

System design options of decentralized autonomous renewable energy systems

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ABSTRACT

Growing climate related disruptions, geopolitical shocks, and increasing public interest in local energy security have intensified the motivation for municipalities to pursue energy autonomy as part of resilient and sustainable energy transitions. However, relying on single cost optimal solutions raises critical questions regarding their social acceptability, economic feasibility, and robustness under uncertainty. To address this gap, this study applies Modeling to Generate Alternatives (MGA) to systematically explore the diversity of near optimal configurations of decentralized renewable energy systems across selected German municipalities. Unlike conventional approaches, this work explicitly quantifies the range and diversity of feasible system designs within defined cost margins, revealing hidden flexibility in municipal energy planning. The results show that municipalities with abundant land and strong renewable potential exhibit substantial diversity within a 10% cost margin, enabling multiple technology pathways that remain robust under varying assumptions. In contrast, land constrained municipalities display limited diversity, with solutions dominated by costly batteries, heat pumps, and heat storage systems. These differences have direct practical implications. Low- and medium-cost municipalities can leverage flexible, socially acceptable pathways, supported by empirical evidence that households are willing to pay 5%–20% more for local energy supply. Conversely, high-cost municipalities exhibit implicit CO₂ abatement costs significantly exceeding typical mitigation ranges, suggesting that full autonomy may be economically inefficient even under near-optimal configurations. Overall, this study demonstrates that MGA provides a novel and powerful framework for linking techno-economic optimization with societal and policy relevant insights, enabling more robust, context specific energy transition strategies. Future work should incorporate transmission infrastructure and transition pathways to better reflect spatial interactions and real-world system evolution.

1. Introduction

Recent climate-related disruptions and geopolitical tensions have renewed interest in enhancing the resilience of local energy systems. Wildfires in California [1] and heatwaves in Southern Europe [2] have caused large-scale power outages, while the floods in Germany's Ahr Valley [3] demonstrated how extreme weather can disrupt centralized electricity and heating infrastructures. At the same time, recent disruptive events such as the Covid-19 Pandemic [4], and 2022 European

gas crisis [5] have demonstrated the vulnerability of relying on imported energy. Such developments have intensified discussions around municipal-level energy autonomy and decentralized renewable energy generation.

A self-sufficient or autonomous municipal energy system integrates local renewable energy sources, energy storage, and demand-side management strategies to create an efficient balance between supply and demand [6,7]. These autonomous energy systems have several advantages, especially when it comes to resilience against disruptive events

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and infrastructure failures. These systems can maintain critical energy supply during large-scale grid disruptions by relying on locally available renewable resources and thereby reducing exposure to fuel price volatility and import dependencies [8–10]. Additionally, decentralized systems can reduce grid dependence and improve the alignment of local generation with demand, particularly in regions with inadequate grid infrastructure [11]. Municipalities often pursue energy autonomy not simply for economic reasons but because of social, financial, and environmental motivations, shaped by local participation, community identity, and evolving policy frameworks [6,10]. This reflects wider evidence that local organizations and community groups actively shape energy transitions by driving project development and influencing public acceptance [12,13]. However, despite the growing interest in autonomy, municipalities vary greatly in terms of their renewable potential, spatial constraints, and the availability of energy infrastructure. Therefore, the identification of local configurations that are feasible, resilient, and socially acceptable for different types of such municipalities is important.

In energy system modeling, different modeling methods use different techniques to reduce the uncertainty of the results that are modeled. Wijesinghe et al. [14] show that in situations where future conditions are uncertain, simulation-based modeling typically use scenario-based models, sensitivity analysis, and forecasting. For the same purpose, optimization models make use of probability values (e.g., robust optimization [15,16]), near-optimal solutions (e.g., Monte Carlo methods [17]), and iterative techniques (e.g., particle swarm optimization [18,19]). In energy system modeling, relying solely on cost in the optimal solution may not accurately reflect real-world transitions due to uncertainties in demand, technology costs, climate conditions, and land availability [20]. Emerging methods such as Modeling to Generate Alternatives (MGA) have been proposed to address this challenge by identifying a diversity of near-optimal designs that reveal substitution possibilities and system flexibility [21]. The MGA method investigates the near-optimal solution space by establishing an extra constraint that enforces solutions to stay within a predetermined range of the optimal objective value. At the same time, MGA adjusts the objective function to pinpoint structurally distinct solutions iteratively [22,23]. Recent work emphasizes that exploring near-optimal energy system configurations can better support real world decision making by incorporating flexibility and stakeholder relevant considerations beyond cost optimality [24]. A variety of MGA methods such as Hop-Skip-Jump (e.g., Refs. [23,25]), variable max (e.g., Ref. [26]), and random vector (e.g., Refs. [27,28]) have been developed and employed in different energy system models over time. A study by Lau et al. [29] shows that the random vector method may have difficulty identifying the maximum and minimum feasible values within the feasible region. Furthermore, variable min/max methods may not be able to vary all variables, resulting in extreme flexibility of the results at the ends of the feasible solution space. Therefore, the authors introduced combined variable min/max and random vector MGA method to leverage the strengths of both approaches. This method helps to obtain a balanced set of MGA solutions that are distributed fairly evenly throughout the solution space.

To the authors' knowledge, Finke et al. [30] are the only researchers to use MGA for municipal energy system optimization thus far. However, no study has used this method to investigate the solution space of autonomous municipal energy systems.

There is a substantial body of literature modeling decentralized and autonomous energy systems [31,32]. Much of this research focuses either on off-grid buildings [33] or on larger spatial scales, such as regions or national systems [34,35]. In contrast, municipal-scale energy autonomy has received comparatively limited attention [36] and has so far been examined mainly in high-income countries, including Switzerland [26] and Germany [37,38]. One notable exception is the work by McKenna et al. [39], who developed feasible energy concepts for small

communities by explicitly integrating local preferences into the modeling process. Using participatory workshops in a German municipality, local priorities were identified and translated into alternative system designs through a combination of multi-criteria decision analysis (MCDA) and linear optimization. These alternatives were subsequently evaluated in terms of economic viability, environmental sustainability, and the degree of local energy autonomy. While this approach provides valuable insights into socially grounded system design, it is resource-intensive and time-consuming, which limits its applicability for large numbers of municipalities. A recent study by Risch et al. [40] which is particularly relevant for the present study, evaluated the potential of weather-robust autonomous energy systems for 11003 German municipalities by performing techno-economic optimizations that minimize annualized system costs for individual municipalities in the year 2045. Under different scenarios and with different assumptions or parameter sensitivities, Risch et al. [40] found that 93% of German municipalities could achieve complete energy autonomy (i.e., off-grid). However, the predefined scenarios based on least cost optimization in Risch et al. [40] might miss unexpected system behaviors and interaction of uncertainties. Especially for off-grid systems without the possibility of energy imports, a wide range of uncertainties could make the planned energy systems infeasible or unreliable. For example, energy demand may change as a result of global warming [41], social opposition could restrict the use of certain technologies [42], and policy decisions could accelerate or delay the achievement of climate goals [43].

This study addresses the gaps identified by applying the MGA approach to autonomous municipalities. By combining the concept of municipal energy autonomy with the generation of near-optimal solutions, the analysis goes beyond cost minimization to uncover substitution options, trade-offs, and alternative pathways that are relevant for investors, policymakers, and local communities. This makes the study distinct from earlier works, as it provides diversified municipal energy system configurations that remain feasible and economically competitive under variations in key assumptions such as technology costs, resource availability, and demand profiles. For this purpose, MGA is implemented in the ETHOS.FINE optimization framework and applied in case studies of identified autonomous municipalities from Risch et al. [40]. The results show the techno-economic flexibility of these municipalities based on the alternative MGA energy system configurations.

This paper is structured as follows: Section 2 illustrates the methodology by explaining the energy system model and the input data that were used. Section 3 provides results obtained followed by a discussion of the results in Section 4. Finally Section 5 presents a summary and conclusions.

2. Methodology

In this section the methodology of the study is presented. Section 2.1 describes the general energy system modeling framework used and the implementation of MGA. The energy system model instance and input data are presented in Section 2.2. Section 2.3 describes the case study used.

