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Power to the People: On the Role of Districts in Decentralized Energy Systems

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Highlights:

- Integration of decentralized models with a centralized national energy system framework.
- Strategic reduction in photovoltaic (PV) installation requirements and system cost through decentralized approaches.
- Optimization of self-consumption to minimize grid reinforcement needs.
- Identification of key trade-offs in PV integration and the importance of energy storage and grid management.
- Exploration of electrification strategies, power-to-methane technologies, and the use of existing gas grids to bridge decentralized and centralized systems.

Abstract: The transition towards renewable and decentralized energy systems is propelled by the urgent need to address climate concerns and advance sustainable development globally. This transformation requires innovative methods to integrate stochastic renewable sources such as solar and wind power and challenging traditional energy paradigms rooted in centralized and continuous energy production. The present study focuses on the Swiss energy system to explore the optimization of energy planning strategies that incorporate decentralized energy production within a centralized framework. Here, we show that a strategic approach to decentralization can significantly reduce annual system costs by 10% to CHF 1230 per capita and increase self-consumption to 68% of the decentralized PV production, emphasizing the need for a hybrid energy-planning model that balances centralized and decentralized models for enhanced system resilience, efficiency, and cost-effectiveness. This research underscores the strategic importance of diversifying energy sources, enhancing energy storage, improving grid flexibility, and laying a foundational framework for policy making and strategic planning. It encourages further investigation into climate impacts, technology synergy, and the integration of district heating, aiming to establish a resilient, sustainable, and autonomous energy future.

Keywords: energy system optimization; renewable energy; decentralization; self-consumption; renewable energy hub; carbon neutrality; energy independence

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1. Introduction

1.1. Context

The urgency to meet the CO_2-reduction goals set by the Paris Accord is driving a global energy transition towards renewable and decentralized systems. This shift demands re-evaluating energy system architecture, moving from centralized and continuous energy production to decentralized and intermittent energy-conversion sites. Such a transition entails the widespread adoption of decentralized renewable energy technologies, significantly altering traditional energy system designs by integrating numerous small-scale, distributed energy resources.

Energy systems vary nationally, reflecting geography, climate, demography, anthropology, and economic differences. These variations influence region-specific demands and renewable energy potentials, necessitating tailored approaches to energy system planning. Therefore, planning must account for regional disparities and strategically place and operate specific technologies. Integrating decentralized prosumers at a district scale with centralized energy systems becomes crucial in this context.

However, developing models that accurately capture the complexities of these varied energy systems presents a challenge for traditional modeling approaches, whether centralized or decentralized. The latter have led to divergent outcomes. As highlighted by Schnidrig et al. [1], centralized models often prioritize wind and PV technologies, utilizing a limited portion of the available solar potential. Conversely, decentralized models, like those proposed by Middelhauve et al. [2], advocate for a PV-dominant energy system that fully exploits solar potential at the district scale. This discrepancy stems from differences in self-consumption patterns, the valuation of energy flows, and the scale of production and consumption units. Accurately reflecting these factors in models is essential for a realistic representation of energy systems and the successful implementation of energy transition strategies.

Moreover, existing models frequently overlook the connection between microstructural elements and macroscopic strategies, hindering a complete understanding of the energy system's dynamics. To comprehend the impacts of various energy system actors, a thorough exploration of self-consumption, local production capabilities, and the role of centralized systems is necessary.

1.2. State of the Art

This section delves into the existing body of research surrounding the modeling and implementation of decentralized energy systems. An extensive review of similar efforts by scientists and companies reveals a spectrum of approaches to power system modeling, emphasizing the importance of adaptability and scalability in various territorial contexts, where a selection is compared in Table 1.

Energy system modeling has evolved from primarily centralized approaches to increasingly incorporating the specifics of diverse regions. The significance of regional differentiation was underscored starting in the 1990s with meteorological distinctions [3] and further advanced by the MERGE model, which considered the world in distinct regions for energy planning [4]. Advancements in computational capabilities have enabled models to achieve greater granularity, moving from the national and continental scales to the modeling of detailed cities and districts. This level of detail is crucial for accurately capturing regional demand and resource availability, as demonstrated by Stadler et al. [5], Clack et al. [6], and Jensen et al. [7]. In this context, the dynamics of interregional energy exchanges, especially concerning electricity and integrating diverse energy sources, are pivotal. Studies by Dujardin et al. [8] and Heide et al. [9], along with investigations into hydrogen storage [10], highlight the complexity of these energy flows, therefore showcasing the needs to model the system complexity with high temporal and spatial granularity.

Recent studies underline the pivotal role of local and regional strategies in the energy-planning process, demonstrating the effectiveness of municipal initiatives and bottom-up models in achieving sustainable energy transitions. Research highlights include the strategic importance of municipalities in regional energy planning, as illustrated by Brandoni et al. [11], who emphasize municipal contributions to energy savings and CO_2 reductions. Similarly, von Gunten et al. [12] address the challenges of implementing local energy plans, suggesting tools for enhancing policy effectiveness. Chomac et al. [13] present an analysis of the formal and legal background fostering green technology adoption among Polish households, emphasizing the significant interest in photovoltaics and heat pumps, which underscores the influence of building characteristics on renewable energy solution adoption. The necessity for systemic and strategic planning that bridges the gap between energy policy and urban development is further advocated by De Pascali et al. [14], pointing towards decentralized energy system solutions as a vector for local sustainability enhancement. Collectively, these studies reinforce the critical importance of integrating local insights and regional considerations into broader energy system modeling and planning efforts, highlighting the pathways toward more resilient and sustainable energy systems through localized initiatives and strategic planning.

The transition towards decentralized energy systems, characterized by enhanced resilience and efficiency, is gaining momentum. Research by Harb et al. [15] and Schütz et al. [16] supports the decentralization of heating systems and energy conversion units within microgrids, respectively. Middelhauve et al. [2] further discuss the optimization of community-level renewable energy hubs, identifying districts as critical entities in local energy systems. Schulz et al. [17] and Bashir et al. [18] demonstrate the potential for substantial energy cost savings and the maximization of self-consumption through optimized photovoltaic systems and the strategic use of storage and demand response solutions. Araujo et al. [19] investigate the integration of decentralized solar PV systems in urban settings, focusing on the challenges of energy surplus management within regulated markets. Their development of a smart management system illustrates the potential for enhancing investment returns and promoting community energy sharing, contributing to the sustainability and self-sufficiency of urban energy systems. Ullah et al.'s exploration of smart grid technologies through efficient load-scheduling schemes [20] further illustrates the potential for improved load management and CO_2 emission reductions. These contributions underscore the critical role of technological advancements and smart grid integration in optimizing on-site renewable energy generation, contributing to energy cost savings and system resilience, and reducing the carbon footprint.

Current models often struggle to integrate micro-level elements with macroscopic strategies effectively. Bastholm et al. [21] and Li et al. [22] emphasize the importance of considering local consumer behaviors and community dynamics within broader energy models. This integration is essential for successfully adopting renewable technologies and developing effective transition strategies that are socially and ethically acceptable. Adamik et al. [23] and Senkpiel et al. [24] explore the integration of organizational dynamics and social science insights into energy system models, advocating for a nuanced understanding of investment behavior, user behavior, and local acceptance within the transformation process. Rogov et al.'s [25] proposal of a multi-level urban resilience framework emphasizes the synchronicity of adaptive cycles across the micro, meso, and macro levels, advocating for a comprehensive approach to urban sustainability and resilience. These contributions reveal the importance of incorporating diverse perspectives and interdisciplinary insights into energy system planning and development. By bridging the gap between detailed operational dynamics and broader strategic objectives, these studies offer valuable pathways toward achieving resilient, sustainable, and technologically advanced energy systems aligned with local and global sustainability goals.

A selection of national and international energy system models integrating subsystems is represented in Table 1, summarizing the specificities of the current energy system models. This paper aims to create a decomposition model that integrates uncertainty assessment by optimizing a national energy system model with sub-regions at a district scale and applies it to the Swiss case study. It, furthermore, integrates the most recent research on regionalized energy models for the case study of Switzerland. Despite significant advancements in energy system modeling, a clear gap persists in comprehensively understanding the interplay between decentralized and centralized systems, particularly in national contexts with varying geographic and demographic factors. This study aims to bridge this gap by proposing a model that synergizes decentralized energy production with national energy-planning objectives.

Table 1. Selection of national and international energy system model selection of subsystem integration overview. ✗ aspect not considered, ✓ aspect considered.

Author	Decomposition	Sub-Region	Main Region	Case Study	Uncertainty
Alcamo et al. [3]	✗	22,500 km^2	Continent	USA	✗
Manne et al. [4]	✗	1/4 world	World	Multiple	✗
IAEA [26]	✗	Districts	Countries	Multiple	✗
Heide et al. [9]	✗	2000 km^2	Continent	America	✗
Capros et al. [27]	✗	Country	Continent	Multiple	✗
Havlìk et al. [28]	✗	Country	Continent	USA	✗
Leuthold et al. [29]	✗	Countries	Continent	Multiple	✗
Rasmussen et al. [10]	✗	2500 km^2	Continent	Multiple	✗
Becker et al. [30]	✗	1600 km^2	Country	NL	✗
Jacobson et al. [31]	✗	States	Country	Multiple	✓
Schlecht and Weigt [32]	✗	Cantons	Country	EU	✗
Morvaj et al. [33]	✗	Houses	Districts	Multiple	✗
Clack et al. [6]	✗	States	Country	✗	✗
Bartlett et al. [34]	✗	Nodes	Country	Multiple	✗
Abrell et al. [35]	✗	Cantons	Country	Multiple	✓
Gholazideh et al. [36]	✗	Nodes	km^2	Multiple	✗
Antenucci et al. [37]	✗	States	Continent	Multiple	✗
Siala et al. [38]	✗	Countries	Continent	Multiple	✗
Tröndle et al. [39]	✗	Communes	Continent	EU	✓
Ruiz et al. [40]	✗	Countries	Continent	Multiple	✗
Bachner et al. [41]	✗	Countries	Continent	Multiple	✓
Siala et al. [42]	✗	Sub-countries	Continent	USA	✗
Pang et al. [43]	✗	km^2	Country	USA	✗
Dias et al. [44]	✗	Districts	City	PT	✗
Bernath et al. [45]	✗	Countries	Continent	✗	✓
Stadler & Maréchal [46]	✗	Communes	Country	✗	✗
Jensen et al. [7]	✗	Sub-countries	Countries	CH	✓
Dujardin et al. [8]	✗	1.7 km^2	Country	CH	✗
Gu et al. [47]	✗	m^2	km^2	USA	✗
Witek and Uilhoorn [48]	✗	Nodes	Country	CH	✓
Holweger et al. [49]	✗	Buildings	Districts	✗	✗
Wakui et al. [50]	✓	Nodes	Grid	✗	✗
Middelhauve et al. [2]	✓	Buildings	Districts	EU	✗

1.3. Resulting Gap and Contribution

Despite advancements in energy system modeling towards decentralized systems, critical research gaps impede the optimal integration of such systems within a comprehensive national framework. This section outlines these gaps and delineates the contributions of the current study to bridge them.

1.3.1. Computational Complexity of Integrating Local Systems

Existing models struggle with the computational burden of accurately representing each local energy system's unique characteristics within a national framework. **Objective:** Develop a methodology to efficiently integrate decentralized prosumers into the national energy system, overcoming computational challenges.

1.3.2. Integration of Micro- and Macro-System Dynamics

There is a lack of frameworks that effectively harmonize local district (micro) energy system elements with the broader (macro) national energy system dynamics. **Objective:** Create a comprehensive regional framework that bridges local district energy systems with national energy strategies, addressing the intermittency of renewable energy sources.

1.3.3. Optimal Balance of Centralization and Decentralization

The energy-modeling field lacks insight into the optimal degree of centralization versus decentralization for achieving thermo-economic efficiency in energy systems. **Objective:**

Explore the impacts of varying degrees of system centralization and decentralization on efficiency, resilience, and cost-effectiveness.

1.3.4. Role of Self-Consumption

The interplay between increased self-consumption rates and energy demand reduction at a local level within the national system is underexplored. **Objective:** Investigate how enhanced self-consumption affects energy system configurations and resilience.

1.3.5. Contribution

This study addresses a crucial methodological gap in energy system modeling and strategic planning by integrating a detailed district-level model in a broad national energy framework, offering a novel perspective on creating resilient, efficient, and sustainable energy systems. Central to our hypothesis is the inadequacy of current models in integrating self-consumption adequately and their failure to account for local constraints, leading to an overemphasis on global optima. By delving into the trade-offs and optimal strategies for transitioning to decentralized energy systems, particularly through the integration of PV systems and self-consumption, this paper lays a foundational framework for future research to optimize energy planning strategies within a national context, thereby addressing a pivotal research gap. The methodology culminates in a scalable and adaptable model that not only transcends traditional energy-planning paradigms, but also charts a path toward a carbon-neutral and independent Swiss energy system.

2. Methods

The methodology adopts a novel approach to integrating decentralized prosumers within the national energy system, aiming to address the identified research gap effectively. Typifying the Swiss building stock into representative districts, optimizing renewable energy hub configurations within each district, and employing a soft-linking methodology to integrate these configurations into a macroscopic energy system framework enable a detailed examination of the trade-offs and benefits of decentralized energy production on a national scale (Figure 1).

Switzerland serves as an exemplary case study for decentralized energy system integration, embodying both the technological and strategic challenges of transitioning towards a more renewable and diverse energy matrix. Its unique energy landscape, marked by a robust foundation in hydroelectric and nuclear power [51,52], is evolving to incorporate renewable sources like solar, wind, small hydropower, and geothermal heating. This demonstrates the substantial potential for energy independence and emphasizes the decentralized nature of the emerging technologies. Positioned strategically at the heart of Europe, Switzerland plays a pivotal role, acting as a conduit between various European energy systems, thereby balancing its own needs with regional energy stability [53]. Its interconnectedness through electricity imports and exports, vital for addressing seasonal energy variations, underscores the broader significance of its transition efforts. The challenges, such as integrating intermittent renewable sources into the grid and reducing dependency on fossil fuel imports, underscore the necessity for innovative approaches. These complexities make Switzerland an invaluable model for the exploration of integrating decentralized energy sources into existing grids, offering insights into the broader implications of such transitions for energy security, economic stability, and environmental sustainability.

2.1. The Prosumer within the Energy System

The methodology delineates the approach to analyzing energy planning strategies by representing decentralized energy producers (*prosumers*$^{\omega}$) within the larger national energy system$^{\Omega}$. This representation is aimed at strategically evaluating decentralized energy contributions to national energy goals rather than enhancing the models' internal structures, as is visible in Figure 1. This figure illustrates the conceptual model used in our study, showcasing the integration of decentralized prosumers within the national energy system. The methodology allows linking regional and national optima, highlighting the interconnections and potential for energy exchange between different energy stakeholders. This visual representation aids in understanding the complex dynamics at play in decentralized energy systems. Prosumers serve as energy consumers and producers, notably via decentralized PV systems. They are conceptualized as energy hubs within typical districts representative of the whole of Switzerland, each defined by buildings linked within an low voltage (LV) grid to the same LV/Medium Voltage (MV) transformer. This process involves three key phases: (1) characterizing the Swiss building stock and distinguishing districts based on district-specific characteristics; (2) using this characterization to identify and optimize renewable energy hub configurations within each typical district, focusing on assessing decentralized energy production capabilities; (3) integrating these optimized configurations into the macroscopic energy system (EnergyScope (ES)$^{\Omega}$) framework and applying them as representative models for broader system analysis and planning.

