

Reducing demand to reduce costs: the system-wide value of energy sufficiency in buildings and mobility

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Abstract:

Energy sufficiency is a central pillar of the energy transition, alongside the deployment of renewable energy and the improvement of energy systems efficiency. However, the reduction of energy demands and its associated behavioral aspects are generally left out in energy system modeling. This paper addresses this gap by proposing a comprehensive methodology that simultaneously designs energy systems across scales, from single buildings and districts to the national energy infrastructure. The hierarchical formulation is based on a nested Dantzig–Wolfe decomposition, which makes it possible to model energy service demand at the local level and to analyze its repercussions at higher levels. Marginal costs serve as information signals between system layers, ensuring that investment and operational decisions are coordinated across scales. The modeling framework represents energy use behaviors alongside techno-economic decisions, evaluating how energy sufficiency in the residential and mobility sectors affects national energy system costs and emissions. The results emphasize the central role of mobility electrification and energy sufficiency in the housing sector for the energy transition. The adoption of energy sufficient lifestyle could reduce total energy system costs by 2 BCHF/yr (-11%) and end-user energy bill expenses by 35%, due to reduced investments in PV capacities, heating systems and grid reinforcements. Ultimately, the cost reduction lowers energy tariffs, measured as marginal costs, and mainly benefits suburban and rural areas with high energy demands for housing and mobility.

Keywords:

Energy sufficiency; decentralized energy system; Dantzig-Wolfe decomposition; MILP; energy policy

1. Introduction

The decarbonization of energy systems relies on expanding renewable energy and using it efficiently. However, as highlighted by the IPCC [1], technology and efficiency alone are not enough. Energy sufficiency, often neglected in energy models and policy, plays a key role by meeting human needs while reducing energy service demand. Lower demand reduces infrastructure reinforcements, costs, and environmental impacts, supporting a more sustainable system. Thus, the energy transition requires not only integrating renewable energy into evolving grids, it also demands understanding how consumption behaviors evolve and how they impact the energy system.

2. State of the Art

In recent years, efforts have been made to connect distributed energy system modelling with models evaluating energy policies at the regional or national scales. In such frameworks, a leading problem, formulated in a top-down manner, determines aggregated, large-scale decisions, while sub-problems, formulated bottom-up, take the upper-level decisions as given and react by adjusting technological choices, operations, or, more generally,

local system design. For example, Luo et al. [2] modeled the capacity expansion of a regional energy system, where the upper-level problem handles investment planning and the lower levels adapt operational decisions accordingly. Similarly, Gong et al. [3] represented a multi-regional energy system in which the leading problem minimizes CO₂ emissions under different climatic objectives, and the sub-problem minimizes systemic costs. Further examples from the literature include regional power system operation that incorporates demand response from distributed energy systems [4],[5],[6] as well as energy policy and macroeconomic impact analyses that account for distributed technology adoption [7].

Although bi-level modeling allows for the incorporation of local dynamics into broader systems, the state of the art primarily focus on techno-economic assessments. Several works [6],[8],[9] explicitly represent actors of the systems, yet their analyses remain restricted to electrical power grids and do not consider evolving consumption behaviors. As Li et al. [10] point out, socio-technical energy modeling constitutes a significant interdisciplinary research gap. Because most energy models neglect the social dimension, the role of energy sufficiency in supporting the energy transition remains largely underexplored.

The aim of this paper is to develop a comprehensive methodology that jointly accounts for the deployment of renewable energy technologies, evolving lifestyles, neighborhood-level energy governance, the transformation of energy grids and national climatic objectives. The model is constructed using a nested Dantzig–Wolfe decomposition approach, in which energy price signals are determined by a top-down model and transmitted to local energy systems, thereby aligning investment and operation across scales. The methodology explicitly represents energy consumption behaviors and socio-economic dynamics alongside techno-economic decisions. Therefore, the paper contributes to assessing the role of energy sufficiency in the residential and mobility sectors in terms of costs and emissions nationwide.

3. Methodology

The methodology is based on a co-optimization framework, presented on Figure 1, that links two open-source models: REHO [11], dedicated to district-scale energy systems, and EnergyScope [12], which operates at the national scale. EnergyScope accounts for energy demands from industry, freight, services and neighborhoods. It optimizes capital investments in large-scale technologies, seasonal energy storage, and network infrastructure to satisfy these demands. Furthermore, it computes energy tariffs to be communicated to REHO by determining the marginal cost of energy carriers. These tariffs are intended to convey to the district energy system model the condition of regional and national grids, including the electricity mix, grid saturation levels, and carbon intensity of energy carriers. At the building and district scales, REHO evaluates investment options and operational strategies for energy conversion and storage technologies to meet end-use demands in domestic hot water, domestic electricity, mobility, and space heating and cooling. Neighborhoods can import energy carriers such as electricity, natural gas, or district heat from regional grids. They can also rely on mobility services outside the district, in the form of public transportation, when such services are not available locally. To maintain computational tractability, the building stock is grouped into representative neighborhoods using a k-medoid clustering approach developed in earlier work [13]. By optimizing both models simultaneously, the modelling framework captures interactions between decentralized and centralized energy systems. This enables the assessment of the wider implications of local practices and consumption patterns, while also analyzing how national policies and climate objectives influence the technical and economic environment in which neighborhoods operate.

