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# From local energy communities towards national energy system: a grid-aware techno-economic analysis

***Cédric Terrier[a], Joseph Loustau[b] and François Maréchal[c]***

[a] *EPFL, Sion, Switzerland, cedric.terrier@epfl.ch*
[b] *EPFL, Sion, Switzerland, joseph.loustau@epfl.ch*
[c] *EPFL, Sion, Switzerland, francois.marechal@epfl.ch*

**Abstract:**

Energy communities are key actors in the energy transition since they optimally interconnect renewable energy capacities with the consumers. Despite versatile objectives, they usually aim at improving the self-consumption of renewable electricity within low voltage electricity networks to maximize the revenues of the community. In addition, energy communities are an excellent opportunity to supply renewable electricity to regional and national grids. However, effective price signals have to be designed to coordinate the needs of the energy infrastructure with the interests of local stakeholders.

The aim of this paper is to demonstrate the potentials of energy communities at the national level with a bottom-up approach. A district energy system having a building scale resolution is modelled in a mixed integer linear programming problem. The Dantzig-Wolfe decomposition is applied to reduce the computational time. The methodology lies within the framework of renewable energy hub, characterized by a high share of photovoltaic. Both investments into energy capacities and their operation are considered. The model is applied on a set of typical districts and weather locations representative of the whole Switzerland.

The extrapolation to the national scale revealed a heterogeneous photovoltaic potential throughout the country. The actual electricity tariffs promote maximal investment into photovoltaic panels in every region, reaching a capacity of 28 GW and generating 32 TWh per year. Since the forecast national energy need is between 12 and 18 TWh per year, a coordinated design is needed to prevent unnecessary investments. An uncoordinated design increases the total costs of the residential energy system by 31% and curtails 24% of the onsite generated electricity. Moreover, the $CO_{2,eq}$ emission of the unnecessary investment is equivalent to 9% of the actual emissions in the residential sector.

**Keywords:**

Energy communities; Renewable energy hub; National systems integration; MILP; Multi-objective optimization

## 1. Introduction

In 2018, the European Parliament has emphasized the role of energy communities in the energy transition and has set up directives to facilitate their creation [1]. Their purpose includes the penetration of renewable energies, the reduction of energy poverty [1], the enhancement of technological acceptance [2] and the improvement of the democratic process [3]. Energy communities aim at supplying the energy needs with high self-consumption of local energy sources. The reduction of the electricity grid reliance prevents costly grid reinforcements, therefore supporting a rapid electrification of the heating and mobility services. By 2050, Photovoltaic (**PV**) installations are expected to represent 50% of the electricity generation capacity worldwide [4]. More specifically, in Switzerland, the electricity demand is expected to reach 55 TWh/yr in 2050, from which 33 TWh/yr will be supplied by hydro power [5, 6]. The remaining electricity will mainly be supplied by PV capacities (11 TWh/yr), wind turbine (4.2 TWh/yr) and geothermal energy (4.3 TWh/yr). The success of PV integration seems to rely on a coordinated integration of energy communities within the infrastructure [1]. The involvement of these actors in investments and operation decisions dictates the energy flows exchanged between the communities and the infrastructure, ultimately affecting the whole energy network structure.

The definition of an energy community is broad but a consensus estimates that it is a local energy system possessing distributed sustainable energy conversion units, both on the supply and demand sides [2]. The concept of energy hub is usually used to model such systems. Multi-energy sources supply a multi-service demand with conversion units being optimally interconnected and operated. Extensive reviews have been carried out on this topic [7, 8]. The scale considered varies from local energy hubs, such as a residential area to

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large scale systems including a whole country. Energy communities are usually built at the neighborhood scale since the proximity facilitates the community governance while being large enough to promote an economy of scale. Based on the literature review (Table 1), the scope of the studies mostly consider a single case study on a neighborhood, resulting in a lack of generality. Some studies investigated the broad impact of local residential systems with typical clusters and extrapolation but the scope relied on single building energy system [9, 10]. Therefore, the potential of energy communities to support the energy transition of the overall infrastructure with renewable integration is yet not assessed.

**Table 1**: Literature review on energy communities: The resolution indicates the considered scale for the investment or demand profiles. The approach shows how the authors handled the complexity of the problem, either by simplifications or by decomposition. The interdependent system feature highlights whether the study considered decision interactions between buildings and between national and local decisions.

| Case study | | Method | | Analysis | | | | |
|---|---|---|---|---|---|---|---|---|
| Scope | Resolution | Model | Approach | Regions dependant | National scope | Systemic constraints | Interdependent systems | Reference |
| Country | Building | MILP | Clustering | ✓ | ✓ | ✗ | ✗ | [9] |
| Country | Building | MILP | Clustering | ✓ | ✓ | ✗ | ✗ | [10] |
| District | Building | MILP | Pre-selection/profiles | ✗ | ✗ | ✗ | ✓ | [11] |
| District | Building | MILP | Profiles | ✗ | ✗ | Grid | ✗ | [12] |
| District | District | MILP | Profiles | ✗ | ✗ | ✗ | ✗ | [13] |
| City | Building | Simulation | Pre-selection | ✗ | ✗ | ✗ | ✗ | [14] |
| District | Building | Simulation | Pre-selection/scenario | ✗ | ✗ | ✗ | ✗ | [15] |
| District | Building | MILP | Bi-level | ✗ | ✗ | ✗ | ✓ | [16] |
| District | District | MILP | Scenario | ✗ | ✗ | ✗ | ✗ | [17] |
| District | Building | MILP | Scenario | ✗ | ✗ | ✗ | ✗ | [18] |
| District | Building | MINLP | Bi-level | ✗ | ✗ | Grid | ✓ | [19] |
| District | Building | MILP | Dantzig-Wolfe | ✗ | ✗ | ✗ | ✓ | [20] |
| District | Building | MILP | Dantzig-Wolfe | ✗ | ✗ | ✗ | ✓ | [21] |
| District | Building | MILP | Profiles | ✗ | ✗ | ✗ | ✗ | [22] |
| District | Building | MILP | Benders | ✗ | ✗ | ✗ | ✓ | [23] |
| District | Building | MILP | Bi-level | ✗ | ✗ | Grid | ✓ | [24] |
| District | District | MILP | Rolling horizons + pre-selection | ✗ | ✗ | ✗ | ✗ | [25] |
| Country | Building | MILP | Dantzig-Wolfe + clustering | ✓ | ✓ | Grid | ✓ | This paper |

