Through net zero energy scenarios for 2050 in Switzerland*

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Abstract

Switzerland's dual ambition of achieving net-zero greenhouse gas emissions by 2050 and phasing out nuclear energy presents significant challenges for its energy system. This report explores scenarios to meet these goals using a linear optimization model that minimizes either total system costs (TOTEX) or global warming potential (GWP). The model incorporates energy demands, conversion technologies, and constraints on resources and capacities, calibrated for 2050 scenarios based on projections and policy targets. This report presents two more sustainable propositions of the Swiss energy system, respectively representing a total cost of 17.2 MCHF/year and global emissions of 14'000 kTCO2/year and a total cost of 16.9 MCHF/year and global emissions of 11'000 kTCO2/year. Achieving this balance requires significant technological advancements and societal shifts, including widespread adoption of renewable technologies. A critical area for further exploration involves carbon capture and storage (CCS) technologies, which need to address the residual greenhouse gas emissions that remain in the optimal scenario.

Keywords:
Swiss energy system, net-zero energy strategy, renewable energy, Sankey diagram, TOTEX, GWP, Pareto.

1. Introduction

In August 2019, the Swiss Federal Council decided, on the recommendation of governmental climate experts [1], to enshrine in law [2] the country's energy perspective for the future: By 2050, Switzerland aims to achieve zero net greenhouse gas emissions. "Net zero" is the global target agreed upon to combat climate change in the second half of the century. The IPCC (Intergovernmental Panel on Climate Change) has determined that reaching net zero CO2 emissions by 2050 is essential to limit global warming to 1.5°C [1]. The term "net" zero implies that residual emissions will be captured using carbon capture technologies. At the same time, following the Fukushima disaster in 2011, the country decided [3] to dismantle its nuclear power plants by 2050. This dual challenge of achieving net-zero greenhouse gas emissions by 2050 while phasing out nuclear power raises critical questions about the future of Switzerland's energy system. In this context, our research seeks to address the following question: how can Switzerland achieve its net-zero emissions target while ensuring a secure and sustainable supply to meet the 2050 energy demand ? To answer this question, two different scenarios representing a complete energetic mix are suggested.

In addition to the scenarios proposed by the Swiss government in their technical report [4], several scientists have conducted more in-depth analyses, exploring the implications and challenges associated with achieving a net-zero energy strategy by 2050. In recent studies, various approaches have been proposed to achieve Switzerland's energy goals by 2050. [5] highlights the role of e-mobility and its impact on electricity demand, suggesting that electrified transport will be critical for meeting net-zero targets. [6] emphasizes a holistic strategy for transforming the national energy system to align with the Federal Council's 2050 goals. [7] presents advancements in photovoltaic technology, particularly in alpine regions, as crucial for winter electricity production. [8] discusses the challenges of phasing out nuclear energy and scaling up solar PV to meet seasonal demand. [9] introduces a novel carbon management framework to integrate biogenic energy sources, while [10] argues for a broader socio-political perspective in forming low-carbon energy scenarios. These diverse perspectives inform the formulation of the energy scenarios explored in this report, aiming to balance technological innovation with socio-political realism.

1.1. 2022 baseline case

According to the Swiss Federal Office of Energy [11], Switzerland's total gross energy consumption in 2022 was equal to

*This document was written as part of the Master's course "ME-409: Energy conversion and renewable energy" of 2024, given by Prof. F. Maréchal and Dr. T-V. Nguyen.

282'000 GWh. This consumption is produced by a wide range of resources and used by different sectors. The most consuming sectors are mobility and residential, together accounting for more than 60% of the total energy consumption.

Focusing on mobility, this sector is responsible for 36% of the energy consumption and for 41% of CO2 emitted. [12]. The most used type of transport is a personal car, representing 70% of person-kilometers covered, while railways represent 16% and buses/tramways only 3%. Passenger cars are mainly powered by petrol and diesel while less than 10% are from hybrid or electric types.

Concerning, the main resources, petrol or petroleum products and nuclear products hold large proportions with respectively 36.7% and 24.9% of the total energy sources. Renewable energies only represent 24.9% of Swiss energy resources with hydraulic and wood respectively accounting to 12% and 4,7%. The Swiss energy system, proposed by the Swiss Federal Office of Energy [11], is described in Fig.1.

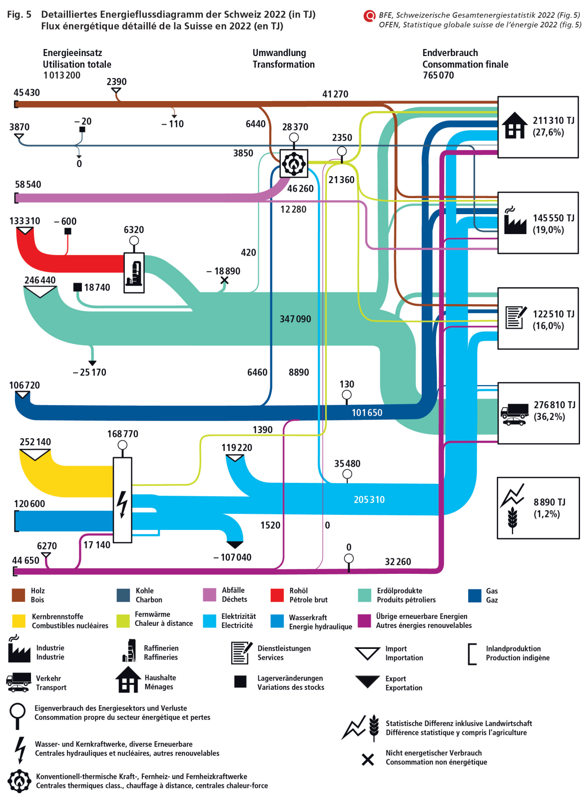

FIGURE 1
Swiss Sankey diagram for 2022 [TJ]

Switzerland has a domestic production of energy equal to 74'783 GWH per year. This production is divided into different installed technologies, summarized in Tab1.

TABLE 1
Installed technologies for Switzerland - 2022

Source	Hydro	Wood	Waste	PV	Wind	Amb. Heat	Biogas	Total
Production [GWh/y]	33500	12619	16261	4594	149	5827	1703	74783

Another important political and economical parameter to consider is Switzerland's dependency on energy-importing countries. Regarding Fig.2 Switzerland is observed to be highly dependent on foreign resources, especially for gas, nuclear, petrol and petroleum products, with all its consumption coming from imports.