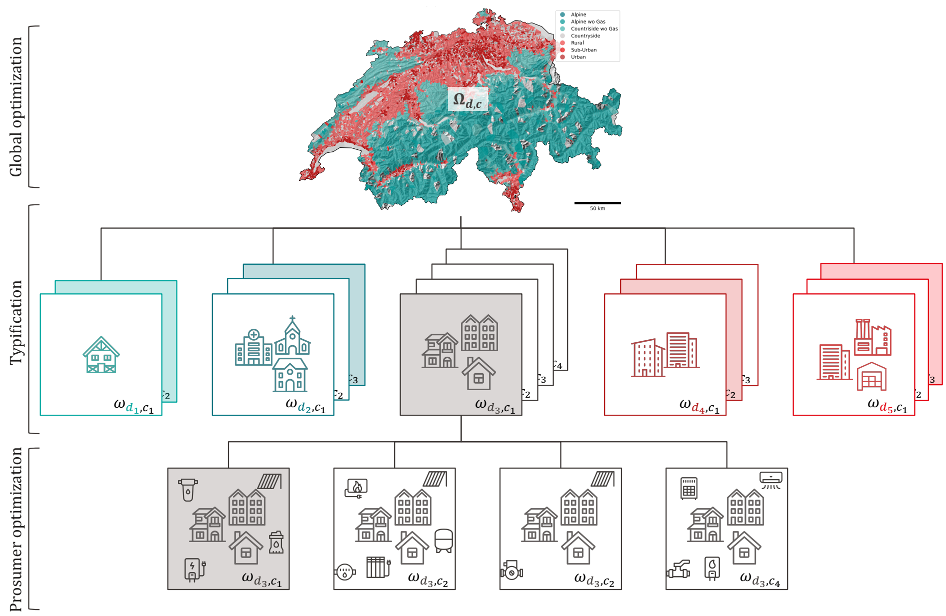


Figure 1. Graphical representation of the methodology followed integrating decentralized prosumers ω into the national energy system ES Ω. The Swiss building stock is typified in typical districts d according to their urban and meteorological characteristics. Within each district d, typical local energy system configurations c are calculated using the Renewable Energy Hub Optimizer (REHO) model. These configurations serve as typologies, which are then regionalized to inform the national energy system, ensuring that local specifics inform broader energy planning and decision-making processes. The macroscopic model receives these local decisions as input parameters and selects an optimal combination $\mathbf{\Phi}_{d,c}$ of configuration c in each district d.

2.1.1. Swiss Building Stock Typification

A strategic approach is adopted to model local energy systems throughout Switzerland with limited computational requirements. The first step is the typification of the Swiss building stock into representative districts. Then, renewable energy hub configurations are obtained within the typical districts, thus effectively reducing the problem's complexity (typification step in Figure 1). This approach allows for a comprehensive, yet computationally efficient integration of decentralized prosumers into the macroscopic energy system framework. In this sense, clustering methods are applied to find a trade-off between computational complexity and information loss.

The methodology begins with characterizing each building and district in the country as outlined by Girardin et al. [54]. This process classifies the building stock based on specific characteristics, including construction year, energy consumption, and architectural features. Districts are categorized based on a comprehensive set of characteristics and divided into three main categories: climate conditions, energy infrastructure availability, and building typology. Climate conditions include factors such as average temperature, solar irradiation, and precipitation, reflecting the environmental context of each district. Energy infrastructure encompasses the existing setup of electric and natural gas grids, highlighting the capacity and distribution network relevant to energy supply and consumption. Building typology refers to buildings' architectural features, construction year, and energy consumption patterns, offering insights into the built environment's diversity and energy needs. Each category is detailed below to provide a more nuanced understanding of how districts are distinguished based on their unique urban and meteorological characteristics.

Once the buildings and districts are typified, a clustering algorithm is applied to the dataset. The specificities considered are the heated surfaces, the district's share of residential, industrial, and service buildings, the annual average temperature and solar irradiation, and the density of electric and natural gas grids. Each feature is evaluated at the district scale to follow the Swiss energy system down to the low-voltage level, thus forming the decentralized energy hubs [1,55]. The k-medoid algorithm is applied and runs over 50 iterations between 6 and 10 clusters as advised by Terrier et al. [56]. A qualitative analysis selects the optimal district typification from the clustering results. The aim is to contextualize the results of the Swiss building stock and ensure a suitable representation of urban, suburban, and rural areas incorporating the different climatic zones. Based on this analysis, seven typical districts are identified to represent the regionalized energy systems in Switzerland. Figure 2 shows their distribution throughout the country. The typical districts differentiate urban centers from rural areas. Moreover, alpine and countryside regions are subdivided into two categories based on the district's connection to a gas infrastructure. More details on the clustering algorithm are provided here [56].

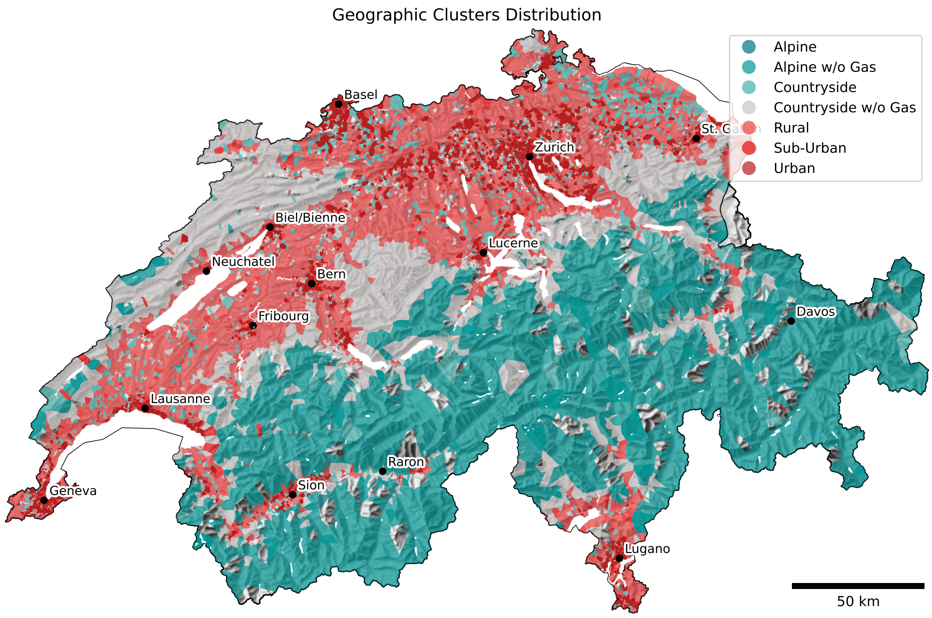


Figure 2. Illustration of the district cluster attribution.

2.1.2. Characterization and Optimization of Renewable Energy Hubs Configurations within Each District

The development of the energy system model introduces a novel structure that integrates decentralized renewable energy hubs with the overarching centralized national energy system. This approach involves identifying optimal configurations for decentralized system elements within each typified Swiss district, exploring their interactions with one another, and centralized energy supply and storage infrastructures (prosumer optimization step Figure 1). The model optimizes energy exchanges between typical districts and central installations, enabling comprehensive analysis of micro- and macro-level energy flows within the national framework. This integration allows for assessing localized energy production and consumption's potential to complement and enhance the national energy system's efficiency and resilience. Additionally, it assesses the effective integration of these decentralized hubs with central energy supply and storage infrastructures, optimizing the overall energy system for efficiency and sustainability. This approach marks a significant advancement in energy system modeling, moving beyond traditional centralized-only frameworks to include detailed representations of decentralized energy potentials and their systemic implications. The configuration that mixes typical districts with central installations is pivotal, enabling a holistic view of the national energy landscape that incorporates both granular, localized insights and broad, systemic perspectives.

The integration of decentralized renewable energy hubs in centralized national energy systems is complemented by a systematic approach that reflects local decision making while managing computational costs. This method involves a precise application of a two-stage Global Sensitivity Analysis (GSA), as outlined by Chuat et al. (2024) [57], tailored to efficiently navigate the solution space of the district energy system model. Initially, the GSA method identifies the most influential parameters to streamline the computational process. This identification is facilitated by the Morris method [58], enabling a qualitative assessment of parameter sensitivity with minimal model evaluations. Subsequent exploration of the model's solution space involves adjusting these key parameters, employing Sobol's sequence [59] to effectively sample their variation, thereby generating diverse energy system configurations. A critical step in this process is the application of a clustering algorithm to simplify the solution space. This simplification allows for the economic and technical dimensions—captured through capital expenditure (CAPEX), operational expenditure (OPEX), the installed capacity of energy conversion technologies, and peak energy exchanges—to be efficiently analyzed. A density-based algorithm, specifically density-based spatial clustering of applications with noise (DBSCAN), is necessitated by the district energy system model's Mixed-Integer Linear Programming (MILP) nature, facilitating the aggregation of solution performance indicators to represent typical configurations. Moreover, the proportion of photovoltaic production consumed within the district highlights self-consumption, which is crucial for understanding local energy dynamics.

Associating each Swiss district with one of the seven typical districts (Figure 2) is a direct application of this method, where the GSA serves not merely as a conceptual framework, but as a concrete analytical tool. This distinction underscores the GSA's role in systematically evaluating and optimizing the interactions between localized energy hubs and the centralized energy system. Through this analytical process, the model captures the essence of district-specific energy dynamics and aligns these local configurations with the broader national energy strategy, ensuring a comprehensive and nuanced understanding of the energy landscape.

2.1.3. Soft-Linking of Macroscopic and Microscopic Modeling

Decentralized prosumers are integrated into the MILP global energy system framework *EnergyScope* based on the typical renewable energy hub configurations identified (Figure 1). In the following, the global decision-making scale is represented by Ω and the local scale by ω. The *EnergyScope* model has been developed by Moret et al. [60] and continuously improved by Li et al. [61] and Schnidrig et al. [1].

Soft-Linking

Each decentralized energy system configuration ω is represented by an installation of energy units f^{ω} and associated energy flows with the grid $f_t^{\omega\pm}$ for each period t and configuration c of each district d. The linking constraints between the two scales of decision making are the resource balances for each energy carrier l (Equation (1)) and the capacity constraints of the grids (Equation (2)). A linear combination of the configurations ω is performed to model the integration of prosumers. The decision variable $\mathbf{\Phi}$ is the weight attributed to each configuration. To summarize, $\mathbf{\Phi}$ decides the configurations ω to activate, therefore inducing local investments and associated energy flows $\boldsymbol{F_t^{\omega\pm}}$ with the global system. This variable defines the optimal share of prosumers in the Ω system (Equation (4)).

$$\boldsymbol{F_t^{\omega\pm}}(d,l,t) = \sum_{c \in \mathcal{CONF}} f_t^{\omega\pm}(c,d,l,t) \cdot \boldsymbol{\Phi}(c,d). \tag{1}$$

Optimization Problem

The optimization problem can be formulated as a total cost minimization, optimizing the decision variables of installed size of units $\boldsymbol{F}$, their operation $\boldsymbol{F_t}$ and $\boldsymbol{\Phi}$ (Equation (3), and the global optimization step Figure 1). The optimization is subject to the mass and energy balance (Equation (5)), where the end uses ($\boldsymbol{EU}$) are satisfied by the operation of technologies and resources ($\boldsymbol{F_t}$), considering layer conversion efficiency η, storage ($\boldsymbol{F_t^{\pm}}$), and district exchanges ($\boldsymbol{F_t^{\omega\pm}}$).

Economic Objective

Similar to energy flows and installed units' size, the total cost $\boldsymbol{C_{tot}}$ is decomposed into the centralized $\boldsymbol{C_{tot}^{\Omega}}$ and the decentralized $\boldsymbol{C_{tot}^{\omega}}$ system total cost (Equation (6)). While the centralized system cost has been taken from Schnidrig et al. [1] (Equation (7)), the decentralized one is composed of the sum of all district investment $\boldsymbol{C_{inv}^{\omega}}(d)$ and maintenance $\boldsymbol{C_{maint}^{\omega}}(d)$ costs, as defined by the decision variable $\boldsymbol{\Phi}(c,d)$ (Equation (8)).

Grid Strain

Based on the configuration selected $\boldsymbol{\Phi}(c,d)$, the local grid strain is calculated by observing the absolute peak power value for the selected configuration c in the decentralized model $f_t^{\omega\pm}$ (Equation (2)). This strain is translated into a potential grid reinforcement need, which is linked to the grid g and the layer l through the difference of the peak power demand and the existing grid infrastructure capacity (Equation (7)).

$$\boldsymbol{F^{\omega}}(d,g(l)) \geq \sum_c (|f_t^{\omega\pm}(c,d,l,t)| \cdot \boldsymbol{\Phi}(c,d)) \tag{2}$$
$$\forall \quad d \in \mathcal{DISTRICTS},\ g \in \mathcal{L}-\mathcal{GRIDS},\ l \in \mathcal{LV} \cup \mathcal{LP},\ t \in \mathcal{PERIODS}.$$

$$\min_{\boldsymbol{F},\boldsymbol{F_t},\boldsymbol{\Phi}} \ \boldsymbol{C_{tot}} \quad s.t. \tag{3}$$

$$\sum_c \boldsymbol{\Phi}(c,d) = 1, \quad 0 \leq \boldsymbol{\Phi}(c,d) \leq 1 \tag{4}$$

$$\begin{aligned} \boldsymbol{EU}(l,t) = &\sum_{tec} \boldsymbol{F_t}(tec,t) \cdot \eta(tec,l) - \boldsymbol{F_t}^{\boldsymbol{Loss}}(l,t) \\ &+ \sum_{sto} \boldsymbol{F_t^{+}}(sto,l,t) - \boldsymbol{F_t^{-}}(sto,l,t) \\ &+ \sum_{d} \boldsymbol{F_t^{\omega+}}(d,l,t) - \boldsymbol{F_t^{\omega-}}(d,l,t) \end{aligned} \tag{5}$$

$$\boldsymbol{C_{tot}} = \boldsymbol{C_{tot}^{\Omega}} + \boldsymbol{C_{tot}^{\omega}} \tag{6}$$

$$\begin{aligned}
\boldsymbol{C_{tot}^{\Omega}} &= \boldsymbol{C_{op}^{\Omega}} + \boldsymbol{C_{inv}^{\Omega}} + \boldsymbol{C_{maint}^{\Omega}} \\
\boldsymbol{C_{op}^{\Omega}} &= \sum_{res}\sum_{t} c_{op}(res,t)\cdot \boldsymbol{F_t}(res,t)\cdot t_{op}(t) \\
\boldsymbol{C_{inv}^{\Omega}} &= \sum_{tec} c_{inv}(tec)\cdot(\boldsymbol{F}(tec) - f_{\exists}^{\Omega}(tec^*)) \\
\boldsymbol{C_{maint}^{\Omega}} &= \sum_{tec} c_{maint}(tec)\cdot \boldsymbol{F}(tec)
\end{aligned} \tag{7}$$

$$\begin{aligned}
\boldsymbol{C_{tot}^{\omega}} &= \sum_{d}(\boldsymbol{C_{inv}^{\omega}}(d) + \boldsymbol{C_{maint}^{\omega}}(d)) \\
\boldsymbol{C_{inv}^{\omega}}(d) &= \sum_{tec}\sum_{c}(c_{inv}(tec)\cdot f^{\omega}(tec,c,d)\cdot \boldsymbol{\Phi}(c,d)) \\
\boldsymbol{C_{maint}^{\omega}}(d) &= \sum_{tec}\sum_{c}(c_{maint}(tec)\cdot f^{\omega}(tec,c,d)\cdot \boldsymbol{\Phi}(c,d))
\end{aligned} \tag{8}$$

$$\begin{aligned}
&\forall \quad c \in \mathcal{CONF},\, d \in \mathcal{DIS},\, t \in \mathcal{PERIODS}, \\
&tec \in \mathcal{TECHNOLOGIES},\, tec^* \in \mathcal{GRID}, \\
&res \in \mathcal{RESOURCES},\, sto \in \mathcal{STORAGE},\, l \in \mathcal{LAYERS}.
\end{aligned}$$