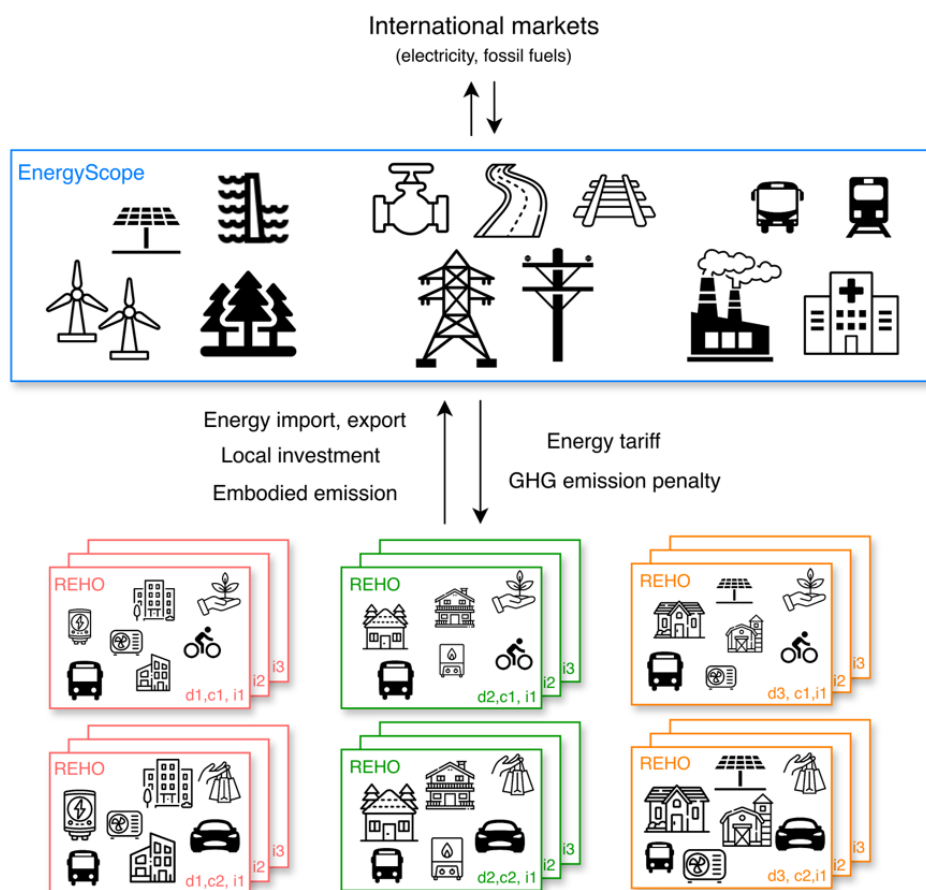


Figure 1: The modeling framework connects energy systems across building, district, and national scales. A set of system configurations are produced for each district $d \in D$ and consumption profile $c \in C$.

3.1. Decomposition Algorithm and Problems Formulations

Figure 2 illustrates the decomposition algorithm. First, sub-problems (**SP**), which represent building energy systems, are solved using fixed energy tariffs. These SPs are optimized for a set of consumption profiles that influence end-use demands and, consequently, the investment and operation of building-level energy technologies. This yields an initial set of building-scale solutions, which are then passed to the intermediate problem (**IP**), representing district energy systems. For each consumption profile, the IP optimizes local self-consumption by enabling electricity exchanges between buildings and determines the necessary investment and operation of mobility technologies to satisfy mobility demands. The resulting district-level solutions are subsequently incorporated into the master problem (**MP**), which models the national energy system using EnergyScope. Once the initialization is completed, the MP calculates the marginal cost of energy and sends this value as updated energy tariffs to the IPs and, in turn, to the SPs. The purpose of the iterative loop is to adjust investments and operations of energy technologies in the lower-level problems according to the price signals provided by the higher-level problems. A new variable, denoted λ , is introduced in both the IPs and the MP and represents the selection of energy system configuration generated by the SPs and the IP, respectively.

