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Urban densification and its impact on energy use in Swiss cities

Städtische Verdichtung und ihre Auswirkung auf den Energieverbrauch von Schweizer Städten

La densification urbaine et son impact sur l'énergie en Suisse

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Executive summary

Translation provided in German and French below

Project scope and aim: This two-year project assessed the potential of urban densification and explored the impact on embodied and operational energy of different densification strategies for neighbourhoods across Switzerland. Increasing the effort to explore densification options that lead to more sustainable neighbourhoods is particularly important given the limited availability of land and increasing Swiss population. The focus of the analysis was on residential urban post-war neighbourhoods (1945-1980). The most important rationale for this specific scope of analysis is to quantify the potential of densifying the already built-up residential urban area where densification is thought to provide simultaneous benefits for improving the energy performance of neighbourhoods. A particular focus is laid on energy, including analysing embodied emissions.

Methods: A geospatial data-driven framework was developed for spatial detection, quantification and evaluation of densification potentials. Different neighbourhood archetypes were designed for distinct densification strategies for each archetype. Based on supervised classification methods, all located residential neighbourhoods were classified. The geographic location of each neighbourhood was evaluated in terms of connectivity and accessibility whereby densification was assumed to save particularly on transportation energy in well-connected and accessible locations. For each archetype existing or newly created architectural urban designs were used as inputs for a building energy simulation tool to assess energy implications for different densification strategies. The effect on operational and embodied emissions of using different construction materials was studied for different construction material scenarios with an enhanced energy simulation software (CESAR-P). The SIA 2032 code was used to calculate the embodied energy and emissions incurred by the refurbishments and the construction of new buildings that are required in each of the densification strategies.

Conclusions and recommendations: Depending on the pursued densification strategy, an additional 0.35 – 1.4 million people (4 – 15% of the current Swiss population) could be accommodated in Switzerland within post-war urban neighbourhoods. The potential within Swiss communities however varies considerably and is not evenly distributed geographically. A densification potential of around 0.7 million people is estimated for the business as usual densification strategy. For a concentrated densification strategy following maximum density based on contemporary urban development criteria, the estimate is about 1.4 million people. Across all scenarios, about half of this potential is located in favourable locations which should be considered first to explore sustainable densification. Whereas the densification potential of post-war neighbourhoods in highly central locations is limited, the potential is considerable in locations with medium centrality and accessibility. We argue that it would be an opportunity lost to pursue a business-as-usual densification strategy instead of realising higher densities in these neighbourhoods. We recommend a stronger focus of the densification discourse on already existing buildings and neighbourhoods instead of new development areas. The different densification strategies resulted in an increase in the combined embodied and operational emissions in all of the reference urban designs. Lower emissions are possible where densification strategies rely on retrofit the existing building stock rather than rebuilding. While energy efficiency and low emissions of new buildings should be considered, also a sustainable strategy for retrofitting already existing buildings should be taken into account in the design process. In this study, all additional occupant capacity is accommodated in new buildings and existing buildings are retrofitted to current target performance. Scaling the results from the reference designs to the rest of Switzerland estimates that the use of timber in the construction would save between 6.4% and 6.8% of emissions for the densification strategies

considered in this study. The development of an early stage design tool for architects and urban planners could provide direct feedback on the embodied and operational energy demand. The consideration of energy and emissions early in the urban design process would foster sustainability. Additionally, the current heterogeneity and ownership structure are challenging for densification that optimises for energy and emissions perspective at the neighbourhood scale. We find that the floor area used per capita has a dominating impact on energy use per occupant and densification potentials and should gain high policy attention when improving the sustainability of densification or reducing energy demands.

Zusammenfassung

Ziel und Umfang des Forschungsprojekts: In einem Zweijahresprojekt wurde das Potential der städtischen Verdichtung und deren energetische Auswirkungen für die Schweiz untersucht. Mithilfe verschiedener Verdichtungsstrategien wurde das Verdichtungspotential räumlich differenziert abgeschätzt. Dabei wurde ein besonderer Analysefokus auf die graue Energie gelegt. Angesichts der begrenzten Verfügbarkeit von Bebauungsflächen und der steigenden Bevölkerung ist in der Schweiz das Aufzeigen verschiedener Verdichtungsoptionen für die Entwicklung nachhaltiger Quartiere besonders wichtig. Der Schwerpunkt der Analyse lag auf den städtischen Wohngebieten der Nachkriegszeit (1945-1980). Dieser spezifische Fokus auf Nachkriegsquartiere bei der Quantifizierung des Verdichtungspotentials rührt daher, dass eine solche Verdichtung gleichzeitig die Möglichkeit bietet, die Energieeffizienz von Quartieren zu verbessern.

Methoden: für die räumliche Erfassung, Quantifizierung und Bewertung von Verdichtungspotenzialen wurde ein räumlicher und datengetriebener Ansatz entwickelt. Verschiedene Quartiersarchetypen wurden für unterschiedliche Verdichtungsstrategien entworfen und mithilfe von (überwachten) Klassifizierungsmethoden alle bewohnten Quartiere der Nachkriegszeit der urbanen Schweiz klassifiziert. Die geografische Lage jedes Quartiers wurde im Hinblick auf ihre Anbindungsqualität und Erreichbarkeit bewertet, wobei davon ausgegangen wurde, dass eine Verdichtung an gut angebundenen und erreichbaren Standorten zu potentiellen Einsparungen im Transportsektor führt. Für die entwickelten Archetypen wurden bestehende oder neu entwickelte architektonische Entwürfe als Input für eine Energiesimulationssoftware (CESAR-P) verwendet, um die energetischen Auswirkungen verschiedener Verdichtungsstrategien zu bewerten. Die Auswirkungen des Einsatzes verschiedener Baumaterialien auf graue Emissionen und Emissionen für den Betrieb wurden für verschiedene Baumaterialszenarien untersucht. Für die verschiedenen Verdichtungsstrategien wurden basierend auf dem Merkblatt SIA 2032 die graue Energie und die Emissionen für neue und sanierte Gebäude berechnet.

Schlussfolgerungen und Empfehlungen: Je nach Verdichtungsstrategie böten städtische Nachkriegsquartiere in der Schweiz Raum für zusätzliche 0.35 – 1.4 Millionen Einwohner und Einwohnerinnen (4 – 15% der heutigen Bevölkerung). Das Potenzial variiert jedoch stark zwischen den Gemeinden und ist geografisch ungleichmässig verteilt. Unter Annahme einer "Business-as-usual"-Verdichtungsstrategie wurde ein Verdichtungspotenzial von circa 0.7 Millionen Menschen abgeschätzt. Bei einer "konzentrierten Verdichtungsstrategie", bei der eine maximale Dichte nach heutigen städtebaulichen Kriterien angenommen wird, wurde das Verdichtungspotential auf circa 1.4 Millionen Einwohner und Einwohnerinnen geschätzt.

In allen Szenarien befindet sich etwa die Hälfte des Verdichtungspotentials in geografisch günstigen Lagen, die für eine nachhaltige Verdichtung prioritär berücksichtigt werden sollten. Während das Verdichtungspotenzial in Nachkriegsquartieren an zentralen Lagen begrenzt ist, ist das Potenzial in Lagen mit mittlerer Zentralität und Erreichbarkeit erheblich. Die Verfolgung einer "Business-as-usual"-Strategie in zentralen Lagen anstelle der Realisierung von höheren Dichten wäre daher eine verpasste Chance für eine nachhaltige Verdichtung. Wir empfehlen eine stärkere Fokussierung des Verdichtungsdiskurses auf bereits bestehende Gebäude und Quartiere anstelle von neuen Entwicklungsgebieten.

Die verschiedenen Verdichtungsstrategien der städtebaulichen Testentwürfe führen alle zu einem Anstieg der kombinierten Emissionen für den Bau und Betrieb der Nachkriegsquartiere. Tiefere Emissionen sind möglich, wenn der bereits vorhandene Gebäudebestand nachgerüstet anstatt durch Neubauten ersetzt wird. Das Fokussieren auf die Energieeffizienz und tiefe Emissionen neuer Gebäude

ist wichtig, eine nachhaltige Nachrüstung und der Umbau bestehender Gebäude sollte aber ebenfalls bereits frühzeitig mit in den Entwurfsprozess einbezogen werden.

In dieser Studie wurden davon ausgegangen, dass alle zusätzliche angenommenen Einwohner und Einwohnerinnen in neuen Gebäuden untergebracht und bestehende Gebäude entsprechend heute aktueller Zielwerte saniert werden. Skaliert man die Ergebnisse der Referenzentwürfe auf die übrige Schweiz, so wird geschätzt, dass der Einsatz von Holzbauten ein Emissions-Einsparungspotential von 6.4 – 6.8 % für die in dieser Studie betrachteten Verdichtungsstrategien ergibt. Wir plädieren für die Entwicklung eines Entwurfswerkzeugs das frühzeitig direktes Feedback zum grauen und betrieblichen Energiebedarf liefert bei architektonischen Projekten. Eine solche Berücksichtigung von Energie und Emissionen in einem frühen Stadium des Stadtplanungsprozesses würde die Nachhaltigkeit fördern.

Die heutige Heterogenität und Eigentumsstruktur ist eine Herausforderung für die Energieoptimierung und nachhaltige Verdichtung auf Quartiersebene. Unsere Studie hat aufgezeigt, dass die genutzte Wohnfläche pro Kopf einen dominierenden Einfluss auf den Energieverbrauch sowie auf das Verdichtungspotenzial hat, und deshalb im Hinblick auf eine nachhaltige Verdichtung in der Schweiz hohe politische Aufmerksamkeit erhalten sollte.

Résumé

Etendue et but du projet: Ce projet, se basant sur deux ans d'études, évalue le potentiel de densification urbaine et explore l'impact en terme d'énergie grise et d'utilisation pour différentes stratégies de densifications des quartiers en Suisse. Il est particulièrement important de multiplier les efforts d'exploration des options de densification menant à des quartiers durables en Suisse compte tenu de la disponibilité limitée des terres et d'une population croissante. L'analyse se concentre sur les quartiers urbains résidentiels de l'après-guerre (1945-1980). La raison principale de ce choix spécifique étant de quantifier le potentiel de zones déjà urbanisées, où des effets de synergie attribués à cette densification sont à supposer. Une attention particulière est accordée à l'énergie, y compris l'analyse des émissions y étant liées.

Méthodes: Un environnement géo-spatial basé sur des données est développé pour la détection spatiale, la quantification et l'évaluation des potentiels de densification. Différents quartiers-type sont conçus pour des stratégies de densification distinctes. Tous les quartiers résidentiels détectés sont alors classés à l'aide de méthodes supervisées. La situation géographique de chaque quartier est évaluée en termes de connectivité et d'accessibilité, la densification permettant supposément d'économiser en particulier de l'énergie liée au transport dans des lieux bien connectés et facilement accessibles. Pour chaque quartier-type, des conceptions architecturales urbaines existantes ou récemment proposées sont utilisées comme données-base d'un outil de simulation énergétique des bâtiments, ceci afin d'évaluer les implications énergétiques des différentes stratégies de densification. L'effet sur les émissions d'utilisation et grises causées par l'emploi de différents matériaux de construction est étudié pour différents scénarios de construction avec un logiciel de simulation énergétique amélioré (CESAR-P). Le code SIA 2032 a été utilisé pour calculer l'énergie grise et les émissions induites tant par les rénovations que les constructions neuves de bâtiments nécessaires pour chacune des stratégies de densification.

Conclusions et recommandations: En fonction des stratégies de densification choisies, 0,35 à 1,4 million de personnes supplémentaires (4 à 15% de la population suisse actuelle) pourraient être logées en Suisse dans les quartiers urbains d'après-guerre. Ce potentiel varie toutefois considérablement de commune en commune et ne se répartit pas de manière homogène sur le plan géographique. Un potentiel de densification d'environ 0,7 million de personnes est estimé pour la stratégie de densification "business as usual". Pour une stratégie de densification concentrée sur les critères actuels de développement urbain, l'estimation est d'environ 1,4 million de personnes. Pour tout scénario, environ la moitié de ce potentiel se situe dans des endroits favorables à une densification durable qui devraient être considérés en premier lieu. Si le potentiel de densification des quartiers d'après-guerre situés dans les lieux très centraux est limité, ce potentiel est considérable dans les lieux moyennement centraux et accessibles. Nous soutenons que ce serait une occasion manquée que de poursuivre une stratégie de densification "business as usual" au lieu de densifier les quartiers moyennement centraux et accessibles. Nous recommandons que le discours sur la densification soit davantage axé sur les bâtiments et les quartiers existants plutôt que sur de nouvelles zones de développement. Les différentes stratégies de densification entrainent une augmentation des émissions grises et d'utilisation dans tous les modèles urbains de référence. Des réductions d'émissions sont néanmoins possibles lorsque ces stratégies reposent sur la modernisation du parc immobilier existant plutôt que sur son remplacement. Si efficacité énergétique et faibles émissions de constructions neuves sont à considérer, il en va de même pour une stratégie de rénovation du parc immobilier existant. Dans la présente étude, tous les occupants supplémentaires sont logés dans des constructions neuves et les bâtiments existants sont modernisés aux standards-cible actuels. En étendant les résultats des conceptions architecturales de référence au reste de la Suisse, on estime que l'utilisation du bois dans la construction permettrait des économies de 6,4 % à 6,8 % selon les stratégies de cette étude. Le développement d'un outil de conception pour

architectes et urbanistes fournirait un retour direct et anticipé sur les demandes énergétiques grise et d'utilisation. La prise en compte de l'énergie et des émissions dès le début du processus de conception urbaine favoriserait la durabilité. En outre, l'hétérogénéité du parc immobilier et la structure foncière actuelle constituent un défi pour une densification qui optimise consommation énergétique et émissions à l'échelle du quartier. Nous constatons que la surface d'habitation utilisée par personne a un impact dominant sur sa consommation énergétique et sur les potentiels de densification et devrait donc faire l'objet d'une grande attention politique pour améliorer la durabilité de la densification ou réduire la demande énergétique.

