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Internal pricing in integrated energy system design

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Environmentally sustainable and economically viable process and energy systems are imperative to a successful energy transition. Often, design configurations are derived from a global perspective, in which the individual needs and interests of actors within the system are overlooked. This work proposes an approach for designing a system considering its entire scope and acknowledging the individual actors within the system. System solutions are generated from the perspective of a universal decision-maker who is aware of the whole system, and the obtained solution space is analyzed regarding implications for the individual actors. Thereby, prices of internal exchanges between actors that would allow for the realization of the optimal integrated system solution while granting each actor their economic objectives are derived. The approach is demonstrated in three distinct case studies varying in size: a bio-based industrial site, a renewable energy community, and a national energy system. All case studies yield system configurations allowing the actors to profit from economic benefits emerging from synergies from internal cooperation. Further research must delve into diverse system settings and actor paradigms to enhance the robustness and applicability of the derived insights.

KEYWORDS

energy system design, energy transition, energy system optimization, multi-actor modeling, internal pricing, energy hubs

1 Introduction

The synthesis and operation of process and energy systems is a highly complex task that is often addressed with optimization-based approaches. In the context of the energy transition, it is crucial that systems are well integrated, profiting from efficient resource exploitation and synergies between actors in the system. Particularly with regard to renewable electricity availability, efficient interaction between entities involved in power generation, consumption, and storage is essential.

The application of optimization-based approaches can result in different ways of dealing with a problem that involves multiple actors, which perspective to take, and what the scope of the problem formulation should be. One option is to identify solutions from the centralized perspective, often applying multi-objective optimization (MOO), where multiple conflicting objectives are considered simultaneously to find a set of Pareto-optimal solutions (Wang et al., 2020). Previous studies feature a wide range of applications from generation expansion modeling (Luz et al., 2018) to the design of hybrid and renewable energy systems (Zou et al., 2010; Clarke et al., 2015) and long term energy system planning (Prebeg et al., 2016). Furthermore, energy system planning in consideration of uncertainty (Di Somma et al., 2018) is presented, as well as the analysis of system integration opportunities within community energy systems (Koirala et al., 2016). Solutions obtained from system-level optimization approaches are usually well-integrated, but lack a guarantee of feasibility, as the effect posed on the actors inside the system might not meet their demands (Schnidrig et al., 2023). Although optimal from a system and integration perspective, some local stakeholders and partners might be faced with subpar solutions, which increases their reluctance to accept those designs (Wang et al., 2020; Schär and Geldermann, 2021). Consequently, optimization of the overall system is coupled with multi-criteria decision-making (MCDM) techniques in order to account for preferences of different actors involved in a system (Wang et al., 2020; Schär and Geldermann, 2021). MCDM evaluates and ranks alternatives based on multiple criteria reflecting stakeholder preferences. Nevertheless, it can introduce subjectivity through criteria weighting and may face scalability issues in complex systems (Wang et al., 2020). Thus, while MOO provides system-level optimal solutions but may overlook individual needs, MCDM incorporates stakeholder preferences but can be subjective and less scalable. Comprehensive reviews of MCDM for energy system planning are provided by Antunes and Henriques (2016); Kumar et al. (2017) and Alizadeh et al. (2020). An overview of combinations MCDM with MOO for energy system planning is provided by Wang et al. (2020).

When competition between actors requires multi-scale approaches to adequately provide decision support, bi-level optimization techniques are often applied. Application areas of bi-level optimization are capacity expansion modeling (Shu et al., 2024), power system planning (Pozo et al., 2017), market biding problems (Wang et al., 2017), and the analysis of carbon taxation (Martelli et al., 2020). Different formulation approaches for bi-level optimization approaches are available in the literature, depending on the underlying analysis (Shu et al., 2024). In general, bi-level optimization problems consist of an upper and a lower-level problem, where the upper level corresponds to the leader, and the lower level represents the followers (Dempe et al., 2015). Bi-level optimization applied to energy systems modeling usually follows a linear formulation for both upper- and lower-level problems (Shu et al., 2024; Wogrin et al., 2020). The objectives of the lower and upper level depend largely on the application: for capacity expansion modeling, a common objective of the upper level is the minimization of cost, while the objectives on the lower level include the maximization of social welfare. Size and complexity of bi-level models is still limited by high computational efforts (Shu et al., 2024). However, bi-level optimization can illustrate decision-making on two levels and provide valuable support in planning problems involving multiple hierarchical levels.

Furthermore, agent-based modeling (ABM) is widely applied to address competition and misalignment of interests between actors in a system and generates solutions considering all their demands. Each agent acts as an individual entity and has limited knowledge of the state of other agents. ABM simulates the interactions of autonomous agents to capture emergent system behaviors, effectively representing decentralized systems. However, it requires detailed behavioral data and can be computationally intensive for large-scale applications. The method has been particularly applied in grid management, energy system optimization, and supply chain management. Comprehensive reviews are presented by González-Briones et al. (2018) and Roche et al. (2010). Game theory expands the concept of agent-based models by setting a framework for the objectives and interactions between the actors. Thereby, a central entity must decide while anticipating multiple subsystems' responses. Thus, the leader does not impose a solution on the followers but analyzes the conditions at the systems' boundaries to identify trade-offs. A common type of leader-follower relationship where a leader makes decisions before a follower is called Stackelberg game (Stackelberg, 2010). They have been widely applied to energy system modeling (Martelli et al., 2020; Kazempour et al., 2011); a review of their application to energy trading among electric vehicles is provided by Adil et al. (2021). Further examples of game theory applications in the energy fields are provided by Yu and Hong (2017) and Sarfarazi et al. (2020). A comprehensive review of applications within the energy system field is provided by He et al. (2020). Game theory models are usually solved with decomposition methods, such as bi-level optimization (Du et al., 2019).

