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Energy futures of representative Swiss communities under the influence of urban development, building retrofit, and climate change

Argyris Oraiopoulos [*], Shashan Hsieh, Arno Schlueter

Architecture and Building Systems, Institute of Technology in Architecture, ETH Zurich, Stefano-Franscini-Platz 1, Zurich CH-8093, Switzerland

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ABSTRACT

Reducing energy demand in buildings is an integral part of many climate change mitigation strategies. Yet, the prospected development of communities is often overlooked when estimating future energy demand. Here, we investigate the future energy demand in representative Swiss communities, considering climate change projections, building retrofit and urban development. Following a scenario-based approach we model urban, sub-urban and rural community archetypes under changing boundary conditions and different time scales using the City Energy Analyst an open-source computational framework. The results demonstrate that the future energy demand of Swiss communities is highly dependant on their development trajectories regarding population growth, occupant density and building use-types. For the urban archetype, the most significant result is the increase of annual space cooling which by 2060 could be comparable to space heating. For the sub-urban, increases in energy demand due to urban development were observed despite retrofit measures, whereas the rural archetype displays high space heating demand across all scenarios. Consequently, predictions for future energy demand at the community scale without considering urban development trajectories are likely to be incomplete. The results demonstrate the relevance of increasing the modelling scale from national to community scale to support decision making on different levels of governance.

1. Introduction

1.1. Background

The Swiss Energy Strategy 2050 sets an ambitious target for a 45% reduction in the energy consumption of Swiss buildings by 2050 (*Gebäudepark 2050 – Vision Des BFE*, 2020). At the same time, projected economic growth, as well as changes in the demographics, are likely to drive further increases in the demand for energy (York, 2007), with climate change imposing additional uncertainty. This presents local communities with great challenges in planning their future development without compromising the national goals for energy demand reduction.

In Switzerland, the Cantons are responsible for their spatial planning. Yet many are faced with congruent challenges as rising migration from neighbouring countries results in 80% of the annual population growth (Marini, 2019). The subsequent urban growth has stretched the local development plans by cantonal and municipal administrations and put the success of their growth management strategies at risk (Gennaio & Hersperger, 2009). However, decisions to influence urban development patterns, partly imposed by the revised spatial planning act, such as densification and high quality internal development, can and have had positive effects (Credit Suisse, 2020; DETEC, 2020; Jaeger, 2014; Pérez, 2013; Weilenmann, 2017). In parallel to the historical expansion of low-density peripheral zones at the fringes of metropolitan areas, there are evidence of increasing living preferences towards rural villages and also evidence of continuous development in suburbia, despite signs of its adverse effects (Mann, 2009; Price et al., 2015; Ströbele, 2017).

The co-benefits and cost dynamics of energy efficiency investments have long been evidenced in Switzerland (Jakob, 2006), which has been at the forefront of energy efficiency in buildings compared to EU countries. A recent study identified Switzerland as one of the top three performers, with the fastest improvements amongst other EU countries between 2000 and 2016 (Bhadbhade et al., 2020). However, there remain significant advancements to be achieved in the Swiss building stock if the Energy Strategy 2050 target is to be reached timely. With the built environment accounting for more than 44% of the final energy use in Switzerland (Streicher et al., 2018), and space heating accounting for more than two-thirds of the total final energy demand in the Swiss built

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* Corresponding author.
E-mail address: oraiopoulos@arch.ethz.ch (A. Oraiopoulos).

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environment (Prognos AG, 2012; Prognos AG, Infras AG, et al., 2020), it is clear that there is high potential for building retrofits to reduce the energy demand in the Swiss building stock. Therefore, the Swiss Federal Office of Energy (SFOE) has outlined increases in building envelope retrofits, as well as in replacements of fossil fuel heating systems, with electric and energy efficient alternatives, in the Energy Strategy 2050 (Prognos AG, INFRAS AG, et al., 2020).

In addition to urban growth and technological development, climate change is projected to have a major impact in Switzerland with an increase in annual mean temperature, an increase in the frequency of heatwaves, and a decrease in frost days (NCCS, 2018). These changes will consequently affect the space heating and cooling demand of buildings, depending on different levels of greenhouse gas concentration trajectories.

Different studies have explored the effects of climate change, building retrofit and urban development on energy demand, yet without taking into account the trade-offs that occur due to their interactions. Considering the time frame 2050–2100, Frank (2005) studied the climate change scenario of 4.4 °C mean annual temperature rise in Zurich. The results showed that heating demand could decrease by up to 44% and 58% in Swiss residential buildings and offices, respectively, while the annual cooling demand could increase by 1050% in offices alone (Frank, 2005). In a more recent study, looking at space heating and cooling demand of buildings under the most severe climate scenario, a 40% decrease in heating degree days and a 1300% increase in cooling degree days by the end of the century were calculated (Berger & Worlitschek, 2019).

Focusing on the impacts of building retrofit until 2060, researchers have found that early and deep energy retrofit allows significant reductions in operational greenhouse gas emissions (Streicher et al., 2021). Likewise, on a global scale, researchers have found that modernising cities through the construction of new eco-communities and the increasing deep retrofits of buildings could mitigate the amount of operational greenhouse gases emitted by neighbourhoods between 53 and 97% by 2050 (Nematchoua et al., 2021). However, purely technical solutions often result in a performance gap that can reduce the scale of the potential savings in energy demand (Schneider et al., 2017). Since, behavioural aspects in energy consumption can have an impact on the energy savings from retrofit programs, it is important to take them into account (Roca-Puigròs et al., 2020). Future housing scenarios, allowing the peri-urban typical Swiss dwellings to meet the “2000 Watt society” targets, have shown that an evolution of social practices and individual behaviours, as well as the development of improved technologies can bring considerable energy demand reductions (Drouilles et al., 2017).

The impact of urban development has been explored in terms of urban form and morphology influencing building energy demand (Ewing & Rong, 2008; Quan & Li, 2021), with studies often investigating the links between different urban form characteristics (e.g., density, building heights, etc.), the associated urban energy demand for space heating and cooling and urban solar energy (Mouzourides et al., 2019; Shi et al., 2021). In one of the limited studies looking at urban development alternatives while assessing the energy performance of buildings and cities, authors have documented that urban development scenarios such as infill development and consolidated development are urban alternatives that can potentially yield the most relevant energy savings (M. Silva et al., 2018). Applying a reversed method, researchers have created urban expansion scenarios based on low-carbon strategies resulting in less ecological impact by promoting compact and infilling urban development (Zhang et al., 2020).

It is evident that much of the existing literature has focused on the individual effects of climate change, building retrofit and urban development scenarios on the energy demand of buildings, cities, and communities. In a rare attempt to combine the effects of such scenarios, researchers quantified the impact of climate change, cooling device uptake and population growth in Switzerland as a whole. The results showed that although space heating demand can decrease to 20 TWh by 2050 (i.e., one third of its current value in 2020), in an extreme scenario, space cooling demand could reach comparable values to that of heating (up to 17.5 TWh), highlighting the critical role of air-conditioning technology uptake and the need for pursuing alternative cooling strategies (Mutschler et al., 2021a). However, although different climate change scenarios were investigated, this research did not consider options for building retrofit and only considered population growth on a national scale. Variables of urban development such as occupant density and building use-type ratio were not considered, constituting a knowledge gap, since such factors can considerably affect energy demand (Mjörnell et al., 2019).

In this research we explore this knowledge gap of interactions between climate change, building envelope retrofit and systems replacement and urban development scenarios, in relation to future energy demand in Switzerland. This work is part of the Real-Time Control Platform project (ReMaP) (*Renewable Management and Real-Time Control Platform (ReMaP*, 2022), which aims at developing a flexible, hardware and software-based research platform for assessing the widespread adoption of renewable energy sources. To assess future technology and their control, this work aims at creating and providing future operational energy demand scenarios representative for Swiss archetypes.

1.2. Scope

This work explores the future energy demand of distinct Swiss community archetypes considering two climate change scenarios that include both the current trend and a rapid greenhouse emissions mitigation scenario, four building retrofit scenarios that comprise of both technological and behavioural aspects, and three comprehensive urban development scenarios based on current and plausible future urban development trends.

The main research question of this work is how urban development impacts the future energy demand of representative communities and thus, to what extent it is possible to achieve the goals outlined in the Swiss Energy Strategy 2050 (*Gebäudepark 2050 – Vision Des BFE*, 2020). To investigate this, we increase the spatial resolution of the analysis from the commonly used national scale to characteristic archetypes, which are represented by existing and typical urban, sub-urban and rural Swiss communities.

The methodology, the community archetypes, the scenarios and scenario results, the tools as well as the findings presented in this work can support planners and authorities in choosing effective paths for the development of urban, sub-urban and rural Swiss communities, being aware of their capacity in relation to the national energy demand reduction targets.

2. Methodology

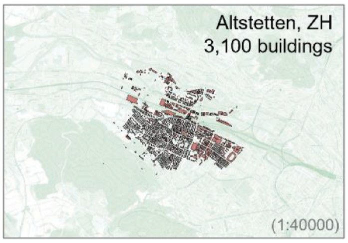
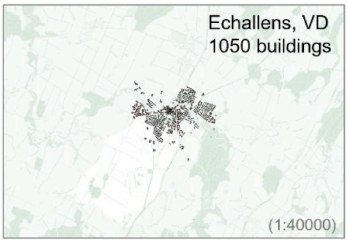
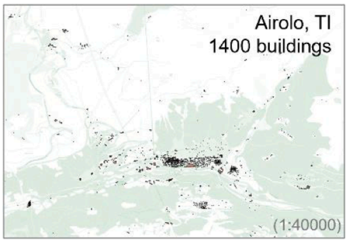
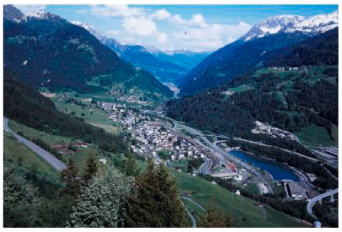
The methodology initially sees the selection of the community archetypes, which will form the basis of this work. Following that, the development of scenarios for urban development, building retrofit and climate change is presented. The modelling tool and the data inputs are finally outlined before presenting the results.

2.1. Selection of community archetypes

Based on the spatial division method of the Swiss Federal Statistical Office (Bundesamt für Statistik, 2012), Swiss municipalities can be divided into three main groups; urban, sub-urban, rural. The urban and sub-urban areas host almost 90% of the Swiss population as well as more than 80% of workplaces and they have the highest built density and mix of building use-types (e.g., the metropolitan regions of Zurich, Basel, Geneva-Lausanne). The rural areas comprise 50% of the total land area but host only 12% of the Swiss population (e.g., alpine regions of Uri, Obwalden, Glarus).

Following the given spatial division, this work focuses on three case

Table 1
The three case study communities used in this work, each representing a community archetype in urban, sub-urban and rural groups. (Photo sources: (Huber, Roger; Kobi, Hans, 2004; Ziebold, 2007b, 2007a)).

Urban Archetype	**Sub-urban Archetype**	**Rural Archetype**
Core city of a large agglomeration	High-density sub-urban commercial municipality	Mixed rural peripheral municipality
Altstetten community, City of Zurich	Echallens, Canton Vaud	Airolo, Canton Ticino
3100 Buildings	1050 Buildings	1400 Buildings
		
		

studies, representing community archetypes in each group (urban, sub-urban and rural). The case study communities were selected due to their representative characteristics fitting the urban/sub-urban/rural categorisation, and the willingness of their municipal offices to provide specific information as well as verify essential assumptions. Basic information from the three case studies is presented in Table 1.

2.2. Urban development scenarios

The urban development scenarios are constructed with a two-step approach. The first step is to identify multiple existing trends through the trend exploration method, and then the second step is to apply the creative-narrative technique to group relevant trends into the same scenarios. Detailed methods and assumptions used in this work are documented in a previous study (Popova et al., 2022).

Table 2
Descriptive variables for the urban development scenarios in the three community archetypes.

	Urban	Sub-urban	Rural
Business As Usual			
Population growth (based on 2020)	2040: +30% 2060: +35%	2040: +40% 2060: +80%	2040: −5% 2060: −15%
MFH occupant density	40 m^2/person	50 m^2/person	60 m^2/person
Spatial Typology[a]	Unchanged	Unchanged	Unchanged
Polycentric Urban Networks			
Population growth	2040: +20% 2060: +30%	2040: +30% 2060: +65%	2040: −3% 2060: −10%
MFH occupant density	35 m^2/person	40 m^2/person	60 m^2/person
Spatial Typology	Unchanged	Urban core	Rural service centre
Digitalisation			
Population growth	2040: +10% 2060: +7%	2040: +45% 2060: +85%	2040: +10% 2060: +15%
MFH occupant density	45 m^2/person	60 m^2/person	80 m^2/person
Spatial Typology	Only add residential	Urban residential	Rural tourist centre

[a] (Bundesamt für Statistik, 2012).

In the first step this study analysed trends and future projections from planning offices (Bundesamt für Raumentwicklung, 2005; Bundesamt für Statistik, 2012) statistical offices, and municipal offices, including population growth, economic growth and urban sprawl.