2.2. Uncertainty Analysis

To assess the uncertainties of integrating the prosumer into the energy system, the approach uses a quasi-Monte Carlo simulation, as per Morokoff's method [62], to evaluate the variations of the solution space of configurations, denoted as $\mathcal{F}$. This is represented by Equation (9), where the solution space $\langle\mathcal{F}\rangle$ is estimated by sampling N times and i corresponds to one specific sample:

$$\langle\mathcal{F}\rangle \approx \frac{1}{N}\sum_{i=1}^{N}\mathcal{F}(x_i). \tag{9}$$

Here, each solution $f^s(x_i)$ of the sample i is computed based on an economic optimization problem (Equations (10)–(13)). The values of x_i are selected using a Sobol sequence $s \in \mathcal{P}(x_i)$, following Sobol's method [59]. The MILP problem focuses on minimizing the objective function f_{obj}, which depends on decision variables $\boldsymbol{f^s}(x_i)$ and cost parameters $\boldsymbol{\pi}^s_{c(i)}$ (Equation (10)). The model adheres to the mass and energy balance constraints expressed in a matrix normal form $\boldsymbol{A}$, relevant to the unit characterization $\boldsymbol{\pi}_{u(i)}$ (Equation (11)). The parameters are distributed around their median values $\boldsymbol{\tilde{\pi}_{u,c}}$ as per distribution $d_{u,c}$ (Equations (12) and (13)).

$$\boldsymbol{f^s}(x_i):\ \min_{\boldsymbol{f^s}(x_i)} f_{obj}(\boldsymbol{f^s}(x_i), \boldsymbol{\pi}^s_{c(i)}) \tag{10}$$

$$s.t.\ \boldsymbol{A}_{\boldsymbol{\pi}_{u(i)}}\cdot \boldsymbol{f^s}(x_i) \geq \boldsymbol{b}_{\boldsymbol{\pi}^s_{u(i)}} \tag{11}$$

$$\boldsymbol{\pi}^s_{c(i)} = P(\boldsymbol{\tilde{\pi}_c}, d_c) \tag{12}$$

$$\boldsymbol{\pi}^s_{u(i)} = P(\boldsymbol{\tilde{\pi}_u}, d_u) \tag{13}$$

$$s \in \mathcal{P}(x_i),\ u \in \mathcal{UNITS},\ c \in \mathcal{COSTS}.$$

Methodological Synthesis for Optimized Energy System Integration

This research delineates an advanced methodological framework for the seamless integration of decentralized energy systems into a national context, focusing on optimizing PV systems and enhancing self-consumption. The study effectively navigates computational constraints by characterizing Swiss buildings into distinct districts and refining renewable energy hub configurations, facilitating a nuanced exploration of local versus national energy dynamics through innovative soft-linking of energy models. This approach permits a granular investigation into the synergies and trade-offs inherent in centralized versus decentralized energy planning, paving the way for discussions on efficiency, resilience, and sustainability impacts. The forthcoming Results Section aims to reveal the strategic benefits of decentralized PV integration, assess self-consumption's efficacy in energy system optimization, and contribute to the discourse on achieving a sustainable, carbon-neutral energy paradigm.

3. Results

The centralization versus decentralization of energy systems plays a pivotal role in the resilience and reliability of the Swiss energy infrastructure. The findings suggest that a decentralized approach, facilitated by widespread PV system integration, enhances energy safety by diversifying energy sources, reducing reliance on external energy imports, and improving the resilience of the energy grid against disruptions. The analysis revealed that a decentralized approach, emphasizing strategic underutilization of PV capacity in favor of local consumption, can lead to a notable reduction in system costs by 10% and decrease PV installation requirements to 35 GW, about 23% of the potential capacity. These findings offer crucial insights into optimizing energy-planning strategies that accommodate both local and national objectives.

The outcomes of a comparative analysis between a novel model incorporating prosumer dynamics at the district level and the traditional centralized model are presented. The analysis is structured into two distinct, yet interconnected segments. Initially, the focus is on evaluating the resilience of both models under uncertainty. Subsequently, the investigation shifts to a parametric analysis of PV penetration, contrasting the centralized and decentralized approaches to highlight the differential impacts on energy system dynamics, thereby elucidating their inherent strengths and limitations in managing uncertainties. This sets the stage for an in-depth exploration of self-consumption within the decentralized framework, examining its influence on system configuration, efficiency, and resilience.

3.1. The Swiss Building Stock

The typification of the Swiss building stock has revealed detailed insights into the country's urban and energy infrastructure characteristics, differentiating regions based on their energy demands and renewable potentials (Figure A1). While region-specific attributes influence the magnitude of local investments in energy units, the most influential parameters resulting from the Morris method are the energy carrier costs (supply and demand), closely followed by the investment costs of PV. These parameters are conditioning the selection of energy units and are, therefore, used to explore the solution space of each typical district energy system using Sobol sampling. Figure 3 illustrates the distribution of the investments for each technology within each district. Substantial differences exist throughout districts, highlighting the need to consider region-specific solutions.

The negative correlation between methane (CH_4) boilers and direct electric heaters or heat pumps highlights the polarity of the energy system regarding energy resource consumption. Cogeneration units and boilers correlate positively, while heat pumps are usually combined with water tanks and PV panels. The PV capacity distribution shows two peaks for most districts. It demonstrates two different energy strategies: improving the self-sufficiency of the districts or increasing the profit by reselling electricity to the grid. While the former strategy involves lower investment in PV panels, the latter encourages prosumers to shift from self-sufficient microgrids to renewable electricity producers for the grid. These local strategies have various consequences for the global energy system. Therefore, it highlights the need to identify a complete solution space at the built environment level to describe prosumers' decision-making trends fully.

While Sobol sampling allows reaching a high level of solution space screening, it also identifies many solutions. The typical configurations are detailed in Appendix C and are clustered based on the installed capacity of the energy-conversion units, network exchanges, and economic indicators. The configurations primarily differentiate themselves by the type of energy carrier they are relying on, either electricity or CH_4. Then, the distinction comes from the level of PV penetration. The latter depends on the resale cost of electricity and the investment cost of PV panels, both parameters used in the Sobol sampling. While the investment portfolios of some configurations are similar, they are differentiated by their operational strategy, thus their annual energy exchanges with the grids. The latter highlights the diversity of prosumers, ranging from a high dependence on grid imports to the ones reducing their total expenditure (TOTEX) by selling excess PV electricity to the community.

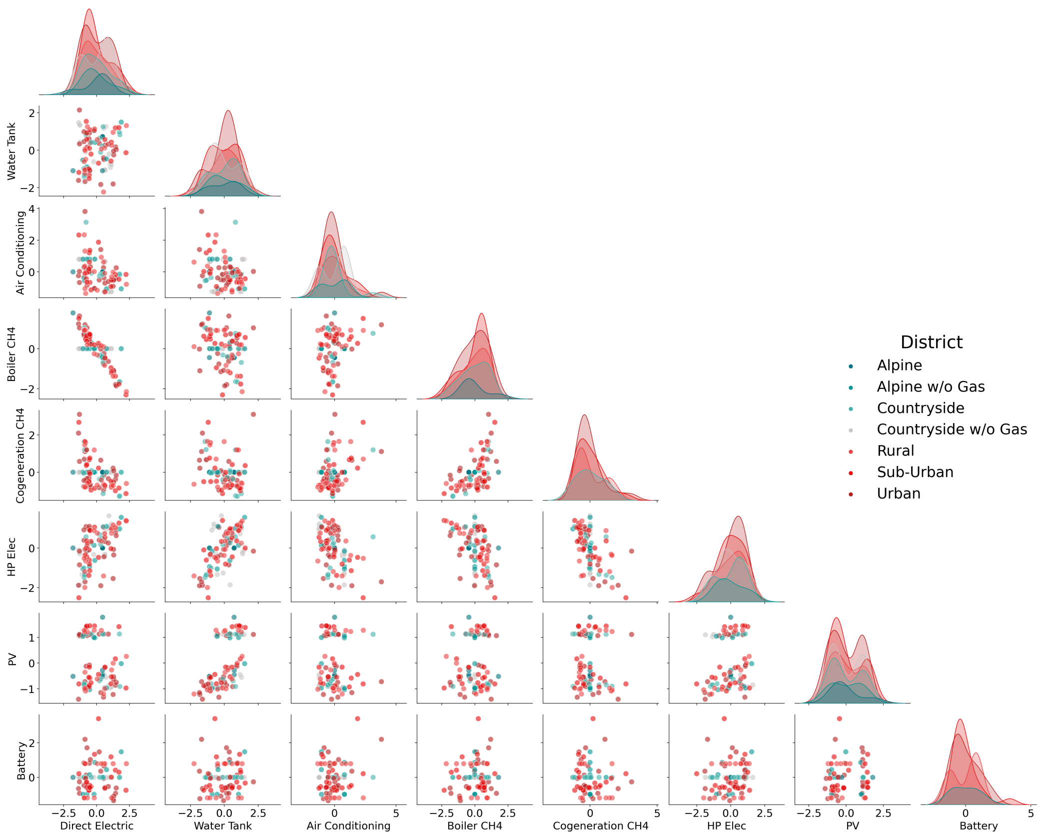
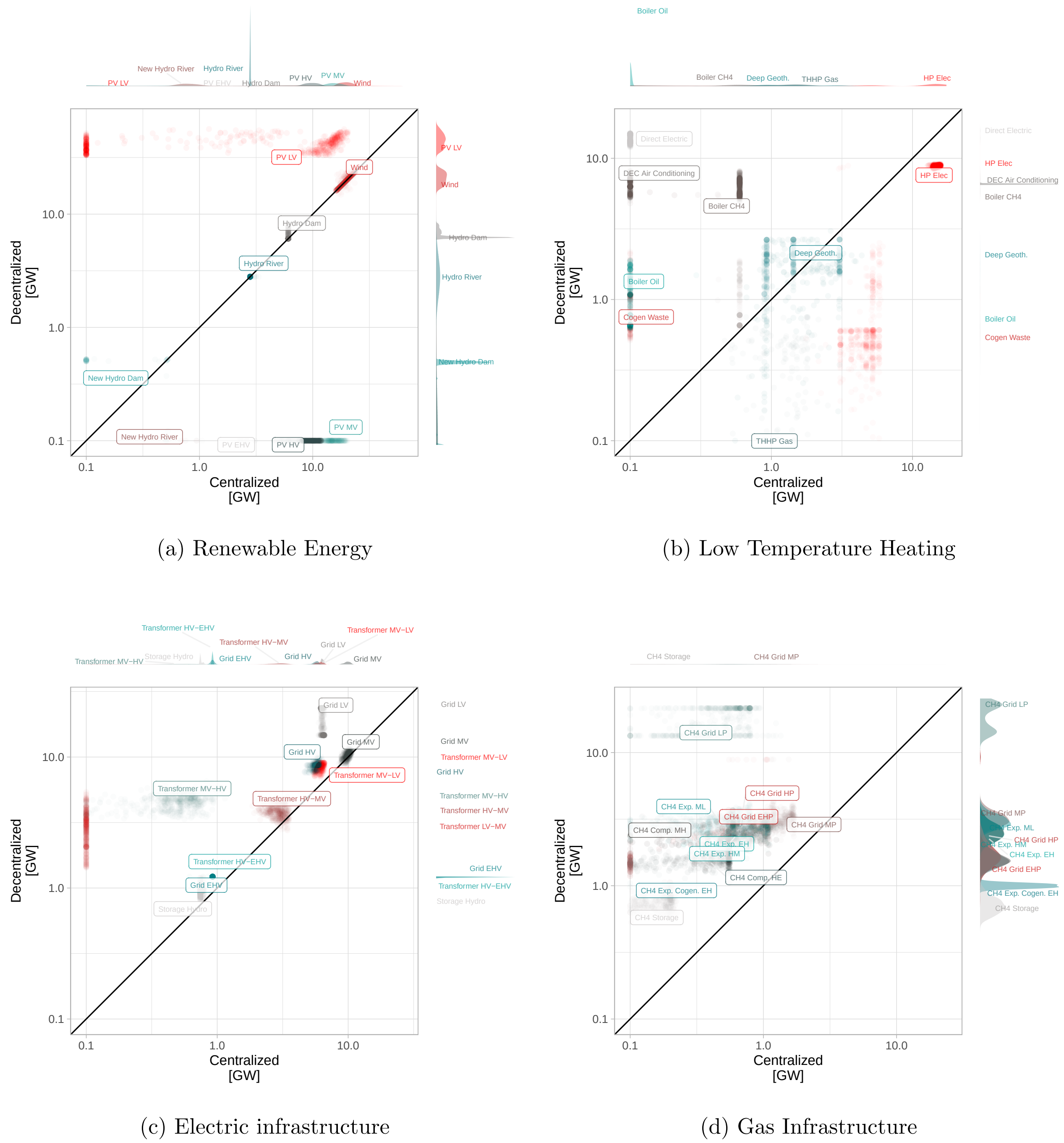


Figure 3. Parity plot of the investment cost of the district technologies for each identified configuration across all districts. The investment costs of each technology are normalized, assuming a Gaussian distribution for each district as the scale of the districts ranges from 1 to 244 buildings.

3.2. Dynamics of Uncertainty: A Model Comparison

This section delineates the comparative performance of the traditional EnergyScope model versus a regionalized adaptation under identical case study conditions: identifying economically optimal configurations for a neutral and independent Swiss energy system in 2050, as determined by a centralized decision-maker perspective. While both models simulate centralized decision-making processes, the regionalized version introduces an evaluation of local and decentralized optima, allowing for the selection of specific configurations tailored to prosumer characteristics. This adaptation potentially deviates from the system's absolute optimum, but provides insights into customized solutions reflective of prosumer dynamics.

Utilizing Sobol's method [59], the adaptability of both models is critically assessed amid variations in energy demand, supply uncertainties, and technological shifts. The objective is to determine each model's robustness in managing diverse energy scenarios. Figure 4 offers a parity plot comparison of the centralized and decentralized model solutions, employing the same Sobol sequence for uncertainty analysis. The plot annotates each installed unit size's frequency, showcasing the distribution density for both models.



(a) Renewable Energy (b) Low Temperature Heating

(c) Electric infrastructure (d) Gas Infrastructure

Figure 4. Parity plot and corresponding density distribution of energy technologies' capacities, contrasting centralized$^{\Omega}$ (X-axis) and decentralized$^{\omega}$ (Y-axis) methods based on 5000 model evaluations. The density distributions along the axes represent the frequency of capacities for each technology. The case study represents the economic optimization of a neutral (no net emission) and independent (no import) Swiss energy system in 2050 for a population of 10 Million. To represent the zero values in the logarithmic scale, the installations at 0 GW have been moved to 0.1 GW.

3.2.1. Renewable Energy

The analysis of renewable energy technology capacities, as depicted in Figure 4a, reveals consistent maximization of wind energy potential at 20 GW across both models. The regionalized model distinguishes itself by incorporating an additional 0.3 GW into new hydro dam plants, enhancing hydro storage for production and consumption balance in 93% of scenarios. This model also projects 30 GW of decentralized PV installations. In contrast, the traditional model maintains a fixed combination of wind and PV systems, with variability in PV technology deployment influenced by economic and other uncertainties.

3.2.2. Heating Technologies

The preference for heat pump utilization in low-temperature heating scenarios is evident in both models (Figure 4b). Divergences are noted in ancillary technology preferences: the regionalized model favors direct electric heating technologies with a capacity of 15 GW, ensuring demand satisfaction during extreme weather periods as per the REHO framework. In comparison, the traditional model primarily utilizes deep geothermal plants in the residential sector, indicating differing approaches to heating technology integration.