Due to its network structure, modeling an energy community at the district scale with building scale resolution usually exceed the computational power. Facing this problem, a popular method is to fix some degrees of freedom by making assumptions and scenarios based on expert knowledge (Table 1). As an example, half of the literature is assuming energy demand profiles or pre-determines the energy system configuration. To promote grid services and renewable energy supply, energy communities should be approached from a service demand perspective rather than an energy demand one. This change of approach is beneficial since it does not assume the type of conversion units [26]. Therefore, it provides flexibility to consider additional constraints, such as the infrastructure capacity or trade-offs between investment and operational costs. In addition, considering each sub-systems within a single optimization reveals the inter-dependency of the decisions and do not force the acceptance of a decision without accounting for the interests of the actors concerned [26]. Therefore, assumptions and scenarios should be considered with care since they tend to oversimplify the view on the problem. Despite the extensive literature existing on the topic of energy communities, a holistic framework is usually not considered.

The main limitations found in the literature are the assumption taken on the type of conversion units installed and the lack of systemic understanding on the role of energy communities. It is yet not clear to which extent these communities can supply renewable electricity to the national energy system considering the actual infrastructure capacity. The performance extrapolation of various local case studies to the national scope is very rare in the literature. Therefore, based on these research gaps, the present study aims at answering the following research questions:

- What are the investment and operation decisions taken within energy communities?
- How does the decisions change with the geographic context?
- What is the potential for energy communities to supply renewable electricity in a country?
- What is the impact to consider the infrastructure capacity constraints?

## 2. Methodology

The energy community is modelled as a renewable energy hub, being defined as a system optimally interconnecting multi-energy streams and conversion units [27]. Additionally, the energy hub is characterized by a high share of renewable energy and aims at maximizing self-consumption. The renewable energy hub is at the district scale within a low-voltage electricity grid deserved by a low to medium voltage transformer. Service demands of each building, such as domestic hot water, domestic electricity and space heating, are supplied by conversion units and a gas and electricity utility. A mixed integer linear programming (**MILP**) formulation optimizes the investment into conversion units and the operation of the energy system. The main decision variables are the decision to install a unit (binary variables) and the size of the units installed (continuous variables). The conversion units include thermal units (air-water heat pumps, gas boilers, electrical heaters) and storage units (thermal tanks and lithium ion batteries). PV panels are the main source of renewable electricity and can be installed on the roof and facades of buildings. Their orientation is a decision variable as described by Middelhauve et al. [27].

Energy and mass balances as well as heat cascade are the main constraints of the model. Electricity and natural gas balances are applied at the building and district scale, allowing synergies between buildings and between energy carriers. Equation (1a) shows the electricity balance between the building electricity fluxes $\dot{E}^{gr}_{b,p,t}$ and the LV/MV transformer exchanges $E^{tr}_{p,t}$. A positive symbol represents an import of energy and a negative one an export. Decision variables are highlighted with **bold** characters. Additionally, technical constraints are considered to model conversion unit and to account systemic capacity. Constraint (1b) is applied to restrict the power exchanged on the transformer level to a specified value $\dot{E}^{tr,max}$. The electricity balance allows sharing renewable electricity within the community to increase the self-consumption, thus reducing operating costs and minimizing the transformer usage. To reduce computational burdens time series are clustered into typical and extreme operating periods using the K-medoids algorithm. The model consider four sets: buildings $B$, typical periods $P$, timesteps of the typical period $T$ and units $U$. More details on the problem formulation are given in the following thesis [9, 27].

$$\sum_{b\in \mathrm{B}}(\dot{\boldsymbol{E}}^{\boldsymbol{gr,+}}_{\boldsymbol{b,p,t}} - \dot{\boldsymbol{E}}^{\boldsymbol{gr,-}}_{\boldsymbol{b,p,t}}) \cdot d_p \cdot d_t = \boldsymbol{E}^{\boldsymbol{tr,+}}_{\boldsymbol{p,t}} - \boldsymbol{E}^{\boldsymbol{tr,-}}_{\boldsymbol{p,t}} \qquad \forall p \in \mathrm{P}, \quad \forall t \in \mathrm{T} \tag{1a}$$

$$\dot{\boldsymbol{E}}^{\boldsymbol{tr,\pm}}_{\boldsymbol{p,t}} \leq \dot{E}^{tr,max} \qquad \forall p \in \mathrm{P}, \quad \forall t \in \mathrm{T} \tag{1b}$$

#### 2.0.1. Objective functions

The objective functions are described in (2a) to (2e). The total costs (**TOTEX**) encompass operating costs (**OPEX**) and capital costs (**CAPEX**). The OPEX correspond to the annual energy costs and revenues from the utilities. The electricity and gas retail tariffs are respectively $c^{el,+}$ and $c^{ng,+}$ and the feed-in tariff is $c^{el,-}$. The variables $E^{tr}$ and $H^{gr,+}$ correspond to the annual electricity and gas exchanges with the utility at the district level. The CAPEX (Eq. 2c) encompass investments and replacement costs of conversion units. The costs are annualized over an $n$ years horizon with an interest rate $i$. The investment costs $C^{inv}$ are linearized with fixed ($i^{c1,u}$) and variable ($i^{c2,u}$) costs and multiplied by the bare modulus $b^u$ [9]. The CAPEX is dictated by two decision variables, the decision to install a unit ($y^u$) and the size installed ($f^u$). When a conversion unit has a lifetime $l_u$ lower than the project horizon $n$, the replacement cost is given by the number of replacements $R$ over the horizon $n$. Multi-objective optimization is performed to evaluate the solution space at the interplay of two conflicting objectives, the operating and capital costs. One objective is upper-bounded by a pre-defined values using an $\epsilon$-constraint while the second objective is minimized. Pareto fronts are generated by varying the $\epsilon$-constraints and by exchanging the objectives constrained and minimized.