2.1. Implementing modeling to generate alternatives in the ETHOS.FINE framework

This study uses the Python-based open-source Framework for Integrated Energy System Assessment (ETHOS.FINE) [44] as the energy system modeling framework. In this framework, a commodity, i.e., a flow of heat or electricity, or fuel, can enter the boundary of the energy system as an import flow, be used inside the system to satisfy a particular demand or leave the boundary of the system as an export flow. For this purpose, ETHOS.FINE consists of five main component classes, that are source, sink, conversion, storage and transmission (see Fig. 1). Source components supply a commodity in the energy

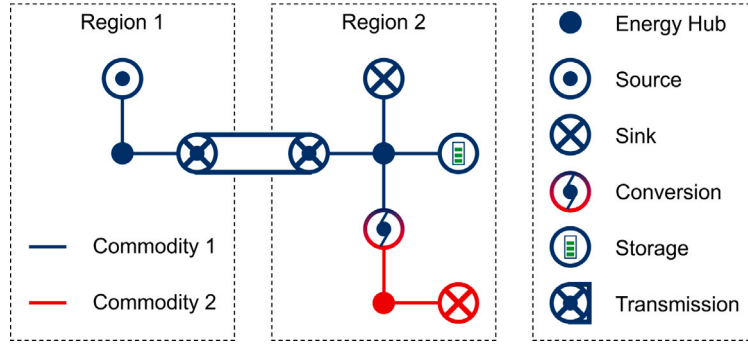


Fig. 1. An illustrative multi-nodal model of an energy system, with basic components for supply, demand, conversion, storage, and transmission between regions. Source: Adapted from Hoffmann et al. [46].

system while sink components have a certain demand for a commodity. Conversion components convert one commodity to one or several other commodities. Storage components can store a commodity over a period of time and transmission components transfer a commodity from one region to another within the same energy system boundary. ETHOS.FINE's optimization objective function is to minimize the net present value of all capacity and operating costs over all modeled investment periods ($i \in \mathbb{I}$), components ($c \in \mathbb{M}$), regions ($r \in \mathbb{R}$), and time steps ($t \in \mathbb{T}$) (see Eq. (1)).

$$\min \sum_i \left(\sum_c \sum_r \left(C_{\text{capex}}^{c,r,i} + \sum_t C_{\text{op}}^{c,i,r,t} x_{\text{op}}^{c,i,r,t} \right) \cdot \frac{1}{(1+d)^{i \cdot |i|}} \right) \quad (1)$$

C_{capex} represents the capital expenditures of the commissioned capacities while c_{op} is the operation cost, x_{op} is the operation-rate variable, d is the discounting factor used for calculating the net present value and $|i|$ represents an investment period interval. ETHOS.FINE converts the input parameters, such as capacity constraints or operating modes of the components, into corresponding optimization constraints. A more comprehensive description regarding ETHOS.FINE framework and the related constraints can be found in Ref. [45].

The first step of this study has been the implementation of MGA within the ETHOS.FINE framework. The aforementioned relatively new combined variable min/max and random vector MGA method by Lau et al. [29] has been used in this study because of its ability to generate the most diverse set of optimization vectors. In this study, 60% of the MGA iterations used the random vector method, while the variable min/max method was used for the remaining 40%. A higher proportion of the random vector method was used so that the gradual trade-offs between technologies could be captured and various system configurations could be identified. When implementing this MGA method in ETHOS.FINE, the objective function mentioned in Eq. (1) is replaced by the MGA objective function which is shown in Eq. (2a). The constraints related to the MGA formulation are defined by Eqs. (2b)–(2c).

$$\min / \max \sum_i \left(\sum_c \sum_r x_{\text{cap}}^{c,r,i} \cdot \beta^{c,r,k} \right) \quad \forall k = 1, 2, \dots, K \quad (2a)$$

s.t.

$$Ax = B \quad (2b)$$

$$\sum_i \left(\sum_c \sum_r \left(C_{\text{capex}}^{c,r,i} + \sum_t C_{\text{op}}^{c,i,r,t} x_{\text{op}}^{c,i,r,t} \right) \cdot \frac{1}{(1+d)^{i \cdot |i|}} \right) \leq C^*(1+\delta) \quad (2c)$$

In the new MGA random vector-based objective function (Eq. (2a)), the sum of installed capacity variables (x_{cap}) multiplied by a random vector β over the investment periods, components, and regions are both minimized and maximized. β is a random coefficient from the continuous interval $[-1.0, 1.0]$ for the random vector method and discrete value selected from the set $\{-1, 0, 1\}$ for the variable min/max method. The minimization and maximization help to consistently explore the feasible region and thus to sample in all directions. Eq. (2b), with

coefficient matrix A , variable vector x and restriction vector B , represents all the constraints that were in the original cost minimization. Additionally, Eq. (2c) is introduced to define the maximum allowable increase in the cost of the energy system. C^* is the optimal cost value of the original optimization problem (Eq. (1)) and δ is the maximum allowable cost increase percentage (slack). This MGA optimization problem with minimization and maximization objective functions is solved for a number of iterations ($k = 1, 2, \dots, K$) as required in order to obtain at most $2K$ number of different near-optimal feasible solutions. Therefore, the original least-cost optimal solution hereafter identified as optimal solution and each of the near-optimal feasible solutions have different installed capacity variables over the investment periods, components, and regions.

2.2. Energy system model ETHOS.FineRegions

The regional energy system model ETHOS.FineRegions [40] applied for selected autonomous municipalities is based on the extended ETHOS.FINE framework [47] and presented in this section. Fig. 2 is a block diagram of the energy system model used, showing the source, sink, conversion, and storage components of a single region. As the municipalities under consideration are not interconnected, the transmission components are not part of this study. The energy system model consists of ten commodities, seven source components, and seven sink components. Electricity can either be purchased or generated using wind, rooftop PV, and open-field PV. Since the focus of this study is solely on energy-autonomous municipalities, a constraint was added to make electricity purchase the last option for contribution to electricity supply. Electricity and heat can also be generated from other commodities such as biomass, biogas, and waste. This is done by converting these commodities to electricity in power and combined heat and power (CHP) plants and to heat in heating and CHP plants.

On the demand side, the sink component electricity demand is the aggregated electricity demand for residential, transport, tertiary sector, and industry. Electricity can be stored in centralized or decentralized Li-ion batteries. Low temperature heat demand is the aggregated heat demand of residential and tertiary sectors. The heat is provided by the district heating system and conversion technologies connected to hydrogen or decentralized heat pumps. Low temperature heat can be stored in centralized and decentralized heat storage. Hydrogen demand is the aggregated hydrogen demand for transport and industry and is met by the production of hydrogen within the municipality. Industrial process heat requirements are represented by three additional commodities: low temperature, medium temperature, and high temperature. Industrial process heat demand is obtained using conversion technologies connected to electricity, hydrogen, bio coal, biogas, and waste.

Demand data for the model are derived from a greenhouse gas-neutral German energy system by 2045 in Stolten et al. [48]. The demands were scaled down to the municipal level, see Risch et al. [40].

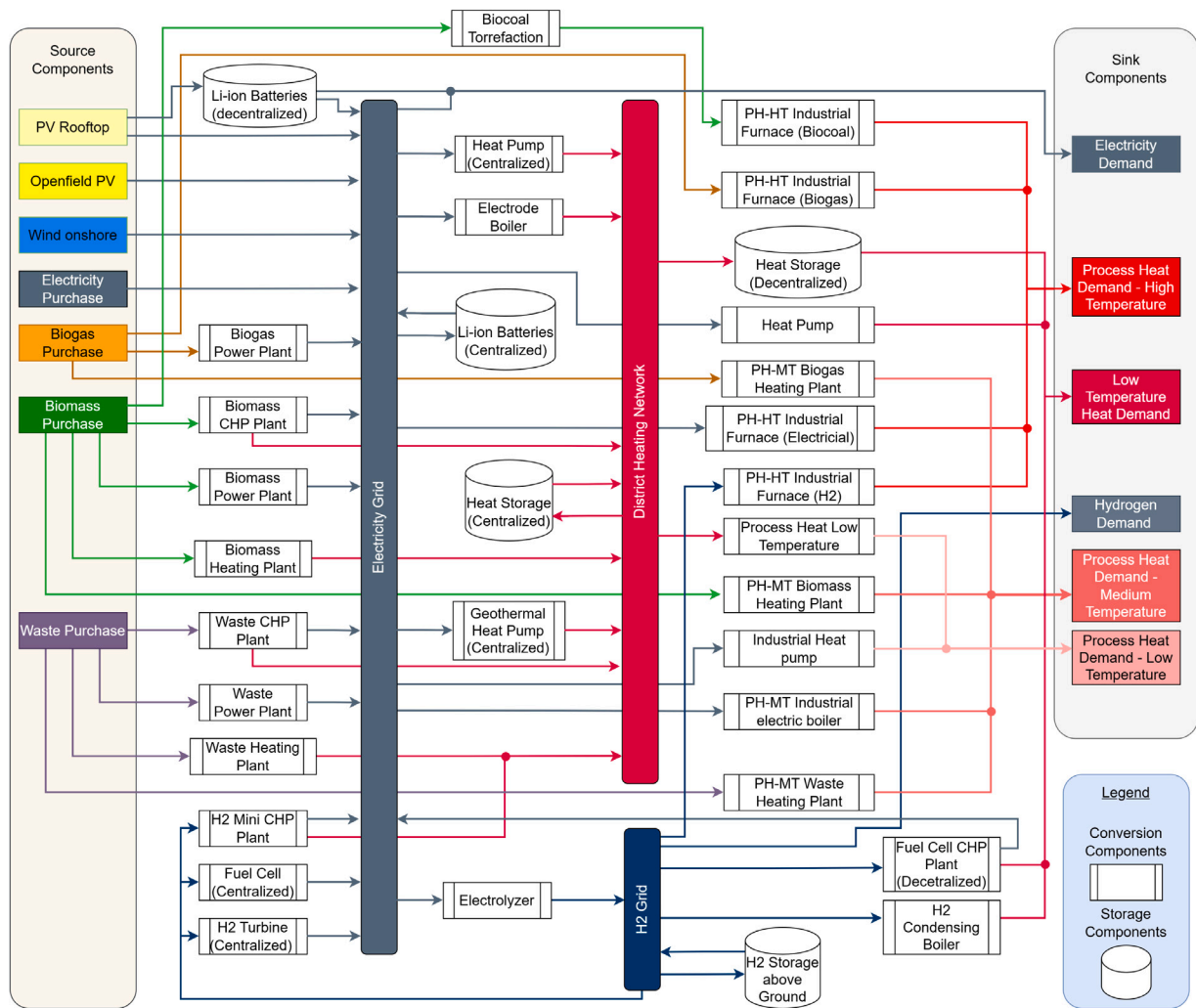


Fig. 2. Block diagram of the components included in the energy system model ETHOS.FineRegions. These components represent technology options in the energy system optimizations of municipalities. Note that the purchase of electricity is not possible for the autonomous (off-grid) municipalities considered in this study.

for detailed information. In each time step, a fixed demand of a given annual profile must be satisfied, which means the operation of the demand components cannot be altered (fixed time series). In each municipality, the maximum amount of energy that can be supplied by renewable energy technologies (wind, solar rooftop PV, open-field PV, biomass, biogas, and waste) is limited by their maximum technical potential which was obtained from [49]. Therefore, these potential values operate as upper bounds for the operational time series of renewable technologies. The techno-economic parameters, such as the capital and operating costs (see Table 1), the interest rate, and efficiencies are based on the study by Stolten et al. [48].