3.2.3. Infrastructure and Techno-Economic Analysis

In the decentralized model, the electric grid infrastructure's resilience (Figure 4c) shows minimal reinforcement required. This suggests a slightly higher burden on the electric grid than the centralized model. The decentralized model necessitates the installation of LV–MV and MV–High Voltage (HV) transformers (ranging from 1 GW to 10 GW), less prominent in the centralized model. This difference is attributed to the decentralized model's overproduction of electricity in summer and the subsequent need for seasonal storage.

The gas infrastructure (Figure 4d) exhibits more significant variability in the decentralized model, reflecting the fluctuating methane demand in gas boilers without requiring substantial infrastructure reinforcement. Both models impose similar strains on energy grid infrastructures, with their primary role being to store seasonal disparities between production and consumption, prioritizing electric and then methane storage.

3.2.4. Inherent Strengths and Limitations in Managing Uncertainties

Figure 4 illustrates the strengths and limitations of the models in managing uncertainty through the distribution of installed sizes across different energy sectors. The decentralized model demonstrated a notable consistency in its configurations, with less variation between different setups than the centralized one. This is evidenced by a narrower distribution range in the installed capacities of renewable energy technologies, where, for instance, wind energy consistently reached capacities close to 20 GW in 85% of the scenarios. Similarly, the adoption of direct electric heating technologies in addition to heat pumps taking the base load in the decentralized model maintained a steady capacity of around 15 GW in 90% of the cases, underscoring its reliability in extreme weather conditions.

In contrast, the centralized model exhibited more significant variability in its configurations, as seen in the broader distributions of technology capacities. This model's approach to managing uncertainties was reflected in the fluctuating allocations to primary energy consumption, with wind energy capacities varying between 18 GW and 22 GW in 98% of the scenarios, and deep geothermal plants in the residential sector showing a capacity range of 0.8 to 3 GW in 70% of the modeled situations. These variations indicate a more dynamic response to changing market conditions and efficiency parameters, as per the Sobol screening.

The decentralized model's strength lies in its ability to provide stable and predictable outputs, making it particularly effective when consistency and reliability are paramount. However, this comes at the cost of potential overproduction in certain areas, such as summer electricity generation. Conversely, the centralized model's flexibility allows for a more responsive adaptation to varying conditions, though it may lead to less predictability in energy outputs. This analysis underscores the need for a balanced approach in energy system planning, considering both the predictability of decentralized solutions and the adaptability of centralized systems in the face of uncertainties.

3.3. PV Integration Strategies: Centralized and Decentralized Models Analyzed

PV technologies compete with themselves, thus directly influencing the remaining energy system. This section focuses on the priority of the PV technologies and their effect on the energy system, parametrizing the penetration of PV installations from the currently deployed size to its maximum potential. By altering the penetration of PV, the analysis seeks to identify the operational, economic, and efficiency impacts.

3.3.1. Energy Trade-Offs

The parametric analysis of PV integration strategies (Figure 5) highlights substantial trade-offs in energy system dynamics. From 0 to 25 GW of PV deployment, biomass plays a critical role and is used until the onset of 25 GW of PV, where it gradually phases out. During this phase, LV PV linearly increases from the existing 4 to 21 GW. Wind energy, initially utilized to its 20 GW maximum, linearly decreases to 0 GW as PV installations soar to 125 GW, with the order of appearance of HV, MV, and finally, Extra-High Voltage (EHV) PV after each reaches its maximum, indicating a shift from diverse renewable sources to predominantly solar. This transition is not without economic implications as the energy system's total cost inflates by 20% due to reliance on biomass and geothermal energy with higher service costs.

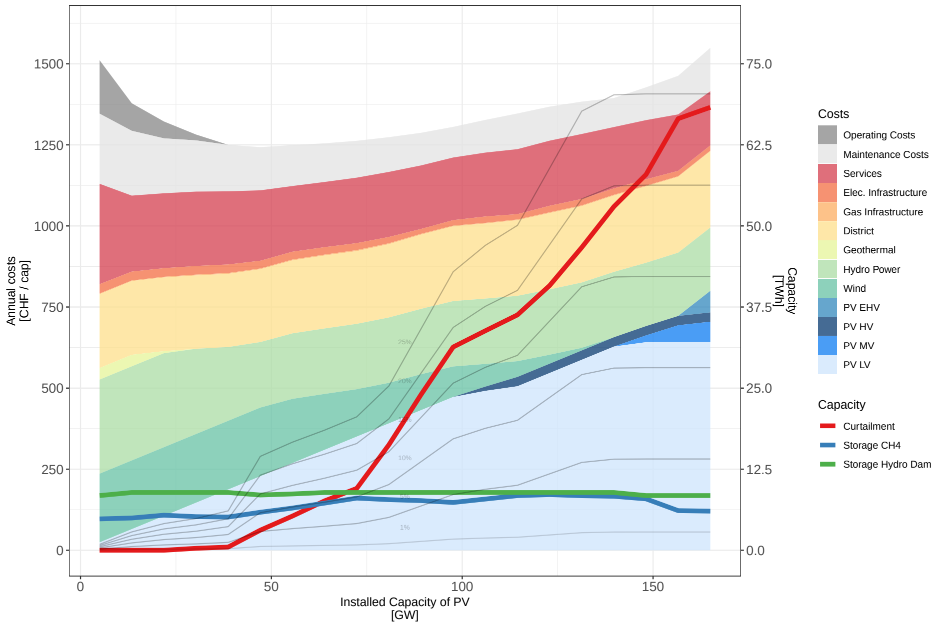
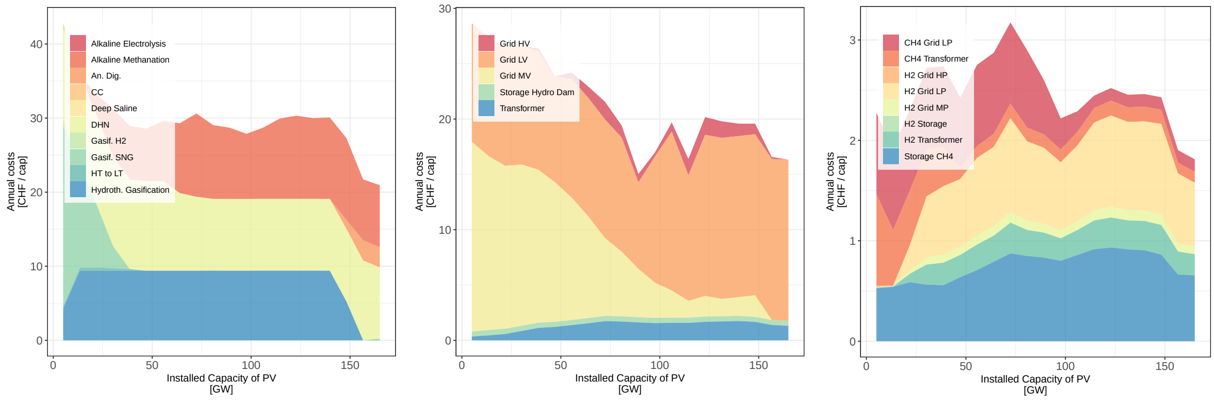


Figure 5. Evolution of energy system costs' composition and storage capacities of the Swiss energy system according to PV installation parametrization. The transparent lines represent the annual PV LV production fractions, allowing us to compare them with the curtailment depending on the installed PV capacity. The case study represents the economic optimization of a neutral (no net emission) and independent (no import) Swiss energy system in 2050 for a population of 10 Million.

The comparative analysis emphasizes the necessity of a mixed approach, combining centralized and decentralized resources for an ideal system. Centralization benefits from utilizing other resources, such as biomass, which is transformed at centralized units for a traditional distribution system, thus reducing the system's efficiency and increasing costs.

3.3.2. Infrastructure

Focusing on the electric (Figure 6b) and gas (Figure 6c) grids, the study reveals significant shifts in infrastructure needs with varying PV levels. At lower PV installations (0 GW–25 GW), the primary energy shortfall is counterbalanced by extensive gasification of biomass and maximum wind utilization. This requires hefty investments in MV electric grids for wind electricity distribution infrastructure and methane infrastructure such as compressors and storage technologies for biogenic gas. However, as PV reaches optimal levels (25 GW–35 GW), electricity becomes the primary energy carrier, reducing the need for gas and, thus, minimizing investments in associated infrastructure.



(a) System Infrastructure (b) Electric grid infrastructure (c) Gas gid infrastructure

Figure 6. Evolution of the sectors' cost composition of the Swiss energy system according to the parametrization of PV installations.

As PV share increases further, the electric grid's configuration evolves. The reduction in wind use diminishes the need for MV grid reinforcement, but increases the reinforcement needed for the LV grid due to decentralized PV. Excess electricity is then stored via the Low Pressure (LP) grid thanks to electrolysis and methanation, necessitating methane storage infrastructure of up to 9.1 TWh, doubling the existing seasonal storage capacity. When wind is phased out completely, the electricity produced in winter suffices, leading to a significant summer curtailment and consequent reduction in the need for gas infrastructure.

3.3.3. Overproduction

Curtailment emerges as a significant issue at higher levels of PV deployment, primarily due to the cost and limitations of transforming and storing excess electricity. Figure 5 represents the curtailment as the blue line, complemented by iso-curves, corresponding to the share of the LV PV production. Curtailment remains negligible until 30 GW of installed PV, but begins escalating beyond this point, reaching 5% of total decentralized PV production at 50 GW. The reduction in wind usage exacerbates seasonal disparities between winter consumption and production, leading to 15% of LV PV electricity curtailment at 80 GW of installed capacity. As MV and HV PV installations are deployed, the situation intensifies, culminating in 23% of curtailment once the full PV potential is exploited. This indicates the growing challenge of managing overproduction as reliance on solar increases, stressing the importance of innovative storage solutions and more flexible grid management to accommodate the fluctuations inherent in a predominantly solar-based energy system.

3.4. Self-Consumption in Focus: Decentralized Model's Perspective

Following the decentralization analysis, self-consumption within the new model plays a pivotal role. This section examines how the integration of prosumer behavior, characterized by simultaneous energy production and consumption, influences the design and efficiency of decentralized energy systems. This analysis aims to reveal how self-consumption shapes the deployment and optimization of renewable energy resources, especially PV, within the decentralized model, offering insights into its impact on the system's overall sustainability, economic feasibility, and adaptability.

3.4.1. Less Is More

The relationship between self-consumption and PV deployment is intricately detailed in Figure 7. As the share of self-consumption increases, the total PV installations decrease, with the most profound reduction occurring at the economic optimum of 75% self-consumption. At this optimum, the decentralized PV investments are reduced to CHF 200/cap, significantly lower than the CHF 600/cap per year at maximum PV deployment.

While optimizing for the total cost at ideal self-consumption, this reduction in PV capacity aligns with a total systemic cost reduction of 10%. The systemic cost at this optimization point stands at CHF 1230/cap, compared to the CHF 1400/cap/year with full PV deployment. By prioritizing self-consumption, the system effectively halves the capacity of PV installations to 100 GW, indicating a strategic underutilization of PV to leverage the economic benefits of self-consumption. This nuanced approach exemplifies the complex balancing act between maximizing renewable energy capacity and achieving economic efficiency and sustainability in the decentralized energy system.

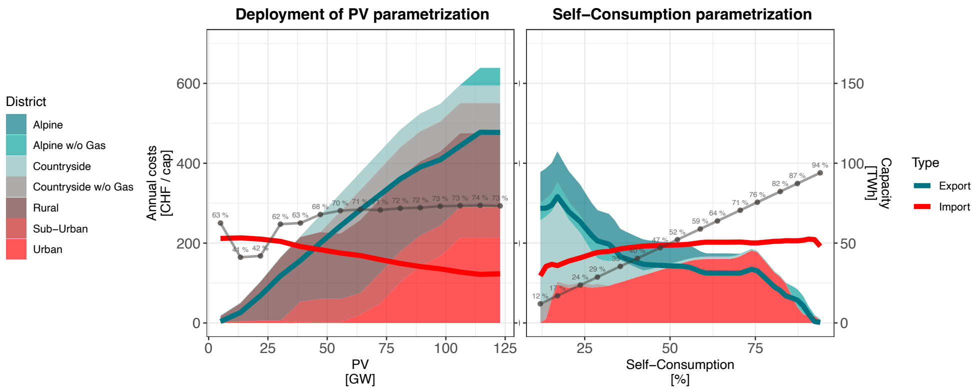


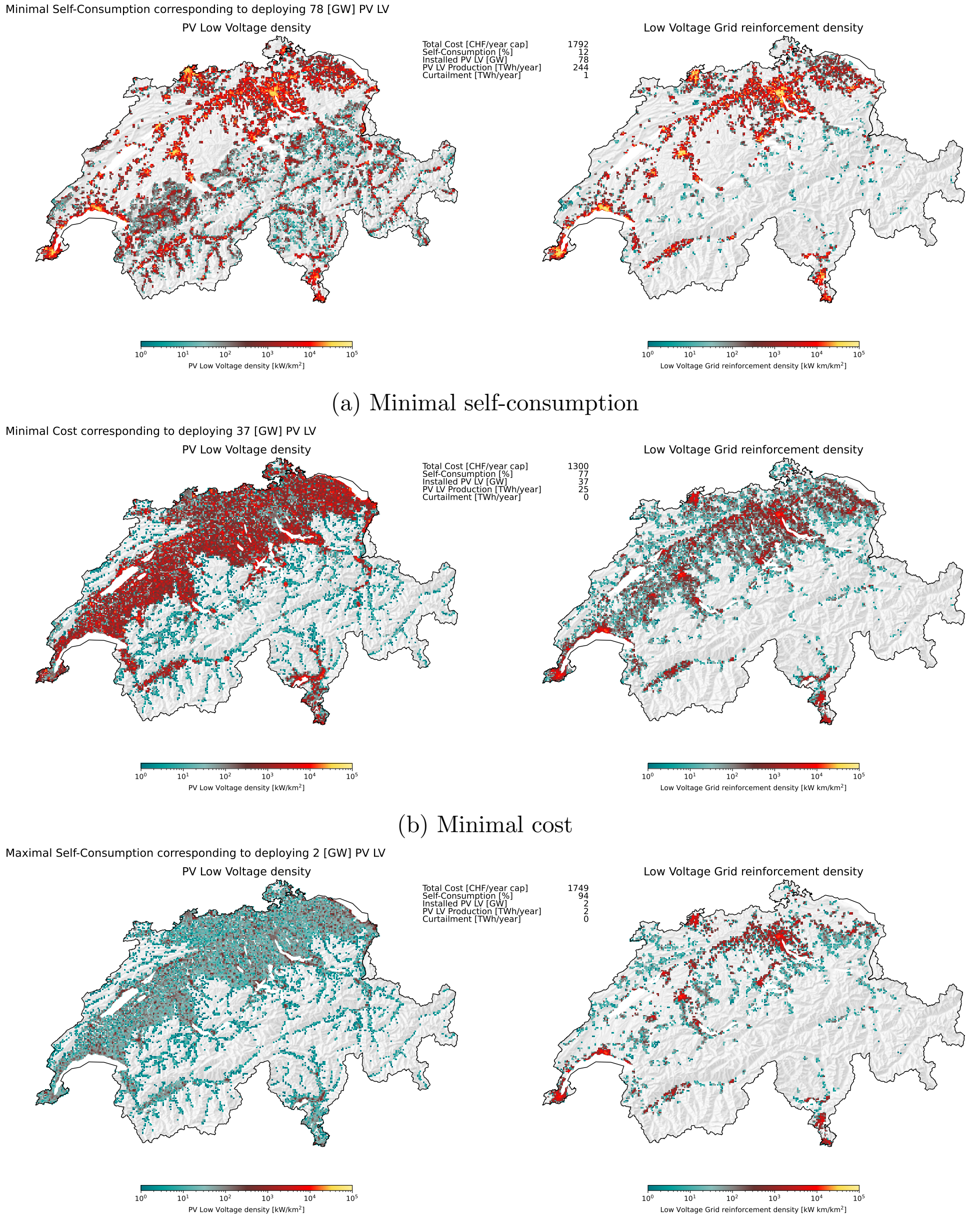
Figure 7. Evolution of PV LV district investments and district electricity import/export for the Swiss energy system according to PV installation and self-consumption parametrization. The points with the gray line represent the systemic decentralized PV self-consumption. The case study represents the economic optimization of a neutral (no net emission) and independent (no import) Swiss energy system in 2050 for a population of 10 Million.

