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Empowering a sustainable urban future: The key role of coordinated settlement development for optimising energy efficiency and socio-economic welfare

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ABSTRACT

The nexus between urbanisation and energy transition represents a critical juncture in the pursuit of sustainable development. As cities continue to grow and expand, their energy needs rise, driving consumption and emissions. Simultaneously, efforts to transition towards renewable energy sources and improve energy efficiency are underway to mitigate climate change and reduce dependence on fossil fuels. However, urbanisation poses a challenge to these efforts, as sprawling cities require more energy for transport, infrastructure and buildings. Reconciling the need for urban development with sustainable energy practices requires integrated spatial planning approaches that consider the spatial layout of residential areas, land use patterns and transport systems. To address this nexus, our study explores the complex interplay between energy efficiency and urban development, alongside communities' quality of life, which is crucial for urban sustainability. We have developed a settlement network model that integrates socio-economic factors and the spatial distribution of energy consumption. Using a U-NSGA 3 algorithm, we have attempted to optimise future settlement network to simultaneously improve the two goals of energy efficiency and socio-economic factors. By optimising settlement networks, we shed light on the relationship between energy efficiency and communities' quality of life arising from different urban development patterns, offering insights for strategic spatial planning and technological advances. Using insights from a Swiss case study, we delineate modified strategies encompassing coordinated development, densification and the use of electric vehicles and building insulation. The results offer practical solutions for policymakers and spatial planners dedicated to fostering sustainable urban development. The overall conclusion underscores the critical significance of a coordinated approach to urban development in attaining overarching sustainability objectives.

1. Introduction

The global consensus on the transition to a zero-carbon society is strengthening (IPCC, 2014). This is based on the urgent need to eliminate greenhouse gas emissions, which necessitates the use of new technologies and an end to the use of fossil fuels (Owen et al., 2018; García-García et al., 2020; Olabi & Abdelkareem, 2022). The envisioned technological and policy shifts for a zero-carbon transition aim to reduce energy consumption for the same services and products that need energy, commonly referred to as 'energy efficiency' (Jollands et al., 2008; Novatlantis et al., 2011; Boulouchos et al., 2022; Yang et al., 2022).

This shift in energy policy and technologies has the potential to make a significant impact on society and the economy, as both are highly dependent on the services enabled by energy (Lovisolo, 2021; Burger et al., 2022). These services include supporting various activities, creating comfortable living spaces and facilitating transportation and communication (Stoeglehner et al., 2011; Fell, 2017; Kalt et al., 2019). Therefore, aside from technological aspects, the execution of the energy transition may entail intricate societal challenges, such as spatial cohesion or disparity (Hess & Sovacool, 2020; Rao & Wilson, 2021). While the aim of the planned technological and policy shift is to increase energy efficiency, the overarching goal is to achieve it without compromising, and ideally improving, the social and economic welfare (Miller et al., 2013). The social dimension of energy transition is often

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inadequately addressed in research (Rao & Wilson, 2021; Akrofi & Okitasari, 2022), with a notable oversight of the potential inequalities that may emerge (Healy & Barry, 2017; Sovacool et al., 2018). Recognising the pivotal socio-economic impacts associated with energy transition initiatives, it becomes increasingly clear that a more focused approach is needed to address this aspect effectively.

Parallel to the actions taken for energy transition, urbanisation is accelerating and human settlements continue to expand (UN-Habitat, 2013; Kii, 2021). The urbanisation process is propelled by population growth (Mahtta et al., 2022), economic development (Dash Nelson & Rae, 2016; Mahtta et al., 2022) and changing patterns of social and cultural life (Gao & O'Neill, 2020; Chen et al., 2022). Urbanisation often brings both socio-economic benefits and burdens for the growing population (Bettencourt et al., 2007). To enhance the benefits of urbanisation, careful planning is needed to improve residents' satisfaction and cultivate a positive living experience in different types of housing, including individual homes, buildings and entire neighbourhoods (Bonaiuto & Fornara, 2004). However, these integral aspects of living satisfaction, such as access to amenities (e.g., schools, retail stores, nature, leisure activities) and ensuring essential household infrastructures (e.g., lighting, cooling and heating), substantially contribute to the overall rise in energy consumption, which is predominantly sourced from fossil fuels and electricity. While urbanisation contributes significantly to the overall increase in energy consumption needed for promoting residential satisfaction, the energy transition underscores the challenge of increasing energy efficiency, forming a nexus between urbanisation and the energy transition (Kaswan, 2009; Boulouchos et al., 2022; Foulds et al., 2022).

The above two parallel processes, the transition to a zero-carbon society and the trend towards urbanisation, are typically studied independently within their policy domains (Wang et al., 2016; Wang et al., 2019). Nevertheless, nearly two-thirds (67 %) of Switzerland's energy is consumed in residential areas by households, covering needs such as transportation, heating and cooling, and will be affected by the development of settlement areas in the future (Brand-Correa et al., 2018; Boulouchos et al., 2022). This is why an integrated spatial plan offers significant potential to balance the two major goals of energy efficiency and residential satisfaction in urbanising areas (Stoeglehner et al., 2016; Asarpota & Nadin, 2020). Still, major urban development strategies often neglect energy distribution and efficiency (De Pascali & Bagaini, 2018). This underscores the pressing need for efforts to integrate spatial planning that are aimed at enhancing energy efficiency while also elevating urban living standards and residents' satisfaction (Stoeglehner et al., 2016; Wang et al., 2016; Asarpota & Nadin, 2020). For instance, the polycentric development strategy, which has been widely adopted in many European countries including Switzerland, falls short of fully integrating energy efficiency goals into spatial planning (Bundesrat et al., 2012). In some contexts, polycentricity is understood merely as morphological decentralisation (Hendrigan, 2019), which not only fails to improve energy efficiency, it can also lead to an increased need for transport and a rise in single-family housing, and thus to greater land consumption (Vale, 2009; Zou et al., 2019; Xu et al., 2021). Addressing this challenge requires a comprehensive reassessment of future development strategies, encompassing both urban and rural areas, to effectively align the energy transition vision with the promotion of a more sustainable society (Boulouchos et al., 2022; Foulds et al., 2022). To achieve the dual objectives of increasing residential satisfaction and energy efficiency, more detailed modelling and assessments need to be carried out, highlighting the existing research gap in this area.

Modelling settlement networks is a promising approach for unravelling the complex relationship between energy transition and urbanisation. These networks act as vital spatial structures that connect the built environment, including buildings and neighbourhoods, through transport systems, fostering vibrant societies (Csapó & Balogh, 2012; Filippova & Zakharov, 2023). The role of settlement networks in shaping the distribution of energy demand shows their importance in steering the transition to a zero-carbon society while improving the living satisfaction of residents (Ewing & Rong, 2008; Calthorpe, 2011; Coenen et al., 2012; Ramaswami et al., 2016). Previous research has identified key settlement network characteristics—such as function, density and size—that influence energy demand (Stoeglehner et al., 2011). Notably, a diverse mix of functions within an area reduces the need for travel, thereby conserving energy, while higher function density enhances the cost-effectiveness of public infrastructure (Bibri et al., 2020). Furthermore, the degree of housing densification significantly affects energy intensity levels (Barles & Knoll, 2019; Tanguy et al., 2020). Current trends in urban development often exhibit energy-intensive, uncoordinated, low-density patterns that rely on fossil fuel-dependent mobility (Newman & Kenworthy, 1999; Mattioli et al., 2020). Through settlement network modelling, we can gain deeper insights into these spatial complexities, paving the way for informed interventions to foster sustainable urban development.

Spatial planning studies have increasingly used multi-objective optimisation algorithms to evaluate trade-offs between potentially conflicting objectives and more integrated planning practices (Keirstead & Shah, 2013; Caparros-Midwood et al., 2015; Memmah et al., 2015; Caparros-Midwood, 2016). Recent advancements in optimisation theory and computational technology allow for the solving of larger, more complex planning problems (Memmah et al., 2015). Meta-heuristic algorithms, like genetic algorithms, are particularly successful in handling complex and time-consuming problems (Abraham & Jain, 2005; Glover & Kochenberger, 2006). Given the complexities inherent in settlement networks and the dual objectives of energy efficiency and enhancing residential satisfaction, the development of multi-objective optimisation is crucial for addressing the diverse goals and interests in real-world planning scenarios (Keirstead & Shah, 2013; Li et al., 2018).

In this article, guided by the need for a comprehensive approach, we explore the intricate interplay between energy efficiency and urban development. By introducing a settlement network model tailored to the intricacies of urban development, we are able to evaluate the impact of different development patterns on community satisfaction and energy efficiency. By applying an evolutionary multi-objective optimisation technique, we investigate the trade-offs between community satisfaction, energy efficiency and the polycentricity of the settlement network. This extends to the spatial dimension of energy efficiency by examining how the centralisation or decentralisation of settlements affects the distribution of energy demand and spatial equity, a crucial socio-economic aspect of the energy transition. These results provide valuable insights for regions facing the challenges of a sustainable and liveable urban environment due to the future urbanisation and energy transition.

2. Methods

2.2. Case study area

In light of the growing awareness of sustainability concerns, Switzerland is actively pursuing an energy strategy geared towards achieving a three- to-fourfold reduction in energy consumption (referred to as the `2000-watt society') (Novatlantis et al., 2011; Boulouchos et al., 2022). Switzerland's dedication to energy efficiency encompasses both the efficiency of mobility and household energy consumption, constituting roughly two-thirds of the overall energy consumption of the nation (Rickwood et al., 2008; Novatlantis et al., 2011; Boulouchos et al., 2022). Prior aggregated assessments have highlighted the substantial theoretical capacity within the Swiss household and mobility sectors to fulfil these efficiency requirements. Most of this potential can be realised in peri-urban areas, as energy practices in these areas are more energy-intensive. Despite identifying theoretical potentials, there is a gap in terms of linking this potential to urban development patterns and finding implementable solutions to achieve the desired reduction in energy consumption. Enhancing homes' energy efficiency through insulation offers a straightforward solution, while addressing mobility energy efficiency requires more intricate measures (Drouilles et al., 2017). The challenge stems from the dynamic nature of the problem: structural changes in settlements impact both transportation and household energy needs (Switalski, 2018). This complexity also extends beyond energy concerns to involve intricate socio-economic dynamics linked to community satisfaction within neighbourhoods, due to evolving settlement structure and the evolving energy system (Motz, 2021; Burger et al., 2022).