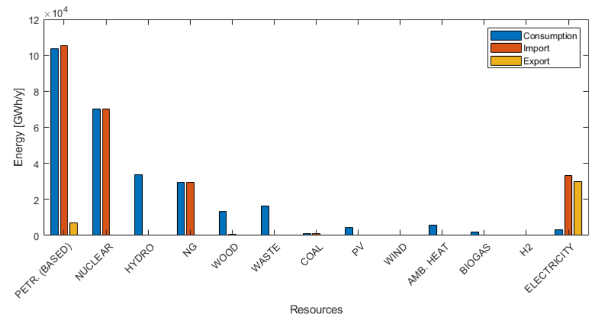

FIGURE 2
Energy consumption, import and export for Switzerland - 2022

Energy end-user expenses in millions of francs for 2022 are shown in Tab.2. The total amount, equal to 34060 MCH, represents 4.4 % of the Swiss nominal GDP.

TABLE 2
Energy end-user expenditure for Switzerland - 2022

Source	Elec	Gas	Wood	Fossil F.	Coal	D. Heat	Total
Expenses [MCH/y]	10490	3430	320	19250	50	570	34060

2. METHODOLOGY

2.1. DESCRIPTION OF THE OPTIMIZATION MODEL

The study is based on a linear optimization model [13] that represents a national energy system, incorporating essential components: Resources (coal, natural gas, uranium, etc.), End-Use Energy demand (electricity, heat, mobility) and Energy conversion technologies (coal plant, wind turbine, photovoltaic panel, etc.).
The model is formulated as a linear optimization problem, aiming to match the energy demand with the available resources while minimizing a specified objective function. The objective function could either minimize total system costs or environmental impacts, depending on the specific analysis. The model consists of decision variables, which represent the quantities of energy produced by each technology or resource, and constraints,

which ensure the system's feasibility by satisfying demand, respecting resource limits, and accounting for technological restrictions.

2.2. KEY DATA AND ASSUMPTIONS

2.2.1. *Scenario A* : BALANCED APPROACH

BASELINE DEMAND FOR 2050

To adapt the model to the 2050 scenario, several assumptions were made. First, the end-use energy demands for mobility, heat, and electricity were interpolated based on 2020 values [13] following Eq.1.

$$\text{Demand}_{2050} = \text{Demand}_{2020} \times \left(1 + \frac{q}{100}\right)^{2050-2020} \tag{1}$$

A growth rate q = 0.8% per year for the Swiss population was assumed to drive the demand for household, service, and transport energy needs. For the industrial sector, energy demand was assumed to grow in line with the GDP, at a rate q = 2.5% per year.

TECHNOLOGY INSTALLED CAPACITIES CALIBRATION

The model also incorporates adjustments to the minimum installed capacities (denoted as f_{min}) of several energy technologies to reflect the potential advancements by 2050. To promote renewable technologies, it is assumed that Switzerland will maintain a minimum installed capacity for these conversion technologies, at least equal to their 2024 levels [14], ensuring that no existing plants will be dismantled. The modification for hydroelectric, wind, biomass and photovoltaic power plants are displayed in Table 3.

TABLE 3
Calibration of minimum installed capacities for 2050 scenario A

Technology	$f_{\text{min, original}}$	$f_{\text{min, calibrated}}$
Hydro	0 GW	17.13 GW
Wind	0 GW	0.10 GW
Biomass	0 GW	0.38 GW
PV	0 GW	6.18 GW

TECHNOLOGIES REMOVAL

In addition to the calibration of installed capacities for various technologies, the maximum installed capacities of nuclear and coal power plants were set to zero. This decision effectively removes these two technologies from the energy mix in the model. This choice aligns with the objective of phasing out nuclear power by 2050 and reducing the reliance on coal, which is known for its significant carbon emissions.

MOBILITY TECHNOLOGIES

The values associated with mobility technologies have been modified. Since the EU plans to mandate that all new cars sold from 2035 onward be zero-emission ([15]), the assumption has been made to set the maximum share ($fmax_{perc}$) of diesel and gasoline powered cars to 5% of the private mobility sector in 2050.

2.2.2. SCENARIO B : POLICY-DRIVEN APPROACH

For this second scenario several policies have been defined in order to drive the 2050 energy planning. These policies, to be applicable, imply the availability of funding by 2050. They cover several areas, such as financing for the energy renovation of buildings, a mobility policy, significant investment in the photovoltaic electricity production industry, and a revision of energy imports

HEAT POLICY

According to Helvetia Energy [16], 50 % of residential buildings in Switzerland are poorly insulated, consuming 2 to 3 times more energy than a household that complies with the relevant standards. Under the government's "Buildings Program" [17], subsidies are available to all homeowners who want to carry out an energy-efficiency renovation. In 2024, 607 million francs from cantonal and federal resources are dedicated to heat consumption measures. These measures are used for insulation improvements and replacing old heating systems by renewable energy sources and low-temperature systems. Renovating residential buildings that do not meet current standards would reduce households heat demand by a 20% factor. Implementing this policy in the model results in a decrease of the low heat system heating demand for households, dropping from 42'200,7 Gwh/y to 29'540GWh/y.

SOLAR PV PANELS TECHNOLOGY

PV panels is one of the most promising renewable technology. It is well accepted by the public and has a great potential for progress in cost and efficiency. This scenario simulates a massive investment in PV panels in Switzerland. This means investments are directed towards expanding PV panel installations on roofs and facades, as well as in alpine regions, where the potential remains largely untapped [18]. To replicate this funding the model forces an installation capacity of solar PV panels of 50GW [19]. Switzerland's projected investment plan in this scenario also includes funding for research. This research enables construction costs to decrease from 650 CHF/kw to 251 CHF/kw using Eq.2 with the learning rate predicted by [20].

$$c_{\text{inv},i,t2} = c_{\text{inv},i,t1} \left(\frac{S_{i,t2}}{S_{i,t1}}\right)^{\beta} \tag{2}$$

Research also enables the GWP construction cost to drop to 200 kgCo2-eq/kw based on [19].

MOBILITY POLICY

To achieve the zero net goal, shifting population mobility habits toward greater use of public transportation should be a key focus. The reliance on personal cars can be attributed to factors such as comfort, inadequate public transportation infrastructure (although Switzerland has a highly developed system), and the cost of subscriptions[12]. By amending Article 81a, Paragraph 2 of the Federal Constitution [21], and making public transportation free, it can be assumed that the share of public transportation usage would significantly increase. Implementing this policy in the model results in maximizing the public mobility share.

IMPORTED ELECTRICITY CARBON CONTENT

As Europe strives to also reach carbon neutrality by 2050 [22] it is sensible to assume that the carbon content of imported electricity from Europe will improve substantially. To reflect this cleaner electricity, the model takes into consideration a carbon content of 12 gCo2-eq/kwh [23] for imported electricity.