3.4.2. Prioritizing Sunny Places Areas

The strategic placement of PV installations in sunny areas underscores the importance of optimizing geographic potentials for increased yield and efficiency. While self-consumption is prioritized in sunny, urban areas, the prioritization is maximized in the systemic approach to overinstall PV to export to less PV-optimal places. The decision to focus PV installations in sunny areas before considering energy exports is a testament to the delicate balance between maximizing local energy production and managing the broader energy network. Exporting energy, especially from high-yield sunny areas, involves additional considerations, particularly the cost of reinforcing the grid infrastructure. This reinforcement can amount to CHF 60/cap at high levels of self-consumption, accounting for 15% of the configuration with decentralized PV. While necessary for managing exports, this cost reflects the broader economic implications of geographic optimization. The system's reliance on sunny areas for self-consumption and subsequent energy export exemplifies the strategic interplay between local resource utilization and broader energy system integration.

3.4.3. Self-Sufficiency Is Key

The transition to increased self-sufficiency in the decentralized model is marked by a significant reduction in grid strain, as illustrated by Figure 8 (right column). This figure shows a clear shift from intensive grid reinforcement needs in centralized urban centers to more dispersed reinforcement across residential areas, particularly as self-consumption reaches higher percentages. At maximum self-consumption, the reinforcement is concentrated in semi-urban and urban centers, with higher demand for imported energy due to the electrification of the heating sector (Figure 8c). This reduces the overall reinforcement need to approximately 100 kW km/km^2. This strategic reduction in grid strain is achieved by integrating centralized storage options. Hydro dams are utilized to their total 8.9 TWh capacity, acting as a primary source of seasonal energy storage, while varying methane storage needs prompt additional infrastructure reinforcement, incurring annual costs between CHF 18 and 25/cap. The cost of accommodating alkaline methanation units, which convert excess electricity into methane, peaks at an additional annual CHF 20/cap. This multifaceted approach, leveraging both centralized storage options and infrastructural adaptations, underscores the pivotal role of self-sufficiency in reducing reliance on centralized systems, enhancing system efficiency, and promoting sustainable energy practices in the decentralized model.



(a) Minimal self-consumption

(b) Minimal cost

(c) Maximal self-consumption

Figure 8. Illustration of the Geographic Evolution of PV LV installation and LV grid reinforcement density according to self-consumption parametrization.

4. Discussion

The integration of decentralized energy models within a centralized framework presents a promising pathway toward achieving a resilient, sustainable, and cost-effective energy system. The study contributes to the field by providing a comprehensive framework for policy-making and strategic planning, encouraging further research into the climate impacts, technology synergy, and the integration of district heating solutions.

4.1. Relevance of a Regionalized Model for Modelers and Energy Planners

The development of a regionalized energy system model, as presented in this study, addresses the critical need for understanding the intricacies of transitioning towards renewable and decentralized systems. This model's significance lies in its capacity to capture the diverse and region-specific energy demand characteristics, renewable energy potential, and infrastructure capabilities. By integrating decentralized energy models within a national-scale framework through soft-linking, the study evaluates the interaction between local production and consumption, highlighting the role of photovoltaic (PV) systems and self-consumption in Swiss energy planning [1]. This approach enhances the model's utility for energy planners and modelers and provides a foundation for strategic planning sensitive to regional disparities.

4.2. Centralized vs. Decentralized Energy Planning Strategies

The comparative analysis between centralized and decentralized strategies and models reveals distinct energy-transition-management approaches. The centralized model, with its broad control scale, is essential for managing large-scale energy storage and distribution, ensuring a stable energy supply. Conversely, the decentralized model emphasizes local optimization and adaptability, demonstrating significant potential in enhancing system resilience and energy independence. This study's findings indicate that, while the decentralized model underutilizes PV capacity to favor local consumption, it strategically reduces system costs by 10% to CHF 1230 per capita and PV installation requirements to 35 GW, about 23% of the potential capacity [1]. Such adaptability is crucial in an era of rapid technological advancements and evolving energy demands, suggesting that a balanced integration of centralized and decentralized strategies could offer a more resilient and efficient energy system.

4.3. Key Trade-offs Identified by the Results

The integration strategies of PV installations underscore significant trade-offs between maximizing renewable energy capacity and achieving economic efficiency. The analysis reveals that encouraging self-consumption reduces grid strain and promotes energy independence. Specifically, the study identifies a reduced need for grid reinforcement and leverages economic benefits by strategically underutilizing PV capacity in favor of local consumption, minimizing the need for extensive grid infrastructure investments. Furthermore, the decentralized model's preference for direct electric heating technologies and localized PV systems reflects a shift towards more flexible, consumer-oriented energy solutions. This approach not only addresses the demands of a transitioning energy system, but also highlights the need for innovative storage solutions and flexible grid management to accommodate high levels of self-consumption and intermittent renewable energy sources.

4.4. Implications for Future Research

The insights derived from this comparative analysis between centralized and decentralized energy models illuminate the path for future research, particularly in energy storage solutions, grid management, and the integration of decentralized entities. The nuanced understanding of PV integration strategies and the pivotal role of self-consumption within decentralized models underscore the complexity of achieving a resilient and sustainable energy future. Further investigation into sector coupling and the adaptation of district configurations across various sectors could enhance the efficiency and sustainability of the energy system. Additionally, exploring the dynamic transition model that accounts for evolving climatic conditions and technological advancements will be crucial in guiding incremental changes and investments over time, ultimately facilitating the achievement of the Paris Agreement targets.

5. Conclusions

This research investigated the dynamics between centralized and decentralized energy planning strategies in the Swiss energy system, focusing on PV system integration and district-level self-consumption. A regionalized model was developed to understand local and national energy system interactions, aiming to optimize energy planning for a carbon-neutral and independent Swiss energy system. This model assessed the impacts of system centralization and decentralization on efficiency, resilience, and cost-effectiveness.

5.1. Regionalized Model Contributions

Regionalized modeling is crucial for developing energy solutions that match regional demand and resource variations, improving system efficiency and effectiveness. The novel clustering approach for identifying typical districts allows for integrating localized energy production and consumption within a national framework. This method addresses computational challenges and improves system sustainability and efficiency. Identifying typical districts enables accurate and efficient energy system modeling, emphasizing the importance of region-specific strategies for achieving a sustainable energy future.

5.2. Centralized vs. Decentralized Planning Insights

The study compared a new regionalized model with traditional models lacking regionalization, focusing on the ability of the regionalized model to identify optimal infrastructure-development strategies. This comparison revealed trade-offs related to efficiency, resilience, and cost-effectiveness, highlighting localized energy solutions' integration challenges and benefits within a national framework.

5.3. Future Research Directions

The findings highlight the need for further research into energy-storage and grid-management solutions to integrate intermittent renewable energy sources effectively. Additionally, the results support policy development that promotes decentralized energy production and local renewable source integration.

This study makes significant strides in energy planning by demonstrating the viability and impact of integrating decentralized energy systems for national sustainability goals. The contributions of this study are not only in its methodological advancements, but also in its practical implications for achieving a resilient and secure energy system in Switzerland. It provides a comprehensive analysis of integrating decentralized energy systems within a centralized national framework, focusing on Switzerland. Key trade-offs in energy-planning strategies were identified, highlighting the strategic importance of self-consumption and the role of PV systems. Future research should continue to explore the synergy between centralized and decentralized approaches, focusing on the potential impacts on energy policy and system optimization.

6. Outlook

As the world navigates the transition to sustainable and autonomous energy systems, the insights from this study pave the way for future research and innovation. The following points outline critical areas for further exploration:

The model's application in understanding the impacts of climate change on building demands and resource availability is crucial. As climate conditions evolve, the optimal configurations for decentralized systems must adapt. Developing a dynamic transition model will provide a roadmap for achieving the Paris Agreement targets while considering the evolving climatic conditions. This will guide incremental changes and investments over time.

In the context of energy systems, the integration of decentralized entities (prosumers) with centralized systems is crucial. This approach recognizes that market-driven mechanisms may not suffice for optimal system performance. Thus, it advocates for a more sophisticated model where direct optimization strategies are employed from the centralized system's perspective. This involves leveraging market forces and implementing additional regulatory and technological interventions. These interventions aim to enhance system efficiency and reliability by effectively harmonizing the contributions of decentralized actors within the broader centralized infrastructure.

Another crucial area is expanding sector coupling and district configuration adaptation in the industry, services, and agriculture sectors. Applying the same methodology to analyze different industrial configurations can provide various services, enhancing the efficiency and sustainability of both sectors via sector coupling.

By addressing these areas, future research can build on the findings of this study to further enhance the resilience, efficiency, and sustainability of energy systems. The journey towards a carbon-neutral and energy-independent future is complex and multifaceted, but it is increasingly achievable with continued research, innovation, and policy support.

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Conflicts of Interest: The authors declare that they have no competing financial interests.

Glossary

CAPEX	capital expenditure
CH_4	methane
DBSCAN	density-based spatial clustering of applications with noise
EHV	Extra-High Voltage
ES	EnergyScope
GSA	Global Sensitivity Analysis
HV	High Voltage
LP	Low Pressure
LV	low voltage
MILP	Mixed-Integer Linear Programming
MV	Medium Voltage
OPEX	operational expenditure
PV	photovoltaic
REHO	*Renewable Energy Hub Optimizer*
TOTEX	total expenditure

Nomenclature

The following nomenclature and parameters were applied:

- Modeling variables: $\boldsymbol{X_m^n}$,
- Modeling parameters: $\boldsymbol{x_m^n}$,
- Modeling sets: $x \in \mathcal{X} - \mathcal{SET}$,
- General parameters not included in the model: X_m^n.

Parameters.		
$\boldsymbol{c}$	Specific cost	[MCHF/$\triangle$]
$\boldsymbol{f_{ext}}$	Existing capacity	[W]
$\boldsymbol{n}$	Number	[$-$]
$\boldsymbol{t}$	Time	[h]
$\boldsymbol{\eta}$	Efficiency	[%]
$\boldsymbol{\tau}$	Annualization factor	[year^{-1}]
Variables		
$\boldsymbol{C}$	Cost	[MCHF]
$\boldsymbol{F}$	Installation size	[GW]
$\boldsymbol{F_t}$	Installation use	$[\frac{\mathrm{GW\,t_{TP}}}{\mathrm{t_{TP}}}]$
$\boldsymbol{\Phi}$	Configuration selection	[$-$]
Sets		
$\mathcal{COST}$	Cost	Investment, operation, and maintenance
$\mathcal{IND}$	Indicators	
$\mathcal{PERIODS}$	Periods	
$\mathcal{TEC}$	Technologies	
Subscripts		
constr	Construction	
inv	Investment	
maint	Maintenance	
obj	Objective	
t	Period	
tot	Total	

Appendix A. Terminology

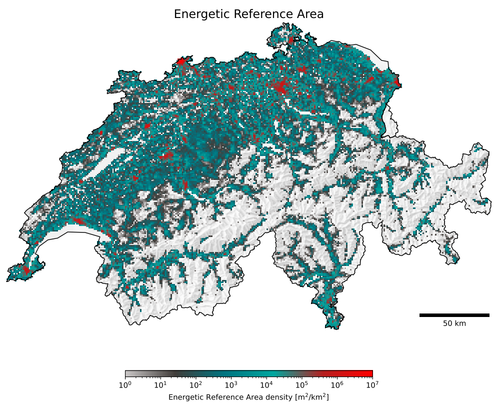
- *Energy-planning strategies*: Refers to the overarching approaches and methods adopted for the development, management, and optimization of energy systems at various scales. These strategies may include policy decisions, infrastructure investments, and operational practices to achieve specific energy system goals, such as sustainability, resilience, or independence.
- *Model structures and capabilities*: Pertains to the technical and computational frameworks used to simulate and analyze energy systems. This includes the internal algorithms, data-handling methods, and analytical processes that determine a model's ability to represent energy dynamics accurately. Model structures and capabilities are distinct from the strategic applications of model outputs in energy planning.
- *Centralized (top-down) models* are defined as those that approach energy system planning from a national or global perspective, often emphasizing large-scale infrastructure and energy flows managed by a central authority. The term "centralized" may also refer to energy-planning strategies that rely on large, centralized energy-production facilities and infrastructure.
- *Decentralized (bottom-up) models* refer to approaches that focus on local energy generation, distribution, and consumption, highlighting the role of individual or community-level actors, such as prosumers. In strategic terms, "decentralization" refers to the shift towards local autonomy and energy production, promoting smaller scale, distributed energy resources.
- *Regionalization in modeling*: Addresses the need to incorporate geographic and regional specificities into energy models, recognizing the diversity of energy demands,

resource availability, and infrastructure conditions across different areas. Regionalization enhances the model's accuracy in representing the spatial dimensions of energy systems.

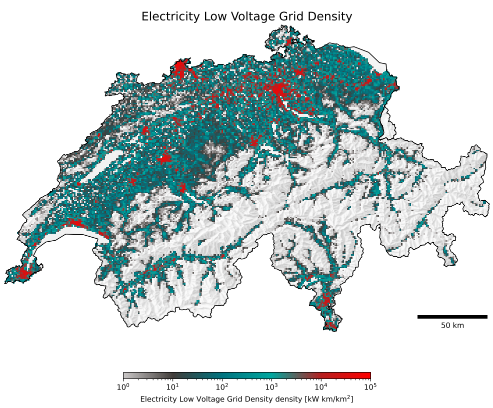
- *Strategy vs. model Clarification*: Throughout this paper, when discussing "strategies", the focus is on energy-planning and -policy implications derived from model analyses. In contrast, discussions on "models" pertain to their structural and computational aspects, including their design to simulate energy system dynamics effectively.

This paper carefully distinguishes between strategic considerations in energy system development (e.g., centralized vs. decentralized approaches) and the technical aspects of energy models (e.g., top-down vs. bottom-up structures). Additionally, it highlights the importance of regionalization in model design to accurately capture the complex realities of national and sub-national energy systems.

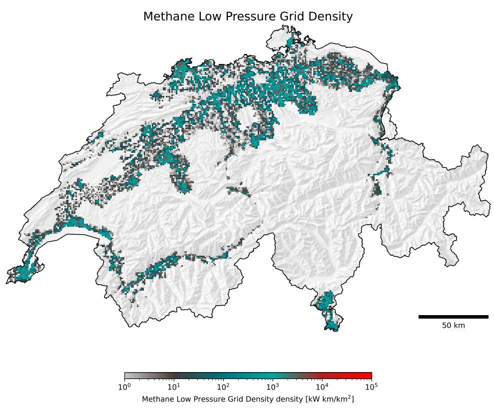
Appendix B. Swiss Energy System Typification



(a) Energy Reference Area density



(b) Low Voltage Electric Grid density



(c) Low Pressure Gas Grid density

Figure A1. Clustering input parameter density representation based on the Swiss building stock distribution.

