Policy mixes for a just, effective, and public budget-conscious household energy transition in Switzerland

Torne Diaz De Heredia, Alexandre; Trutnevyte, Evelina

How to cite

TORNE DIAZ DE HEREDIA, Alexandre, TRUTNEVYTE, Evelina. Policy mixes for a just, effective, and public budget-conscious household energy transition in Switzerland. In: Energy policy, 2026, vol. 208, p. 114872. doi: 10.1016/j.enpol.2025.114872

This publication URL: https://archive-ouverte.unige.ch/unige:187562

Publication DOI: 10.1016/j.enpol.2025.114872

Energy Policy 208 (2026) 114872

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Policy mixes for a just, effective, and public budget-conscious household energy transition in Switzerland

Alexandre Torné [*], Evelina Trutnevyte

Renewable Energy Systems, Institute for Environmental Sciences (ISE), Section of Earth and Environmental Sciences, University of Geneva, Switzerland

ARTICLE INFO

Keywords:
Policy mixes
Microsimulation
Distributional justice
Equity
Energy investments
Residential buildings

ABSTRACT

Policy mixes for decarbonizing residential buildings offer significant potential for greenhouse gas emission savings but involve trade-offs with public spending and distributional justice. Using microsimulation and based on survey data, we evaluate the potential effect in the near term of policy mixes with various bans, requirements, taxes, and subsidies by quantifying their impact on the immediate investment opportunities for heating and electricity of a representative sample of 6′355 Swiss households. Substantial emission savings are already profitable for many households even without policy intervention. However, a requirement to install solar photovoltaics (PV), combined with subsidies for PV, heat pumps, and envelope retrofits alongside increased energy taxes, can promote greater emission savings at limited public cost, while allowing for lower and more equally distributed heating and electricity costs for households. Added to this mix, an ambitious requirement to deeply retrofit the worst insulated buildings can achieve further emission and energy savings, albeit at comparatively high public costs or with exacerbated inequalities without retrofit subsidies. Without special support, low-income, elderly, and rural households and dwelling owners risk bearing a higher economic burden to achieve collective emission savings. By integrating rich survey data with detailed techno-economic microsimulation, this study offers a replicable framework to quantitatively evaluate energy policy mixes in Switzerland and beyond.

1. Introduction

Decarbonizing residential buildings is key because their energy use contributed to 17 % of global energy-related CO_2 emissions in 2021 (IEA, 2022), 15 % of greenhouse gas emissions in the European Union (Balaras et al., 2023), and 22 % in Switzerland (FOEN, 2023; Romano et al., 2024; SFOE, 2024). Despite high emission levels, a so-called energy efficiency gap remains (Camarasa et al., 2019; Jaffe and Stavins, 1994; Zielonka and Trutnevyte, 2024), referring to the slower-than-cost-optimal adoption of energy efficiency measures and low-carbon technologies (Hesselink and Chappin, 2019). Various policy instruments aim to close this gap and prevent further carbon lock-in, helping households overcome their structural, economic, behavioral, and social barriers to the required energy investments (Hesselink and Chappin, 2019; Hirst and Brown, 1990). Relevant policy instruments range from market-based instruments, such as carbon or energy taxes and subsidies, to regulations that include bans on fossil fuel-based systems and requirements for renewable energy generation, and other persuasive measures, such as information campaigns (McCormick, 2017; Wiese et al., 2018). Multiple studies have shown that single policy instruments can be partially successful, but will not be sufficient alone to achieve a deep decarbonization of the building sector. Stringent and coordinated policy mixes are thus needed (Chen et al., 2019; Economidou et al., 2020; Knobloch et al., 2019). However, energy policies are mostly evaluated from the quantitative perspective in isolation (Rosenow et al., 2016). There is thus a growing need for ex-ante quantitative evaluations of energy policy mixes to better understand the interactions between policy instruments and their effects (Maor and Howlett, 2021; Spyridaki and Flamos, 2014; Wiese et al., 2018).

Beyond emission savings, all policy mixes have co-benefits and adverse side effects (Deng et al., 2017; Lamb et al., 2020). Mitigation is rarely the only goal as there are other policy objectives and constraints too, such as affordability in terms of policy costs and impact on the public budget, implementation feasibility, social and political acceptance, or justice (Del Rio et al., 2012; Peñasco et al., 2021). The inclusion of multiple evaluation criteria that capture elements of policy effectiveness, efficiency, and fairness (Vollebergh, 2023) and the explicit analysis of trade-offs is therefore a must in ex-ante policy evaluations,

* Corresponding author. Uni Carl Vogt, Boulevard Carl Vogt 66, CH-1211 Geneva 4, Switzerland.
E-mail address: alexandre.torne@unige.ch (A. Torné).

https://doi.org/10.1016/j.enpol.2025.114872
Received 29 January 2025; Received in revised form 7 August 2025; Accepted 1 September 2025
Available online 11 September 2025

even if this was traditionally not common (Bhardwaj et al., 2019; Markkanen and Anger-Kraavi, 2019). Among evaluation criteria, justice and in particular distributional justice that focuses on the allocation of policy benefits and burdens (Zimm et al., 2024) is key, both morally in order to avoid exacerbating inequalities and to protect the most vulnerable (Klinsky et al., 2017) and practically in order to gain social and political acceptance of new policies (Brückmann et al., 2023; Clayton, 2018; Dechezleprêtre et al., 2022; Maestre-Andrés et al., 2019). However, the distributional justice implications of energy and climate policy, as well as the trade-offs between their justice, effectiveness, and costs remain an emerging area of research, especially with quantitative methods (Klinsky and Winkler, 2018; Montenegro et al., 2021; Rao et al., 2017; Zimm et al., 2024). Other tenets of justice, such as recognitional and procedural justice which are more often evaluated qualitatively, are important too to capture the multi-faceted nature of energy justice related to policies (Jenkins et al., 2016).

Modeling can be used to investigate distributional impacts from the quantitative perspective, for example, on groups of individuals, households, and firms (Montenegro et al., 2021). Input-output models have the strength of capturing direct and indirect price impacts of carbon taxation on the expenditures of households (Steckel et al., 2021). Computable general equilibrium models can cover the effects of a wider array of policies on the whole economy and thus also on the income of households (van Ruijven et al., 2015; Vandyck et al., 2022; Wallenko and Bachner, 2025). Agent-based and microsimulation models focus on the direct effects of policies, but are especially suited for representing distributional impacts on heterogenous population subgroups if supported by rich survey data (Soubelet et al., 2024; Torné and Trutnevyte, 2024). This is a distinguishing feature of such models as otherwise the most common practice has been to depict distributional impacts across household groups only for different levels of income or consumption (Fischer and Pizer, 2019; Vandyck et al., 2022). With agent-based and microsimulation models, policy impacts are simulated bottom-up at the micro level by representing various decision rules and sometimes agent interactions. To obtain insights into the overall policy effects, individual impacts are quantified across samples representative of the whole population, accounting for various social, technical, and context characteristics (Burgard et al., 2020; Klevmarken, 2022).

Despite their ability to capture distributional justice implications, most agent-based and microsimulation models have focused on the influence of a few policy instruments on technology adoption over time (Hesselink and Chappin, 2019; Mundaca et al., 2010). Rarely more than one type of low-carbon technology or energy efficiency measure have been considered at the same time, even if combined energy investments, for instance, heat pumps with solar photovoltaic (PV), offer appealing decarbonization solutions (van der Kam et al., 2024). Only some agent-based models of the building stock (e.g., Nägeli et al., 2020; Vivier and Giraudet, 2024) have evaluated the effects of more complete policy mixes in the residential sector on private and societal costs, energy and emission savings, and fuel poverty. However, other distributional impacts or other measures of distributional justice (Torné and Trutnevyte, 2024; von Platz, 2018) have not been included. So far, the focus on modeling the dynamics of policy instruments over time, agent behavior, and other real-world frictions to energy investments have come at the expense of modeling a richer suite of various policy instruments and their mixes, various household energy investments and their combinations, and the disaggregation of policy impacts across household groups.

In this context, we develop a novel microsimulation approach that integrates detailed household microdata with a broad range of energy co-investments to evaluate policy mixes aimed at decarbonizing the residential sector. We adapt an analytical method to screen through a wide range of policy mixes and, accounting for interactions, identify the most influential policy instruments, assess their individual effects, and uncover appealing combinations. We apply this combined methodology to Switzerland, and estimate the potential effect in the near term of policy mixes with various bans, requirements, taxes, and subsidies that could accelerate the decarbonization of electricity and heat in residential buildings. We evaluate the mixes based on their impact on households' immediate opportunities for energy investments, and quantify their effectiveness in terms of promoted emission savings, their potential costs to the public budget, and their distributional justice implications in terms of equally distributed opportunities for energy investments and economic burden across multiple sociodemographic groups. We focus on Switzerland addressing calls to focus more on decarbonization efforts by people of high socioeconomic status, responsible for a disproportionate share of greenhouse gas emissions (Nielsen et al., 2021). We set out to answer three research questions. First, what are the trade-offs between the promoted greenhouse gas emission savings, public spending, and distributional justice of energy policy mixes targeting the Swiss residential sector? Second, which energy investments and policy mixes are associated with which outcomes? Which policy mixes stand out as appealing based on the measured outcomes? Last, what are the distributional impacts of the policy mixes across household groups?

2. Methodology and data

We use data from a representative sample of Swiss households (Section 2.1) and evaluate a comprehensive suite of policy mixes (Section 2.2) using microsimulation. Specifically, we quantify the effects of the mixes at the micro level and on households' investment opportunities related to heating and electricity (Section 2.3), as shown in Fig. 1. We then use the results across the household sample to evaluate each policy mix in terms of potential emission savings, net public spending, and distributional justice outcomes (Section 2.4) and explore trade-offs between these. Next, to increase the interpretability of results, we cluster the policy mixes regarding their outcomes and investigate which policy instruments characterize each cluster (Section 2.5). This allows for analyzing the effect of policy instrument combinations and promoted energy investments on the policy mix outcomes and identifying appealing combinations of policy instruments. Last, we measure the distributional impacts of the mixes across various household groups.