2.3. Case studies

Risch et al. [40] identified that 93% of Germany's 11,003 municipalities are technically capable of becoming completely autonomous by 2045. This means that each municipality would be able to fully satisfy its own energy demands using energy sources located within its borders. The present study selects a sample of five municipalities from various German states, Neuschoo, Ilmenau, Müden (Mosel), Urmitz, and Kahl am Main, to investigate the flexibility in technology options for energy autonomous systems.

In a first step, the energy system model ETHOS.FineRegions (Section 2.2) was used to create model instances for these five municipalities, and the total annual system cost of each municipality in

the year 2045 was determined. The term “specific system cost” was introduced to facilitate a comparison of costs between municipalities with different conditions, such as geographical area, population, and demand structure. The specific system cost is defined as the ratio of the total annual system costs for meeting municipal demands to the sum of all demands that have been converted to electricity-equivalent demands [40]. The characteristics of the selected municipalities are summarized in Table 2.

In the present study, the autonomy cost level of each municipality is categorized as follows determined by its specific system cost. A specific system cost of less than 100 €/MWh is considered low cost, 100–500 €/MWh is considered medium cost, and costs higher than that are considered high cost. Neuschoo and Ilmenau are both regarded as low-cost autonomous municipalities. Ilmenau's larger population has not hindered its ability to achieve low-cost autonomy due to the municipality's extensive geographical area, which translates to a substantial renewable energy potential. Conversely, very high specific system costs have been observed in Urmitz and Kahl am Main, which indicates that these municipalities practically can hardly become energy autonomous. The lower population of these two municipalities compared to Ilmenau is offset by a similar limitation on land availability for renewable energy development. As a result, the use of costly battery storage and heat pumps with higher capacity is essential for achieving energy autonomy [40]. Although Müden has a very low population, it has a higher specific system cost than low-cost autonomous municipalities due to lower land availability.

Table 1

Capital costs (capex) and operating costs (opex) of selected components obtained from Stolten et al. [48].

Type of component	Component	Capex	Opex (as % of capex)
Renewable energy	Biomass CHP plant	3350 €/kW	4.3%
	Wind	1025 €/kW	2.5%
	Biogas power plant	863 €/kW	8%
	Rooftop PV	528 €/kW	2.1%
	Open-field PV	345 €/kW	1.7%
Storage	Decentralized batteries	311 €/kWh	2.5%
	Centralized batteries	142 €/kWh	2.5%
	Decentralized heat storage	30 €/kWh	4%
	Centralized heat storage	0.59 €/kWh	3%
	Decentralized heat pumps	1111 €/kW	2.5%
Heating	Industrial heat pump	860 €/kW	2.5%
	Centralized heat pump	760 €/kW	0.85%

Table 2

Summary of the municipalities used in the study. Annual electricity equivalent energy demand is the aggregated energy demand for electricity, heat, hydrogen, and industrial process heat converted to electricity equivalent values.

Autonomy cost level	Municipality	State	Population	Area (km ²)	Annual electricity equivalent energy demand (GWh)	Specific system cost (€/MWh)
Low cost	Neuschoo	Niedersachsen	1171	14.47	25.79	65
Low cost	Ilmenau	Thüringen	38 891	198.69	414.33	92
Medium cost	Müden (Mosel)	Rheinland-Pfalz	642	7.49	3.27	120
High cost	Urmitz	Rheinland-Pfalz	3435	3.77	33.14	988
High cost	Kahl am Main	Bavaria	8033	10.64	75.49	2064

These five municipalities were mainly selected because some of them were discussed in detail in the study by Risch et al. [40], allowing for direct comparison with the results obtained in the present study. Further, the selected municipalities differ substantially in their specific system cost, reflecting differences in land availability, renewable resource potential, and demand density. The three-tier classification used in this study (low-, medium-, and high-cost autonomy) is intended to capture this variation systematically. The present study therefore selects Neuschoo, Ilmenau, Müden, Urmitz, and Kahl am Main as representative cases of these three cost-driven typologies as opposed to describing the five case-study municipalities in isolation.

After determining the optimal cost for each of the five municipalities, the MGA objective function (Eq. (2a)) is run for 100 iterations to obtain the maximally different near-optimal solutions for each municipality. For this purpose, a 10% slack (δ) is employed to enable meaningful structural diversity in near-optimal solutions while staying within the typical uncertainty range of model input parameters and system costs. After the 100 iterations, Neuschoo, Ilmenau, and Müden each obtained 100 maximally different near-optimal feasible solutions, while Urmitz, and Kahl am Main obtained 90 and 25, respectively. For each municipality, the maximum allowable cost increase is reached in all the maximally different feasible MGA solutions identified.

3. Results

This section presents the results obtained by applying MGA for selected autonomous municipal energy systems. Section 3.1 examines how the installed capacity of the renewable energy technologies vary for each municipality with different MGA solutions. The variation of the storage components is investigated in Section 3.2. Section 3.3 investigates the flexibility in low-temperature and process heat supply and Section 3.4 examines in sensitivity analyses, how the slack value affects the obtained results.

3.1. Flexibility in the installed renewable energy capacity

This section examines the diversity of installed capacities of the selected renewable energy based technologies for the MGA results of each

municipality. Fig. 3 shows the variation in the installed capacities of the selected technologies for Neuschoo, Ilmenau, Müden, and Urmitz.

In Neuschoo, the capacity for open-field PV, wind, and rooftop PV varies widely across the MGA solutions, especially for open-field PV (ranging from 0–12.2 MW) and rooftop PV (from 0–7.5 MW). This suggests that a wide range of renewable configurations remain financially feasible, with a cost difference of no more than 10% from the optimal level. Rooftop PV capacity fluctuates in the MGA solutions but generally rises as open-field PV falls, indicating that when ground-mounted space is reduced, rooftop installations could replace these capacities. The MGA solutions which do not involve open-field PV (from 72nd solution onwards), could lead to greater acceptance of energy systems, for example by reducing the landscape impact of renewable energy infrastructure [50]. MGA solutions from 86–91 demonstrate that this municipality is capable of functioning exclusively with wind and rooftop PV without needing to operate biomass CHP plants. However, in reality, relying heavily on a few high intermittent energy sources may indicate the need for increased electricity storage [51].

Ilmenau exhibits a broad range of capacities in all five technologies. Rooftop PV is a prime example of this wide range of capacity, with variations between 0–269.8 MW. Furthermore, in a 10% cost range, Ilmenau has the capability to increase the open-field PV and wind capacity to a greater extent. This again highlights a large feasible solution space, which is supported by Ilmenau's vast land availability and strong renewable resource base. In Ilmenau, rooftop PV is largely present in the MGA solutions with less or no open-field PV. This suggests that, even when cost constraints are relaxed in near-optimal MGA solutions, rooftop PV is utilized only when it is truly necessary, due to the higher cost of rooftop PV compared to open-field PV (see Table 1). In Ilmenau, Neuschoo, and Müden, a solution without wind capacity is unavailable. Unlike, open-field PV and rooftop PV, wind plants can generate electricity throughout the day provided there is adequate wind in the region. These municipalities are therefore dependent on wind power to meet their nighttime energy demands, especially when comparatively cheaper PV is unavailable. This shows that energy autonomy in such municipalities would not be possible if they were to oppose onshore wind [42].

Müden, a medium-cost municipality, displays lower but still noticeable variability, particularly in wind and biomass CHP capacities.