2.3. MULTI-OBJECTIVE OPTIMIZATION : COST-EMISSION TRADE-OFF

It is essential to find a balance between the conflicting objectives of minimizing the GWP and the TOTEX. A GWP-focused optimization can lead to significant investments, while an economic optimization might result in an unsustainable GWP. Utilizing the Pareto front allows for a multi-objective approach, offering an optimal trade-off between these two conflicting objectives.
To build the curves, constraints on GWP or TOTEX have been incrementally added to the model following Eq.3 (eg. for a constraint on TOTEX).

$$TOTEX_{GWP_{min}} - \frac{i}{n} \times (TOTEX_{GWP_{min}} - TOTEX_{min}) \tag{3}$$

2.4. UNCERTAINTY AND SENSITIVITY ANALYSIS

Since the model inputs are based on assumptions and because of exogenous factor to certain parameters, there are uncertainties that need to be quantified to ensure the robustness of the systems. We investigate the sensitivity of our system to variations in certain key inputs. To accomplish this, a standard sensitivity analysis is performed by varying uncertain parameters by ±20% and then analyzing the resulting impact on the final energetic mix.

2.4.1. UNCERTAINTY ON SCENARIO A

In the first scenario, we aim to measure the sensitivity of the designed system to the installed capacity of wind power plants. Due to acceptance concerns, the maximum installed capacity of windmills may vary. Additionally, there are topographical challenges in Switzerland that impact the implementation of windmills.
Natural gas plays a significant role in a renewable energy-dominated scenario to address intermittency. However, its price is highly uncertain due to geopolitical factors, such as the ongoing conflict between Ukraine and Russia. This uncertainty needs to be quantified as a sensitive parameter in the planning and management of energy resources.

2.4.2. UNCERTAINTY ON SCENARIO B

In the second scenario, the robustness of PV power plants is crucial due to their strong dependency on this technology. It is important to justify the direction of subsidies for this technology to ensure they are being used effectively. Therefore, a sensitivity analysis is performed on the minimum installed capacity of PV power plants.
Another important uncertainty concerns the carbon content of imported electricity. The assumption is that most European countries, from which Switzerland imports electricity, will aim for cleaner energy sources. This assumption will most likely reveal to be truthful and neighboring countries have already made great strides in that domain. The question is to what extent will countries follow the promises to meet net-zero emission goals made during the Paris agreement of 2015 [24]. The goal of this sensitivity analysis is then to study how robust is the presented energy system to fluctuations in the carbon content of imported electricity.

3. RESULTS

3.1. *Scenario A*

PARETO

Selecting the value closest to zero on the Pareto front (Fig.3) the minimum achievable GWP and TOTEX have been reached. The optimal solution, represented by the largest orange dot, has a TOTEX value of 17'228 MCHF/year and a GWP value of 14'015 ktCO2-eq/year. The CAPEX and OPEX values of this optimum for *Scenario A* is given in Fig.15 with the blue bar. It offers a balanced solution with moderate values across all objectives, avoiding extremes in both GWP and TOTEX.

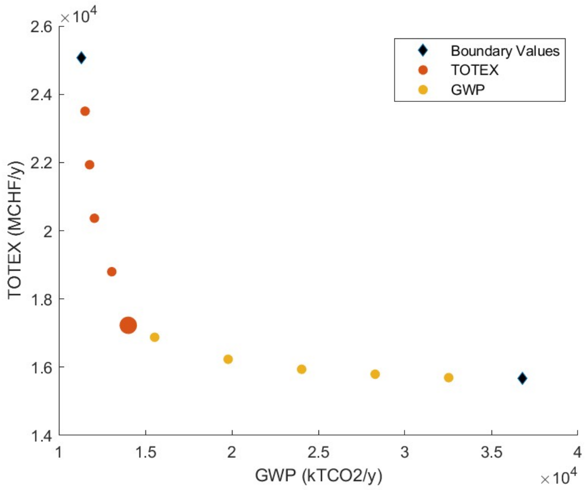

FIGURE 3
Pareto front for conflicting minimization of TOTEX and GWP for *Scenario A* multi-objective optimization process

To assess the key parameters driving the solution towards optimality, the energy mix trends across different points on the

Pareto front have been analyzed. For that several key points on the graphic are selected (Table 4)

TABLE 4
Points of the Pareto front analysis

Point	GWP (ktCo2-eq/y)	TOTEX (MCHF/y)
GWP bound	11 290	25 070
Intermediate point n°1	11 780	21 933
Optimal point	14 015	17 228
Intermediate point n°2	24 035	15 938
TOTEX bound	36 779	15 660

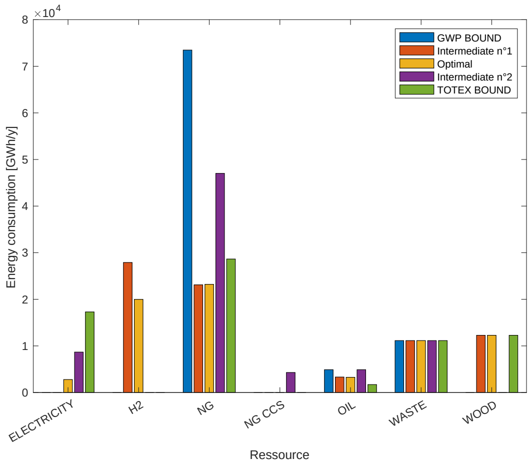

FIGURE 4
Evolution of resources along different points of Pareto front - *Scenario A*

In Fig.4 the trends for the evolution of resources among the different points of Pareto front (Fig.3) is analyzed. Natural gas is utilized in every scenario, with its consumption increasing as the solution shifts from the GWP-bound to the TOTEX-bound. At the optimal point, natural gas consumption is slightly higher than in the two cleaner scenarios but does not experience a significant increase. Hydrogen use is notable only in the two cleaner scenarios (GWP-focused), with no hydrogen deployment in the optimal scenario. Regarding oil, the optimal system minimizes oil consumption, aligning with a fossil-free energy vision.

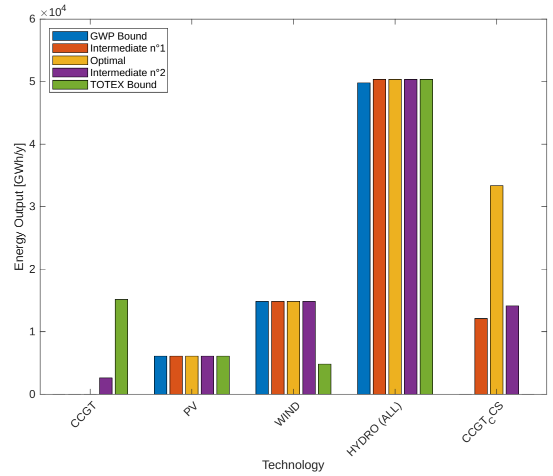

FIGURE 5
Evolution of electricity conversion technologies output along different points of the Pareto front - *Scenario A*

It is interesting to relate resources consumption to annual energy output (Fig.5) or installed capacities (Fig.6) of different technologies. The nonzero plateau in natural gas consumption is tied to CCGT and CCGT-CS technologies, which remain necessary to ensure a reliable base load and compensate for the intermittency of renewable energy sources. Renewable energy contributions (Fig.5) remain relatively stable across scenarios, except in the TOTEX-bound case, where wind turbine utilization is significantly reduced. Nonetheless, the optimal case tends to increase the use of pyrolysis and thermal solar technologies (Fig.6).