Considering the complexities of this problem, we selected a case study area located at the confluence of the cantons of Zurich, Schaffhausen and Thurgau, on the Swiss Plateau (Fig. 1). This region was selected to investigate the dynamic interactions among settlement structures, energy efficiency and the associated socio-economic dynamics at the interface between urban and rural areas. Encompassing 41 municipalities and over 385.2 km^2, this region consists of a diverse mix of urban and rural communities, which are expected to undergo substantial urbanisation and settlement expansion in the coming years. Significant changes are expected, including a population increase of 33.2 % by 2040 and the creation of 5532 new jobs, particularly in Frauenfeld (ARE, 2014). More than 50 % of the dwellings in this area are single-family homes, which are known for their lower population density and higher energy consumption. This is amplified by decentralised settlement structures, necessitating longer travel distances (Drouilles et al., 2017).

The selected case study area is of strategic importance for our research in particular because it is home to many pilot and demonstration projects initiated by the Swiss Federal Office of Energy, which form an important interface between research and implementation. Such areas aim to enhance the development status of new technologies and policies to facilitate their implementation on a wider, national scale. Furthermore, the area hosts the ongoing development of thermal networks. These networks provide thermal energy to multiple buildings through water or steam pipes, and their development is influenced by various factors, including future urban development. Therefore, the planning of future energy systems, such as thermal networks, can benefit from a better understanding of the future distribution of household energy demands.

In addition to the above, the study area faces the challenge of coordinated development, which is a hallmark of Switzerland's decentralised approach to spatial planning. The Swiss governance model, which emphasises the autonomy of the local and cantonal levels, offers both opportunities and challenges for sustainable development. This approach allows for tailored solutions and responsive decision-making based on the unique future needs of each municipality (e.g., new local residential buildings and insulation practices). Amidst the individual endeavours of municipalities, certain ones have earned certification as Swiss Energy Cities. This recognition is awarded to municipalities that develop and implement a sustainable energy policy and positions them as proactive participants in the realisation of energy sustainability goals. Yet, achieving energy targets, particularly in the mobility domain, presents challenges requiring collective action and careful coordination among municipalities. Individual initiatives, though commendable, fall short in addressing the intricate interdependencies among communities (Khiali-Miab et al., 2022). Attaining these targets requires a nuanced balance, necessitating coordinated efforts to foster cohesive development plans across municipalities and cantons. Finally, our case study can shed light on the intricacies of this coordination challenge and aims to provide insights that can lead to more effective urban development planning.

Approximately 80 % of the Swiss population resides within the Swiss Plateau. Investigating the interconnection between energy efficiency and urban development in this case study region advances our understanding of sustainable development in analogous locales across the Swiss Plateau and other communities globally. The insights gained are transferable to different regions and will facilitate the search for pragmatic solutions for coordinated development and the promotion of sustainable energy initiatives.

2.2. Modelling overview

Fig. 2 is a schematic flow diagram of our integrated model, which serves as a tool for exploring the relationship between the energy transition and residential satisfaction, both of which are influenced by changes in settlement structures. To construct this integrated settlement network model, we undertook three main steps, as detailed in Sections 2.3–2.9.

The initial step involved providing the necessary input data, as highlighted in the green boxes. These inputs encompass factors such as population distribution; leisure distribution; business distribution (for simplicity, we call them 'basic spatial distributions'), including retail store densities; and job distribution, as well as trip distribution at an initial point in time (2010). We can categorise these distributions as residents and the amenities that serve them.

As a second step, we calculated the changes in trip distribution as a function of changes in basic spatial distributions. Future alterations in the settlement network resulting from urbanisation can impact the basic spatial distributions, thereby influencing trip patterns and energy consumption due to new commuting patterns. Additionally, it affects residential satisfaction, due to changes in accessibility to amenities. Thus,

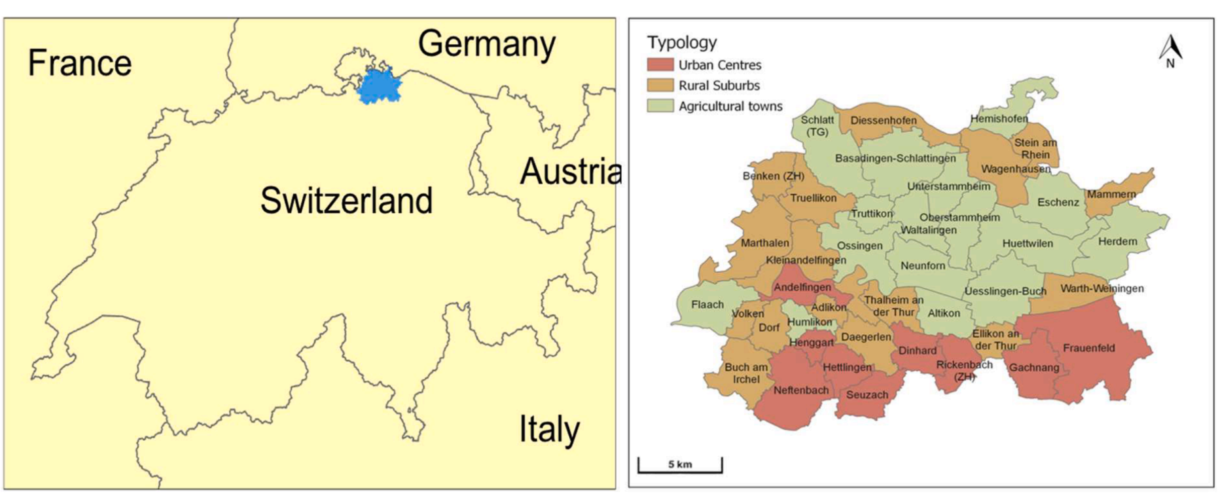

Fig. 1. The case study region. (Left) Map showing the area's location within Switzerland. (Right) Map displaying the municipalities and their classifications according to their numbers of inhabitants.

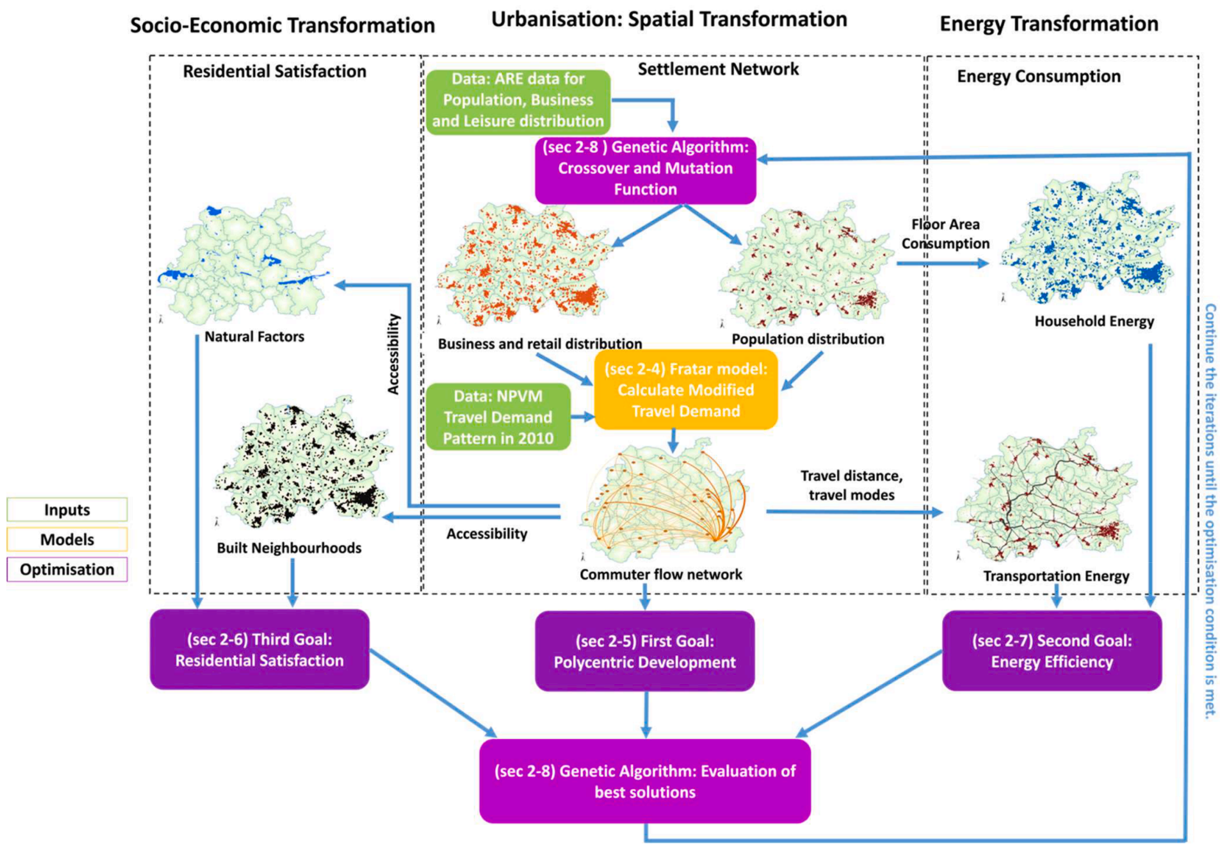

Fig. 2. Schematic overview of the integrated modelling approach; Exploring the interplay among settlement development patterns, socio-economic benefits and energy consumption.

modifying trip distribution is an intermediary step because it is needed for calculating subsequent changes in our two objectives: energy consumption and residential satisfaction. These calculations were performed using an intermediate module, as represented by the yellow box.

The yellow box represents the Fratar model (explained in detail in Section 2.4), which calculates travel demands within the case study area based on updated spatial distribution of residents and the amenities. This module uses the initial trip distribution data from the Swiss National Passenger Model (NPVM) and calculates a modified trip distribution within the new settlement structure. Adjusted trip flows and accessibility to amenities are determined and then used in the calculation of the objectives through the genetic algorithm in later steps.