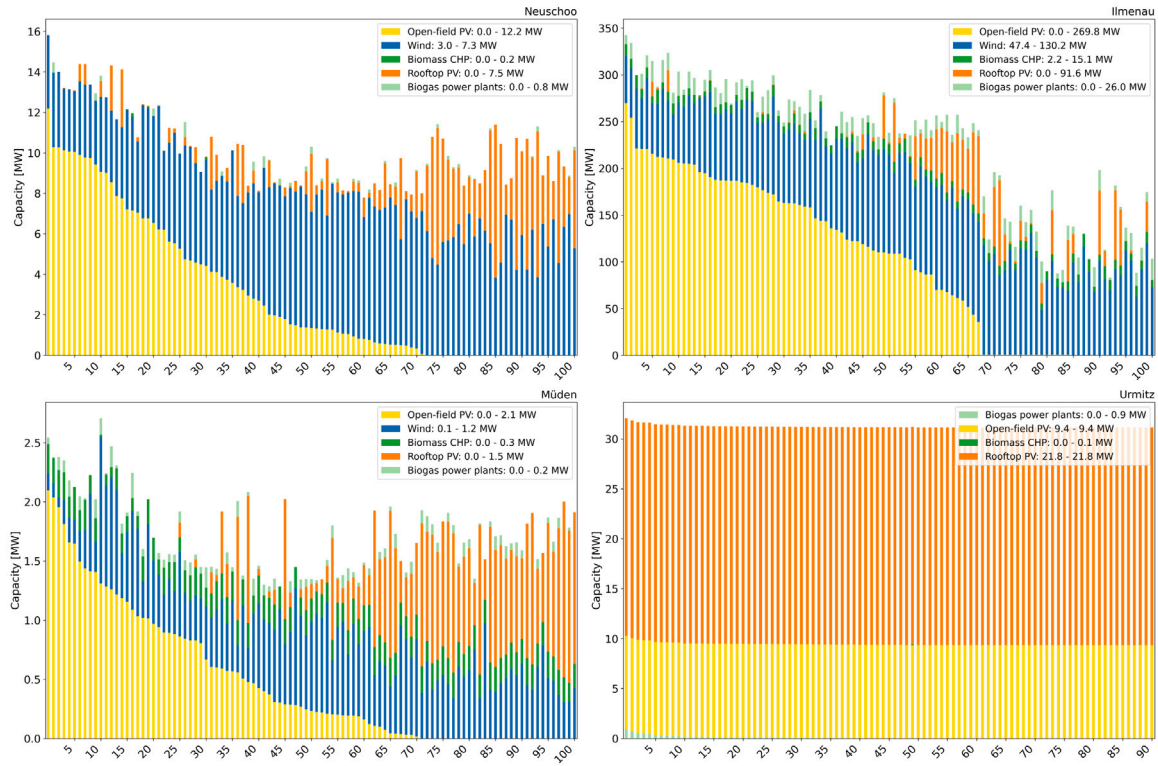


Fig. 3. Composition of the installed capacities of the selected renewable energy technologies for the near-optimal solutions across four municipalities. Kahl am Main, the other high-cost municipality exhibits similar behavior as Urmitz (constant open-field and rooftop PV capacities but changing Biomass CHP capacities) and is therefore not included in the figure. For Neuschoo, Ilmenau, and Müden, open-field PV capacities are sorted in descending order along the x-axis (solutions), and the capacities of all other technologies are aligned accordingly. For the municipality of Urmitz, the same procedure was followed with biogas power plant capacities sorted in descending order. The legend indicates the range of capacities of each technology in the obtained MGA solutions.

However, the magnitude of the capacity changes is smaller. For example, wind remains 0.1–1.2 MW and open-field PV remains below 2.1 MW. This suggests limited flexibility, which is due to tighter land or resource constraints. Müden exhibits similar capacity variability to that of Neuschoo. As can be seen, Müden also uses more rooftop PV in solutions where there is no open-field capacity. However, unlike in Neuschoo, the lost capacity from open-field PV in Müden cannot be fully replaced with rooftop PV and wind alone. Therefore, Müden needs to utilize more biomass CHP and biogas power plants in these solutions. The existing variability in Müden indicates that several configurations can meet the autonomy criteria. However, the scope for substitution is more modest compared to Neuschoo or Ilmenau.

Urmitz, a municipality with high specific system costs, exhibits near-zero variability across all MGA solutions. The values obtained for open-field PV and rooftop PV in Urmitz do not change in the MGA solutions. Their inability to significantly deviate from the optimal design suggests that a 10% cost margin does not allow for viable alternative solutions. However, a small variation in biogas power plant capacity can be observed in Urmitz. Even though the biogas power plant has a optimal capacity of 60 kW, a 10% cost increase has helped reach a capacity of up to 900 kW. At first glance, increasing capacity at the expense of higher costs does not seem sensible, but in reality, flexible biogas plants could prevent periods of lost load [52] due to inadequate system design. Another reason for using more biogas in the MGA solutions in Urmitz is that the 10% cost escalation cannot be used to increase the capacity of low-cost renewable energy technologies, such as wind and open-field PV, due to the land constraints and population density in the municipality. This underlines the inflexibility and fragility of energy autonomy scenarios in some municipalities.

3.2. Flexibility in the storage capacity

This section investigates the variation of storage components in selected municipalities with MGA solutions based on the variation of their storage capacities. There is a clear variability in centralized battery capacities in the MGA solutions for Neuschoo (see Fig. 4). MGA solutions show that an autonomous system in Neuschoo could operate even without any centralized batteries within a 10% cost relaxation. Lower energy demand and adequate renewable energy availability lead to reduced centralized battery storage requirements in this municipality. The optimal solution for Ilmenau shows a centralized battery capacity of around 100 MWh and the average centralized battery capacity in the MGA Solutions of Ilmenau is approximately 150 MWh. Ilmenau has a higher annual electricity equivalent demand and at the same time a higher availability of renewable energy resources. For this reason, MGA solutions tend to invest more in centralized batteries. These batteries can be used for long-term electricity storage, especially in the summer when PV is abundant. This shows that, even if there is an adequate renewable supply, battery storage may be needed if the region has a higher energy demand. Müden, the medium-cost municipality has an optimal centralized battery capacity of 0.32 MWh and an average MGA centralized battery capacity of 0.42 MWh. Converse to Ilmenau, Müden use additional centralized battery capacity, mainly to store electricity from its limited renewable sources. Section 3.1 showed that both Urmitz and Kahl am Main have a very limited flexibility with renewable energy sources. Therefore, Kahl am Main is expected to have high centralized battery storage capacities in MGA solutions, primarily for storing as much electricity as possible from these limited resources. Surprisingly, Fig. 4 shows that the maximum MGA centralized battery capacity in Kahl am Main is only slightly higher than its optimal centralized battery capacity. This shows that the municipality's limited

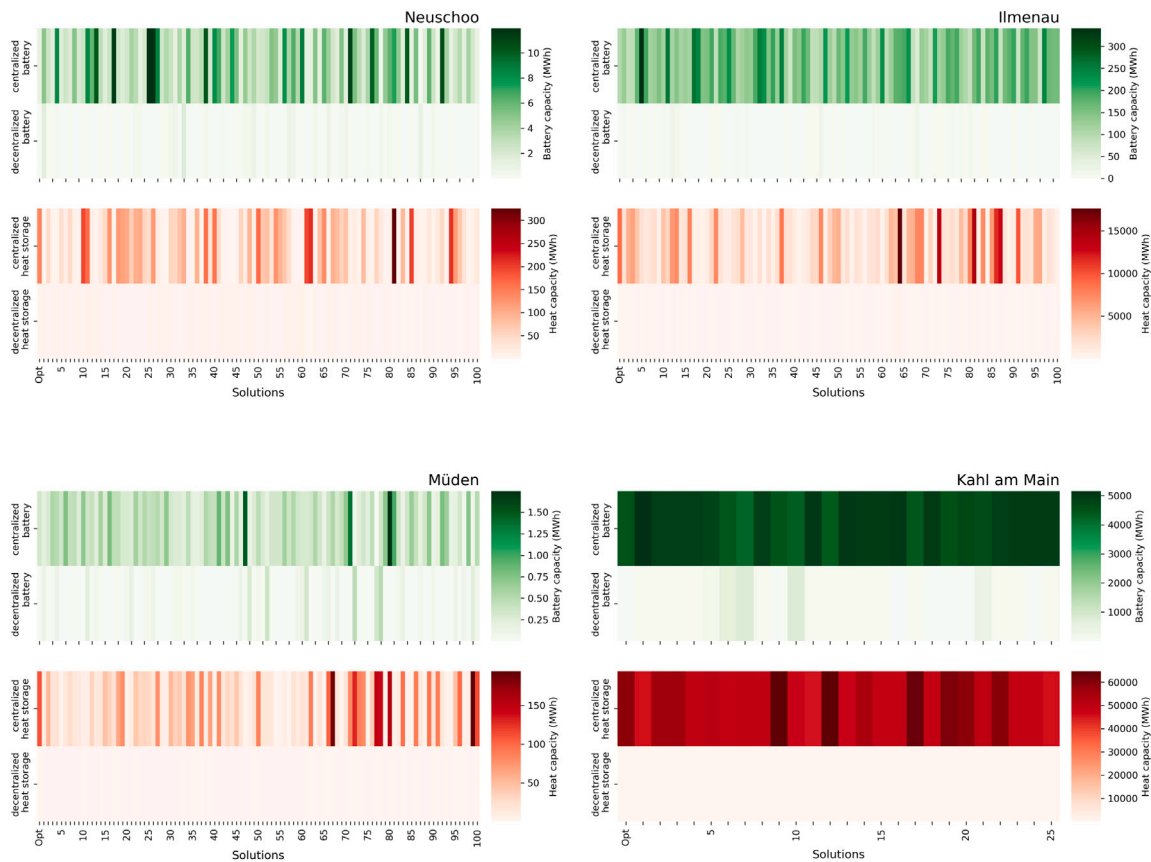


Fig. 4. Variation of centralized battery capacity, decentralized battery capacity, centralized heat storage capacity, and decentralized heat storage capacity in the optimal and MGA solutions for selected municipalities illustrated in heat plots. On the x-axis, 'Opt' represents the optimal solution, with the solutions from 1 onwards being the MGA solutions. Due to the storage component capacity varying similarly with MGA solutions in Urmitz and Kahl am Main, only the latter is used in this figure.

availability of renewable resources is marginally sufficient to meet energy demands and as a result there is not much excess electricity to store in centralized batteries even with a 10% cost relaxation.