2.1. Swiss household sample

Adapting an earlier approach by Torné and Trutnevyte (2024), we build a representative sample of Swiss households with data from the Swiss Household Energy Demand Survey (SHEDS) (Weber et al., 2017) complemented by data from the Household Budget Survey (HBS) (BFS, 2015). The HBS has data on household income and expenditures for 9′955 Swiss households from 2015 to 2017, and the SHEDS has information on the postal codes, dwelling characteristics, energy equipment, and energy consumption of 12′716 households from all Swiss cantons (states) but Ticino from 2018 to 2023. The households and their main information are taken from the SHEDS, while the HBS is used to weigh the SHEDS households and impute values of disposable income. We take a non-parametric statistical matching approach (D'Orazio et al., 2006) and weigh each SHEDS household by adding up the cross-section statistical weights of all equivalent HBS households per a set of matching variables and then dividing that weight by the number of equivalent SHEDS households. Weights, which are accounted for in all analyses, allow scaling the results up to the whole of Switzerland. Then, to each SHEDS household, we impute the average value of disposable income of all equivalent HBS households with the same set of matching variables. The matching variables – close to those by which the HBS is made representative – are: household structure (including age and gender information), quintile of equivalized disposable income, dwelling tenure (tenant/owner), rural-urban-periurban settlement type, and canton of residence. When necessary, we harmonize this set of categorical variables to be common between both surveys. We additionally impute missing values for other important variables through regression: the quintile of equivalized disposable income, electricity consumption, and heating consumption (see Appendix A1 for details). The resulting

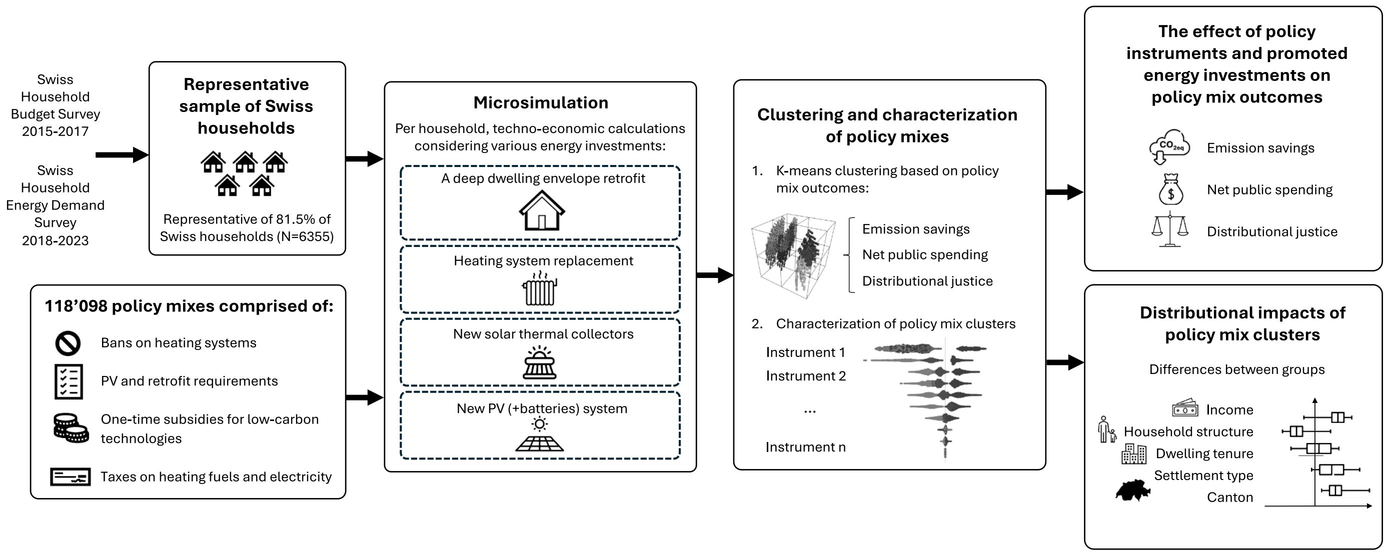

Fig. 1. Methodological workflow.

household sample (N = 6′355) is representative of 81.5 % of the diversity of households in the original HBS sample. Descriptive statistics for the variables are available in Appendix A2, alongside examples of household final data in Appendix A3. Appendix A4 shows the representativeness of the merged sample regarding multiple sociodemographic groups.

2.2. *Policy mixes*

We simulate Switzerland-wide policy mixes (Table 1) to decarbonize the residential sector – including energy taxes, incentives for low-carbon technologies, and regulations related to buildings – by taking a greenfield approach. We take inspiration from the current Swiss policy (EnDK, 2023, 2022, 2015; Fedlex, 2024, 2020, 2016; FOEN, 2021; Francs énergie, 2024; SFOE, 2016; Silgeneve, 2023), from ongoing discussions about future policies (e.g. EnDK, 2024; État de Vaud, 2023; FOEN, 2024; RTS, 2023; Swiss Parliament, 2023), and also consider more ambitious versions of these policies to explore new ways to accelerate decarbonization. With all possible combinations of policy instruments from Table 1, we simulate 118′098 different policy mixes.

Table 1
Simulated policy instruments.

Bans on heating systems	• On installing new electric boilers • On installing new electric and oil boilers • On installing new electric, gas, and oil boilers
PV and retrofit requirements	• No requirement • To install solar PV when renovating roof • To deeply retrofit the envelopes of all dwellings with G and F envelope efficiency labels. See Appendix B1 for the assumptions on the required depth of retrofit. • To deeply retrofit the envelopes of all dwellings with G to D envelope efficiency labels • A double requirement: to install solar PV and retrofit dwellings with G and F envelope efficiency labels • A double requirement: to install solar PV and retrofit dwellings with G to D envelope efficiency labels
One-time subsidies for low-carbon technologies and retrofits	• No subsidies • 20 % of investment costs for heat pumps, wood boilers, district heating connections, dwelling envelope retrofits, solar thermal collectors, solar PV, and electric batteries • 40 % of investment costs for the same technologies
Energy taxes	• Low: 120 CHF/tCO_{2eq} for heating fuels and 1.5 cCHF/kWh for electricity • Mid: 165 CHF/tCO_{2eq} for heating fuels and 2.1 cCHF/kWh for electricity • High: 210 CHF/tCO_{2eq} for heating fuels and 2.6 cCHF/kWh for electricity

2.3. *Microsimulation of investment opportunities*

We quantify energy investment opportunities for every household in our sample under each of the policy mixes. These involve techno-economic calculations of the annualized discounted long-run costs for heating and electricity, the resulting emission savings, and the received public spending of various combinations of energy investments. The energy investment options considered are: (1) whether to deeply retrofit the envelope of the dwelling; (2) whether to keep or replace the heating system; (3) whether to install solar thermal collectors as a complement to the heating system; and (4) whether to install solar PV with or without batteries (see Appendix B1 for the specific assumptions on the size, cost, emissions, efficiencies, and lifetimes of the various investment options). With a similar model structure to past studies (Hesselink and Chappin, 2019; Sachs et al., 2019; Wilson and Dowlatabadi, 2007), we adopt a depreciation economic assessment approach (Streicher et al., 2020), and per household and policy mix select the combination of investment options with the minimum annualized discounted long-run costs. These long-run costs account for the costs of heating fuels and electricity, operation and maintenance, the annualized investment costs for new equipment, and the residual value of existing equipment (see Appendix B2 for further details).

Our techno-economic calculations also account for the effects of the policy instruments. Bans on new electric, gas, and oil boilers and requirements to install solar PV systems and to retrofit dwelling envelopes are taken into account when determining the set of investment options available to each household. Investing in PV systems and solar thermal collectors is discarded for households that already have this equipment, and retrofits are discarded for those conforming with a Minergie or better energy efficiency standard (Minergie, 2024). There are some additional constraints on no disconnections from district heating, no switching from gas to oil boilers, no new wood boilers in urban areas due to air quality regulations and lack of storage space (Marcelino et al., 2019; Nägeli et al., 2020). We also consider some location-based constraints: that district heating connections as well as air-, water-, and geothermal-source heat pumps are not an option for the households whose postal code area had no buildings with such a heating system at the end of 2023 (FSO, 2023). The rest of the policy instruments – subsidies for low-carbon technologies and taxes on heating fuels and electricity – are accounted for when calculating the investment and operational costs of each investment option. Since price elasticities for electricity and heating fuels are low in Switzerland (Filippini and Kumar, 2020; Volland and Tilov, 2018), demand reductions are not considered when simulating taxes.

To investigate what policy action can activate a just household energy transition, we take a static microsimulation approach and simulate the effects of all policy instruments within a mix at once and just one time, focusing on the immediate future. Therefore, in this study, bans on installing new electric, gas, and oil boilers target households whose heating system has reached the end of its lifetime in 2025 and must replace it in the near term, which represents 42.6 % of households in our sample (34.6 % with electric, gas and oil boilers). The rest of the households are not that affected by such installation bans in this period as early retirements of heating systems are very rarely cost effective considering the systems' residual value. Similarly, the PV requirement that we simulate affects households with a roof that has reached the end of its lifetime in 2025, constituting 22.9 % of households in our sample. We identify households having to replace roofs and heating systems in the near term with survey-based information on their year of installation and assuming theoretical lifespans (see Appendix B1). Retrofit requirements affect dwellings based on their efficiency. The requirement targeting dwellings with G and F envelope efficiency labels affects 44.0 % of households in our sample, while the requirement for dwellings with G to D envelope efficiency labels affects 63.2 %.

2.4. Evaluation of policy mix outcomes

We evaluate policy mixes regarding four main outcomes (see Appendix B3 for further details on the calculations):

- **Emission savings:** the total promoted CO_{2eq} emission savings per year if households implement the energy investments with minimum long-run cost, including emissions from electricity and heating fuel consumption and embodied emissions of new energy investments. Therefore, this measure represents an upper threshold of the mitigation potential of the mixes.
- **Net public spending:** the sum in Swiss francs (CHF) of subsidies paid by the public budget minus revenues generated by energy taxes in the five years after the policy enforcement, assuming that households claim all available subsidies and implement the energy investments with minimum long-run cost. This net public spending represents public funds needed in the short run, but without considering the policies' design, implementation, and enforcement costs.
- **Distributional justice:** two criteria that show the extent to which the policy mixes can represent an economic burden for households in the long run and how equally this burden is distributed. These two criteria complement each other as higher equality in the distribution of costs does not necessarily mean more justice if it also promotes higher costs.
  - o **Average cost share for heating and electricity of households**: the average of the minimum annualized costs of heating and electricity over the annual disposable income that households can achieve under each policy mix.
  - o **Gini coefficient of household heating and electricity cost shares:** the level of equality in the distribution of the minimum annualized costs of heating and electricity divided by the annual disposable income that households can achieve under each policy mix. Although designed to measure income inequality, the Gini coefficient (Gini, 1997) has been used to operationalize (in)equality across fields (Jacobson et al., 2005; Pehle et al., 2025; Sasse and Trutnevyte, 2020; Sitthiyot and Holasut, 2020).

For our analysis of distributional justice, we only consider direct costs related to heating and electricity as described in Section 2.3. We do not consider indirect costs such as cost increases of other types of consumption due to energy taxes, or the costs of financing subsidies, which is equivalent to assuming that funds for subsidies are raised in a distributionally neutral way when comparing policy mixes.

To evaluate distributional impacts in further depth, we also quantify **the average shares of heating and electricity cost of various household groups** defined by household structure, quintile of equivalized disposable income, dwelling tenure, settlement type, and canton of residence. This indicator measures the minimum relative cost for heating and electricity that different household groups can achieve under each policy mix. It can also be interpreted as the economic effort that the households must make to achieve the promoted emission savings that we report for each policy mix. As Swiss tenancy law allows full pass-through of low-carbon heating and electricity investments from dwelling owners to tenants in the long run (VMWG, 2024), we assume such pass-through to quantify the worst-case scenario for tenants. However, there are cases when dwelling owners do not increase the rent after making energy investments because such increase would also require adjusting rent terms retrospectively according to the actual interest rates, and the owners might end up losing. A previous study showed that assuming full pass-through or not has little effect on the justice rankings of different fossil fuel boiler bans and of the household groups more and less affected by the bans (Torné and Trutnevyte, 2024).