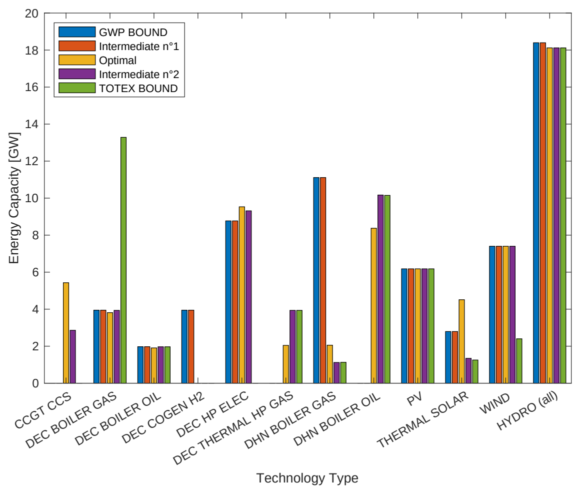

FIGURE 6
Evolution of the major changement of the technology installed capacities along the different points of the Pareto front - *Scenario A*

For the mobility sector (Fig. 7), GWP-bound increases the number of passenger using vehicle BEV or FC, while the TOTEX-bound scenario increases public trains and freight train. The optimal case follows the TOTEX-bound scenario unless for diesel bus (which increases, and TOTEX case tends to favor natural gases buses). Some incentives from the government on public transportation could be necessary, and therefore change there bounds for relative shares.

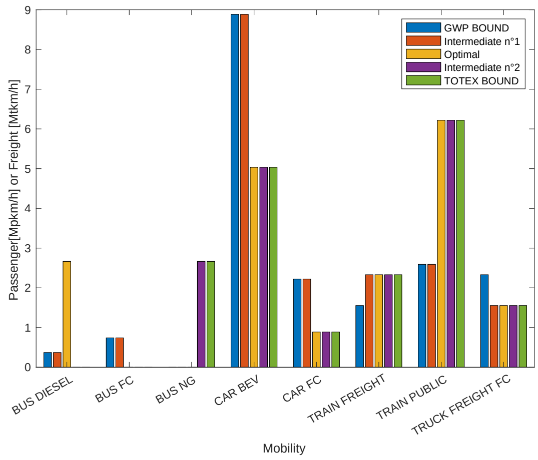

FIGURE 7
Passenger and freight fluxes for different mobility technologies - *Scenario A*

DESCRIPTION AND COMPARISON OF *Scenario A* TO 2022

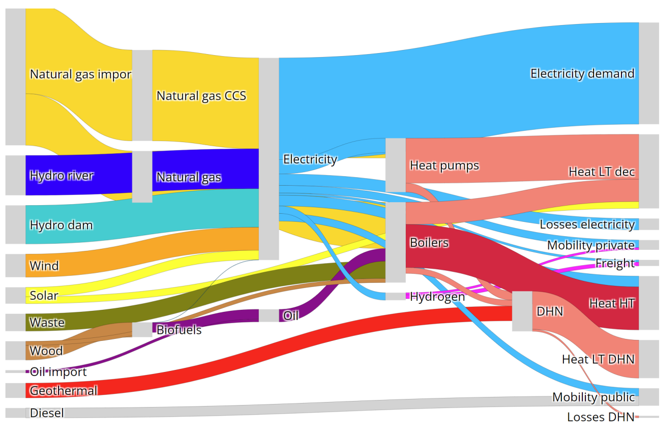

FIGURE 8
Sankey diagram of the optimal solution for *Scenario A*

The comparison between Switzerland's 2022 energy system and the projected 2050 optimal energy mix highlights a fundamental transformation towards a cleaner, more sustainable energy future. In 2022, the energy system was heavily reliant on fossil fuels, particularly oil products (252,140 TJ) and natural gas (168,770 TJ), which dominated the transportation, heating, and industrial sectors. Electricity, though significant, was largely supplied by hydroelectricity and nuclear energy, while imports also played a critical role in meeting demand.

By 2050, the energy mix undergoes a substantial shift. The reliance on fossil fuels, particularly oil, is drastically reduced, replaced by an expanded role for renewable energy sources such as solar, wind, and hydro. Natural gas remains in use but incorporates carbon capture and storage (CCS) to limit emissions, ensuring it aligns with decarbonization goals. The importance of electricity increases dramatically, emerging as the primary energy carrier to meet demands for heating (via heat pumps), mobility, and district heating networks (DHN). Additionally, the role of hydrogen grows considerably, especially in industrial processes and freight transport, supporting the overall shift towards low-carbon alternatives.

This evolution reflects a clear trend: while 2022's energy system was characterized by high fossil fuel dependency and associated emissions, the 2050 scenario prioritizes electrification, renewable energy, and carbon-neutral technologies. The result is a more decarbonized, efficient, and diversified energy system capable of meeting Switzerland's long-term climate and sustainability targets.

SENSITIVITY TO WIND INSTALLED CAPACITY

Changing the minimum installed capacity for wind did not affect the outcome of the model, as the installed capacity was consistently fixed at the maximum installed capacity throughout the analysis. The baseline installed capacity, along with the -20% and +20% scenarios, is summarized in Table 5.

TABLE 5
Installed capacity scenarios for wind turbines.

	-20%	Baseline	+20%
f_{min}	5.92 GW	7.4 GW	8.88 GW
Installed Capacity	5.92 GW	7.4 GW	8.88 GW

This approach underscores the robustness of wind turbines within our energy mix. Despite challenges related to public acceptance and the difficulty of implementation in Switzerland's complex topography, wind turbines—despite their relatively low installed capacity—prove to be a reliable technology on which our green energy mix Scenario A can confidently depend, independent of any uncertainties surrounding the technology. This reinforces the essential role of wind turbines in achieving a resilient, predominantly renewable energy mix.