For decentralized batteries, the capacity in the majority of the MGA solutions in Neuschoo, Ilmenau, and Müden all tends to zero, largely due to its higher cost. However, despite the higher cost, Kahl am Main increases the decentralized battery capacity up to 800 MWh in some of the MGA solutions from 0 MWh in the optimal solution. This is largely due to rooftop PV being the most widely used renewable energy technology in this region, where land is limited, and also because decentralized batteries are connected with rooftop PV systems. As a result, any excess rooftop PV electricity can be stored in the decentralized batteries. This reduces the need for re-dispatch of larger, centralized batteries.

Fig. 4 further illustrates the variation in the capacity of centralized and decentralized heat storage with the optimal and MGA solutions. The fact that all municipalities have a higher number of non-zero centralized heat storage capacity values shows that it is an essential component in each municipality. According to Risch et al. [40], the seasonal storage demand in the energy autonomous municipalities is primarily met through thermal storage. This is evident by having more diversity in the MGA results of decentralized heat storage compared to that of decentralized battery storage capacity. Decentralized heat storage is connected to the low-temperature non-process heat demand. For high-cost municipalities such as Kahl am Main, placing storage closer to end users (see Fig. 2) has a key advantage that can offset the higher unit cost of decentralized heat storage. Due to the limited availability of renewable technologies in these municipalities, a considerable portion of the low-temperature heat demand is met by technologies that

use electricity, such as heat pumps, rather than converting renewable electricity directly into heat. When low-cost renewable energy, such as open-field PV, is available, heat pumps can convert the electricity generated by it into heat. Decentralized heat storage units can then store this cheaply generated heat, allowing the system to meet demand later in the day, especially during periods when open-field PV is unavailable.

Fig. 5 shows the variation in the state of charge (SOC) of the battery storage in MGA solutions, based on the 10%–90% percentile bands in MGA solutions for three municipalities. The narrow 10th–90th percentile centralized battery SOC band in Ilmenau is an indication of low variability across MGA solutions, suggesting that centralized battery storage operation is robust and not highly sensitive to alternative system configurations. However, short-term fluctuations are indicative of active daily cycling, likely driven by consistent larger demand balancing. In Müden, the wider percentile band indicates greater variability among MGA solutions. This suggests that centralized battery storage operation is more sensitive to changes in system design. The battery frequently cycles at lower SOC levels, which implies tighter system constraints and greater dependence on storage to balance limited renewable resources. Fig. 4 shows that Ilmenau has a higher centralized battery capacity variation compared to Müden. However, Ilmenau demonstrates consistent battery operation throughout the year with MGA solutions. Conversely, Müden exhibits minimal variation in centralized battery capacity. However, the limited capacity configurations result in notably different storage utilization patterns. In Kahl am Main, a very limited flexibility can be observed with centralized battery SOC rising steadily from late spring, peaking in September–October, and starting to drop in late autumn. This indicates that the Kahl am Main energy system prefers to store electricity from its limited

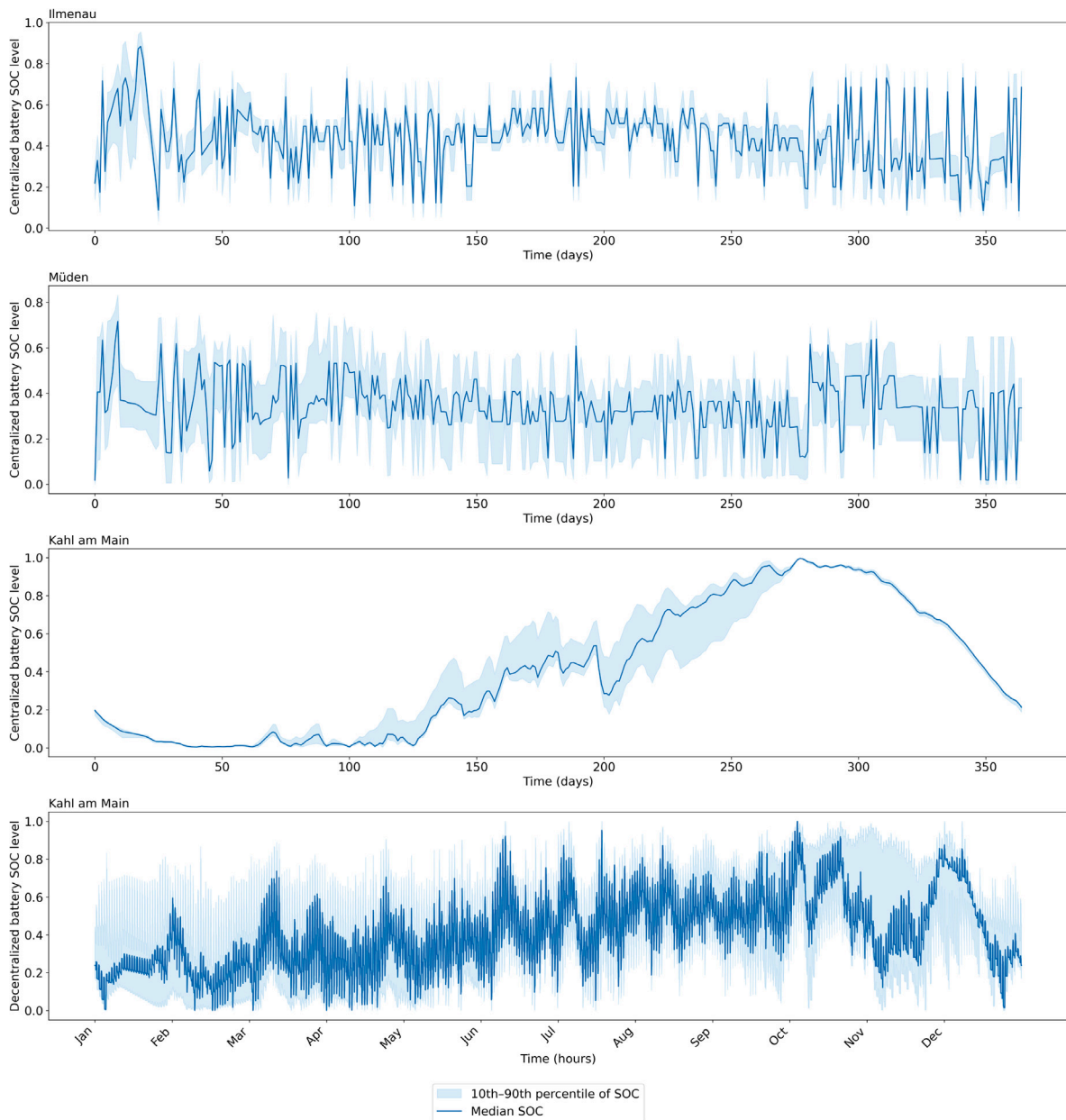


Fig. 5. Battery operation across MGA solutions visualized using median trajectories and 10%–90% percentile bands. The battery capacity identified in each MGA solution was used to normalize the SOC values. For centralized battery storage, daily aggregated values are used, while hourly values are used for decentralized battery storage.

renewable sources so that it can be used effectively during the winter, when renewable energy such as PV is scarce. The decentralized battery SOC in Kahl am Main exhibits significant high-frequency fluctuations throughout the year, with a wider range of values across the 10th–90th percentile. In contrast to centralized storage, decentralized storage responds more quickly to short-term fluctuations in local generation and demand. Similar to the centralized case, the increasing trend toward higher SOC levels in later months reflects seasonal effects, but with significantly more variability. This suggests that, although it does not fundamentally change the overall system constraints observed in Kahl am Main, decentralized storage introduces additional operational flexibility.

3.3. Flexibility in the low-temperature and process heat supply

Air-source heat pumps (ASHPs) with an hourly time-varying coefficient of performance (COP) of 2.3–4.2 were utilized in this study.

A wide range of feasible capacities in centralized heat pumps is evident in Urmitz and Kahl am Main (see Fig. 6a). Additionally, in Neuschoo, Ilmenau, and Urmitz, most MGA solutions allocate less capacity than the optimal solution. For example, in Urmitz, the optimal solution of centralized heat pump capacity is 137.3 MW, but a MGA solution as low as less than half that optimal capacity can also be observed. Kahl am Main exhibits different behavior, with high centralized heat pump capacities in the optimal solution that remain dominant across MGA results. This is due to a structurally constrained system that relies heavily on centralized heat supply. It further suggests that centralized heat pumps are one of the few viable options to meet demand in the face of limited renewable availability. For decentralized heat pumps in Neuschoo and Ilmenau (see Fig. 6b), MGA solutions generally prefer higher capacities than the optimal solution, which is the opposite of what was observed with centralized heat pumps in these two municipalities. Despite having a