2.5. Clustering and characterization of policy mixes

As we aim to explore how specific combinations of policy instruments are linked to general tendencies in the outcomes of policy mixes, we first group policy mixes regarding these outcomes. We then use an XGBoost algorithm (Yang et al., 2021) and Shapley additive explanations (SHAP) values (Lundberg et al., 2020) to investigate which policy instruments characterize each outcome group. We group policy mixes using K-means clustering (Ikotun et al., 2023) based on the four considered policy mix outcomes: promoted emission savings, net public spending, the average household shares for heating and electricity cost, and the Gini coefficient of these shares. K-means clustering is well-suited for large-n samples like ours and has a centroid-based technique that helps us split our ensemble of mixes based on distinct levels of their continuous outcome variables. We choose the number of clusters based on a silhouette metric (Rousseeuw, 1987). An XGBoost model that is trained to classify combinations of policy instruments into the clusters allows us to capture the non-linear relationships between policy instruments and the general outcomes of the policy mixes. We use XGBoost as it is the model with the best classification accuracy out of the four machine learning models that we test (see Appendix Table C1 and Fig. C1). SHAP values allow us to interpret the model's results by retrieving the most important policy instruments for this classification. SHAP values combined with XGBoost have been used to unravel non-linear relationships for multiple applications (e.g., Batunacun et al., 2021; Jaxa-Rozen and Trutnevyte, 2021; Yang et al., 2021). We also explore how energy investments are linked to general tendencies in the outcomes of policy mixes by retrieving the total capacity of different heating system types, solar PV and batteries, and retrofit savings that are promoted by each cluster of policy mixes.

3. Results

3.1. Trade-offs between policy mixes

Our analyzed policy mixes yield a large variety of outcomes in terms of promoted emission savings, net public spending, and distributional justice (Fig. 2). At this point, we do not find a single-best policy mix that outperforms the rest in the four outcomes considered (cf. Discussion section), and therefore there is always a trade-off to accept. However, we observe a group of policy mixes – those at the upper left and front corner of Fig. 2 – that can be considered better solutions to encourage emission savings, as for similar levels they promote comparatively lower and more equal relative heating and electricity costs for households at similar or lower potential costs for the public budget. There are synergies too, for example, when more public spending leads to lower household cost and lower Gini values and thus higher distributional justice, or when it leads to higher emission savings as these measures are positively correlated (Appendix Fig. C2). Nevertheless, the specific regulation in place and how subsidies are allocated to the different low-carbon technologies have an important impact, as public spending alone only explains a limited portion of the variance in emission savings. There is an even stronger correlation between equality and costs to households: policy mixes that promote less expensive energy investments also promote a more equal distribution of costs among households, leading to a more decisive justice outcome. Policy mixes that would potentially require lower public spending and lead to lower costs for households do not necessarily encourage lower emission savings, meaning that some energy investments lead to emission savings that are more cost-effective than others.

By encouraging energy investments with subsidies and taxes and enforcing them through regulation, policy mixes yield total emission savings above 4.8 $MtCO_{2eq}$/year and up to 5.9 $MtCO_{2eq}$/year for a sample size of 81.5 % of the whole Swiss household population. If these savings are proportionally scaled to the whole of Switzerland, without considering embodied emissions, they translate to more than 60 % of the emissions from heating fuel and electricity use in residential buildings in

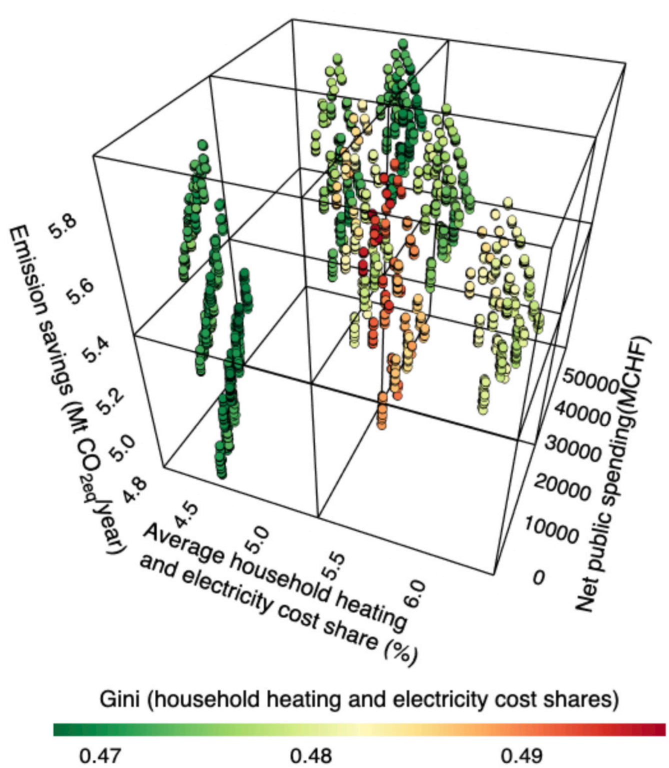

Fig. 2. Trade-offs between promoted emission savings, net public spending, level of equality and average household heating and electricity cost shares of all 118′098 simulated policy mixes. Equality is operationalized through the Gini coefficient, with 0 corresponding to perfect equality and 1 to perfect inequality. Results are obtained from a sample which covers 81.5 % of the size and diversity of all Swiss households as captured by the HBS (BFS, 2015), and thus do not represent total values for the whole of Switzerland.

2021. Importantly, 3.5 $MtCO_{2eq}$/year of total savings are already economically profitable for households with no policies (Appendix Fig. C9), confirming the existence of the energy efficiency gap. Policy mixes thus promote 35 %–68 % additional emission savings beyond those that are anyway economically profitable for households. The majority of emission savings are mainly due to reduced heating fuel use as a consequence of retrofits and the electrification of heating. These savings largely outweigh the embodied emissions of new installations and retrofits, as well as potential slight increases in emissions from households' electricity use, even with our pessimistic assumption where the emission factor of the Swiss electricity is static (Appendix Fig. C9).

3.2. The relation between energy investments and policy mix outcomes

Here, we aim to explore which energy investments are promoted by the different policy mixes and how promoting some energy investments over others is associated with policy mix outcomes. We capture general tendencies in outcomes by clustering the 118′098 policy mixes (Section 2.5), where we obtain sixteen clusters (Fig. 3 and Appendix Table C2 for descriptive statistics). This step enables us to link ranges of promoted energy investments to ranges of outcomes (Fig. 4 and Appendix Fig. C3). After presenting all clusters, we present here results for four representative clusters that cover the span of the outcomes we consider, while the results for the rest of the clusters are available in Appendix C.

Even without policy, there are some energy investments that appear more cost-attractive in the long run for households than others. Heat pumps represent the largest share of cost-attractive heating system capacity, especially air-source heat pumps which can be implemented in most locations (Fig. 4 and Appendix Fig. C3). To a more limited extent, district heating is also a feasible and cost-attractive option. Even if not banned, oil, gas, electric, and wood boilers are not as competitive energy investments in terms of long-run costs as heat pumps and district heating. Policy mixes that promote further emission savings than those that are anyway profitable without any policy do so by further promoting the phaseout of oil and gas boilers, favoring the abovementioned low-carbon heating systems, through retrofits, and also promoting solar PV beyond the comparatively small amount that is profitable for households without subsidies. Despite modeled subsidies and taxes, and although electric batteries and solar thermal collectors can be interesting from other perspectives, neither appear as cost attractive for households under any simulated policy mix.

In terms of the relation between different energy investments and policy mix outcomes, on one hand, clusters that with similar retrofit savings promote higher uptake of solar PV (e.g. the forest green-colored cluster with respect to light purple-colored cluster in Fig. 4) also encourage a higher uptake of heat pumps. Consequently, oil boilers are phased out to a greater extent and larger emission savings can be obtained. The reason for this is that the availability of self-produced electricity makes heat pumps more cost-attractive than fossil fuel boilers, and also reduces the overall carbon intensity of the electricity that households consume. Despite Switzerland's high share of renewable electricity already, and the expectation that the carbon content of Swiss electricity is going to decrease with the electricity sector transition (Prognos AG; INFRAS AG; TEP Energy GmbH; Ecoplan AG, 2021), it is still non-negligible due to the imports from the neighboring countries (Romano et al., 2024). On the other hand, promoting decarbonization through retrofitting the dwelling envelope and thus allowing lower installed heating capacities and lower heating fuel use (e.g., the salmon- and light blue-colored clusters in Fig. 4) leads to more unequal and higher costs for households than solely focusing on the electrification of heating. Deep dwelling envelope retrofits are an expensive solution (Appendix B1): they lead to either high costs for households if subsidies are low, high public spending if subsidized, or both. Only policy mix clusters promoting low levels of energy savings through retrofits (e.g. the forest green- and light purple-colored clusters in Fig. 4) achieve both low and more equally distributed costs for households at constrained

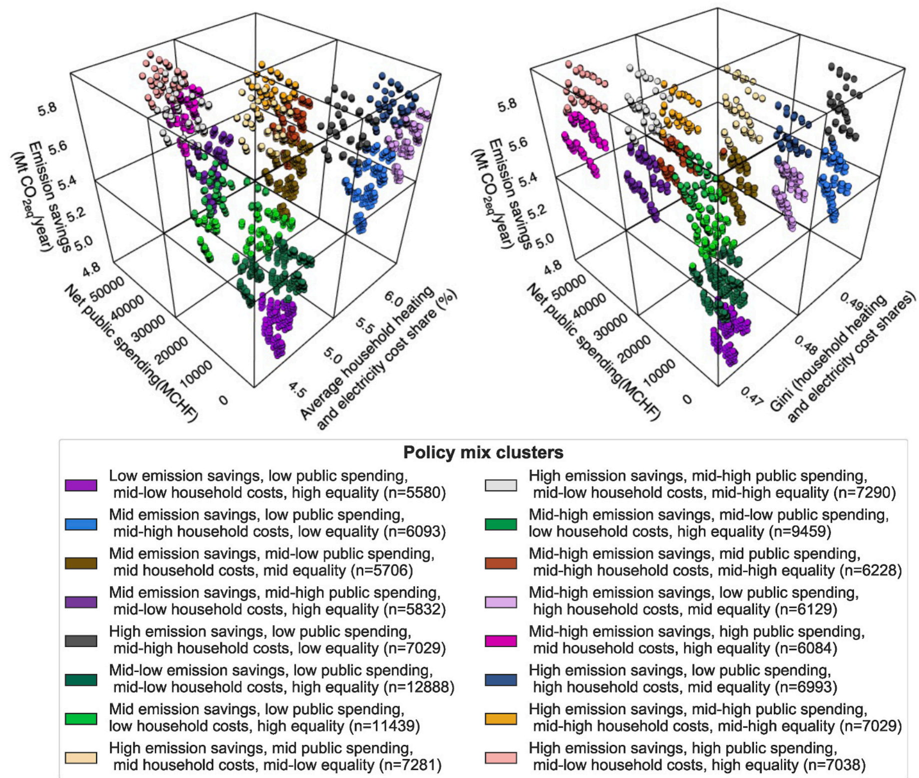

Fig. 3. Policy mix clusters obtained through K-means clustering. The two cubes depict the four different measured outcomes for the 118′098 policy mixes that we simulate. The legend shows cluster names and the number n of policy mixes per cluster.