The final step, represented by the integration module in purple boxes, involved implementing the genetic optimisation algorithm (U-NSGA 3). This mechanism allows for adjustments to the basic spatial distributions across different municipalities, enabling the calculation of the final effects of urbanisation prospects. By using a residential utility function, we estimated the residential satisfaction of the communities residing in this region (Section 2.6). Based on the updated settlement network, we then assessed the energy consumption of households related to their types of housing and commuting distances (Section 2.7). To uncover the general trade-offs and relationships among urban development patterns, energy consumption and residential satisfaction, we embedded the nexus model of the settlement network within an iterative evolutionary optimisation algorithm, U-NSGA 3. This optimisation process integrated the various components of the system to reveal relationships and trade-offs among the output indicators, which will be explained later in more detail. Additionally, crossover and mutation functions within the genetic algorithm were employed to enhance exploration and the exploitation of feasible urban development solutions, facilitating the search for optimal residential satisfaction and energy efficiency (Section 2.8). Through this integration, optimal distributions of residents and the amenities can be determined, resident satisfaction can be measured and energy consumption patterns across the region can be identified.

2.3. *Modelling settlement network*

The settlement network forms the basis of our model of spatial interdependence and serves a dual purpose in our analysis. First, it serves as a tool to account for potential drivers of urbanisation, such as population, business and leisure development in the future (Khiali-Miab et al., 2022). Second, the updated settlement network provides the basis for estimating future changes in residents' satisfaction and the distribution of energy consumption in the region.

In our settlement network model, we use NPVM zones as nodes within an interconnected system, with these zones corresponding to the smallest spatial units used for transport modelling in Switzerland. While finer spatial units exist, NPVM zones offer the most detailed scale available for capturing trips between residential areas (ARE, 2014). Establishing links between nodes is essential for completing the network, with each link representing the cumulative demand for trips between nodes across various activities, such as work and recreational journeys. These links illustrate the dynamic interactions among areas under different development scenarios, as detailed in Section 2.9.

Our model considers various attributes associated with nodes within the settlement network, which are recognised as having an impact on residents' satisfaction when choosing a neighbourhood (Schirmer et al., 2014). These attributes are drawn from existing literature and surveys conducted and used by the Swiss Federal Office for Spatial Development (Schirmer et al., 2011; Schirmer et al., 2014) and include static and dynamic factors. While static attributes remain constant throughout all iterations, dynamic attributes evolve with each iteration, reflecting changes in the settlement network due to future changes in basic spatial distributions and travel patterns. Further details on these attributes are explained in Appendix 1.

2.4. Settlement network modification

The significant changes resulting from urbanisation manifest themselves primarily in the relocation of households, businesses and leisure facilities ('basic spatial distributions'). This dynamic process theoretically enables the modelling of its impact on various attributes, including travel times, accessibility metrics and the change of rental prices. These are intermediary factors needed for the final calculation of both goals, residential satisfaction and energy consumption.

In our study, we applied the Fratar method to recalculate the new trip distributions resulting from the changes in basic spatial distributions, which affect the entire settlement network. The Fratar method involves iterative matrix calculations in which the commuting flow values between pairs of nodes within the settlement network are updated for the year 2040 based on data from 2010. This iterative process has a higher efficiency and better calculation time, and has proven to be highly accurate, generally deviating from the actual commuter flow values by only 3 % to 5 % (de Dios Ortuzar & Willumsen, 2011).

To implement the Fratar method, we first established the relationship between population growth and the increase of amenities (e.g., businesses and educational centres, retail and leisure facilities) with the travelling patterns in the case study area. These are the factors attracting residents to commute for various purposes, such as work, shopping, education and leisure activities, to different nodes. Consequently, an increase in population within a node generates more trips originating from it (ARE, 2014).

Next, we recalculated the total number of trips originating from and terminating at different nodes. Our assumption was that an increase in amenities in a particular node will result in a higher total number of trips drawn to that location. Similarly, we posited that the flow of trips originating from a node was positively correlated with the population residing in it. To quantify these relationships, we introduced growth factors, denoted as τ_i and Γ_i, which connect changes in population and amenities within node i to the total number of trips originating from and attracted to that node, respectively. These factors were computed as follows:

$$\tau_i = \frac{Population_{future(i)} - Population_{base(i)}}{Population_{base(i)}} \tag{1}$$

$$\Gamma_i = \frac{Amenities_{future(i)} - Amenities_{base(i)}}{Amenities_{base(i)}} \tag{2}$$

where $Population_{base(i)}$ and $Amenities_{base(i)}$ are the population size and the number of amenities, respectively, of node i in the base year. Similarly, $Population_{future(i)}$ and $Amenities_{future(i)}$ are the future population size and available amenities at node i. The total number of future trips originating from node i is equal to $(O_i * \tau_i)$, where O_i is the total number of trips initiated from node i in the base year. The total number of future trips attracted to node i is equal to $(D_i * \Gamma_i)$, where D_i is the total number of trips to node i in the base year.

Afterwards, the trips were assigned to node pairs i and j by defining pairwise growth rates g'_{ij}. Multiplying these growth rates by the number of trips in the base year $(w_{ij} * g'_{ij})$ yielded the trip volume between nodes i and j in a future scenario. To calculate g'_{ij}, the following constraints on the total number of trips had to be satisfied:

$$\sum_j w_{ij} * g'_{ij} = O_i * \tau_i \tag{3}$$

$$\sum_i w_{ij} * g'_{ij} = D_j * \Gamma_j \tag{4}$$

As our settlement network is large, we preferred to solve the above equations using an iterative process, rather than using linear algebra. The iterative algorithm to find all t_{ij} values is as follows:

a) $n = 1$, set all $g_i j^1 = 1$.

b) $$g_{ij}^{n+1} = g_{ij}^n * \frac{O_i * \tau_i}{\sum_j g_{ij}^n * w_{ij}} \text{ all } i \in I, \text{ all } j \in J \tag{5}$$

c) $$g_{ij}^{n+2} = g_{ij}^{n+1} * \frac{D_j * \Gamma_j}{\sum_i g_{ij}^{n+1} * w_{ij}} \text{ all } i \in I, \text{ all } j \in J \tag{6}$$

d) Iterate steps (2) and (3) until the variation in g'_{ij} value is less than 0.1.

2.5. Measuring polycentric urban development

As highlighted earlier, an important urban planning strategy involves fostering polycentric development, which entails establishing multiple key hubs within a metropolitan area instead of relying solely on a central business/residential district. Polycentricity, as advocated in the Swiss Spatial Concept by authorities such as the Swiss Federal Council (Bundesrat) and the Conference of the Cantonal Governments (2012), promotes sustainability by distributing resources and amenities more evenly across the urban landscape. The Swiss Spatial Concept uses polycentricity as the core of the integration of transport and energy systems, taking socio-economic aspects into account. To evaluate the efficacy of this strategy, we first needed to quantify the degree of dispersion among these settlement centres. Following each iteration of settlement adjustment, we assessed how dispersed the settlement network had become. These analyses were crucial for understanding the impact of polycentric development on other sustainability objectives, particularly energy efficiency and residents' satisfaction, as noted in previous research (Lee & Lee, 2014; Burger et al., 2017).

Numerous polycentricity indicators are available, such as those from ESPON 1.1.1 and ESPON 1.4.3 (Dühr, 2005; Meijers, 2008a; Arcaute et al., 2015). However, these indicators do not consider the connections between settlement centres and focus only on the settlement size distribution. Alternatively, we can use network theory to measure the polycentricity of settlements as a whole connected system (Khiali-Miab et al., 2019). Recently, Khiali-Miab and colleagues suggested using the structure of the commuter flow network, measured by Global Reaching Centrality (GRC), as an indicator of settlement network's centrality. Polycentricity is then related to the inverse of GRC (i.e., a less central network indicates greater polycentricity), which has been found to correlate with average gross metropolitan income. In this study, we calculated GRC from the trip flow network using the following function:

$$Polycentricity \sim \frac{1}{GRC} \tag{7}$$

$$GRC = \frac{\sum_{i \in V} \left[C_R^{\text{Max}} - C_R(i)\right]}{N - 1} \tag{8}$$

In Eq. (8), C_R^{Max} represents the maximum local reaching centrality among all nodes in network V, while N denotes the total number of nodes in the network. The local reaching centrality of node i, denoted by $C_R(i)$, is calculated using the following method:

$$C_R(i) = \frac{1}{N-1} \sum_{j:0<d(i,j)<\infty} \frac{\sum_{k=1}^{d(i,j)} w_i^k(j)}{d(i,j)} \tag{9}$$

where $d(i,j)$ represents the directed trip volumes from node i to node j, while $w_i^k(j)$ denotes the commuter flow at the kth step along the path between nodes i and j. As our planning goal included maximising polycentricity, our primary objective within the optimisation algorithm was to maximise the $\frac{1}{GRC}$ value.

2.6. Modelling residents' perceived satisfaction

Residents' preferences play a crucial role in addressing questions about urban development (Pagliara et al., 2010; Schirmer et al., 2014). Understanding what influences people's preferences regarding their living environment can provide insights into broader issues, such as societal responses to urban development and strategies endorsed by policymakers (Bodenmann et al., 2014). In each iteration of our model, it was important to account for the socio-economic status of the community whilst also evaluating urban development patterns. The preferences of individuals or households have a direct impact on their satisfaction and reflect residents' desires for access to amenities such as schools, leisure activities, nature and affordability. Aligning urban development with these preferences can improve residents' overall quality of life. Understanding and integrating these preferences into urban development planning is necessary for providing residents with amenities, services and infrastructure that contribute to their well-being and quality of life (Bundesrat et al., 2012).

$$\begin{aligned} Utility \;=\; & \beta_1 * ln(distance\ to\ previous\ location) + \beta_2 * ln(distance\ to\ job\ and\ amenities) \\ & + \beta_3 * (Share\ of\ post\ 1980\ neighbourhoods) + \beta_4 * (Neighbourhood\ homogeneity) \\ & + \beta_5 * (Lake\ and\ river\ view) + \beta_6 * (Average\ distance\ to\ green\ spaces) \\ & + \beta_7 * (Municipality\ type) + \beta_8 * (Public\ transport\ quality) + \beta_9 * (Access\ to\ highway) \\ & + \beta_{10} * (Access\ to\ public\ transport\ station) + \beta_{11} * (Shopping\ and\ leisure\ density) \\ & + \beta_{12} * (Population\ density) + \beta_{13} * (Retail\ business\ density) \\ & + \beta_{14} * (Service\ business\ density) + \beta_{15} * (Rent) \end{aligned} \quad (10)$$

To estimate the expectations of the community, we used the mathematical expression illustrated in Eq. (10). This function used in our model comes from years of research (Schirmer et al., 2011; Bodenmann et al., 2014; Schirmer et al., 2014; Bodenmann et al., 2015) that was further adapted by the Swiss Federal Office for Spatial Development (ARE) for modelling the behavioural preferences of the Swiss population regarding land use and residential locations (ARE, 2017).

