.

**The meaning of the “policy cost” in a partial equilibrium framework like STEM.** In a partial equilibrium framework, the term “policy cost” is defined as the difference in the total energy system cost with and without a specific policy/target, i.e., between the BAU and the suite of the net-zero CO<sub>2</sub> emissions scenarios assessed. Given that we do not account for feedback on the energy system to the rest of the economic sectors, we cannot claim that this is the overall cost associated with a specific policy measure. As we also do not account for the distributional impacts of the increased costs on different income classes, our results on the costs of the energy transition have limited information about the affordability of the energy transition.

The total energy system cost comprises: (a) capital costs for investing into and dismantling technologies for energy conversion, transmission and use, renovations and energy savings; (b) fixed and variable operation and maintenance costs; (c) costs for imports and domestic resource extraction and production; (d) revenues from exports; (e) delivery costs for energy carriers; (f) taxes and subsidies of energy carriers and technologies; (g) revenues from recuperation of embedded commodities accrued when a technology’s dismantling releases some valuable commodities and; (h) salvage value of technologies and embedded commodities at

the end of the planning horizon. Moreover, the cost structure of the model is vintage-dependent. Thus, the costs for renewing the existing energy system infrastructure, independently of its decarbonisation, are included in the analysis.

The model's objective is the discounted system cost from 2020 to 2050. For the discounting, a social discount rate of 2.5% is used. It should be noted that sectoral interest rates are applied for investments in energy technologies in the different sectors, which are higher than the social discount rate. In the end-use sectors, the interest rate is set to 5.5%, which implies a 3% risk premium (or hurdle rate) in the investment decision. In the supply sectors, the interest rate for investing in large-scale energy supply technologies is 2.5%, while the interest rate for investing in medium and small-sized energy technologies is 5.5%.

Further, we calculate costs for the baseline scenario (BAU), which does not achieve decarbonisation targets but extrapolates the current energy supply and consumption trends and the stated energy and climate policies in the Swiss legislation.

Our analysis does not include external costs associated with environmental damage, resource depletion, or human health. Moreover, our analysis does not include the distributional impacts of the energy transition on households of different income classes. Thus, it does not address equity concerns and affordability of the energy transition.

### Data availability

STEM is calibrated using the Swiss energy statistics, which can be downloaded from the Swiss Federal Office of Energy (<https://www.bfe.admin.ch/bfe/en/home/supply/statistics-and-geodata/energy-statistics/overall-energy-statistics.html>) and also from the Swiss Federal Statistical Office (<https://www.bfs.admin.ch/bfs/en/home.html>). STEM input data is available at the SCCER Joint Activity Scenarios and Modelling Platform (<https://data.sccer-jasm.ch>).

The modelling assumptions regarding macroeconomic and demographic developments, energy prices, technology costs and performance, etc., are provided in Supplementary Data File 1, publicly accessible in Zenodo: <https://doi.org/10.5281/zenodo.7767243>

Extensive results from all scenarios assessed are publicly accessible in Supplementary Data File 2 in Zenodo: <https://doi.org/10.5281/zenodo.7767243>

Moreover, all source data for the charts and graphs are available in HTML files. The files can be opened with any text editor to inspect the code and the data, while the figures can be reproduced and downloaded as images by opening the HTML files with any browser. The source code and data of the charts as HTML are accessible in Zenodo: <https://doi.org/10.5281/zenodo.7767243>

Additional data (assumptions and results) of this study are available from the corresponding author upon a reasonable request.

### Code availability

The code and documentation of the TIMES model are open source. The documentation of the model is provided by the ETSAP website (<https://iea-etsap.org/index.php/documentation>), while the code is available on ETSAP GitHub ([https://github.com/etsap-TIMES/TIMES\\_model](https://github.com/etsap-TIMES/TIMES_model)). For the charts produced for this paper, we use the HighCharts free version (<https://www.highcharts.com>), and all scripts and source data for making the charts are available on the JSFiddle platform (<https://jsfiddle.net/user/fiddles/public/>).