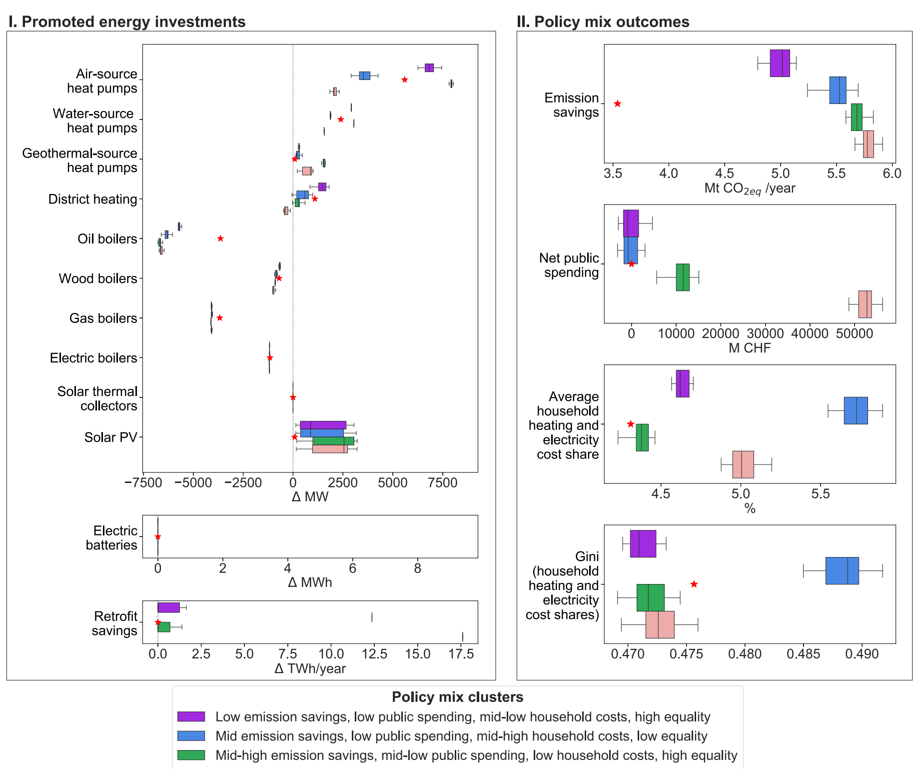

Fig. 4. Promoted energy investments and outcomes of four selected clusters of policy mixes. Appendix Fig. C3 presents the rest of the clusters. Promoted energy investments are represented as the change in the total capacity of heating systems, PV, batteries, and retrofit savings of our sample if households implemented the most economically attractive energy investments under each policy mix. For reference, the red stars represent the most economically attractive energy investments and respective outcomes without any policy. The legend shows cluster names. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

public spending.

3.3. The relation between policy instruments and policy mix outcomes

In order to investigate which combinations of policy instruments are associated with which policy mix outcomes, we identify which policy instruments characterize each of the sixteen clusters of mixes that we obtained in Fig. 3. Using an XGBoost classification model and the analysis of SHAP values, we retrieve results for the same four clusters presented in Section 3.1 here (Fig. 5) and display the remaining clusters in Appendix Fig. C5. We focus on the analysis of policy instrument combinations and not of standalone policy instruments because the effect of the policy instruments on public spending, emission savings, and justice largely depends on the rest of the instruments in the mix (Appendix Fig. C6). Overall, the most important policy instruments to characterize the clusters, i.e. those with higher mean absolute SHAP values and thus the highest influence on policy mix outcomes, are the requirements to install PV when renovating roofs and to retrofit the envelopes of worst-insulated dwellings (Appendix Fig. C4). Subsidies for dwelling retrofits are the second most influential instrument (Appendix Fig. C4) with a big effect on household costs and public spending (Appendix Fig. C6). Subsidies for heat pumps and to a smaller extent energy taxes are the third and the fourth most important instruments respectively (Appendix Fig. C4), especially influencing promoted emission savings (Appendix Fig. C6). Subsidies for PV panels are also important in determining which combinations of energy investments appear as the most profitable for households (Appendix Fig. C4) and therefore influencing the policy mix outcomes. However, the bans on installing electric and fossil fuel boilers, as well as subsidies for district heating, wood boilers, electric batteries, and solar thermal collectors have lower or even null effect (Appendix Fig. C4). Bans almost do not affect the possible ranges of promoted emission savings by the policy mixes (Appendix Fig. C6) and are not particularly associated with policy mixes promoting high emission savings (see Appendix Fig. C5) because in the near term they would only affect a portion of households with fossil fuel heating systems, and most importantly, because the most profitable option of new heating system for these households is rarely a fossil fuel boiler anyway.

Mid-high and high emission savings above 5.6 $MtCO_{2eq}$/year for a sample size 81.5 % of the whole Swiss household population are most associated with a combination of high energy taxes and high subsidies for heat pumps. We obtain this result by identifying the policy instruments with high SHAP values that describe clusters promoting mid-high and high emission savings (e.g., the salmon- and forest green-colored clusters in Figs. 4 and 5) and not the rest of the clusters (e.g., the light blue- and light purple-colored clusters in Figs. 4 and 5). On top of these instruments, a PV requirement and high subsidies for PV and retrofits (therefore most of the forest green-colored cluster in Figs. 4 and 5) promote slightly higher emission savings above 5.8 $MtCO_{2eq}$/year and 14 times the solar PV capacity up to 3220 MW. The advantage of this combination of policy instruments is that substantial savings are promoted at constrained public spending and, at the same time, households can achieve low and equally distributed long-run costs of heating and electricity. A retrofit requirement on top of the PV requirement, with the high energy taxes and heat pump subsidy mentioned above (most of the salmon-colored cluster in Figs. 4 and 5 and the dark blue, yellow, light grey and dark grey-colored clusters in Appendix Fig. C3 and C5), promote even slightly higher emission savings above 5.9 $MtCO_{2eq}$/year and at least 12.4 TWh/year of energy savings, instead of at most 0.8 TWh/year without the retrofit requirement. However, this combination of

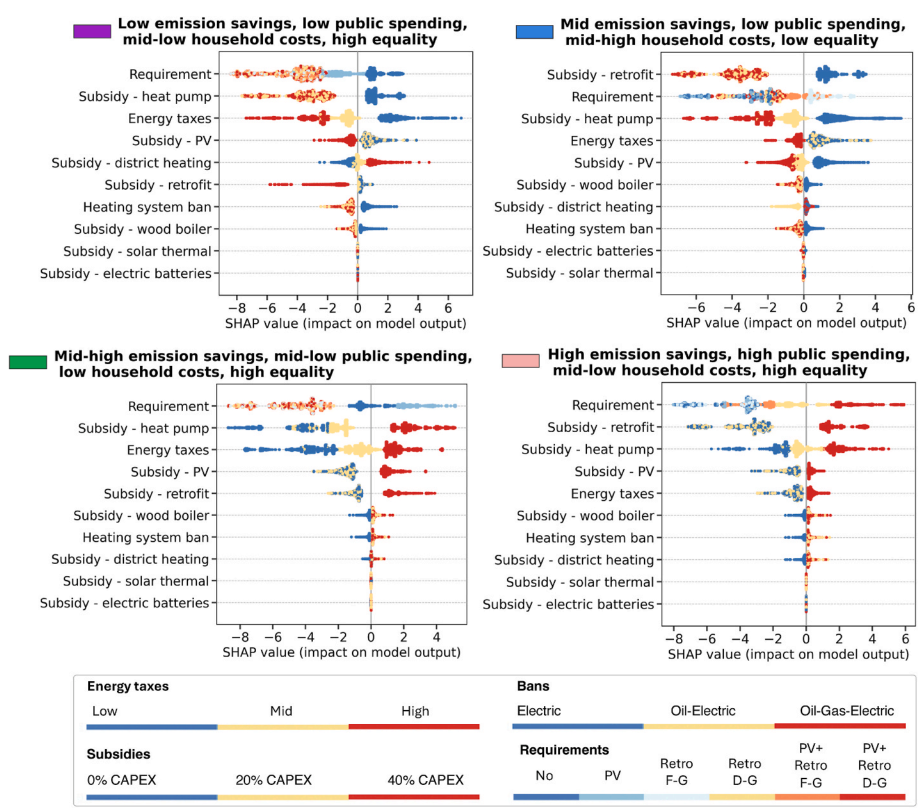

Fig. 5. Impact of policy instruments (as SHAP values) on the policy mix outcomes (as XGBoost classification models of four selected clusters of policy mixes). Appendix Fig. C5 presents the rest of the clusters. SHAP values – represented as points – depict the extent to which each policy instrument of each policy mix contributes to classifying that policy mix as part of a cluster (positive SHAP value) or as not being part of a cluster (negative SHAP value). The color of the SHAP values refers to the level of the policy instrument, as displayed in the legend. Therefore, clusters of policy mixes are most characterized by the top-listed type of policy instruments, and by the levels with the highest SHAP values. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

instruments comes with the trade-off of higher public spending and/or higher household costs, depending on the retrofit subsidies. Another option to promote high emission savings above 5.8 $MtCO_{2eq}$/year and at least 12.4 TWh/year of energy savings would be a retrofit requirement only, high energy taxes, and a high heat pump subsidy (most of the cream-colored cluster in Appendix Fig. C3 and C5). However, compared to the same mix but with the PV requirement, up to 10 times less PV capacity would be promoted.

High net public spending is mostly associated with high subsidies for dwelling envelope retrofits up to 40 % of investment costs when combined with stringent retrofit requirements affecting dwellings with G to D efficiency labels. This is the combination of policy instruments with high SHAP values that describes clusters with high public spending (i.e. the dark pink- and salmon-colored clusters in Appendix Fig. C3 and C5) and not the rest. High subsidies for retrofits but with less stringent retrofit requirements only for dwellings with G and F efficiency labels are also associated with clusters with high – but slightly lower – public spending (i.e. the dark purple- and light grey-colored clusters in Appendix Fig. C3 and C5). Additionally, by observing the distribution of public spending across individual policy instruments (Appendix Fig. C6), we find that first subsidies for heat pumps, and then to a lower extent for PV, are also important in determining the potential costs for the public budget. Compared to subsidies for other low-carbon technologies, the same proportional changes in the amount of these subsidies lead to higher changes in public spending. As we measure the potential short-term impact of the policy mixes on net public spending (see Section 2.4) and because the different tax levels only lead to very limited changes in the distribution of net public spending (Appendix Fig. C6), we find that taxes have a limited effect on net public spending.

On one hand, distributional justice, defined as the promotion of equally distributed and low relative heating and electricity costs for households, is associated with a combination of the PV requirement, high energy taxes, and high subsidies for heat pumps, PV, and retrofits (i.e., the forest green-colored cluster in Figs. 4 and 5). It is also associated with policy mixes characterized by no requirements, and high subsidies for heat pumps (part of the light green-colored cluster in Appendix Fig. C3 and C5). These combinations of instruments receive high SHAP values for clusters with high equality and low costs for households and not the rest. In addition, a combination of no requirements with no or low subsidies for low-carbon technologies (the light purple-colored cluster in Fig. 5 and dark green-colored cluster in Appendix Fig. C3 and C5) also promotes equally distributed and only slightly higher costs for households. The former of the combinations is associated with mid-high emission savings, while the latter can be described as an environment with almost no policy that promotes low emission savings. Almost no policy promotes mid-low and equally distributed relative household costs as, even though investments are not subsidized, households are not forced to energy investments that are not the most economically profitable in the long run. On the other hand, low equality in the distribution of household costs is particularly associated with the requirement to retrofit dwellings with G and F efficiency labels and low subsidies for retrofits (Appendix Fig. C6 and the dark grey and light blue-colored clusters in Appendix Fig. C3 and C5). A combination of the more stringent requirement to retrofit dwellings with G to D efficiency labels and low subsidies for retrofits is associated with slightly lower inequality as this combination affects more households, but also with the highest average household costs (i.e. the dark blue- and light pink-colored clusters in Appendix Fig. C3 and C5).