Content

Abbreviations

A	Archetype
ARE	Bundesamt für Raumentwicklung
BFS	Bundesamt für Statistik
CCCC	All-concrete Scenario
CESAR-P	Combined Energy Simulation and Retrofit in Python
FAR	Floor Area Ratio
GFA	Gross Floor Area
KBOB	Koordinationskonferenz der Bau- und Liegenschaftsorgane der öffentlichen Bauherren
OECD	Organisation for Economic Co-operation and Development
RF	Random Forest
RQ	Research Question
S	Densification Strategy
SIA	Swiss Society of Engineers and Architects
SM	Supplementary Material
SVM	Support Vector Machine
TTCT	Timber Intensive Scenario
UBEM	Urban Building Energy Modelling
USU	Urban Structural Units

1 Objectives and scope of the project[i]

1.1 Introduction

Urban densification has been put forward as an urbanization strategy for the efficient use of limited space for living, to intensify the built form and to realise compact cities as opposed to sprawling cities[1,2]. Building sustainable cities necessitates sustainable urbanization to reduce per capita environmental impacts of living in cities. However, as a result of urban sprawl, the percentage of very-low-density areas is increasing in most OECD countries and is leading to environmental problems such as increased air pollution and greenhouse gas emissions[3]. The predominant pattern is that urban areas are expanding faster than their population and green areas are vanishing[4]. In most European countries, rather than densification, land take is by far still the dominant land management strategy[5]. As a first response to the call for increased densification, undeveloped existing building zones in urban areas have been the focus of analysis. In many places, this is accompanied by urban transformation efforts focused on the conversion of industrial wastelands or brownfield areas to residential neighbourhoods by the replacement with new buildings[5]. However, the availability of undeveloped building zones or suitable former industrial sites is limited and in many cases becoming scarce. Transforming already built-up residential neighbourhoods by recycling land is critical when creating space for an increasing population given limited land resources.

The densification of the urban built environment has direct implications on the used energy for constructing and operating buildings and neighbourhoods. Whereas densification enables to absorb an increasing population, the effect on energy use is not well understood yet. Energy impacts of densifications are the focus of intense and ongoing debates. We contribute to this debate by providing a comparison of energy demand (operational and embodied) for different densification strategies and upscale it to the national scale based on an archetypical approach.

1.2 Project scope

The scope of current densifications and energy studies is very different. Studies differ with respect to the considered geographic scales, their considered densification or energy focus or the detail of analysis. The scope of this analysis and the underlying motivation for choosing a specific focus is summarised in the following enumeration:

i.) The geographical focus is limited to urban areas. For Switzerland, different spatial definitions exist to classify urban spaces. We use the existing definition "Raum mit städtischem Charakter"[6] to spatially limit our analysis as we start from the assumption that densification is most sustainable in urban areas and this is also where currently highest needs for additional housing can be found in Switzerland.

ii.) The unit of analysis is entire residential neighbourhoods, as opposed to estimating densification potentials of individual buildings. Such a focus on neighbourhoods potentially enables integrated planning whilst realising densification potentials opening up possibilities to reap long-term sustainability impacts.

iii.) We exclusively consider neighbourhoods from the post-war period (1945–1980). Post-war neighbourhoods are particularly interesting due to their overall poor energy performance which provides a window of opportunity for energy sensitive densification and building

[i] Large parts of this project report were also published in a very similar form in Eggimann et al. (2021).

retrofit, their large densification potentials due to their modernistic typological arrangement and because they are facing their second renovation cycle[7–9]. Domschky et al[10] define the post-war construction period as approximately ranging from 1945–1970 with a definitive shift towards different home and building types happening sometime in the middle of the 1970s. In our analysis, we consider buildings with an age of construction from 1945–1980, since the year 1980 is the classification limit of our available building data set.

iv.) Newly assigned zones for future development with currently no buildings are ignored and we thereby focus on the densification of the existing building stock.

v.) Neighbourhoods that consist predominantly of single-family homes are ignored as they are not primarily suitable for densification. The key reason is that typically in such a context densification projects are challenging due to the circumstance of encountering multiple landowners aggravating the adaptation of the existing building stock in a coordinated way[11].

vi.) Additional zones inside the settlement area such as graveyards, allotments or public parks are not taken into consideration. Neighbourhoods serving non-residential purposes such as industrial buildings, churches or schools are also excluded from the analysis.

vii.) With help of geospatial information on specially protected buildings or zones, we explore the influence of potential preservation orders, which potentially restrict densification.

viii.) The operational energy simulation is carried out on reference urban designs that represent each neighbourhood archetype. These are based on real projects or were developed by us. Then they were simplified into 2D polygons that were extruded using height data to determine the building volume for energy simulation.

ix.) Additionally, this study considers the impact of material choice (timber vs concrete) on the embodied and energy performance of the densification strategies of each reference design. The embodied emissions are based on the carbon and grey energy intensities for the construction of roofs, walls in the SIA 2032 code.

x.) The analysis of energy assumes that all existing buildings in each of the supplied reference designs are retrofitted to the target standard of the SIA 380 code. All new buildings are constructed to meet the current new-build regulations.

1.3 Objectives and research questions

The overarching aim of this project is to assess potentials for sustainable densification and explore energy implications for different densification strategies to support decision-makers in regional and urban development processes in Switzerland. Our overall hypothesis in this research project is that the densification of existing current residential neighbourhoods does not only bear considerable potential but is also particularly sustainable and allows the implementation of more sustainable energy infrastructure systems. We test this hypothesis on a national scale for Switzerland and include constraining factors that limit the practicability of densification projects. We assess densification potentials of residential post-war urban neighbourhoods and assess implications on energy.

The overarching research questions (RQ) of this project can be summarized as follows (see Section 5 for respective answers):

RQ1: What is the spatial distribution of post-war neighbourhoods in Switzerland?

RQ2: Can urban post-war neighbourhoods be classified into different archetypes and be identified across Switzerland?

RQ3: What is the urban densification potential in post-war neighbourhoods and how does the potential change depending on the chosen densification strategy?

RQ4: How is the densification potential spatially distributed?

RQ5: Does densification have a positive impact on the overall energy consumption and CO_2 emissions of neighbourhoods (change in heating, cooling and electricity demand)?

RQ6: For which neighbourhood archetypes and characteristics does additional densification have a positive or negative effect on their total energy demand, the share of renewable energy sources and CO_2 emissions?

RQ7: How does future redevelopment affect the total energy demand of neighbourhoods?

RQ8: Which influencing factors have the greatest effect on the total energy consumption of sites and neighbourhoods?

RQ9: What is the impact on the embodied energy of the densification strategies when all original buildings are kept?

2 Project background

This chapter provides the background of this research project. After discussing densification and sustainability more broadly in Section 2.1, a more specific introduction is provided for the Swiss context in Section 2.2. Section 2.3 provides a short discussion surrounding energy and densification.

2.1 Densification and sustainability

Sustainable densification is increasingly put forward as an approach to tackle the increasing population and limited availability of land. The relationship between densification, urban form and sustainability is however complicated[1,12,13]. For example, the 'compact-city-paradox' describes the contradicting tendencies of attributing high sustainability to high urban density and high-quality living to low-density[14]. The 'paradox of intensification'[15] describes the effect that population density increases can result in worsening local environments, despite per capita sustainability gains which are made possible by densification. Densification in cities is a complex phenomenon and multiple qualities are affected by densification processes that cities should have, such as 'maximum levels of aesthetic and functional, economic and operational, environmental and energetic, and social and process quality'[16]. Densification may have potentially conflicting impacts on either of these qualities and needs to carefully consider and balance economic, environmental and social aspects. Densification studies increasingly include multiple aspects, facilitated by the developments in open data availability and geographical information systems. Amer and Attia[18] for example establish sustainability criteria for decision making for roof stacking or Erick and Marisol[19]. Flores et al.. Flores et al.[19] present a raster-based spatial multi-criteria analysis based on an analytical hierarchical process for assessing the suitability of densification with help of environmental, economic and liveability variables.

The importance of good connectivity with transportation infrastructures is commonly highlighted in the densification literature[22,2]. Densification is also closely linked to infrastructure networks that transport water, people, goods or energy across geographical space. High-density areas enable sharing infrastructure with more people, making it for example possible to achieve lower per-capita infrastructure costs or reducing per capita greenhouse gas emissions[22,23]. Densification holds the promise of multiple advantages, particularly reducing the need for mobility if densification takes place in central and well accessible locations[24,25]. Urban density affects vehicle ownership as with increasing urban density a trend was observed towards a lower number of vehicles per person[26], promising lower noise and air pollution levels and improving the quality of life[27,28]. Marini et al[29] for example use agent-based modelling to compare effects on air pollution or commuting behaviour for different densification scenarios in Switzerland. Studies such as these highlight that depending on how urban planning and the allocation of a growing population unfolds, densification strategies have far-reaching implications on mobility and network-based transportation capabilities. The effects on energy are more specifically discussed in Section 2.3.

Based on this brief discussion of densification and sustainability, we conclude that it is critical to densify at central location with good connectivity having good transportation infrastructures[22,2]. Sustainable densification will therefore need to focus on locations with good accessibility and connectivity primary to maximize the reduction of energy-intensive transportation and try to shift the modal split towards public transportation[3]. Also, typically these locations have a better capability of how other infrastructure systems such as electricity or telecommunication networks can cope with increasing demands. This project, therefore, starts from the assumption that the accessibility and connectivity is a good indicator for sustainable densification.

2.2 Densification in Switzerland

In Switzerland, densification is high on the political agenda and the focus of intense debates. Newly coined phrases such as 'density stress' or 'growth pain'[3] reflect existing anxieties surrounding current demographic developments. It has been widely recognized that densification of the existing building stock is decisive to address the increasing housing need due to the population increase in Switzerland. Switzerland has a current population of 8.67 million and is faced with an increasing population and limited availability of space. The suitable area for settlement is estimated to be only around 30%[3] and development sites are in common competition with agricultural land[33]. The recent Swiss history of urbanisation is complex but the overall picture is that the urbanization process has been unguided and land-intensive: The dominant development was a scattered as well as a compact expansion of cities, resulting in new settlements and the construction of single-family homes, extensive infrastructure facilities or shopping centres in Swiss agglomerations[34,35]. However, Swiss regulations promote inward settlement development to create compact settlements[36–38]: Urban developments are supposed to take place where higher densities are conceivable from a spatial planning perspective, particularly in larger contiguous neighbourhoods where the development is not opposed to overriding private or public interests[37].

Different densification assessments have been previously performed in Switzerland to estimate densification potentials at a regional or national scale. Particularly related and noteworthy studies are conducted by Domschky et al. 2016[1], Gams 2015[39], ILG 2012[36], Nebel et al 2017[40], Nebel et al 2012[41] or Wüest Partner 2018[11]. These studies however each have a different scope of analysis than this project (cf. Section 2.1) which needs to be considered when comparing their findings with findings from this study.

2.3 Energy and densification

Cities having high population densities, high energy prices and high incomes are observed to have the lowest carbon emissions[2]. It is found that urban density influences energy use as much as energy efficiency improvements, and the spatial configuration of urban areas is critical for greenhouse gas reduction[42]. The relationship between urban density and energy is however non-trivial as urban density results in various effects such as urban heat islands, changes in shading or influences potentials for urban greening or renewable generation[43–45]. Numerous authors study impacts of urban form or urban density on energy: Chhipi-Shrestha et al.[46] for example, link densification to the water-energy-carbon nexus. Others quantify the influence of the urban form of buildings on energy demand or assess wider energy system impacts[47,48]. Mohajeri et al.[49] simulate changes to energy demand and supply in a rural Swiss case study for a densification and expansion scenario and find for their specific case study, that in the case of densification, heating demands are lower by 8–12 % by 2050 due to the solar gains and reduced heating loss due to the compactness of buildings. For cooling, the authors find that a densification strategy needs 3–6% more cooling in the short term but saves 12–15% cooling demand in the long term. Vuckovic et al.[50] simulate for a densified Vienna neighbourhood reduced temperatures during daytime due to shading but slightly higher temperatures during night time. For Switzerland, Hollenstein[51] explores the densification impacts on primary energy demand for not yet exhausted building zones. From an energy system perspective, the impact of urban density on energy is particularly strong because of various energy infrastructure networks (e.g. electricity grid, gas network, district heating or cooling)[52]. This is because the efficiency of networks is strongly influenced by effects such as economies of scale or economies of density[53,54].

Urban building energy modelling (UBEM) is the simulation of multiple buildings contained within a district, city or country. UBEM is primarily concerned with operational energy but there is a large diversity in the end-users, spatial scales, temporal scales and the methodologies used for the assessment[55]. It has been proposed to take into account embodied emissions in the environmental impact of buildings otherwise a similar performance gap to the operational performance could be encountered[56]. One of the most common debates in the construction field is timber vs concrete construction. Both have their advantages and disadvantages but timber is often evaluated as the option with the lowest relative embodied emissions[55,57]. Timber has also been proposed as a carbon sink due to the CO_2 absorbed during tree growth[58]. A simplified approach to evaluating embodied emissions in typical construction elements in Switzerland is followed in the SIA 2032 standard[59]. The life cycle adopted in the SIA 2032 has recently been shown to be an accurate estimate based on a probabilistic assessment[60].

A review of studies into the lifecycle emissions in buildings highlighted that typically there is a lack of accurate and consistent data and a lack of interest in the impact of embodied energy by the public and industry stakeholders.

Ibn-Mohammed et al. recommend a robust, whole-life carbon accounting framework to account for lifecycle emissions of buildings[61]. A more recent review from 2020 reveals that the situation has changed very little and that a 'notable and cross-sectoral effort' is still required for the transition of the building and construction sector that involves the critical stakeholders across the building lifecycle[62]. The authors call for a clear policy narrative to drive this change.

Concluding from this, a methodology should be adopted that combines UBEM with embodied energy to get a holistic picture of how the buildings required for each densification strategy perform[63].

3 Methodological approach

An overview of the major modelling steps I – VI is provided in Figure 1. This chapter provides more detail for each of these steps in the following sections.