Appendix C. District Energy System Configurations

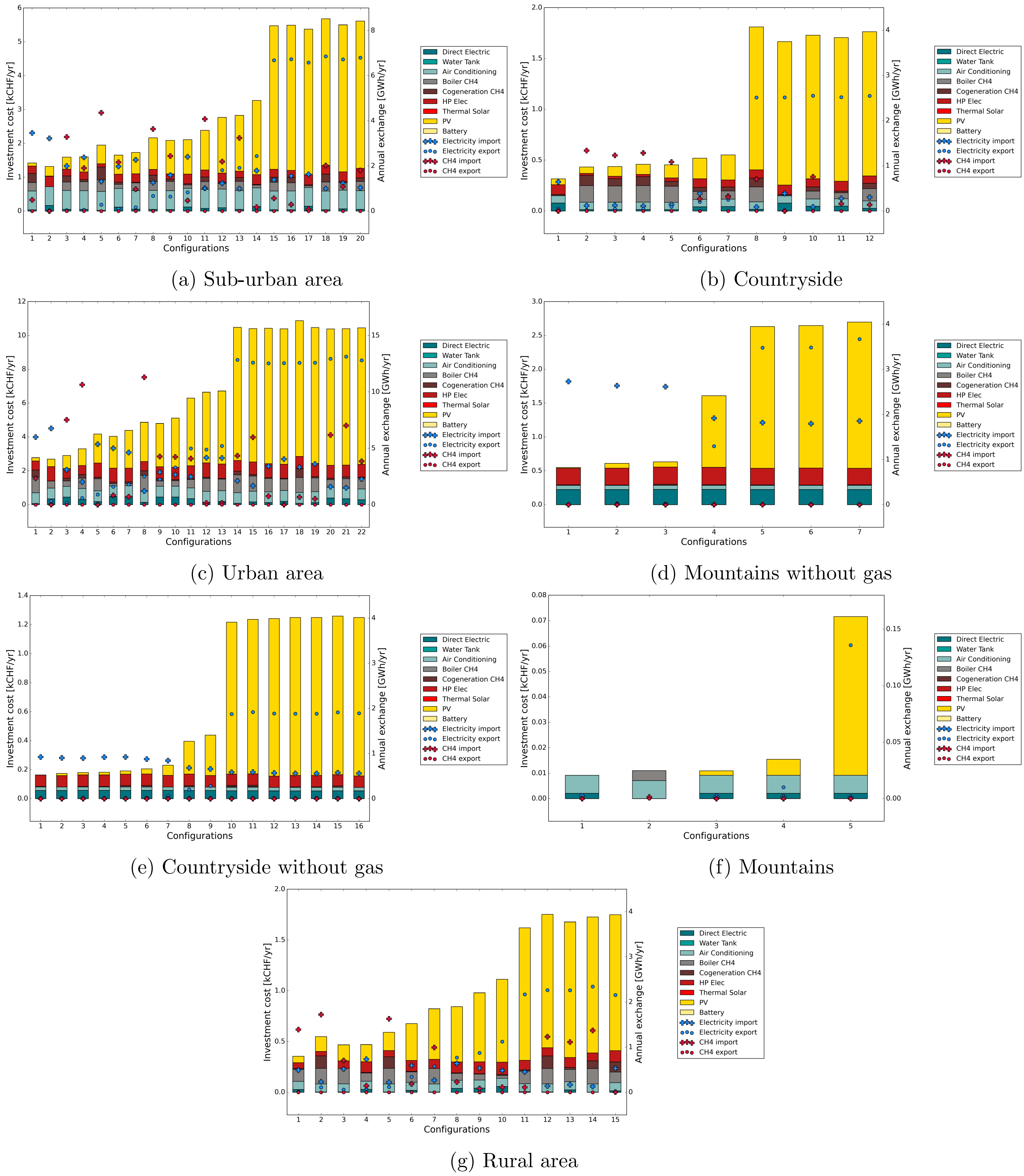
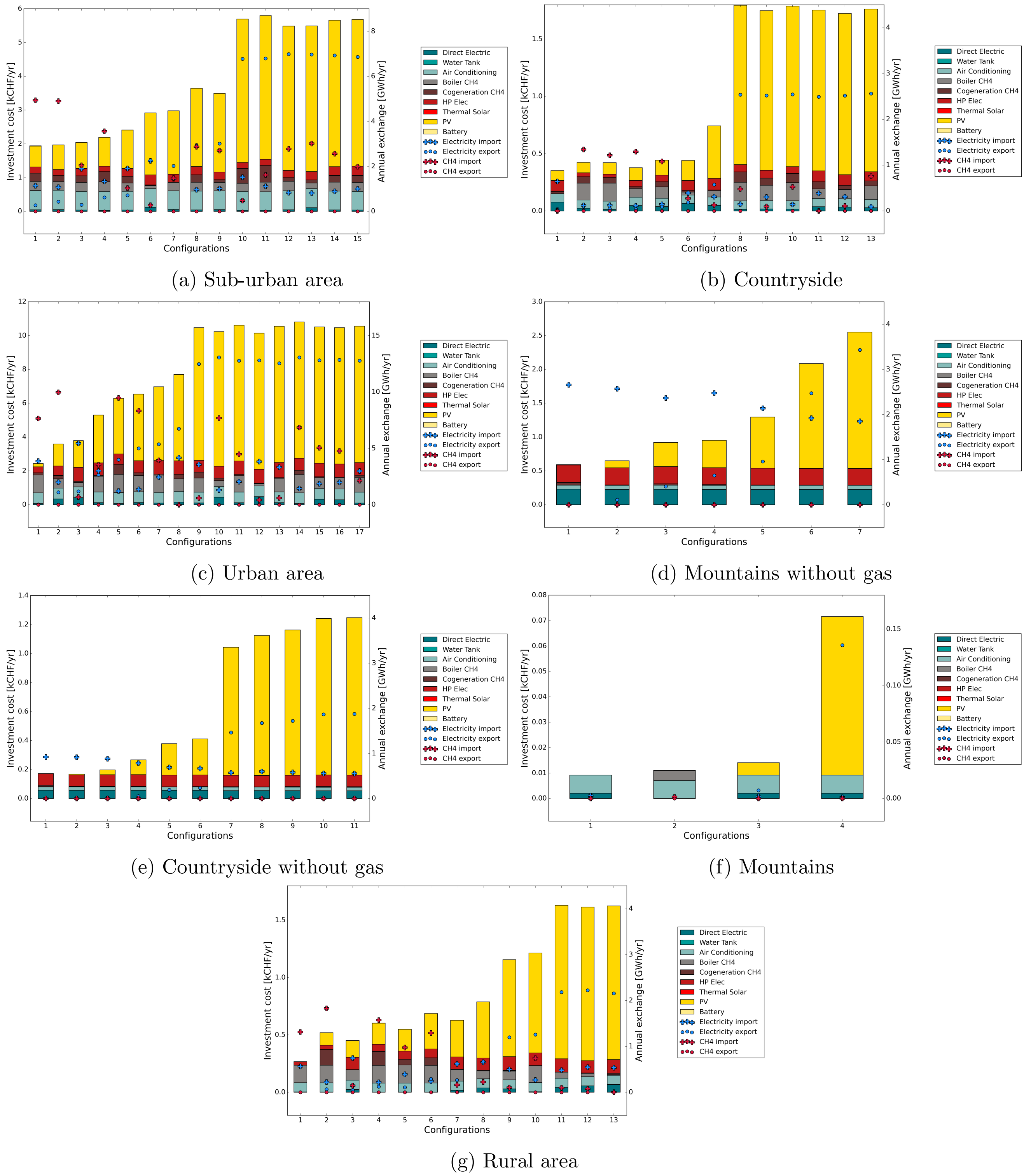


Figure A2. Identified configuration of the districts.



(a) Sub-urban area (b) Countryside
(c) Urban area (d) Mountains without gas
(e) Countryside without gas (f) Mountains
(g) Rural area

Figure A3. Identified configuration of the districts with renovated buildings.

Appendix D. PV Integration Strategies

Appendix D.1. Energy System

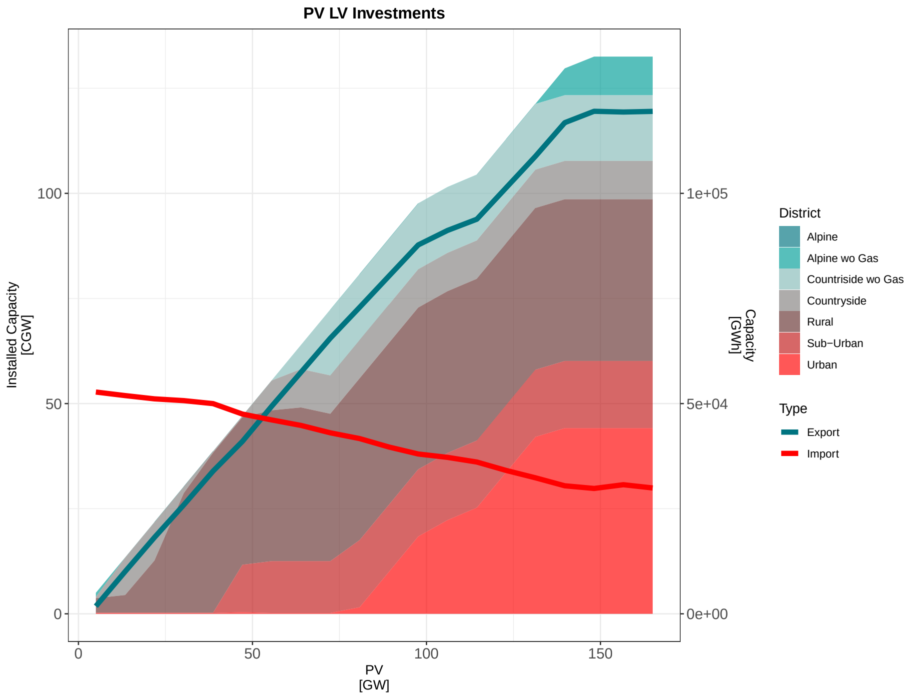


Figure A4. Evolution of district PV evolution of the Swiss energy system according to the PV installation parametrization. Case study of the economic optimization of a neutral (no net emissions) and independent (no imports) Swiss energy system in 2050 for a population of 10 Million people.

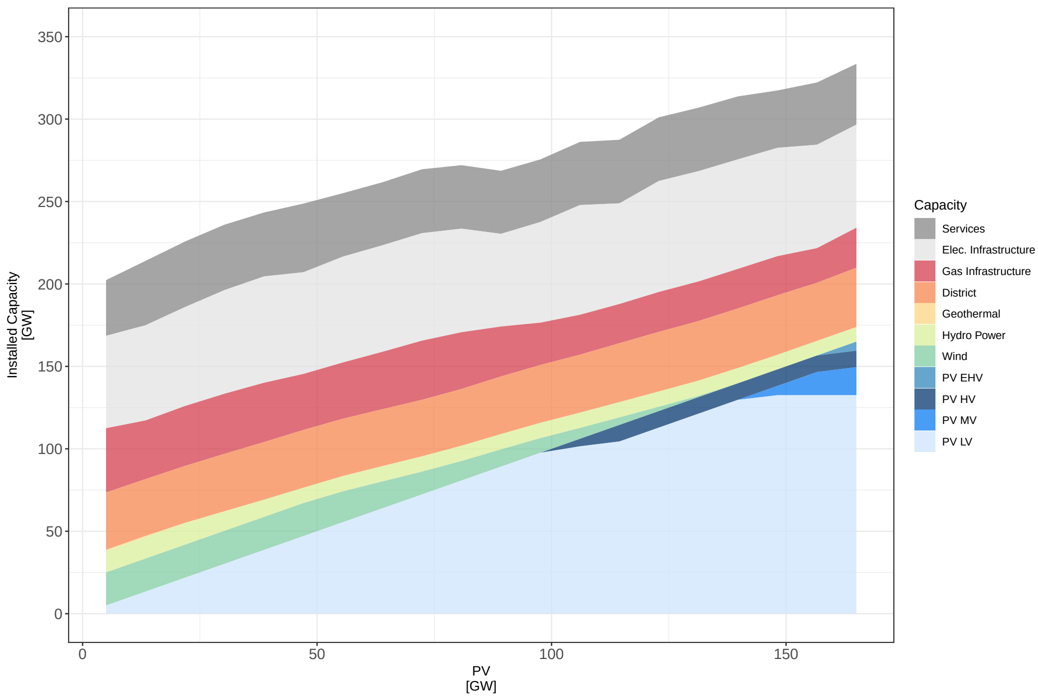
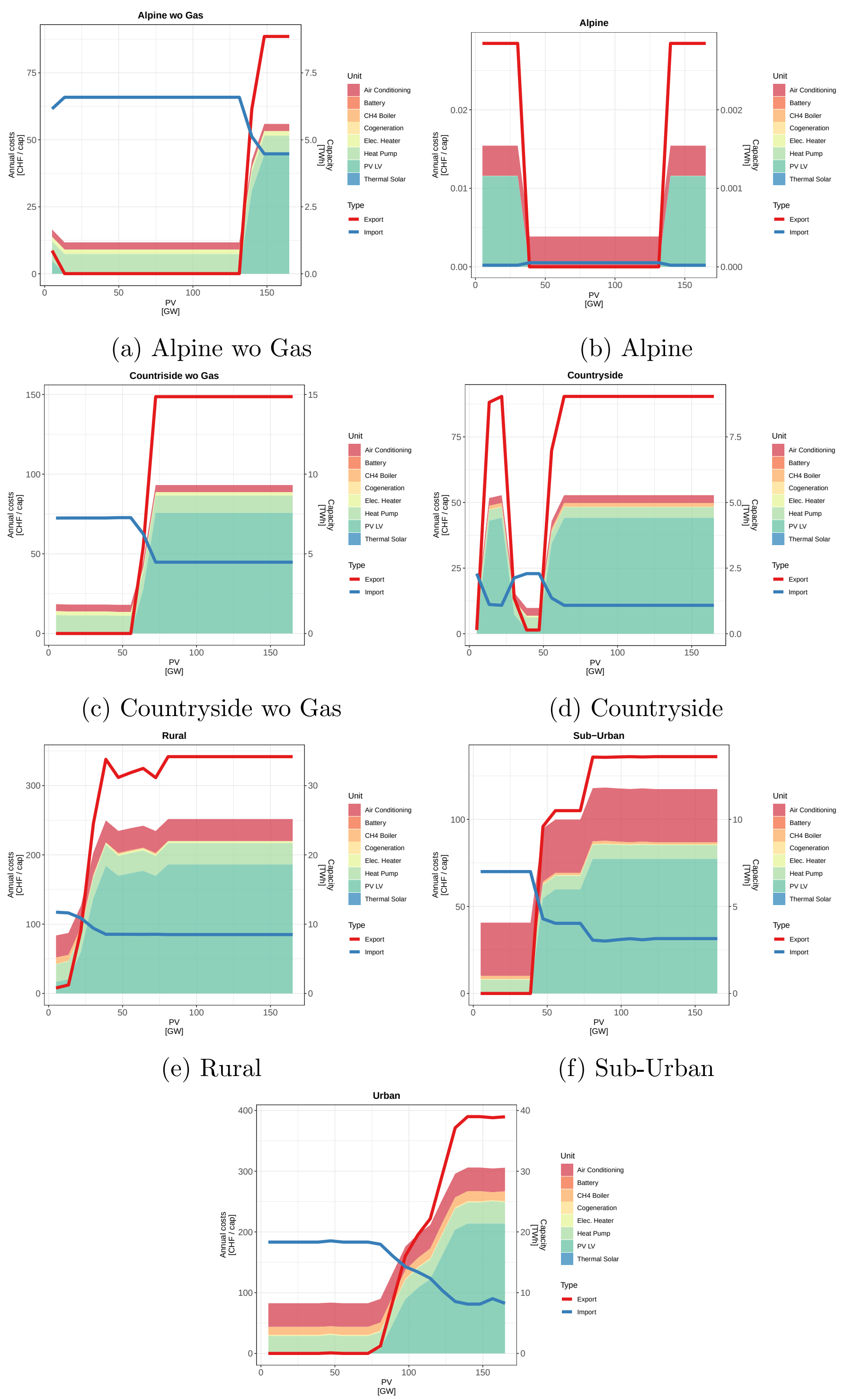


Figure A5. Evolution of energy system composition of the Swiss energy system according to PV installation parametrization. Case study of the economic optimization of a neutral (no net emissions) and independent (no imports) Swiss energy system in 2050 for a population of 10 Million people.