3.4. Distributional impacts by household groups

To give further insights into distributional justice, we quantify the distributional impacts of the policy mixes across household groups. We find disparities in the extent to which the different groups can achieve low heating and electricity costs relative to their disposable income in the long run, especially across equivalized income quintiles and household structures (Fig. 6 and Appendix Fig. C7). For the clusters promoting the most unequal distribution of costs among households (i.e. the light blue- and dark grey-colored clusters in Appendix Fig. C3), we find differences up to 8.0 % in average heating electricity cost shares between household structures, and 11.2 % between the most and least affluent household groups (Appendix Fig. C7). Under all policy mix clusters and on average, the lowest-income group, older people living alone, dwelling owners (considering full pass-through of energy investment costs from the property owners to tenants), rural households, and households from the less populated cantons are those whose minimum achievable heating and electricity costs are the highest. Put differently, these are the groups that would need to make the highest economic effort to achieve the collective emission savings promoted by the different clusters in Fig. 4 and Appendix Fig. C3. On the flip side, the highest income group, couples with children, tenants, urban households, and households from the cantons of Geneva and Lucerne, would need to make the lowest economic effort. Household groups that face the highest long-run costs align closely with those that would need to face the highest investment relative to disposable income, or, in other words, the most credit-constrained (Appendix Fig. C8). However, the latter are only dwelling owners and not tenants, as tenants face investment costs only indirectly and spread over time through rent increases. Conversely, owner-occupants of dwellings must raise these upfront costs and, only if they have access to loans, can distribute payments over time.

There are very few differences between policy mix clusters in the order of household groups by minimum achievable heating and electricity cost shares. Although most policy mixes impose higher costs than no policy, the order of household groups by cost is also very similar with and without policies. This means that the extent to which households can achieve low heating and electricity costs in the long run is mostly driven by the pre-existing dwelling characteristics and not policy mixes. However, policy mixes including retrofit requirements (e.g. the salmon- and light blue-colored clusters in Fig. 6) especially target and economically burden men over 65 years old who live alone. Concentrating the economic burden on this household group helps explain why policy mixes with retrofit requirements obtain a lower equality outcome. With retrofit requirements, older men would be imposed large investments and bear the highest economic burden because, in this study's sample and among groups of people living alone, they live in and own more often larger houses with low envelope efficiency, have comparatively high electricity and heating consumption, and have a comparatively low disposable income (Appendix Table A4). Overall, high household costs relative to disposable income are due to a combination of factors. They are associated with households with fewer members, as these households have lower income and can profit less from the economies of sharing compared to households with more members. High costs are also associated with households living in larger dwellings more often located in less densely populated areas, as they require bigger systems and thus more expensive energy investments. Households living in older dwellings are also associated to high costs, as these dwellings tend to be more carbon intensive and thus require more energy investments.

4. Discussion

Our findings show that certain policy mixes in Switzerland would perform well in terms of encouraging emission savings with limited public spending and distributional justice, without substantial trade-offs. Requiring households to install PV when renovating roofs, increasing the current energy taxes, and offering subsidies of up to 40 % of investment for heat pumps, PV, and retrofits would encourage substantial emission savings. This would be achieved by making fossil fuel heating rarely cost-attractive in the long run, increasing the attractiveness of heat pumps, reducing the carbon footprint of household electricity consumption, and promoting some retrofits where closer to being economically profitable. While these types of policy mixes would impose PV investments on households that renovate roofs, the issue of

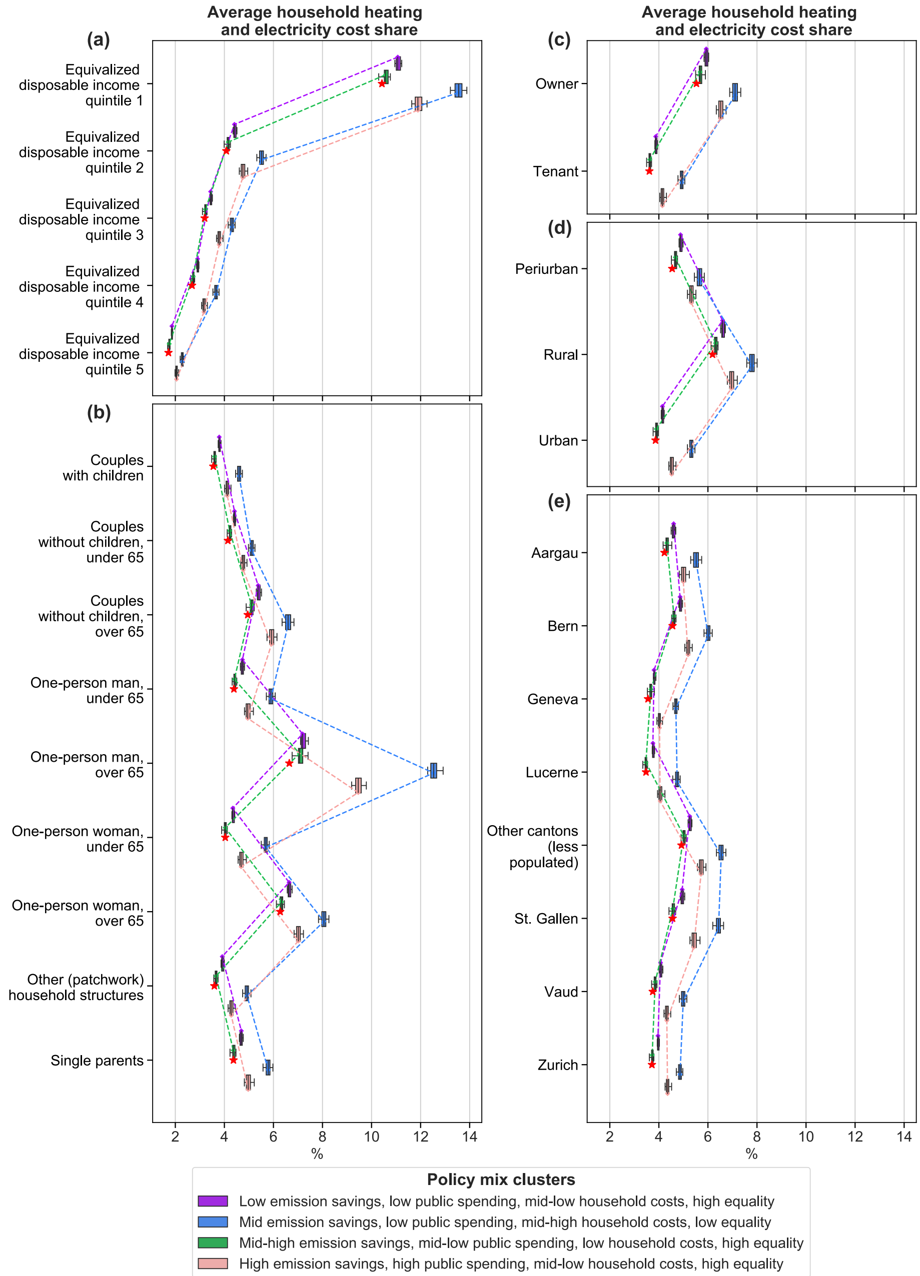

Fig. 6. The average heating and electricity cost share that households grouped by (a) equivalized disposable income quintile, (b) household structure, (c) dwelling tenure, (d) settlement type, and (e) Swiss canton can achieve under the four selected policy mix clusters. Appendix Fig. C7 presents results for the rest of the clusters. For reference, the red stars represent the average heating and electricity cost share that household groups can achieve without any policy. The current figure also represents the extent to which different groups must make an economic effort to achieve the collective CO_{2eq} emission savings promoted by each policy mix cluster in Fig. 4. Dotted lines connect the medians of the average cost shares of each policy mix cluster. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

households being credit-constrained is limited compared to other policy mixes and it could be mitigated by low-interest loans or rent-a-roof PV schemes. The PV requirement would additionally allow multi-family buildings to overcome the barrier of deciding on a common project to profit from economies of scale. Such a policy mix would result in comparatively low and equally distributed heating and electricity costs for households in the long run relative to their disposable income. The mix would also have a limited impact on public spending as we show, and it could be socially acceptable too as it aligns with popular policies in Switzerland: more generous subsidies, better information, less bureaucracy related to subsidies and building permits, and higher focus on PV and heating systems, despite tax-related measures not being popular (Wekhof and Houde, 2023). On top of the policies mentioned above, with greater than current ambition, Switzerland could also oblige dwellings with the least efficient envelopes to be deeply retrofitted. While this would ensure further emission and energy savings in line with Swiss energy efficiency goals (EnDK, 2022), requiring such retrofit depths with high subsidies for retrofits would imply a high cost burden on the public budget. Lower subsidies would otherwise imply higher household investments and would place an especially high economic burden on older people living alone and less affluent households, leading to higher and more unequally distributed costs among households. Higher access to loans – often difficult to obtain by older and less affluent people – could counter these adverse impacts. At the expense of energy and cost savings, less ambitious versions of this requirement could counter its adverse impacts too.

Despite several studies evaluating ex-ante emission savings in the residential sector due to energy policy mixes (Hesselink and Chappin, 2019; Mundaca et al., 2010), we found only one similar study by Nägeli et al. (2020) for Switzerland. In contrast to us, Nägeli et al. (2020) modeled temporal dynamics and considered bounded rationality in investment decisions, since their main goal was to estimate emission savings and not to explore distributional justice implications. Despite the different approaches, some results are compatible between the two studies. Similar to us, they found that renewable generation requirements are effective in promoting the phase out of residential fossil fuel heating in Switzerland, especially with financial incentives on top. Furthermore, they observed that financial incentives alone are not enough to promote dwelling retrofits as we also did, because substantial energy savings through retrofits are only promoted in the presence of requirements. However, they noted that bans are key to phasing out fossil fuel heating, which we did not find as we do not consider other barriers and drivers to technology adoption than costs. In our analysis, fossil fuel heating is rarely the most cost-attractive option in the long run anyway. Apart from bans, we also acknowledge that other complementary policy instruments could help households overcome behavioral and other barriers, achieving higher emission savings. For instance, green leases could help overcome the tenant-owner dilemma (Ástmarsson et al., 2013), low-interest loans could help overcome the lack of capital barrier, and awareness campaigns, energy labels, or energy audits could overcome the households' lack of information (Hesselink and Chappin, 2019). Personal carbon allowances and energy-saving feed-in tariffs are also examples of innovative policies that could further encourage emission savings (Bertoldi, 2022). In terms of public spending, Nägeli et al. (2020) similarly found that revenues from the CO_2 tax will most likely not be sufficient to cover spending on subsidies in the long run. To ensure the cost-effectiveness of the policy mix, there is hence a need for better targeting of subsidies to support those in need and avoid free-riding (Allcott et al., 2015).