$$\boldsymbol{TOTEX} = \boldsymbol{OPEX} + \boldsymbol{CAPEX} \tag{2a}$$

$$\boldsymbol{OPEX} = c^{el,+} \cdot \boldsymbol{E}^{\boldsymbol{tr,+}} - c^{el,-} \cdot \boldsymbol{E}^{\boldsymbol{tr,-}} + c^{ng,+} \cdot \boldsymbol{H}^{\boldsymbol{gr,+}} \tag{2b}$$

$$\boldsymbol{CAPEX} = \frac{i(1+i)}{(1+i)^n - 1}(\boldsymbol{C}^{\boldsymbol{inv}} + \boldsymbol{C}^{\boldsymbol{rep}}) \tag{2c}$$

$$\boldsymbol{C}^{\boldsymbol{inv}} = \sum_{u=1}^{U} b^u \cdot (i^{c1,u} \cdot \boldsymbol{y}^{\boldsymbol{u}} + i^{c2,u} \cdot \boldsymbol{f}^{\boldsymbol{u}}) \tag{2d}$$

$$\boldsymbol{C}^{\boldsymbol{rep}} = \sum_{u=1}^{U}\sum_{r=1}^{R} \frac{1}{(1+i)^{r\cdot l_u}} \cdot (i^{c1,u} \cdot \boldsymbol{y}^{\boldsymbol{u}} + i^{c2,u} \cdot \boldsymbol{f}^{\boldsymbol{u}}) \tag{2e}$$


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## 2.1. Decomposition

The energy community model has a building scale resolution, with case studies up to 100 buildings. Due the network structure and long computation time, the Dantzig-Wolfe decomposition is applied on the original MILP problem. The methodology is described in detail in [27]. The constraint matrix of the original problem is block-angular. Each building energy system represents a subsystem independent from other subsystems except for the resources balance and capacity constraints, being linking constraints. The model is decomposed into two problems: a master problem (**MP**) and several sub problems (**SPs**). Linking constraints, such as energy balances, epsilon constraints or the transformer capacity are included in the MP and represent the district energy system problem. The MP receives building energy system designs from the SPs and selects an optimal configuration for each building by a linear combination of the proposals. Each design account for an investment into conversion units and associated energy flows with the district low voltage grid. Within an iteration loop, the SPs find new design proposals based on price signals sent by the MP. The latter correspond to the dual values of the linking constraints that are inserted in the SPs objective function as Lagrangian multipliers. The SPs are formulated as reduced costs, meaning that a solution with a negative value has the potential to improve the MP objective. The algorithm terminates when the SPs cannot find negative reduced costs.

## 2.2. Key performance indicators

Key performance indicators (**KPI**) are used to quantify solutions performance. The self-consumption (**SC**) is the share of onsite generated electricity being consumed within the district. The self-sufficiency (**SS**) corresponds to the share of the electricity demand being supplied by onsite generated electricity. PV curtailment is the share of onsite generated electricity being neither self-consumed, nor sold to the grid. Finally, similarly to the total cost, the global warming potential (**GWP**) accounts for both the construction and operation emissions from the consumption of energy resources (3d) as described in [27]. Emissions related to conversion units installation are taken from the Ecoinvent database and are calculated with the method IPCC 2013 and the version 3.6.

$$\text{SC} = (E^{gen} - E^{curt} - E^{tr,-})/E^{gen} \tag{3a}$$

$$\text{SS} = (E^{gen} - E^{curt} - E^{tr,-})/(E^{gen} - E^{curt} - E^{tr,-} + E^{tr,+}) \tag{3b}$$

$$\text{PVC} = E^{curt}/E^{gen} \tag{3c}$$

$$\text{G}^{op} = \sum_{\substack{p\in P\\ t\in T}} \left( g^{el,TR}_{p,t} \cdot (E^{tr,+} - E^{tr,-}) + \sum_{b\in B} g^{ng}_{p,t} \cdot H^{gr,+}_{b,p,t} \right) \tag{3d}$$

## 2.3. Case Study

Since Switzerland possesses 17’844 LV/MV transformers [28], a kmedoid clustering algorithm is applied to find the most representative districts. The case study is built under a geographic information system (**GIS**) approach to adequately describe the energy demand and sources. Clustering features consider real-estate typologies (heating surface, roof area, service demands, building category, construction year) and geographic ones (annual solar irradiation, average temperature, infrastructure density). Typical Swiss weather profiles had been assessed for each district by Stadler et al. [9]. With this approach, versatile district typologies are considered within a single case study. The five most representative districts are selected for this case study. The representative roof area of each typical district is used for extrapolation to the national scale. Figure 1 presents the distribution of each typical district within Switzerland and Figures 8 to 12 provide a geographical visualization of the district in the Appendix. The present study aims at analysing the impact of energy communities on the national energy system. Therefore, it is assumed that each district in Switzerland is an energy community.

Most data are open source and provided by the Swiss government. The building characteristics, such as the height, heated areas or types of construction come from cantonal and federal Official Buildings Registry [29]. Energy standards such as the envelope heat transfer, building heat capacity and domestic electricity demand as well as the internal and external heat gains are calculated based on Swiss national standard norms [30]. These data are used to build the 1R1C thermal model of the buildings [31]. The outdoor temperature and solar irradiation come from Meteonorm [32]. These time series are clustered into ten typical periods and two extreme periods using k-medoids clustering. The project horizon is 20 years and an interest rate of 2% is taken. The electricity and gas retail tariff are respectively fixed to 0.27 CHF/kWh and 0.14 CHF/kWh and the feed-in tariff is 0.17 CHF/kWh. These values are based on the average energy tariffs in Switzerland for the years 2022-2023 [33]. The carbon content of electricity are taken from [34] and equals 0.1 kg $CO_2$/kWh$_{el}$ both at the import and export. More details on buildings, units and weather data parameters are detailed in [27].