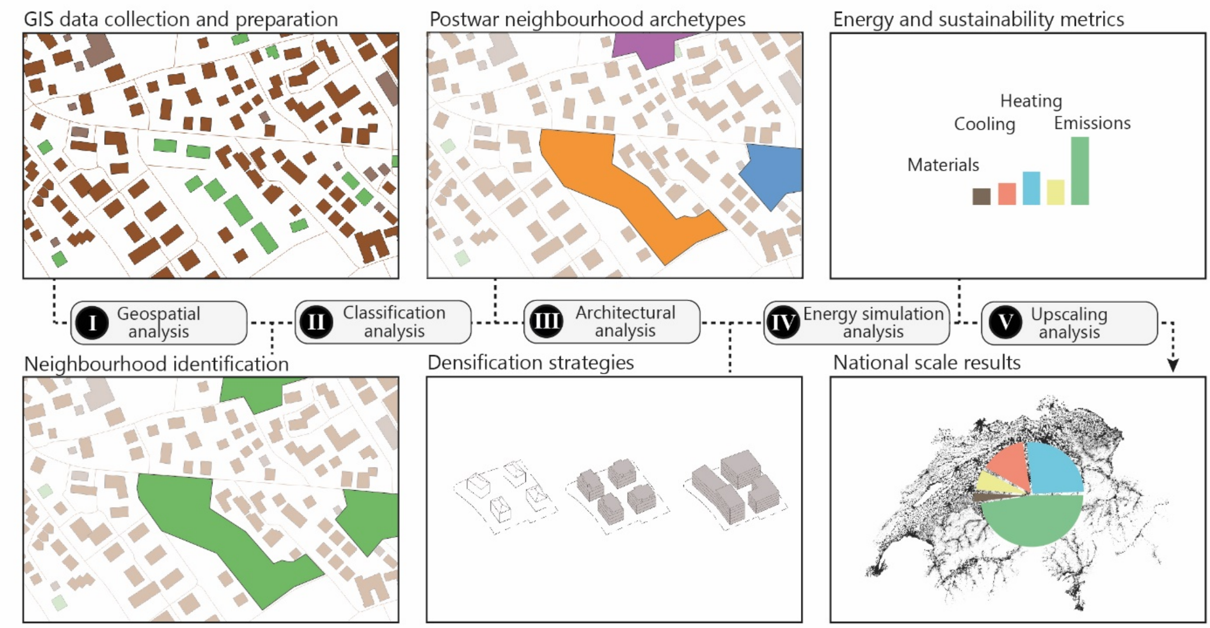


Figure 1: **Overview of the main methodological steps I – VI of this project to assess densification potentials and energy implications at the national scale.**

3.1 Geospatial analysis (I)

3.1.1 Data collection and preparation

First, a diverse range of spatial and non-spatial datasets has been collected from various sources[64]. Our analysis relies on the following key open-source and proprietary data:

- Federal Registry of Residential Buildings and Dwellings[65]
- swissBUILDINGS[66]
- Building zones[6]
- Cadastre data[68]
- TLM3D dataset[69]
- OpenStreetMap building data[70]
- ARE Community Typology[71]
- Information on the protection of historical monuments[72]

Particularly building-related information is crucial for our analysis. A particular challenge is that the spatial scope covers all urban regions of Switzerland and not all data (e.g. cadastre data) are freely available for the case study regions. All collected semantic building information is spatially joined to geometric building properties of the swissBUILDINGS3D. As the swissBUILDING3D dataset is out of date for certain geographic locations, we added wherever possible building geometries from the publicly available OpenStreetMap dataset.

3.1.2 Neighbourhood definition and localization

As the focus of this analysis is neighbourhoods, they were first defined and spatially located. There is no clear scientific definition of what constitutes a neighbourhood from a dimensional point of view[73]. The neighbourhood definition depends strongly on the geographical context: For Switzerland, other authors list examples of neighbourhoods typically in the range of 150 – 500 occupants[10]. To consider very small neighbourhoods and for sensitivity considerations, we assume an even lower minimum occupant size of 150. For selecting such Urban Structural Units (USU), we use two different approaches based on the minimum floor area (GFA_{floor}) and urban density ($GFA_{density}$) which allows exploring the sensitivity of how neighbourhoods are defined:

- The average floor area per person is ~46m^2 in Switzerland[74]. To derive the gross floor area (GFA) which includes space used for stairs, cellars or walls, we apply a factor of 1.2[75]. This results in an average of 55 m^2 GFA per person. Based on the minimum number of neighbourhood occupants (p_{min}), the respective minimum neighbourhood GFA is calculated as given in Eq. 1:

$$GFA_{floor} = p_{min} * 46 \text{ m}^2 * 1.2 \quad \textbf{(1)}$$

- For Swiss cities, an urban density of 150 persons per hectare can be considered as dense, which corresponds to a gross floor area ratio of about 85%[76]. We assume this minimal gross floor area ratio to hold for our neighbourhoods and calculate the minimum neighbourhood GFA as given in Eq. 2:

$$GFA_{density} = \frac{p_{min} * 46 \text{ m2} * 1.2}{0.85} \quad \textbf{(2)}$$

After the identification of all neighbourhoods according to these criteria, some resulting neighbourhoods are very large and very heterogeneous. Therefore, neighbourhoods are spatially intersected with the minor road network which provides a refined segmentation of neighbourhoods improving the neighbourhood archetype classification.

3.1.3 Characterisation of the neighbourhood location

Sustainable densification will need to focus on central and well accessible locations. We classify the locational centrality and accessibility of each USU as ‘low, ‘medium’ or ‘high’. The semantic description of place with terms such as "central" or "peripheral" is conceptually challenging[77]. Therefore, we evaluate the geographical location of each USU based on a fuzzy analytic hierarchy process: We spatially intersect two geospatial datasets which provide information on public transport accessibility and transportation time to urban centres[78] to evaluate point-based categorical accessibility (Table 1). If multiple accessibility classes are assigned to a neighbourhood, the class with the largest spatially intersecting area is used. Figure 2 shows the resulting accessibility and centrality classification for an example region.

Table 1: Evaluation of the accessibility with help of travel time to centres and public transportation classes[79].

Travel time to centre		Transport grade		Urban centrality classification	
Minutes	Points	Class	Points	Points	Category
0 – 10	3	A	4	7	high
10 – 20	2	B	3	4 – 6	medium
20 – 40	1	C	2	0 – 3	low
40 – 80	0	D	1	-	-
> 80	0	-	0	-	-

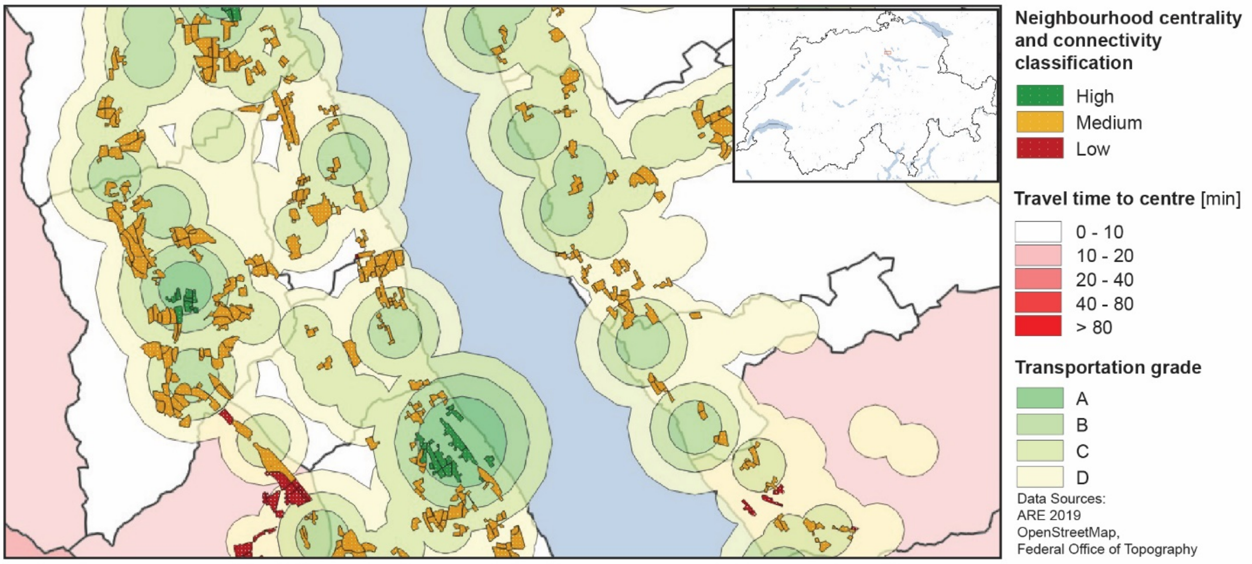


Figure 2: Example of the centrality and connectivity classification based on travel time to an urban centre and public transportation grade.

3.1.4 Neighbourhood characterisation

For the later supervised classification of all identified Swiss neighbourhoods, the neighbourhoods need to be described and characterized. This was performed with help of the listed descriptive variables in Table 2. These variables were calculated as follows:

$$f_1 = \frac{BB_A - B_A}{BB_A} \quad (3)$$

$$f_2 = BB_A * BB_{l_{min}} \quad (4)$$

$$f_3 = \frac{2 * \sqrt{B_A / \pi}}{BB_r} \quad (5)$$

$$f_4 = \frac{N_A}{N_{GVA}} \quad (6)$$

$$f_5 = \frac{N_{POP}}{N_A} \quad (7)$$

where BB_A is the bounding box area, B_A the building footprint area, $BB_{l_{min}}$ the minimum bounding box polygon side, B_A the building area, BB_r the radius of the bounding box, N_A the neighbourhood area, N_{GFA} the building floor area, N_A the neighbourhood area, N_{POP} the neighbourhood population and N_{GFA} the neighbourhood gross floor area. Variables that are based on individual building properties (f_1, f_2, f_3) are calculated across all neighbourhood buildings and weighted with the building occupancy. The building morphology variables capture different building morphology aspects such as compactness or elongation. The Schumm's index (f_3) as defined by Maceachren[80] provides the relationship between the radius of the circle of the same area as the building divided by the radius of the circumscribing circle.

Table 2: Overview of descriptive variables used to characterize and classify urban post-war neighbourhoods.

Variable	Description	Unit
f_1	Building morphology index indicating complexity	-
f_2	Building morphology index indicating elongation	-
f_3	Schumm's index	-
f_4	Open space index	-
f_5	Population density	people * plot area ha^{-1}

3.2 Post-war neighbourhood archetype definition (II)

The urban built form varies considerably across different geographical contexts[81,82]. Archetypes are particularly useful to simplify and generalize the urban building stock, typically because of limited computational power or in the case of being able to perform only limited detailed analysis due to time constraints. Here, our primary motivation for using archetypes is the challenge of creating a large number of detailed urban design studies for different densification strategies and to upscale to the national scale.

Based on expert knowledge, we have defined different post-war neighbourhood archetypes each having distinct characteristics. We defined the following archetypes:

- A1: Large iconic monolithic building structures
- A2: Compositional ensembles of solitary buildings
- A3: Compositional ensembles as clusters of similar buildings
- A4: Linear housing and open city block structures
- A5: Heterogeneous detached apartment buildings

The archetypes A1, A2 and A3 are mainly large-scale housing estates (so-called 'Grands Ensembles') and were primarily built in the 1960s and 1970s. The archetypes can be differentiated from an architectural and urban design point of view and their identification is carried out manually using two different approaches in parallel: On the one hand by analysing the cadastral plans with the located post-war neighbourhoods in the metropolitan areas of Basel, Bern, Geneva, Lugano and Zürich and on the other hand by literature research on existing housing estates of the post-war period. To differentiate between the neighbourhoods, we consider various characteristics, such as building typologies, the spatial relationship between the buildings or the spatial relationship between the buildings and their surroundings (Table 3).

Table 3: Architectural characterisation of post-war neighbourhood archetypes (A1 – A5).

	A1	A2	A3	A4	A5
General description	large iconic monolithic building structures	compositional ensembles of solitary buildings	compositional ensembles as clusters of similar buildings	linear housing and open city block structures	heterogeneous detached apartment buildings
Usage	homogeneous residential, few social and community facilities, sometimes commercial uses	mainly residential, few social and community facilities, sometimes commercial uses	mainly residential, few social and community facilities, sometimes commercial uses	homogeneous residential, very few social and community facilities	homogeneous residential, very few social and community facilities, sometimes commercial uses
Building form and typology	singular, strongly iconic	various large compact buildings: slabs, high-rise, low-rise	mostly linear and/or sweeping volumes	compact linear volumes with often larger depths	squared, compact
Building placement	autonomous	free composition of different building typologies	repetitive composition, mostly very strict geometric layout	mixed, parallel and/or perpendicular to streets	mixed, non-directional layout
Open spaces	large continuous open spaces	large fragmented open spaces	large fragmented open spaces	some open spaces	little open space
Accessibility	addresses and driveway(s) mostly within site	addresses and driveway(s) mostly within site	addresses and driveway(s) mostly within site	mainly street-side orientation	primarily street-side orientation

3.3 Data-driven classification of neighbourhoods (III)

We apply supervised classification algorithms to the defined archetypical post-war neighbourhoods A1 – A5. Supervised classification depends on the choice of algorithm, algorithm-specific parameters, the data scaling, the training sample or the number and selection of feature variables[7]. The choice of variables describing the underlying data is crucial, as it influences how much weight is attributed to a certain feature. For example, using many variables describing the urban form assigns more weight to morphological characteristics. As the supervised classification of highly multi-dimensional data is challenging, typically not more than a handful of feature variables are used for classification as relying on a small number of variables reduces the need to acquire large training datasets. A further complication is high collinearity between variables. With the help of dimensionality reduction techniques such as principal component analysis, the collinearity can be addressed and the number of parameters reduced to principal components[84]. For our analysis, we rely on the feature variables listed in Table 2 to describe the post-war neighbourhoods.

We explore different classification algorithms such as support vector machine (SVM) or random forest (RF), different data scaling methods and feature variable combinations. As the value ranges across the different variables is very different and the variable units are incomparable, we transform our feature space values by scaling to values from 0 to 1. Because we have an imbalanced dataset, accuracy is not a good measure and we resort to the F-measure for the cross-validation. We tune our hyperparameters with a grid search to provide the best parameter combinations and explore the plausibility of the classification results by cross and face validation. The used classification algorithms are employed with the python based scikit-learn package[8]. The geolocation of the identified real-world examples of the archetypes A1– A5 used for classification is provided in the Supplementary Material (SM) in Eggimann et al (2021)[86].

3.4 Densification strategies (IV)

Domschky et al.[8] collected information on post-war densification case studies for entire neighbourhoods in Switzerland. Across their case studies, the change in population due to densification measures range from a few percentages to up to double the number of inhabitants and neighbourhoods with low densities show generally highest potential. Densification thus depends on the case study context as well as on the overall strategy.

In this project, characteristic densification strategies are explored:

- S: 'Current situation', i.e. no densification.
- S1: 'Below-average' densification strategy through renovation, increase in height, extension or supplementary buildings to reach current average archetype specific densities. In this strategy, only neighbourhoods with below-average floor-area ratios are densified to current average floor area ratios.
- S2: 'Business as usual' densification strategy through the replacement of existing buildings either as a whole or in phases in accordance with the currently common adaptation of building zones.
- S3: 'Concentrated densification' strategy through the replacement of existing buildings either as a whole or in stages with a maximum density based on contemporary urban development criteria (not in compliance with current legislation).

The densification strategies are schematically visualized in Figure 3. Wherever possible, for each strategy and archetype, current and future densities are assessed based on executed projects, literature case studies and own urban design studies.