The modeling framework enables the representation of various consumption patterns within the SPs and IPs and their integration into the national energy system. In doing so, it produces IP configuration options for the MP that are adapted to specific lifestyle scenarios. The methodology thus directly links consumption behaviors with the transformation of national energy grids.

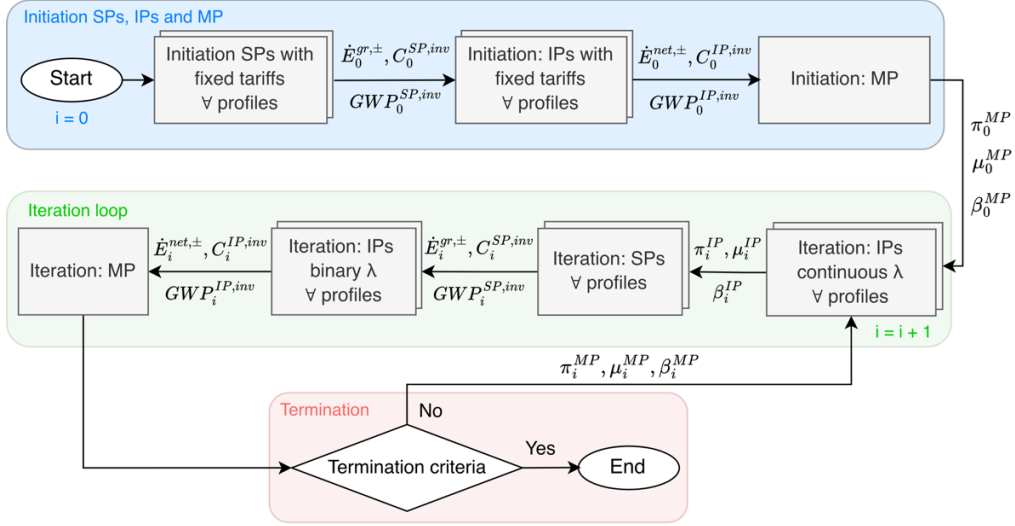


Figure 2: Decomposition algorithm. The SPs and IPs are initialized for each consumption profile under fixed energy tariffs. Then, within the iterative loops, the marginal costs from the MP and IPs are used to generate new configurations.

The following section outlines the formulations of the MP, IP, and SP. To clarify which parameters are exchanged between the problems, decision variables are highlighted in bold>. The MP aims to minimize total cost, encompassing both operational and capital expenditures, as expressed in Eq. (1). Operating costs C^{op} cover expenses related to the extraction of domestic resources or their procurement through international markets, Eq. (2). Capital costs C^{inv} account for the annualized expenditures of large-scale energy technologies $u \in U$ alongside investments made at the neighborhood level, $C^{IP,inv}$. The variable f denotes the installed capacity of energy technologies and f^{ext} refers to pre-existing capacity. The decision variable λ^{MP} governs the selection of IP system configurations $i \in I$ for each district $d \in D$ and must satisfy convexity constraints, Eq. (5). The energy balance is captured in Equation 4, where end-use demands at the national level (\dot{E}^{eud}) and within neighborhoods ($\dot{E}^{net,\pm}$) are satisfied by the output of energy conversion (\dot{E}) and storage units ($\dot{E}^{sto,\pm}$), with network losses \dot{E}^{loss} accounted for across each energy layer $l \in L$. The main linking constraints of the MP are the convexity constraints Eq. (5) and energy balances, Eq. (4), associated respectively with the dual variables μ^{MP} and π^{MP} . These dual values reflect the sensitivity of total costs to relaxations of their corresponding constraints, and are subsequently incorporated into the IP objective function, as described below. It should be highlighted that the configurations proposed by the IP, defined by $C^{IP,inv}$ and $\dot{E}^{net,\pm}$, depend on the set of consumption profiles $c \in C$ analysed in the IP and SP. Equation 6 is used to align the population share of each consumption profile with actual or predefined values.

$$\text{Min } C^{op} + C^{inv} \quad (1)$$

$$C^{op} = \sum_{l,t \in L,T} c_{l,t}^{op} * \dot{E}_{l,t} * d_t \quad (2)$$

$$C^{inv} = \frac{i(1+i)^n}{(1+i)^n - 1} * \sum_{u \in U} c_u^{inv} * (f_u - f_u^{ext}) + \sum_{i,c,d \in I,C,D} C_{i,c,d}^{IP,inv} * \lambda_{i,c,d}^{MP} \quad (3)$$