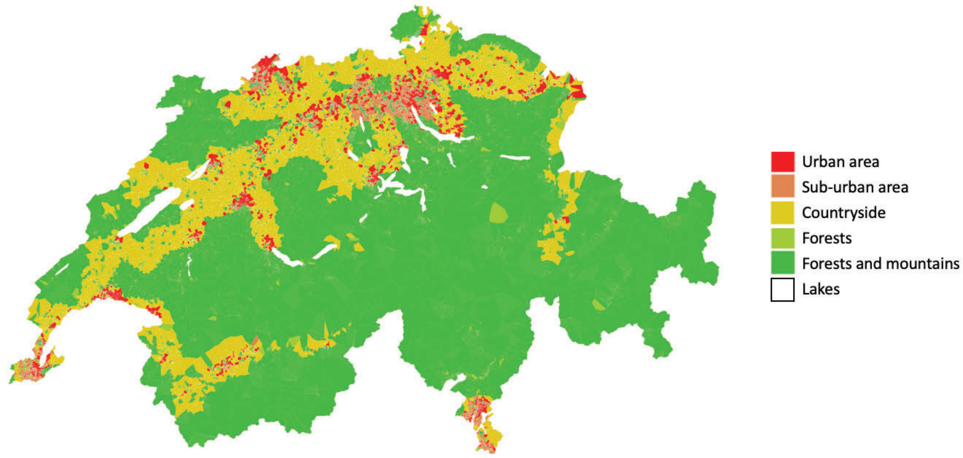


**Figure 1**: Typical districts distribution in Switzerland. The centroids differentiate the urban and weather typologies of Switzerland.

## 3. Results and Discussion

The discussion follows two axis. First, the decision trends taken within energy communities are analysed and contextualised with their geographic and urban density characteristics. Multi-objective optimization between the capital and operating costs is performed to extract the solution trends. Then, the solutions are aggregated and extrapolated to the whole country. The potential of energy communities is analysed in terms of renewable electricity supply. Finally, grid constraints and curtailment are applied to assess the cost and energy efficiency impact of a coordinated and uncoordinated investment strategy.

### 3.1. Region specific Energy Community Investments

Investment trends into energy conversion units are summarized in Figure 2. The investment and operating cost breakdown are presented respectively with red/yellow and green colors. The total cost of the system is located on the right with the blue columns and the revenues from selling electricity corresponds to the white columns. The figure shows the solution spectrum for the typical district 3, representing the countryside districts. The gas boiler solution corresponds to the one with the lowest investment and highest operational cost. The latter is decreased by substituting the base load heat supply from the boiler with a heat pump. Then, the operating costs are further decreased by a progressive investment into solar panels. Due to the profitable electricity tariffs, the energy community reaches net zero operating cost with an average investments into PV units. The operating costs are further decreased by an investment into batteries, allowing a larger investment into PV units and a higher self-consumption. Depending on the interest of the actors, the energy community moves from a passive energy consumer to a renewable electricity supplier for the utility. Similar solution trends are found throughout the other typical districts, even though the magnitude of the investments varies. Figure 3 presents the pareto optimal solutions for each of the typical district. Within the positive operating cost region solutions are similar since they correspond to solutions with few PV integration. Therefore, heating and electricity services are mainly supplied by purchasing energy from the grid and there is no interests into renewable electricity sharing. On the other hand, within the region with high PV integration, the solutions diverge based on the geographic location. The energy community with the lowest operating cost corresponds to the countryside one due to the low building density, large roof surface area and a sufficiently large community allowing economies of scale. On the other side, the district 4 has the highest operating cost, mainly due to the small size of the community. Between the two extremum are located dense urban areas having a large economy of scale but a large energy demand density and small mountain villages with low economies of scale and high thermal demand but large roofs surfaces and high solar irradiation.

### 3.2. National scale impact of Energy Communities

The electricity tariff of today favors a high implementation of PV. Figure 4 presents a sensitivity analysis on the annual renewable electricity generated by energy communities in Switzerland for a range of feed-in and retail tariffs. Below a certain energy tariff, the PV investment is not profitable due to the affordable electricity cost from the grid. The investment threshold is delimited by the lower black line. On the other side, the up-


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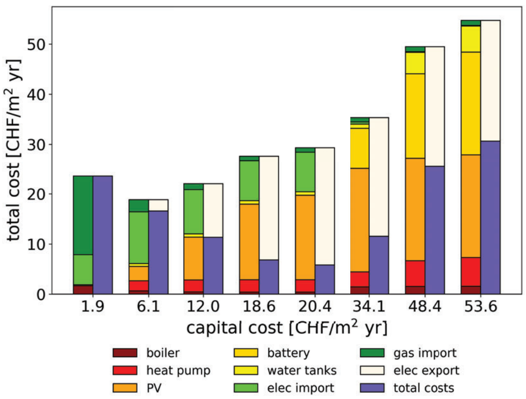


**Figure 2**: Cost breakdown of the pareto optimal solutions for the district 3 (Figure 11). The left column represents the costs. The right column stacks the total cost (blue) and the electricity revenues (white).

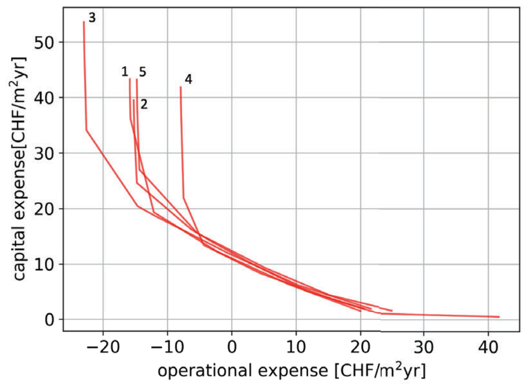


**Figure 3**: Pareto front for the 5 typical districts. The number refers to the district label in Figures 8 to 12.

per investment limit maps the region where the PV capacity reaches its maximum of 28 GW, representing an annual electricity production of 32 TWh/yr. Since the PV potential varies throughout the typical districts, there exists a spectrum of solutions. First, the district with high solar potential are activated at low electricity tariffs, then investments with lower profitability are activated as the price signals sent by the national infrastructure becomes more attractive. Actual energy tariffs promote a full investment into PV panels, reaching a potential of 32 TWh/yr. However, the optimal PV deployment in Switzerland ranges between 12 and 18 TWh/yr [5, 35]. Therefore, the price incentives should be located in the yellow and green areas. As a conclusion, there is a discordance between the price signals sent by grid operators and the needs of the infrastructure, which could result into costly grid reinforcements or curtailment. Such situations are socially unfair since the former induces costs to customers and the latter might render some investments unprofitable. Ultimately, this conflicting situation might generates mistrust in renewable deployments, therefore in the energy transition. In the following section, the impact of curtailment is analysed in terms of energy efficiency and costs.