Received: 3 August 2022; Accepted: 21 April 2023;

Published online: 08 May 2023

### References

- UNFCCC. Ahead of Paris 2015 Climate Change Agreement, Switzerland Submits its Climate Action Plan to UN. *Press Release* <https://unfccc.int/news/switzerland-submits-its-climate-action-plan-to-un> (2015).
- UNFCCC. Updated or new NDCs submitted. *Process and meetings* <https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement/nationally-determined-contributions-ndcs/NDC-submissions> (2021).
- Bachelet, M. Midnight survival campaign for the planet. *United Nations—Human Rights—Office of the High Commissioner* <https://www.ohchr.org/EN/NewsEvents/Pages/DisplayNews.aspx?NewsID=26565&LangID=E>.
- SFOEN. *Long term Climate Strategy of Switzerland*. <https://www.news.admin.ch/%0Anewsd/message/attachments/65081.pdf> (2021).
- Masood, E. & Tollefson, J. 'COP26 hasn't solved the problem': scientists react to UN climate deal. *Nature* **599**, 355–356 (2021).
- BFE. *Energy Strategy 2050 after the Popular Vote* (BFE, 2017).
- ElCom. *Security of the electricity supply in Switzerland, 2025*. <https://www.elcom.admin.ch/dam/elcom/de/dokumente/2021/studiestromversorgungssicherheitschweiz2025.pdf.download.pdf/StudieStromversorgungssicherheitSchweiz2025.pdf> (2021).
- Demski, C. et al. National context is a key determinant of energy security concerns across Europe. *Nat. Energy* **3**, 882–888 (2018).
- Bocca, R., Ashraf, M. & Jamison, S. *Fostering Effective Energy Transition 2021 Edition*. *World Economic Forum* [https://www3.weforum.org/docs/WEF\\_Fostering\\_Effective\\_Energy\\_Transition\\_2021.pdf](https://www3.weforum.org/docs/WEF_Fostering_Effective_Energy_Transition_2021.pdf) (2021).
- Luderer, G. et al. Residual fossil CO<sub>2</sub> emissions in 1.5–2 °C pathways. *Nat. Clim. Chang.* **8**, 626–633 (2018).
- Bauer, C., Cox, B., Heck, T. & Zhang, X. *Potentials, costs and environmental assessment of electricity generation technologies—Update*. [https://www.bfe.admin.ch/bfe/de/home/news-und-medien/publikationen/\\_jcr\\_content/par/externalcontent.external.exturl.pdf/aHR0cHM6Ly9wdWJkYi5iZmUuYWRtaW4uY2gvZGUvcHVibGJlYX/Rpb24vZG93bmVWQvOTgyNi5wZGY=.pdf](https://www.bfe.admin.ch/bfe/de/home/news-und-medien/publikationen/_jcr_content/par/externalcontent.external.exturl.pdf/aHR0cHM6Ly9wdWJkYi5iZmUuYWRtaW4uY2gvZGUvcHVibGJlYX/Rpb24vZG93bmVWQvOTgyNi5wZGY=.pdf) (2019).
- van Soest, H. L., den Elzen, M. G. J. & van Vuuren, D. P. Net-zero emission targets for major emitting countries consistent with the Paris Agreement. *Nat. Commun.* **12**, 2140 (2021).
- van Vuuren, D. P. et al. Alternative pathways to the 1.5 °C target reduce the need for negative emission technologies. *Nat. Clim. Chang.* **8**, 391–397 (2018).
- Thees, O., Erni, M., Lemm, R., Stadelmann, G. & Zenner, E. K. Future potentials of sustainable wood fuel from forests in Switzerland. *Biomass Bioenergy* **141**, 105647 (2020).
- Burg, V., Bowman, G., Hellweg, S. & Thees, O. Long-Term Wet Bioenergy Resources in Switzerland: Drivers and Projections until 2050. *Energies* **12**, (2019[CE1]).
- Sutter, D., Werner, M., Zappone, A. & Mazzotti, M. Developing CCS into a realistic option in a country's energy strategy. *Energy Procedia* **37**, 6562–6570 (2013).