SENSITIVITY TO NATURAL GAS PRICE

A major assumption of the model is the constant cost of the different available resources. Moreover *Scenario A* majorly relies on the use of natural gas (NG) and natural gas with Carbon Capture and Storage technologies (CCS). These resources are an especially variable factor. Indeed, their cost is highly dependent on several factors: economic, political, and geopolitical. Thus, it is important to perform a sensitivity analysis focusing on the cost of natural gas. Different scenarios could lead to an increase or decrease of these costs, which are investigated with sensibility tests of +/- 25% and one of +50%. As in the initial model, both NG and NG CCS costs are modified equivalently and have the same value. The GWP is fixed to the optimal value obtained: 14'015 ktCo2-eq/y (Table 4) while the TOTEX is minimised.

Under both low fluctuations, +/-25%, the TOTEX has minor changes (Table 6), while both NG and NG CCS remain the main

TABLE 6
Results of sensibility analysis for *scenario A* on NG / NG CCS

Scenario	Optimal	-25%	+25%	+50%
TOTEX [MCHF/y]	17228	-4.7%	+4.5%	+8.2%
NG [GWh/y]	33180	+0.1%	+1.1%	-3.4%
NG_CCS [GWh/y]	58371	+0%	-7%	-52%
% all resources energy consumption:NG	28.5%	28.5%	30%	37%
% all resources energy consumption:NG CCS	50%	50%	48%	32%

resources for energy consumption, representing more than 75% of all resources in energy consumption. However, with a higher cost of +50%, the model is drastically impacted. The TOTEX rises of more than 8%and NG CCS is halved. The total energy consumption [GWh/y] is lowered and new resources are used such as H_2. Nevertheless, the most considerable change is on the installed technology side, the PV installed capacity triples from 6.18 GW to 19.6 GW while all technologies using NG or NG CCS have their installed capacity slightly reduced.
Thus this analysis shows some potential flows in *Scenario A* as it is highly dependent on the prices of NG and NG CCS and while low fluctuations do not excessively affect the optimal scenario, an important increase of the costs of NG and NG CCS produces a major change of the global scenario. Even if such an increase seems excessive, different less predictable events such as the Ukrainian invasion have already led to a high cost augmentation in Europe and Switzerland [25]. This added to a rarefaction of NG can lead to such a scenario and needs to be taken into consideration.

3.2. *Scenario B*

The second scenario outlined in this report simulates various policies that the Swiss government could feasibly implement by 2050. It also incorporates realistic projections for multiple factors that could positively impact Switzerland's carbon emissions. The changes made to the model in order to simulate this scenario are explained and justified in section [2.2.2].

PARETO

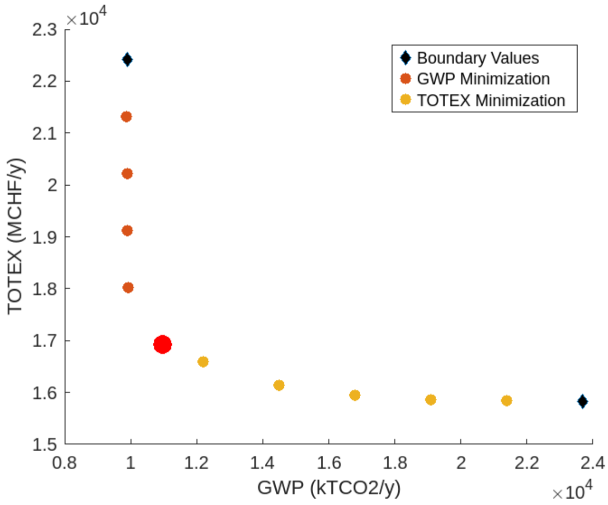

FIGURE 9
Pareto front of the *scenario B* for conflicting minimization of TOTEX and GWP

To assess the key parameters driving the solution towards optimal case, the energy mix trends across different points on the Pareto front have been analyzed. For that several key points on the graphic are selected (7)

TABLE 7
Points of the Pareto front analysis for the *scenario B*

Point	GWP (ktCo2-eq/y)	TOTEX (MCHF/y)
GWP bound	9 863.55	22 410.30
Intermediate point n°1	9 894.49	20 216.00
Optimal point	10 967.81	16 923.00
Intermediate point n°2	16790.00	15 948.66
TOTEX bound	23 684.57	15 826.03

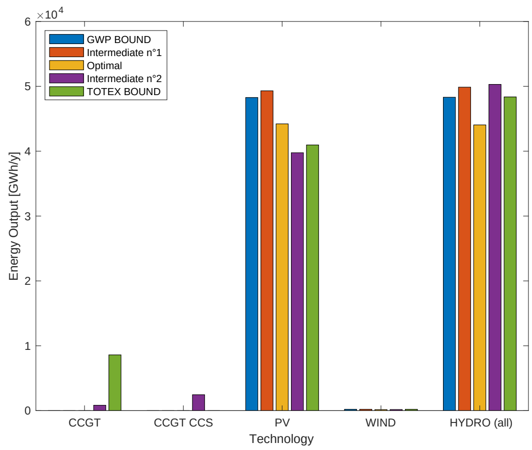

FIGURE 10
Evolution of electricity conversion technologies output along along the different points of the Pareto front - *Scenario B*

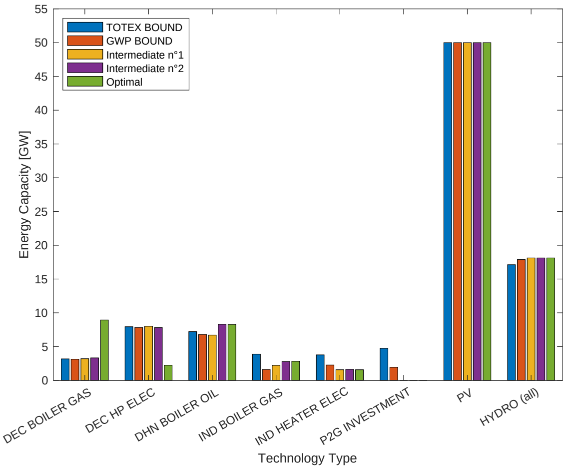

FIGURE 11
Evolution of the major technology installed along the different points of the Pareto front - *Scenario B*

In *Scenario B*, resources vary during different stages of the Pareto front. The TOTEX BOUND case favors the use of natural gas, while the GWP BOUND case increases the share of hydrogen. The optimal case diversifies its resource mix more, including imported electricity, natural gas, waste, and wood (Fig.12). In comparison to the 2022 situation (Fig.**??**), petroleum and nuclear are replaced by other energy sources.

Electricity generation is primarily supported by photovoltaic solar panels and hydropower technologies. The use of wind turbines is negligible (only 0.10 GW). The TOTEX case favors combined cycle gas turbine (CCGT) plants to reduce reliance on PV panel energy output (Fig.10). This could be a concern, as this scenario predominantly relies on just two main energy sources.