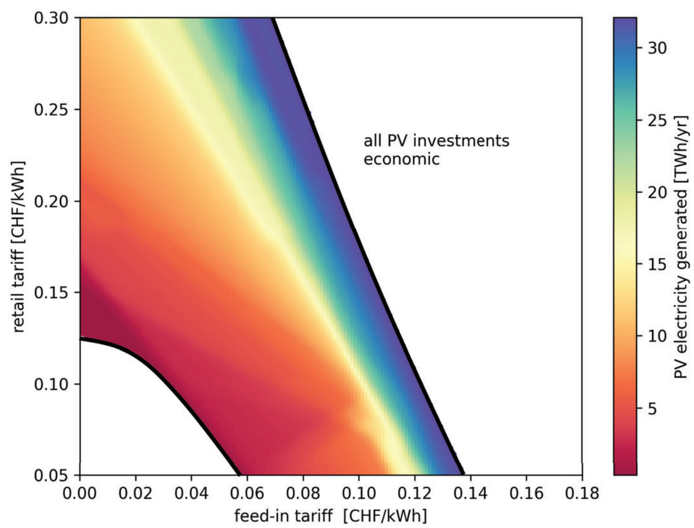


**Figure 4**: Yearly renewable electricity generation from PV units in energy communities for the whole Switzerland. The electricity supply is presented based on the electricity retail and feed-in tariffs. Data were calculated for the minimum total costs.

To support the analysis, two scenarios are considered. In the first one, an investment decision in PVs and heat pumps is taken today. Then, PV curtailment is applied on the energy system. The operation and investment into batteries are optimized with fixed sizes of PV and heat pump units. In the second scenario, the investment and operation decisions of the overall energy systems are taken considering grid curtailment. Therefore, the PV and heat pump capacities vary with the level of curtailment. The aim of these two scenarios is to assess the impact of grid curtailment on a decision taken today. Figure 5 shows the load duration curve of the electricity fluxes between energy communities and the national grid. The electricity tariffs promote a net export of electricity of 26 TWh/yr, 6 TWh/yr being self-consumed within the communities. The curtailed system reduces by half the maximum export power. In the first scenario, most of the peak is removed while the base load remains stable. This outcome is beneficial for the grid utility since the annual export is less intermittent and decreases to 19 TWh. However, from the perspective of the households, the PV investment is oversized since the optimal export with variable PV capacity would have been 15% lower (dashed red line).

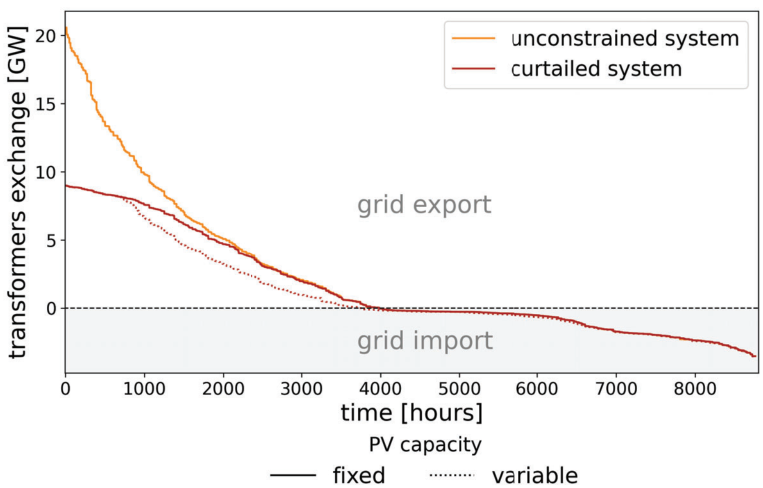


**Figure 5**: Load duration curve of the electricity imports and exports for energy communities in Switzerland. The unconstrained solution is constrained to reduce the maximum power peaks by half. Two design scenarios are considered, one accounting curtailment in the investment decision (variable PV) and the other one being imposed curtailment after investment decision (fixed PV).

Figures 6 and 7 further detail the energy efficiency, costs and impacts of the two scenarios. They compare metrics to the level of annual electricity export. Based on the renewable needs of the national energy system, an annual electricity export reduction by 8 TWh/yr is needed, decreasing the energy communities exports from 26 TWh/yr to 18 TWh/yr. With a fixed PV design, energy communities invest into batteries to compensate the PV over-investment with self-consumption (Figure 6). For an electricity export reduction of 8 TWh/yr, the battery investment is still not profitable and the SC and SS respectively increase to 18.5% and 50%. In the second scenario, the consideration of the grid capacity in the planning phase decreases the PV capacity by 22%. This decreases the SS from 48% to 46% but increases the SC from 17% to 22% and minimized grid curtailment (5%). The latter is 5 times higher in the first scenario (24%). While a coordinated design promotes self-consumption with a well sized PV capacity, the uncoordinated one reduces export peaks only with curtailment. The energy system is designed to generate large amount of electricity. Therefore, the high presence of renewable electricity in energy communities makes the SS high and the system less flexible to reduce the power peaks with self-consumption.