$$\dot{E}_{l,t}^{eud} + \sum_{i,c,d \in I,C,D} (\dot{E}_{i,c,d,l,t}^{net,+} - \dot{E}_{i,c,d,l,t}^{net,-}) * \lambda_{i,c,d}^{MP} = \dot{E}_{l,t} - \dot{E}_{l,t}^{loss} + \sum_{s \in S} (\dot{E}_{s,l,t}^{sto,+} - \dot{E}_{s,l,t}^{sto,-}) \sim [\pi_{l,t}^{MP}] \quad (4)$$

$$\sum_{i,c \in I,C} \lambda_{i,c,d}^{MP} = 1, \quad 0 \leq \lambda_{i,c,d}^{MP} \leq 1, \quad \sim [\mu_d^{MP}] \quad (5)$$

$$\sum_{i \in I} \lambda_{i,c,d}^{MP} \geq \eta_{c,d}^{profile} \quad \forall i, d, l, t \in I, D, L, T \quad (6)$$

The IP represents district-level energy systems and interconnect building energy systems into low-voltage grids. It also connects local energy demands to national energy networks, coordinating district-level operations with price signals derived from the MP to mitigate potential grid congestion. Additionally, it influences the design of building energy systems by transmitting price signals from the district energy network. The IP is formulated analogously to the MP. Its objective function represents the reduced total cost of the district, covering the operational costs $C^{IP,op}$, which depends on the energy $\dot{E}^{net,\pm}$ exchanged with the national networks, as well as costs associated with district-scale energy technologies. The marginal cost of energy carriers π^{MP} is used as energy tariff and investment costs comprise expenditures at the building level, $C^{SP,inv}$, as well as costs associated with district-scale energy technologies. The weights λ^{IP} attributed to each SP configuration must satisfy the convexity constraint given in Equation 11. The dual values corresponding to the energy balance and convexity constraints of the IP are embedded into the objective functions of the SPs. Mobility is modelled as an energy layer and expressed in person-kilometres. An electric vehicle fleet and conventional cars can provide mobility services at the district scale ($\dot{E}_{mobility}^-$) while consuming electricity or gasoline ($\dot{E}_{elec/gasoline}^+$). In addition, mobility services can be provided to the district by public transportation networks ($\dot{E}_{mobility}^{net,-}$), which would then appear as an end-use demand in the MP energy balance (Eq. 4).

$$\text{Min } C^{IP,op} + C^{IP,inv} - \mu^{MP} \quad (7)$$

$$C^{IP,op} = \sum_{l,t \in L,T} \pi_{l,t}^{MP} * (\dot{E}_{l,t}^{net,+} - \dot{E}_{l,t}^{net,-}) * d_t \quad (8)$$

$$C^{IP,inv} = \frac{i(1+i)^n}{(1+i)^n - 1} * \sum_{u \in U} c_u^{inv} * (f_u - f_u^{ext}) + \sum_{i,b \in I,B} C_{i,b}^{SP,inv} * \lambda_{i,b}^{IP} \quad (9)$$

$$\dot{E}_{l,t}^{net,+} - \dot{E}_{l,t}^{net,-} = \dot{E}_{l,t}^{eud} + \sum_{i,b \in I,B} (\dot{E}_{i,b,l,t}^{gr,+} - \dot{E}_{i,b,l,t}^{gr,-}) * \lambda_{i,b}^{IP} + \sum_{u \in U} \dot{E}_{l,u,t}^- - \dot{E}_{l,u,t}^+ \sim [\pi_{l,t}^{MP}] \quad (10)$$

$$\sum_{i \in I} \lambda_{i,b}^{IP} = 1, \quad 0 \leq \lambda_{i,b}^{IP} \leq 1, \quad \sim [\mu_b^{IP}] \quad \forall i, b, l, t \in I, B, L, T \quad (11)$$

The SP represents the lowest level, building energy systems. It accounts for both capital and operational decisions at the building scale, along with energy exchanges occurring between buildings and the district energy networks, $\dot{E}^{gr,\pm}$. Space heating demand \dot{Q}^{SH} is explicitly defined in Equation 16, where heat losses are calculated using the building thermal coefficients U and K, and the air temperature difference between the indoor T^{in} and the outdoor T^{ext} environments.

$$\text{Min } C^{SP,op} + C^{SP,inv} - \mu^{IP} \quad (12)$$

$$C^{SP,op} = \sum_{l,t \in L,T} \pi_{l,t}^{IP} * (\dot{E}_{l,t}^{gr,+} - \dot{E}_{l,t}^{gr,-}) * d_t \quad (13)$$

$$C^{SP,inv} = \frac{i(1+i)^n}{(1+i)^n - 1} * \sum_{u \in U} c_u^{inv} * (f_u - f_u^{ext}) \quad (14)$$

$$\dot{E}_{l,t}^{gr,+} - \dot{E}_{l,t}^{gr,-} = \dot{E}_{l,t}^{eud} + \sum_{u \in U} (\dot{E}_{l,u,t}^- - \dot{E}_{l,u,t}^+) \quad (15)$$

$$\dot{Q}_t^{SH} = \dot{Q}_t^{gain} - U * A^{era} * (T_t^{in} - T_t^{ext}) - K * A^{era} * (T_{t-1}^{in} - T_{t-1}^{ext}) \quad \forall l, t \in L, T \quad (16)$$