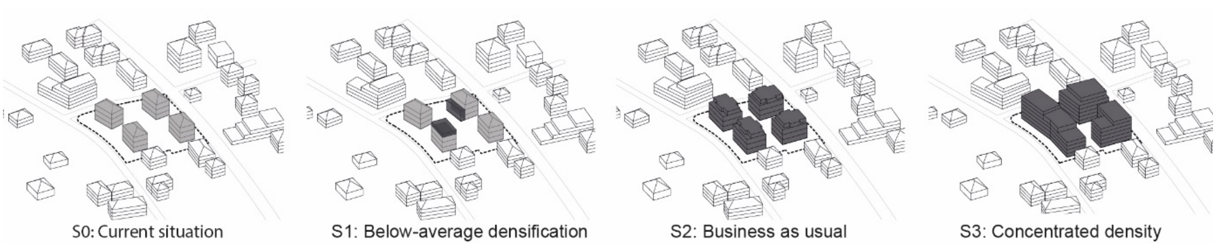


Figure 3: **Schematic overview of the densification strategies. The current situation (no densification) is shown in S0. For the below-average densification strategy (S1) all neighbourhoods with below-average densities are densified to calculated mean archetype density. The business as usual strategy (S2) follows the current prevailing replacement strategy and the concentrated density strategy (S3) assumes replacement with contemporarily considered maximum densities.**

The densification strategies aim for spatial improvement and qualitative incorporation of the surrounding context. Figure 4 lists all case studies that have been used to calculate densification potentials per archetype and densification strategy. For strategy S1, average current floor area ratios (FAR) are calculated per archetype based on the supervised archetype classification. For strategies S2 and S3, a linear relationship is fitted between current and future floor area ratios, which allows estimating neighbourhood specific future densities in relation to current density values. When calculating future densities, a maximum density is assumed (FAR_{max}) which corresponds to the maximum assessed FAR value per archetype and strategy. Strategy S1 was not further considered for the energy analysis (Section 3.6) as no urban designs were generated for this scenario.

3.5 Reference urban designs

3.5.1 Preparation of urban designs for densification analysis

Specific urban designs which are considered to provide space of good quality from an urban design perspective were implemented for all combinations of identified archetypes and densification strategies. These reference urban designs consist of built projects, studies developed by others, as well as densification ideas developed by us. The number of designs does not reflect all potentially possible densification options but it is based on publicly accessible material such as specialized journals, published competitions and accomplished studies. From an urban planning perspective, all selected neighbourhoods have a potential for densification. The chosen reference designs are therefore a collection of qualitatively meaningful projects but do not represent a quantitative study.

Our basic approach was to take as many references as possible from already published or built projects in which one of the strategies has already been applied to gain reliable and comparable data information. The other remaining strategies were then developed based on this existing strategy. For example, concerning archetypes A2 and A3, the examples from Domschky et al.[10] or published studies were primarily taken as a starting point and used to develop the other strategies for each project. For archetype 4, mainly built examples, as well as published studies of strategy S2 were taken as a starting point to derive the other strategies from. These are of course ideal examples, especially in Bern and Zurich, as large numbers of such developments can be found in these cities. We preferably selected projects that are currently being discussed and for which the necessary data was available. For archetype 5, however, we mainly had to use our own designs, since that archetype has a relatively small scale, therefore allows only for a limited range of densification possibilities and such projects are rarely published. Our overall focus in preparing the reference urban designs was on the qualitative preservation or even the improvement of urban qualities of the respective neighbourhood regarding its densification potential. For each strategy, spatially sensible solutions were used, which integrate in the best possible way into the context, provide high-quality outdoor spaces, allow mixed-uses and provoke typological diversity. The chosen examples fulfil these criteria.

For developing reference urban designs and densification strategies, not all combinations could be achieved or are realistic, given the current urban context. For archetype A1, we assume that densification is not possible as these neighbourhoods are commonly listed. The same could be said about certain neighbourhoods from other archetypes, which is exemplified by the current discussion on the Tscharnergut (archetype 2) regarding its retrofitting and/or partial replacement. A critical question that we are well aware of. Nonetheless, we have chosen to subject archetypes 2 to 5 to a thought experiment to open the field of investigation to both theoretical and practical examples, as this has promised and finally also brought us relevant observations for our study. This approach also seemed legitimate to us, since in Switzerland historic preservation information has so far not been available in a harmonized manner at the national level.

Due to its ownership structure, we assume that the densification strategy S3 is not applicable for archetype A5, as this archetype is for the most part confronted with the same hurdles as e.g. single-family home neighbourhoods. We, therefore, assumed for archetype A5 and strategy S3 that densification takes place in the same way as in strategy S2. Potentials are calculated by multiplying current neighbourhood populations with the ratio of future to current FAR. The urban designs are provided in Appendix 10.2.

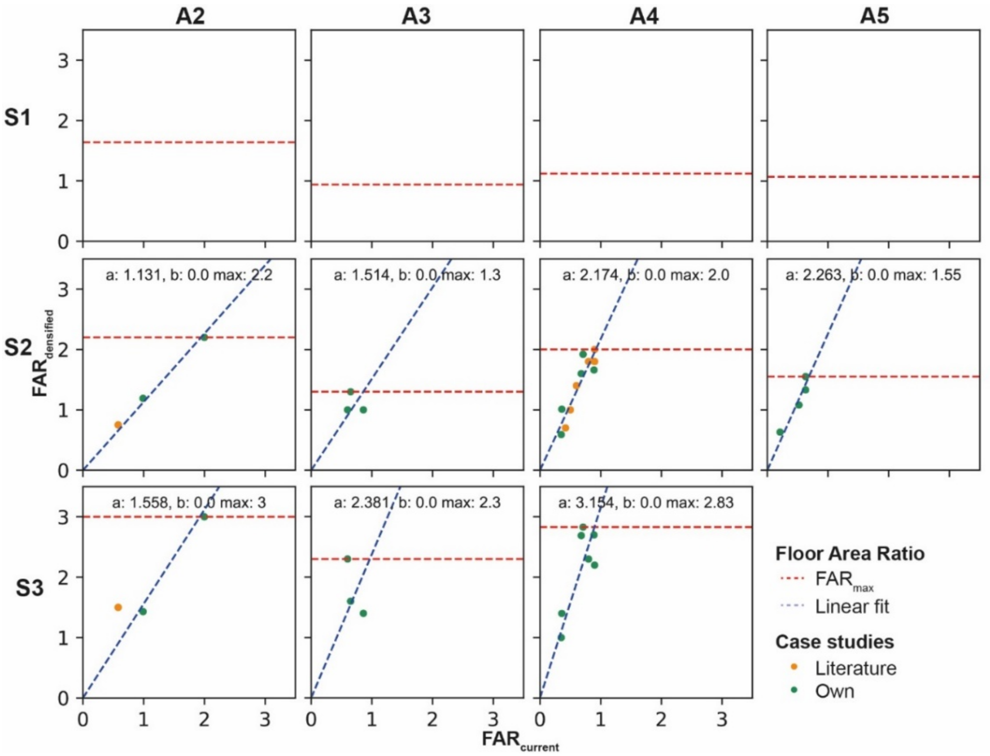
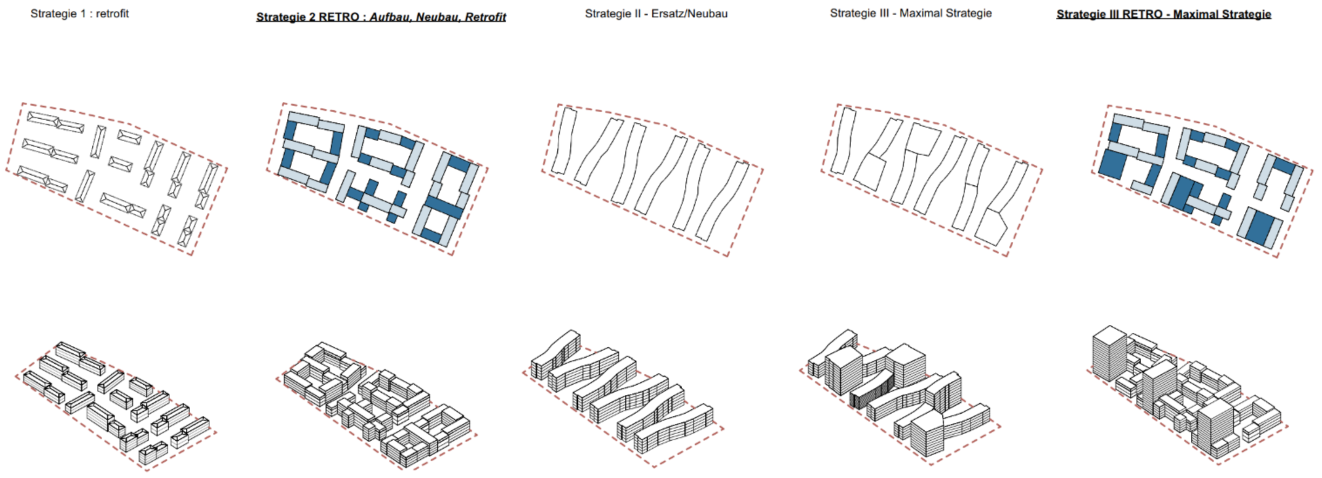


Figure 4: **For each densification strategy (S1 – S3) densified floor area ratios ($FAR_{densified}$) are calculated based on own urban designs and case studies from the literature. A linear relationship is fitted between current ($FAR_{current}$) and densified FAR. Neighbourhoods are only densified up to a maximum densified FAR value (FAR_{max}). Only feasible combinations of strategies and archetypes are shown.**

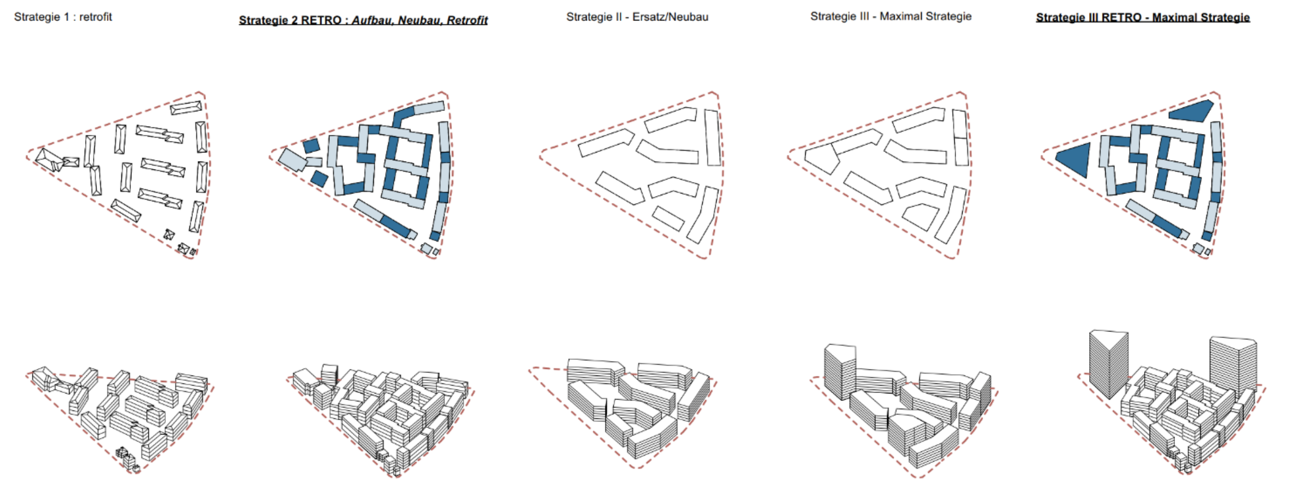
3.5.2 Preparation of revised urban designs

After the results of the energy analysis were available, we redesigned two exemplary reference designs of the archetype A4 intending to reduce the embodied emissions that result from the construction of the new buildings. In the revised designs, all existing buildings were kept. The additional population quota for each densification strategy was first accommodated through the construction of an additional floor on top of the existing buildings and then additional buildings were constructed in-between the existing buildings to achieve the same population as the original S2 and S3 densification strategies.

These retrofit/plus strategies, like the others, were elaborated taking into account the described spatial qualities, but two major factors were "put aside": By building in between, a lot of new, but also very small scale and fragmented buildings were created, whose economic efficiency does not correspond to today's norm. The filling of gaps also brings a loss of unsealed areas. Whereas in the business as usual strategy (S2), the footprint of the buildings remains roughly the same, in this case, the existing buildings are built less high, but more extensively. These revised strategies were nevertheless considered as important possible solutions since the city as a heterogeneous structure is subject to the premise of continued growth and such retrofit/plus strategies could show a relevant change from economic business as usual to an energy-focused urban development. Although, these two retrofit/plus strategies (S2-retro-plus and S3-retro-plus) have only been studied on the basis of a few examples. The calculated impacts were derived from these but would need to be studied in more detail in a further step.
The original and revised designs for the densification strategies of the Casarecce and Drüegg are shown in Figure 5.



Casarecce revised densification strategies



Drüegg revised densification strategies

Figure 5: Casarecce and Drüegg revised reference urban design for the A4 neighbourhood archetype. In these designs, the buildings outlined in light blue are extended by one floor and the dark blue polygons represent new buildings (from left to right: Existing neighbourhood, S2-retro-plus, S2, S3, S3-retro-plus).

3.6 Energy analysis (V)

CESAR-P is an energy modelling platform for the simulation of the energy performance of buildings and retrofitting strategies at a district scale. It was developed in 2018[8] and has recently been released as open-source[89]. CESAR-P has been previously used to assess the retrofitting scenarios in districts across Switzerland[88] and to evaluate the feasibility of decentralised energy storage[90]. At the core of CESAR-P is a set of construction and building usage archetypes, based on statistical information and standards, which are used to parameterize individual building models in EnergyPlus. The internal conditions and occupancy profiles for each building type are taken from the SIA 2024 standard[91]. EnergyPlus is a whole building simulation software that uses mass and heat balance equations to model the energy flows across the thermal zones of a building[92].

In this project, the functionality of CESAR-P was extended to address the following:

a) The custom definition of construction archetypes based on the material choice used in each densification strategy. This choice is based on the intensity of timber vs concrete in new builds - a topic that has been investigated in several earlier studies[86,8].

b) The calculation of embodied emissions and grey energy incurred by new buildings. The reference values from the SIA 2032 standard were used to determine the embodied emissions and grey energy associated with each construction element.

Reference urban designs were prepared for each neighbourhood archetype. Each reference design comprised of building footprint polygons with height data for each densification strategy. The building footprints were the geometric input for the energy simulation. CESAR-P extrudes each polygon uniformly using building height to estimate the building volume. The number of floors in each building was calculated by CESAR-P by dividing the building height by the default 2.4m per floor. The energy reference area in all cases was assumed to be 100% of the gross floor area. This energy reference area is used to determine internal loads from occupancy and equipment which are taken from the SIA 2024 standard. A summary of the physical characteristics of each reference urban design is shown in

Table 4 for existing buildings and in Table 5 for new buildings.