Since the peak shaving strategy of the second scenario is to decrease the PV capacity, the onsite generated electricity decreases faster with peak reduction compared to the first scenario. To generate the renewable electricity needs of the country, a peak reduction of respectively 41% and 58% is needed in the first and second scenarios (Figure 7). This trend is as well visible on Figure 5 since the scenario with fixed PV capacity has a flatter profile than the one with variable capacity. The oversized PV capacity and curtailment induces a total cost difference of 31% between the two scenarios. The larger amount of electricity sold to the grid in the first scenario do not compensate for the high investment cost on the contrary to the second scenario

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where the total costs are balanced between lower electricity revenues and lower investments. From the GWP perspective, both scenarios are usually net negative since they contribute to reduce the carbon content of the grid. At an electricity export reduction of 8 TWh/yr, the scenarios respectively decrease the GWP by -1.5 and -2.1 kg $CO_{2,eq}/m_2$. This has to be contextualised with the actual Swiss GWP of the residential sector, being 6.6 kg $CO_{2,eq}/m_2$ [36]. The difference of 0.6 kg $CO_{2,eq}/m_2$ between the two scenario is due to the embodied carbon content of the PV installation in the first scenario. It represents 9% of the Swiss residential GWP and 1.5% of the direct GWP in the whole country [36].

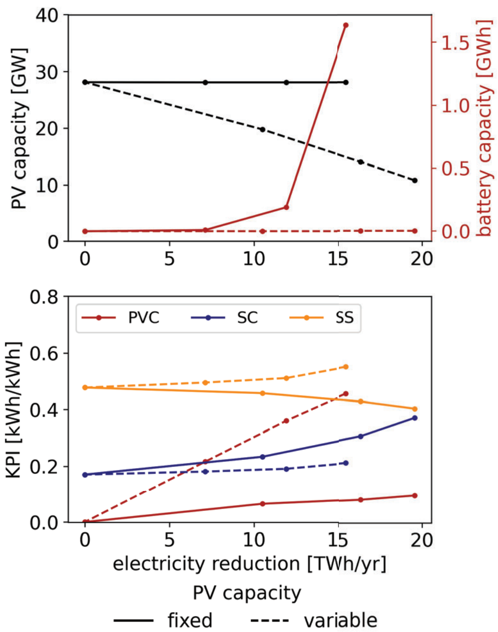


Figure 6: PV and battery capacity with PV indicators for the two scenarios based on the level of electricity export reduction. A reduction by 8 TWh/yr of the unconstrained solution is needed in Switzerland.

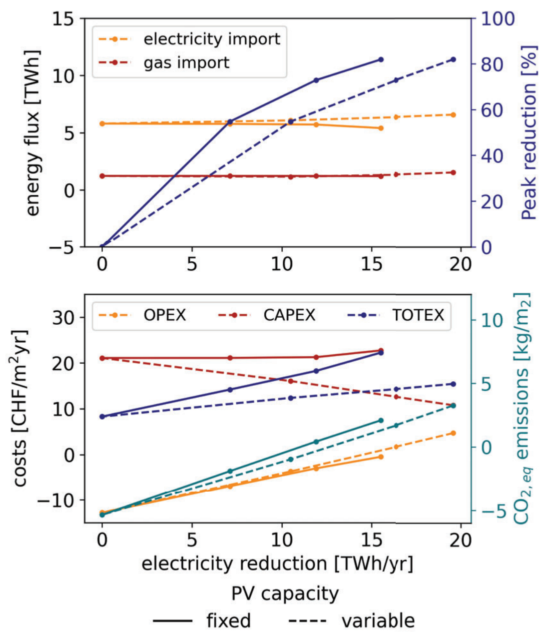


Figure 7: Energy fluxes with the utility, costs and $CO_{2,eq}$ impact metrics. All values are given after extrapolation to the whole country.

## 4. Conclusion

The objective of this paper was to highlight the decisions trends within energy communities and their integration in the national energy infrastructure. The community is modeled as a renewable energy hub with investment into conversion units. Typical districts are considered to extrapolate the results to the national scale. Multi-objective optimization and grid constraints are applied to meet the renewable electricity supply from the communities to the forecast national needs in 2050. The main outcomes of the study are listed below:

- The investment trends are homogeneous throughout the typical energy communities, even though the investment magnitude into solar panels differs between urban, countryside and isolated areas.
- The PV potential of the residential sector in Switzerland reaches 32 TWh/yr. The associated PV capacity is 28 GW.
- The actual electricity tariffs promote an excessive PV integration in the national electricity system. Based on national guidelines, the annual electricity supply from PV panels could exceed by a factor two the demand, being between 12 and 18 TWh/yr.
- Uncoordinated price signals induce an oversized PV capacity. Grid constraints curtail 24% of the generated electricity and increase by 31% the total costs compared to a coordinated planning, where the energy communities design their energy system based on the needs of the infrastructure. Moreover, the GWP difference between the uncoordinated and coordinated designs represent 9% of the residential total emissions.

The presented results contribute to a better understanding on the decision inter-dependency between small scale actors and national energy systems. The holistic approach encompassing various stakeholders within a single optimization favors a coordinates energy transition and increases the technological acceptance into a decision. Grid operators and national institutions should communicate properly the right price signals to local stakeholders to prevent unfair investments and mitigate costs and emissions. The extension of the work includes a better definition of the national infrastructure, accounting its energy flows and reinforcement costs. To this extent, bi-level and nested decomposition methods have a high potential at linking optimization tools modeling the various decision levels.

## 5. 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 project acronym. The authors bear sole responsibility for the conclusions and the results of the presented publication.