We implemented the ARE's final equation, which comprises 15 factors that can influence the utility of residents for living in a location. In the utility function, the coefficients β_i indicate the significance of each factor for the perceived utility, given a set of location factors. As shown in Table 1, the weight of each of these factors (such as the distance to work, share of newly built structures, the average distance to nature, the density of different businesses and retail stores and rent prices) is represented by a coefficient (β_i) that indicates the relative importance of the factor i in determining the overall quality of different locations. Many of these location factors changed with each iteration of our optimisation, due to changes in the settlement network. By plugging in the values for these factors, it was possible to calculate the utility to the population living in a given location and compare it to other potential settlement network patterns.

In the equation, we used natural logarithms for the distance factors, indicating that the utility derived from these factors diminishes more rapidly as the distance decreases. The significance of distance in accessibility to employment and residential areas varies with the scale of the trip. When choosing a trip destination within the same city, proximity to the new neighbourhood is more important, indicating a preference for a more local proximity to the needs of the community. Conversely, when residents must travel to an entirely new city for their needs, employment or a new residential location, the neighbourhood factor diminishes in importance. This emphasises how distance influences preferences, showing that proximity becomes less important as the distance of the trip increases. We incorporated this effect because it aligns with existing literature on modelling location choices in Switzerland and is firmly grounded in economics (Schirmer et al., 2014; Dubernet et al., 2022).

Utility values are dimensionless (Houthakker, 1950); however, as there is a monetary variable inside the utility function (rent price), it is possible to transform dimensionless utility values into estimated monetary values by using the concept of willingness to pay (WTP) for rent in a certain location. Here, WTP is the maximum amount of rent that a resident is willing to pay for a location and factors provided in those locations. It is important to note that the utility function and WTP values are subjective, but nevertheless a good estimate of the perceived satisfaction with neighbourhood changes under certain settlement network development patterns.

Table 1
Overview of key factors influencing residential location preferences (ARE, 2017).

Key utility categories	Summary of explanation
Distance from residence and work	Household's perception of a new neighbourhood is negatively influenced by distances from their social network, current residence or amenities. There is a strong attachment to their neighbourhood. This impact lessens as the distance increases.
Built environment	The architectural periods of a neighbourhood shape household preferences. Households prefer areas with a high proportion of old (pre-1945) or new (post-1980) buildings, while homogeneity is seen negatively. However, diverse built environments attract those interested in the neighbourhood for economic reasons or the diversity of nearby amenities.
Proximity to nature	A location's natural attributes, such as proximity to green spaces, rivers and views of lakes are perceived positively by residents. However, a simultaneous consideration of all nature-related parameters may lead to overfitting. Therefore, lake views and average distance to green spaces were the key parameters considered in our model.
Accessibility	Accessibility to highways and public transport stations is crucial for households' living location. This accessibility provides convenient and efficient transportation options and can offer economic benefits. In our model, gravity-based accessibilities are used. This considers the inverse of the distance to the nearest significant transport hub as an indicator of accessibility.
Rent	The rental price of a housing unit, considered in relation to the household's disposable income, is a key factor in residential location preference and can give an estimate of residents' WTP for certain neighbourhood characteristics. A new rent price is estimated in each optimisation iteration based on changes in housing supply and demand and the given price elasticity.

Based on earlier studies on the Swiss housing market (Bodenmann et al., 2013; Bodenmann et al., 2014; Bodenmann et al., 2015), changes in rents were calculated using Eq. (11):

$$Rent\ Price = Original\ Rent * \left(1 + \left(Elasticity * \frac{New\ Demand - Original\ Demand}{Original\ Demand}\right)\right) \quad (11)$$

where elasticity is a measure of how responsive the price is to changes in housing demand in a residential zone, as calculated by Bodenmann et al. (2015).

Original rent is the rent price in the base year, and the new demand is calculated based on the new settlement pattern in our model.

The factors in the utility function are summarised in Table 1, and a detailed explanation is provided in Appendix 2.

2.7. Modelling energy consumption

The total annual commuting energy demand can be estimated using Formula (12). This calculation considers the total vehicle-kilometres travelled for each mode of transportation, the vehicle use factor and the energy factor specific to that mode. By multiplying these factors together, we can obtain a rough approximation of the energy demand related to commuting for different transportation modes.

$$Energy\ Commuting = \sum_{(i\ and\ j)\quad all\ settlementsMode} share_k * Demand_{ij} * Distance_{ij} * Use\ factor_k * Energy\ factor_k \quad (12)$$

where *Energy Commuting* represents the total energy demand for commuting within the region. The summation runs over all pairs of settlement nodes (*i,j*).

Mode $share_k$ is the proportion of commuters using transportation mode *k*.

$Demand_{ij}$ represents the number of commuters traveling between nodes *i* and *j*.

$Distance_{ij}$, is the distance between nodes *i* and *j*.

Use $factor_k$, represents the vehicle use factor for mode *k*.

Energy $Factor_k$ is the energy demand factor specific to transportation mode *k*.

Eq. (13) calculates the total energy required for heating and cooling in various types of housing.

$$Energy\ devoted\ to\ heating\ and\ cooling = \sum_{i\ \in\ settlement\ typesFloor} Area(i) * Specific\ Heating\ Demand(i) \quad (13)$$

The equation's parameters are as follows:

Energy devoted to heating and cooling represents the total energy demand for heating and cooling purposes in all types of housing. The calculation is the summation of each type of energy used in all housing types in the study area.

Floor Area (i), represents the total floor area of the buildings in the given housing type (i).

Specific Heating Demand(i), refers to the energy demand per unit of floor area for heating and cooling in the housing type (i).

The equation calculates the energy demand for heating and cooling by multiplying the floor area of each type of housing with its specific heating demand. By adding the energy demand across all types of housing, we get the total energy required for heating and cooling in the study area.

Finally, the sum of the energy demand for transport, heating and cooling gives the total household energy demand.

$$Total\ Household\ Energy = Energy\ Commuting + Energy\ devoted\ to\ heating\ and\ cooling \quad (14)$$

2.8. Integration module: multi-objective genetic optimisation (U-NSGA 3)

The use of multi-objective optimisation algorithm in our study is necessary, facilitating the assessment of trade-offs between potentially conflicting objectives as guided by the literature (Keirstead & Shah, 2013; Caparros-Midwood et al., 2015; Memmah et al., 2015; Caparros-Midwood, 2016). Among common meta-heuristic optimisation methods, we have selected the U-NSGA-3 algorithm, a genetic algorithm particularly successful in handling complex and time-consuming problems with three objectives and preserving solution diversity (Seada & Deb, 2015). As we consider three different goals in this research, we have used Pareto fronts, which are the outcome of a genetic algorithm, for showing the interplay among these objectives: polycentricity, energy efficiency and residential satisfaction.

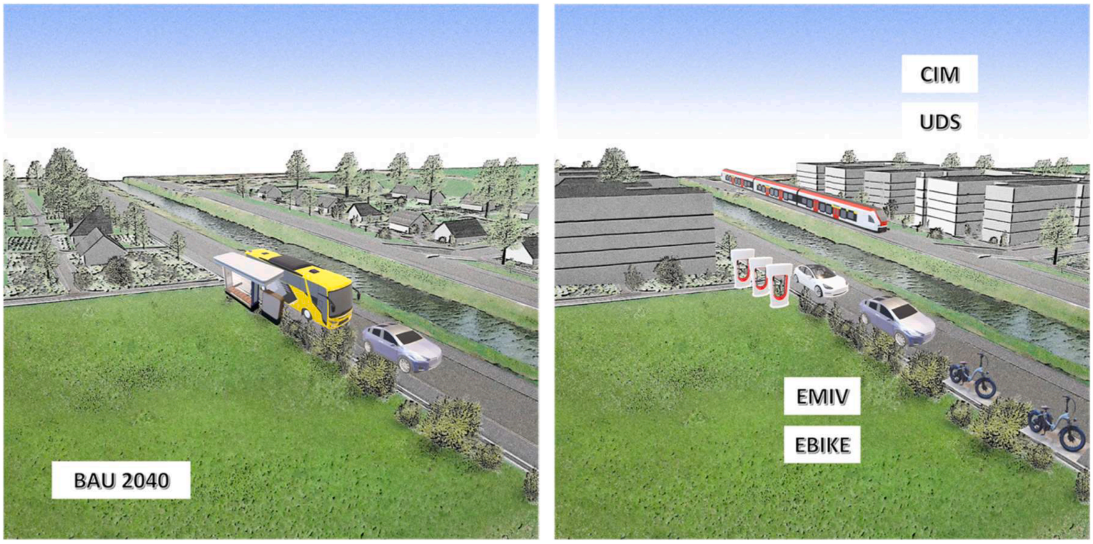

Fig. 3. Schematic visualisation of 2040, a comparative overview of diverse future scenarios for densified urban development and transportation choices. Images adapted from the CHECNET Survey (Dubernet et al., 2022). The technological transformation is represented by the EMIV, EBIKE and CIM scenarios, while UDS represents the urban densification strategy.

Table 2
Summary of factors and potential impacts of the various scenarios considered in the study.

Scenario	Description
Business as usual (BAU 2040)	Assumes that urbanisation will continue until 2040, according to the population growth predicted in each municipality, but that energy technology and urban development practices will remain without major changes. This is a baseline projection for the expected state of the region in 2040 without technological transformations and/or policy interventions. In this scenario, only the level of polycentricity can change.
Complete transition to electrified transportation (EMIV)	Envisions a comprehensive shift to electric power across all transportation modes, including personal vehicles, regional public buses and other forms of transport. It aims for significant reductions in emissions and improvements in overall energy efficiency throughout the transportation sector.
Shift from personal vehicles to e-bikes for short-distance travel (EBIKE)	Imagines a substantial change in transportation habits, with individuals using e-bikes for short-distance trips instead of personal vehicles. This scenario aims for multiple benefits, such as decreased traffic congestion and reduced emissions.
Urban densification strategy (UDS)	Envisions a future where urban development focuses on creating dense, mixed-use neighbourhoods to increase land use efficiency and reduce floor area consumption. This scenario considers changes in socio-economic benefits and energy efficiency, reducing the effects of sprawling patterns, decreasing the need for space heating and cooling energy demands and affecting rent prices through changes in demand.
Comprehensive building insulation and Minergie certification (CIM)	Envisions a future where all buildings undergo extensive insulation improvements and achieve Minergie certification, a Swiss standard for energy-efficient housing. This scenario aims for energy savings and a minimised environmental footprint in the housing sector, contributing to the overall reduction of greenhouse gas emissions and promoting a more sustainable settlement network.