Table 4: Averaged physical characteristics of the existing buildings specified in each reference urban design.

	Average of GRND_AREA [m²]	Average of GROSS_AREA [m²]	Average of HEIGHT [m]	Average of PERIMETER [m]
A2	635.5	4323.7	22.4	127.4
Hardau	681.2	6673.9	35.9	127.4
Tscharnergut	621.1	3585.1	18.1	127.4
A3	391.7	1674.5	11.8	86.8
Irchel	208.7	807.5	11.6	59.3
Köniz-Buchsee	684.4	3061.7	12.0	130.8
A4	300.8	891.1	11.8	79.6
Casarecce	233.9	651.4	10.6	68.8
Drüegg	307.2	849.9	13.5	83.4
Lochhacker	574.7	2077.7	11.9	115.0
A5	285.6	856.7	11.6	71.8
Goldbach	216.7	650.0	13.2	60.3
Winzerhalde	354.4	1063.3	9.9	83.2

Table 5: Averaged physical characteristics of the new buildings specified in each reference urban design.

	Average of GRND_AREA [m²]	Average of GROSS_AREA [m²]	Average of HEIGHT [m]	Average of PERIMETER [m]
A2	**676.3**	**5175.9**	**29.6**	**129.3**
Hardau	**1159.6**	**6811.3**	**26.1**	**188.6**
S2	1430.3	4949.2	13.7	217.8
S3	1043.6	7609.3	31.4	176.0
Tscharnergut	**456.6**	**4432.6**	**31.2**	**102.4**
S2	517.5	3392.8	20.7	112.8
S3	414.5	5152.4	38.5	95.3
A3	**408.6**	**2542.0**	**16.9**	**87.1**
Irchel	**221.7**	**1303.7**	**16.4**	**62.0**
S2	253.6	1182.4	13.8	67.7
S3	195.2	1404.7	18.5	57.2
Köniz-Buchsee	**545.6**	**3450.1**	**17.3**	**105.4**
S2	628.7	4700.1	21.0	118.3
S3	515.4	2995.6	16.0	100.8
A4	**809.7**	**5299.5**	**23.3**	**141.8**
Casarecce	**1173.1**	**5865.6**	**19.0**	**204.8**
S2	1234.8	6173.8	19.0	214.1
S3	1142.3	5711.4	19.0	200.1
Drüegg	**727.6**	**5476.0**	**24.8**	**129.7**
S2	758.8	4552.6	19.8	137.3
S3	702.7	6214.7	28.8	123.7
Lochäcker	**630.3**	**4472.4**	**24.4**	**106.7**
S2	608.4	4258.7	23.1	98.7
S3	639.8	4564.0	25.0	110.2
A5	**369.8**	**1929.1**	**17.9**	**79.7**
Goldbach	**450.5**	**2258.0**	**17.7**	**87.4**
S2	357.0	1428.0	16.5	76.2
S3	544.0	3088.0	19.0	98.6
Winzerhalde	**326.7**	**1753.6**	**18.0**	**75.5**
S2	335.1	1488.0	14.6	76.0
S3	319.4	1986.0	21.0	75.2

Representative constructions for each building element (roof, ground floor, external wall and internal floor) were selected from the Lesosai 2020 standard construction library[93]. Lesosai is a software program used to certify compliance of a construction design to local building standard[94]. Lesosai is predominantly designed for certification against the Swiss building standards. Three different construction scenarios were applied to each densification strategy (all concrete, majority concrete, timber intensive). The construction scenarios applied to each building element are summarised in Table 7.

Table 6: **Construction scenarios. Blue squares (C) indicate a concrete construction and brown squares (T) represent a timber construction.**

	Roof	Internal ceilings/floors	Ground	External walls
All concrete (CCCC)	C	C	C	C
Majority concrete (CCCT)	C	C	C	T
Timber intensive (TTCT)	T	T	C	T

For each urban design, the new and retrofitted buildings were identified for each scenario. It was assumed that all existing buildings are renovated in all scenarios. The construction of the existing buildings was taken from the CESAR-P default library for post-war buildings (1949-1978), which is the closest match to the age category used for clustering. This assigns a typical construction profile based on the practices from this time period. The CESAR-P default library was created from building surveys and standards[88]. For consistency, each building type was assigned as residential across all reference designs. The insulation thickness of each construction is adjusted for compliance with the SIA 380 target U-values. The representative constructions for each building element are shown in Table 7.

Table 7: **Material layers of each construction element used to parameterize the simulation models.**

Construction	SIA 2032 element	Timber	Concrete	U-value
Roof	C4.4	20mm Particle Board 277mm Insulation 40mm Air Gap 20mm Medium Hardwood 20mm Particle Board 10mm Medium Hardwood 20mm Air Gap 20mm Medium Hardwood	20mm Internal Render 150mm Concrete 377mm Insulation 50mm Synthetic Render	0.09
Ground Floor	C4.1/G4	61mm Pine 275mm Insulation 61mm Pine	10mm Parquet Floor 50mm Mortar 200mm Reinforced concrete 295mm Insulation 20mm Render	0.11
External Wall	C2.1	40mm Pine 295mm Insulation 40mm Pine	20mm Render 150mm Concrete 307mm Insulation 20mm Bitumen	0.11
Window	E3/F2	2015 Low E Triple	2015 Low E Triple	0.788
Internal Floor	C4.1/G4	60mm Wood, hard 40mm Pine 110mm Air gap 20mm Pine	10mm Parquet Floor 50mm Lightweight Render 200mm Reinforced concrete 20mm Internal Render	NA

The models generated by CESAR-P are simulated in EnergyPlus. All the scenarios were simulated using a Zurich weather file for the reference year 2015.

To calculate the embodied emissions, the SIA 2032 standard was used. The SIA 2032 details an early-design stage approach to calculating the embodied emissions and grey energy incurred through the construction of buildings. The standard provides amortised annual values of embodied energy and emissions across the economic lifetime of each building element. Using the amortised values, the operational energy consumption of the building was compared against the embodied energy of the construction. The SIA is comprised of several building element groups, each with multiple options that influence the embodied energy of the building. The SIA 2032 elements corresponding to each construction are listed in Table 7. The appropriate option was selected in each simulation run to investigate the impact of the timber and concrete construction. To establish the percentage construction choice has on the overall embodied energy of the building, the remaining SIA element codes, detailed in Appendix Section 10.3, were defined as constant for all buildings.

To quantify the impact of the construction choice on the neighbourhood archetype, the embodied and operational energy totals were calculated across each neighbourhood and divided by the number of occupants. This calculation assumes a constant value of 46m^2/occupant as published by the BFS. Figure 13 shows the grey energy for: i) additional insulation added during retrofits, ii) construction material choice for new buildings and iii) the new build baseline, calculated using the assumptions detailed in Appendix Section 10.3.

The revised densification strategies S2-retro-plus and S3-retro-plus (cf. Section 3.4.2) involved extending the original buildings by one additional floor. To calculate the embodied energy, it was assumed that the lower parts of the extended buildings were retrofitted as standard. It was assumed that the extensions consist of an additional floor constructed in timber. The embodied energy required to construct timber walls and roofs for the extension was taken from the SIA 2032.

3.6.1 Comparison and validation against existing standards

The combined primary energy used for the operation and construction of the building was calculated at 74.7 kWh/m^2/year which is just below the target value of 86kWh/m^2/year as specified in the SIA 2040[95].

We also compared against the SIA 380[96] and found that the buildings performed below the heating demand limit values, which is expected due to the specification of materials to meet the target U-value of the standard, see Table 7. The buildings in this study had an average space heating demand of 24 kWh/m^2 (22 kWh/m^2 for new buildings and 26 kWh/m^2 for retrofitted buildings).

3.7 Upscaling analysis (VI)

For obtaining national scale results and to upscale analysis performed at the archetype level, the findings obtained for each archetype were combined with the classification results of each neighbourhood.

To upscale the densification results, the future FAR was calculated per densification strategy and archetype (see Section 3.4). Densification potentials are thus calculated for every classified neighbourhood by multiplying current neighbourhood populations with the ratio between future and current FAR.

To upscale the energy-related results, the number of inhabitants as well as the total floor area per archetype and densification strategy was calculated based on the supervised classification. The results of this are shown in Figure 6.

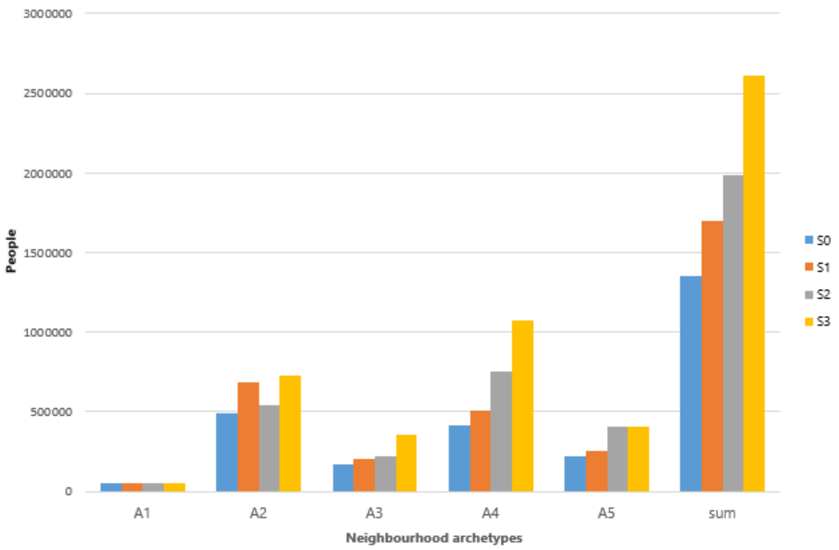


Figure 6: Total population per neighbourhood archetype (A1 – A5) averaged over all methodological densification strategies for Switzerland. S3 for A5 is ignored, as this combination is not assumed for densification (cf. Section 3.4).

For the energy upscaling, we averaged the obtained calculations results across all the different methodological densification strategies considering the neighbourhood definition (cf. Section 0) and supervised classification (Section 3.3). Assuming constant maximum densification values (cf. FAR_{max}, Figure 6) resulted in higher densification potential for S1 than for S2 for the neighbourhood archetype A2. This can be explained that in the case of S2, neighbourhoods with current low densities reach lower densities than the calculated average FAR values in S1. This is a limitation from using averaged future FAR values in S1 instead of a linear relationship (cf. Figure 4). This means that neighbourhoods with currently very low FAR values may reach lower future FAR values in S2 than in S1. Densification potentials for the densification strategy S1 are therefore potentially overestimating potential for S1. If the current maximum allowed FAR per neighbourhood would be readily available, this limitation could be overcome and the estimation be improved. The number of occupants in each densification strategy was multiplied by the per occupant values for embodied energy and emissions shown in Figure 13 and Figure 14 respectively.

4 Methodological limitations

Our analysis reveals several limitations and research opportunities that could be assessed in follow-up studies to improve and extend the presented analysis.

The localisation of potential densification neighbourhood sites necessitates good data availability, particularly up-to-date building attributes (i.e. construction age, number of floors, or refurbishment status) and ideally cadastre data with precise plot geometries. We ignored currently already refurbished and renovated post-war neighbourhoods, as our building dataset does not include information on refurbishment. As a consequence, estimated potentials may be lower as already some post-war neighbourhoods have undergone refurbishment or densification. The availability of further data indicating the feasibility for densification, e.g. related to noise, building ownership or the preservation status would further improve the analysis. More case study data or additional urban designs would improve the relationship between densification strategies and archetypes. However, detailed urban design of case studies to define densification strategies is laborious and automated procedures could be explored. Further analysis could also focus on the definition of additional densification strategies, such as strategies allowing even higher densities in particularly suitable locations. Alternatively, if high-resolution information on current maximum densities based on current regulations were available, remaining potentials according to current regulations could be estimated more accurately. Whereas structural densification typically is the result of constructing additional living space for a given area by measures such as urban infill or roof-stacking, per capita living space can also be reduced by other measures such as the moving of empty nesters or reducing the per capita living space[97]. We only considered structural densification, i.e. changes in floor area assuming constant floor area per person over time. Reducing living space is however a far-reaching social innovation, necessitating broad transformations of culturally established norms. We have used centrality and accessibility as sustainability indicators for the assessment of neighbourhoods. They serve as indicators for the sustainability of a location's densification. However, location alone does not capture the full range of possible sustainability indicators. More detailed sustainability indicators such as energy, costs, emissions or water consumption over the entire life cycle could be investigated[58]. The presented geospatial framework based on the identified archetypes could however be easily extended for the quantification of a full range of other densification impacts. Finally, our performed quantitative analysis of densification potentials needs to be followed by more qualitative assessments of densification potentials focusing on other factors such as architectural qualities or the embedding of densification projects in the wider socio-economic context to realise highly liveable densified neighbourhoods[19,98–100]. Also, more attention could be given for example to urban greening for preventing the densification-paradox or providing more qualitative densification potentials[101].

One focus of this study was the impact of the choice of construction material for each densification strategy. This is in line with the relative embodied performance of timber and concrete materials[58]. There is now a wide range of timber and concrete based materials that vary considerably in their thermophysical characteristics and their carbon/energy intensity[9]. The variability, particularly in the latter, could have a significant impact on the findings. It is however particularly challenging to collect accurate life-cycle values for material or construction, as there are many contributing factors that influence the embodied energy depending on the system boundaries considered. In this study, existing standards were used to obtain values of the carbon/energy intensity and the thermal-physical properties required for simulation. This is considered the best available approach for the scope of this study. As more data become available regarding the prevalence of types of timber and concrete used in the industry, their spatial availability relative to each neighbourhood and their embodied energy, it could be used to provide a more accurate picture of the impact of not only densification strategies but also the implications of other urban planning studies.

We have focused on the improvement in terms of modifications to the building envelope, which is a relatively simplistic view of the overall impact of energy that occurs through densification. To carry out a more detailed investigation would involve widening its boundaries: Questions such as the impact of densification on the energy use for mobility and additional infrastructure to support more people would be critical considerations. Such a study would go beyond the capabilities of building energy simulation and would require a holistic, cross-sector approach in the evaluation of embodied and operational emissions. The complexity of such an investigation would increase exponentially with the factors considered and the more assumptions made, would widen the uncertainty. Nevertheless, this work has provided a key segment that could readily be integrated into a more detailed study.

5 Results and findings

This chapter addresses the research questions (RQ) outlined in Section 1.3.