3.2 Case Study

The case study is aligned with the objectives of the Swiss Energy Strategy 2050 [14]. In the building and mobility sectors, a full decarbonization is planned through the phase-out of fossil fuel boilers and conventional cars. The electricity demand arising from energy services electrification will be covered by PV and wind power,

which together are expected to account for 53% of electricity production. Existing hydropower capacity is projected to remain unchanged, providing 45% of the total electricity demand.

At the building and district levels, investments are performed into heat pumps, electric heaters, natural gas boilers, PV panels, district heating networks, electric and conventional vehicles, water tanks, batteries, air conditioning systems, and building renovation. A broad range of energy technologies is available at the national scale, such as hydroelectric dams, thermal power plants, wind turbines, alpine PV installations, cogeneration units, and synthetic gas production and storage systems. More information on assumptions are available in the documentation of REHO [11] and EnergyScope [15]. A set of 12 representative districts is used to capture the urban, geographic, and socio-economic diversity of the residential sector. These districts are identified based on the low-voltage grid density, annual mean outdoor temperature, building form factor and median household income.

To adequately capture the diversity in energy service consumption, the models integrate typical consumption lifestyles of the Swiss population. These representative lifestyles are derived from a study from Sütterlin et al. [16] performing a population segmentation based on a nationally representative survey and hierarchical agglomerative clustering, identifying six characteristic lifestyle groups. The clustering relied on features such as consumption intensity, psychosocial mindset, and levels of policy support. Table 1 presents the consumption patterns associated with each profile. At the building level, the parameters concern heating and cooling setpoints as well as the indoor floor area. Because mobility is represented at the district scale, the adjusted parameters in the IP include the daily travel distance, car occupancy, and the modal split among private vehicles, public transport, and soft mobility. Each parameter shown in Table 1 reflects a behavioral trait that interacts with the demand for energy services, while each profile represents a specific combination of energy consumption behaviors, which characterizes a lifestyle. While the optimization model identifies the optimal set of technologies to meet energy service demands efficiently, the lifestyles under study aim at modifying the level of services to be provided. Subsequently, energy-sufficient lifestyles reducing the total costs of the energy system will be identified by varying the proportion of each lifestyle within the population.

Table 1: Energy service consumption for each typical lifestyle in Switzerland as identified by Sütterlin et al. [15].

Parameter	environment- conconscious	budget- conconscious	indifferent	techie	traditional	sustainable
Indoor space [m ² /cap]	56,7	52,7	52,7	46,4	60,8	48,6
Heating setpoint [°C]	19	21	22	20	21	18
Cooling setpoint [°C]	24	24	24	24	24	24
Daily travel [km/cap/day]	43,1	35,2	31,8	43,7	28,7	49,1
Cars occupancy [cap/car]	1,75	1,55	1,33	1,43	1,57	1,33
Private mobility [% _{pkm}]	43	58	85	54	66	54
Public mobility [% _{pkm}]	44	31	9	34	26	31
Soft mobility [% _{pkm}]	13	11	6	12	8	15
Cars ownership [cars/cap]	0.47	0.53	0.62	0.57	0.52	0.62
Charging flexibility [%]	100	100	100	100	100	100
Population share [%]	26	28	7	10	23	6

4. Results and Discussion

To illustrate how energy sufficiency affects energy systems, Figures 3 show a local sensitivity analysis for four factors: daily travel demand, modal shift between private cars and public transport, electric vehicle adoption, and per capita indoor floor area. Figures 3.1 and 3.2 depict how total costs and electricity consumption vary with daily travel demand, and with indoor area or modal split. In each case, a complete electrification of mobility is assumed. Although travel demand and modal split affect electricity consumption, they have only a minor impact on total costs, since the electricity used to charge vehicles is generated locally from renewable sources. In this context, the floor area per capita becomes the main driving factor for reducing costs: every square meter

per capita reduction in floor area decreases total costs by 227 MCHF/yr on average. Figures 3.3 and 3.4 present the same analysis but for the case of gasoline-powered vehicles. The low mobility electrification sharply rises total costs by 9.5 BCHF/yr (+66%) on average due to substantial fossil fuel imports. Under these conditions, any reduction in mobility demand, whether through shorter travel distances or an increased use of public transportation, strongly affects total costs. It should be emphasised that the figures reflect only the costs associated with the energy system; consequently, investment in mobility infrastructure is not included in this analysis and will be addressed at the end of the discussion.