Appendix D.2. Districts



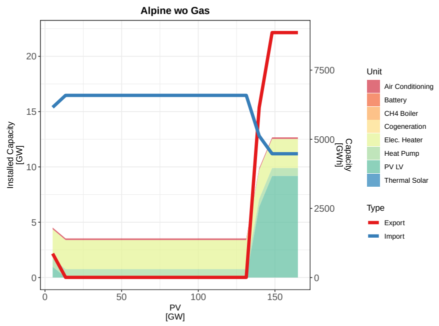
(a) Alpine wo Gas (b) Alpine

(c) Countryside wo Gas (d) Countryside

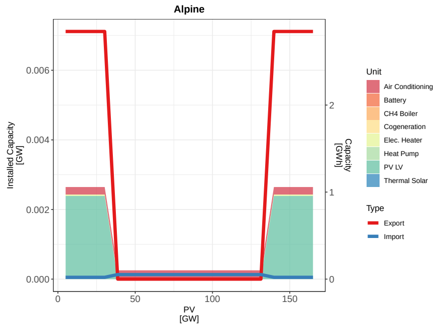
(e) Rural (f) Sub-Urban

(g) Urban

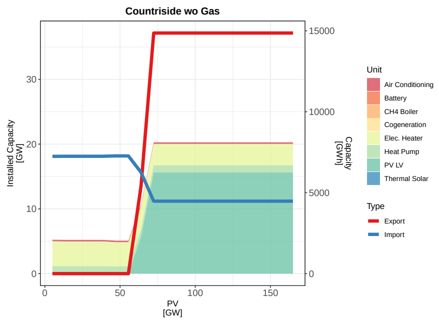
Figure A6. Evolution of energy system districts' cost composition of the Swiss energy system according to PV installation parametrization.



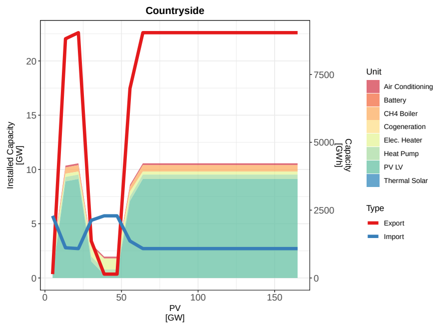
(a) Alpine wo Gas



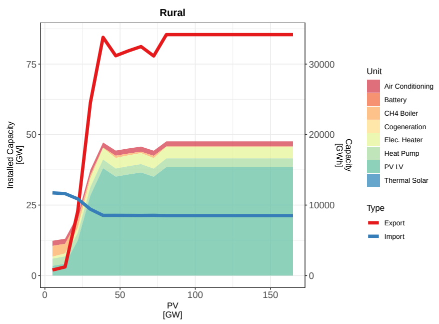
(b) Alpine



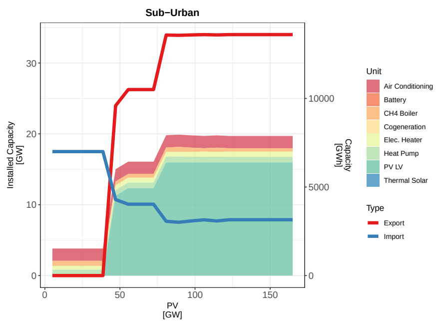
(c) Countriside wo Gas



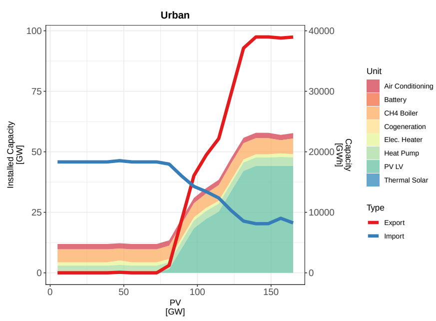
(d) Countryside



(e) Rural



(f) Sub-Urban



(g) Urban

Figure A7. Evolution of energy system district composition of the Swiss energy system according to PV installation parametrization.

Appendix D.3. Sectors

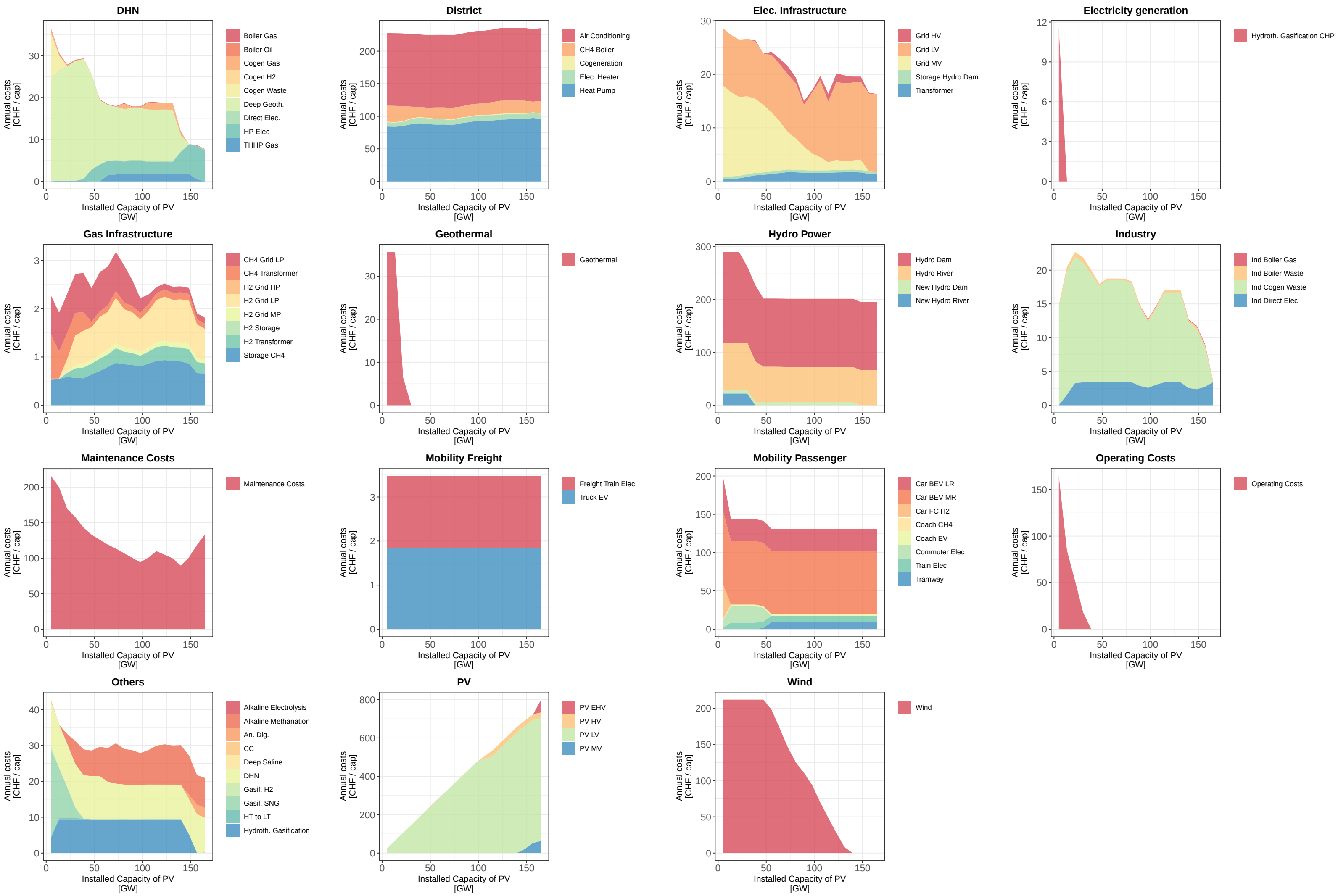


Figure A8. Evolution of sector investments according to PV installation parametrization.

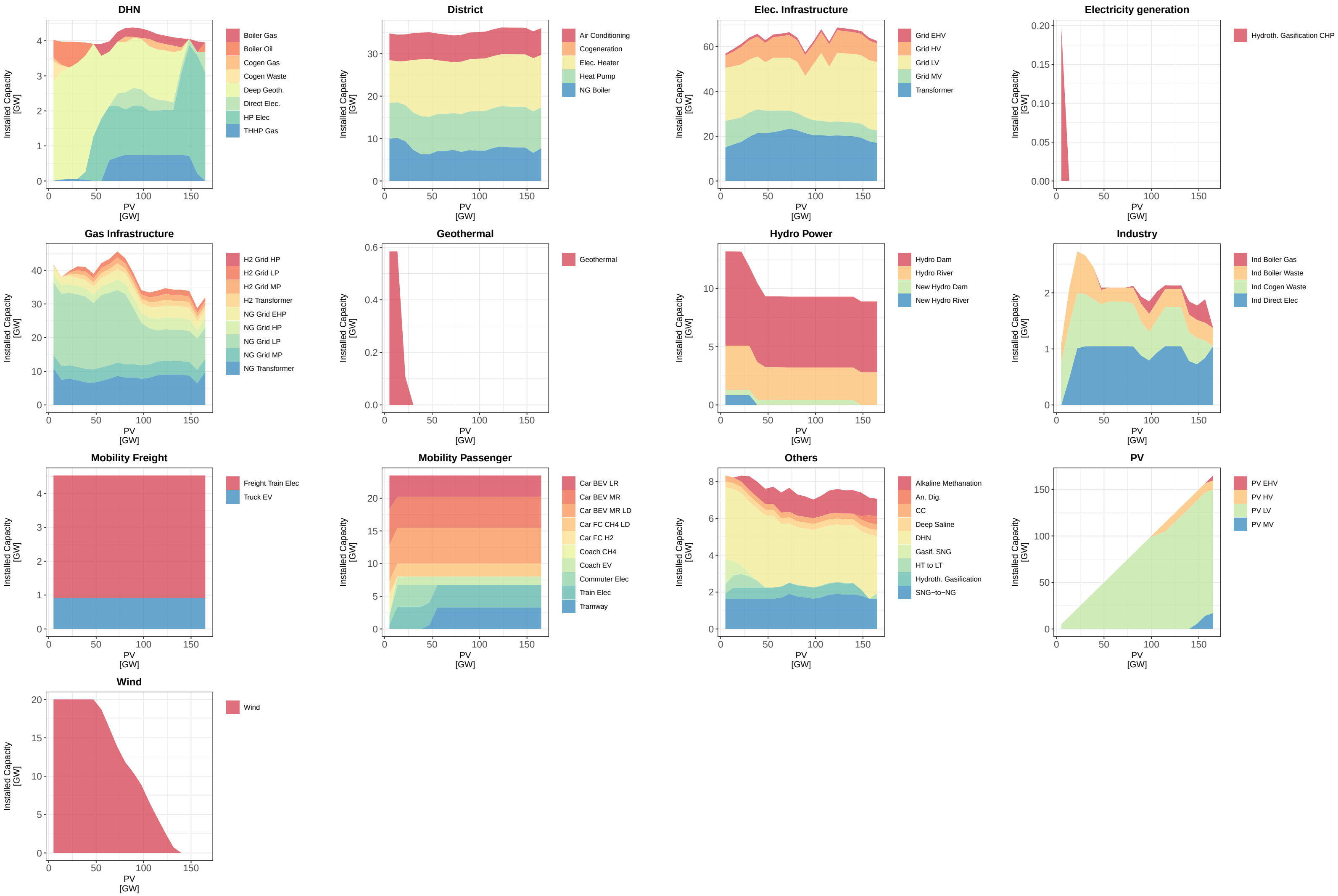


Figure A9. Evolution of sectoral installed capacities according to PV installation parametrization.

Appendix E. Self-Consumption in Focus

Appendix E.1. PV Districts

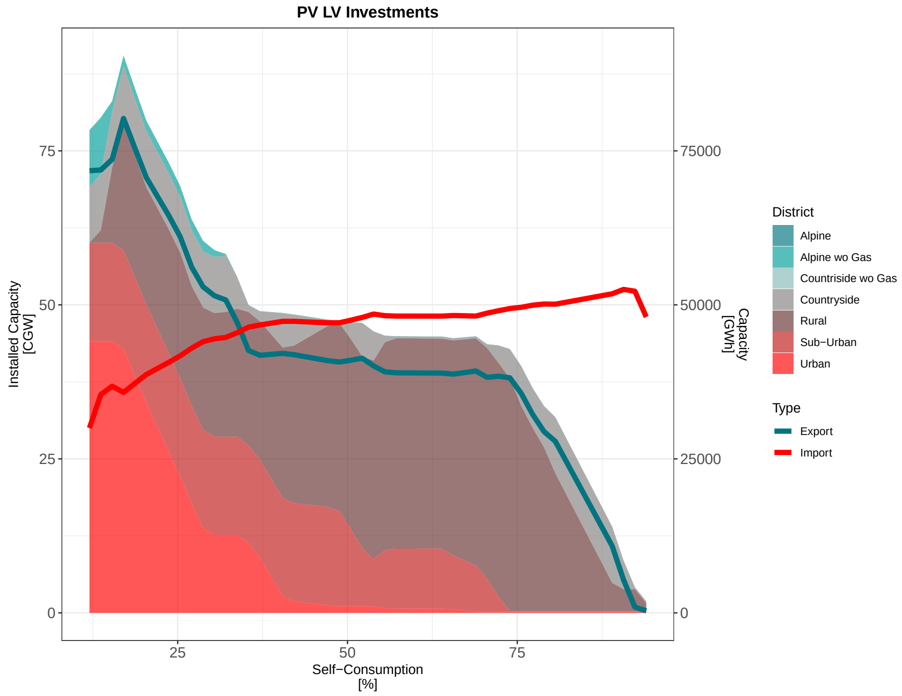
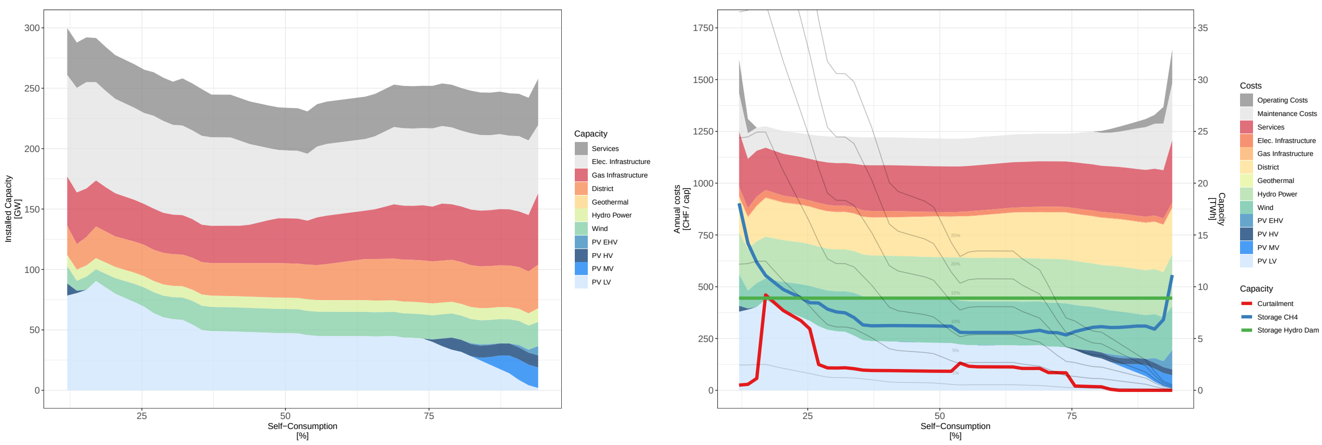


Figure A10. Evolution of district PV evolution of the Swiss energy system according to the self-consumption parametrization. Case study of the economic optimization of a neutral (no net emissions) and independent (no imports) Swiss energy system in 2050 for a population of 10 Million people.