5.1 Answer RQ1: Geographic location of post-war neighbourhoods

We estimate that currently, about 1.35 million people are living in Swiss urban post-war neighbourhoods on an estimated ~9'000 ha building floor area. The geographical location concerning the centrality and accessibility is shown in Figure 7 for all identified Swiss neighbourhoods. Densities between 150 – 300 inhabitants per hectare can be considered as high, densities above 300 as very high[7]. The evaluation of the geographical location differs across the population density range: Whereas neighbourhoods having currently lower population density values are more often situated in less central locations, centrally located neighbourhoods reach typically higher population density values. A first general finding is that potential areas with currently low densities and therefore high densification potentials are on average less suited from a locational and thus sustainability point of view. However, we find also neighbourhoods with relatively low population densities and good overall accessibility which are interesting neighbourhoods for densification. This considerable spatial differentiation of the post-war neighbourhoods in terms of their geography allows for good prioritising concerning sustainability implications.

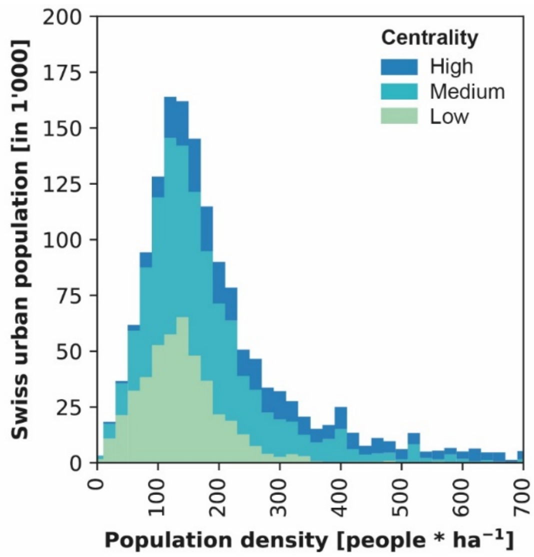


Figure 7: Population density and geographic location of all identified Swiss urban post-war neighbourhoods.

5.2 Answer RQ2: Neighbourhood archetype classification and distribution

The most plausible classification of our defined neighbourhood archetypes (Section 3.2) was obtained with a support vector machine and random forest classifier (cf. Section 3.3). To include the sensitivity of the neighbourhood classification, we combine principal component analysis (having 3 principal components) with the two classification algorithms. This provides us with in total 4 different approaches for which the resulting floor area per archetype is shown in Figure 8. Even though we observe a consistent pattern of the different classifications, we note particular differences in classification frequencies for the archetypes A1, A3 and A4. The difference in the classification results reflects the challenge of capturing important architectural and urban elements such as façade orientation or building orientations, which we do not capture directly with our feature variables. Also, there is no standard delineation (i.e. in terms of morphology or building heights) of different archetypes and their definition is fuzzy. The heterogeneity of buildings within neighbourhoods further complicates the neighbourhood classification as opposed to, e.g. the classification of individual buildings. Additionally, we only consider residential post-war buildings, which means that the morphological differences between the archetypes may be less pronounced than in the case of considering the entire building stock. Our data-driven classification of archetypes reveals the difficulty of defining clearly distinguishable archetypes and capturing their key distinctive properties with simple indicators.

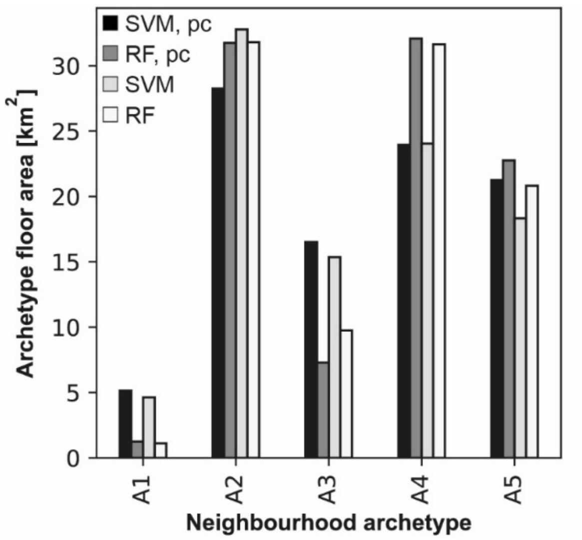


Figure 8: Archetype classification based on support vector machine (SVM) and random forest (RF) classification with and without the use of principal component (pc) analysis.

The spatial location of the different archetypes across all of Switzerland concerning the degree of centrality and connectivity is shown in Figure 9. For the neighbourhood falling into the category high centrality and connectivity, the archetypes A3 and A5 are a bit less represented. However, all archetypes can be found in the identified "medium" category, which also contains the largest number of inhabitants.

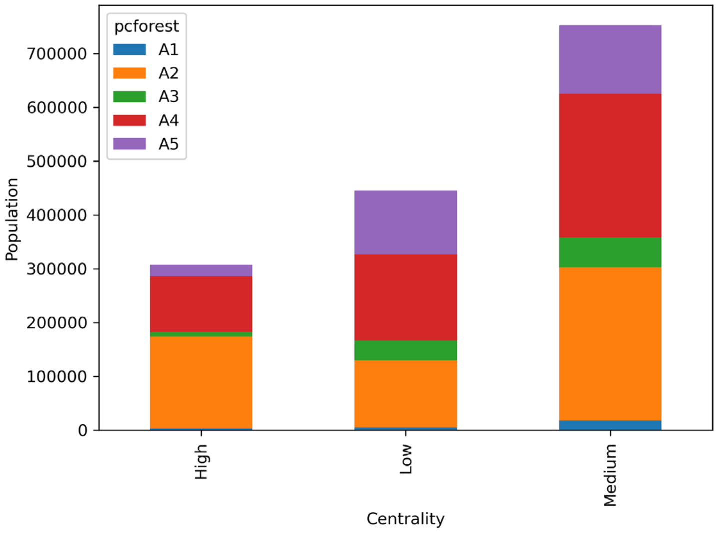


Figure 9: Distribution of the population within the different neighbourhood archetypes for the different geographical locations (high, low and medium centrality and connectivity classification as outlined in Section 3.1.3).

5.3 Answer RQ3: Swiss densification potentials

Total Swiss densification potentials per densification strategy, as well as the distribution in relation to the accessibility and centrality, are shown in Figure 10. Average densification potentials range across the densification strategies between 0.35 – 1.24 million people (corresponding to between 4 – 15 % of the current population). The centrality and accessibility are high for about 8 – 17 % of the potential and low for about 36 – 39 %. As expected, densification potentials are largest for the densification strategy S3 and smallest for the strategy S1. However, the differences are considerable, particularly between strategies S2 and S3. This highlights that there is considerable room for manoeuvre when setting maximum densification regulations.

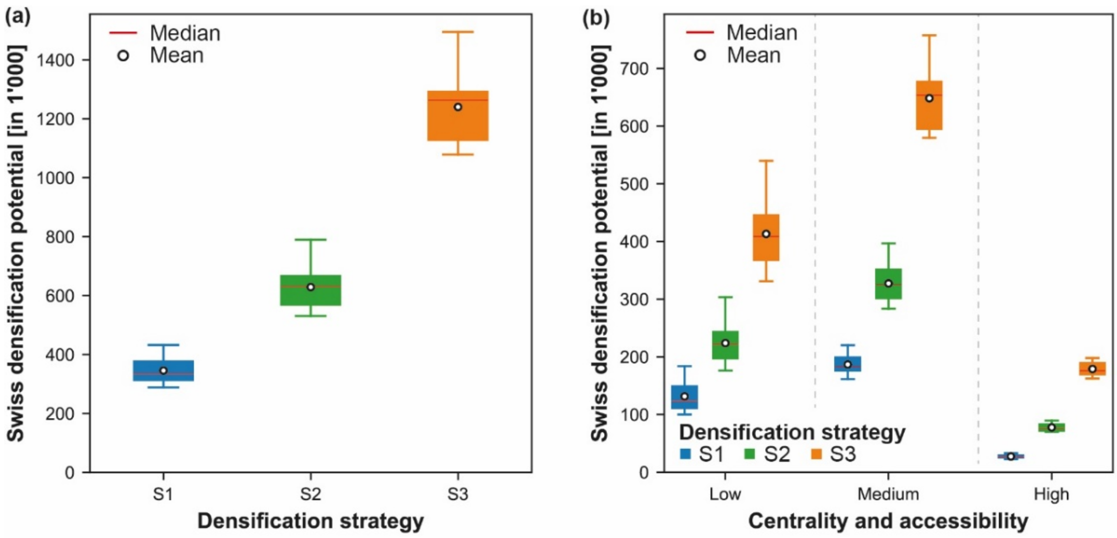


Figure 10: (a) National densification potentials per densification strategy and (b) according to their centrality and accessibility. The boxplots show combined methodological uncertainties whereby whiskers depict the full value range.

We note that for the locations with high centrality, the densification potentials are relatively small across all densification strategies. Given their economic importance due to their profitable location, many neighbourhoods already have high densities and/or have been densified. Even if neighbourhoods with low centrality and accessibility have potential especially if a concentrated densification strategy is adapted, these neighbourhoods should not be given priority from a sustainability perspective. The most interesting potentials are therefore neighbourhoods with medium urban centrality and accessibility. We find that there are many such neighbourhoods where particularly high potentials could be realized if a concentrated densification strategy (S3) were implemented. If only implementing a business-as-usual densification strategy (S2), the resulting potentials are much lower. We argue that it would be a missed opportunity for these neighbourhoods particularly if a business-as-usual densification strategy were to be pursued.

We note considerable methodological uncertainties as both the parametrization of the neighbourhood concept as well as the neighbourhood archetypes are imprecise, i.e. there are no unequivocal definitions. Furthermore, the classification of the archetypes depends on the supervised classification approach. These uncertainties reveal that for densification potential analysis, calculated numbers are not fixed but depend on a range of different assumptions and show the importance of communicating them.

We also aimed to take into account the potentially complicating effects on densification caused by listed buildings or listed zones. This is however challenging due to the lack of generally available data at the national level. Since national official cadastre data listing buildings or zones where potentially strict regulations apply are not readily available, we resort to a case study analysis of the Canton of Bern[72]. Protected zones and buildings potentially worthy to preserve are intersected with the identified neighbourhoods. A first estimate reveals that about 3.6 % of all identified buildings within post-war neighbourhoods potentially have a preservation order. Adding all buildings which also fall into specially protected zones, the total affected population increases to 4.7 %. These regional estimates enable a first evaluation of the potential impact preservation orders might have. However, a more in-depth analysis is needed with more complete data.

5.4 Answer RQ4: Spatial distribution of the densification potential

Simulated densification potentials vary considerably across administrative boundaries. As expected, the largest and most urban cantons such as Zurich (ZH), Bern (BE) or Geneva (GE) have the highest potentials in absolute terms. In relative terms, there is also considerable potential in cantons such as Zug (ZG) or Neuchâtel (NE) which supports the focus shift away from the main urban centres. The high-resolution overview of the densification potential on a community level in Figure 11 reveals that the overall pattern is similar across the different densification strategies. However, densification potentials are not distributed evenly across space: When comparing the centrality of the calculated potential in Figure 12, we note that particularly communities next to core-city centres have many neighbourhoods with medium centrality and accessibility, which could potentially accommodate a considerable amount of additional inhabitants (>20% of the current population). At the same time, we note that the potential resulting from neighbourhoods having a high centrality and accessibility is located in only a few communities.

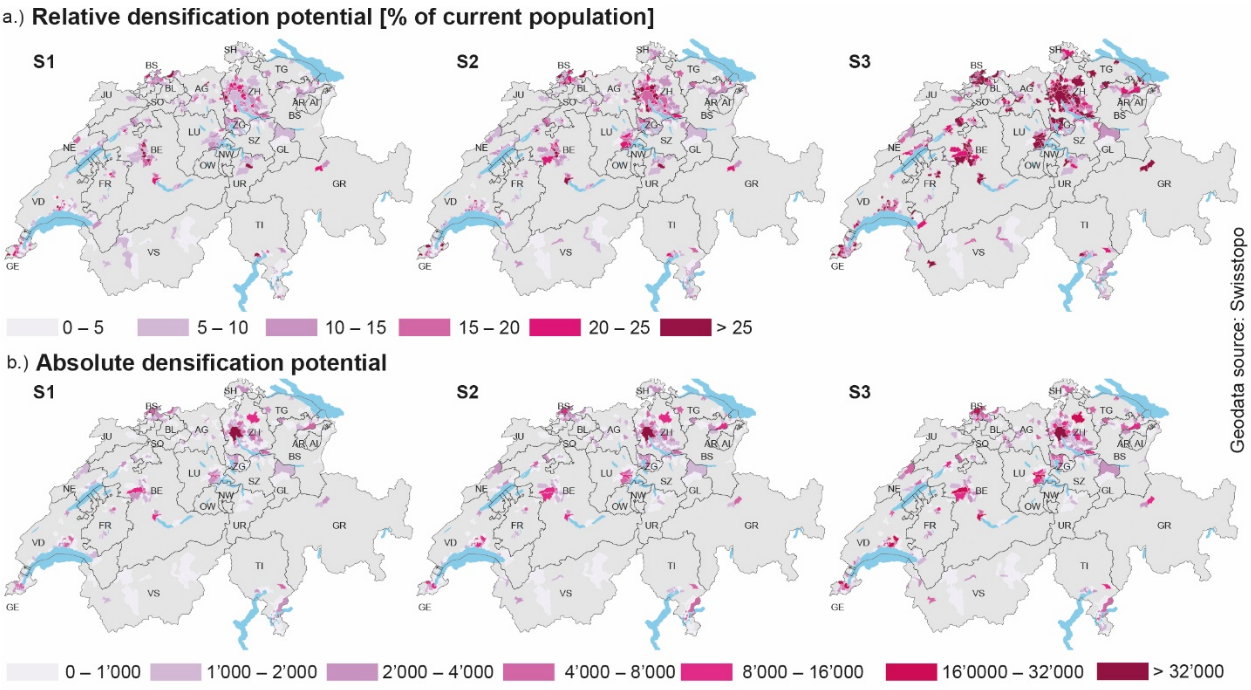


Figure 11: Mean densification potentials for the densification strategies S1 – S3 (a) given as a percentage of the current population per community and (b) in absolute numbers of inhabitants.