While significant work addresses the design of integrated process and energy systems, the problem is often addressed from the perspective of a universal decision-maker, neglecting the impacts and interests of the individual system actors. However, it is likely that the transition of the energy system towards more sustainability, including the vast penetration of volatile renewable resources, a shift towards alternative technologies such as electric vehicles in the residential sector, and alternative production processes in the industry, will lead to a more decentralized system involving new actors. To activate the full synergistic potential of such highly interconnected systems, it is crucial to consider the interests and needs of these actors when striving for optimally integrated system configurations. As such, the significance of considering heterogeneous actor demands in energy system design has been demonstrated for the development of European energy communities by Lode et al. (2022). However, contributions that account for multiple actors often consider the objective functions of all actors when designing systems, not necessarily leading to the optimal solution from the system perspective.

To address the identified limitations, the presented approach integrates system-level optimization with individual actor preferences, aiming to generate solutions that are both globally efficient and locally acceptable, thus enhancing feasibility and stakeholder acceptance.

The objective of this paper is to present a universal approach that identifies system configurations preferable for involved actors, defines pricing strategies for internal exchanges, and allocates investments among actors. Thereby, the system

Abbreviations: ABM, agent-based model; CAPEX, capital expenditure; DSO, distribution system operators; GHG, greenhouse gas; GWP, global warming potential; MCDM, multi-criteria decision-making; MILP, mixed integer linear programming; MOO, multi-objective optimization; MP, master problem; OPEX, operating expenditure; SP, sub-problem; TOTEX, total expenditure; TSO, transmission system operator.

configuration is chosen from a given set of configurations, emerging from the solutions of a system-level optimization problem. Each configuration is defined by specific investments and flows of materials and energy. By moving beyond the traditional vision of a global optimum, our method identifies potential opportunities and trade-offs of system-optimal solutions for involved actors, allowing for the analysis from different perspectives. Thus, the benefits of integration can be quantified from the perspective of the different actors, while respecting system optimality. The methodology combines the advantages of previously discussed methods — such as the system-level optimization of MOO, the stakeholder inclusivity of MCDM, and the actor-specific focus of ABM — without their respective limitations.

It is worth noting that the initial research activities that led to this work are part of the thesis (Chapter five) of one of the authors (Granacher, 2023), where synergies between an industrial site and a residential district are discussed in the context of an integrated energy system. While our previous research activities aimed towards providing insights regarding potential synergistic effects for one specific multi-actor system, the research presented herein expands on the previous approach and generalizes it to any multi-actor energy system, demonstrating its relevance for addressing different challenges related to the energy transition. The developed methodology is described in the following sections, and its universal applicability is demonstrated on three case studies, varying in size and complexity. These case studies illustrate how different systems — with unique actors, flows, and investment decisions — can be analyzed using our proposed method to identify preferable system configurations and adequate pricing strategies for internal exchanges. The first case involves a bio-based industry and a residential district, showcasing how a symbiotic association reduces costs and emissions. The second case examines a renewable energy community, reflecting the exchanges and benefits among owners, renters, and utility companies. The third case applies the methodology to the Swiss energy system, providing insights into equitable cost and benefit distribution across diverse stakeholders.

2 Methods

For a given superstructure, which in this context is a system model encompassing all possible installations and flows between actors within the system, a selection of design configurations on the system level is generated. For this purpose, an optimization problem is solved, considering the overall system performance in the objective. Different strategies can be applied to generate a multitude of optimal system-level design configurations. For instance, a multi-objective formulation with varying objective weights or an ε-constraint formulation can be applied, or parameters of the optimization problem can be varied to generate a diverse solution space of different configurations. In the case studies presented in this paper, different approaches are demonstrated. Each obtained system configuration features unique design characteristics, potentially making it interesting to a decision-maker or system actor.

TABLE 1 Elements of the mathematical formulation of the optimization problem.

Sets	
$a \in \mathbf{A}$	Actors, $a' \in \mathbf{A}$, $\{(a,a') \mid a \neq a'\}$
$a^o \in \mathbf{A}$	Objective Actor
$i \in \mathbf{I}$	Investments
$r \in \mathbf{R}$	Resources
$s \in \mathbf{S}$	System Configurations
Parameters	
$\gamma^{inv}_{a,i,s}$	Cost of investment i allocated to actor a in configuration s
$\zeta_{a,a',r,s}$	Flow of resource r from actor a to a'
$\gamma^{op,e^{+/-}}_{r,s}$	Price of resource r purchased from or sold to the outside of system
$\zeta^{e^{+/-}}_{a,r,s}$	Flow of resource into$^{(+)}$ or out$^{(-)}$ of the system
$\tau_{a,i}$	Annualization factor for investment i allocated to actor a
$\mu^{low/up}_{r}$	Upper/Lower price bound for resource r
Free variables	
$\mathbf{c}^{tot}_{\mathbf{a}}$	Total cost of actor a
$\mathbf{c}^{op}_{\mathbf{a,a',r,s}}$	Price of resource r exchanged between actors a and a' in configuration s
Binary variables	
y_s	Activation of configuration s

After the initial solution generation, a second optimization problem is formulated to choose from the given set of obtained system configurations $s \in \mathbf{S}$, and to determine the prices of internal exchanges between actors. In the presented formulation of this second optimization problem, decision variables are denoted as lower-case bold Latin letters, and parameters as lower-case Greek letters. Sets are denoted in upper-case bold Latin letters, and set members in lower-case Latin letters. Relevant parameters, variables and sets are summarized in Table 1 and the framework is illustrated in Figure 1. For each actor $a \in \mathbf{A}$ of the system, the total cost they are subjected to is defined by the annualized investment cost and operating cost, including buying and selling of resources $r \in \mathbf{R}$, as well as cost for potential maintenance they need to account for (Equation 2).