Overall, three nation-wide urban development trends were observed. First, the use of inward development and densification strategies of the core cities to combat urban sprawl. Second, future population growth in urban areas may decrease due to declining environmental quality, density stress, and traffic congestion motivating the urban population to relocate outside of the city. Third, because of the ongoing digitalization of work, not least boosted by the COVID pandemic, the flexibility of the workplace decreases the demand for offices and drives their conversion into mixed-use or residential spaces. These nationwide trends are the basis for the future urban development scenarios in this study.

In the second step of scenario construction, the observed trends were grouped and combined with creative techniques, intuition, and implicit background knowledge of experts (in our case several e-mail interviews with municipal planning offices were conducted to help shape the narrative), resulting in the initial narrative of three overarching urban development scenarios:

2.2.1. *"Business-As-Usual (BAU)"*

In this scenario, urban areas experience high growth of population and economic activity. Urban sprawl takes place around metropolitan core cities, while densification strategies are used within urban areas. Sub-urban areas continue to have strong growth and rural areas experience further economic decline and population decrease.

2.2.2. *"Polycentric urban network (PUN)"*

In this scenario, urban areas remain on a growth trajectory but at the same time sub-urban and rural areas follow their own spatial development concepts and transform into well-connected hubs with attractive

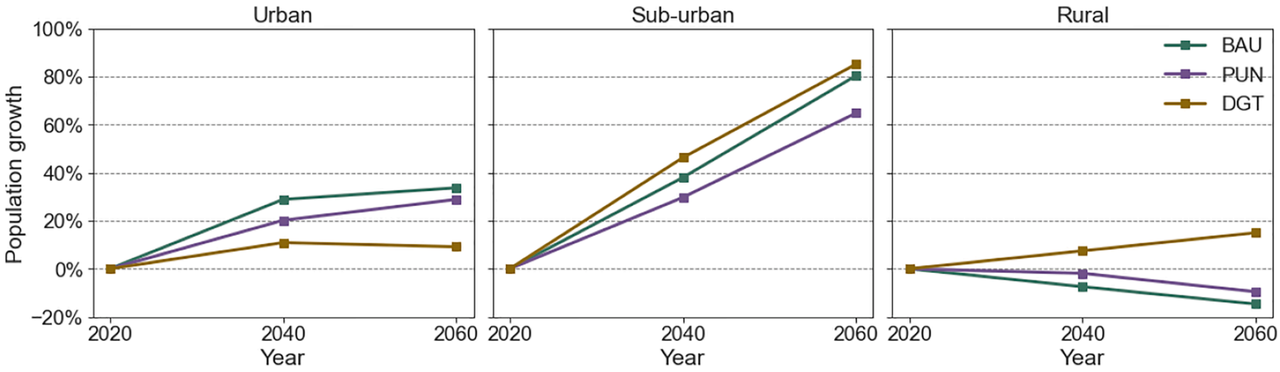


Fig. 1. Population projections in the years 2040 and 2060 under the three urban development scenarios for the three community archetypes.

living conditions to satisfy the need of residents for working, educational and shopping opportunities.

2.2.3. *"Digitalization (DGT)"*

The Digitalization scenario assumes increasingly flexible work conditions.[1] Thus, urban areas start experiencing lower population growth as sub-urban and rural areas become more attractive to live in due to remote working possibilities and higher environmental quality.

Following these narratives, the different urban development scenarios had to be translated into specific variables. The parameters of population, residential occupancy density, and building use-type ratio are essential for projecting total-built area per building use-type, which is the input for urban building energy modelling and were therefore explored in detail in each scenario.

Table 2 summarizes the future projections of these parameters under the three urban development scenarios in the three community archetypes.

For this work, the future years of 2040 and 2060 were chosen for investigation because the energy systems designed today will likely be used for up to 50 years, starting from 2020. The Swiss national population growth projection[2] until 2050 is between 10 and 30% (Swiss Federal Statistical Office, 2022b), with variations between different cantons. For the BAU scenario, the urban area is expecting the most vigorous population growth since urban sprawl is the dominating phenomenon, while the rural area is expecting the strongest decline in population. On the contrary, for the DGT scenario, the population of the urban community starts declining between 2040 and 2060, while the sub-urban and rural areas are facing the highest growth. In the PUN scenario, the population growth is more evenly distributed across all three communities as the result of well-connected networks and increasing services in sub-urban and rural areas. Fig. 1 shows the projected growth in future populations compared to 2020.

The current Swiss national average residential occupant density is about 47 m^2 per occupant (Swiss Federal Statistical Office, 2022a) with variations between different residential building categories. In some cases, municipalities have targets regarding the residential occupancy density for new buildings. In Echallens, for example, stakeholder interviews revealed that the target for multi-family houses is 50 m^2 per person. In this work, such projections are extrapolated from historical data, current densities, and future targets. The BAU scenario follows the future targets from the municipalities if available, while the DGT scenario assumes that the required living space will increase due to the need for home office spaces. In the PUN scenario, it is assumed that the required living space would decrease due to the strong incentive to contain building areas and the increase in public services.

Swiss spatial typologies (Bundesamt für Statistik, 2012), which include nine urban, seven sub-urban, and nine rural typologies, have been used to quantify the building use-type ratios. Under the BAU scenario, all communities retain their original (2020) spatial typologies, with the urban community in urban core within large agglomeration, the sub-urban community in sub-urban service municipality with high density, and the rural community in rural peripheral mixed municipality. Under the PUN scenario, both sub-urban and rural communities are assumed to increase the portion of offices and other commercial buildings, with the sub-urban community likely to take up characteristics of a middle-size urban agglomeration, while a rural community is likely to take up characteristics of a rural central service municipality. Under the DGT scenario, it is assumed that sub-urban communities become more attractive to live in, while the rural communities also increase in commercial and institutional buildings, with the sub-urban community resembling a middle-size urban residential municipality and the rural community resembling a rural tourism municipality. The urban community remains the same typology under both PUN and DGT scenarios.

Fig. 2 shows the projected population and gross floor areas (GFA) of all three urban development scenarios for the three community archetypes. Overall, the largest growth in population and GFA is observed in the sub-urban community across all scenarios, whereas in the urban community the growth is distinct but relatively smaller, especially in the DGT scenario. In the rural community, it is only the DGT scenario that sees increases in population, while the total GFA is reduced due a decrease in industrial areas.

The growth in GFA is not only induced by population growth but also by the change in building use types. Fig. 3 presents the projected building use-types in all community archetypes under different urban development scenarios in the year 2060. It is assumed that the mix of building use types in 2040 and 2060 is similar. The figure shows that the biggest GFA growth is in the sub-urban community under the PUN scenario due to the increase in office, commercial, and institutional buildings.

According to GFA per use type of each scenario in each year, the additional built and removed GFA in 2040 and 2060 are calculated. An automated area assignment algorithm then allocated these areas to existing building footprints (Hsieh et al., 2021). This is an optimization problem in which the variables are the number of floors to be added or

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[1] The digitalization scenario assumes lower shares of offices buildings, different occupancy patterns and higher occupant densities [m^2/person] in residential buildings, which were based on multiple studies in the USA, Canada, and Poland during the COVID-19 pandemic (Abdeen et al., 2021; Kawka & Cetin, 2021; Rouleau & Gosselin, 2021; Swiss Federal Statistical Office, 2022a). Here it is assumed that 20-30% of the occupants are working from home, driving changes in energy consumption during weekdays. Yet, the magnitude of peak energy consumption from lighting and appliances remains the same.

[2] Various data sources were used to collect information on population and occupancy densities in 2020 and for futures years 2040 and 2060. These sources included cantonal reports and regulations, statistical offices, and literature regarding housing development trends. When values were not available, a linear trend extrapolation was assumed for calculating these.

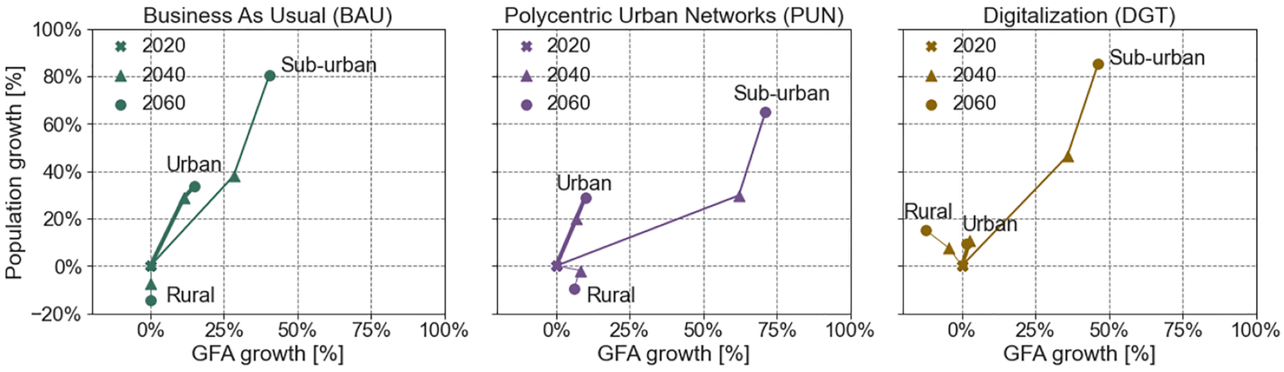

Fig. 2. Projected growth in population and gross floor areas (GFA) for the three community archetypes, under the three urban development scenarios in 2040 and 2060.

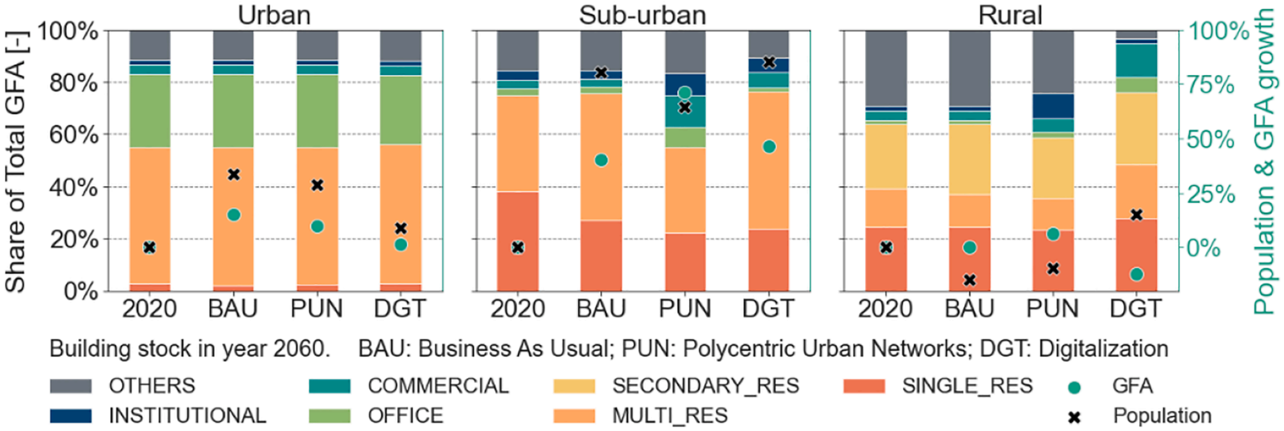

Fig. 3. Projected Gross Floor Areas per building use-type in the year 2060 for the three community archetypes, under three urban development scenarios.

Table 3
Energieperspektiven 2050+ (Prognos AG, INFRAS AG, et al., 2020).

Specific Parameters	Energieperspektiven 2050+
Energy efficiency systems retrofit	2030:45%, 2050:80%
Energy efficiency envelope Retrofit Rate	1.6%
Specific Heating demand (post-retrofit)	35–50 kWh/m^2
Energy Efficiency	Specific consumption SIA 2024 values or even better (SIA 380/1[a])
Final Use	Oil <1% after 2050 Gas 5–30% after 2050
Space Cooling	“*By 2060 around two thirds of the areas will be cooled*” (Prognos AG, INFRAS AG, et al., 2020)

[a] (Bundesamt für Energie BFE, 2009).

removed per use type in each building, and the objective is to minimize the difference between the achieved GFA and the targeted GFA per use type. The area assignment respects local urban planning regulations, including building heights, permitted building uses, and planned development. In case when new building use types are introduced to the district, these new use types are randomly assigned to the buildings, located in permitted zones, before running the area assignment algorithm. The plausibility of the constructed scenarios was verified with local planning authorities through personal interviews.

2.3. Building retrofit scenarios

In Switzerland the national Energy Strategy 2050 outlines the aims of the Swiss government to reduce the energy consumption of the Swiss buildings from 100 TWh (average 2010–2015) to 55 TWh by 2050 (*Gebäudepark 2050 – Vision Des BFE*, 2020). To accommodate for this, building retrofit scenarios were developed using the deductive method and a 2 × 2 matrix technique (Rhydderch, 2017, p. 2; Schwartz, 1998). Building retrofit measures were defined in coherence with the measures described in the Swiss Energieperspektiven 2050+, as listed in Table 3 (Prognos AG, INFRAS AG, et al., 2020).