Starting with potential urban development solutions, which are selected randomly, the algorithm undergoes multiple iterations, refining these solutions towards an optimal trade-off, known as the Pareto front. The iterative process in U-NSGA3 involves the gradual development and refinement of solutions over time, mimicing the natural selection principle of survival of the fittest in natural evolutionary processes, until the final Pareto front is reached. Eventually, the Pareto front represents the intersection of urbanisation, energy efficiency and socio-economic impacts, offering valuable insights into potential trade-offs and facilitating informed decision-making for urban development. More details on the optimisation method are presented in Appendix 3.

2.9. Scenario design: technological changes and policy practices by 2040

Using the primary model of the settlement network, we are able to assess the urban development patterns to maximise energy efficiency and residential satisfaction. In the Swiss context, however, expected technological and political changes can have a significant impact on energy efficiency, particularly in the household and mobility sectors, which are sources of uncertainty in our model. For example, a new technology may influence household and mobility energy consumption. As a result, what is found to be an optimal development pattern based on our information today could lose its viability amidst substantial changes in the technological and policy landscape in the future. Therefore, scenario design becomes crucial for addressing these uncertainties (Braunreiter & Blumer, 2018). To reduce such uncertainties, we have used scenarios to consider expected changes. By running the settlement network optimisation under different scenarios, we can then identify common optimal patterns that are independent of technological and policy changes and variations due to such transformations. The purpose of running our model under varying scenarios is not only to navigate uncertainties, but also to advocate for technological and policy changes that could contribute to more favourable urban development.

In Swiss energy research, scenarios are of central importance for informed decision-making in the face of an uncertain future, which has led to the design of numerous scenarios (Drouilles et al., 2017; Boulouchos et al., 2022; Burger et al., 2022). For instance, in a study by Drouilles et al. (2017), scenarios were created to assess the feasibility of meeting Swiss energy efficiency targets. In developing their scenarios, they focussed on significant, expected changes in mobility and household technologies, in addition to policy practices. While their scenarios

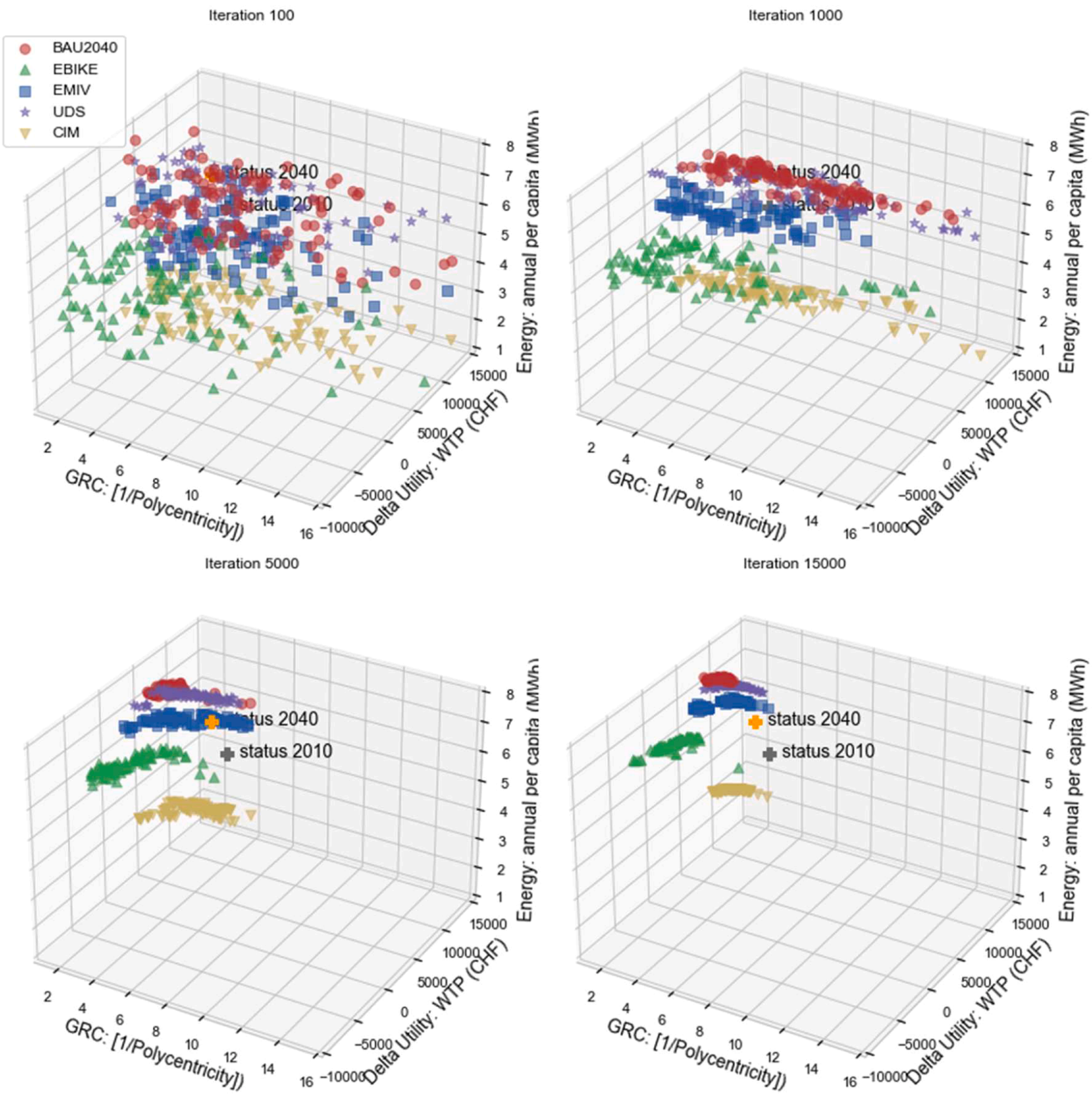

Fig. 4. Evolution of the Pareto front solutions in the three-dimensional planning outcome space under different transformation scenarios (in iteration steps 100, 1000, 5000 and 15,000). The initial steps are closer together because the evolution eventually converges as the iteration progresses and does not change much towards the end of the optimisation.

form the foundation of our scenario design, they may not fully consider the broader context of urban development. Our scenarios have two main requirements: first, that they can dissect the formerly aggregated efficiencies by urban category (e.g., rural, peri-urban and urban) and provide details on individual municipalities instead, and second that they can provide trade-offs with other goals of urban development, such as communities' socio-economic status. However, Drouille et al.'s work was not designed to differentiate the roles played by the individual municipalities; thus, it is unable to show the crucial aspect of coordination within a settlement network.

To address these aspects, we focused on individual municipalities, instead of broad municipality categories, to enhance the resolution of calculations concerning energy consumption. Additionally, we incorporated the adoption of alternative mobility vehicles, such as e-bikes and e-vehicles (Axhausen, 2023; Ballo et al., 2023), which will undoubtedly impact accessibility patterns within the settlement network and energy efficiency. With these scenarios, we could ascertain the feasibility of achieving the potential energy targets indicated by Drouilles et al. (2017) and illuminate the specific contributions and roles of each municipality in achieving these potentials, highlighting how the intricate coordination among municipalities contributes to the overall functioning of the settlement network.

The various future scenarios employed in this study fall into two primary categories: spatial restructuring and technological transformation. Spatial restructuring focuses on planning strategies that transform densification patterns. By contrast, technological transformation involves innovations in the transportation and energy sectors for energy-efficient mobility and housing. Each scenario's characteristics and objectives are summarised and represented schematically in Fig. 3.

Table 2 presents a summary of the scenarios, the details of which are provided in Appendix 3.

3. Results

We calculated annual per capita energy demand, changes in socio-economic benefits and the polycentricity for the projected basic spatial distributions in 2040 (based on ARE predictions) to compare

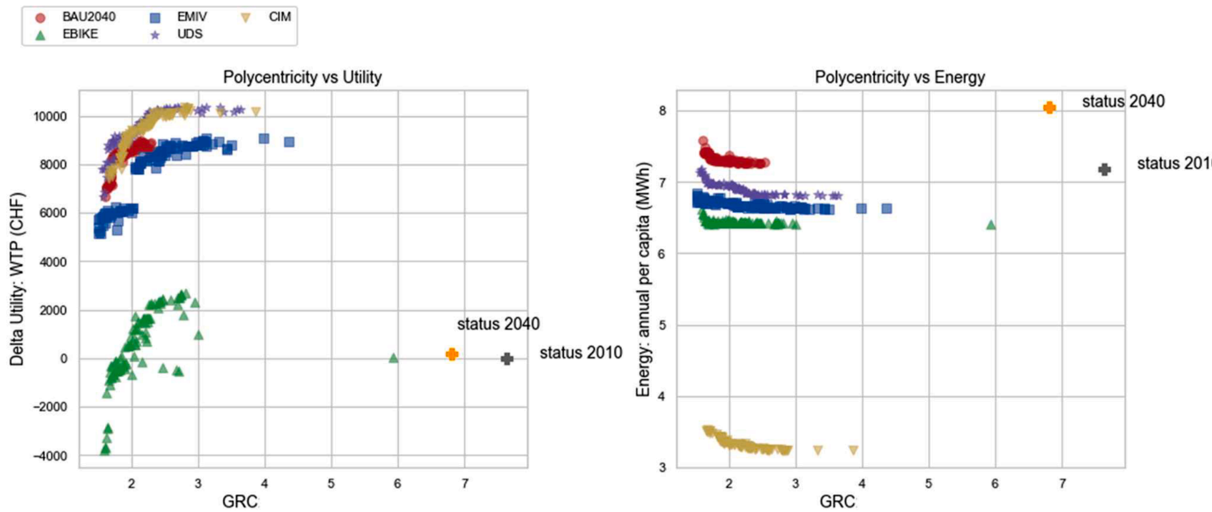

Fig. 5. Two-dimensional Pareto front solutions under various transformation scenarios, showcasing the trade-offs between polycentricity and socio-economic benefits (left), and between polycentricity and annual per capita energy consumption (right) for the projected spatial distribution of population and amenities in 2040, compared to 2010. Technological change is represented by the EMIV, EBIKE and CIM scenarios, and UDS represents the results from the urban densification strategy.