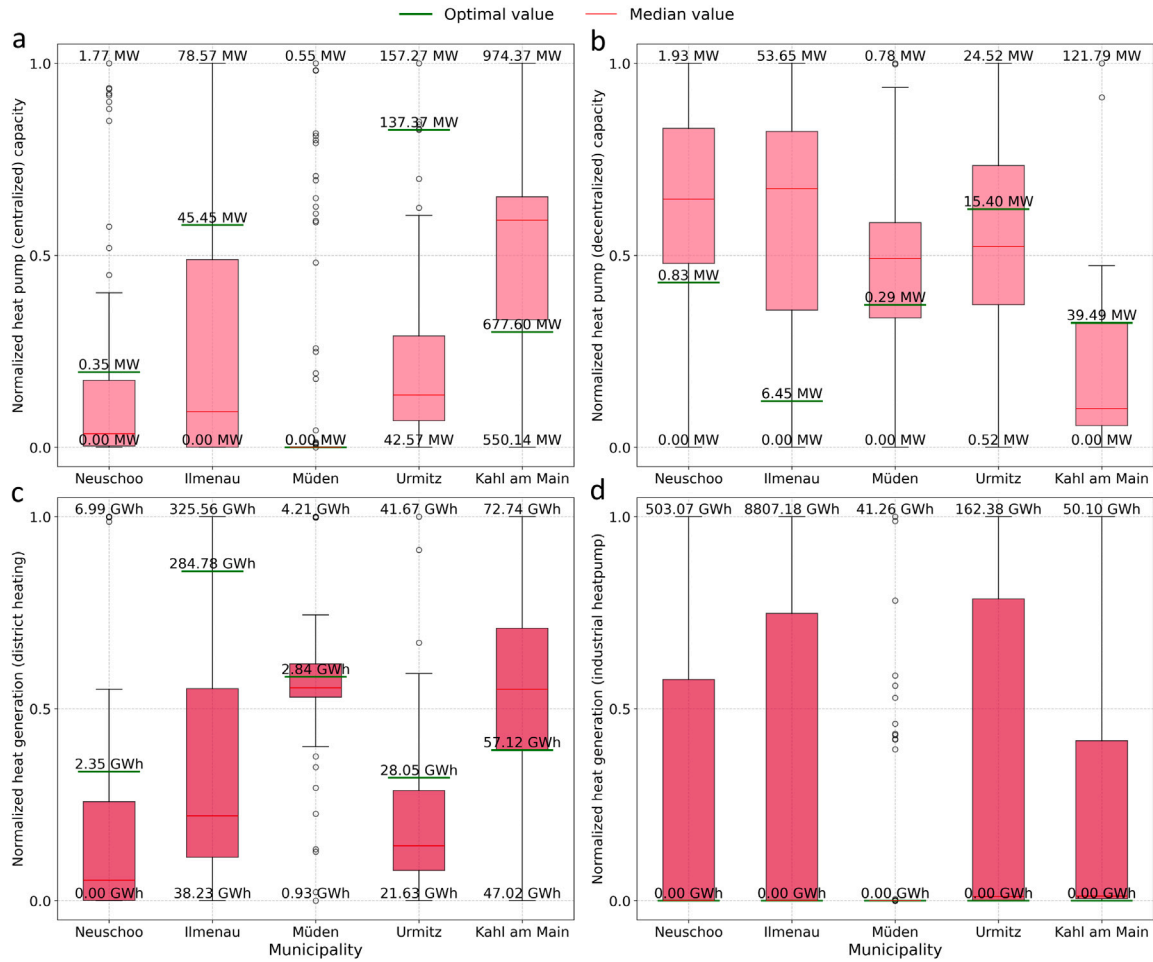


Fig. 6. Variation of normalized centralized heat pump capacity (a), normalized decentralized heat pump capacity (b) normalized heat generation in district heating (c), and normalized heat generation in industrial heat pumps (d) with the range of MGA solutions illustrated in box plots. Green lines show the normalized value of the optimal solution and the red lines indicate the normalized median value of all MGA solutions and the optimal solution. The lowest, highest, and optimal actual values are indicated in each plot. For e.g., the normalized value of 0 for centralized heat pump capacity in Neuschoo represents the smallest actual capacity (0.0 MW) identified in the MGA solutions, while the normalized value of 1 represents the largest actual capacity (1.77 MW). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

higher cost, the increased use of decentralized heat pumps in MGA configurations shows the importance of using MGA in energy system modeling. When the strict cost minimization is relaxed in these municipalities, it may bring non-cost advantages such as increasing self-sufficiency and reducing heat losses because decentralized heat pumps can directly convert electricity to low temperature heat. Conversely, Kahl am Main prefers a less decentralized approach to heat pumps in MGA solutions. This could be due to the higher investment and operational costs of decentralized heat pumps and the fact that system design favors centralized infrastructure because the integration of centralized heat pumps with district heating could provide cost advantages and flexibility in fulfilling the higher energy demand in this municipality.

Fig. 2 showed that district heating and industrial heat pumps are the only sources which supply low temperature process heat. In the majority of the municipalities, more than half of the MGA solutions are lower than the optimal value for district heating (see Fig. 6c). This suggests that, while district heating is cost-efficient under strict optimal conditions, it can be substituted in near-optimal cases without significant cost penalties, possibly by localizing process heat production through other technologies. Fig. 6d shows that despite their moderate cost, industrial heat pumps are absent from the optimal solution in all municipalities but are preferred in MGA solutions. Therefore, industrial heat pumps have become a viable alternative to district heating in

the MGA solutions. This further illustrates that when an additional 10% cost margin is available, MGA solutions attempt to maximize low-cost alternatives which is heat pumps against district heating in this instance. Many MGA solutions related to industrial pumps in Ilmenau and Neuschoo achieve exceptionally high values within the 10% cost relaxation. Therefore, these municipalities might have the option to vary the heat generation from industrial heat pumps to align with various external factors, such as policies, grid constraints, and carbon neutrality targets.

3.4. Sensitivity of the slack value

The results so far were obtained for a slack value of 10%. The results show that a greater diversity in capacities of some technologies such as open-field PV is possessed by some municipalities, such as Ilmenau, while no or very less diversity is possessed by high-cost municipalities such as Urmitz. This means that a 10% cost increase might not be enough for high-cost municipalities to provide a wide range of alternative energy system options. Conversely, it should be investigated whether greater diversity exists in low-cost municipalities, even for lower slack values. Therefore, the sensitivity of some component capacities to the slack was identified for each municipality as shown in Fig. 7.

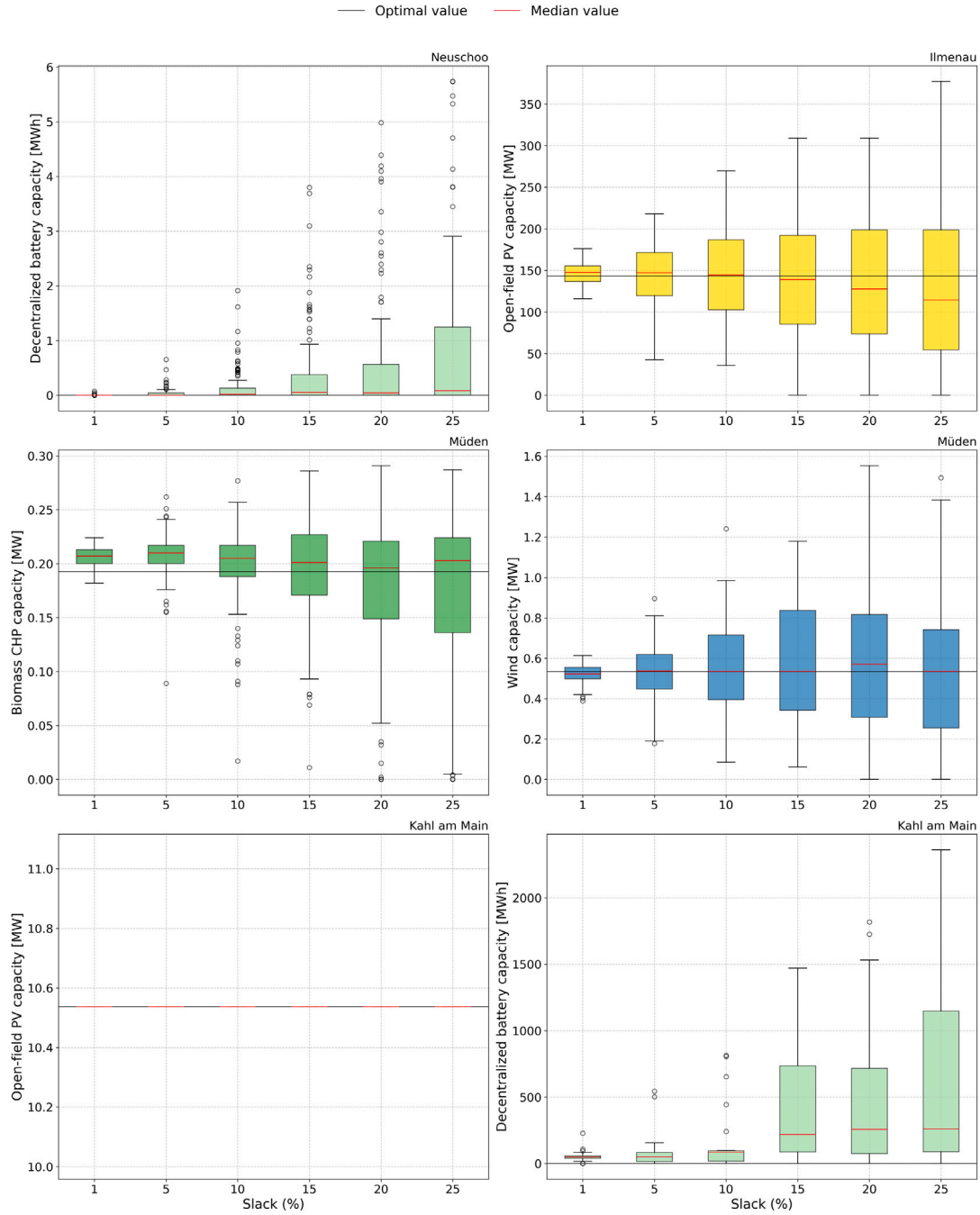


Fig. 7. Sensitivity of the results to slack values of 1%, 5%, 15%, 20%, and 25% for selected components in the municipalities. The horizontal black line denotes the value in the optimal solution and the red line shows the median value of all MGA solutions.