The deductive method provides the theoretical background to develop the scenarios and it produces a 2 × 2 matrix, resulting in four (4) distinct scenarios, based on the consideration of the following five (5) consecutive steps (Rhydderch, 2017, p. 2; Schwartz, 1998). Firstly, in

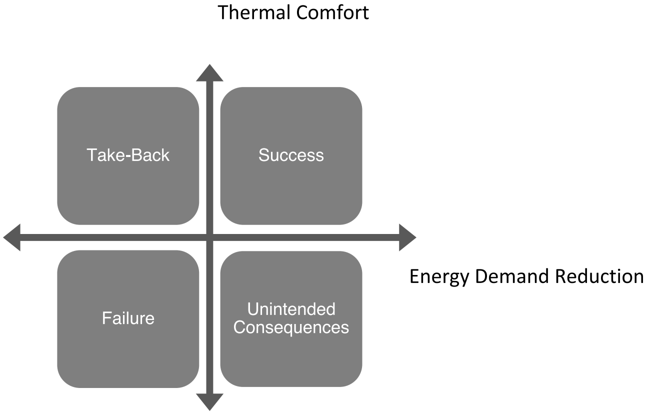

Fig. 4. Representation of the retrofit scenarios based on the axes created by the Deductive method.

setting the standards, the object of analysis is defined as the building stock in Switzerland and more specifically the future energy demand in these community archetypes, taking into consideration the urban development these might adopt. The goal is to reduce the energy demand by applying envelope and systems retrofit pathways but without compromising the well-being of the users and occupants of the buildings. Secondly, in *shaping the framework*, the theory calls for exploring the drivers of change, which are identified as the climate crisis, the policy legislation (the Energy Strategy 2050 (Prognos AG, INFRAS AG, et al., 2020)), the projected population growth and the associated planning of the infrastructure.

Thirdly, in *formulating the analysis*, the impact and uncertainties are identified. Here the impact is the final reduction of the energy demand through the application of energy efficiency retrofit based on the Energy Strategy 2050 targets. Uncertainty addresses rebound effects that lead to an increase in energy demand as well as the unintended consequences that could result from the implementation of energy efficiency retrofits. Several studies indicate that increasing the insulation and airtightness of buildings trough retrofit can, for example, result in higher summertime indoor temperatures which can become a significant issue for the occupants' wellbeing (Lomas & Porritt, 2017). Furthermore, take-back factors such as reverting to the higher indoor temperatures due to apparent energy savings after retrofit can affect the overall energy demand reduction of retrofitted buildings. Fourthly, in *selecting the axes*, the metrics relevant for the research objective are chosen, such as in this case the energy demand reduction and the uncertainty regarding the thermal comfort. Lastly, in *creating the scenarios*, the trade-offs between these two axes, energy demand reduction and thermal comfort, are formulated.

The four retrofit scenarios (Fig. 4) each comprise of a combination of potential future states of Swiss buildings with regards to retrofit and how policies and occupants might respond to increasing temperatures due to climate change via the installation of cooling systems and cooling and heating setpoints adjustments. In the following section we describe the four scenarios in more detail.

2.3.1. *"Scenario success"*

For the scenario 'Success', the energy demand reduction (due to the extent of the retrofit and the warming climate) reaches the levels defined by the Energy Strategy 2050 and at the same time the levels of thermal discomfort are kept comparable to the 2020 levels. The heating supply is decarbonized by replacing nearly all fossil fuel heating systems with more efficient electrical systems (i.e. heat pumps), resulting in an energy supply mix aligned with the Energieperspektiven 2050+ (Prognos AG, INFRAS AG, et al., 2020). Mechanical cooling is allowed in all buildings as long as these have had significant energy efficiency retrofit measures installed. Therefore, installation of cooling systems is coupled with envelope energy efficient retrofits. In addition, occupants have accepted a wider comfort envelope - adapting to warmer indoor temperatures by setting the cooling setpoint at 27 °C, one degree higher than that recommended in the Swiss standards (SIA, 2015).

2.3.2. *"Scenario take-back"*

For the scenario 'Take-Back', the energy demand reduction does not reach the Energy Strategy 2050 target since the rate of retrofit has not been increased as compared to current levels (2015–2020), but thermal comfort is kept at acceptable levels. In this scenario, a rebound effect is explored, where the occupants are taking back some of the energy savings achieved through energy efficiency retrofit by enforcing a stricter thermal comfort envelope. Hence heating setpoints are set to 21 °C and cooling setpoints to 25 °C (one degree higher for heating and one degree lower for cooling as compared to the Swiss standard). Residents are allowed to install cooling devices after having retrofitted the envelope, therefore thermal discomfort is again kept minimal levels, comparable to those in 2020. Furthermore, the supply has not been decarbonized as heating systems are being replaced at a slow rate, allowing large parts of the non-retrofitted building stock to operate on fossil fuels until 2060.

Table 4
Main assumptions of the building retrofit scenarios.

	Success	Take Back	Unintended Consequences	Failure
Envelope Retrofit Rate	3%	1%	3%	1%
Heating Systems Retrofit Rate	10%	3%	5%	1%
Cooling Systems Take-Up Rate	3%	1%	3%	1%
Heating Set Point	20 °C	21 °C	20 °C	21 °C
Cooling Set Point	27 °C	25 °C	27 °C	25 °C
Envelope Retrofit Standards	SIA 380/1[a]	SIA 380/15[a]	SIA 380/15[a]	SIA 380/15[a]
Space Cooling	all buildings	all buildings	only non-residential	only non-residential

[a] (Bundesamt für Energie BFE, 2009).

Table 5
Retrofit rates and percentage of the building stock retrofitted for the years 2040, 2050, 2060.

Retrofit Rate (%)	2040	2050	2060
10	87.8	95.8	97.7
5	64.2	78.5	84.2
3	45.6	59.9	66.6
1	18.2	26	30

2.3.3. *"Scenario unintended consequences"*

In this scenario, the energy demand reduction is aligned with the Energy Strategy 2050 target but there is excessive thermal discomfort in homes since cooling in residential buildings has been discouraged by official policies in order to achieve the required energy demand reduction and avoid summer peak loads. The supply has been decarbonized to a large extent, but a significant number of buildings are still operating with fossil fuel heating systems in 2060. Thermal comfort envelopes are wider as in the success scenario, in a societal effort to consciously reduce the amount of energy required to provide acceptable indoor thermal conditions.

2.3.4. *"Scenario failure"*

In this scenario, the Energy Strategy 2050 energy demand reduction target is not met and there is extensive discomfort in homes since cooling systems are restricted by local policies. The energy efficiency annual retrofit rate for building envelopes does not exceed the 2020 threshold of 1%, which is also the annual rate at which fossil-fuel-based heating systems are being replaced with electric heat pumps, resulting in high shares of heating systems operated by fossil fuels in 2060. In addition, the uptake of space cooling in the non-residential sector is increased as setpoints are reduced to 25 °C, contributing to a further increase of the related energy demand. The following tables outline the design variables for each of the building retrofit scenarios.

As it can be derived from Table 4, the energy efficiency retrofit standards for the building envelope are based on the SIA 380/1 standards (Bundesamt für Energie BFE, 2009) and are the same for any building that is retrofitted in this work, depending, however, on its construction year (i.e., construction archetype). An important difference is the rate at which the building stock will be retrofitted (see Table 5), where for each scenario there is a specific fraction of the building stock undergoing an envelope energy efficiency retrofit. For retrofit that only addresses the heating system, fossil fuel-based heating systems are

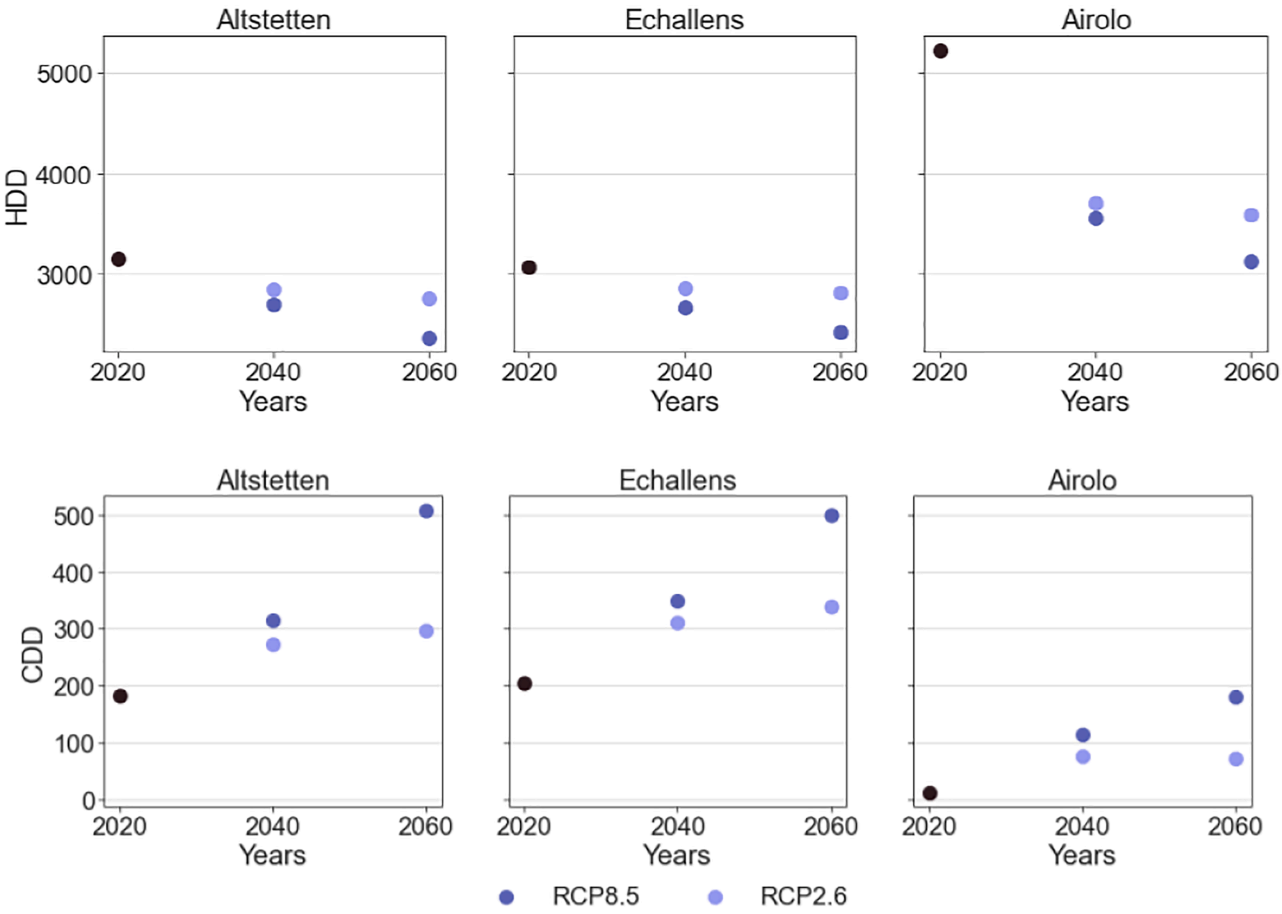

Fig. 5. Heating Degree Days (HDDs) and Cooling Degree Days (CDD) of all three case study communities in the year 2020, 2040, and 2060 under RCP2.6 and 8.5 scenarios (the assumed indoor temperature is 20 °C, and the base temperatures are 12 °C and 18.3 °C for heating and cooling respectively. Base temperatures describe the outdoor temperatures when no heating or cooling systems are required).

replaced by electric heat pumps.

For the assessment of thermal comfort a simplified approach was applied based on a well-established static criterion, the number of hours during which the internal temperature is above a certain temperature threshold (Gupta et al., 2017). This threshold was set according to the setpoint of the space cooling systems during summertime. To be able to assess the thermal discomfort at a large scale, the percentage of buildings with more than 10% of hours with internal temperature above the space cooling temperature setpoint threshold was used. In 2020 the current regulations suggest a cooling setpoint temperature of 26 °C, while in the retrofit scenarios the setpoints are altered based on different hypotheses as described above.

2.4. *Climate change scenarios*

The selection of the climate projections for the years 2040 and 2060 was based on the information from the Swiss National Centre for Climate Services (NCCS) (NCCS, 2018). These scenarios follow the three main Representative Concentration Pathways (RCP), which vary in the concentration of greenhouse gas (GHG) emissions in the atmosphere. Each RCP assumes a certain degree of GHG emissions mitigation. The RCPs selected represent a business-as-usual scenario (RCP8.5) and a rapid mitigation scenario that limits the warming of global mean temperature to 2 °C (RCP2.6). Local weather data of the status quo and future scenarios for each case study community was acquired from Meteonorm (METEOTEST, 2018). The weather files for these locations have been produced using Metenorm Version 8.0.4.21990. The Meteonorm has been validated in previous studies and its accuracy has been reported with a variable uncertainty between 2 and 10% (Mueller et al., 2018; Remund, 2015). Fig. 5 shows the heating degree days (HDD) and cooling degree days (CDD) for RCP2.6 and RCP8.5 for the three case study communities. The RCP2.6 scenario presents higher HDD and lower CDD compared to RCP8.5 at the same location and year. In terms of HDD, a downward trend is observed between the year 2020 and 2060, with a significant drop for the rural community (Airolo) by the year 2060, while the CDD show an upward trend with increased intensity for urban (Altstetten) and sub-urban (Echallens) communities by the year 2060. Besides the general trend over the years, the scale of HDDs and CDDs in Airolo is also different from the other two case study districts. This is because Airolo, similar to majority of rural communities in Switzerland, is located at a higher altitude (1175 m) compared to Altstetten (404 m) and Echallens (617 m).