## 6. Appendix

**Figure 8**: Typical district 1: urban area

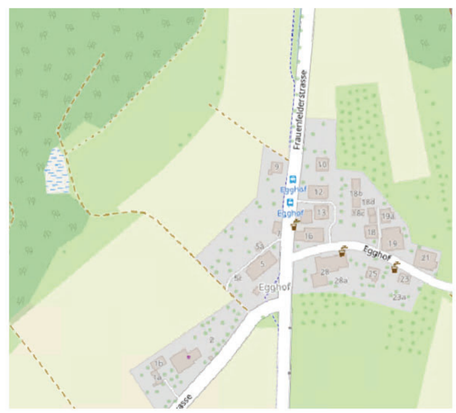


**Figure 9**: Typical district 4: forest area


**Figure 10**: Typical district 2: suburban area

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**Figure 11**: Typical district 3: countryside area

**Figure 12**: Typical district 5: mountain area

## 7. Nomenclature

**Table 2**: Nomenclature Table

| Abbreviation | Definition |
|---|---|
| PV | Photovoltaic |
| MILP | Mixed Integer Linear Programming |
| CAPEX | Capital cost |
| OPEX | Operating cost |
| TOTEX | Total cost |
| MP | Master Problem |
| SP | Sub Problem |
| KPI | Key Performance Indicator |
| SC | Self-Consumption |
| SS | Self-Sufficiency |
| GWP | Global Warming Potential |
| GIS | Geographic Information System |
| $E^{tr,+}$ | Electricity import from the low voltage transformer |
| $E^{tr,-}$ | Electricity export to the low voltage transformer |
| $E^{gr,+}$ | Electricity import from the microgrid |
| $E^{gr,-}$ | Electricity export to the microgrid |
| $E^{gen}$ | Onsite generated electricity |
| $E^{curt}$ | Curtailed electricity |
| $H^{gr,+}$ | Natural gas import from the gas utility |

## References


[1] European Parliament. "DIRECTIVE (EU) 2018/ 2001 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL - of 11 December 2018 - on the promotion of the use of energy from renewable sources". en. In: (2018), p. 128.

[2] Henner Busch et al. "Policy challenges to community energy in the EU: A systematic review of the scientific literature". en. In: *Renewable and Sustainable Energy Reviews* 151 (Nov. 2021), p. 111535. ISSN: 13640321. DOI: 10.1016/j.rser.2021.111535. URL: https://linkinghub.elsevier.com/retrieve/pii/S1364032121008133 (visited on 11/02/2022).

[3] Tineke van der Schoor et al. "Challenging obduracy: How local communities transform the energy system". en. In: *Energy Research & Social Science* 13 (Mar. 2016), pp. 94–105. ISSN: 22146296. DOI: 10.1016/j.erss.2015.12.009. URL: https://linkinghub.elsevier.com/retrieve/pii/S2214629615300967 (visited on 10/05/2022).

[4] Internation Renewable Energy Agency. “World Energy Transitions Outlook”. In: (2021).

[5] Swiss Federal Office of Energy. *ENERGY STRATEGY 2050, MONITORING REPORT 2019*. Tech. rep. 2019.

[6] Swiss Federal Office of Energy. *Perspectives énergétiques 2050*. Tech. rep. 2913.

[7] Mohammad Mohammadi. “Optimal management of energy hubs and smart energy hubs – A review”. en. In: *Renewable and Sustainable Energy Reviews* (2018).

[8] Yeong-Geon Son et al. “Multi Energy System With an Associated Energy Hub: A Review”. en. In: *IEEE Access* 9 (2021), pp. 127753–127766. ISSN: 2169-3536. DOI: 10.1109/ACCESS.2021.3108142. URL: https://ieeexplore.ieee.org/document/9523745/ (visited on 02/12/2023).

[9] Paul Michael Stadler. “Model-based sizing of building energy systems with renewable sources”. fr. PhD thesis. Lausanne, 2019.

[10] Leander Kotzur et al. “Bottom-up energy supply optimization of a national building stock”. en. In: *Energy and Buildings* 209 (Feb. 2020), p. 109667. ISSN: 03787788. DOI: 10.1016/j.enbuild.2019.109667. URL: https://linkinghub.elsevier.com/retrieve/pii/S0378778819319863 (visited on 06/21/2021).

[11] Auyon Chakrabarti et al. “Optimisation and analysis of system integration between electric vehicles and UK decentralised energy schemes”. en. In: *Energy* 176 (June 2019), pp. 805–815. ISSN: 03605442. DOI: 10.1016/j.energy.2019.03.184. URL: https://linkinghub.elsevier.com/retrieve/pii/S0360544219306048 (visited on 01/26/2022).

[12] Portia Murray, Jan Carmeliet, and Kristina Orehounig. “Multi-Objective Optimisation of Power-to-Mobility in Decentralised Multi-Energy Systems”. en. In: *Energy* 205 (Aug. 2020), p. 117792. ISSN: 03605442. DOI: 10.1016/j.energy.2020.117792. URL: https://linkinghub.elsevier.com/retrieve/pii/S0360544220308999 (visited on 03/12/2022).

[13] Moritz Mittelviefhaus et al. “Optimal investment and scheduling of residential multi-energy systems including electric mobility: A cost-effective approach to climate change mitigation”. en. In: *Applied Energy* 301 (Nov. 2021), p. 117445. ISSN: 03062619. DOI: 10.1016/j.apenergy.2021.117445. URL: https://linkinghub.elsevier.com/retrieve/pii/S0306261921008357 (visited on 03/12/2022).

[14] Alaa Alhamwi et al. “Modelling urban energy requirements using open source data and models”. en. In: *Applied Energy* 231 (Dec. 2018), pp. 1100–1108. ISSN: 03062619. DOI: 10.1016/j.apenergy.2018.09.164. URL: https://linkinghub.elsevier.com/retrieve/pii/S0306261918314752 (visited on 06/21/2021).

[15] Michael Kramer, Akhila Jambagi, and Vicky Cheng. “Bottom-up Modeling of Residential Heating Systems for Demand Side Management in District Energy System Analysis and Distribution Grid Planning”. en. In: (2017), p. 8.

[16] Tetsuya Wakui et al. “Two-stage design optimization based on artificial immune system and mixed-integer linear programming for energy supply networks”. en. In: *Energy* 170 (Mar. 2019), pp. 1228–1248. ISSN: 03605442. DOI: 10.1016/j.energy.2018.12.104. URL: https://linkinghub.elsevier.com/retrieve/pii/S0360544218324708 (visited on 05/25/2021).

[17] Jonathan Reynolds et al. “Operational supply and demand optimisation of a multi-vector district energy system using artificial neural networks and a genetic algorithm”. en. In: *Applied Energy* 235 (Feb. 2019), pp. 699–713. ISSN: 03062619. DOI: 10.1016/j.apenergy.2018.11.001. URL: https://linkinghub.elsevier.com/retrieve/pii/S0306261918317070 (visited on 06/21/2021).