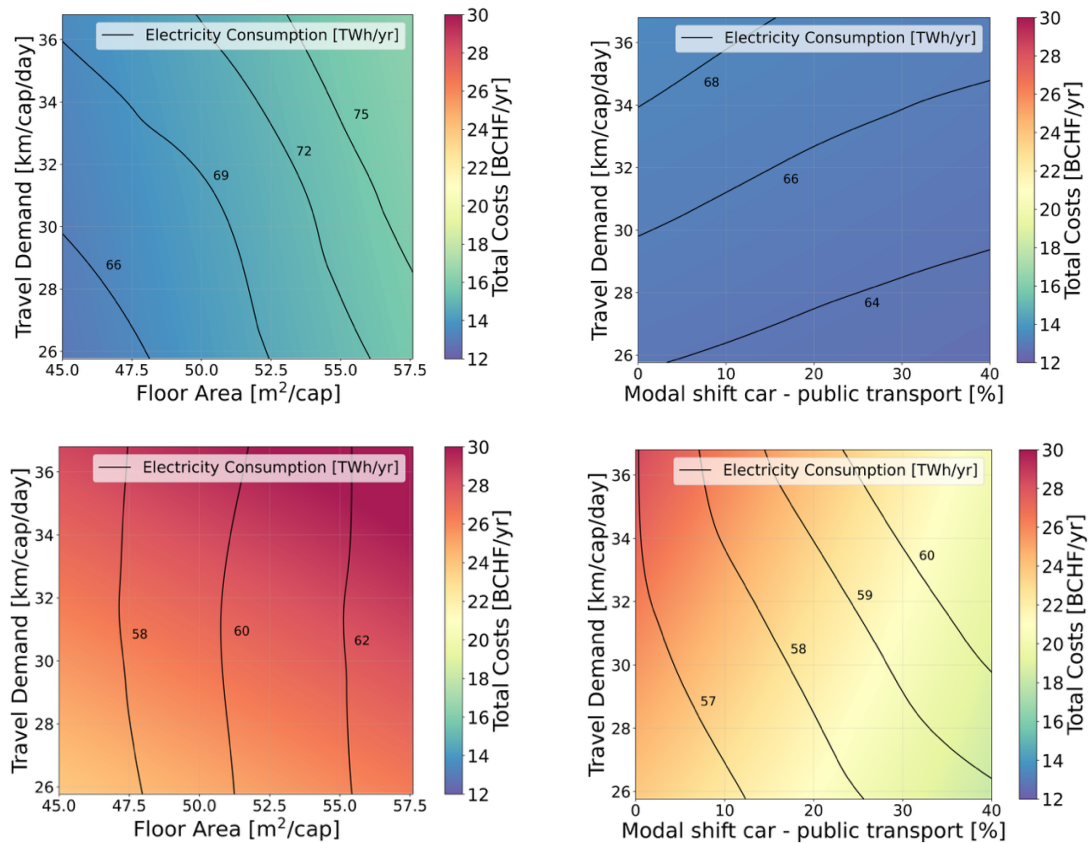


Figure 3: Sensitivity analysis evaluating how total energy system costs and electricity demand respond to changes in mobility electrification, indoor floor area, daily travel demand, and the modal split between cars and public transport. The figure excludes investments in vehicles as well as road and rail infrastructure reinforcement.

To bring the analysis closer to reality, representative consumption lifestyles are incorporated into the model. The objective is to identify current ways of living that, if broadly adopted, could facilitate the energy transition. Figures 4 illustrate how varying the population shares of two specific lifestyle affects the costs of the energy systems, assuming in each case a linear reduction of all other lifestyles from their initial population distribution. The traditional profile is characterized by high indoor heating setpoints, intensive car usage, and large per capita floor area. The high energy demands increase the need for PV capacities and large heating systems, which in turn necessitates additional grid reinforcements and results in an overall total costs increase of 2.6 BCHF/yr (+16%). Conversely, the sustainable profile has the lowest indoor floor area per capita. Therefore, a wide-spread adoption of this lifestyle would reduce energy system costs by 2 BCHF/yr (-11%), with reductions observed in almost every cost category.