2.5. *Modelling*

2.5.1. *Tool*

The modelling framework used to simulate the energy demand of the community archetypes was the City Energy Analyst (CEA) (Fonseca et al., 2019). The CEA is an open-source computational framework for the analysis of urban building energy modelling (UBEM), which has been applied for case studies in multiple cities in Switzerland (Fonseca, 2016; Maiullari et al., 2019), Singapore ((Troitzsch et al., 2020), (Shi et al., 2020)) and other locations. The CEA uses reduced-order physics-based models, to forecast heating, cooling, and electricity loads of single or aggregated buildings, allowing for the modelling of dynamic energy exchanges between buildings, systems, users, and the environment, in an hourly temporal resolution (Fonseca et al., 2019) . In addition, a plug-in for transforming the building stock according to the urban development scenarios, as projected for the years 2040 and 2060 was developed.(Hsieh et al., 2021).

2.5.2. Data

Building stock information, including building geometry, age, use, fabric, and systems, are fundamental inputs to the CEA. The comprehensive GWR (Eidgenössisches Gebäude und Wohnungsregister) database for all buildings in Switzerland is available from the Swiss Federal Statistical Office (Bundesamt für Statistik, 2021). This database provides building geo-locations, building use-types, construction years, number of floors, and building systems for the building stock in 2020. The building geometry to establish the urban archetypical models was based on building footprints retrieved from OpenStreetMap and building heights from the GWR database. Input variables for building construction such as envelope U-values were inferred based on the construction year and building regulations at the time. Information regarding the existing heating and cooling systems was obtained from the GWR database and controlled by setting the setpoint temperatures. The occupancy schedules were taken from the Swiss norms (SIA, 2015).

Residential building use types make up the largest share of the building stock in all three community archetypes. Typical modelling approaches categorise residential buildings into single and multi-residential use types. However, these primarily represent primary residences. In 2020, around 18% of municipalities in Switzerland, however, had more than 20% share of secondary homes, and these municipalities are mostly rural (Bundesamt für Raumentwicklung, 2021). In the rural community archetype, 35.7% of the buildings are secondary homes. As not all the secondary homes are labelled in the GWR database, 35.7% of residential buildings in the rural archetype of Airolo were randomly selected and assigned as secondary homes. The automated process of organizing building information from GWR to create building models in the CEA was made available in an open repository (Mok, 2020).

2.5.3. Verification

With the building stock information collected from the GWR database, building footprints from OpenStreetMap, building construction and building archetype databases for Switzerland (Fonseca et al., 2016; SIA, 2015) the building models for energy simulation are complete. However, the validation of the model remains of significant importance if the findings are to be trusted (Oraiopoulos & Howard, 2022). Although it has not been possible to acquire data on measured energy consumption from any of the case study communities, a comparison was possible between the simulated heating demand data in the three community archetypes for 2020 and the average values taken from the Swiss Residential Building Stock Model (Streicher et al., 2019), for single and multi-residential buildings (Fig. 6). The Swiss Residential Building Stock Model is a bottom-up statistical model that derives residential building energy demand for urban, sub-urban and rural areas from the national-scale survey provided by Cantonal Building Energy Performance Certificate (also known as CECB or GEAK).

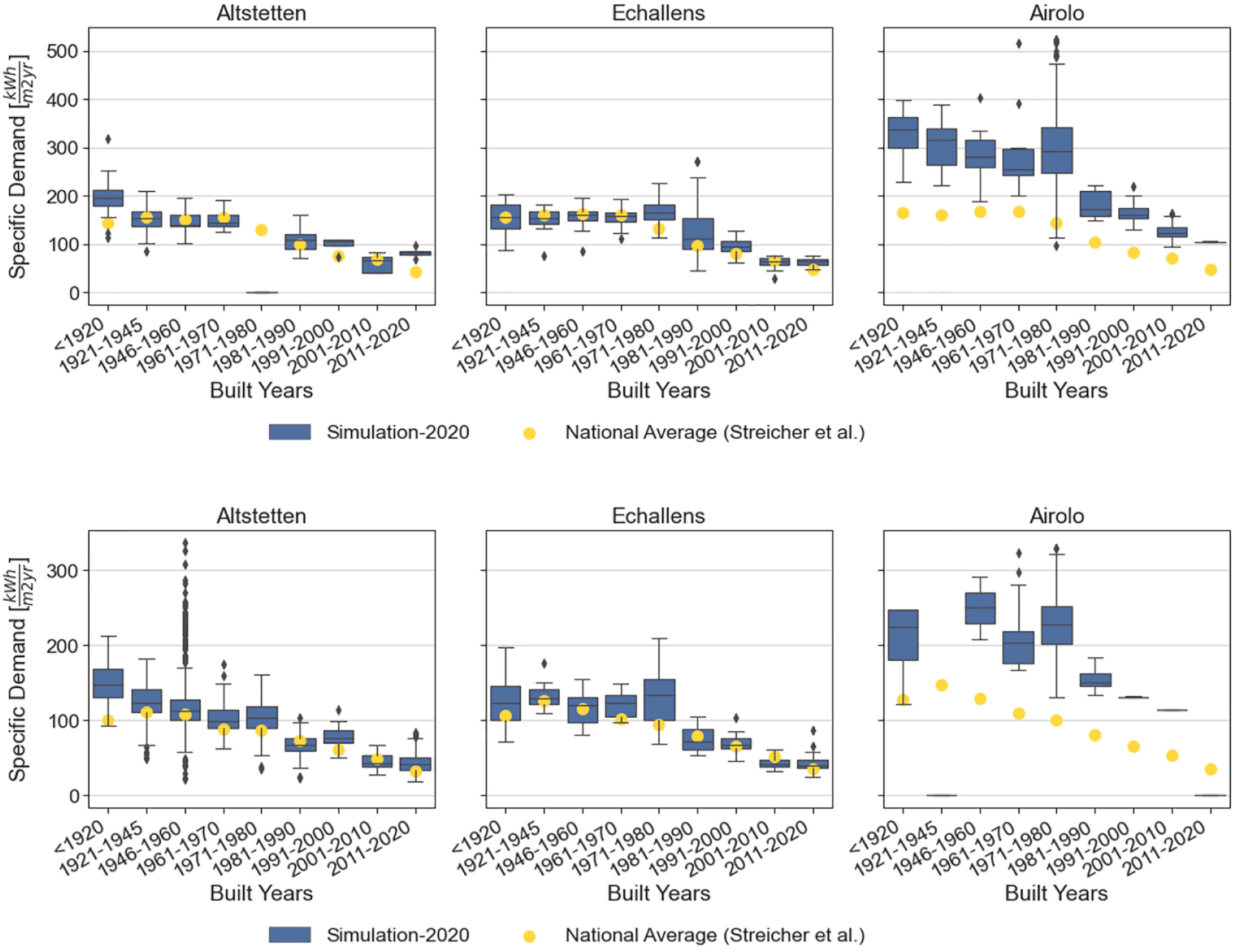

Fig. 6. Simulated area-specific space heating demand of single-residential (top row) and multi-residential (bottom row) buildings of the three case study communities compared to national average values per built period (Streicher et al., 2019). The value is calculated using the energy reference area.

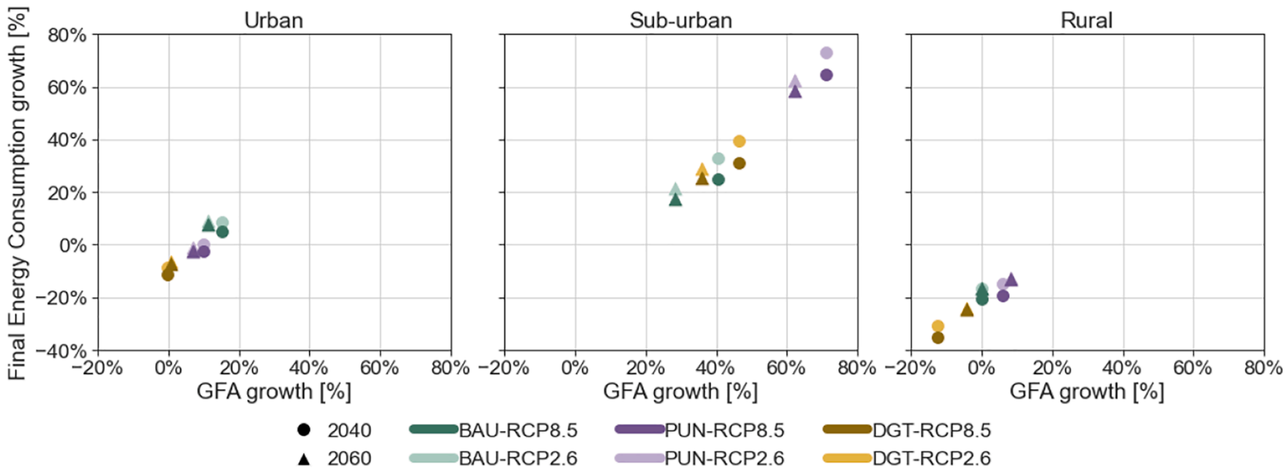

Fig. 7. Projected growth in final energy demand and Gross Floor Area (GFA) in 2040 and 2060 for the three community archetypes.

The resulting space heating demand from the current study shows good agreement with the Swiss Residential Building Stock Model for the urban and sub-urban case study communities (Altstetten and Echallens). For the urban case study community, the simulation results for space heating are higher than the national average space heating demand in rural areas. This could be caused by two reasons. First, the rural case study selected is situated in a high altitude and thus a colder climate, which leads to higher space heating demand compared to national average. Second, in this study, the assumption of occupant density is higher than the one of the Swiss Residential Building Stock Model, which takes the values defined in SIA standards (SIA, 2015), assuming 30 m^2 and 50 m^2 per person in multi-family and single-family houses respectively (Federal Statistical Office, 2021). For this study, the occupancy densities of residential buildings are estimated based on the total residential building floor areas and the population provided by the GWR database and national statistics.

Furthermore, validation of the CEA has been published in previous research, where the outputs have been compared to empirical data as well as to simulated EnergyPlus data, resulting in percentage errors of between 1 and 19% at the neighbourhood and city district scales (Fonseca et al., 2016; Fonseca & Schlueter, 2015). Additionally, a sensitivity analysis of input data in the CEA has been previously performed, where architectural properties (window-to-wall ratio, occupant density and envelope leakiness), thermal properties (U-values, G-values, thermal mass and emissivity of building surfaces), operating parameters (set point temperatures and ventilation rates) and internal loads (heat gains due to occupancy, appliance use and lighting) were explored in-depth (Mosteiro-Romero & Schlueter, 2021).

3. Results and discussion

The results present the energy demand for the three community archetypes across the scenario categories (urban development, climate change, building retrofit). It must be noted that the corresponding carbon emissions were not investigated at this stage as this falls out of the project's scope.

3.1. Impact of urban development

The total growth in final energy demand and the annual and monthly breakdowns by energy end-use are presented. It must be noted that these results do not include any building retrofit measures (hence the large percentage of fossil fuel-based heating systems and energy-inefficient buildings) but include a 100% space cooling systems uptake in all building use types.

Fig. 7 shows the projected growth in final energy demand and Gross Floor Area (GFA) compared to the year 2020 under the three urban development scenarios (BAU, PUN, and DGT) for all three community archetypes. A rather strong relationship between the growth in GFA and final energy demand can be observed. The variation of the final energy demand of the urban archetype remains within $a \pm 20\%$ range, while an up to 36% reduction in final energy demand is observed for the rural archetype. The sub-urban archetype experiences a strong growth in final energy consumption, due to the increase in GFA across different building use types.

Fig. 8 presents the annual final energy demand by end-uses in the year 2060 compared to the year 2020. For all community archetypes, space heating end-use becomes less dominating by 2060, but still accounts for the largest share of final energy demand, which is around 40% for the urban archetype, 40–50% for the sub-urban archetype, and 50–60% for the rural archetype. The second biggest final energy demand is due to electricity for lighting and appliances, around 35% in the urban community, between 30 and 40% in the sub-urban archetype, and 25–30% in the rural archetype, while domestic hot water demand remains at a rather stable share.

In alignment with existing literature (Mutschler et al., 2021b; R. Silva et al., 2022), the results show that space cooling demand will increase in future years. However, the projected final energy demand for space cooling increases only by up to 10% (maximum, found in the urban archetype) by 2060, as compared to 2020, mainly because building envelope and heating systems retrofit is not considered in this scenario but also due to the space cooling supply systems being of high efficiency (assumed to be air-source heat pumps).