Table 3
Summary of Pareto front solutions under different transformation scenarios and their respective ranges for socio-economic benefits (delta utility), energy demand per capita and GRC values.

Projected	Socio-economic benefits (CHF)		Annual per capita energy demand (MWh)		GRC	
Status 2010	0		7.18		7.64	
Status 2040	191		8.06		6.8	
Pareto solution range	Lower	Higher	Lower	Higher	Lower	Higher
BAU2040	6680	8974	7.26	7.59	1.62	2.53
EMIV	5155	9082	6.62	6.85	1.52	4.36
EBIKE	−3802	2695	6.42	6.61	1.59	5.94
UDS	6680	10,368	6.81	7.18	1.56	3.64
CIM	7440	10,342	3.23	3.52	1.66	3.86

them with 2010 levels. The comparison revealed that, without any structural or technological transformations of the settlements, the GRC decreases from 7.6 to 6.8, indicating an increase in polycentricity. There is also a slight increase of 192 CHF in estimated socio-economic benefits and an increase in annual per capita energy use, from 7.2 MWh in 2010 to 8.06 MWh in 2040.

In addition to the fixed points referring to the status in 2010 and 2040, the optimisation process resulted in a set of 100 distinct non-dominated solutions (i.e., a Pareto front) for each of the scenarios. Each of the 500 solutions on the five Pareto fronts shows a settlement network pattern that is optimised to its fullest potential. Each of these solutions on the Pareto front corresponds to a unique settlement network structure with a specific spatial distribution of amenities and population across municipalities. Each solution for urban development yields a unique value for each of our three goals, residents' satisfaction (measured by delta utility), energy efficiency (measured in annual energy demand per capita in MWh) and polycentric development (measured by the centrality of the network). The position of each point in Figs. 4 and 5 indicates the best value that can be achieved for one goal if the other two goals are held constant. So, the Pareto fronts also inform us about the best possible balance among the three planning goals (Figs. 4 and 5). In Fig. 5, we converted the 3D scatterplot into a series of 2D scatterplots to better illustrate the trade-offs among the three objectives. This provides a clearer visual representation of the trade-offs among them (Table 3).

The evolution of Pareto fronts in the three-dimensional space under various scenarios are illustrated at iteration steps 100, 1000, 5000 and 15,000 (Fig. 4). This evolution stems from the optimisation efforts aiming to improve all planning goals through the redistribution of spatial distribution and restructuring of the settlement network.

In the beginning of optimisation, the iterations shown in the figure

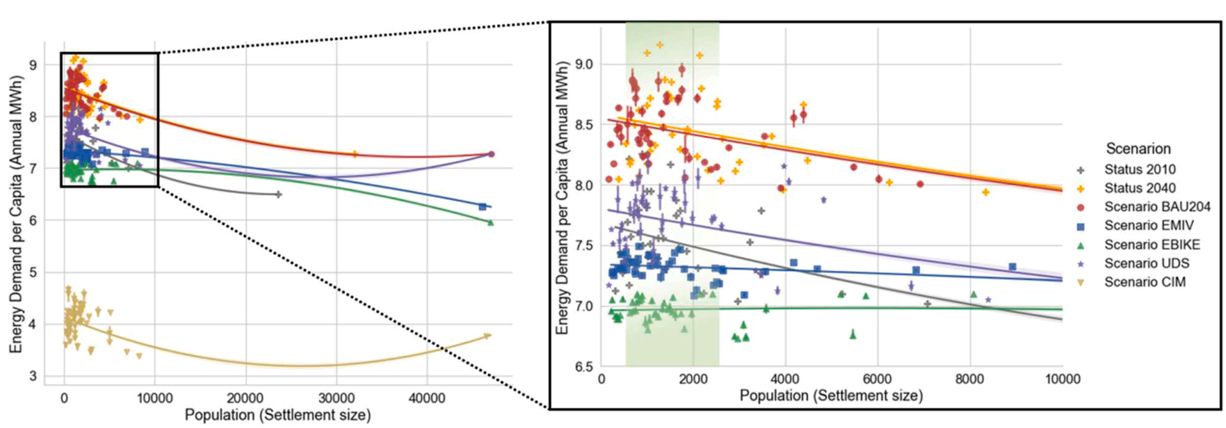

Fig. 6. Spatial distribution of socio-economic benefits in relation to settlement size and per capita energy demand.

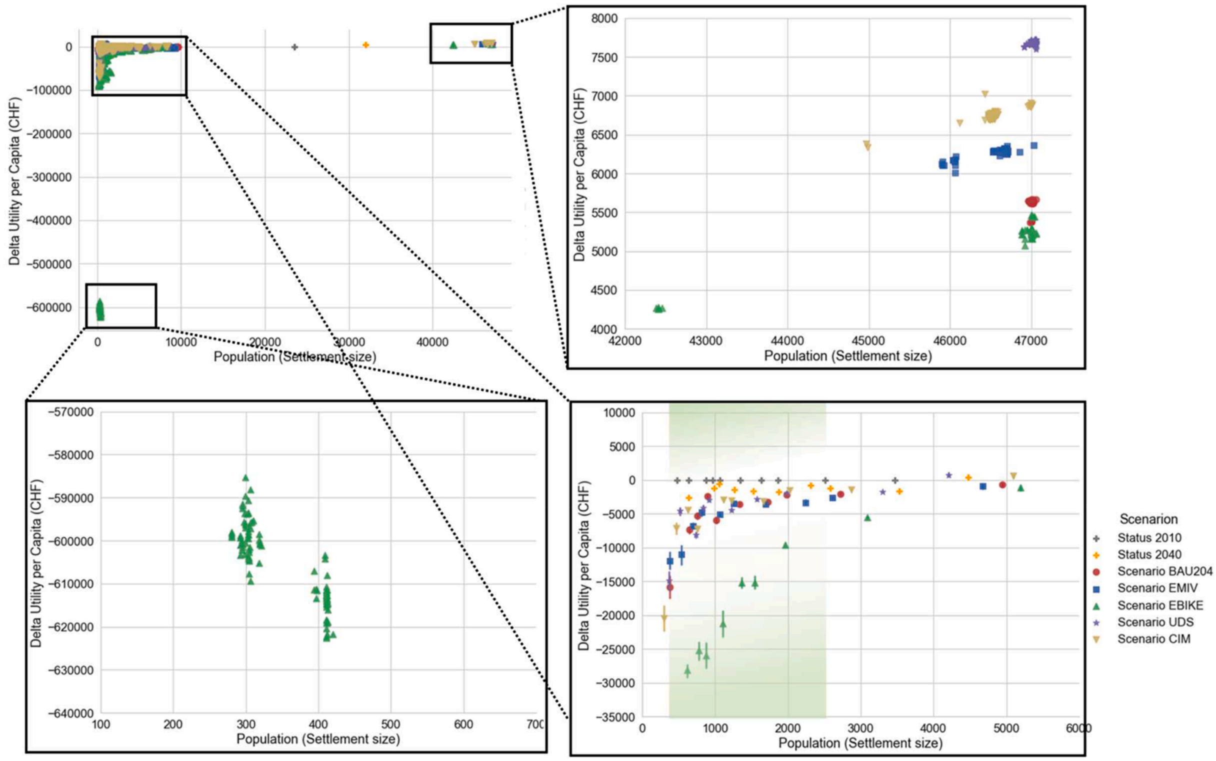

Fig. 7. Spatial distribution of socio-economic benefits in relation to settlement size, illustrated for areas of varying sizes: small ones (bottom-left), medium ones (bottom-right), and large ones (top-right).

are closer, signifying a swift convergence of potential solutions. As the algorithm advances, it moves towards a more stable and optimised set of solutions. Towards the end of the optimisation, the changes between iterations become negligible, suggesting that the Pareto front has converged upon the optimal solutions. The overall evolution of the Pareto fronts is always towards an ideal point. The evolution of the Pareto fronts towards the upper left quadrant in Fig. 5 (left) reflects the desire for a more polycentric settlement with greater residents' satisfaction. Also, as the Pareto fronts move towards the lower left quadrant in Fig. 5 (right), the algorithm aims to find urban development solutions that are more polycentric and have lower energy demand.

Global Reaching Centrality measures the level of settlement network's centralisation, whereas polycentricity aims to decentralise the settlement network by promoting multiple centres of activity. In modelling the optimisation processes, the goals of maximising polycentricity and minimising the GRC are the same, as they both seek to decentralise the network.

The technological scenarios are shown by the EMIV, EBIKE and CIM scenarios, and the structural changes can be represented by either the BAU2040 or UDS scenarios. A significant result to highlight is the differentiation of Pareto fronts based on these scenarios. This shows that technological transformations and policies will change the trade-offs among levels of residential satisfaction, energy efficiency and polycentric development. For example, enhancing residential satisfaction in the presence of new mobility tools (such as e-vehicles) is more achievable, as the range of the Pareto front is wider and the slope is steeper in this scenario compared to BAU2040. This allows for more solution spaces for polycentric development, meaning we have a higher leverage for the positive effects of settlement restructuring in the presence of the new mobility tools.

The analyses of various scenarios revealed that the UDS scenario, which envisions the densification strategy, yields the highest range of socio-economic benefits, reaching up to 10,368 CHF. In contrast, the EBIKE scenario led to the lowest range of socio-economic benefits, with a minimum value of CHF −3802. In the scenarios that focused on transport technologies (EBIKE and EMIV), the average socio-economic benefit was lower than in the BAU2040 scenario; however, these scenarios offered a wider range of potential solutions for GRC, and thus more opportunities to achieve a higher level of polycentricity.

Regarding per capita energy demand, the BAU2040 scenario, which emphasises polycentric restructuring without technological changes, has the highest energy demand, reaching a maximum of 7.59 MWh annual per capita consumption. In contrast, the other four scenarios, which involve technological changes, show higher energy efficiency. Notably, the CIM scenario demonstrates the most significant energy efficiency, exhibiting the lowest energy demand per capita, at a minimum of 3.23 MWh.