- Ringrose, P. S. & Meckel, T. A. Maturing global CO<sub>2</sub> storage resources on offshore continental margins to achieve 2DS emissions reductions. *Sci. Rep.* **9**, 17944 (2019).
- UNDP. *World Population Prospects 2019*. <https://population.un.org/wpp/Download/Standard/Population/> (2019).
- Peng, W. et al. Climate policy models need to get real about people—here's how. *Nature* **594**, 174–176 (2021).
- Kannan, R. & Turton, H. *Switzerland energy transition scenarios - development and application of the Swiss TIMES Energy system Model (STEM)*. *Final Report to Swiss Federal Office of Energy, Bern* <https://www.psi.ch/sites/default/files/import/eem/PublicationsTabelle/2014-STEM-PSI-Bericht-14-06.pdf> (2014).
- Bauer, C. et al. *Potentials, costs and environmental assessment of electricity generation technologies*. *Swiss Federal Energy Office* <https://www.psi.ch/ta/PublicationTab/Final-Report-BFE-Project.pdf> (2017).
- Zhang, S. & Chen, W. Assessing the energy transition in China towards carbon neutrality with a probabilistic framework. *Nat. Commun.* **13**, 87 (2022).
- Sognaes, I. et al. A multi-model analysis of long-term emissions and warming implications of current mitigation efforts. *Nat. Clim. Chang.* **11**, 1055–1062 (2021).
- Pye, S., Li, F. G. N., Price, J. & Fais, B. Achieving net-zero emissions through the reframing of UK national targets in the post-Paris Agreement era. *Nat. Energy* **2**, 17024 (2017).
- Innosuisse. *SCCER Energy Funding Programme 2013–2020*. [https://www.innosuisse.ch/dam/inno/en/dokumente/themenorientierte-programme/Energie/finalreportsccer.pdf.download.pdf/Energy\\_Funding\\_Programme\\_Final\\_Report.pdf](https://www.innosuisse.ch/dam/inno/en/dokumente/themenorientierte-programme/Energie/finalreportsccer.pdf.download.pdf/Energy_Funding_Programme_Final_Report.pdf) (2021).
- UNFCCC. *Switzerland First NDC (Updated submission)*. [https://unfccc.int/sites/default/files/NDC/2022-06/Swiss\\_NDC\\_2021-2030\\_incl\\_ICTU\\_December\\_2021.pdf](https://unfccc.int/sites/default/files/NDC/2022-06/Swiss_NDC_2021-2030_incl_ICTU_December_2021.pdf) (2021).
- Panos, E. & Kannan, R. in *Limiting Global Warming to Well Below 2 °C: Energy System Modelling and Policy Development* (eds. Giannakidis, G. et al.) 155–172 (2018).
- Babonneau, F., Thalmann, P. & Vielle, M. Defining deep decarbonization pathways for Switzerland: an economic evaluation. *Clim. Policy* **18**, 1–13 (2018).
- Landis, F., Marcucci, A., Rausch, S., Kannan, R. & Bretschger, L. Multi-model comparison of Swiss decarbonization scenarios. *Swiss J. Econ. Stat.* **155**, 12 (2019).
- Xexakis, G., Hansmann, R., Volken, S. P. & Trutnevyte, E. Models on the wrong track: Model-based electricity supply scenarios in Switzerland are not aligned with the perspectives of energy experts and the public. *Renew. Sustain. Energy Rev.* **134**, 110297 (2020).
- Panos, E., Kober, T. & Wokaun, A. Long term evaluation of electric storage technologies vs alternative flexibility options for the Swiss energy system. *Appl. Energy* **252** (2019).
- Kannan, R. & Hirschberg, S. Interplay between electricity and transport sectors—integrating the Swiss car fleet and electricity system. *Transp. Res. A: Policy Pract* **94**, 514–531 (2016).
- Panos, E. & Kannan, R. The role of domestic biomass in electricity, heat and grid balancing markets in Switzerland. *Energy* **112** (2016).