Despite only accounting for up to 10% of total final energy demand by 2060, the space cooling demand is the determining factor of the peak electricity demand from the grid. Fig. 9 shows the peak electricity demand in each month by end-uses by 2060. In all three community archetypes, the annual peak occurs in the summer months when the demand for space cooling is high. The strong presence of space heating in the rural community archetype is due to the current surveyed data from GWR, that show electric heating systems (i.e., heat pumps, direct electric heaters) are primarily present in the rural case study community, with buildings in urban and sub-urban areas primarily supplied by oil and gas.

3.2. Impact of climate change

The impact of two climate change scenarios, RCP 2.6 and RCP 8.5, on space heating and space cooling load by 2040 and 2060 was mainly explored. Space heating load will likely decrease in the future, as indicated in the Heating Degree Days (HDDs) (see Fig. 5). Fig. 10 presents the total space heating load results in the three community archetypes

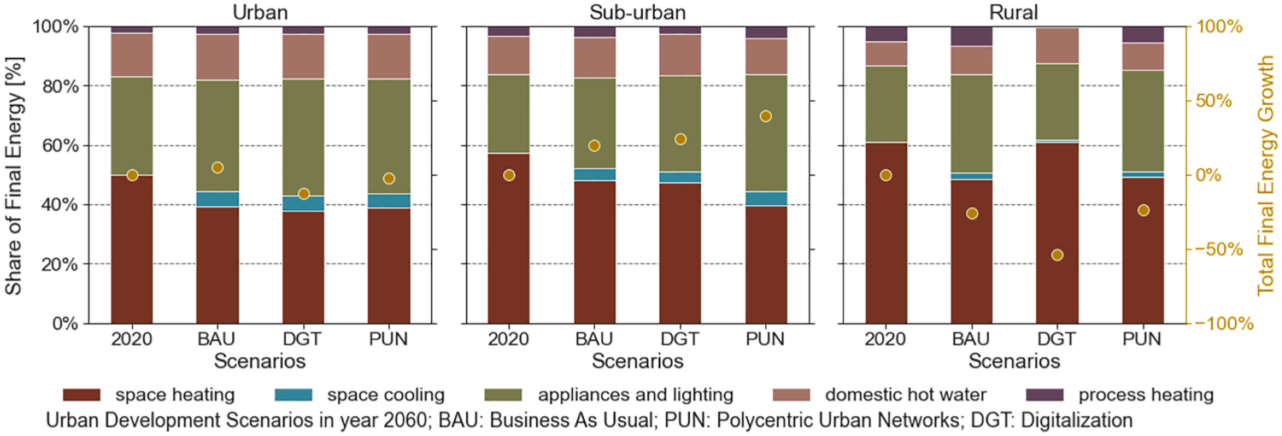

Fig. 8. Total final energy demand breakdown by end-uses in 2060, under RCP 8.5 climate scenario, for the three community archetypes.

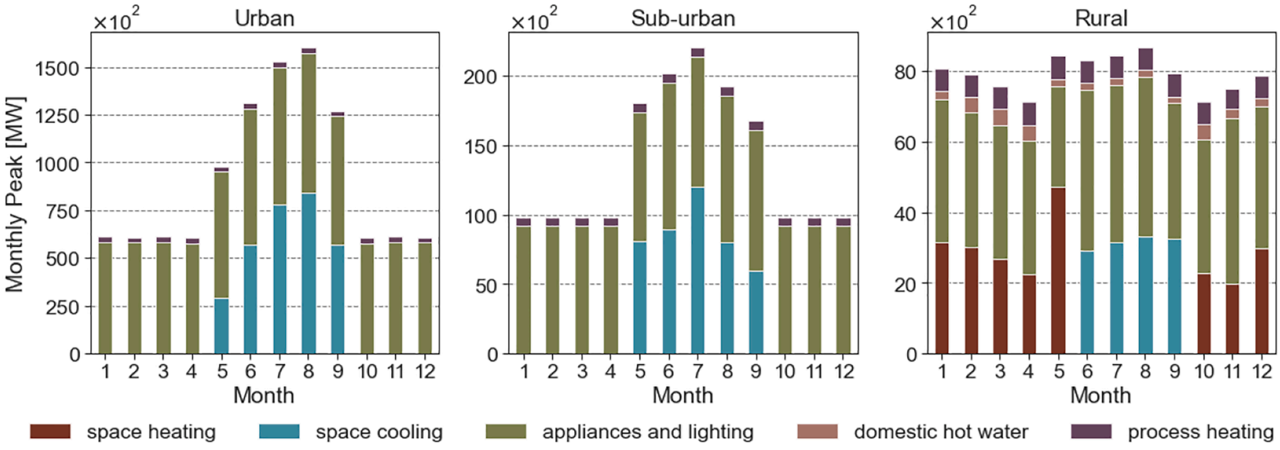

Fig. 9. Monthly peak grid electricity demand by end-uses in 2060, under RCP 8.5 climate scenario, for the three community archetypes.

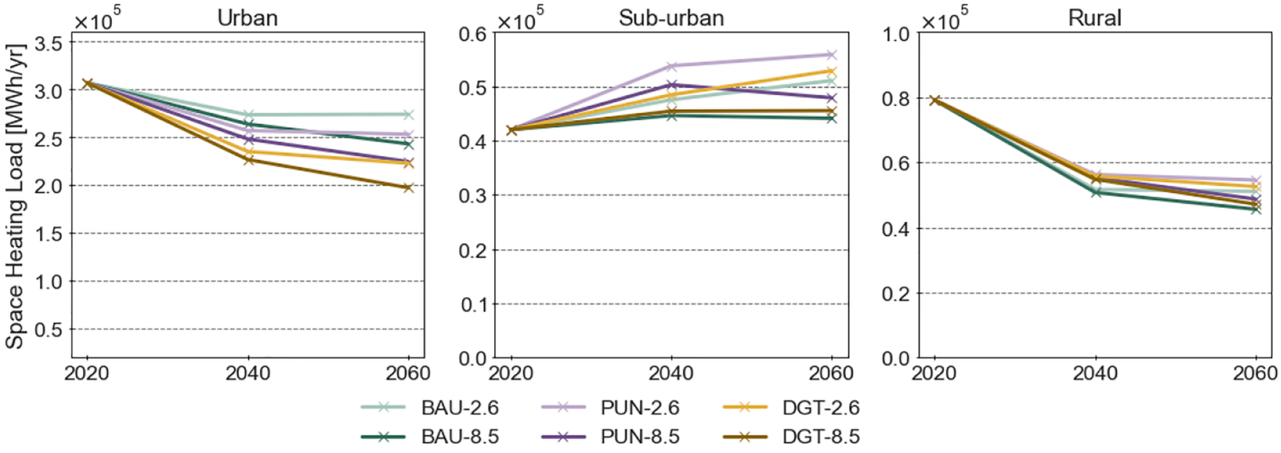

Fig. 10. Projected annual space heating loads of three community archetypes under three urban development scenarios (BAU, PUN, DGT) and two climate scenarios (RCP2.6, RCP8.5).

for climate and urban development scenarios. The differences in the results between the two climate scenarios are more pronounced in 2060 compared to 2040, where the climate scenarios further diverge the heating loads in 2060 compared to 2040. The total space heating loads in urban, sub-urban, and rural communities under RCP2.6 will be higher than RCP8.5 by 2040, with the difference further increasing by 2060. The results further suggest that the energy demand estimation might be unrealistic and thus misleading without considering urban development: Although the estimated HDDs show a downward trend in space heating demand, space heating loads in the sub-urban community archetype are likely to increase due to the substantial increase in total GFA.

An abnormality in the data can be seen for the PUN scenario of the sub-urban archetype combined with the RCP 8.5 climate scenario, which

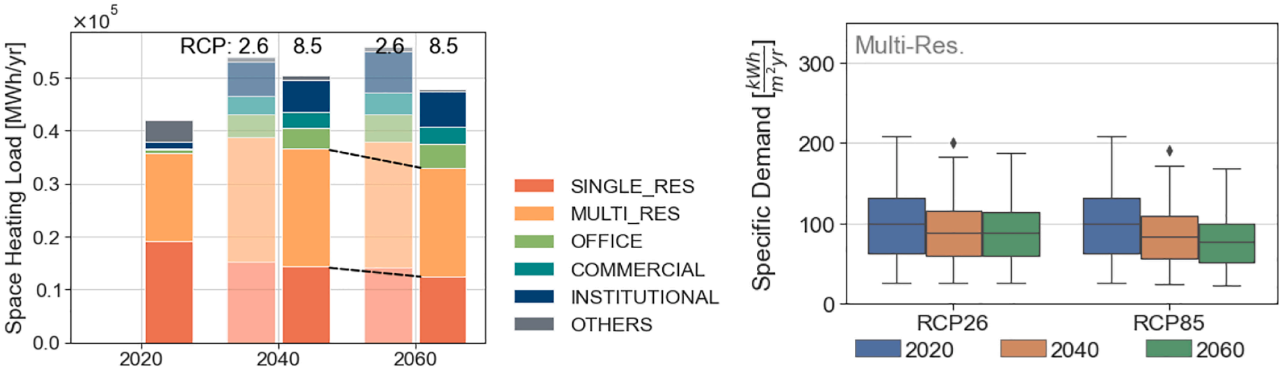

Fig. 11. (Left) space heating load per building use-type (Right) specific space heating demand per energy reference area of multi-residential buildings, in the sub-urban community archetype, in 2020, 2040, 2060, under RCP2.6 and RCP 8.5 scenarios.

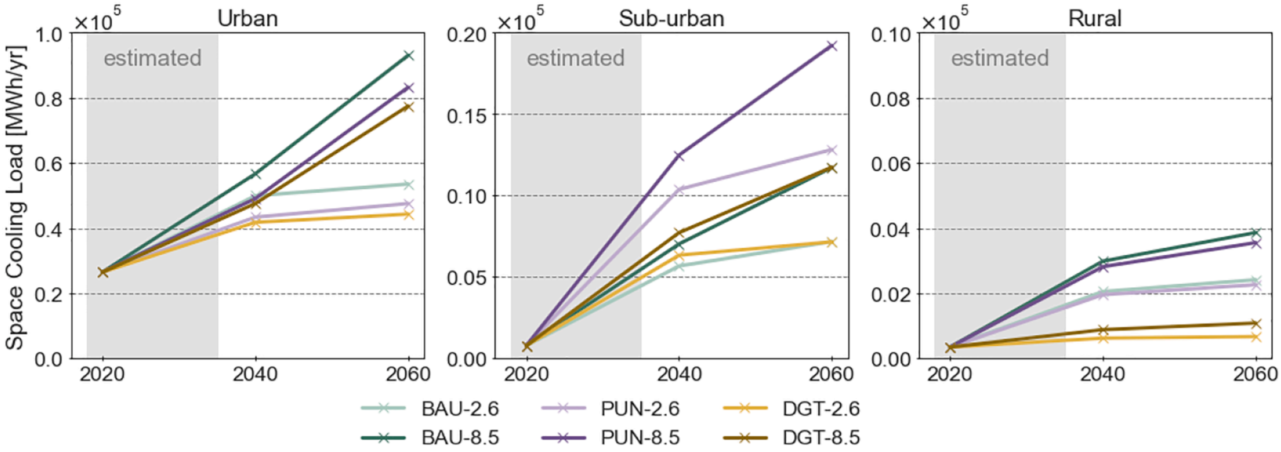

Fig. 12. Projected annual space cooling loads of three community archetypes under three urban development scenarios (BAU, PUN, DGT) and two climate scenarios (RCP2.6, RCP8.5).

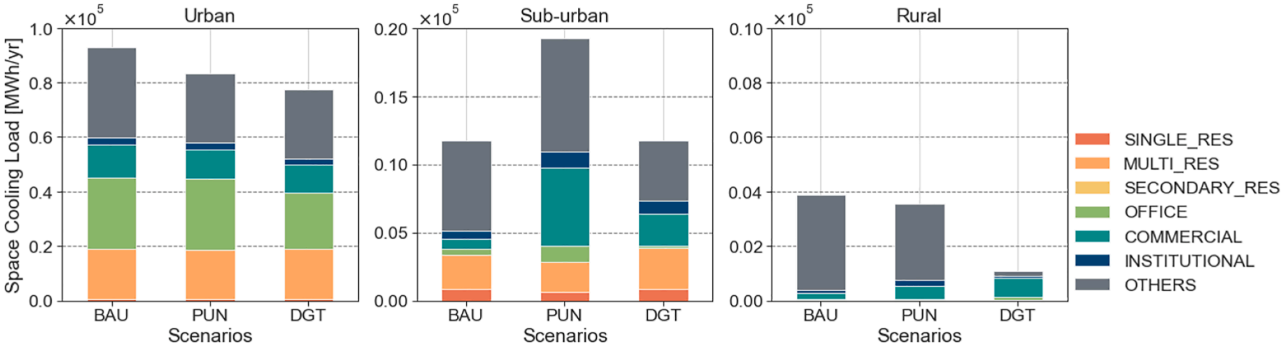

Fig. 13. Space cooling load per building use-type under RCP8.5 in 2060.

follows a downward trend with the total heating load decreasing from 2040 to 2060. Investigating further, Fig. 11 (left) reveals that from 2040 to 2060, the total space heating load for multi-residential buildings (the largest single use-type) increases under RCP2.6 but decreases under RCP8.5. This is mainly due to the weaker GFA growth between 2040 and 2060 (compared to that between 2020 and 2040) under the PUN scenario (see Fig. 2), but also due to the general impact of the more severe RCP 8.5 climate scenario, leading to larger reductions in space heating demand (Fig. 11 (right)).