This scenario requires a 1.5 times increase in the energy output of hydropower technologies and a tenfold increase in the energy output of solar panels. A complete graphical analysis of this sector is available in the appendix (Fig. 17).

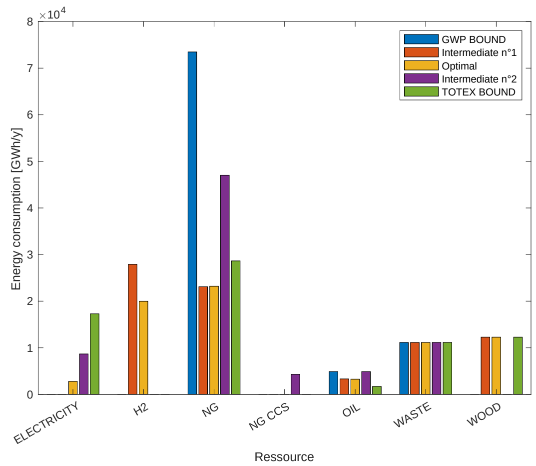

FIGURE 12
Evolution of resources along different points of Pareto front - *Scenario B*

In the mobility sector, the ratio of passenger mobility attributed to public transportation remains at 0.45 for all points on the Pareto front, even though the initial share in this scenario has been increased. The optimal case follows the TOTEX-bound case, except for fuel cell buses. The most important mode of passenger transportation is electric vehicles. For freight transport, all points on the Pareto front favor the use of trains, except for the GWP-bound case (Fig. 13).

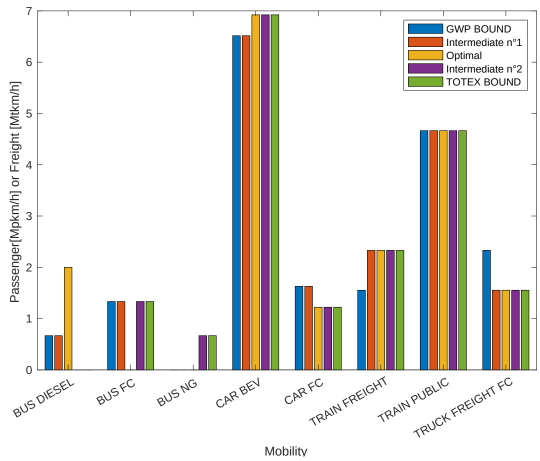

FIGURE 13
Evolution of the mobility sector along different points of Pareto front - *Scenario B*

COMPARISON WITH 2022

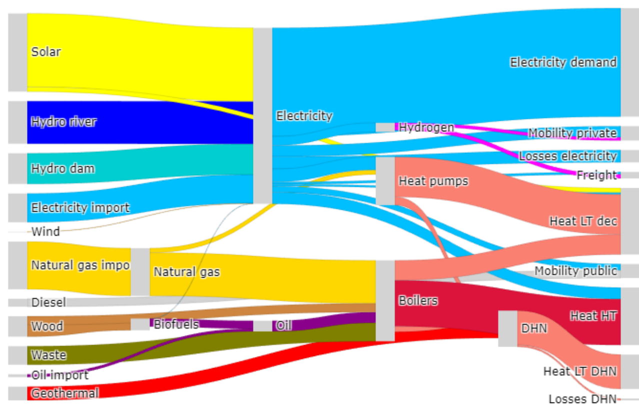

FIGURE 14
Sankey diagram of the optimal solution for *Scenario B*

By comparing the *Scenario B* energy system with the one of 2022, it is evident that new policies have significantly promoted the adoption of renewable energies, with solar energy taking a central role in the 2050 energy mix. Photovoltaics (PV) contribute a substantial share due to their scalability and suitability for both large-scale and decentralized installations. Hydropower, already a key resource in 2022, remains vital, supported by optimized management of river and dam-based production. Wind energy, though less prominent than PV, supplements the mix,

further diversifying renewable sources. In this scenario, electricity emerges as the dominant energy carrier, enabling a fully renewable-based energy system to meet all electricity demands, including those for private mobility, public transportation, and freight, which rely on a combination of renewable and imported electricity.
The reliance on fossil fuels has been dramatically reduced, with coal entirely phased out and oil and diesel representing only minor imports. Natural gas use has also seen a noticeable reduction, replaced by renewable alternatives and electrified solutions. Heat pumps have become a major technology for heating, replacing traditional boilers and leveraging the abundant renewable electricity. Hydrogen emerges as a complementary vector, particularly for industrial applications and mobility sectors where direct electrification is less feasible.
Efficiency improvements are another hallmark of the 2050 energy system, with reduced transmission and distribution losses compared to 2022. The electrification of mobility, encompassing both private and public transport, underscores the shift toward an electricity-dominated energy landscape.

SENSITIVITY TO PV

To gain perspective and a better understanding of the presented energy system, a sensitivity analysis has been conducted. Several uncertain parameters were chosen to determine their impact and the robustness of the system. Great assumptions were made concerning PV solar panels. The installed capacity for this scenario was set at 50GW, a source-backed value but nethertheless a rather optimistic prediction. The model was run 3 times optimizing the GWP by reducing each time the installed capacity for PV panels by 10GW. Interesting results transpired from this iteration, as shown in Table 8.

TABLE 8
Sensitivity Analysis of Installed PV Capacity on Energy Production and CO2 Emissions

Iterations	Minimum Installed PV Capacity (GW)	PV Energy Output (GWh/y)
1	50 GW	40,000 GWh/y
2	40 GW	33,478 GWh/y
3	30 GW	30,500 GWh/y
4	20 GW	30,500 GWh/y

For minimum installed capacities under 40GW, the model chooses to install 33.9 GW of solar PV panel power capacity, which converts to 33,478 GWh/y worth of energy. As this value doesn't change when the minimum capacity is decreased, it can be considered as being the optimal value for this technology. In these designs, the gap created by the reduction of PV panels is compensated by different energy sources. The largest contribution comes from importing electricity from neighbouring countries. For an energy system optimized to generate 33,478 GWh/y of electricity coming from solar energy, Switzerland will need to purchase 25.5 GWh/y of electricity to satisfy its demands. This represents an increase of 8.2 GWh/y compared to the previously discussed optimal scenario. Other energy sources are used to meet the demand; geothermal electricity sees an increase of 1.87 GWh/y, while wind electricity production rises from 0.160 GWh/y to 1.43 GWh/y. Reducing the installed capacity of PV solar panels to 33.9 GW has a slight benefit regarding CO2 emissions (900 kgCO2-eq/y reduction), however, the biggest advantage of this system concerns the homogeneity of the electricity mix. It is less solar dominant and relies on a more diverse set of energies (wind, geothermal, hydraulic, imports...). This is beneficial because solar energy is highly dependent on seasonal variations. On the other hand, reducing the proportion of solar energy increases Switzerland's reliance on imports, which can be subject to price and carbon content fluctuations due to factors such as geopolitical events.