The Pareto fronts provide valuable insights, such as how total socio-economic benefits and energy demands change under different specific scenarios; however, they do not provide information on the spatial distribution of these socio-economic benefits and energy demand within the study region, which is important for evaluation of an equitable transformation. To further explore our results, we present Figs. 6 and 7, which show the relationships among settlement size, per capita energy demand and increased socio-economic benefits under different scenarios. These offer more detailed spatial insights into the distribution of benefits and energy demands resulting from the adoption of new technologies.

Fig. 6 is a scatter plot illustrating the relationship between the distribution of energy demand and settlement sizes in the region. Quadratic regression curves are used as trend lines to illustrate qualitative changes across different population sizes. Although the primary goal is not to make exact quantitative predictions, these trend lines help to show the different effects of population size on per capita energy demand. A curved trend line indicates that the impact of a particular scenario differs between larger and smaller settlements.

We observed that, while the average energy demand for the BAU2040 scenario is only slightly lower than for the Status 2040

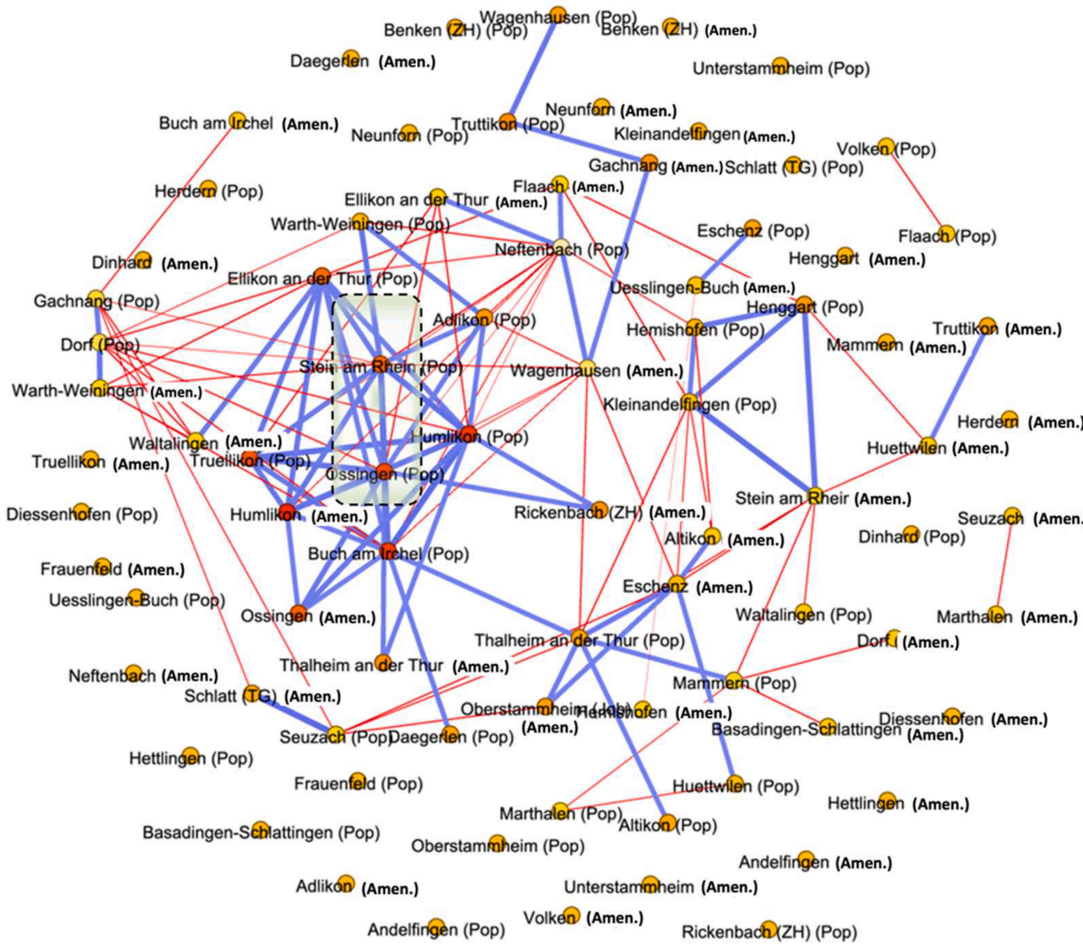

Fig. 8. Correlation network illustrating the relationships between municipalities based on variations in development f population and amenities. Each node represents a municipality, and the edges indicate positive (blue links) or negative correlations (red links) in their urban development patterns. The nodes' colours show the levels of centrality of a node in the correlation network.

scenario, the disparities between the energy demands of different settlements have decreased in BAU2040 (Fig. 6), indicating greater equality in energy consumption. The UDS scenario (in Fig. 6) has a lower energy demand than BAU2040, but its impacts are mainly observed in smaller settlements, but it leads to high disparities in medium-sized ones. The UDS scenario does not significantly affect energy demand in larger settlements, as its primarily aim is to lessen suburban sprawl and reduce floor area consumption.

Both the EMIV and EBIKE scenarios (Fig. 6) demonstrate a more equitable distribution of energy demand across all settlements; however, they exhibit a greater capacity to reduce energy demand in larger settlements, compared to small and medium-sized ones.

The CIM scenario (Fig. 6) has the highest energy efficiency among all scenarios, but similar to the UDS scenario, it leads to a high disparity of energy demand in medium and small settlements. This indicates that the impact of the CIM scenario on energy demand varies greatly depending on the settlement size and particularly affects smaller and medium-sized ones.

The results presented in Fig. 7 provide a detailed analysis of the relationship between the distribution of socio-economic benefit and settlement size under different scenarios. By focusing on three specific areas, the figure highlights the differences in the impact of the scenarios on areas of different sizes (small, medium and large). Therefore, to better illustrate the differences among categories, we have focused on these three specific areas in the figure.

For larger settlement centres (Fig. 7, top-right), it becomes evident that spatial restructuring consistently leads to positive outcomes across all scenarios, with urban densification proving the most beneficial, followed by the building insulation scenario. Interestingly, the EBIKE scenario, which might exhibit a negative average socio-economic impact at certain polycentricity levels (see Fig. 5), still provides benefits for larger settlements, similar to the EMIV scenario. In other words, even e-bikes as an alternative mobility solution can only be beneficial in larger settlement centres.

Medium-sized settlement centres (the green shadow in Fig. 7, with 600 to 2500 inhabitants) show a greater disparity in socio-economic changes under all scenarios. Although most of the socio-economic consequences in the medium-sized areas are negative, there are a few cases with positive consequences. The EBIKE and EMIV scenarios cause the greatest disparity in socio-economic impacts for medium-sized areas, indicating that the impacts of these scenarios depend on the specific context and characteristics of the area itself.

Small towns (as depicted in Fig. 7, bottom-left) are primarily where the negative socio-economic impact of the EBIKE scenario is felt. This finding suggests that, even if the EBIKE scenario is not effective in improving socio-economic status in smaller towns (i.e., it is even detrimental to these areas), it may still offer benefits to larger areas. This shows the high vulnerability of the small and medium areas to technological changes in mobility.

We conducted an analysis of the correlations between all 500 solutions for urban development within our study region and created correlation networks to explore relationships among different municipalities based on variations in their optimal development and development outcomes (socio-economic changes and energy demand).

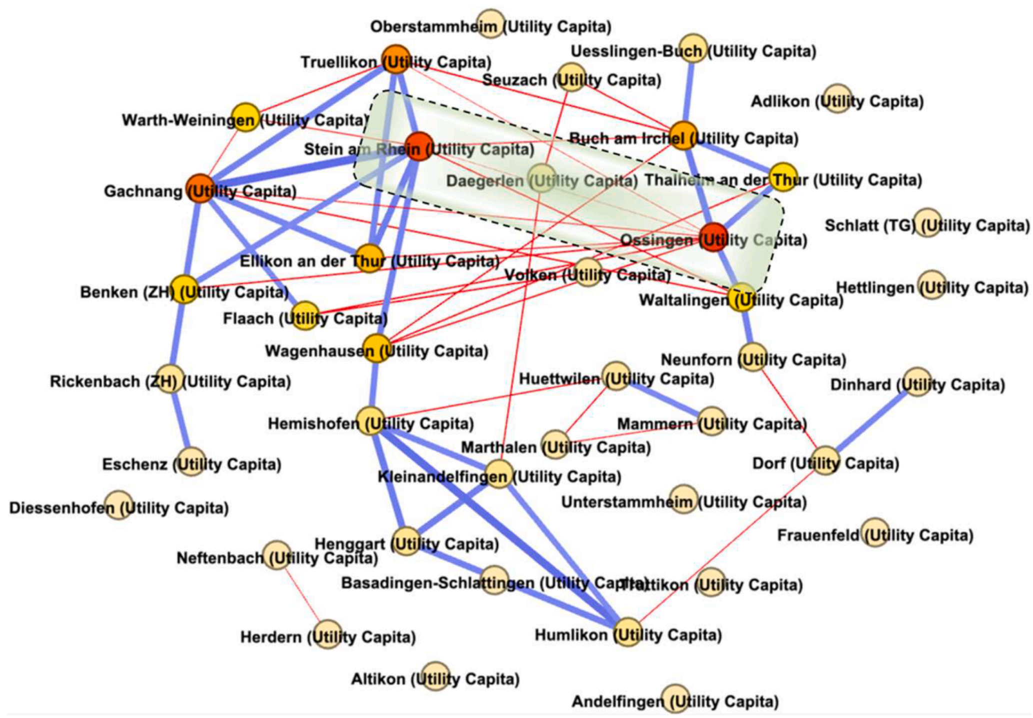

Fig. 9. Correlation network depicting the relationships among settlement centres, based on per capita socio-economic changes. Each node represents a municipality, and the edges signify positive or negative correlations (blue or red links) in their socio-economic dynamics. The nodes' colours show the level of centrality of a node in the correlation network.

Notably, we omitted the correlation network for energy demand, as per capita energy demand only varies among scenarios. Examples of these correlations are presented in Figs. 7 and 8. In these figures, blue or red lines denote the relationship between the development patterns of two municipalities. Blue connections indicate that these municipalities tend to develop in tandem, while red connections suggest an inverse relationship, where growth in one settlement centre is accompanied by stagnation or decline in the other, to maintain the overall goals of the region.

When considering achieved goals assigned to individual municipalities, such as energy efficiency and socio-economic benefits, the implication is that the benefits to these municipalities are correlated. For instance, municipalities connected by blue links in Fig. 9 are likely to experience improvements in their socio-economic status in tandem. This consistent meta-pattern is observed across all five scenarios.