Space cooling load is likely to increase in the future, based on the Cooling Degree Days (CDDs) (see Fig. 5), with the differences between the two climate scenarios more pronounced in 2060 compared to 2040.

Fig. 12 presents the results for total space cooling loads, due to the impact of both climate scenarios and urban development scenarios, assuming all buildings are equipped with cooling systems in the future in all three community archetypes.[3]

It can be observed that the cooling loads diverge substantially between the two climate scenarios in 2060 compared to 2040, especially in

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[3] For the year 2020, the cooling loads displayed in Figure 13 are estimations, assuming only commercial buildings are equipped with space cooling systems. This is due to the lack of information on cooling systems in the GWR database (Bundesamt für Statistik, n.d.) at the time of data extraction.

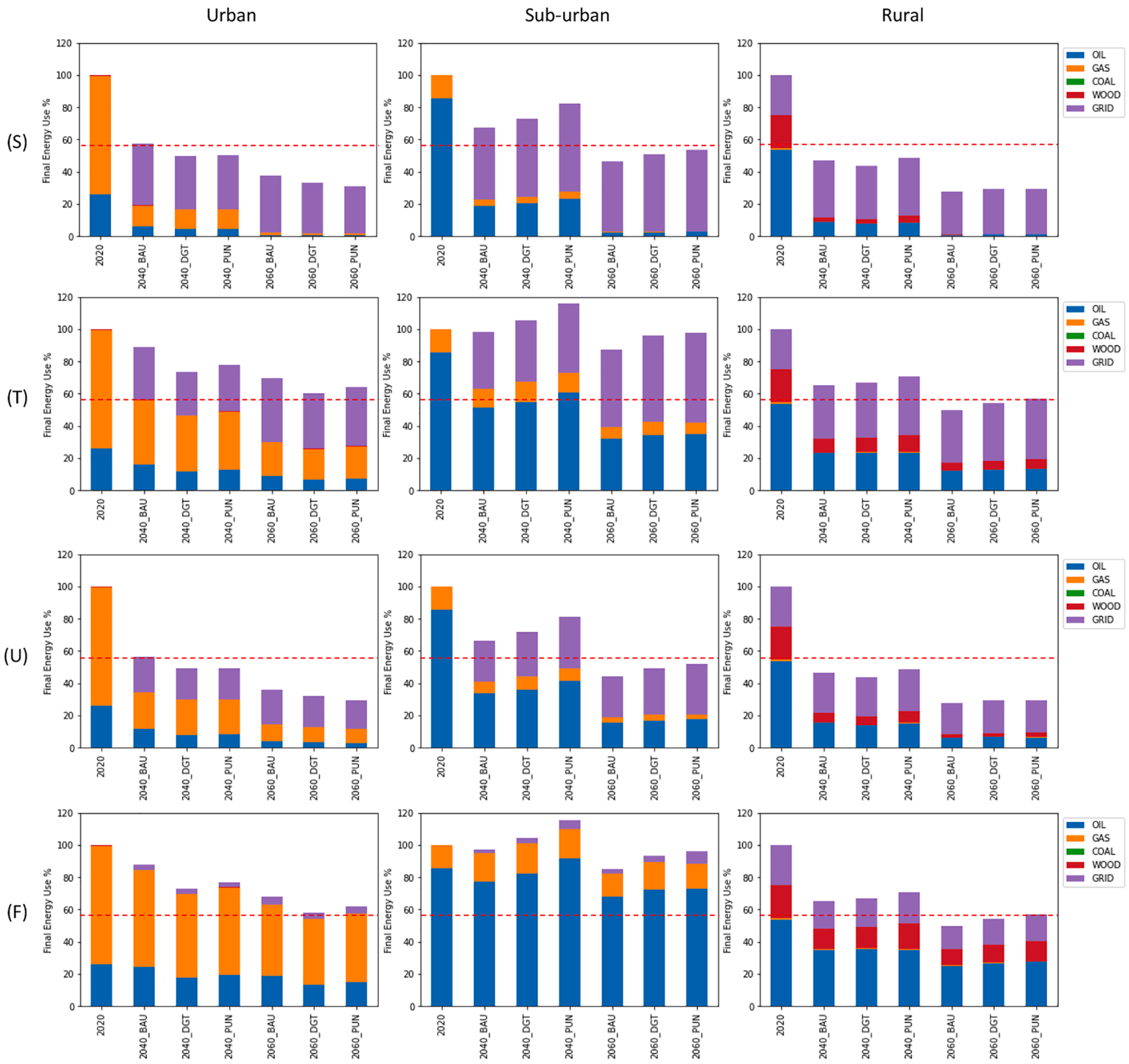

Fig. 14. Final energy demand for the three community archetypes (Urban, Sub-urban, Rural) for all four retrofit scenarios (S: Success, T: Take-Back, U: Unintended Consequences, F: Failure) and all three urban development scenarios (BAU: Business As Usual, PUN: Polycentric Urban Network, DGT: Digitalization) and the climate change scenario RCP 8.5. The red dotted line indicates the 45% reduction in final energy consumption by 2050 outlined in the Energy Strategy 2050. The Y-axis notes the energy demand of 2020 as the 100% mark.

the case of the urban community archetype. The total space cooling loads in urban, sub-urban, and rural communities under RCP 2.6 are lower than RCP 8.5 by 2040, exhibiting a larger spread by 2060. The considerable variations in the sub-urban community in the year 2060, as compared to the two other archetypes, are due to the significantly more diverse building use-types of non-residential buildings between the different urban development scenarios.

Fig. 13 shows the space cooling load per building use-type in the year 2060. The major contributors to the space cooling loads are non-residential use-types (office, commercial, and industrial). For space heating, the residential building use-types were mainly responsible for most of the loads. In the sub-urban community archetype, the total GFAs of non-residential use-types in the PUN scenario, and especially the increased commercial use-type, result in significantly higher cooling loads compared to the BAU and DGT scenarios.

The rural community archetype does not exhibit high space cooling loads by 2060, mainly due to the higher altitude location of the case study community of Airolo, where most residential buildings do not require space cooling load with the cooling set-point at 26 °C. However, this result could vary for rural communities located at lower altitudes, where the specific cooling demand of residential buildings could potentially increase.

3.3. *Impact of building retrofit*

In addition to urban development and climate change scenarios, this section presents the impact of retrofit scenarios for the three community archetypes in terms of energy demand (final energy use demand, space heating and space cooling end-use demand and specific space heating and space cooling demand) and thermal comfort. The industrial use-type buildings have been excluded due to large uncertainties in their associated energy demand.

3.3.1. Final-use energy demand

The final energy demand is calculated after the retrofit scenarios are implemented and compared to the status quo case in 2020, to evaluate whether the Energy Strategy 2050 target of a 45% reduction in energy consumption of buildings can be achieved and under which scenario assumptions.

Fig. 14 shows an overview of the results regarding the final energy demand across all case study communities for all urban development scenarios in future years 2040 and 2060, based on the climate change scenario RCP 8.5. An important limitation is an uncertainty about the exact final energy demand for the status quo year 2020, which acts as the base case. However, the proportions of fuel in 2020 reflect those found in the GWR database. In the urban community archetype, gas is the dominant fuel, oil for the sub-urban archetype, and in the rural community archetype, a considerable amount of wood is used.

Overall, the success scenario translates to a small fraction of fossil fuels in the final energy demand in future years, as also indicated in the Energy Strategy 2050 (see Table 3), with grid electricity dominating the final energy demand across case study communities and urban development scenarios. However, current trends are better aligned with the take back scenario, where envelope retrofit rates as well as heating systems replacements is close to 1%. This indicates that current policies and market drivers are not responding sufficiently to the overall targets set by the Swiss government for decarbonising the building stock timely. Envelope retrofit rates need to be substantially increased from the current national threshold of 1%, to at least 3% in urban and rural community archetypes (as in Success scenario). In the case of sub-urban communities, they need to go beyond 3% if the energy reductions outlined in the Energy Strategy 2050 are to be met. In addition, heating systems replacement rates would need to exceed the envelope retrofit rates by at least a factor of three, reaching a 10% annual rate (as in Success scenario), if the decarbonization challenge is to be met successfully, with envelope energy-efficient retrofit as well as heating systems replacement both playing a critical role.

An interesting observation is the impact of all retrofit scenarios on the rural community archetype in comparison to the urban and sub-urban archetypes. The heating degree days projections for 2040 and 2060 for this case study community could be partly responsible for the significant reductions in energy demand across all retrofit scenarios. Similarly, in terms of building use-types, single residential buildings, that account for a large portion of the stock in the rural community archetype, allow for greater reductions in energy demand compared to multi-residential buildings. More profound, though, is the difficulty of bringing the sub-urban community archetype closer to the target of the Energy Strategy 2050. Even for the success scenario, the energy demand reduction by 2060 surpasses the required threshold marginally. Especially for the PUN scenario this is mainly due to the increased commercial use-types and population growth.

Overall, the results in Fig. 14 show that the urban development scenarios explored in this work can have a substantial impact on whether Switzerland meets the Energy Strategy 2050 targets for energy demand reduction. Table 6 below compares the Success scenario and the details outlined in the Swiss Energieperspektiven 2050+ (Prognos AG, INFRAS AG, et al., 2020), highlighting the similarities between the two in terms of retrofitting rates, space heating and space cooling.

3.3.2. Space heating and space cooling end-use demand

One of the most important aspects when implementing and evaluating retrofit strategies is the end-use energy demand reduction. In this work, the measures in terms of envelope retrofit are uniform across all retrofit scenarios. A comparison between community archetypes and urban transformation scenarios is seen in Fig. 15.

For the urban community archetype, the highest space heating energy demand reduction can be observed for the DGT urban development scenario when using the RCP 8.5 weather data, throughout all retrofit scenarios. For the rural community archetype, it is the BAU scenario with the RCP 8.5 weather data that results in the maximum space heating energy demand reduction by 2060 across all retrofit scenarios. For these two community archetypes, the different retrofit rates for envelope (3% and 1%) and systems (1–10%) applied in retrofit scenarios result in profound space heating energy demand reductions for both 2040 and 2060, ranging between 20 and 50% for 2040 and 30–65% for 2060, depending on the urban development scenario and climate change scenario.

However, this is not the case for the sub-urban community archetype. For the Success and Unintended Consequences scenario, the reduction in space heating energy demand is lower, ranging between 10 and 20% for 2040 and 20–40% for 2060. More importantly, for the Take-Back and Failure retrofit scenarios of the sub-urban community, assuming a retrofit rate of 1%, there are hardly any reductions for 2040. Instead, there are increases in the space heating energy demand of up to 20% for the PUN urban development scenario with the RCP 2.6 climate data. For the year 2060, there is only a reduction of the space heating energy demand for the RCP 8.5 scenario.

Overall, the findings in Fig. 15 show that the selection of urban development scenario as well as envelope retrofit scenario can have a significant impact on the reduction of space heating energy demand. If the Energy Strategy 2050 targets are to be met, it might be effective if future urban development in urban areas is based on a transformation that is aligned with the Digitalisation scenario presented in this work, with a 3% envelope retrofit rate implemented as a minimum. Also, in rural areas, a 3% envelope retrofit rate ought to be applied. The Business-As-Usual urban development scenario has a more profound impact on energy demand reduction due to the assumption of a shrinking population, the other two scenarios, however, display similar energy demand reduction. In sub-urban communities there needs to be a much higher envelope retrofit rate, possibly 5% and above, if the reduction is to succeed in reaching the Energy Strategy 2050 target. Here, the Polycentric Urban Network scenario exhibits the highest space heating energy demand.

Table 6
Comparison between Swiss Energieperspektiven 2050+[a] and the Success retrofit scenario.

Specific details	Energieperspektiven 2050+	Success Retrofit Scenario
Energy efficiency envelope retrofits	2040: 27.6%, 2060: 44%	2040: 45.6%, 2060: 66.6%
Energy efficiency systems replacement	2030: 45%, 2050: 80%	2040: 87.8%, 2050: 97.7%
Energy efficiency envelope retrofit rate	1.6%	3%
Energy efficiency systems replacement rate	NA	10%
Specific Heating demand (post-retrofit)	35–50 kWh/m^2	25–50 kWh/m^2
Specific Cooling demand (post-retrofit)	NA	0–6 kWh/m^2 (residential)
Energy Efficiency standards	SIA 2024 target values or even better (SIA, 2015)	SIA 2024 target values or even better (SIA, 2015)
Final Energy Use	Oil <1% after 2050 Gas 5–30% after 2050	Oil <1% by 2060 Gas < 5% by 2060
Space Cooling Demand (by 2060)	“By 2060 around two thirds of the areas will be cooled”	66% of residential 100% of commercial

[a] (Prognos AG, INFRAS AG, et al., 2020).