SENSITIVITY TO CARBON CONTENT OF IMPORTED ELECTRICITY

An other important assumption made to model the optimal energy sytem for *Scenario B* was the drop in the carbon content of the imported electricity. Running the model while optimizing the GWP and keeping the same maximum value on the TOTEX with a $\pm 20\%$ on the carbon content of imported electricity produces similar results. The GWP stays in an acceptable range of 10'066 ktCo2-eq/y to 10'176 ktCo2-eq. As expected, the amount of imported electricity shows some slight variations and is compensated by the other energy sources of the system without impacting the GWP nor the TOTEX value. The conclusion is that this energy system is robust and can achieve comparable outcomes even if neighbouring countries do not meet their Paris Agreement commitments.

3.3. COMPARISON OF SCENARIOS *A* AND *B*

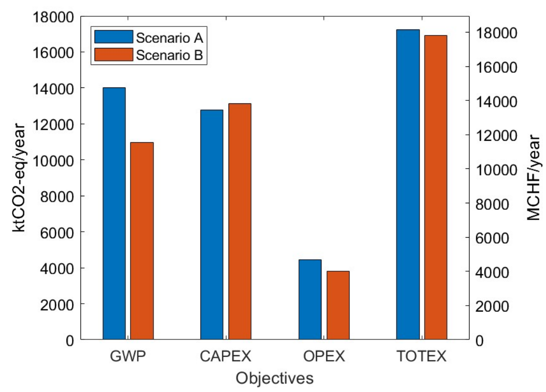

FIGURE 15
Comparison of optimal scenarios A and B

TABLE 9
Comparative table of the major changes between *Scenario A* and *Scenario B*

	case	Scenario A	Scenario B
Natural gas	TOTEX	120136.048 [GWh/y]	73480.035 [GWh/y]
Solar pv pannel	Optimal	6.179 [GW]	50 [GW]
Wind turbines	Optimal	7.40 [GW]	0.102000 [GW]
public transport ratio	Optimal	0.6	0.45
Electric cars	Optimal	5.034 [Mpkm/h]	6.922448 [Mpkm/h]

This table highlights the distinct approaches of Scenario A and Scenario B.
Scenario A relies more heavily on conventional energy sources, using significantly more natural gas (120,136.048 GWh/y), while also increasing wind energy with 7.4 GW of installed capacity. In contrast, Scenario B has a less carbon impact approach, with a strong focus on solar energy. It is also implementing more electric cars (6.92 Mpkm/h) and less public transport (0.45 ratio), suggesting a shift towards personal electric vehicles. The use of solar panels in Scenario B underlines its reliances on renewable energy, at the cost of a less diversified mix energy grid, while Scenario A maintains a more balanced energy mix with both renewable and conventional sources. Ultimately, these two scenarios reflect different strategies in achieving the zero net objective, with Scenario B prioritizing renewable energy and Scenario A a diversified infrastructure to achieve the energy needs.

4. DISCUSSION

4.1. SCENARIO A

The chosen optimal solution for scenario 1 presents a GWP of 14'015,15 ktCO2-eq/year is quite high compared to the emissions absorption potential of 11'000 ktCO2-eq/year outlined by the Swiss Confederation in the report on Energy outlook 2050+. While not impossible, it entails that this scenario relies heavily on Carbon capture technologies to reach the Net zero target. The efficiency and use of said technologies needs to be significantly increased. This would necessitate a larger investment which increases the TOTEX value or Switzerland will need to rely more on neighboring countries for carbon absorption. Regarding energy producing technologies scenario A presents main changes compared to the 2022 energy mix. For this scenario to be plausible there needs to be major investments in renewable energies, mainly in wind technologies. In 2022, the installed capacity was 0.102 GW while the model suggests an installation capacity of 7.4GW. This value represents the maximum potential capacity in Switzerland. Achieving this would require substantial investment and a significant shift in public mindset to embrace such a transformative change to the Swiss landscape. Investments are also necessary in technologies largely underused in 2022 in Switzerland such as thermal solar, representing 4.5 GW compared to 0.4 GW nowadays, and geothermal, representing 2 GW in 2050. Hydraulic energy are also optimised, gaining 1 GW to achieve a 12GW production, while biomass and waste would quadruple to more than 1.1 GW and 1.2 GW respectively.
To meet the remaining demand for heating and electricity production, the scenario recommends importing natural gas, which, despite its environmental impact, is a preferable option compared to the energy sources used in 2022.
This scenario requires a 60% share of passenger mobility attributed to public transportation compared to today's 21%. To reach such a high proportion it will require a massive societal and behavioral shift coupled with strict regulations. To encourage the behavioral change Switzerland will most likely have to put in place a nation wide campaign of free of charge or at least cheaper public transport. This measure would amount to a significant financial burden for the Swiss government and might not be enough. To achieve 60%, the Swiss government will also need to implement regulations to limit the number of private vehicles allowed on the road. The *one-day-per-week* (OPDW) vehicle regulation or the even stricter *odd-and-even* (OAE) solution have already been tested and proven in many cities in China. Studies [26] prove that setting up these regulations tends to push people to seek alternative means of transportation.
Many valuable lessons can be derived from this scenario, offering important insights that contribute to a deeper understanding of the situation. In general, compared to 2022, the energy mix is way more diverse and homogeneous rather than being dependent mainly on 3 energy sources. This makes for a more efficient and complementary energy mix all year long.

4.2. SCENARIO B

The optimal scenario for scenario 2 has a GWP of 10'967.81 ktCo2-eq/year. This value falls well under scenario 1's value and more crucially it does not exceed the emissions absorption potential of 11'000 ktCo2-eq/year set by the Swiss confederation. This entails that following this scenario, reaching Switzerland's net-zero target would be technically feasible. While this is certainly promising it is important to recall that to achieve the presented scenario, Switzerland will need to put in place major technological and societal transformations.