34. Schulz, T. F., Kypreos, S., Barreto, L. & Wokaun, A. Intermediate steps towards the 2000W society in Switzerland: An energy-economic scenario analysis. *Energy Policy* **36**, 1303–1317 (2008).
35. Rüdösli, M., Romano, E., Eggmann, S. & Patel, M. K. Decarbonization strategies for Switzerland considering embedded greenhouse gas emissions in electricity imports. *Energy Policy* **162**, 112794 (2022).
36. Züttel, A. et al. Future Swiss Energy Economy: the challenge of storing renewable energy. *Front. Energy Res.* **9** (2022).
37. Pickering, B., Lombardi, F. & Pfenninger, S. Diversity of options to eliminate fossil fuels and reach carbon neutrality across the entire European energy system. *Joule* <https://doi.org/10.1016/j.joule.2022.05.009> (2022).
38. Kirchner, A. et al. *Energieperspektiven 2050+*. <https://www.bfe.admin.ch/bfe/de/home/politik/energieperspektiven-2050-plus.exturl.html/aHR0cHM6Ly9wdWJkYi5iZmUuYWRTaW4uY2gvZGUVcHVibGljYX/Rpb24vZG93bmxvYWQvMTAzMjM=.html> (2021).
39. VSE, EMPA & EBP. *Energieversorgung der Schweiz bis 2050 (Energy Supply in Switzerland until 2050)*. <https://www.strom.ch/de/energiezukunft-2050/resultate#studienbericht> (2022).
40. Burger, P., Emmenegger, R. & Sohre, A. Energy futures as societal futures: Co-evolutionary scenarios linking futures of society and decarbonized energy systems in Switzerland 2050. *Futures* **140**, 102955 (2022).
41. Marcucci, A., Panos, E., Guidati, G., Schlecht, I. & Giardini, D. *JASM Framework and Drivers Definition*. <https://sccer-jasm.ch> (2020).
42. Guidati, G. et al. *Biomass and Waste Potentials for Energy Use* (2020).
43. Notter, D. A., Meyer, R. & Althaus, H.-J. The Western Lifestyle and Its Long Way to Sustainability. *Environ. Sci. Technol.* **47**, 4014–4021 (2013).
44. Sidler, C. & Humm, O. *Besser planen, besser bauen—Optimieren mit Minergie*. [https://www.minergie.ch/media/planer\\_d.pdf](https://www.minergie.ch/media/planer_d.pdf) (2019).
45. Streicher, K. N. et al. Optimal building retrofit pathways considering stock dynamics and climate change impacts. *Energy Policy* **152**, 112220 (2021).
46. Vossebein, A., Muster, S., Betschart, U. & Koelliker, B. *Studie Potential Demand Side Management in der Schweiz*. <https://pubdb.bfe.admin.ch/de/publication/download/9887> (2019).
47. SFOE. *Swiss electricity statistics*. <https://www.bfe.admin.ch/bfe/en/home/supply/statistics-and-geodata/energy-statistics/electricity-statistics.html> (2020).
48. Diamond, L., Aschwanden, L., Adams, A. & Egli, D. Revised potential of the Upper Muschelkalk Formation (Central Swiss Plateau) for CO<sub>2</sub> storage and geothermal electricity. In: *SCCER SoE Annual Conference* 18 (2019).
49. OECD/IEA. *Carbon Capture and Storage and the London Protocol*. [https://iea.blob.core.windows.net/assets/a0a0ee83-6842-4c28-b64d-a01df895bee8/CCS\\_London\\_Protocol.pdf](https://iea.blob.core.windows.net/assets/a0a0ee83-6842-4c28-b64d-a01df895bee8/CCS_London_Protocol.pdf) (2011).
50. The heat is on. *Nat. Energy* **1**, 16193 (2016).
51. Johan, R. et al. A roadmap for rapid decarbonization. *Science* **355**, 1269–1271 (2017).
52. Wyns, T., Khandekar, G., Robson, I. *Industrial Value Chain: a Bridge Towards a Carbon Neutral Europe*. [https://www.ies.be/files/Industrial\\_Value\\_Chain\\_25sept\\_0.pdf](https://www.ies.be/files/Industrial_Value_Chain_25sept_0.pdf) (2018).
53. Cox, B., Bauer, C., Mendoza Beltran, A., van Vuuren, D. P. & Mutel, C. L. Life cycle environmental and cost comparison of current and future passenger cars under different energy scenarios. *Appl. Energy* **269**, 115021 (2020).
54. Loulou, R., Goldstein, G., Kanudia, A., Lettila, A. & Remme, U. *Documentation for the TIMES Model*. [https://iea-etsap.org/docs/Documentation\\_for\\_the\\_TIMES\\_Model-Part-I\\_July-2016.pdf](https://iea-etsap.org/docs/Documentation_for_the_TIMES_Model-Part-I_July-2016.pdf) (2016).
55. Cherp, A., Vinichenko, V., Jewell, J., Brutschin, E. & Sovacool, B. Integrating techno-economic, socio-technical and political perspectives on national energy transitions: a meta-theoretical framework. *Energy Res. Soc. Sci.* **37**, 175–190 (2018).