[18] B. Pickering and R. Choudhary. “District energy system optimisation under uncertain demand: Handling data-driven stochastic profiles”. en. In: *Applied Energy* 236 (Feb. 2019), pp. 1138–1157. ISSN: 03062619. DOI: 10.1016/j.apenergy.2018.12.037. URL: https://linkinghub.elsevier.com/retrieve/pii/S0306261918318555 (visited on 06/21/2021).

[19] Samira Fazlollahi, Gwenaelle Becker, and François Maréchal. “Multi-objectives, multi-period optimization of district energy systems: II—Daily thermal storage”. en. In: *Computers & Chemical Engineering* 71 (Dec. 2014), pp. 648–662. ISSN: 00981354. DOI: 10.1016/j.compchemeng.2013.10.016. URL: https://linkinghub.elsevier.com/retrieve/pii/S0098135413003384 (visited on 06/21/2021).

[20] Thomas Schütz et al. “Optimal design of decentralized energy conversion systems for smart microgrids using decomposition methods”. en. In: *Energy* 156 (Aug. 2018), pp. 250–263. ISSN: 03605442. DOI: 10.1016/j.energy.2018.05.050. URL: https://linkinghub.elsevier.com/retrieve/pii/S0360544218308703 (visited on 02/22/2021).


 https://doi.org/10.52202/069564-0305

[21] Marco Wirtz et al. “5th generation district heating and cooling network planning: A Dantzig–Wolfe decomposition approach”. en. In: *Energy Conversion and Management* 276 (Jan. 2023), p. 116593. ISSN: 01968904. DOI: 10.1016/j.enconman.2022.116593. URL: https://linkinghub.elsevier.com/retrieve/pii/S0196890422013711 (visited on 01/27/2023).

[22] Carl Haikarainen, Frank Pettersson, and Henrik Saxén. “A decomposition procedure for solving two-dimensional distributed energy system design problems”. en. In: *Applied Thermal Engineering* 100 (May 2016), pp. 30–38. ISSN: 13594311. DOI: 10.1016/j.applthermaleng.2016.02.012. URL: https://linkinghub.elsevier.com/retrieve/pii/S1359431116301387 (visited on 02/03/2023).

[23] Tetsuya Wakui, Moe Hashiguchi, and Ryohei Yokoyama. “Structural design of distributed energy networks by a hierarchical combination of variable- and constraint-based decomposition methods”. en. In: *Energy* 224 (June 2021), p. 120099. ISSN: 03605442. DOI: 10.1016/j.energy.2021.120099. URL: https://linkinghub.elsevier.com/retrieve/pii/S0360544221003480 (visited on 02/03/2023).

[24] Boran Morvaj, Ralph Evins, and Jan Carmeliet. “Optimization framework for distributed energy systems with integrated electrical grid constraints”. en. In: *Applied Energy* 171 (June 2016), pp. 296–313. ISSN: 03062619. DOI: 10.1016/j.apenergy.2016.03.090. URL: https://linkinghub.elsevier.com/retrieve/pii/S0306261916304159 (visited on 02/03/2023).

[25] Javier Silvente et al. “A rolling horizon optimization framework for the simultaneous energy supply and demand planning in microgrids”. en. In: *Applied Energy* 155 (Oct. 2015), pp. 485–501. ISSN: 03062619. DOI: 10.1016/j.apenergy.2015.05.090. URL: https://linkinghub.elsevier.com/retrieve/pii/S0306261915007230 (visited on 02/03/2023).

[26] Caroline Bastholm and Annette Henning. “The use of three perspectives to make energy implementation studies more culturally informed”. en. In: *Energy, Sustainability and Society* 4.1 (Dec. 2014), p. 3. ISSN: 2192-0567. DOI: 10.1186/2192-0567-4-3. URL: https://energsustainsoc.biomedcentral.com/articles/10.1186/2192-0567-4-3 (visited on 11/29/2022).

[27] Luise Middelhauve and Francois Marechal. “About Data Reduction Techniques and the Role of Outliers for Complex Energy Systems”. In: (2022). URL: https://www.sciencedirect.com/science/article/abs/pii/B978032385159650292X.

[28] Rahul Gupta, Fabrizio Sossan, and Mario Paolone. “Countrywide PV hosting capacity and energy storage requirements for distribution networks: The case of Switzerland”. en. In: *Applied Energy* 281 (Jan. 2021), p. 116010. ISSN: 03062619. DOI: 10.1016/j.apenergy.2020.116010. URL: https://linkinghub.elsevier.com/retrieve/pii/S0306261920314537 (visited on 06/13/2021).

[29] Federal Statistical Office. “Federal Register of Buildings and Dwellings”. In: (2019).

[30] SIA. “SIA 380/1:2016 Heizwärmebedarf. Schweizerischer Ingenieur und Architektenverein”. In: (2016).

[31] Luc Girardin. “A GIS-based Methodology for the Evaluation of Integrated Energy Systems in Urban Area”. PhD thesis. EPFL, 2012. DOI: 10.5075/epfl-thesis-5287. URL: http://infoscience.epfl.ch/record/170535/files/EPFL_TH5287.pdf.

[32] J. Remund et al. *METEONORM - Global Meteorological Database for Engineers, Planners and Education*. 2003.

[33] Association des producteurs d’énergie indépendants. *Carte interactive des rétributions*. 2023. URL: https://www.vese.ch/fr/pvtarif/.

[34] Alessio Santecchia. “Enabling renewable Europe through optimal design and operation”. en. In: (2022).

[35] Jonas Schnidrig et al. “A modelling framework for assessing the impact of green mobility technologies on energy systems”. en. In: *34th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems (ECOS 2021)*. Taormina, Italy: ECOS 2021 Program Organizers, 2022, pp. 928–940. ISBN: 978-1-71384-398-6 978-1-71384-393-1. DOI: 10.52202/062738-0083. URL: http://www.proceedings.com/062738-0083.html (visited on 01/29/2023).

[36] Office fédéral de l’environnement OFEV. “Indicateurs de l’évolution des émissions de gaz à effet de serre en Suisse”. fr. In: (2022).