In the suggested formulation, $\zeta_{a,a',r,s}$ denotes the internal exchange of resource r from actor a to a', in system configuration s at price $\mathbf{c}^{op}_{\mathbf{a,a',r,s}}$. Thus, in this optimization problem $\zeta_{a,a',r,s}$ are parameters originating from the configurations obtained from the system-level optimization, while prices are decision variables. Resources that can not be balanced between actors internally are imported or exported over the system boundaries, denoted by $\zeta^{e^{+/-}}_{a,r,s}$. Resource streams exchanged with the market are distributed to the

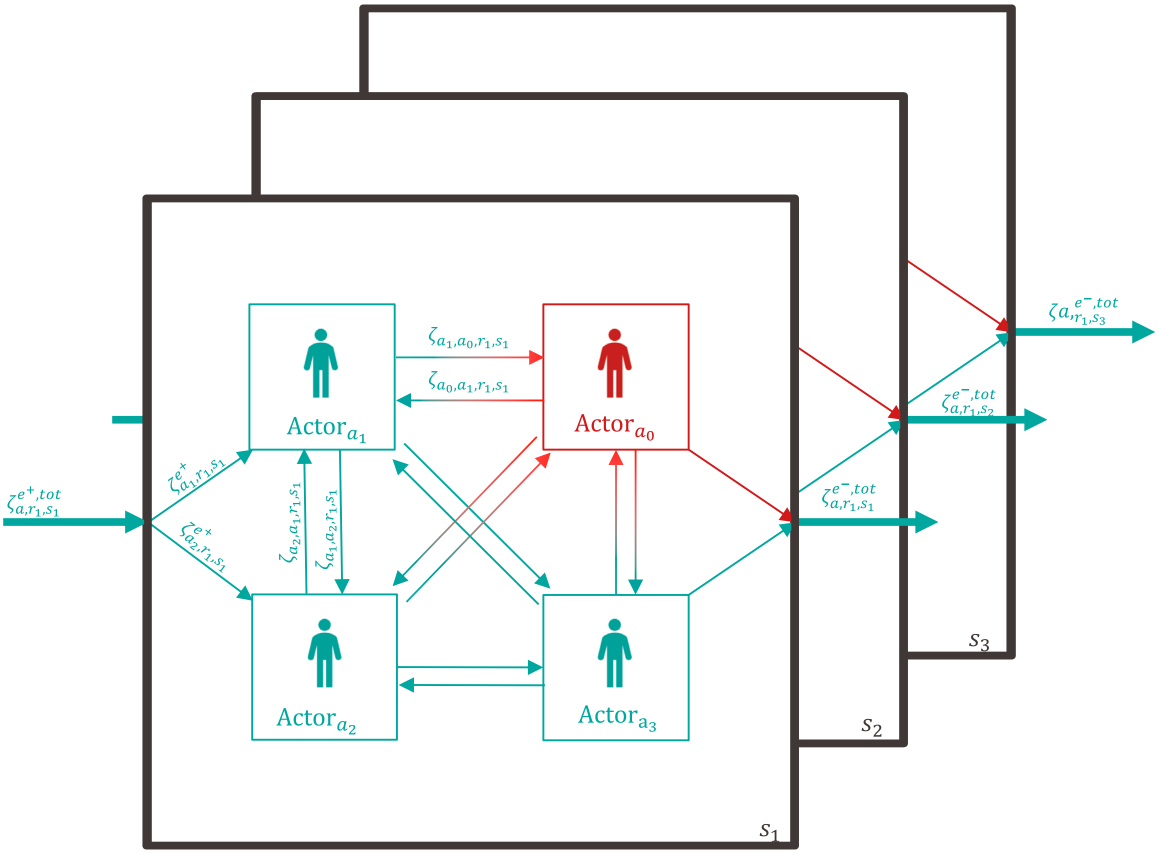

FIGURE 1
Scope considered in the proposed approach. Each system configuration s is characterized by multiple actors that exchange flows of energy and material among themselves, and with the external market.

internal actors over a bundling instance that dictates the external market price $\gamma^{op,e^{+/-}}_{r,s}$ for imported or exported products. Thereby, these market costs directly influence the prices for internally exchanged products. The annual investment that each actor a needs to account for in a system configuration s originates from the results of the previously conducted system-level optimization and is defined by the sum of cost $\gamma^{inv}_{a,i,s}$ over all investments $i \in \mathbf{I}$ allocated to actor a in a given system configuration, annualized by $\tau_{a,i}$ (Equation 2).

Only one system configuration can be selected, ensured by the binary decision variable y_s (Equation 5). To linearize the optimization problem, Equation 3 constrains the prices of internal exchanges to zero in all configurations but the one chosen by the optimizer, using the binary decision variable y_s. For the selected configuration ($y_s = 1$), the prices of resources are constrained by the parameterized bounds $\mu_r^{low/up}$.

For solving the problem and generating a set of solutions, the cost function of one actor a^o is minimized (Equation 1), while the cost functions of the other actors are constrained by varying parameters ε_a (Equation 4). Thus, the solutions of this second optimization problem consist of the system configuration selected and the prices for internal exchanges.

$$\min \quad \mathbf{c}^{tot}_{\mathbf{a^o}} \tag{1}$$

$$\text{st: } \mathbf{c}^{tot}_{\mathbf{a}} = \sum_s^{\mathcal{S}} y_s \left[\sum_i^{\mathcal{I}} \frac{\gamma^{inv}_{a,i,s}}{\tau_{a,i}} \right] + \sum_s^{\mathbf{S}} \sum_r^{\mathbf{R}} \sum_{a'}^{\mathbf{A}} \left[\mathbf{c}^{op}_{\mathbf{a,a',r,s}} \cdot \zeta_{a,a',r,s} - \mathbf{c}^{op}_{\mathbf{a',a,r,s}} \cdot \zeta_{a',a,r,s} \right] + \sum_s^{\mathbf{S}} y_s \sum_r^{\mathbf{R}} \left[\gamma^{op,e^+}_{r,s} \cdot \zeta^{e^+}_{a,r,s} - \gamma^{op,e^-}_{r,s} \cdot \zeta^{e^-}_{a,r,s} \right] \quad \forall a \in \mathbf{A} \tag{2}$$

$$\mu_r^{low} \cdot \mathbf{y_s} \leq \mathbf{c}^{op}_{\mathbf{a,a',r,s}} \leq \mu_r^{up} \cdot \mathbf{y_s} \qquad \forall a \in \mathbf{A}, \forall a' \in \mathbf{A}, \forall s \in \mathbf{S}, \forall r \in \mathbf{R} \tag{3}$$

$$\mathbf{C}^{tot}_{\mathbf{a}} \leq \varepsilon_a \quad \forall a \in \mathbf{A} \backslash a^o \tag{4}$$

$$\sum_s^{S} y_s = 1 \tag{5}$$

3 Application

The method is applied to three different case studies representative of common design problems relevant to the energy transition. Although they vary in size and are related to different fields of application, they all include multiple actors who interact with each other within a system. The following provides an overview of each system. As this paper aims to demonstrate the usability of the developed approach for various applications, the individual case study descriptions are kept short, and relevant related work is referenced for further information.