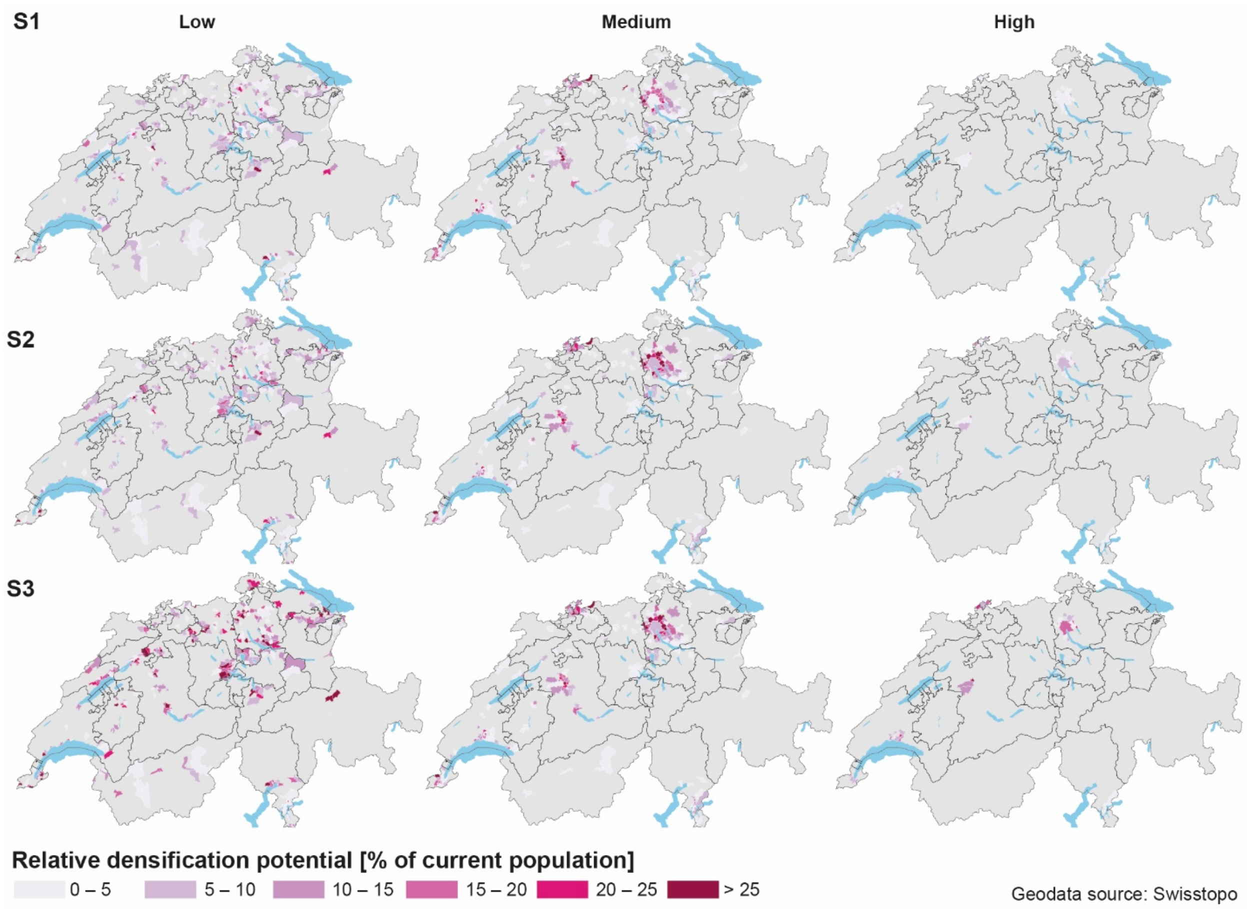


Figure 12: **Mean relative densification potentials per centrality and accessibility class (low, medium, high) and densification strategy (S1 – S3) as a percentage of the current community population. Absolute potentials are provided in the SM Note 3 in Eggimann et al. (2019).**

When comparing our results with existing studies, the scope of the respective analysis must be considered: Wüest Partner (2018)[1] for example estimate that within all existing Swiss developed and undeveloped building zones, there is room for an additional 2.59 million people. Nebel et al (2017)[40] estimate an overall Swiss densification potential of between 0.7–1.4 million people when considering undeveloped land reserves and the transformation of industrial sites. When only considering inward land-use reserves and densification of already built sites to maximum densities according to current regulations, they estimate a potential of 0.36–0.91 million people. This compares well with our calculated densification potential for our business-as-usual densification strategy (S2), where we estimate an average potential of 0.6 million people. Generally, we confirm the pattern that urban centres and agglomerations also show the highest potential when focusing on the sustainable densification of post-war neighbourhoods[12,4].

5.5 Answer RQ5: The impact of densification on the total energy consumption and CO_2 emissions

As discussed in the review, it is increasingly important to consider both the operational and the embodied energy and emissions in the assessment of the environmental impact of each densification strategy. Figure 13 and Figure 14 show the total aggregated emissions per occupant per year for each neighbourhood archetype. These graphs were created based on the specified reference urban designs (see Appendix B). Total energy and total emissions are comprised of both operational and embodied energy and emissions of the following components:

i) The **construction choice**, which is the embodied energy and emissions incurred through the construction of the key building elements (wall, roof, ground floor, internal floors) of new buildings in timber and concrete as specified in the SIA 2032.

ii) The **new build baseline**, which are the embodied energy and emissions incurred through the construction of all other building elements of new buildings that are not directly linked to the construction material choice e.g. excavation. The full list of assumptions is provided in Appendix 10.3.

iii) **Retrofits** are the embodied energy and emissions incurred through the addition of new materials (e.g. adding insulation or replacing windows) to the existing buildings of each scenario.

iv) **Operational energy and emissions** are comprised of the annual heating and cooling demand. The carbon emissions associated with heating assume gas as the heating carrier. The carbon intensity for gas heating assumed by CESAR-P is 0.281 $kgCO_2eq/kWh$.

These assumptions and the reasoning behind these components are explained in more detail in Section 3.5.

In this analysis, we have evaluated the energy and emission performance of each reference design per occupant. This metric enables a human-centric perspective on the impact of densification. In the first analysis (Figure 13 and 14), we consider the impact across all occupants in the neighbourhood. This metric helps us understand the overall impact on the neighbourhood based on the degree of densification that is achieved. In the second analysis (Figure 15 and 16), we only consider the energy and emissions incurred during the construction of new buildings and their occupants. The purpose of this enables planners to understand the impact of constructing new buildings to house occupants.

5.5.1 Total occupants

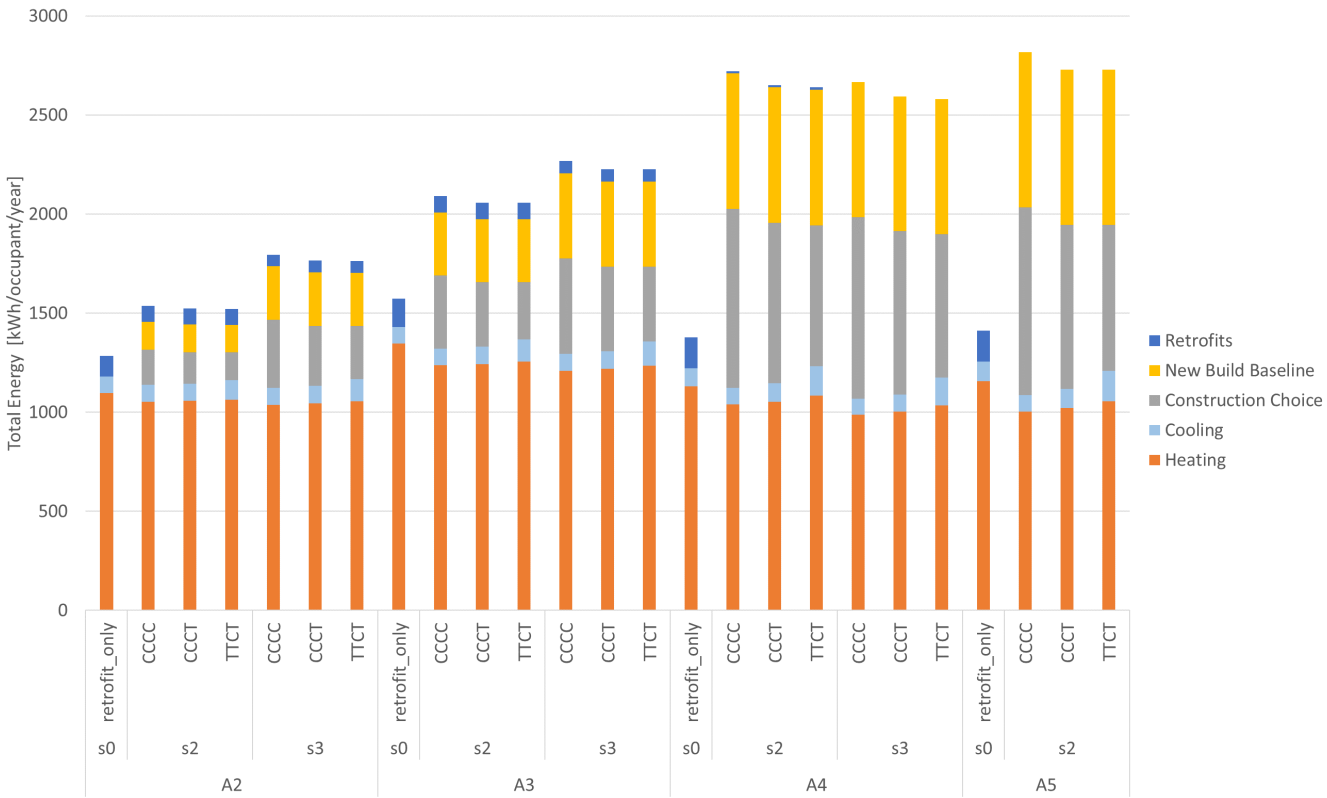


Figure 13: Total energy for each construction scenario and densification strategy for each neighbourhood archetype (A2-A5).

This analysis shows that increased densification of archetypes A2 and A3 results in an increase in total energy per occupant; whereas A4 shows a decrease in the energy per occupant as densification increases. The reason for this is likely due to the degree of densification achieved across the different neighbourhood archetypes. The reference designs of A4 increase the original population of the neighbourhood by 300% for the concentrated densification strategy (S3) compared to approximately 50% for A2 (S3) and 75% for A3 (S3). This significantly higher increase in the population means that the embodied energy is spread across more occupants which results in improved performance for the higher densification of A4.

The heating demand makes up a larger fraction of the A2 and A3 neighbourhoods because these designs kept the majority of existing buildings. Retrofitted buildings also perform worse than the new buildings and there is a slight reduction in the energy demand per occupant for scenarios A4 and A5. Neighbourhood archetypes A4 and A5 have a higher proportion of embodied energy because each of their representative urban designs was mostly rebuilt for each densification strategy. The 'retrofit-only' strategy has the lowest embodied energy because it only contains existing retrofitted buildings and no new buildings were added. However, in this case, no densification is achieved. From this analysis, it can also be seen that the construction choice of the main building elements (roof, wall, ground, floors) accounts for approximately 50% of the embodied energy categories of the new buildings in all scenarios.

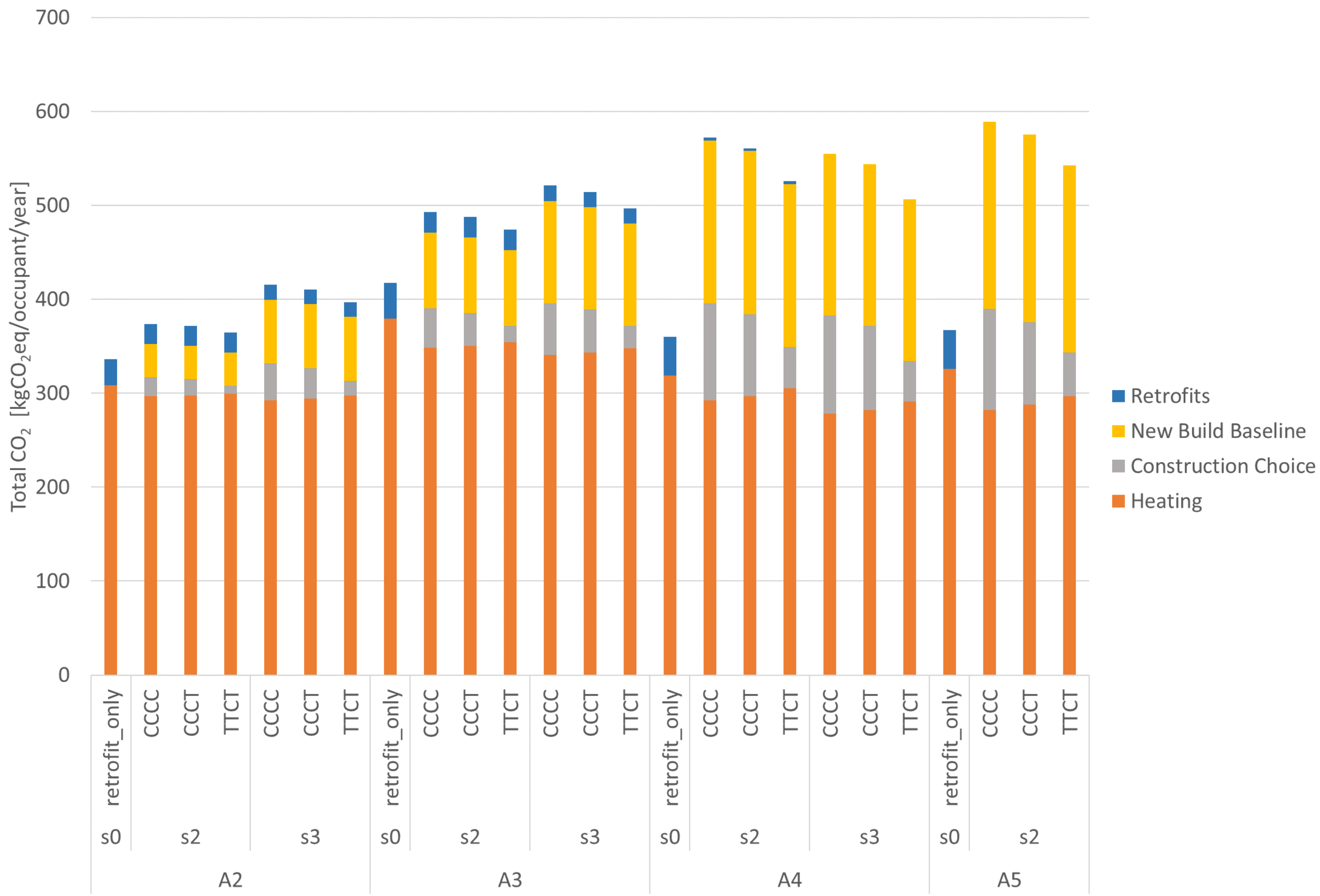


Figure 14: **Total emissions for each construction and densification strategy for each neighbourhood archetype (A2-A5). Cooling demands for residential buildings are assumed to be met by passive measures so embodied emissions have not been assigned.**

The embodied and operational emissions for each scenario are shown in Figure 14. This shows a similar pattern to the embodied and operational energy. The biggest difference in the two graphs is the greater reduction in emissions as a result of construction material choice – this is explored in more detail in Section 5.6. Also, note that we assumed that the heating system is supplied by a gas boiler for all properties. If a gas-boiler system is replaced by a heat pump, the operational emissions could be reduced by approximately two-thirds based on the values of carbon intensity listed in the KBOB[103].