Although some of our findings resonate with insights from existing energy justice literature, a key contribution of our study is the nuanced quantification of distributional policy impacts due to the richness of the underlying data. Recent studies have started quantifying distributional aspects using nationally representative microdata (Landis et al., 2019; Vandyck et al., 2021; Weitzel et al., 2023), yet they often focus on climate policies, depict impacts across fewer societal groups, or represent a more limited suite of available technical solutions. We screen through a wide array of mixes to decarbonize the Swiss residential sector and find that on average, less affluent households, older people living alone, dwelling owners, rural households, and households from the less populated cantons are the groups who appear as the most economically burdened since, relative to their disposable income, they are required to face higher investments to minimize long-run costs for heating electricity, and because these minimum achievable costs are higher than for other household groups. Although such costs are a useful indicator to quantify the justice of mixes, they are just minimum costs and not necessarily the actual costs that households will pay, as we assume that the households choose the combination of investments that leads to the least annualized discounted long-run costs. In reality, under policy mixes that encourage investments rather than enforce them through regulation, the actual costs might be higher and might even change the rankings of the most economically burdened. For instance, without bans, the users of fossil fuel heating would most likely incur higher costs than the minimums we show, as their familiarity with the technology will likely refrain them from investing in other technologies that might be cheaper in the long run (Lang et al., 2021). Incurring higher costs could also be especially the case for male people, people with a lower level of education, and people with a higher rental value for their homes, because in Switzerland these groups especially report high investment costs as a barrier to energy investments (Wekhof and Houde, 2023). Older people and female people could also incur higher costs than calculated as they especially report cautiousness to invest because they feel that they are too old and do not have enough time to gather the benefits (Wekhof and Houde, 2023). Last, tenants would also most likely incur higher costs than the minimums we show as the energy investment decision depends on dwelling owners, and their interests might not align. In sum, barriers to profitable investments that especially affect certain household groups risk exacerbating inequalities. Therefore, apart from promoting additional emission savings, justice promotion is another reason to include complementary policies to the ones we simulate in the mix.

Overall, we provided a methodology and new insights into which energy policy mixes Switzerland could adopt to foster a just, effective, and budget-conscious household energy transition. Results regarding the potential for emission savings and public spending of policy mixes are to some extent applicable to countries with a similar dwelling stock in terms of equipment and energy consumption. Results regarding distributional impacts could be transferred to countries that, in addition, have a similar household distribution, e.g., dominated by urban tenants living in flats and high income with respect to energy expenditures. Moreover, the methodology is replicable and can be applied in other contexts as long as similar survey data exists. However, for more predictive rather than explorative purposes, such as estimating expected rather than potential emission savings from specific policy mixes, the modeling of energy investment decisions would need to be more realistic and involve economic, structural, and behavioral barriers to investments, as well as drivers like peer effects. For that, there are options to model bounded rationality (e.g., Edelenbosch et al., 2022) or use implicit discount rates (Schleich et al., 2016). A complementary option to estimate expected emission savings rather than an upper treshold, would be to use empirical lifespans of equipment instead of the theoretical ones used for cost-benefit analysis. Longer empirical lifespans would better replicate the natural replacement cycle of equipment as households extend equipment usage for various reasons, such as postponing investments imposed by regulation.

Regarding future work, a dynamic rather than static modeling approach, accounting for evolving prices, emission factors, costs, technology retirements, household composition, and the aging of population and dwellings, could be implemented to explore the effects of policy mixes over time to 2050 and their sequencing. Such an approach would yield new insights; for instance, the expected decrease of the emission factor of electricity consumed in Switzerland (Prognos AG; INFRAS AG; TEP Energy GmbH; Ecoplan AG, 2021) would make policy mixes that promote electricification even more attractive from the emission savings perspective compared to our current static analysis based on recent emission factors. To account for these evolving conditions, we are extending the model of this study to be dynamic in a future publication, where we will also incorporate empirical lifespans of equipment and implicit discount rates that capture resistance to energy investments. In future work, our focus on three evaluative outcomes of emission savings, public spending, and justice could also be expanded, especially in terms of justice. Apart from quantitatively evaluating distributional justice, the procedural, recognitional, corrective, and transitional justice of the energy policy mixes could be explored too (Zimm et al., 2024). Regarding distributional justice, equality in terms of the distribution of household costs could take into account over and underconsumption, justice could be estimated using other justice principles than only equality (Torné and Trutnevyte, 2024; von Platz, 2018), and it could be based on the distribution of other impacts than only costs (Ürge-Vorsatz et al., 2016). Future work could also explicitly measure energy poverty (e.g., through a Low Income Low Energy Efficiency indicator (GOV.UK, 2025)) and capture cases of deprivation (Vivier and Giraudet, 2024). It could also examine the feasibility of implementing the mixes and consider their design, implementation, and enforcement costs (van den Bergh et al., 2021), or investigate their political viability and social acceptance (Huber et al., 2020). Rebound effects (Böhringer and Rivers, 2021), which could lessen the effectiveness of policy mixes, and indirect effects of policy mixes through the economy (Naess-Schmidt et al., 2015), for instance, the additional distributional impacts associated with financing expensive policy mixes, could also be considered.

5. Conclusion and policy implications

This study advances the quantitative evaluation of residential decarbonization policies by introducing a static microsimulation approach that combines highly granular microdata – linking household socio-economic and technical dwelling characteristics – with the representation of rich technical detail through a broad range of energy co-investments available to households. This enables a nuanced quantification of distributional justice impacts across multiple household groups, alongside policy effectiveness and cost. This study also showcases an analytical method to screen across a wide array of policy mixes and, taking account of interactions between instruments, to obtain valuable insights on the most influential instruments, on the effects of individual instruments, as well as on appealing combinations of instruments.

We apply this methodology to Switzerland and evaluate the immediate potential for emission savings of the policy mixes, how they could impact public budget spending, and especially to what extent and how equally they could represent an economic burden for households. As expected, we find that regulation rather than price-based instruments shape these outcomes the most. We also find that although substantial emission savings are already profitable for households in Switzerland even without policy, a combination of a PV requirement, increased energy taxes, and high subsidies for heat pumps, PV and retrofits would promote even higher emission savings at limited costs to the public budget, while allowing for lower and more equally distributed heating and electricity costs for households. Additional requirements to deeply retrofit the least efficient dwelling envelopes would ensure further emission savings and lower energy consumption, but at a high cost for the public budget. Lowering retrofit subsidies could counter this adverse effect, but at high and more unequally distributed costs among households. Our study also reveales that lower-income households, older people living alone, dwelling owners, rural residents, and those from less populated Swiss cantons risk bearing a higher economic burden to achieve collective emission savings. Adding complementary policies to the mix could protect these household groups, further ensuring justice, and help these and other households overcome real-world barriers to energy investments, further ensuring emission savings.

Apart from providing policy insights for Switzerland and a replicable methodology for other countries, this study underscores broader policy implications. First, specific policy instruments interact to amplify or dim individual effects on emissions, costs, or distributional justice as we demonstrate, hence policy decision-making should not solely rely on evaluations of standalone instruments. Second, decision-makers should require researchers to carefully evaluate regulation-based policies. While regulation-based instruments can be more effective than market-based ones in achieving emission savings and other goals, since they enforce rather than merely encourage mitigation, these regulation-based instruments also carry a higher risk of negative consequences on justice. Third, as this study also demonstrates, there is a risk that some policy mixes can concentrate negative economic impacts on specific societal groups and exacerbate existing inequalities. As these justice implications are not straightforward to foresee, it is crucial to quantify distributional impacts and not only aggregated effects. Finally, where possible, high-quality large-n survey data should be repeatedly collected on household energy use and spending as this data enables micro-level simulations of policy effects that are an effective way to uncover distributional impacts.

CRediT authorship contribution statement

Alexandre Torné: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Evelina Trutnevyte:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT in order to improve the readability and language of the manuscript, only on a few occasions. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

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

Acknowledgments

The research published in this publication was carried out with the support of the Swiss Federal Office of Energy as part of the SWEET consortium EDGE. The authors bear sole responsibility for the conclusions and the results presented in this publication. The authors would also like to thank Dr. Gracia Brückmann, Dr. Florian Landis, and Prof Dr. Philippe Thalmann, for their feedback in the making of the study.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enpol.2025.114872.

Data availability

The data that has been used is confidential.

References

Allcott, H., Knittel, C., Taubinsky, D., 2015. Tagging and targeting of energy efficiency subsidies. Am. Econ. Rev. 105, 187–191. https://doi.org/10.1257/AER.P20151008.

Ástmarsson, B., Jensen, P.A., Maslesa, E., 2013. Sustainable renovation of residential buildings and the landlord/tenant dilemma. Energy Policy 63, 355–362. https://doi.org/10.1016/J.ENPOL.2013.08.046.

Balaras, C.A., Dascalaki, E.G., Patsioti, M., Droutsa, K.G., Kontoyiannidis, S., Cholewa, T., 2023. Carbon and greenhouse gas emissions from electricity consumption in european union buildings. Buildings 14. https://doi.org/10.3390/BUILDINGS14010071, 2024Page 71 14, 71.

Batunacun, Wieland, R., Lakes, T., Nendel, C., 2021. Using shapley additive explanations to interpret extreme gradient boosting predictions of grassland degradation in Xilingol, China. Geosci. Model Dev. (GMD) 14, 1493–1510. https://doi.org/10.5194/GMD-14-1493-2021.

Bertoldi, P., 2022. Policies for energy conservation and sufficiency: review of existing policies and recommendations for new and effective policies in OECD countries. Energy Build. 264, 112075. https://doi.org/10.1016/J.ENBUILD.2022.112075.

BFS, 2015. Household budget survey. https://www.bfs.admin.ch/bfs/en/home/statistics/economic-social-situation-population/surveys/hbs.html. (Accessed 31 January 2023).

Bhardwaj, A., Joshi, M., Khosla, R., Dubash, N.K., 2019. More priorities, more problems? decision-making with multiple energy, development and climate objectives. Energy Res. Social Sci. 49, 143–157. https://doi.org/10.1016/J.ERSS.2018.11.003.

Böhringer, C., Rivers, N., 2021. The energy efficiency rebound effect in general equilibrium. J. Environ. Econ. Manag. 109, 102508. https://doi.org/10.1016/J.JEEM.2021.102508.

Brückmann, G., Berger, S., Caviola, H., Hahnel, U.J.J., Piana, V., Sahakian, M., Stadelmann-Steffen, I., Group, with the S.S.S. and H.E.R., 2023. Towards more impactful energy research: the salient role of social sciences and humanities. PLOS Climate 2, e0000132. https://doi.org/10.1371/JOURNAL.PCLM.0000132.