3.1 Bio-based industry and residential district

Industrial sites that operate on bio-based resources hold the potential to co-produce biofuels and provide waste heat to other consumers, thereby contributing to the reduction of greenhouse gas (GHG) emissions and increasing local resource efficiency. In the presented case study, this opportunity is explored in the example of a Kraft pulp mill and a nearby residential district. With the presented approach, we investigate potential economic and environmental synergies that evolve for individual actors by exploiting cooperation opportunities, while taking favorable system-level configurations in consideration. A detailed investigation of the interaction of a biorefinery with a residential district is available in our previous work (Granacher et al., 2023) and Chapter five of the corresponding thesis (Granacher, 2023). Herein, as the objective is to demonstrate the general applicability of the suggested method, main insights are summarized.

In the conventional configuration used as a reference, the mill co-produces pulp and electricity, whereas the residential district satisfies its heating, electricity and transportation demands by importing resources from the market. In the integrated system, the mill operator has the option to make investments to enable the additional production of biofuels from gasification of the pulping process residues. Furthermore, the option to sell waste heat to a district heating network operator can be explored.

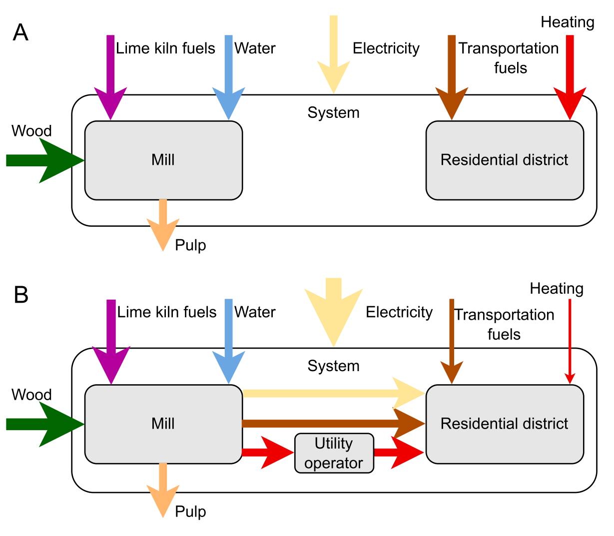

FIGURE 2
System configurations of pulp mill and residential district. **(A)** Conventional system of mill and residential district. **(B)** Integrated system of mill and residential district.

The district heating network can be operated either with CO_2 or water as heat transfer fluid. Biofuels produced at the mill can be stored in intermediate storage tanks, electricity can be exchanged in both directions between mill and district. For the residential district, the option to satisfy heating, fuel and electricity demands by alternative means emerging from the interaction with the mill are enabled. Figure 2 shows the considered system in its conventional and integrated state.

3.1.1 Actors

We consider three actors in our system, the mill operator, the residential district and the operator of a utility network.

3.1.1.1 Mill operator

The mill operator is supposed to produce 1,000 air-dried tons of pulp per day. Pulp and surplus electricity generated during production are sold, while resources required for the production can be purchased on the market.

3.1.1.2 Residential district

The residential district has 85,000 inhabitants. For each inhabitant, domestic hot water, space heating, electricity and mobility demands are taken into account, as further specified in Granacher et al. (2023). Heat can be provided from conventional gas boilers, or through a district heating network. Electricity can be purchased on the market, self-produced from photovoltaic, or provided by the pulp mill. Mobility demands can be satisfied with conventional or bio-fuels.

3.1.1.3 Utility network operator

The operator of the utility network buys heat from the pulp mill and provides it to the residential district. They also have other installations to provide heat to the district. As in the conventional configuration, the mill and the residential district do not interact with each other, there is no district heating network in place and thus no utility operator. The total cost that all actors are subject to is calculated in consideration of the investment they make as well as the operating cost resulting from the exchange of commodities with the market, and with each other.

3.1.2 Initial problem formulation

Initial system configurations are generated by solving a mixed integer linear programming (MILP) problem considering total cost and global warming potential (GWP) as objectives and applying the ε-constraint method. The solutions are generated in consideration of time-dependency of parameters, accounting for the volatile character of electricity availability and prices, as well as the district demands. In order to keep the model at a reasonable size, k-medoids clustering is applied to the set of time-dependent parameters, and four typical timesteps, representing the seasons during a year, are obtained and deployed for result generation.

At each timestep, mass and energy balances need to be closed for each unit in the superstructure; everything that can not be provided system-internally needs to be imported from the market. For more information on the general formulation of this first optimization problem that yields the considered system configurations, the interested reader may consult Kantor et al. (2020); for details about the case study of integrating a pulp mill with a residential district, Granacher et al. (2023) can be consulted.

3.1.3 Configuration generation

For the hereafter presented case study, 20 system configurations are generated with the first optimization problem by varying model parameters that might be subject to uncertainty in the future, such as resource prices, investment cost and environmental metrics of commodities. Sobol sampling is used to generate a parameter distribution, and for each set of parameters, the respective Pareto-frontier for total expenditure (TOTEX) and environmental impact in the form of global warming potential (GWP) is generated.