In Neuschoo, when the slack increases to more than 1%, the range in the decentralized battery capacity expands considerably, with capacities ranging from nearly zero to higher values with an upward trend. However, the median value in each slack is very low suggesting that decentralized battery deployment is not structurally essential in Neuschoo, but rather, becomes one of several interchangeable options when higher system costs are permitted. Ilmenau's open-field PV capacity shows a systematic shift, both upward and downward, as slack increases. The optimal solution relies on approximately 150 MW. However, higher slack levels allow for capacities of more than 300 MW, and the interquartile range broadens substantially. This reflects a higher open-field PV potential and greater internal degrees of freedom

for balancing supply and demand in this municipality. The outcomes further suggests that Ilmenau is an ideal location for solar expansion, where PV deployment is a robust and flexible option.

An increasing but limited scalability of capacity with the increasing slack value is seen in wind plants in Müden. Fig. 3 showed that, in MGA solutions with less or no open-field PV, expensive biomass CHP plants need to be operated alongside wind and rooftop PV to fulfill the energy demand in Müden. However, as Fig. 7 shows, the capacity of biomass CHP plants can decrease with increasing slack, indicating that achieving complete independence from biomass CHP requires higher investments in Müden. It can be further observed that wind capacity increases with the slack value however, the median wind capacity

remains near the optimal wind capacity value across increasing slack levels. This suggests a well-defined optimal deployment of wind capacity. As a result, the expansion observed in the higher slack values indicates that additional wind capacity serves as an alternative design option rather than a system configuration that is broadly preferred.

In Kahl am Main, open-field PV capacity is invariant across all slack levels. The rationale behind this is that Kahl am Main has opted to fully utilize its maximum open-field PV potential, even in the cost-optimal solution. Therefore, regardless of how much the slack value increases, Kahl am Main utilizes the maximum open-field PV potential because open-field PV is the cheapest renewable energy source available in the municipality. This shows that PV deployment in Kahl am Main is a permanent part of the system because it plays an essential role in meeting demand. Therefore, increasing the slack value does not tend to increase renewable technology capacities in high-cost municipalities. Instead, an increased decentralized battery capacity with higher slack values in Kahl am Main indicates that, in high-cost municipalities, the additional cost flexibility is connected with increased storage capacities.

4. Discussion

This section critically assesses the obtained results. In Section 4.1, the results are compared with previous literature findings. In Section 4.2, the practical implications of the results for each type of municipality are examined and Section 4.3 presents into the limitations of this study.

4.1. Comparison with previous studies

As mentioned in Section 2.3, this study is based on five municipalities which were identified by Risch et al [40] as being able to be completely autonomous (i.e., off-grid) by 2045. While the present study is generally consistent with previous literature, MGA solutions highlight important additional possibilities for system designers.

According to Risch et al [40], only 40.0% of the wind potential, 28.9% of the open-field PV potential, and 0% of the rooftop PV potential are deployed in Ilmenau in the grid-independent scenario. Nevertheless, this configuration has resulted in a renewable curtailment of 29.8 GWh. Ilmenau has a wind capacity potential of 199 MW. The MGA solutions of the present study demonstrate that for a cost increase (slack) of 10%, Ilmenau can function even with a wind capacity of 23% of the potential capacity and use more, less expensive open-field PV. In the MGA solution with the least wind capacity in Ilmenau, centralized batteries have a 138% higher capacity than in the cost-optimal energy system. This higher centralized battery capacity is useful in storing excess wind energy, which otherwise would have to be curtailed. Therefore, this alternative MGA configuration in Ilmenau could aid not only reducing renewable energy curtailment but also in addressing potential local opposition to wind turbine development (e.g., Refs. [53, 54]). Risch et al [40] further show that the energy system in Ilmenau can achieve further flexibility by utilizing excess electricity with a 6.6 MW electrolyzer to produce hydrogen and through intermediate storage in a 0.27 GWh hydrogen storage facility. The present MGA analysis shows that electrolyzer capacities between 3.2–11.4 MW and hydrogen storage between 0.004–1.04 GWh are feasible in Ilmenau. If there is a deviation from the point forecast in demand or solar output, this extra electrolyzer capacity ensures that spikes can be absorbed without re-dispatching or spilling. Therefore, this extended range illustrates how near-optimal solutions can strengthen sector coupling and seasonal balancing options, offering low-cost municipalities such as Ilmenau greater design flexibility and the ability to maintain feasible and cost-efficient energy system configurations under varying assumptions, without significant additional costs.

For Urmitz, which is a municipality with high costs associated with energy autonomy, Risch et al. [40] show that some system components are decisive for autonomy. For example, Urmitz has a large centralized

heat pump, with the cost of the heat pump amounting to 30.8% of the total cost. A major disadvantage of large, centralized systems is their vulnerability as a single point of failure. If the central unit malfunctions or shuts down, the flexibility of the entire system may be compromised, which could have catastrophic effects, especially on municipalities with high energy demand, such as Urmitz. The MGA Solutions in Urmitz have a higher preference for less centralized heat pump capacities and some preference for higher decentralized heat pump capacities, as compared to the optimal system (see Fig. 6). This will not only diversify the supply portfolio but also reduces the vulnerability to single-point failures inherent in highly centralized systems, thereby enhancing overall system reliability and resilience.

4.2. Practical implications of the study

Previous studies have shown that municipalities often strive for autonomy due to social, financial, and environmental motivations, and these motivations are shaped by local participation and policy frameworks rather than by cost considerations alone [6,10]. The present study identified how such motivations for autonomy can be operationalized through the diversity of near-optimal system configurations, allowing municipalities to align energy system designs with local preferences, constraints, and policy objectives through the use of obtained MGA solutions.

The obtained MGA results highlight substantial diversity in renewable deployment and storage configurations for low-cost autonomous municipalities with large renewable energy potential and lower energy demand. When such substantial diversity exists, policymakers have the opportunity to devise adaptive regulations that preserve affordability while respecting local preferences, such as the opposition to wind farm development. For instance, in Ilmenau, even 1% increase in the optimal cost would result in a –19% to 22% change in open-PV solar capacity compared to the optimal capacity (see Fig. 7). Therefore, stakeholders in these municipalities have significant flexibility to increase or reduce renewable capacity according to their needs. In medium-cost autonomous municipalities such as Müden, the MGA results show fewer but still significant substitution possibilities. Unlike in low-cost municipalities, a limited diversity in renewable energy technologies was available. However, a greater diversity in centralized heat storage and decentralized heat pumps was demonstrated, which were primarily used to store and supply the low-temperature heat obtained from limited renewable sources. For investors, this means clearer risk management through hedging against resource or land constraints. This ensures autonomy remains feasible without excessive reliance on one costly technology, even under tight conditions. In high-cost municipalities such as Kahl am Main, the limited range of solutions underscores the vulnerability of autonomy, and also highlights the importance of some key components identified in MGA alternatives. For example, the results showed that no matter how much slack increases, Kahl am Main cannot increase its open-field PV share. Therefore, open-field PV is a robust investment choice for the investors, regardless of cost flexibility. This shows that, MGA results provide investors with insight into where extensive autonomy remains feasible, guiding them toward more resilient and stable opportunities. Some MGA results obtained for Urmitz indicated a preference for higher capacities for decentralized batteries and heat pumps than the optimal values. As a result the public in these municipality can benefit from enhanced reliability through decentralized heat and battery systems, which reduce dependence on single points of failure.

Additionally, the societal willingness to pay (WTP) for increased autonomy or local renewable supply plays a crucial role in determining which MGA solutions are socially acceptable. Empirical evidence suggests that households may accept 5%–20% higher energy expenditures in exchange for greater energy independence, local environmental benefits, or participation in community energy systems [6]. The average cost of electricity for a German household is currently 396 €/MWh in

Table 3

Benefits associated with relaxing the cost-optimality constraint through MGA. The table summarizes how increased slack values create additional technological flexibility and how these alternative configurations can support societal acceptance, policy objectives, and investment robustness in municipalities with different autonomy cost levels.

Municipality (cost level)	Slack sensitivity findings from Section 3.4	Benefits gained from increased slack	Societal/policy relevance
Neuschoo (low)	Above 1% slack, decentralized battery capacity expands from near zero to substantially higher values while median remains low	Additional design flexibility through rooftop PV–battery coupling and household-level storage options	Supports household energy autonomy and may justify higher willingness-to-pay for local energy supply and storage ownership
Ilmenau (low)	Increasing slack broadens open-field PV capacity from roughly the optimal level (approx. 150 MW) to more than 300 MW	Larger renewable deployment flexibility and greater freedom to substitute technologies	Enables adaptive planning and allows policymakers to accommodate local preferences (e.g., reduced wind deployment or different land-use priorities) while maintaining affordability
Müden (medium)	Higher slack enables lower biomass CHP dependence and higher wind capacities	Reduced reliance on a single dispatchable renewable technology and increased diversification of supply	Provides investors with hedging opportunities against biomass availability and land constraints while maintaining autonomy
Kahl am Main (high)	Open-field PV remains fixed at all slack levels, but decentralized battery capacity increases with slack	Reveals that storage rather than generation is the main flexibility option in constrained municipalities	Identifies robust investment priorities and highlights where autonomy remains feasible despite limited renewable potential

2025 [55]. Therefore, based on the specific system costs of the municipalities, all low and some medium-cost municipalities are more likely to be willing to pay for energy autonomy based on a MGA solution with even more than 10% slack. In this context, MGA solutions provide a structured way to identify which alternative system configurations fall within socially acceptable cost ranges, enabling stakeholders to select designs that balance affordability with local preferences and autonomy goals. For example, Fig. 7 shows that the capacity of decentralized batteries in Neuschoo increases with the slack value. Since decentralized battery storage is coupled with rooftop PV, it is highly likely that households will have a higher WTP in order to benefit from coupling rooftop PV with more battery energy storage. A higher WTP means that a higher decentralized battery capacity based on a higher slack could be obtained, which could ultimately lead to household energy autonomy, going beyond municipal autonomy.