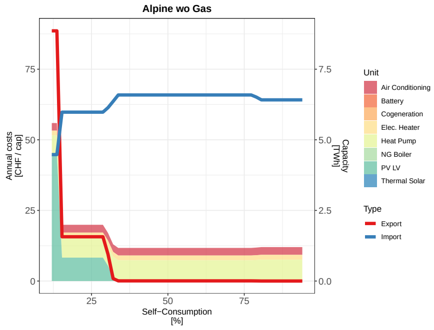
Appendix E.2. Energy System



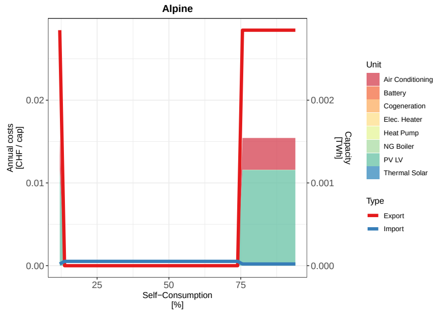
(a) Installed capacities (b) Cost composition

Figure A11. Evolution of energy system composition of the Swiss energy system according to the self-consumption parametrization. Case study of the economic optimization of a neutral (no net emissions) and independent (no imports) Swiss energy system in 2050 for a population of 10 Million people.

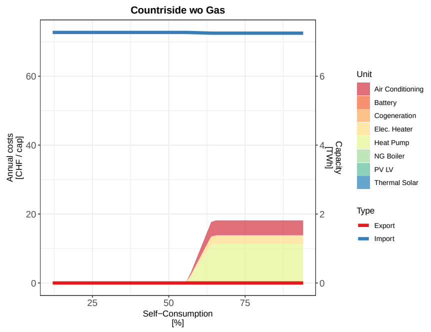
Appendix E.3. Districts



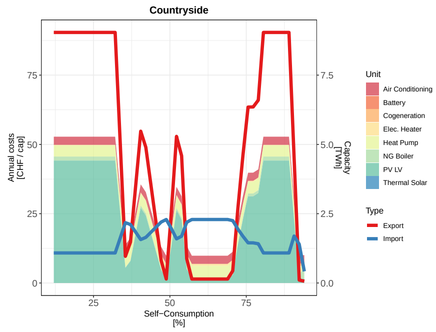
(a) Alpine wo Gas



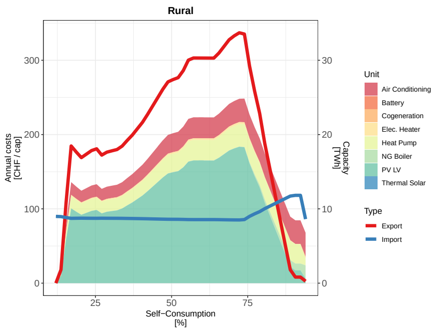
(b) Alpine



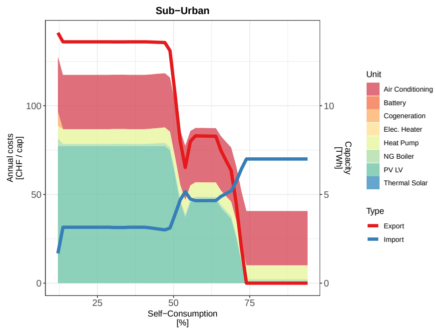
(c) Contryside wo Gas



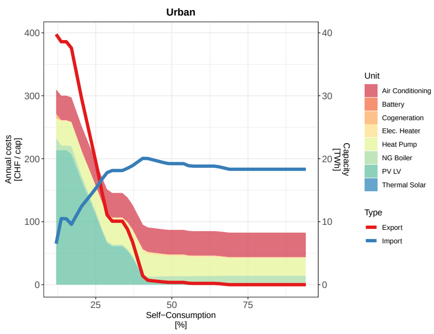
(d) Countryside



(e) Rural

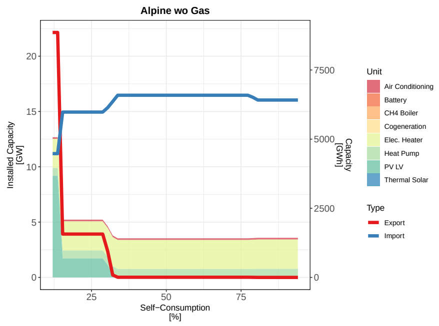


(f) Sub-Urban

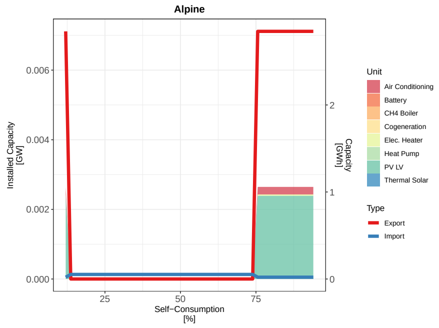


(g) Urban

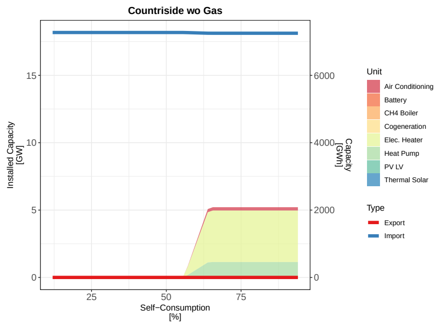
Figure A12. Evolution of energy system districts' cost composition of the Swiss energy system according to self-consumption parametrization.



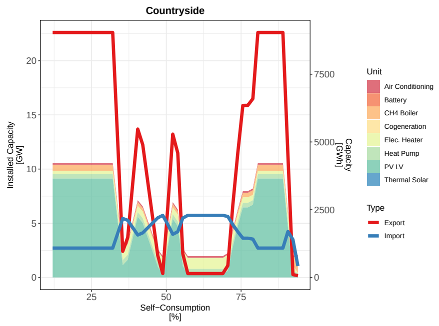
(a) Alpine wo Gas



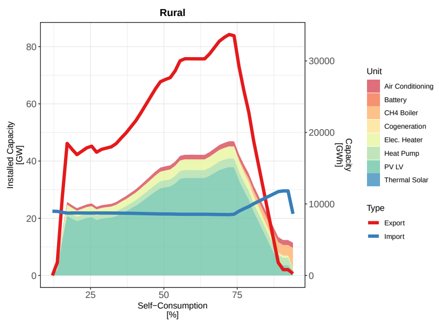
(b) Alpine



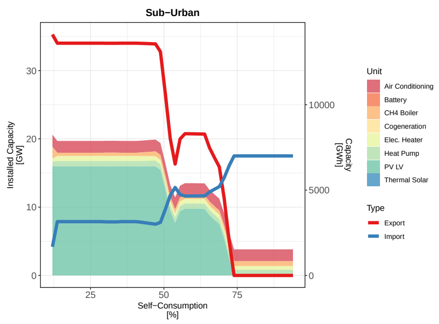
(c) Contryside wo Gas



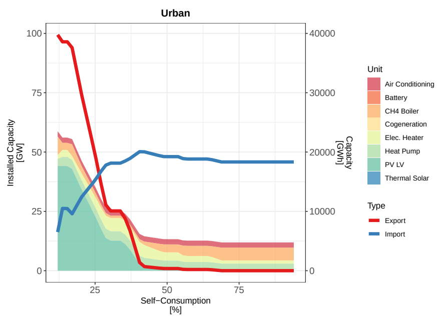
(d) Countriside



(e) Rural



(f) Sub-Urban



(g) Urban

Figure A13. Evolution of energy system district composition of the Swiss energy system according to self-consumption parametrization.

Appendix E.4. Sectors

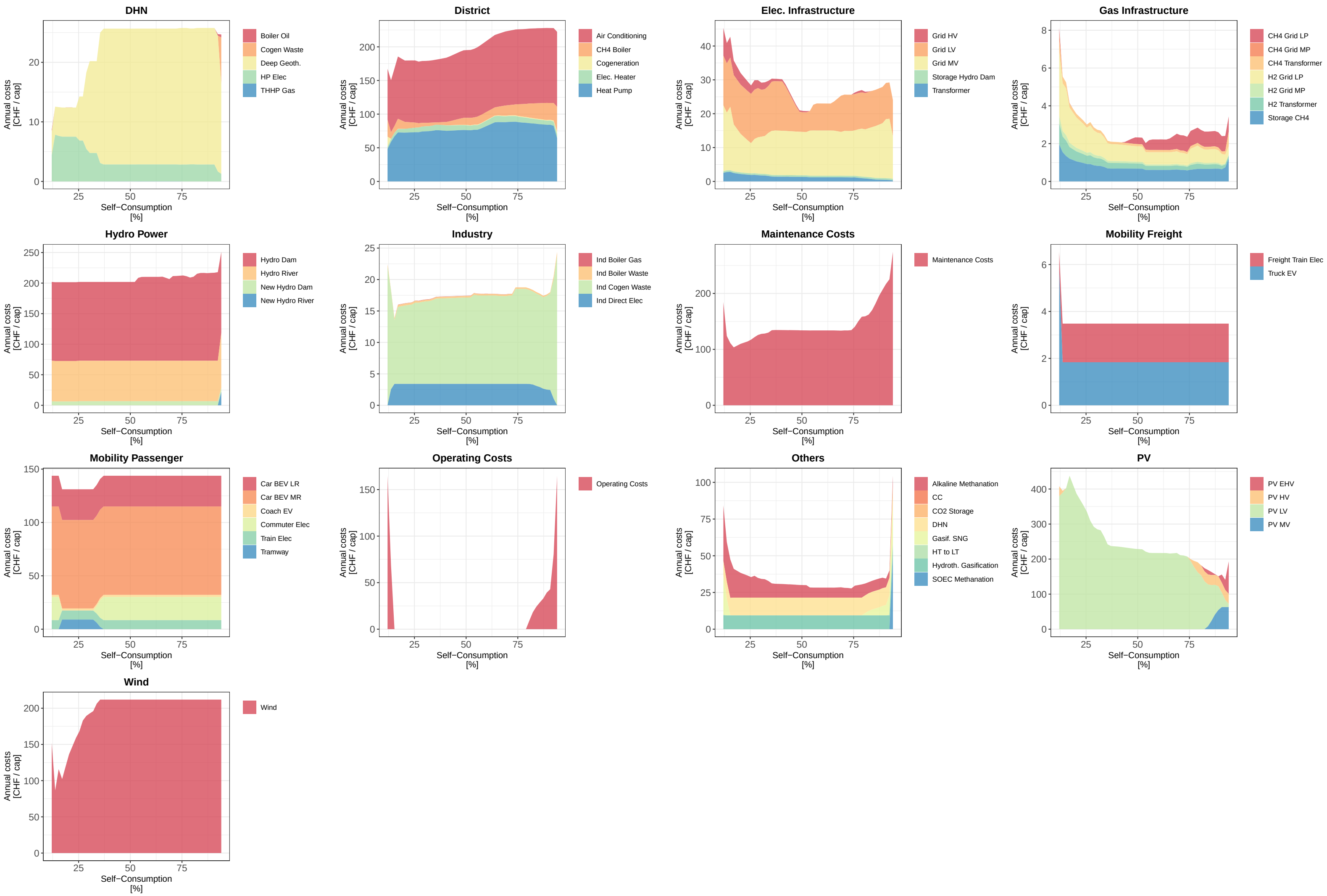


Figure A14. Evolution of sector investments of the Swiss energy system according to self-consumption parametrization.

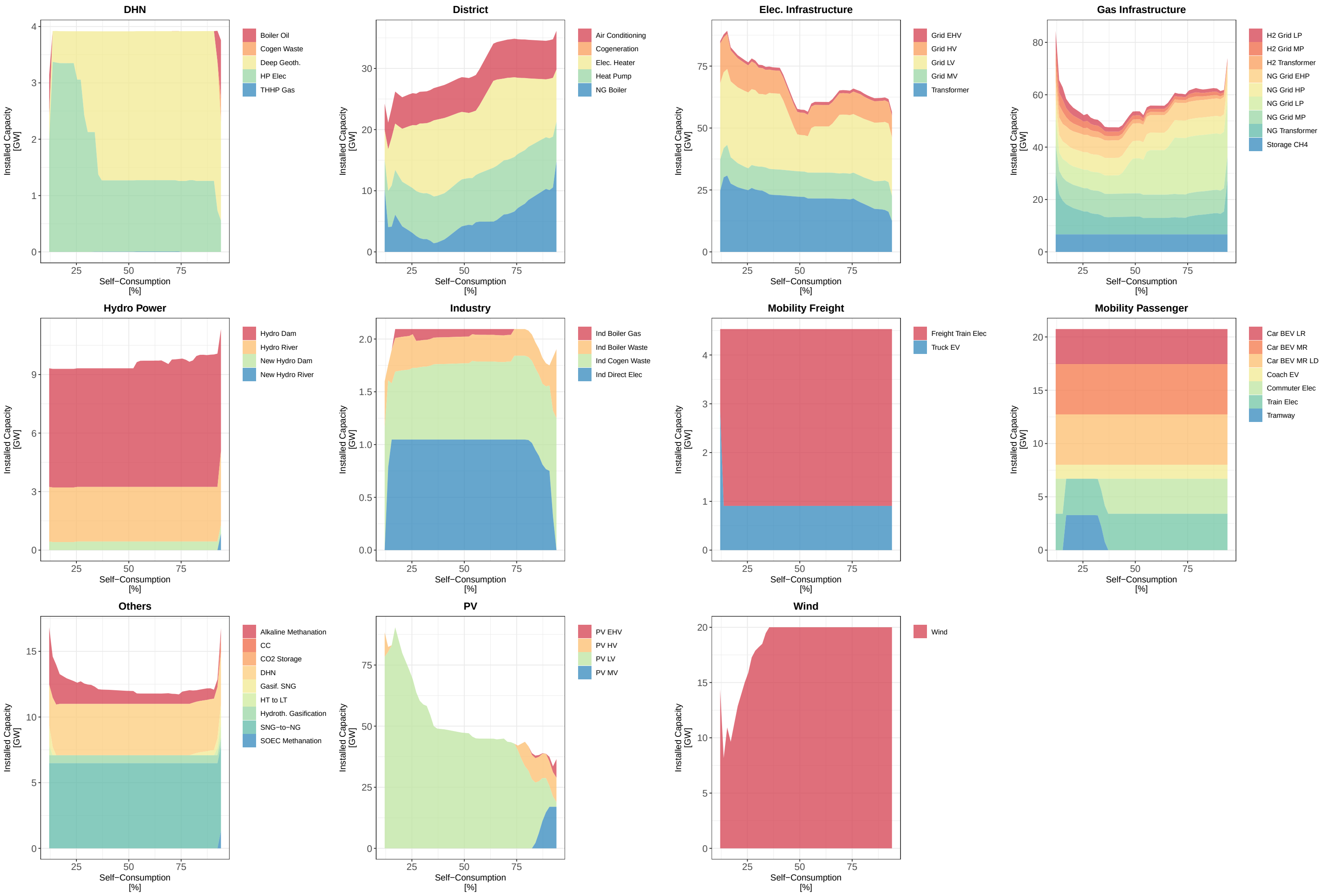


Figure A15. Evolution of sectoral installed capacities of the Swiss energy system according to self-consumption parametrization.

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