56. Kannan, R. Dynamics of long-term electricity demand profile: Insights from the analysis of Swiss energy systems. *Energy Strateg. Rev.* **22**, 410–425 (2018).
57. Fuchs, A. et al. *ISCHES—Integration of stochastic renewables in the Swiss electricity supply system. Final report to Swisselectric Research and to Swiss Competence Centre Energy and Mobility* <https://www.psi.ch/lea/HomeEN/Final-Report-ISCHES-Project.pdf> (2017).
58. Lehtilä, A. & Giannakidis, G. *TIMES Grid Modeling Features*. <http://iea-etsap.org/docs/TIMES-RLDC-Documentation.pdf> (2013).
59. Panos, E. & Lehtilä, A. *Dispatching and unit commitment features in TIMES*. [https://iea-etsap.org/docs/TIMES\\_Dispatching\\_Documentation.pdf](https://iea-etsap.org/docs/TIMES_Dispatching_Documentation.pdf) (2016).
60. Lehtilä, A. & Noble, K. *TIMES Early Retirement Capacity*. <http://iea-etsap.org/docs/TIMES-Early-Retirement-of-Capacity.pdf> (2011).
61. Lehtilä, A., Giannakidis, G. & Tigas, K. *Residual Load Curves in TIMES*. <http://iea-etsap.org/docs/TIMES-RLDC-Documentation.pdf> (2014).
62. Panos, E., Lehtilä, A., Deane, P. & Sharma, T. *Enhancing the flexibility in TIMES: Introducing Ancillary Services Markets*. <https://iea-etsap.org/projects/TIMES-BS-Documentation.pdf> (2019).
63. Hille, S. L., Weber, S. & Brosch, T. Consumers' preferences for electricity saving programs: evidence from a choice-based conjoint study. *J. Clean. Prod.* **220**, 800–815 (2017).
64. Soland, N., Loosli, S., Koch, J. & Christ, O. Acceptance among residential electricity consumers regarding scenarios of a transformed energy system in Switzerland—a focus group study. *Energy Effic* **11**, 1673–1688 (2018).
65. Hunziker, C., Schulz, N. & Wache, H. Shaping aggregated load profiles based on optimized local scheduling of home appliances. *Comput. Sci.—Res. Dev.* **33**, 61–70 (2018).
66. Gan, C. K., Strbac, G., Openshaw, D., Power, U. K. & Uk, N. Investigation of the impact of electrifying transport and heat sectors on the UK distribution networks. In: *21st Int. Conf. Electricity Distribution (CIRED)* 6–9 (2011).
67. Papadaskalopoulos, D., Strbac, G., Mancarella, P., Aunedi, M. & Stanojevic, V. Decentralized participation of flexible demand in electricity markets—Part II: Application with electric vehicles and heat pump systems. *IEEE Trans. Power Syst.* **28**, 3667–3674 (2013).
68. Streicher, K. N., Allan, J., Murray, P., Bollinger, A. & Marcucci, A. *Energy efficiency in buildings* [https://sccer-jasm.ch/JASMPapers/JASM\\_energyEfficiency\\_buildings.pdf](https://sccer-jasm.ch/JASMPapers/JASM_energyEfficiency_buildings.pdf) (2020).
69. eicher+pauli. *Weissbuch Fernwärme Schweiz—VFS Strategie*. [https://www.fernwaerme-schweiz.ch/fernwaerme-deutsch-wAssets/docs/Dienstleistungen/Weissbuch/Fernwaerme\\_Weissbuch-deutsch.pdf](https://www.fernwaerme-schweiz.ch/fernwaerme-deutsch-wAssets/docs/Dienstleistungen/Weissbuch/Fernwaerme_Weissbuch-deutsch.pdf) (2014).
70. JASM. *Transformation of the Swiss Energy System for a Net-Zero Greenhouse Gas Emission Society*. [https://sccer-jasm.ch/JASMPapers/JASM\\_White\\_paper.pdf](https://sccer-jasm.ch/JASMPapers/JASM_White_paper.pdf) (2021).
71. Weimer-Jehle, W. et al. Socio-technical energy scenarios: state-of-the-art and CIB-based approaches. *Clim. Change* **162**, 1723–1741 (2020).
72. Kober, T., Schiffer, H.-W., Densing, M. & Panos, E. Global energy perspectives to 2060—WEC's World Energy Scenarios 2019. *Energy Strateg. Rev.* **31**, 100523 (2020).
73. WEC. *World Energy Trilemma Index*. [https://www.worldenergy.org/assets/downloads/World\\_Energy\\_Trilemma\\_Index\\_2022.pdf?v=1669842216](https://www.worldenergy.org/assets/downloads/World_Energy_Trilemma_Index_2022.pdf?v=1669842216) (2022).
74. FOEN. *Revision of the CO<sub>2</sub> Act* (FOEN, 2020).
75. Rogelj, J. et al. A new scenario logic for the Paris Agreement long-term temperature goal. *Nature* **573**, 357–363 (2019).
76. Swissgrid. *Netz 2025*. <https://www.swissgrid.ch/swissgrid/de/home.html> (2015).
77. Kätzlitz, A. et al. *TYNDP 2022 Scenario Report*. <https://2022.entsos-tyndp-scenarios.eu/download/> (2022).