Burgard, J.P., Dieckmann, H., Krause, J., Merkle, H., Münnich, R., Neufang, K.M., Schmaus, S., 2020. A generic business process model for conducting microsimulation

studies. Statistics Transition New Series 21, 191–211. https://doi.org/10.21307/STATTRANS-2020-038.
Camarasa, C., Nägeli, C., Ostermeyer, Y., Klippel, M., Botzler, S., 2019. Diffusion of energy efficiency technologies in European residential buildings: a bibliometric analysis. Energy Build. 202, 109339. https://doi.org/10.1016/j.enbuild.2019.109339.
Chen, H., Wang, L., Chen, W., 2019. Modeling on building sector's carbon mitigation in China to achieve the 1.5 °C climate target. Energy Effic 12, 483–496. https://doi.org/10.1007/s12053-018-9687-8.
Clayton, S., 2018. The role of perceived justice, political ideology, and individual or collective framing in support for environmental policies. Soc. Justice Res. 31, 219–237. https://doi.org/10.1007/s11211-018-0303-z.
Dechezleprêtre, A., Fabre, A., Kruse, T., Planterose, B., Chico, A.S., Stantcheva, S., 2022. Fighting climate change: international attitudes toward climate policies, OECD. OECD Econ. Dep. Work. Pap. https://doi.org/10.1787/3406f29a-en.
Del Rio, P., Ragwitz, M., Steinhilber, S., Resch, G., Busch, S., Vienna, T.U., Eeg, Klessmann, C., De Lovinfosse, I., Nysten, J.V., Fouquet, D., Johnston, A., 2012. Assessment Criteria for Identifying the Main Alternatives - Advantages and Drawbacks, Synergies and Conflicts.
Deng, H.-M., Liang, Q.-M., Liu, L.-J., Anadon, L.D., 2017. Co-benefits of greenhouse gas mitigation: a review and classification by type, mitigation sector, and geography. Environ. Res. Lett. 12, 123001. https://doi.org/10.1088/1748-9326/aa98d2.
D'Orazio, M., Zio, M. Di, Scanu, M., 2006. Statistical Matching: Theory and Practice. John Wiley & Sons.
Economidou, M., Todeschi, V., Bertoldi, P., D'Agostino, D., Zangheri, P., Castellazzi, L., 2020. Review of 50 years of EU energy efficiency policies for buildings. Energy Build. 225, 110322. https://doi.org/10.1016/J.ENBUILD.2020.110322.
Edelenbosch, O.Y., Miu, L., Sachs, J., Hawkes, A., Tavoni, M., 2022. Translating observed household energy behavior to agent-based technology choices in an integrated modeling framework. iScience 25, 103905. https://doi.org/10.1016/J.ISCI.2022.103905.
EnDK, 2024. Révision complète du Modèle de prescriptions énergétiques (MoPEC). https://hubenergiebatiment.ch/gros-plan/ouverture-de-la-consultation-relative-a-la-revision-complete-du-modele-de-prescriptions-energetiques-mopec/. (Accessed 18 March 2024).
EnDK, 2023. État de la politique énergétique et climatique dans les cantons 2023.
EnDK, 2022. Politique du bâtiment 2050+.
EnDK, 2015. Modèle de prescriptions énergétiques des cantons. https://www.endk.ch/fr/politique-energetique/mopec. (Accessed 18 March 2024).
État de Vaud, 2023. Révision de la loi sur l'énergie. https://www.vd.ch/djes/revision-de-la-loi-sur-lenergie. (Accessed 22 May 2024).
Fedlex, 2024. Federal act on the protection of the environment. Chapter 2, Art. 49.3. https://www.fedlex.admin.ch/eli/cc/1984/1122_1122_1122/en. (Accessed 24 July 2024).
Fedlex, 2020. Loi fédérale sur la réduction des émissions de gaz à effet de serre. https://www.fedlex.admin.ch/eli/fga/2020/2013/fr. (Accessed 21 March 2024).
Fedlex, 2016. Federal energy law (LEne). Chapter 5, Art. 25.2. https://www.fedlex.admin.ch/eli/cc/2017/762/fr. (Accessed 24 July 2024).
Filippini, M., Kumar, N., 2020. Gas demand in the Swiss household sector. https://doi.org/10.1080/13504851.2020.1753875.
Fischer, C., Pizer, W.A., 2019. Horizontal equity effects in energy regulation. J. Assoc. Environ. Resour. Econ. 6, S209–S237. https://doi.org/10.1086/701192.
FOEN, 2024. Rapport explicatif sur l'ordonnance sur la protection du climat.
FOEN, 2023. Greenhouse gas emissions in Switzerland [WWW Document]. https://www.bafu.admin.ch/bafu/en/home/topics/climate/state/data.html. (Accessed 3 June 2023).
FOEN, 2021. CO2 levy. https://www.bafu.admin.ch/bafu/en/home/topics/climate/info-specialists/reduction-measures/co2-levy.html. (Accessed 9 March 2023).
Francs énergie, 2024. Les programmes de subvention en Suisse. https://www.francsenergie.ch/fr/programmes-de-subvention. (Accessed 3 September 2023).
FSO, 2023. Federal register of buildings and dwellings: energy/heat source heating. https://www.geocat.ch/geonetwork/srv/eng/catalog.search#/metadata/44598622-14ca-4937-a65b-3d3c2207f8a5. (Accessed 18 March 2024).
Gini, C., 1997. Concentration and dependency ratios. Riv. Politic. Econ. 87 (8–9), 769–790.
GOV.UK, 2025. Fuel Poverty Methodology Handbook 2025: Low Income Low Energy Efficiency (LILEE).
Hesselink, L.X.W., Chappin, E.J.L., 2019. Adoption of energy efficient technologies by households – barriers, policies and agent-based modelling studies. Renew. Sustain. Energy Rev. 99, 29–41. https://doi.org/10.1016/j.rser.2018.09.031.
Hirst, E., Brown, M., 1990. Closing the efficiency gap: barriers to the efficient use of energy. Resour. Conserv. Recycl. 3, 267–281. https://doi.org/10.1016/0921-3449(90)90023-W.
Huber, R.A., Wicki, M.L., Bernauer, T., 2020. Public support for environmental policy depends on beliefs concerning effectiveness, intrusiveness, and fairness. Environ. Pol. 29, 649–673. https://doi.org/10.1080/09644016.2019.1629171.
IEA, 2022. Tracking buildings 2022. https://www.iea.org/energy-system/buildings. (Accessed 1 July 2024).
Ikotun, A.M., Ezugwu, A.E., Abualigah, L., Abuhaija, B., Heming, J., 2023. K-means clustering algorithms: a comprehensive review, variants analysis, and advances in the era of big data. Inf. Sci. 622, 178–210. https://doi.org/10.1016/J.INS.2022.11.139.
Jacobson, A., Milman, A.D., Kammen, D.M., 2005. Letting the (energy) Gini out of the bottle: Lorenz curves of cumulative electricity consumption and Gini coefficients as metrics of energy distribution and equity. Energy Policy 33, 1825–1832. https://doi.org/10.1016/J.ENPOL.2004.02.017.
Jaffe, A.B., Stavins, R.N., 1994. The energy-efficiency gap what does it mean? Energy Policy 22, 804–810. https://doi.org/10.1016/0301-4215(94)90138-4.
Jaxa-Rozen, M., Trutnevyte, E., 2021. Sources of uncertainty in long-term global scenarios of solar photovoltaic technology. Nat. Clim. Change 11 (3), 266–273. https://doi.org/10.1038/s41558-021-00998-8, 11 2021.
Jenkins, K., McCauley, D., Heffron, R., Stephan, H., Rehner, R., 2016. Energy justice: a conceptual review. Energy Res. Social Sci. 11, 174–182. https://doi.org/10.1016/J.ERSS.2015.10.004.
Klevmarken, A., 2022. Microsimulation. A tool for economic analysis. Int. J. Microsimul. 15, 6–14. https://doi.org/10.34196/IJM.00246.
Klinsky, S., Roberts, T., Huq, S., Okereke, C., Newell, P., Dauvergne, P., O'Brien, K., Schroeder, H., Tschakert, P., Clapp, J., Keck, M., Biermann, F., Liverman, D., Gupta, J., Rahman, A., Messner, D., Pellow, D., Bauer, S., 2017. Why equity is fundamental in climate change policy research. Glob. Environ. Change 44, 170–173. https://doi.org/10.1016/J.GLOENVCHA.2016.08.002.
Klinsky, S., Winkler, H., 2018. Building equity in: strategies for integrating equity into modelling for a 1.5°C world. Philos. Trans. A Math. Phys. Eng. Sci. 376. https://doi.org/10.1098/RSTA.2016.0461.
Knobloch, F., Pollitt, H., Chewpreecha, U., Daioglou, V., Mercure, J.F., 2019. Simulating the deep decarbonisation of residential heating for limiting global warming to 1.5 °C. Energy Effic 12, 521–550. https://doi.org/10.1007/S12053-018-9710-0/FIGURES/10.
Lamb, W.F., Antal, M., Bohnenberger, K., Brand-Correa, L.I., Müller-Hansen, F., Jakob, M., Minx, J.C., Raiser, K., Williams, L., Sovacool, B.K., 2020. What are the social outcomes of climate policies? A systematic map and review of the ex-post literature. Environ. Res. Lett. 15, 113006. https://doi.org/10.1088/1748-9326/ABC11F.
Landis, F., Rausch, S., Kosch, M., Böhringer, C., 2019. Efficient and equitable policy design: taxing energy use or promoting energy savings? https://doi.org/10.5547/01956574.40.1.flan40, 73–104.
Lang, G., Farsi, M., Lanz, B., Weber, S., 2021. Energy efficiency and heating technology investments: manipulating financial information in a discrete choice experiment. Resour. Energy Econ. 64, 101231. https://doi.org/10.1016/J.RESENEECO.2021.101231.
Lundberg, S.M., Erion, G., Chen, H., DeGrave, A., Prutkin, J.M., Nair, B., Katz, R., Himmelfarb, J., Bansal, N., Lee, S.I., 2020. From local explanations to global understanding with explainable AI for trees. Nat. Mach. Intell. 2 (1), 56–67. https://doi.org/10.1038/s42256-019-0138-9, 2 2020.
Maestre-Andrés, S., Drews, S., van den Bergh, J., 2019. Perceived fairness and public acceptability of carbon pricing: a review of the literature. Clim. Policy 19, 1186–1204. https://doi.org/10.1080/14693062.2019.1639490.
Maor, M., Howlett, M.P., 2021. Policy instrument interactions in policy mixes: surveying the conceptual and methodological landscape. SSRN Electron. J. https://doi.org/10.2139/SSRN.3790007.
Marcelino, G., G Lanzinha, J.C., Wu, P.-Y., Johansson, T., Calame, N., Freyre, A., Rognon, F., Callegari, S., Rüetschi, M., 2019. Air to water heat pumps for heating system retrofit in urban areas: understanding the multi-faceted challenge. J. Phys. Conf. Ser. 1343, 012079. https://doi.org/10.1088/1742-6596/1343/1/012079.
Markkanen, S., Anger-Kraavi, A., 2019. Social impacts of climate change mitigation policies and their implications for inequality. Clim. Policy 19, 827–844. https://doi.org/10.1080/14693062.2019.1596873.
McCormick, J., 2017. Carrots, Sticks & Sermons, Carrots, Sticks and Sermons: Policy Instruments and their Evaluation. Routledge. https://doi.org/10.4324/9781315081748.
Minergie, 2024. Minergie system renewal. https://www.minergie.ch/de/standards/modernisierung/. (Accessed 18 March 2024).
Montenegro, R.C., Fragkos, P., Dobbins, A.H., Schmid, D., Pye, S., Fahl, U., 2021. Beyond the energy system: modeling frameworks depicting distributional impacts for interdisciplinary policy analysis. Energy Technol. https://doi.org/10.1002/ente.202000668.
Mundaca, L., Neij, L., Worrell, E., McNeil, M., 2010. Evaluating energy efficiency policies with energy-economy models. Annu. Rev. Environ. Resour. 35, 305–344. https://doi.org/10.1146/annurev-environ-052810-164840.
Naess-Schmidt, S., Bo Hansen, M., Von Below, D., 2015. Literature Review on Macroeconomic Effects of Energy Efficiency Improvement Actions.
Nägeli, C., Jakob, M., Catenazzi, G., Ostermeyer, Y., 2020. Policies to decarbonize the Swiss residential building stock: an agent-based building stock modeling assessment. Energy Policy 146, 111814. https://doi.org/10.1016/J.ENPOL.2020.111814.
Nielsen, K.S., Nicholas, K.A., Creutzig, F., Dietz, T., Stern, P.C., 2021. The role of high-socioeconomic-status people in locking in or rapidly reducing energy-driven greenhouse gas emissions. Nat. Energy 6 (11), 1011–1016. https://doi.org/10.1038/s41560-021-00900-y, 6 2021.
Pehle, H., Sasse, J.P., Trutnevyte, E., 2025. Regional inequalities in air quality and health co-benefits due to climate change mitigation in the European electricity sector. Clim. Change 178, 1–22. https://doi.org/10.1007/S10584-024-03851-X/FIGURES/6.
Peñasco, C., Anadón, L.D., Verdolini, E., 2021. Systematic review of the outcomes and trade-offs of ten types of decarbonization policy instruments. Nat. Clim. Change 11 (3), 257–265. https://doi.org/10.1038/s41558-020-00971-x, 2021 11.
Prognos AG, INFRAS AG, TEP Energy GmbH, Ecoplan AG, 2021. Swiss Energy Perspectives 2050+. Technical report.
Rao, N.D., Van Ruijven, B.J., Riahi, K., Bosetti, V., 2017. Improving poverty and inequality modelling in climate research. Nat. Clim. Change. https://doi.org/10.1038/s41558-017-0004-x.
Romano, E., Patel, M.K., Hollmuller, P., 2024. Applying trade mechanisms to quantify dynamic GHG emissions of electricity consumption in an open economy - the case of Switzerland. Energy 311, 133398. https://doi.org/10.1016/j.energy.2024.133398.