According to Trutnevyte et. al [21], the cost of CO₂ abatement in Europe for very high self-sufficiency (80%–100%) is around 300–600 €/tCO₂. Therefore, translating the specific system costs identified in Section 2.3 into implicit CO₂ abatement costs indicates that some high-cost autonomous configurations lie far above the typical mitigation costs for such autonomous regions. For example, using the German grid carbon intensity (332 gCO₂/kWh in 2025 [56]) as the baseline, a fully autonomous renewable system in Urmitz with specific system costs of €988/MWh corresponds to an implicit CO₂ abatement cost of approximately €3068/tCO₂. This significantly exceeds typical literature values hence, achieving full autonomy while considering CO₂ abatement may not be economically justifiable for such high-cost municipalities. In contrast, medium-cost municipalities with lower specific system costs and low-cost municipalities exhibit relatively diverse MGA solutions, indicating that their implicit CO₂ abatement costs are likely to remain closer to the typical mitigation range. For example, the specific system cost of €120/MWh in Müden corresponds to a CO₂ abatement cost of approximately €361/tCO₂. Therefore, the municipality has the freedom to choose an alternative energy system configuration (e.g., with increased wind capacity or decreased district heating) based on a MGA solution even with more than 25% slack and remain within the aforementioned CO₂ abatement values.

While the preceding discussion highlighted the practical implications of selected MGA solutions, the benefits associated with increasing the slack value are not uniform across municipalities. Depending on local resource availability, Section 3.4 showed that additional cost flexibility enables different forms of technological diversification and system adaptation. Table 3 summarizes the key benefits obtained through increased slack values for representative municipalities and relates

these benefits to their societal, policy, and investment relevance. This demonstrates that the additional costs permitted by MGA can enable alternative system configurations that better align with stakeholder preferences, risk management objectives, and local energy transition strategies.

The results presented in Table 3 reveal a systematic relationship between the cost of energy autonomy and the flexibility of municipal energy system design. Municipalities with low autonomy costs exhibit a substantially larger near-optimal solution space, allowing multiple technology combinations to achieve similar system costs. In contrast, municipalities with high autonomy costs are characterized by a limited number of feasible alternatives and a stronger dependence on specific technologies. Ilmenau, despite its substantially larger population and demand than Neuschoo, exhibited comparable or greater diversity in near-optimal solutions because of its larger geographical area and renewable potential. Conversely, Urmitz and Kahl am Main, despite differing considerably in population and demand from one another, both showed near-zero flexibility because of shared land constraints.

From a planning perspective, these findings suggest that municipalities should not be evaluated solely based on the cost of achieving energy autonomy. While cost-optimal solutions identify the least-cost pathway, they provide limited insight into the flexibility available for adapting to future developments. In contrast, MGA reveals the extent to which alternative system configurations can achieve similar costs while relying on different technology portfolios. The flexibility patterns observed across the five case-study municipalities indicate that municipalities with low autonomy costs generally possess larger near-optimal solution spaces, whereas municipalities with high autonomy costs are characterized by more constrained design options. These patterns are likely representative of other municipalities with similar techno-economic characteristics across Germany. Consequently, municipalities with larger near-optimal solution spaces may be better positioned to adapt to future changes in technology costs, resource availability, societal preferences, and policy constraints. Therefore, MGA provides information for the extension of traditional cost-optimal planning to the quantification of the degree of options available within autonomous energy system designs.

4.3. Limitations of the study

This study is based on an analysis of only five municipalities because of the large amount of computational time and storage capacity required to obtain multiple MGA solutions for a large number of

municipalities. Although these municipalities were chosen to represent different cost levels and therefore potentials for reaching autonomy, the small sample size limits the generalizability of the findings to all German municipalities. For example, Neuschoo and Ilmenau are both considered low-cost municipalities, but Ilmenau is a municipality with a larger degree of renewable energy flexibility, whereas Neuschoo has much less flexibility. Nevertheless, the study provides important insights into the flexibility of options for designing autonomous systems.

In Section 2.1, it was demonstrated that the MGA results vary with the β , which is a random coefficient between -1 and 1 . All the different MGA solutions for a municipality were obtained by changing this β value iteratively. The combined MGA approach used in this study leverages the complementary strengths of random vector and variable min/max methods, enabling both broad exploration of the near-optimal solution space and identification of extreme system configurations. However, unexplored β values could still lead to alternative system configurations that are not included in the current analysis. Additionally, the MGA results depend on the chosen slack (10%). Although sensitivity analysis was tested for other slack values, this formulation still bounds the conclusions, and higher or lower tolerances could alter the range of feasible alternatives. In the future, therefore, further approaches for systematically searching the entire solution space with MGA [57,58] should also be applied.

This study did not consider transmission components for any of the commodities examined. Primarily, the municipalities are entirely autonomous, and therefore, they have no need for imported energy. Moreover, these five municipalities are not in close proximity to each other. Not considering transmission components strengthens the focus on autonomy but reduces applicability to real-world conditions where inter-municipal or regional transmission could significantly lower costs and further increase the flexibility.

Future work will expand the model to include a larger and more diverse set of municipalities across Germany. This will allow for a more robust assessment of the generalizability of autonomous energy system configurations. Additionally, more systematic approaches to exploring the near-optimal solution space will be implemented. These approaches will build on established advances in modeling to generate alternatives in order to better capture the full diversity of feasible system designs beyond randomly sampled configurations. Furthermore, future studies will explicitly incorporate transmission components and inter-municipal energy exchange. This will allow for a comparative evaluation of the cost efficiency, resilience, and flexibility of fully autonomous versus interconnected systems.

5. Conclusions

This study used the modeling to generate alternatives approach to explore the diversity of autonomous municipal energy systems. The five case-study municipalities were selected as representative cases of the three cost-driven autonomy typologies identified across the broader population of German municipalities capable of energy autonomy. The results show that near-optimal solutions offer valuable insights as they highlight technological substitution options, the role of storage, and potential trade-offs in renewable energy deployment. Municipalities with low autonomy costs possess substantially larger near-optimal solution spaces than municipalities with high autonomy costs. This pattern is expected to generalize to other municipalities within the same cost typology. Substantial flexibility was found for municipalities with abundant land for renewable energy, enabling investors, policymakers, and the public to balance economic efficiency with social acceptance and land-use constraints. Although some municipalities had more limited substitution possibilities, they still offered scope for risk diversification and targeted policy interventions to support autonomy. In municipalities with a low techno-economic potential for energy autonomy, the limited range of possible system solutions highlighted

the vulnerability of autonomous energy provision. This emphasizes the importance of decentralization and modularity, as well as the potential role of investors in mitigating equity concerns.

The MGA-based analysis further shows that flexibility, cost levels, and technological substitution possibilities vary substantially across municipalities, shaping the feasibility and societal acceptability of pursuing energy autonomy. While low- and medium-cost municipalities can draw on diverse and socially acceptable pathways, high-cost municipalities face implicit CO₂ abatement costs far above typical mitigation ranges, making full autonomy economically questionable.

A key contribution of this study lies in the application of MGA at a high spatial resolution to municipal-scale autonomous energy systems, which remains largely underexplored in the literature. Unlike conventional approaches that focus on a single optimal pathway, this work quantifies the diversity, robustness, and structural characteristics of near-optimal solutions across municipalities with several cost typologies. Furthermore, the study uniquely links techno-economic modeling outcomes with societal and policy-relevant dimensions, such as willingness to pay and implicit CO₂ abatement costs, providing a more comprehensive basis for real-world decision-making. The observed relationship between autonomy cost and solution-space diversity further suggests that municipalities with larger MGA solution spaces may be better positioned to adapt to future disruptions and uncertainties. Consequently, MGA can serve not only as a tool for exploring alternative energy system configurations but also as a means of assessing the resilience and adaptive capacity of autonomous municipal energy systems.

Overall, the findings highlight that MGA can guide municipalities, investors, and policymakers toward autonomy strategies that are not only technically well equipped but also aligned with local willingness to pay and long-term climate policy objectives. Future work should extend the framework to include transmission infrastructure and alternative MGA formulations to better capture spatial interactions and reduce methodological biases.

CRedit authorship contribution statement

Lovindu Wijesinghe: Writing – original draft, Software, Methodology, Conceptualization. **Jann Michael Weinand:** Writing – review & editing, Methodology, Conceptualization, Supervision. **Noor Titan Putri Hartono:** Writing – review & editing, Data curation, Supervision. **Russell McKenna:** Writing – review & editing, Data curation. **Detlef Stolten:** Writing – review & editing, Funding acquisition, Data curation. **Jochen Linßen:** Writing – review & editing, Supervision.

Declaration of competing interest

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

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Data availability

Data will be made available on request.

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