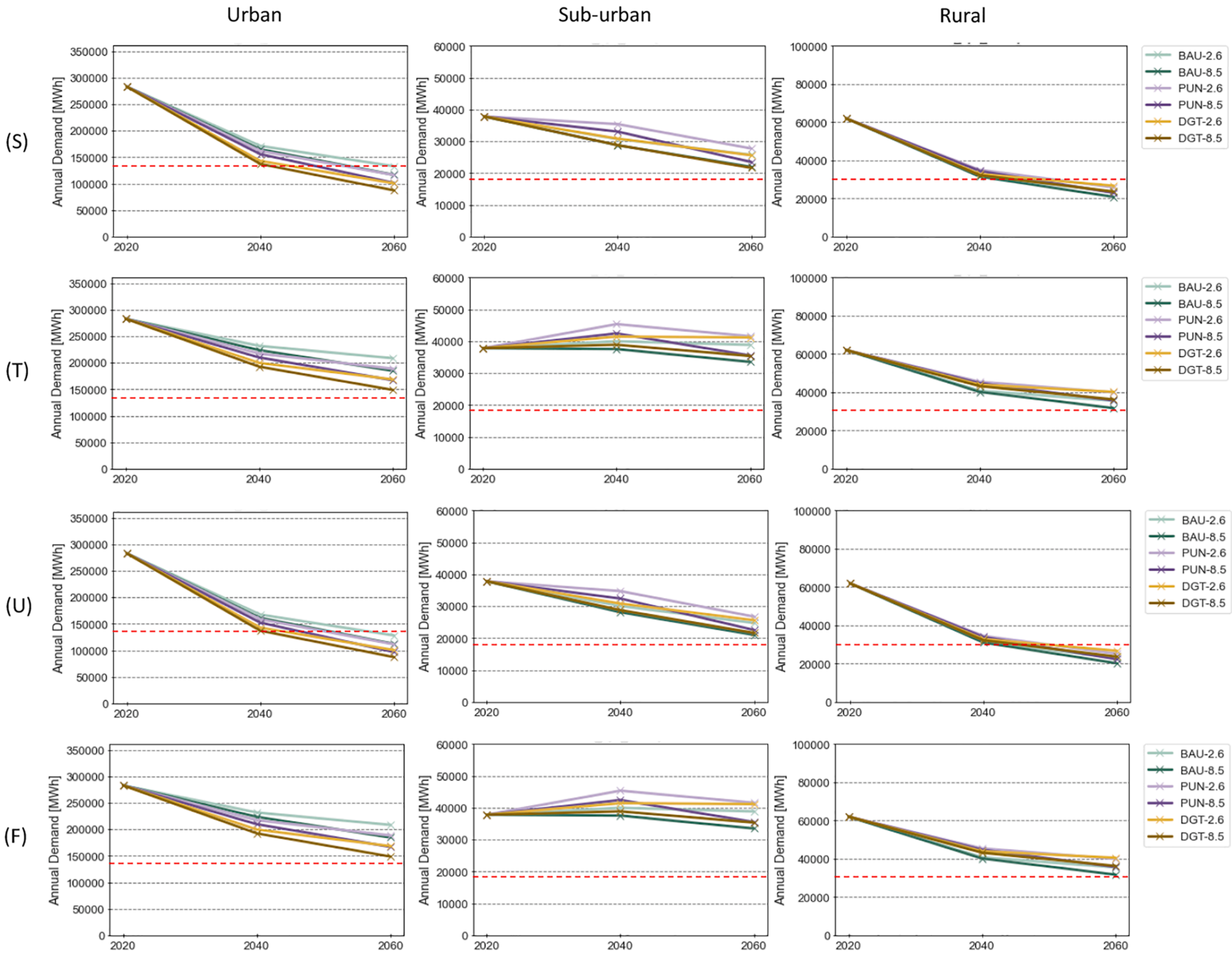

Fig. 15. Annual space heating demand (MWh) for 2020, 2040 and 2060, for the three community archetypes (Urban, Sub-urban, Rural) for all four retrofit scenarios (S: Success, T: Take-Back, U: Unintended Consequences, F: Failure) and all three urban development scenarios (BAU: Business As Usual, PUN: Polycentric Urban Network, DGT: Digitalization) and two climate scenarios (RCP 2.6, RCP 8.5). The red dotted line marks the 45% reduction in energy outlined in the Energy Strategy 2050.

Fig. 16 compares community archetypes and urban transformation scenarios in terms of space cooling energy demand. It has to be noted that since there are currently no publicly available data with regards to space cooling demand in Switzerland, the values for 2020 were based on the ranges (6–20 kWh/m^2) given for the service sector by existing research (Persson & Werner, 2015; Silva et al., 2022; Werner, 2016) and were only applied to non-residential buildings. For the urban and sub-urban community archetypes space cooling is assumed to be 13 kWh/m^2 for non-residential buildings, while for the rural community archetype 6 kWh/m^2 for all non-residential buildings.

One of the first things to note in Fig. 16 is the different scale on the Y-axis between urban, sub-urban and rural community archetypes, which, for total space cooling energy demand, is needed because of the different size of the archetypes. For the urban community archetype, the impact of warmer climate scenarios can be observed across urban development scenarios, with the darker colours in the graphs depicting the RCP 8.5 climate. For the sub-urban community archetype, it is the Polycentric Urban Network scenario that requires higher energy demand for space cooling, due to the higher proportion of retail buildings. In the rural community archetype, the Digitalisation scenario results in a distinctive increase in space cooling energy demand between 2040 and 2060, due to the higher fraction of commercial use-type buildings. A further observation is a difference in space cooling demand between different retrofit scenarios, especially between the Success and Take-Back scenarios, where although much fewer (about 50% less) residential buildings have space cooling systems installed in the Take-Back scenario compared to the Success scenario, the decrease of 2 °C in the space cooling setpoint (27 °C for Success and 25 °C for Take-Back) results in similar levels of space cooling demand for these two retrofit scenarios, indicating the importance of the take-back factor in terms of comfort when occupants can afford to maintain more strict comfort envelopes due to savings from energy efficiency envelope retrofits.

Overall, from Fig. 15 and Fig. 16, it can be observed that the space cooling energy demand takes up different proportions in comparison to the heating energy demand when taking different community archetypes into consideration. By 2060, for urban communities, it can be observed that the space cooling demand is comparable to the heating energy demand in terms of magnitude, especially for the Success and Take-Back scenarios, where there is mechanical space cooling in commercial as well as retrofitted residential buildings, with space cooling being close to 70% of the heating energy demand (e.g., for DGT). In sub-urban communities, the space cooling energy demand can potentially rise to up to 60% of the heating energy demand for certain urban development scenarios (e.g., PUN). In comparison, for rural communities, the space cooling demand remains at 1–5%, marking it less relevant as compared to heating energy demand.

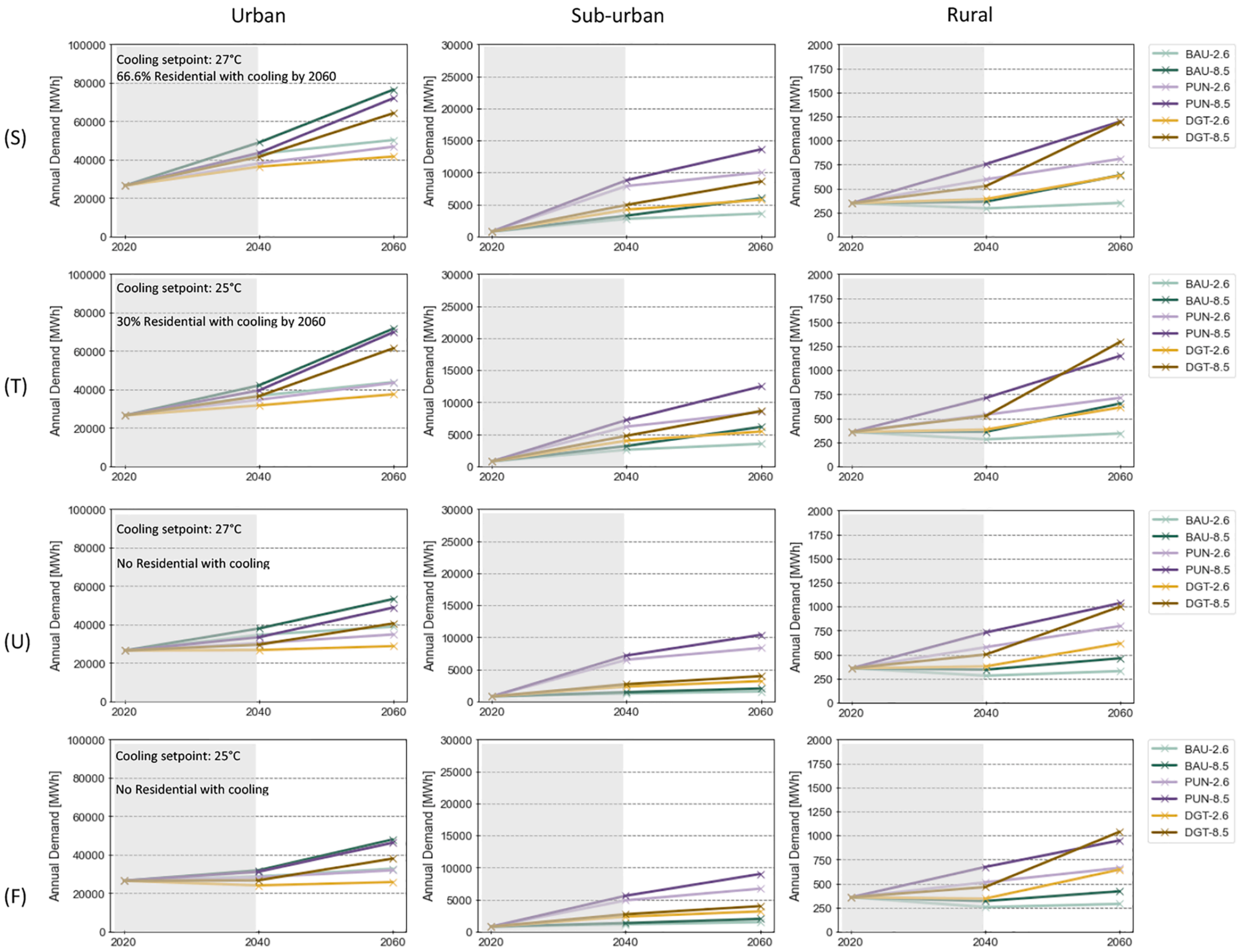

Fig. 16. Annual space cooling demand for 2020, 2040 and 2060, for the three community archetypes (Urban, Sub-urban, Rural) for all four retrofit scenarios (S: Success, T: Take-Back, U: Unintended Consequences, F: Failure) and all three urban development scenarios (BAU: Business As Usual, PUN: Polycentric Urban Network, DGT: Digitalization) and two climate scenarios (RCP 2.6, RCP 8.5).

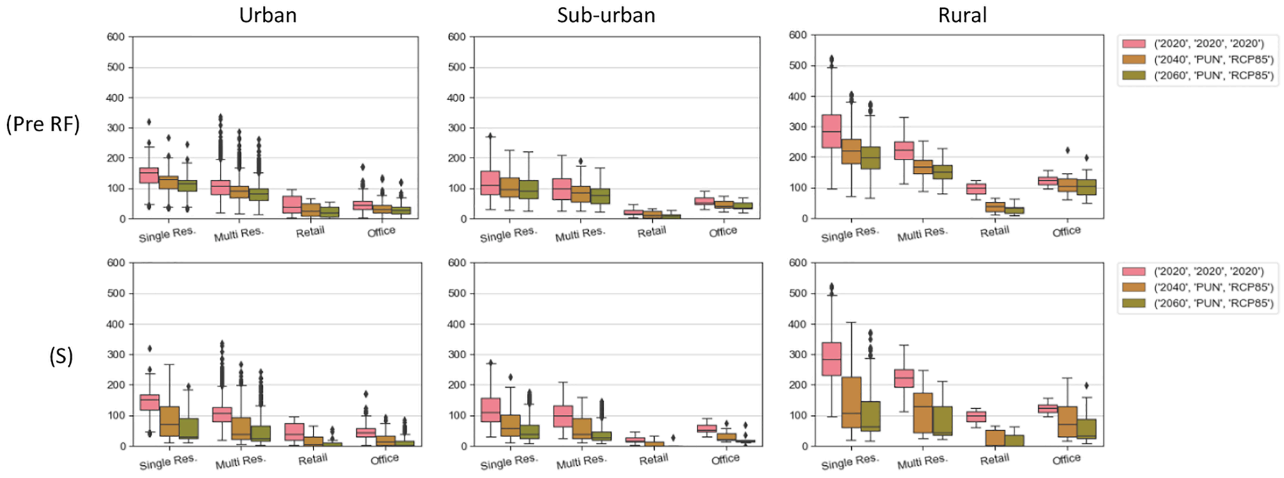

Fig. 17. Specific demand for space heating (kWh/m^2) for the Residential, Office and Retail use types, for the three community archetypes (Urban, Sub-urban, Rural) for pre retrofit (Pre RF), the Success retrofit scenario, and the Polycentric Urban Network urban development, for climate scenario RCP 8.5.