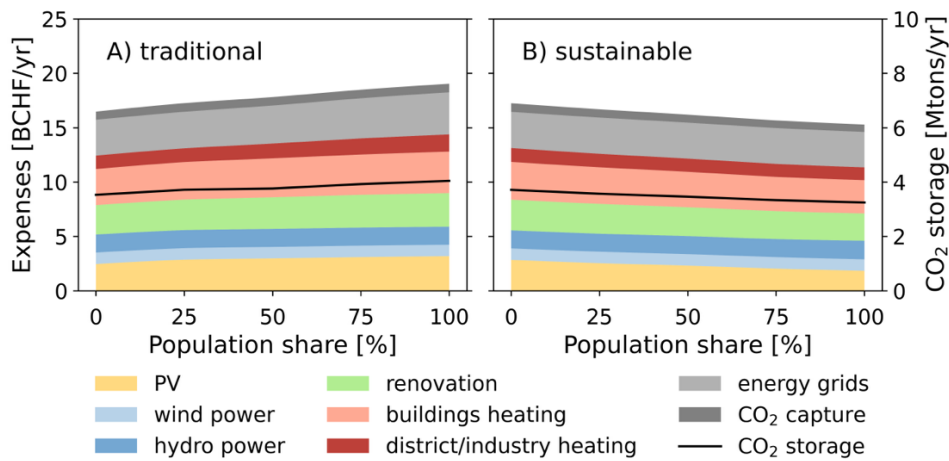


Figure 4: Total energy system costs broken down by sector with an evolving population share adhering to the traditional or sustainable profiles. The distribution of the other typical profiles is made in proportion to their respective base values.

The rise in costs caused by energy-intensive lifestyles directly impacts end-users' energy bills, as it influences both investment requirements and the marginal cost of energy. Figures 5 show how energy bills for residential and mobility services are distributed among end-users across the country. The figures provide a visual illustration of energy poverty inequalities, considering the socio-economic context of each neighborhood to estimate median income. If the entire population followed the traditional profile, average energy expenditures for electricity, heating, cooling, and mobility would amount to 2.84% of net income. This share could fall to 1.74% (-35%) if energy sufficient behaviors were adopted. These figures can be compared with federal statistics, which estimate that household energy spending on energy for housing and mobility accounted for about 3.45% of their net income in 2019 [17]. It is important to note that Figures 4 are based on a scenario of fully electrified mobility, whereas energy expenditures in 2019 mostly accounted for the use of conventional vehicles. Therefore, the substantial cost savings seen across both population groups compared with current spending result as well from the phase-out of fossil fuels.

Beyond lowering average energy bills, energy-sufficient lifestyles also reduce energy cost disparities across the country. The explanation is straightforward. Buildings in rural areas are typically less compact and have lower thermal insulation than those in cities. As a result, they consume proportionally more energy for space heating in winter, precisely when the marginal cost of electricity is amplified by energy-intensive consumption lifestyles. Consequently, energy-sufficient lifestyle mainly benefits suburban and rural communities by lowering electricity cost, which in turn contributes to reducing energy poverty and enhancing energy justice.

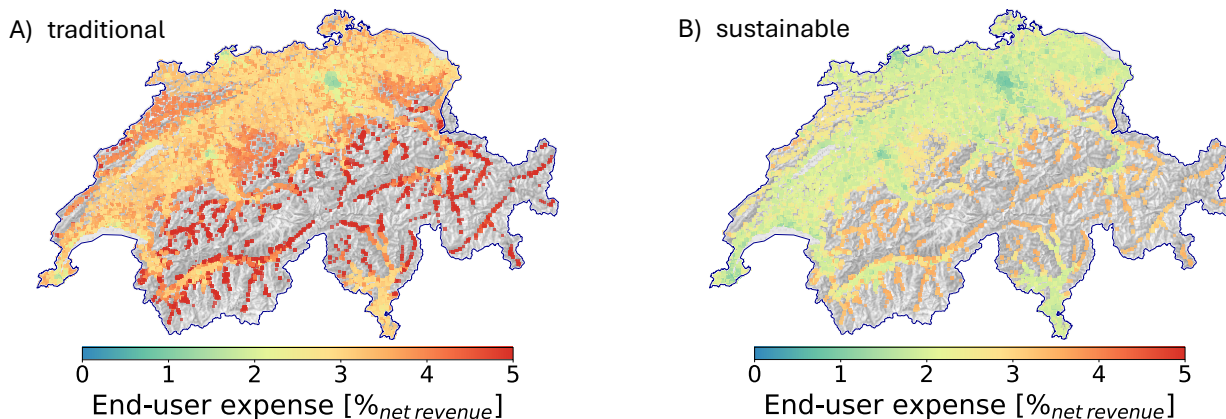


Figure 5: Distribution of energy expenses for housing and mobility assuming that the entire Swiss population follows a single typical consumption profile.