3.1.4 Adaptations of second optimization formulation towards actor perspective

The obtained system configurations are used to analyze the benefits of integration for the actors of the system by applying the presented approach. For each actor, the investment they make in a given solution is contributing to their cost, as well as the sum of bought and sold commodities, both from the market and from the other actors. In order to generate a set of diverse solutions, the total cost of the mill operator and the payback period faced by the utility operator are constrained, while the cost of the residential district is minimized. The scope of the analysis is summarized in the Supplementary Table S1.

3.2 Renewable energy community

The emerging framework of renewable energy communities, based on increasing decentralized capacities and distributed resources, reveals the need to distinctly consider the allocation of costs among the different stakeholders of the system. The expenditures of these stakeholders, and in particular their distribution over time, can vary significantly depending on the initial investments made and market energy tariffs observed. We thus apply the proposed approach to derive insights on promising pricing strategies of internal energy exchanges that enable potential synergies among actors.

3.2.1 Actors

Three key stakeholders are identified for the renewable energy community, see Figure 3.

3.2.1.1 Renters

Renters (R) are the people who occupy the dwellings, with a corresponding need for domestic electricity and heating. They are portrayed as passive participants in the district energy system, solely engaging in the consumption of end-use energy without the ability to make a choice regarding the building equipment (quality of thermal envelope, heating device) nor to make any investment. Thus, they lack the capacity to exert influence over other stakeholders, and their financial balance always results in a net expenditure of operational costs paid to the Utility (U) ($\mathbf{c}^{\text{op}}_{\mathbf{U,R}}$) or to the Owners (O) ($\mathbf{c}^{\text{op}}_{\mathbf{O,R}}$).

3.2.1.2 Owners

These actors are entrusted with choosing the appropriate equipment for their buildings and making the corresponding investment γ^{inv}_{O}. They can sell the locally-generated solar electricity either to the Utility ($\mathbf{c}^{\text{op}}_{\mathbf{O,U}}$) or to the Renters ($\mathbf{c}^{\text{op}}_{\mathbf{O,R}}$).

3.2.1.3 Utility

This actor stands for the company responsible for exchanging resources outside the energy community and distributing them inside of it. They can balance local production and demand by purchasing ($\gamma^{\text{op},e^{+}}_{U}$) or selling ($\gamma^{\text{op},e^{-}}_{U}$) commodities outside the energy community perimeter at fixed prices, and can also participate to the internal market by selling electricity to the Renters ($\mathbf{c}^{\text{op}}_{\mathbf{U,R}}$) or purchasing it from the Owners ($\mathbf{c}^{\text{op}}_{\mathbf{O,U}}$). Eventually, they are responsible for the district-scale equipment and have to make the corresponding investment γ^{inv}_{U}.

3.2.2 Initial problem formulation

In order to apply the developed approach to investigate internal pricing strategies between actors, the open-source Renewable Energy Hub Optimizer (REHO) model (Lepour et al., 2024) is adapted and used to generate a set of initial system configurations. This model is a decision support tool designed to investigate the deployment of energy conversion and storage technologies in urban systems. It leverages a MILP framework to simultaneously address the optimal design and operation of capacities, catering to multi-objective considerations across economic, environmental, and efficiency criteria. The Dantzig-Wolfe decomposition, an approach based on a master problem (MP) and sub-problems (SPs), is implemented and represents the perspective of the district interface (i.e., transformer perspective) and of each individual building. The SPs decide on the selection and sizing of energy storage and conversion units at the building scale. The conversion units supply the end-use demands of the buildings regarding space heating, domestic hot water, and domestic electricity by converting imported energy carriers or onsite renewable energy. The operation is subject to energy and mass balance at the building scale. The MP applies a second energy and mass balance between the buildings and the imports and exports at the district electricity transformer. This bi-level formulation of the problem is suitable to reduce computational costs and to model actors at different scales. More information on the modeling methodology is available in Middelhauve (2022), Terrier et al. (2024).

3.2.3 Configuration generation

An initial set of typical building energy system configurations is generated by running a multi-objective optimization and varying the weight of capital expenditure (CAPEX) and operating expenditure (OPEX) in the objective function. Each configuration is fully characterized by the decision variables of all the SPs, which are the installed units and their hourly operation throughout a year. It therefore fixes the investments and energy exchanges between buildings and with the district utility.

3.2.4 Adaptations of second optimization formulation towards actor perspective

The actors allocation optimization approach is based on the decomposition method already implemented in REHO. The configurations of the SPs are inserted into the district MP, where a binary decision variable is assigned to each SP configuration. The MP describes the district utility and selects one SP configuration for each building. The objective function of the MP is the minimization of the costs for one particular actor, while the costs of the other actors are constrained with parameterized ε-values. The tariffs for