3.3.3. Specific space heating and space cooling energy demand

When evaluating the retrofit strategies, it is worth considering the reduction of the specific demand to quantify the extent of the reduction across building use-types in the building stock. Fig. 17 presents the specific demand for space heating before the retrofit scenarios are applied, and after. For uniformity across community archetypes, the Polycentric Urban Network (PUN) urban development scenario is selected to capture the breadth of the results. One of the first

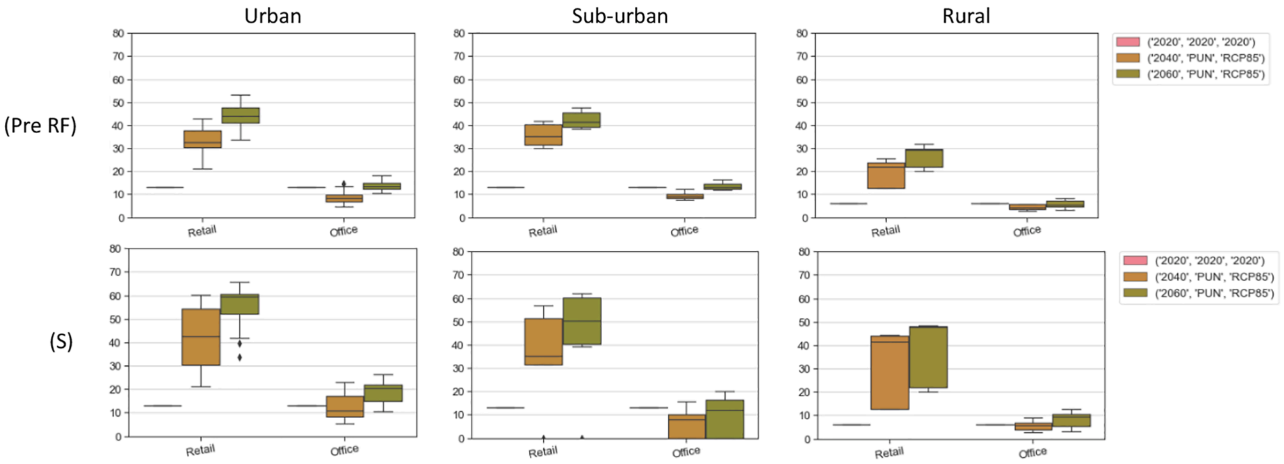

Fig. 18. Specific demand for space cooling (kWh/m^2) for the Office and Retail use-types, for the three community archetypes (Urban, Sub-urban, Rural) for pre retrofit (Pre RF), the Success retrofit scenario and the Polycentric Urban Network urban development, for climate scenario RCP 8.5.

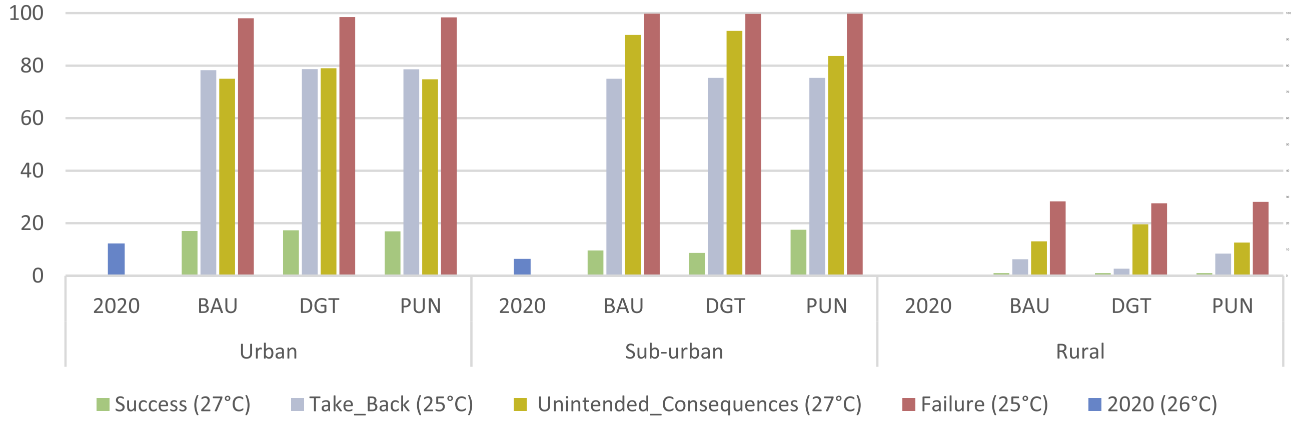

Fig. 19. Percentage of buildings (all use-types) with more than 10% of summertime hours where internal temperature is above the space cooling setpoint in the four building retrofit scenarios (S: Success, T: Take-Back, U: Unintended Consequences, F: Failure) and for 2020, for the three community archetypes (Urban, Sub-urban, Rural) and all three urban development scenarios (BAU: Business As Usual, PUN: Polycentric Urban Network, DGT: Digitalization) and one climate projection scenario (RCP 8.5).

observations with regards to specific space heating demand is the significant differences between the rural community archetype and the other two, where the values for the rural community archetype are twice as high across building use-types. This can be attributed to the higher portion of single residential buildings in the rural community but also to the climatic differences due to the higher altitude of the rural case study community location. In the Pre-retrofit results (top row), the reduction between years is mainly due to the climate change scenario (RCP 8.5), and it can be observed in the pre-retrofit cases across all community archetypes, yet more profoundly for the residential building use-types (single and multi-residential) in the rural community archetype. Furthermore, the specific space heating demand is significantly reduced due to the extent of the retrofit (higher retrofit rates for both envelope and systems) in the case of success retrofit scenario. This brings the final value closer to the Energieperspektiven 2050+ recommendations for the year 2050 (50 kWh/m^2) for residential buildings. For offices and retail buildings, the demand for space heating is not as high and especially after the Success retrofit scenario, it drops to very low levels by 2060, for the urban and sub-urban archetypes.

Fig. 18 presents the specific demand for space cooling before the retrofit scenarios are applied and after for non-residential buildings. The results displayed are focused on the Polycentric Urban Network urban development and RCP 8.5 climate scenario, as this is the one that would most likely present a substantial increase in space cooling demand for the majority of the cases. Overall, it can be observed that the use-types of retail and office require substantial space cooling demand in all cases, with the space cooling demand for retail often being at least twice as large as that for offices.

3.3.4. Thermal comfort

To assess the extent of thermal discomfort at the community level, the results focused on the percentage of buildings with more than 10% of summertime hours exhibiting an internal temperature above the space cooling setpoint temperature, as presented in Fig. 19 below.

Fig. 19 shows the extent of thermal discomfort in buildings in the three community archetypes, between the different urban development and retrofit scenarios, for the year 2060 and the climate projections with the least amount of GHG emissions mitigation (RCP 8.5). One of the first observations is the small deviation between the results for 2020 and those for the Success retrofit scenario across all community archetypes and all urban development scenarios. At the same time, the remaining three retrofit scenarios (Take Back, Unintended Consequences and Failure) all present very large percentages of buildings with thermal discomfort, especially in the urban and sub-urban communities. In the rural community archetype, the extent of thermal discomfort is not as pronounced, neither in 2020 (1% of buildings with more than 10% of summertime hours where internal temperature is above 26%) nor in the 2060 urban development scenarios.

The significance of the results increases when considering the demand for space cooling in 2060, presented in Fig. 16. In the case of Success and Take Back retrofit scenarios, the space cooling demand by 2060 in the urban community are comparable (Fig. 16), however the extent of thermal discomfort is significantly different (Fig. 19), stressing the benefits of the Success scenario. However, it is important to stress the assumptions taken. One of the main hypotheses is that space cooling systems are only present in residential buildings after the envelope has been retrofitted. This is an important point that current and future policies should reflect upon, especially in urban communities where demand for space cooling could rise significantly. Here the suggestion is that there should be a trade-off between the increase in space cooling demand and the reduction in space heating demand (i.e., one should have to apply extensive building retrofit and therefore reduce the energy demand to install space cooling systems and increase the energy demand). This way, future energy demands could be balanced out.

Moreover, as outlined above, the increased demand for space cooling can have a substantial impact on the electricity grid. Here, the Success scenario, with more buildings to have space cooling but higher setpoints can result in a lower demand for increased capacity of the electricity grid as compared to the Take-Back scenario, while offering to reduce thermal discomfort across the community archetypes. It is important to note that the space cooling setpoint temperatures applied in this work are rather conservative. Since the occupants are often free to choose this threshold, it could mean that in practice even 25 °C might be higher than what is applied in real world indoor environments. Therefore, applying innovative cooling systems and methods (e.g., increased air movement, radiant cooling, increased efficiency, occupant warnings) are necessary to ensure lower setpoints do not jeopardise the success of future energy demand reduction strategies.

4. Conclusion

This work presented the analysis of future energy demand in representative Swiss community archetypes, taking into consideration future scenarios with regards to climate change, building envelope and systems retrofit measures and urban development. Overall, the results demonstrate the importance of increasing the spatial resolution from the national scale to the community scale, when investigating the interactions between such scenarios and energy demand. The results highlight the significance of urban development on energy demand, as well as how the different scenarios uniquely impact the energy demand of different community archetypes.

- For the urban community archetype, the increase of space cooling in the future is most relevant, which, by 2060, could be comparable to that of space heating. This suggests that although building retrofit can lower the demand for space heating by a factor of two or more, the increased levels of airtightness and insulation, together with the effects of climate change, can in turn increase energy demand close to 2020 levels, due to the increased demand for space cooling. Therefore, carefully designed regulations should be in place to reduce the uptake of air conditioning units and ensure these are only allowed under specific conditions, for example if all possible passive cooling measures have first been applied.
- For the sub-urban community archetype, the results showed the largest variations in energy demand, with the scenarios often resulting in the increase instead of the reduction of the total final energy demand, despite retrofit measures. This illustrates the significant uncertainty inherent when planning the future development of such areas, as this increase is primarily driven by the expected growth in floor space of the sub-urban areas. Hence urban development should include an optimized energy planning from the early stages of design, giving priority to upgrades of the electricity grid and networks, to harness local renewable energy potentials to mitigate the adverse effects of increasingly well-connected hubs with attractive living conditions, on the energy demand.
- The rural community archetype was found to be more tolerant towards changing boundary conditions, also because these areas are expected to have the smallest amount of change in total built area. The results showed that regardless of the urban development or retrofit scenarios, space heating demand will continue to dominate end-use energy demand in rural communities. Therefore, focus should be given to reduce heating energy consumption of the existing building stock as well as the transition from fossil-based to more efficient, electricity-based heat generation. In this work the rural case study is situated in a higher altitude, therefore this result should be carefully extrapolated to the rest of rural communities in Switzerland.
- The effects of climate change impact the future demand for space cooling primarily for urban and sub-urban communities, with the non-residential use-types acting as the main contributors. Urban development scenarios with increased GFA of such use-types (PUN) are affected the most. Subsequent increases of energy demand in annual but also in hourly peaks can result in potentially critical implications on energy systems. The impact of urban heat islands in denser sub-urban or urban settlements, which has not been quantified in this study, will additionally contribute to the increase of cooling energy demand, and decrease of comfort.
- The results for building envelope retrofit and heating and cooling systems replacement showed that the existing trends in the Swiss building stock, partly showcased by the Take-Back scenario, are not driving the building stock towards achieving the formulated goals in time. The potential rebound effects as well as the slow retrofit and replacement of both the building fabric and systems respectively are an important challenge that needs to be addressed in national energy efficiency policies rather urgently. To achieve the 45% reduction target as set in the Energy Strategy 2050 of Switzerland, only the Success scenario with significantly higher retrofit rates than today was successful. Applied over 40 years, an estimated 3% retrofit rate for building envelopes and a 10% rate of replacement of existing, fossil fuel-based building systems with efficient technologies (i.e. heat pumps), proved to be sufficient.

As in any other large scale foresight study assumptions are taken, which impose certain limitations. First, it is important to note that the aim of 45% energy demand reduction taken as a benchmark for all communities is, in its original formulation, a single national overarching target for Switzerland. It is to be expected that, dependant on the local context, this will be easier to achieve and can even be surpassed (e.g. in urban areas), whereas in other contexts it could prove difficult (e.g. in sub-urban). Furthermore, although the verification of the model was performed, this was not done using measured data from the same communities as the ones modelled, however, the modelling tool used has been utilised extensively in published research, maintaining the confidence in the results. Additionally, for the retrofit scenarios, embodied carbon emissions are not considered. Their inclusion will most likely impact the choice of most optimal retrofit measures, potentially leading to further challenges in achieving the 45% energy demand reduction target of the Swiss Energy Strategy 2050. Finally, this work did not include any data nor analysis on socioeconomic parameters as well as impact the complexity of the behaviour of building occupants, that could influence the urban development trajectories. Further technological advances, the integration of electric vehicles, the impact of renewable energy and the uptake of local energy storage are all developments which can significantly affect the implementation of future policies and the complexity of their interaction will have to be addressed in future methodologies. Future research will look at the application of the presented methodology to an increased number of communities and the expansion of the results across Switzerland.

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.

Data availability

Data will be made available on upon request.

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