One of the main biases in the analysis so far has been to show the effect of consumption behaviors on the cost of the energy system only, without accounting for the need to reinforce mobility infrastructures. The analysis presented below aims to address this limitation. Investments in private and public vehicles are

estimated based on the mobility services they can deliver, which depend on car occupancy, and on travel demand, itself driven by modal split and daily travel distances. The reinforcement of road and rail infrastructures is derived by comparing the mobility demand they must accommodate to the demand observed in 2022. Costs are then obtained by linearly scaling investments reported in 2022 by the Federal Office of Statistics [18]. Figures 6 provide a view on the effect of energy sufficiency in the scenario of a fully electrified mobility. In contrast to the findings reported previously, a modal shift towards public transport and the daily travel demand substantially lowers total costs. This indicates that although public mobility offers limited advantages from an energy perspective, it fundamentally transforms the landscape when viewed from a mobility infrastructure perspective.

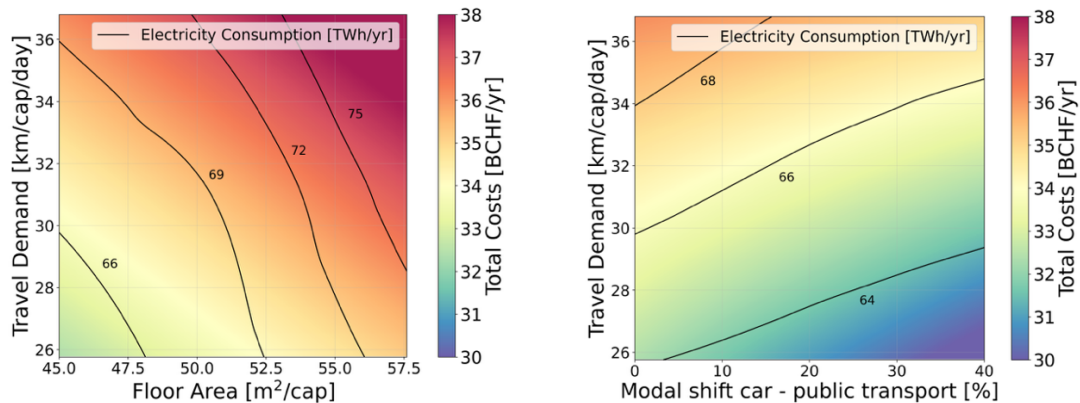


Figure 6: Sensitivity analysis evaluating how energy system and mobility infrastructure costs respond to changes in indoor floor area, daily travel demand, and the modal split between cars and public transport.

6. Limitations

The main contribution of this study was the development of a methodology that dynamically links energy systems across scales under diverse consumption patterns. However, one of the main limitations is that the representation of evolving lifestyles assumes shifts between lifestyles without taking into account the internal dynamics driving behavioral changes. These evolutions usually result from complex dynamics that social sciences study. Assessing the national-scale impacts of local interventions that promote behavioral tipping, such as neighborhood governance or shared mobility, is a clear outlook for future work. In addition, the proposed modeling framework could serve to examine how different population groups adopt new technologies, as well as their resistance to change. In essence, the study offers a picture of the energy system in 2050 but does not clarify the social and technological developments that lead to that situation.

5. Conclusion

The findings suggest that priority should be given on the electrification of mobility, whether private or shared, to phase out fossil fuel and lower both costs and emissions. Furthermore, adjusting living standards toward smaller dwellings emerges as a sustainable strategy across all scenarios because it directly influences the capacity of heating technologies, PV installation, and grid congestion in winter. Lastly, energy-sufficient mobility behaviors appear to be critical when considering investment in the transportation infrastructure. However, from an energy perspective and in the context of a fully electrified mobility, mobility sufficiency plays a limited role. It should be noted that this study did not evaluate the effects of mobility on land use, mineral depletion, or human health. Additional research in life cycle assessment is required to comprehensively determine the impacts of mobility.

The wide-spread adoption of lifestyles already existing in the Swiss population and that are more sufficient in terms of indoor space demands and space heating could lower total energy costs by 2 BCHF/yr (-11%). The lowered investments in energy grids and electricity production capacities would reduce overall energy bills for housing and mobility by 35%. What is more, the reduction is especially significant in rural regions with high energy needs, as lower investments in energy grids lead to reduced energy tariffs.

6. Data Availability

The data used in this study was produced with the open-source optimization tools REHO [11] and EnergyScope [12]. Readers may generate similar data using the REHO python package available here (<https://pypi.org/project/REHO/>) and the EnergyScope Python package available here (<https://pypi.org/project/energyscope/>). Documentation is provided for both tools [11], [15].

7. Fundings

The research published in this report was carried out with the support of the Swiss Federal Office of Energy SFOE as part of the SWEET consortium SWICE and Industrial Services of Geneva (SIG). The authors bear sole responsibility for the conclusions and the results of the presented publication.

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