Rosenow, J., Fawcett, T., Eyre, N., Oikonomou, V., 2016. Energy efficiency and the policy mix. Build. Res. Inf. 44, 562–574. https://doi.org/10.1080/09613218.2016.1138803.

Rousseeuw, P.J., 1987. Silhouettes: a graphical aid to the interpretation and validation of cluster analysis. J. Comput. Appl. Math. 20, 53–65. https://doi.org/10.1016/0377-0427(87)90125-7.

RTS, 2023. Les cantons envisagent d'installer des toits solaires sur chaque maison. https://www.rts.ch/info/economie/13397573-les-cantons-envisagent-dinstaller-des-toits-solaires-sur-chaque-maison.html. (Accessed 18 March 2024).

Sachs, J., Meng, Y., Giarola, S., Hawkes, A., 2019. An agent-based model for energy investment decisions in the residential sector. Energy 172, 752–768. https://doi.org/10.1016/J.ENERGY.2019.01.161.

Sasse, J.P., Trutnevyte, E., 2020. Regional impacts of electricity system transition in central Europe until 2035. Nat. Commun. 11. https://doi.org/10.1038/s41467-020-18812-y.

Schleich, J., Gassmann, X., Faure, C., Meissner, T., 2016. Making the implicit explicit: a look inside the implicit discount rate. Energy Policy 97, 321–331. https://doi.org/10.1016/J.ENPOL.2016.07.044.

SFOE, 2024. Statistique de l'électricité. https://www.bfe.admin.ch/bfe/fr/home/approvisionnement/statistiques-et-geodonnees/statistiques-de-lenergie/statistique-de-l-electricite.html/. (Accessed 5 July 2024).

SFOE, EnDK, 2016. Modèle D'Encouragement Harmonisé des cantons (ModEnHa).

Silgeneve, 2023. Règlement d'application de la loi sur l'énergie(REn) – dernières modifications au 29 août 2023. https://www.lexfind.ch/fe/fr/tol/31667/fr. (Accessed 19 July 2024).

Sitthiyot, T., Holasut, K., 2020. A simple method for measuring inequality. Palgrave Commun. 6 (1), 1–9. https://doi.org/10.1057/s41599-020-0484-6, 2020 6.

Soubelet, A., Torné, A., Thalmann, P., Trutnevyte, E., 2024. Distributional justice, effectiveness, and costs of current and alternative solar PV incentive schemes in Switzerland. Environ. Res. Lett. 19, 064075. https://doi.org/10.1088/1748-9326/ad4dba.

Spyridaki, N.A., Flamos, A., 2014. A paper trail of evaluation approaches to energy and climate policy interactions. Renew. Sustain. Energy Rev. 40, 1090–1107. https://doi.org/10.1016/J.RSER.2014.08.001.

Steckel, J.C., Dorband, I.I., Montrone, L., Ward, H., Missbach, L., Hafner, F., Jakob, M., Renner, S., 2021. Distributional impacts of carbon pricing in developing Asia. Nat. Sustain. 4 (11), 1005–1014. https://doi.org/10.1038/s41893-021-00758-8, 2021 4.

Streicher, K.N., Mennel, S., Chambers, J., Parra, D., Patel, M.K., 2020. Cost-effectiveness of large-scale deep energy retrofit packages for residential buildings under different economic assessment approaches. Energy Build. 215, 109870. https://doi.org/10.1016/j.enbuild.2020.109870.

Swiss Parliament, 2023. Panneaux solaires obligatoires lors de rénovations. https://www.parlament.ch/fr/services/news/Pages/2023/20230314114638264194158159038_bsf057.aspx. (Accessed 18 March 2024).

Torné, A., Trutnevyte, E., 2024. Banning fossil fuel cars and boilers in Switzerland: mitigation potential, justice, and the social structure of the vulnerable. Energy Res. Social Sci. 108, 103377. https://doi.org/10.1016/J.ERSS.2023.103377.

Ürge-Vorsatz, D., Kelemen, A., Tirado-Herrero, S., Thomas, S., Thema, J., Mzavanadze, N., Hauptstock, D., Suerkemper, F., Teubler, J., Gupta, M., Chatterjee, S., 2016. Measuring multiple impacts of low-carbon energy options in a green economy context. Appl. Energy 179, 1409–1426. https://doi.org/10.1016/j.apenergy.2016.07.027.

van den Bergh, J., Castro, J., Drews, S., Exadaktylos, F., Foramitti, J., Klein, F., Konc, T., Savin, I., 2021. Designing an effective climate-policy mix: accounting for instrument synergy. Clim. Policy 21, 745–764. https://doi.org/10.1080/14693062.2021.1907276.

van der Kam, M., Lagomarsino, M., Azar, E., Hahnel, U.J.J., Parra, D., 2024. An empirical agent-based model of consumer co-adoption of low-carbon technologies to inform energy policy. Cell Rep. Sustain. 1, 100268. https://doi.org/10.1016/J.CRSUS.2024.100268.

van Ruijven, B.J., O'Neill, B.C., Chateau, J., 2015. Methods for including income distribution in global CGE models for long-term climate change research. Energy Econ. 51, 530–543. https://doi.org/10.1016/j.eneco.2015.08.017.

Vandyck, T., Temursho, U., Landis, F., Klenert, D., Weitzel, M., 2022. Prices and standards for vertical and horizontal equity in climate policy. SSRN Electron. J. https://doi.org/10.2139/ssrn.4144282.

Vandyck, T., Weitzel, M., Wojtowicz, K., Rey Los Santos, L., Maftei, A., Riscado, S., 2021. Climate policy design, competitiveness and income distribution: a macro-micro assessment for 11 EU countries. Energy Econ. 103, 105538. https://doi.org/10.1016/J.ENECO.2021.105538.

Vivier, L., Giraudet, L.-G., 2024. Is France on track for decarbonizing its residential sector? Assessing recent policy changes and the way forward. https://doi.org/10.13039/501100001665.

VMWG, 2024. Swiss tenancy law, ordinance on the rent and leasing of residential and commercial premises. Art 14. https://www.mietrecht.ch/db/gesetze_show.php?ArtNr=14&Gesetz=VMWG. (Accessed 15 April 2024).

Volland, B., Tilov, I., 2018. Price Elasticities of Electricity Demand in Switzerland: Results from a Household panel. IRENE Working Papers.

Vollebergh, H., 2023. Evaluating policy packages for a low-carbon transition – principles and applications. Ecol. Econ. 212, 107919. https://doi.org/10.1016/J.ECOLECON.2023.107919.

von Platz, J., 2018. Principles of distributive justice. In: The Palgrave Handbook of Philosophy and Public Policy. Springer International Publishing, Cham, pp. 397–408. https://doi.org/10.1007/978-3-319-93907-0_31.

Wallenko, L., Bachner, G., 2025. Are rural households hit hardest? Exploring the distributional effects of region-specific compensation payments in the Austrian CO2 pricing scheme. Energy Econ. 141, 108118. https://doi.org/10.1016/J.ENECO.2024.108118.

Weber, S., Burger, P., Farsi, M., Martinez-Cruz, A.L., Puntiroli, M., Schubert, I., Volland, B., 2017. Swiss Household Energy Demand Survey (SHEDS): objectives, design, and implementation. Competence Center for Research in Energy. Society, and Transition.

Weitzel, M., Vandyck, T., Rey Los Santos, L., Tamba, M., Temursho, U., Wojtowicz, K., 2023. A comprehensive socio-economic assessment of EU climate policy pathways. Ecol. Econ. 204, 107660. https://doi.org/10.1016/J.ECOLECON.2022.107660.

Wekhof, T., Houde, S., 2023. Using narratives to infer preferences in understanding the energy efficiency gap. Nat. Energy 8 (9), 965–977. https://doi.org/10.1038/s41560-023-01303-x, 2023 8.

Wiese, C., Larsen, A., Pade, L.-L., 2018. Interaction effects of energy efficiency policies: a review. Energy Effic 11, 2137–2156. https://doi.org/10.1007/s12053-018-9659-z.

Wilson, C., Dowlatabadi, H., 2007. Models of decision making and residential energy use, 32, 169–203. https://doi.org/10.1146/ANNUREV.ENERGY.32.053006.141137.

Yang, C., Chen, M., Yuan, Q., 2021. The application of XGBoost and SHAP to examining the factors in freight truck-related crashes: an exploratory analysis. Accid. Anal. Prev. 158, 106153. https://doi.org/10.1016/J.AAP.2021.106153.

Zielonka, N., Trutnevyte, E., 2024. Probabilities of Reaching Required Diffusion of Granular Energy Technologies in European Countries. Preprint. https://doi.org/10.21203/rs.3.rs-4039857/v1.

Zimm, C., Mintz-Woo, K., Brutschin, E., Hanger-Kopp, S., Hoffmann, R., Kikstra, J.S., Kuhn, M., Min, J., Muttarak, R., Pachauri, S., Patange, O., Riahi, K., Schinko, T., 2024. Justice considerations in climate research. Nat. Clim. Change 2024, 1–9. https://doi.org/10.1038/s41558-023-01869-0.