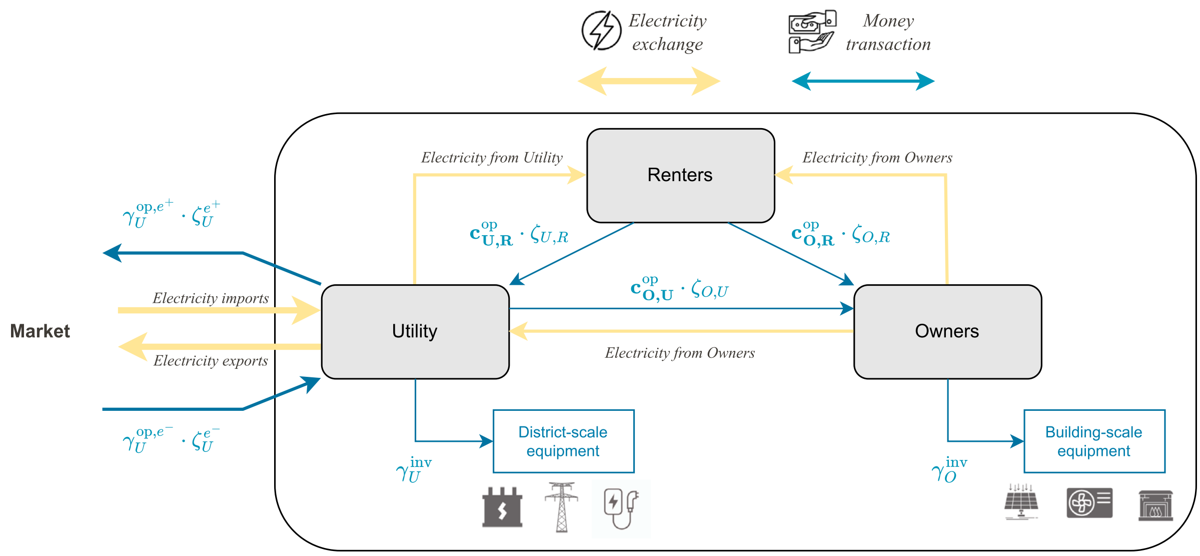

FIGURE 3
Stakeholders' interactions for renewable energy community application.

energy imported or exported outside the boundaries of the district are fixed, but inside the district, the tariffs are actor-specific decision variables. The parameterization of this optimization problem is provided in Supplementary Table S1 in the Appendix.

3.3 National energy system

Managing a national energy system like the one of Switzerland involves coordinating various actors, each pursuing different objectives and operating at varying scales. These actors – from consumers to national-level producers and transmitters – contribute to the complexity of energy and financial flows within the system. With increasing integration of renewable energy sources and the emergence of prosumers (consumers who also produce energy), the traditional dynamics between actors are shifting. This evolution presents challenges in achieving an equitable distribution of costs and benefits among all stakeholders, particularly for ensuring that the financial burden does not disproportionately fall on end consumers. The intent of this case study is to identify strategies that ensure a balanced financial impact across all stakeholders, facilitating equitable cooperation in the national energy system. An extended version of this analysis is presented in Schnidrig et al. (2024a), while herein the main aspects are summarized.

3.3.1 Actors

Three key actors in the Swiss energy system are identified; see Figure 4.

3.3.1.1 Consumers

Consumers are transitioning from passive energy users to active participants, known as prosumers. Prosumers consume and produce energy locally by investing in decentralized energy generation technologies such as PV installations. This shift enables them to influence the energy system and other actors by providing locally-generated energy, reducing reliance on centralized energy sources.

3.3.1.2 Distribution system operators (DSO)

The DSO encompasses entities responsible for managing and distributing energy services at the local level, primarily within cities and districts. These actors operate the local energy grids and ensure the efficient delivery and balance of energy services at low and medium voltage levels. The emergence of prosumers introduces new dynamics for the DSO, requiring the management of bidirectional energy flows and the integration of distributed generation into the grid infrastructure.

3.3.1.3 Transmission system operator (TSO)

The TSO operates at the national level, overseeing energy production and transmission on a broader scale. This actor is critical in balancing the national grid, facilitating energy imports and exports, and ensuring system stability. The increasing decentralization due to prosumer activity affects the operational dynamics of the TSO, necessitating adaptations in investment strategies and coordination with other actors to maintain grid reliability.

3.3.2 Initial problem formulation

To explore strategies for achieving a balanced financial impact among stakeholders, we apply the publicly available EnergyScope model (Schnidrig et al., 2023), which performs global economic optimization of the Swiss energy system for 2050. The model accounts for energy and mass resources' import and export dynamics, including electricity, methane, hydrogen, gasoline, light fuel oil, coal, and biomass. By representing Switzerland's energy exchange mechanisms and interactions with neighboring regions, the model allows to examine the implications of different energy system configurations on the identified actors.

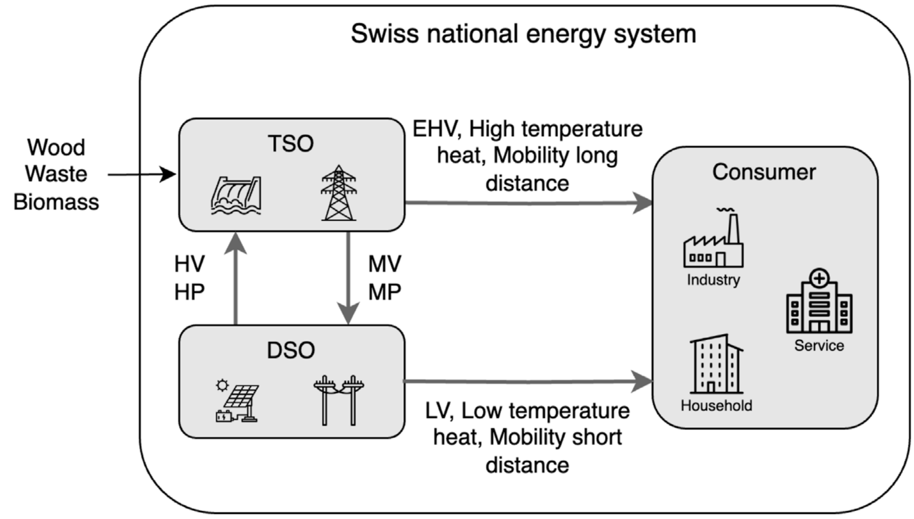

FIGURE 4
Representation of the identified actors and flows for an energy-independent and CO_2-neutral Swiss energy system. The energy flows between the actors are modeled as a multi-level infrastructure. There are four levels for voltage (V) and pressure (P): low (L), medium (M), high (H) and extremely high (EH).

This case study focuses on an energy-independent and CO_2-neutral Switzerland in 2050. Market flows are limited to harvesting local resources — such as fossil and biogenic waste, wood, and other biomass — to simulate a self-sufficient energy system. The objective is to investigate how varying degrees of PV penetration impact the roles and costs for each actor and to identify configurations that promote equitable cost distribution without disproportionately affecting consumers.

3.3.3 Configuration generation

Different initial configurations are generated by varying the installed PV capacity from 0 GW to its maximum potential of 50 GW in increments of 2.5 GW, resulting in 20 distinct configurations. These configurations are defined by the selection of harvesting, conversion, and end-use technologies, which facilitate the exchange of energy and mass flows among actors.