First and foremost, the report in which the potential value for emissions absorption figures emphasizes that in order to reach this potential, significant developments and investments are needed in Carbon capture technologies in the next decades. The report states that with the right investments Switzerland will be able to treat 4'000 ktCo2-eq/year of it's emissions. That leaves about 7'000 ktCo2-eq/year of emissions that will have to be sent to neighbouring countries. As highlighted in the Energy Outlook 2050+ report, this is feasible; however, it implies that Switzerland will remain heavily dependent on its neighbors. This dependency comes with a monetary cost that is not reflected in the TOTEX value and complicated to evaluate.
To make this scenario conceivable, beyond advancements in carbon capture technologies, a significant shift in both technical and societal norms would be required.
First of all the private mobility sector needs to be heavily decreased as this scenario requires a 45% share of passenger mobility attributed to public transportation, compared to today's 21% figure. This not only suggests a substantial social change as the public transport share needs to grow by 24% to meet the target, but it also presents a huge technical challenge. Improving the efficiency of the Swiss train system, which is already one of the most efficient in the world, is no small feat. However, it is essential in order to accommodate the anticipated surplus of daily passengers and to persuade the population to adapt to this change in their habits. An other way of convincing Switzerland's population is to reduce transport fees or put in place regulations as has been discussed in the discussion for

scenario A.

From the sankey diagram for scenario B (Fig.14) and from the policies that have been put in place (section 2.2.2) it is primordial to state the importance of solar energy in this scenario. This model relies highly on technological advancements for solar PV panels. While the changes to the model are all based on reliable sources they are still very optimistic predictions. As long as solar panels are economically viable it won't be difficult to convince the Swiss people to accept a massive investment plan in solar technologies. The great challenge is then to make solar panels economically sound: previously stated sources motivated the choice to cut the construction costs of PV panels from 650 CHf/KW to 251 CHf/KW. While this might be possible in 2050 it will necessitate massive improvements in PV panels technologies and power grid management.
In addition to everything that has been discussed, statements made for scenario A regarding geothermal, biomass and hydrolic energies still apply here.

4.3. LIMITATIONS AND CHALLENGES

While the model provides a valuable framework for analysis, it has several limitations. The demand projections may not fully capture the intricacies of Switzerland's evolving lifestyles or potential disruptions (Global wars, natural disasters...). The calibration of technology capacities introduces subjectivity and relies on speculative assumptions regarding future technological development. Finally, exogenous factors, such as geopolitical events, technological breakthroughs, or extreme climate phenomena, are not accounted for in the model, which limits its ability to capture a broad range of uncertainties.

5. CONCLUSION

In conclusion, both scenarios presented in this report offer valuable insights on how to shape the Swiss energy sector. It goes without saying that the proposed solutions are not flawless, and improvements can always be made. Uncertainties will inevitably play a significant role when dealing with predictions that extend far into the future. This report has highlighted some of the most important ones though some still remain undefined. Nevertheless, both scenarios provide a fundamental basis to better understand which sectors need investments and improvements.
As a starting point, carbon capture technologies is a sector which has been showcased in both scenarios. Investing in this technology seems to be of paramount importance for Switzerland to reach its net-zero goal by 2050. It is then recommended to enhance investments in technologies such as Direct Air Capture, Membrane gas separation and increase research in more novel technologies such as Cryogenic Carbon Capture and chemical looping.
A key learning emerged from comparing scenario A and B. By implementing the right improvements and innovations in PV panels, it is possible to drastically reduce global carbon emissions. As seen thanks to the sensitivity analysis that was done on Scenario B, an optimal value of 33.9 GW for the installed capacity of PV panels was found. It is advisable to collaborate with solar technology manufacturers and research projects all around the world to help accelerate its development. In addition to this, incentives for the population have to be put in place to encourage PV panels installations while working closely with power grid regulators to set up an energy market better equipped to deal with the surge in independent renewable energy sources. Since solar energy is very seasonal dependent we recommend to also invest heavily in wind energy in parallel to PV panels. The first scenario has showed that wind turbines can play a significant role in an electricity mix without driving the price too high. Solar panels operate better during the summer while wind energy is more efficient during the winter making it a highly complementary technology to pair with the solar-heavy energy mix.
Scenario A and B have demonstrated that promoting the use of public transportation significantly contributes to reducing Switzerland's carbon footprint. Reaching scenario B's 45% share of passenger mobility seems to be a more realistic goal for 2050. Implementing policies mentioned in [2.2.2] such as making public transport free for under 25s will help achieve that threshold. Scenario B presents a balanced and sensible approach by increasing the proportion of electric vehicles in parallel with the increase in public transport. We strongly recommend the Swiss government to continue offering incentives to purchase electric vehicles as to maintain the current positive trend in EV sales.
This report gives a non exhaustive list of recommendations for the Swiss government in order to reach its net-zero goal by 2050. It is based on current trends and predictions and thus doesn't take into account unforeseen events whether beneficial, such as a sudden improvement of an energy's efficiency, or detrimental, such as wars or natural disasters. It is still important to consider the insights gained from this report in order to develop a strong and coherent strategy for the future, with the key takeaway being that, with the right choices and efforts, achieving a carbon neutral energy system by 2050 is not an impossible task; rather, it is a realistic goal.

ACKNOWLEDGEMENTS

The authors would like to thank Prof. F. Maréchal, Dr. T-V. Nguyen and all the TAs for their help in writing this report.

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APPENDIX

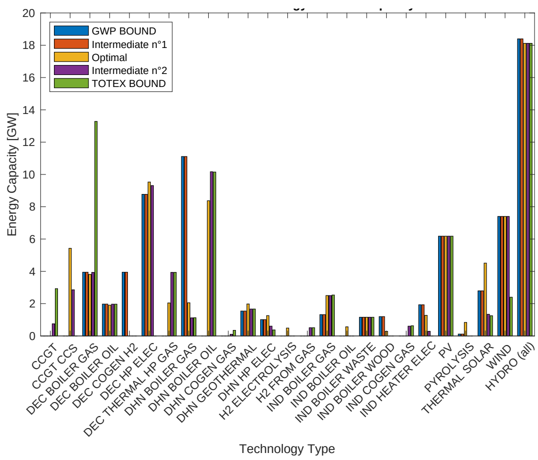

FIGURE 16
Evolution of the installed technology along the different points of the Pareto front

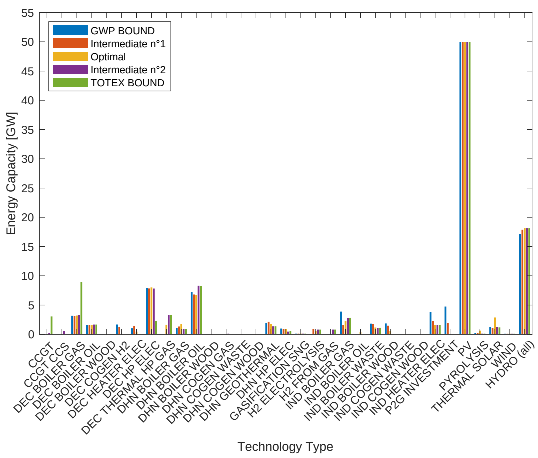

FIGURE 17
Evolution of the installed technology along the different points of the Pareto 2