Furthermore, three primary settlement clusters are revealed in the correlation network. Each cluster comprises centres showing positive correlations among their optimal development and socio-economic outcome. Conversely, there are some negative correlations among these clusters.

An interesting observation is that the links among the development correlations may differ from the observed correlations among socio-economic outcomes for different municipalities. For instance, Stein-am-Rhein and Ossingen, identified in the green area of Figs. 8 and 9, exhibit a positive correlation in development (Fig. 8), indicating simultaneous development, but in terms of socio-economic outcome (Fig. 9), there is a negative correlation, suggesting that while population growth occurs simultaneously, socio-economic benefits do not increase proportionately.

These correlation networks show the intricate interplay among municipalities in maintaining alignment with the Pareto fronts. The complexity of these relationships demonstrates that factors influencing the development and socio-economic outcome of each municipality may not always align or produce trivial outcomes.

4. Discussion

In Section 3, we highlighted our results. First, we illustrated the evolution of Pareto fronts resulting from the spatial restructuring of settlement areas under different scenarios. Second, we analysed the changes in socio-economic benefits and energy demand across all municipalities of different sizes. Third, we examined the correlation network of relationships among municipalities to better understand the matters related to their overall coordination. In the following, we discuss the implications of our results.

4.1. The relationships among planning goals (polycentricity, energy efficiency and socio-economic benefits)

The analyses of different Pareto fronts showcase that various transformation strategies, such as the adoption of new technologies, has the significant potential to enhance all three planning objectives within our study region. This suggests that a more integrated approach to planning and urban development could potentially enhance socio-economic benefits and energy efficiency, outperforming the current predictions about 'Status 2040′. This is in line with previous findings on the great potential for improving energy efficiency, as also noted by Drouilles et al. (2017). We were able to break down the contributions of the different municipalities to achieving the regional sustainability goals and were able to include more socio-economic factors to address concerns about the social equity of the energy transition. This would be an extension of previous studies.

It is essential to consider that this potential regional improvement may come with certain compromises, particularly when it comes to polycentricity. The slopes of the Pareto fronts (in Fig. 5) suggest a negative relationship between both socio-economic benefits of energy efficiency with polycentricity, implying that the pursuit of a more polycentric urban structure could compromise the benefits normally associated with the concentration of the urban population and social interactions (Meijers, 2008b). This complexity raises concerns about this urban development strategy, as planners must balance the potential benefits of a polycentric approach against the impacts on socio-economic benefits and energy efficiency (Neuman, 2005).

Technological changes appear to be the primary drivers of the overall movement of the Pareto fronts, acting as catalysts for or barriers to achieving planning goals. In contrast, trade-offs within the Pareto fronts predominantly stem from changes in polycentricity (Fig. 5). This observation emphasises the distinct, yet interconnected, impacts of technology and spatial structures on energy demand and socio-economic benefits (Neuman, 2005).

Taking a closer look at the Pareto fronts in Fig. 5 (right), we can see that the relatively flat Pareto fronts suggest that energy efficiency is influenced more by technological changes than by changes in spatial structure (Rode et al., 2017). Looking at the relationships between energy consumption and polycentricity (the difference between minimum and maximum energy demand within a scenario is small), while the jumps between different technological innovations (the difference between the scenarios) are larger. Put more simply, the impact of spatial structure on energy efficiency can be more easily offset by technological advances, as mentioned previously by Rode et al. (2017). For example, if polycentric development is a goal for our study region, the associated increased energy consumption can easily be mitigated by new technologies and policy adaptations. A similar analysis of the Pareto fronts in Fig. 5 (left) can show that spatial restructuring, in terms of changing polycentricity, has a greater impact on socio-economic benefits than it does on energy consumption. This is because socio-economic benefits decrease enormously for GRC values below 2 (while the slopes are flatter for the energy demand Pareto fronts).

The Pareto fronts also suggest that the scenarios involving significant technological transformations, such as the CIM and EMIV, lead to lower per capita energy consumption than structural changes do, as in the BAU2040 and UDS. In contrast, structural transformation scenarios like the BAU2040 and UDS scenarios result in greater socio-economic benefits than technological scenarios. Our research indicates that housing insulation has a substantial impact on energy efficiency and socio-economic benefits, as it is also confirmed as important in other regions of the world (Zhou et al., 2018). This may involve reassessing energy policies and investment strategies, allocating resources to insulation efforts and researching advanced insulation materials and technologies. Although insulation is highly impactful, a comprehensive planning approach that also includes transportation efficiency and electrification improvements should still be maintained.

4.2. The importance of spatial dimension for assessing sustainable development

In all scenarios (except parts of the EBIKE scenario), the average socio-economic benefits can be increased significantly within the region. However, it is important to consider how these benefits are distributed among municipalities. On the one hand, both technology and spatial structures affect small and medium-sized municipalities, leading to significant disparities between their socio-economic benefits (Fig. 7) and energy efficiency (Fig. 6). Thus, our study shows that small and medium-sized municipalities are the places most vulnerable to technological and structural changes (Meijers & Burger, 2022), but they have not attracted sufficient attention in former studies (Partridge et al., 2008). The larger municipalities, on the other hand, are mainly affected by technological changes and are only marginally affected by structural changes. Even if the sum of their benefits and costs shows an overall total benefit to the region, the larger municipalities will always benefit in all scenarios. This is perhaps because the benefits to the larger municipalities are greater than the costs to the smaller municipalities, and they typically have more efficient infrastructures. Not only do small and medium-sized municipalities tend to lose their absolute benefits, but the overall regional disparities increase under all scenarios.

Fig. 5 shows that any type of spatial restructuring would require more energy consumption than the predicted 2040 status, yet based on Fig. 6, the total increased energy demand is not equally distributed across municipalities. For example, we see that the smaller settlement centres, such as rural areas, will need more energy per capita, due to polycentric development, but this is not, *per se*, good or bad, unless we cannot plan for supplying and redistributing the energy more equitably (Rutherford & Coutard, 2014). It is important to recognise that technological changes, combined with urbanisation, will lead to regional inequalities, which will require early attention and planning.

These regional disparities become even more important when we consider that polycentric development, conceived primarily as a strategy for increasing regional equity, fails to reduce disparities the in face of technological changes. However, it is important to think about steering urban development so that benefits and costs are distributed more equitably within municipalities.

4.3. Spatial coordination is a key to sustainability goals

Our analysis, as shown by correlation networks in Figs. 8 and 9, reveals that energy demand and socio-economic benefits are interconnected among municipalities, even when they are geographically distant (i.e., they are tele-coupled). This finding provides a more comprehensive understanding of the relationships within municipalities. The examples of connections between socio-economic benefits and energy efficiency within a larger network of municipalities highlight that achieving sustainability goals requires planning and coordination beyond geographical proximity. Our results could thus provide the basis for a better understanding and tackling of the sustainability issues that are so concerning in urbanising areas (Wu et al., 2020; Li et al., 2023). By examining the interconnected nature of municipalities and their development impacts on one another, better-informed decisions can be made to ensure a fairer distribution of benefits, energy consumption and the socio-economic welfare of communities.

In addition to the above, our analysis underscores the importance of considering the diverse qualities of municipalities when implementing spatial transformations, since the impacts of new technologies and policies can vary considerably across municipalities, depending on their type, location factors and the position of a municipality within the larger settlement network.

4.4. Research limits

We acknowledge several limitations in our study. To address these, it would be valuable to incorporate input from stakeholders such as transport companies (including public transport and shared mobility providers), the real estate industry and other key stakeholders. This could be achieved through workshops, surveys or participatory optimisation processes, allowing for a more comprehensive and realistic understanding of the social dimension.

Considering the stakeholder structure is crucial in urban development, as they significantly influence the feasibility of certain development solutions that we have found. This broader perspective would enable us to contextualise the results of our study more effectively and to explore more efficient Pareto front solutions. This approach aligns with recommendations from transdisciplinary urban planning concepts (Cilliers et al., 2014; Zhou et al., 2021) and case studies (Després et al., 2011), facilitating a more holistic and nuanced approach to urban development.

Another limitation of our study is the dynamic nature of social preferences, which are shaped by various factors that alter people's values, beliefs and behaviours over time. This is also noted in the literature on utility functions (Guo & Bhat, 2007; King & Kay, 2020). Future research should consider the temporal dynamics of social systems, to gain a deeper understanding of how evolving social preferences impact urban development and utility functions.

Emerging technologies and evolving transport modalities, like shared mobility tools, electric vehicles and e-bikes, could have implications for public transport use. This calls for considering infrastructure management, particularly in response to polycentric development. Decentralised settlements could further inflate the cost of national infrastructure (Bauknecht et al., 2020).

Furthermore, our study focused on the demand side of energy. Future planning efforts should consider both the demand and the supply sides of energy (Boulouchos et al., 2022). Decentralised settlement networks will eventually need a decentralised supply of energy; as such, it may require a different approach to energy generation infrastructure, distribution and financing (Stoeglehner et al., 2011). Future research can complement our findings to show the implications of settlement network decentralisation on the supply side of energy systems, such as power grids' flexibility, resilience and costs (Bouffard & Kirschen, 2008).

5. Conclusion

Our paper explores the interconnections among urbanisation, energy transition and their potential impacts on social and economicaspects. By integrating these elements, we have uncovered significant challenges, particularly regarding the spatial distribution of energy demand and socio-economic benefits, and the balancing of various planning goals.

While implementing significant structural changes in settlement networks may not be feasible in the short term, grasping the implications of a coordinated approach to urban development can inform future planning decisions. By assessing the need for changes in the planning paradigm, we can explore more effective strategies for sustainable development that harmonise social, economic and environmental considerations.

Our study equips policymakers and practitioners with essential insights for prioritising integrated and coordinated urban development. Through such an approach, we can design better development strategies that foster sustainable and equitable energy transition amidst unprecedented technological, environmental and urban changes. Ultimately, our research aims to empower urban communities as they navigate the complexities of contemporary urbanisation.

CRediT authorship contribution statement

Amin Khiali-Miab: Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Anthony Patt:** Writing – review & editing, Supervision, Conceptualization. **Pius Krütli:** Writing – review & editing, Validation, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no conflict of interest.

Data availability

Data will be made available on request.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.scs.2024.105418.

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