## Acknowledgements

This study was performed within the Swiss Competence Centre for Energy Research Joint Activity Scenarios and Modelling (SCCER JA-S&M). This project received funding from the Suisse Innovation Agency (InnoSuisse). The authors would also like to thank Prof. Dr Russell McKenna for providing suggestions and comments during the internal review of the paper. The authors also thank the two anonymous reviewers for their feedback in improving the quality of the manuscript.

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E.P.: Conceptualisation, Data Curation, Methodology, Formal Analysis, Writing—original draft, Writing—review and editing. K.R.: Conceptualisation, Data Curation, Methodology, Formal Analysis, Writing—review and editing. S.H.: Conceptualisation, Technology Performance Assessment and Analysis, Funding acquisition, Writing—review and editing. T.K.: Conceptualisation, Supervision, Project administration, Writing—review and editing.

## Competing interests

The authors declare no competing interests.

## Additional information

**Supplementary information** The online version contains supplementary material available at <https://doi.org/10.1038/s43247-023-00813-6>.

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**Peer review information** *Communications Earth & Environment* thanks Paul Burger and the other, anonymous, reviewer(s) for their contribution to the peer review of this work. Primary Handling Editors: Alessandro Rubino, Joseph Aslin and Clare Davis. Peer reviewer reports are available.

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