The adapted EnergyScope model employs a top-down MILP approach to distinguish between centralized and decentralized technologies as analyzed in Schnidrig et al. (2024b). The installed capacities of energy units and their associated infrastructure are allocated among actors based on their production levels at different voltage and pressure levels. This allocation allows to analyze the impacts of varying PV penetration on each actor's investments and operational costs within the multi-actor framework.

3.3.4 Adaptations of second optimization formulation towards actor perspective

Once the configurations are generated via EnergyScope, the investments are distributed among the actors, thus revealing different business schemes. In addition, internal exchange flows are associated with the actors concerned. Finally, the total cost of the consumers and TSO are varied between ±100% while minimizing the total cost of the DSO in order to explore the solution space of the internal cost optimization problem. The details of this analysis can be found in the Supplementary Table S1.

4 Results

4.1 Bio-based industry and residential district

An initial set of 20 system configurations is obtained by solving the MILP formulation of the superstructure optimization. The obtained configurations are used to formulate the second optimization problem that determines the prices of internal exchanges as previously described. 500 solutions are obtained by varying the ε-bounds on the cost of the mill operator and the payback period the utility operator is subjected to. In each of these solutions, the optimizer determines which configuration to use and what the prices for the internally exchanged commodities (heat, electricity, fuels) should be. Figure 5 shows the obtained solution space. Out of the 20 system configurations, five are chosen in the second optimizer problem, out of which two are selected in over 85% of the cases (configurations 6 and 8).

In the most frequently chosen configuration, the mill operator is investing to co-generate biofuels from bark and black liquor gasification and is also investing in carbon capture units (Figure 6). 30% of the black liquor and all of the available bark are gasified, which represents the current upper limits defined in the superstructure optimization problem due to operational limitations. By importing electricity from the grid when it is available at modest prices, biofuel production is enhanced by a co-electrolysis unit, converting CO_2 and electricity to syngas that can complement fuel production. The produced fuel is used in the residential district for mobility. This electricity import on the mill level increases the overall system-level electricity demand by 100%. Furthermore, waste heat

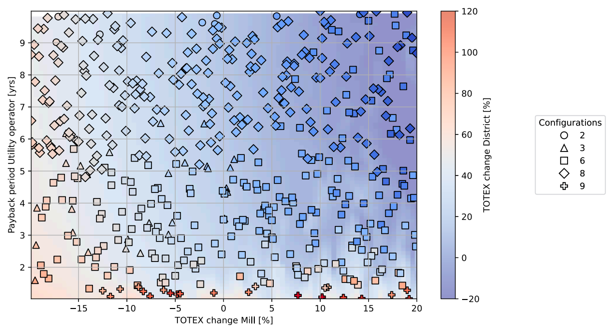

FIGURE 5
Economic implications for system actors of bio-based industry and residential district in obtained solution space. Shape indicates the chosen system configuration.

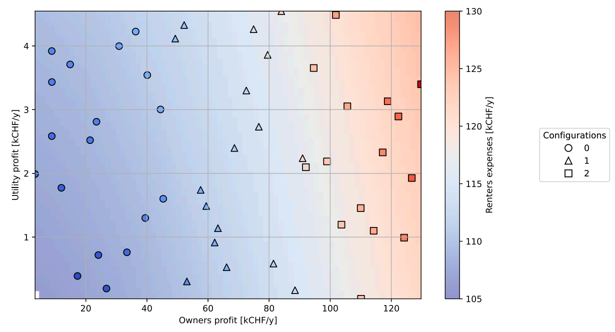

FIGURE 7
Profits and expenditures for the actors of a renewable energy community.

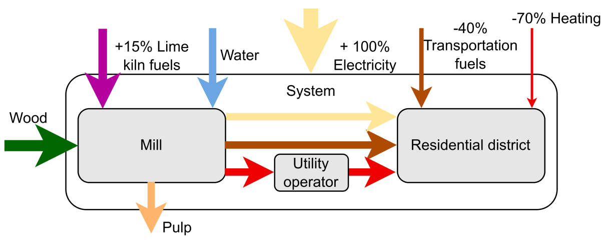

FIGURE 6
Integrated system, representing the configuration that is chosen most by the optimization of prices on internal flows.

is provided to the district *via* a district heating network, operated on CO_2 to exploit cooling opportunities offered to the mill. This way, the self-sufficiency of the system, considering energy demands of mill and residential district can be increased by 18%, whereas the biogenic emissions on the mill site are reduced by 15%. The overall direct fossil emissions of the system are reduced by 50% compared to conventional, non-integrated operation, and costs on the system level – not accounting for internal exchanges between the actors – are reduced by 3%. Depending on how the mill's and utility operator's economic performance are constrained, this solution enables a reduction of the economic burden of the residents in the district by up to 40%, compared to the non-integrated operation.

Overall, it has been shown that by exploiting synergies emerging from cooperation between the considered actors, not only benefits on the system level can be enabled, but also positive effects for the individual actors emerge. Besides the reduction of environmental impact on the system level, economic benefits are enabled by collaboration in this particular case study. It needs to be mentioned that this effect is highly sensitive to the assumed electricity prices and that another system setting might lead to different results regarding promising integration options.

4.2 Renewable energy community

Following the same logic as in the previous case study, an initial set of diverse system configurations is obtained by solving the MILP formulation for an energy community comprising 30 buildings, optimized under a sampling of 10 different tariff conditions, yielding 10 system configurations. Our multi-actor approach is then used to explore the solution space. A total of 50 optimization runs are conducted, always minimizing the Renters portfolio, while simultaneously imposing parameterized ε-constraints on both the Owners' and Utility's portfolios. The price of internally exchanged electricity is determined based on the objective of minimizing the Renters' expenditures while restraining both the Owners' and Utility's profits to a specified fraction of their respective maximal value.

Figure 7 displays the obtained solution space. Among the 10 system configurations tested, 3 are consistently recognized as preferred by the model, with a distribution strongly related to the Owners' expenditures. The expansion of installed PV capacity empowers Owners to sell electricity generated on-site and boost their profits. The Utility has a narrower range of options, primarily involving adjustments to internal electricity pricing. On the other hand, Renters face severe limitations, as reducing their final bill will be at the expense of reducing other stakeholders' profits. Eventually, it is essential to note that it is not a zero-sum game between the three stakeholders, as imports and exports are permitted beyond the energy community's boundaries (i.e., the district is not a closed system).

The selected system configurations distinguish themselves mainly on the installed PV capacity, translating directly in electricity export, which ultimately correlates with Owners' and Utility profits. Indeed, among the existing domain of each system configuration, Owners increase internal market electricity tariffs to raise profit. Then, as internal tariffs reach the limit set by the external market, the system adopts a new configuration with a higher investment in PV capacities and, therefore, with a higher potential at making a profit. The trend is accompanied by a rising use of natural gas. This latter is disadvantageous to Renters, but beneficial to Owners because of the additional solar-generated electricity that can be fed into the Utility.

The decomposition of investment and operational costs for the different configurations is available in supplementary material.

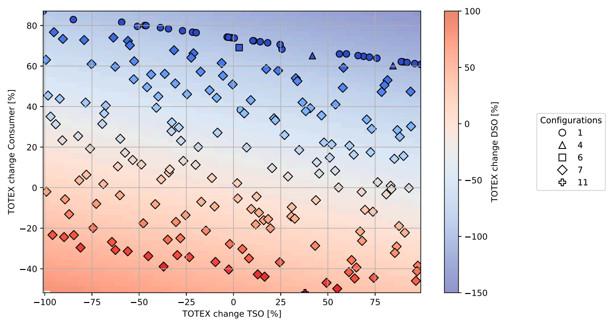

FIGURE 8
Solution space for the minimization of DSO total expenditure. The TOTEX changes of the actors represent the feasible range of variation of the ε-constraints.

4.3 National energy system

Applying the multi-actor approach to the 20 initial system configurations, we performed a total of 1,500 optimizations using the proposed approach. Not all configurations led to feasible solutions, but among the 20 proposed configurations, five were identified as preferred by the multi-actor model. The selection of configurations varied depending on the actor whose cost was minimized in the objective function of the second optimization problem.

Figure 8 illustrates the solution space when minimizing the total expenditure of the DSO. Configuration number 7, featuring a PV penetration of 38 GW, was chosen as the optimal solution in 83% of the optimizations. The preferred configurations generally correspond to higher levels of PV deployment, situated near the Pareto front at the upper end of the figure. The color coding of the data points represents the cost of the actor considered in the objective function—in this case, the DSO.

The increased electricity production from PV installations allows the DSO to trade more resources with the TSO, thereby reducing its own costs. However, this cost reduction for the DSO comes at the expense of the other actors. Since the energy balance is always maintained between the three actors (with no exports), the TSO is required to produce less and purchase the excess electricity generated by the DSO.

The application of the ε-constraint method leads to different cost allocations, representing imbalanced cost distributions among the actors. Specifically consumers who primarily consume energy without opportunities for revenue generation are significantly affected by this relaxation. This outcome is attributed to the fact that the TSO can influence the DSO through resource exchanges, mitigating the direct financial consequences of the DSO's cost minimization on the TSO.

5 Conclusions and outlook

This paper presents a universally applicable method for identifying promising process and energy system configurations, and defining the prices of flows among actors within the system that make a configuration interesting to all actors. By accounting for both system-level performance and individual actor impacts, the proposed method establishes a robust framework for exploring the complexities and interdependencies inherent in modern process energy systems. It facilitates the design of integrated systems that are both globally efficient and locally acceptable, effectively addressing current energy system questions. Thereby, our integrated approach combines the advantages of existing methods—such as the system-level optimization strengths of multi-objective optimization, the stakeholder inclusivity of multi-criteria decision analysis, and the actor-specific focus of agent-based modeling. The method was demonstrated on three case studies of varying sizes and complexities. These case studies illustrated how different process and energy systems can be analyzed using the proposed method, showcasing the method's flexibility and broad applicability rather than being the main focus of the presented research.

It is important to note that the presented approach is based on the assumption that the involved actors agree on the acceptable bounds for their respective target indicators before determining the internal pricing strategy. For example, this could include agreeing on a maximum acceptable payback period for the investment realized by a specific actor. The approach was initially developed for scenarios where one actor represents a community of multiple stakeholders whose costs are minimized, while others are companies or municipalities with rather long-term planning horizons. We considered that this setup would allow the actors to agree on strategic objectives prior to defining the pricing strategy for collaboration. However, while the approach does not necessarily result in pricing strategies where the maximum acceptable target limitations are reached, it is likely that not all actors will agree on targets in advance. Nevertheless, in this case the approach could still be used in identifying the maximum potential gains for each actor by redefining the considered hierarchy of actors in the optimization problem. This could then inform a productive discussion on potential trade-offs in developing a pricing strategy.

Future work will involve applying the method to compare different business models with various financing and remuneration schemes, thus balancing the interests between different actors. The presented method provides a foundation for further research to delve deeper into the fine-tuning of integrated, multi-actor systems, exploring additional scenarios, technological integrations, and policy implications.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors upon request, without undue reservation.

Author contributions

JG: Conceptualization, Methodology, Validation, Formal Analysis, Visualization, Writing–Original Draft. JS: Conceptualization, Methodology, Validation, Formal analysis, Visualization, Writing–Original Draft. AC: Software, Validation, Formal analysis, Visualization, Writing–Original Draft. DL: Software, Validation, Formal analysis, Visualization,

Writing–Original Draft. CT: Software, Methodology, Validation, Writing–Original Draft. RC-A: Conceptualization, Methodology, Writing–Original Draft. FM: Conceptualization, Funding acquisition, Supervision, Writing–review and editing.

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Conflict of interest

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Supplementary material

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