Figure 13 and Figure 14 show that the neighbourhood archetypes with the highest portion of new builds (A4 and A5) have considerably more embodied energy/emissions per occupant than the archetypes that kept the majority of existing buildings (A2 & A3). This means that densification strategies that can increase the number of occupants while at the same time, limiting the construction of new buildings, will achieve the best performance in terms of embodied energy/emissions.

5.5.2 Occupants of new buildings

The impacts of constructing new buildings are evaluated for additionally added occupants which are placed in new buildings for each densification strategy. Figure 15 and Figure 16 show the total energy and total emissions per new occupant. Through this analysis, there is a slight improvement observed per occupant for the concentrated densification strategy (S3) vs the business as usual (S2) (the only exception is A3 where a slight increase is observed between S2 and S3). As this analysis only considers the impact of new buildings, the densified strategies of neighbourhoods A2 and A3 now resemble the plots of A4 and A5 shown in Figure 13. Figure 16 shows that the use of timber achieves a reduction of between 7.9% (A3 S3) and 9.6% (A4 S3) in the total CO_2 for each densification strategy.

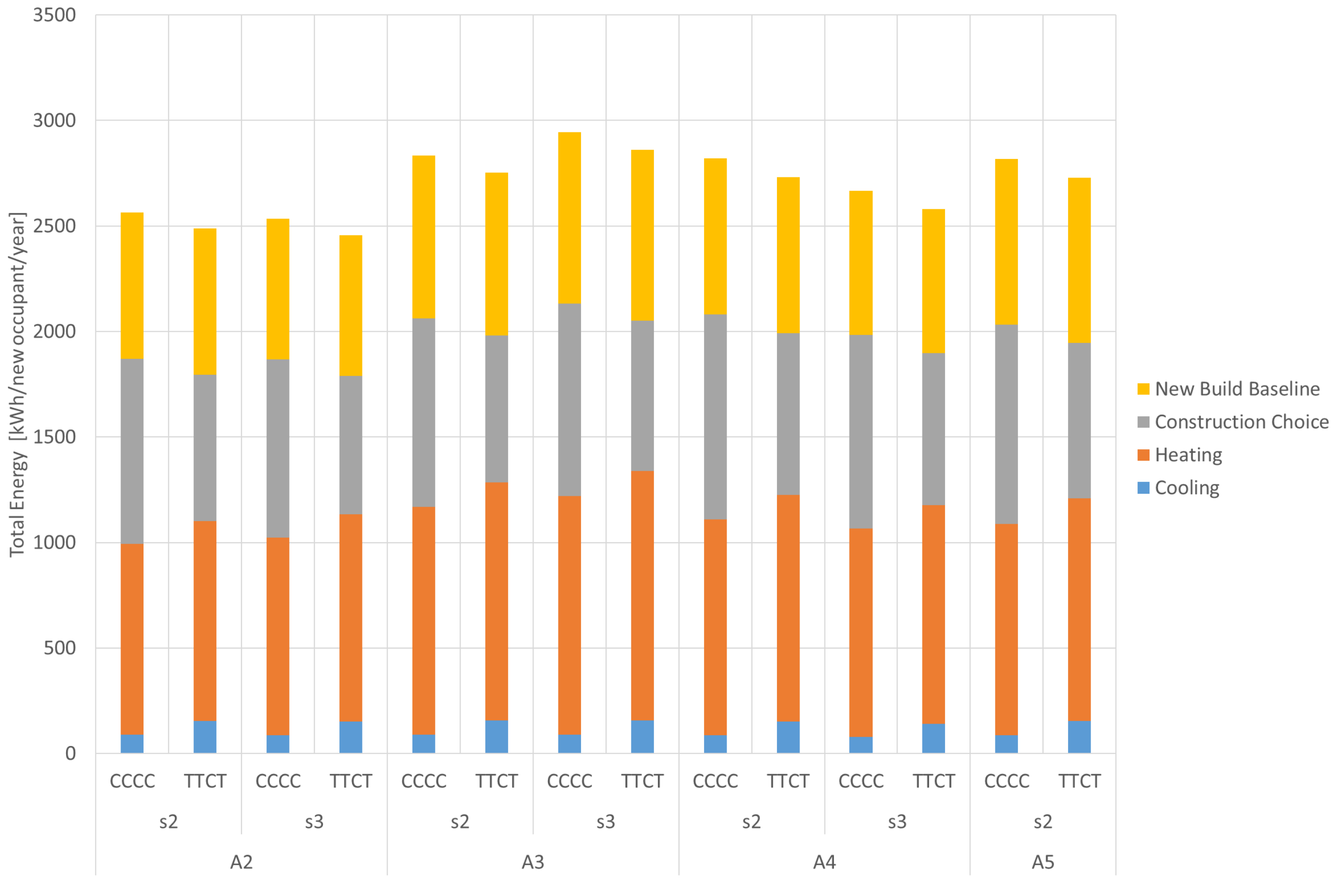


Figure 15: Total energy for new buildings and the new occupants for each neighbourhood archetype and densification strategy.

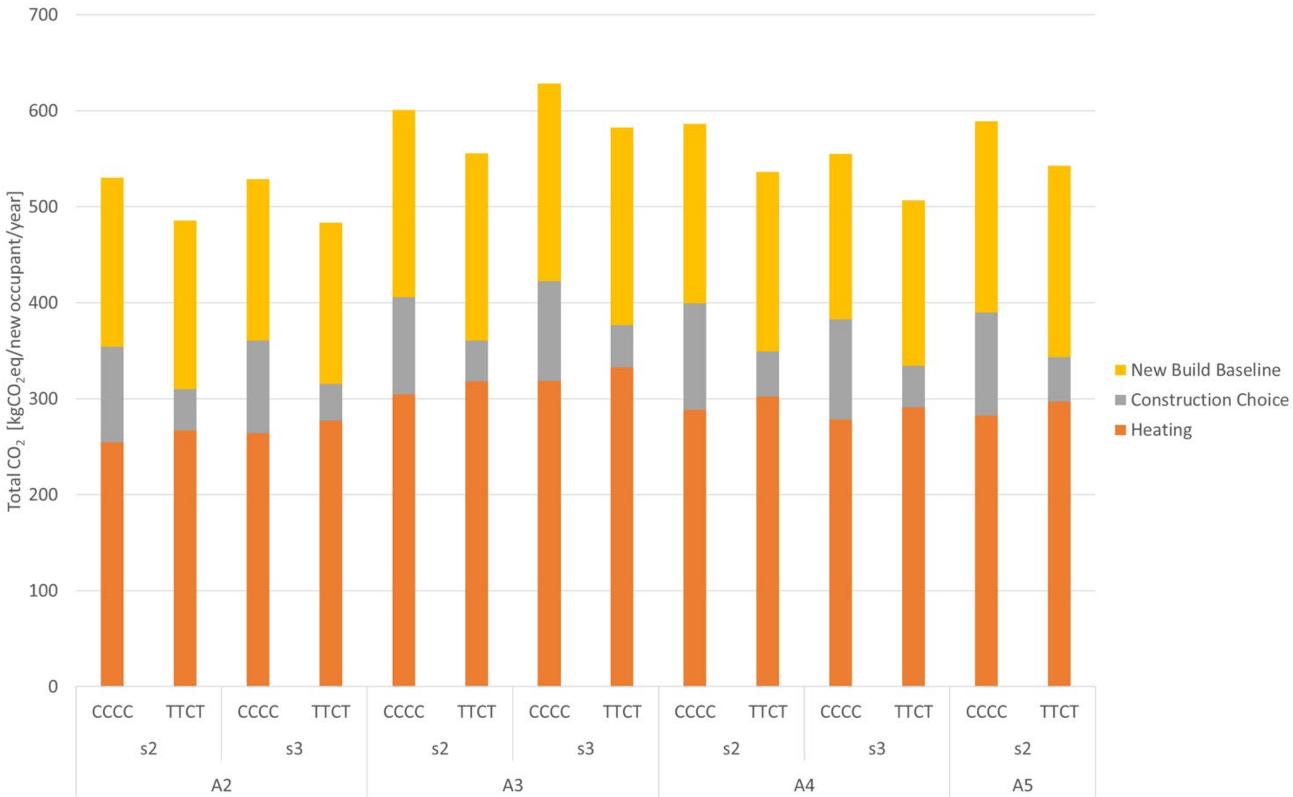


Figure 16: Total CO_2 for new buildings and their new occupants for each neighbourhood archetype and densification strategy.

This analysis shows a slight increase in the total energy per new occupant at Tscharnergut (A2), Irchel (A3), Köniz-Buchsee (A3) and Lochäcker (A4) for the concentrated densification strategy (S3). The difference in performance observed between reference designs of the same archetype shows that there are aspects of the design of new buildings that affect the energy performance per building. Feedback during the early design process could help designers understand the implications of their choices. A more detailed overview of the total energy impact for each reference urban design is provided in Appendix 10.5.

The construction of new buildings to accommodate new occupants as part of a densification strategy will inevitably lead to an increase in energy consumption for the neighbourhood; however, there are critical design choices that could lead to a better energy performance per occupant for the higher densification scenarios. In this study, the best performing archetype was the A4 archetype which primarily involved the construction of large buildings to house many occupants. The worst performing archetype was A3, which saw a small increase in the total energy per occupant, this is likely a result of more material being required to house a smaller number of occupants. This study assumed a fixed floor area per occupant; however, if there is a rationale to support more occupants per floor area in one building type or neighbourhood archetype then this would also improve the per occupant performance. A more detailed, controlled parametric study of the built form is required to understand the interrelationships between design choice and the impact of total energy/emissions. This would also require more detailed data on the materials and the processes used to construct the building. A useful metric in such a study would be the quantity of material required per occupant and this would have an associated energy and carbon intensity.

5.6 Answer RQ6: The influencing factors of densification on energy demand, share of renewable energy sources and embodied CO_2 emissions

The previous answer (RQ5) established that densification increases the total amount of energy consumed by the neighbourhood. This RQ investigates the influencing factors within each of the densification scenarios, to establish what can be done to further improve performance. Firstly the impact of the choice of timber versus concrete on embodied and operational performance is investigated. In the second part, the impact on the design of the available solar potential is calculated.

5.6.1 Timber versus concrete for construction

This project focused on operational energy demand and embodied emissions resulting from the choice of construction materials used in each of the densification strategies. The values of embodied energy and embodied carbon were taken from the SIA 2032 standard to investigate the impact of material choice in each of the densification strategies. These values are assumed to represent the average impact of using timber and concrete in the construction of buildings. The authors acknowledge that there are many different forms of concrete and some may have a better environmental footprint than timber. There is also the potential to recycle and re-use materials that will reduce the reported embodied energy and emissions. The purpose of this study is to indicate the impact of the choice of using concrete versus timber for the different building elements. A detailed life cycle assessment of the building products should be considered on a project basis.

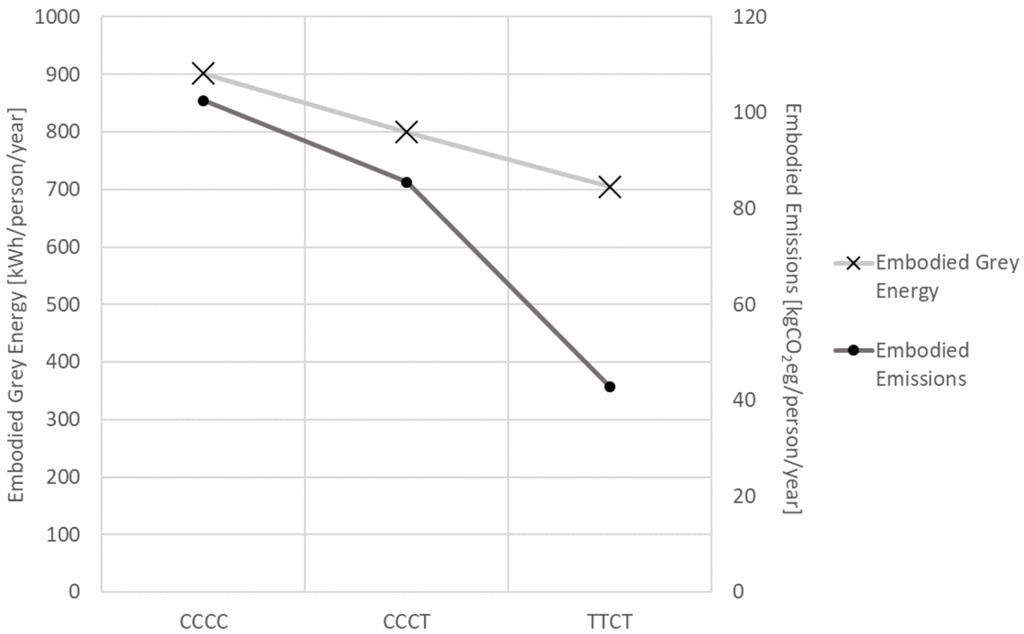


Figure 17: Averaged embodied emissions and grey energy due to material construction choice per person per year.

The average embodied emissions and grey energy across all of the neighbourhoods and densification strategies are shown in Figure 17. This shows that the choice of the timber intensive scenario (TTCT) has on average 50% of the embodied emissions of the all-concrete scenario (CCCC). The reason for the sharp drop in embodied emissions between the CCCT and TTCT scenario compared to the embodied grey energy, is because the specific embodied grey energy for timber internal floors (11

MJ/m^2/year) is similar to concrete (13MJ/m^2/year) however the embodied emissions for timber (0.6 kgCO_2eq/m^2/year) is around just over a third of the value for concrete (1.5 kgCO_2eq/m^2/year) according to SIA 2032. This is a result of the carbon sequestration properties of timber throughout its lifecycle.

The results of the operational energy simulation averaged across all neighbourhoods and densification strategies are shown in Figure 18. Heating is currently the dominant demand and is an order of magnitude higher than the cooling demand for the buildings of this study. The timber intensive scenario (TTCT) has higher cooling demand (+40%) and slightly higher heating demand (+2.3%) compared to the majority of concrete construction (CCCC). The difference in the cooling demand is due to the higher thermal mass achieved using concrete and the difference in heating is negligible. The energy savings using concrete may become more important in a warming climate; however, active cooling is currently rarely used in residential buildings in Switzerland.

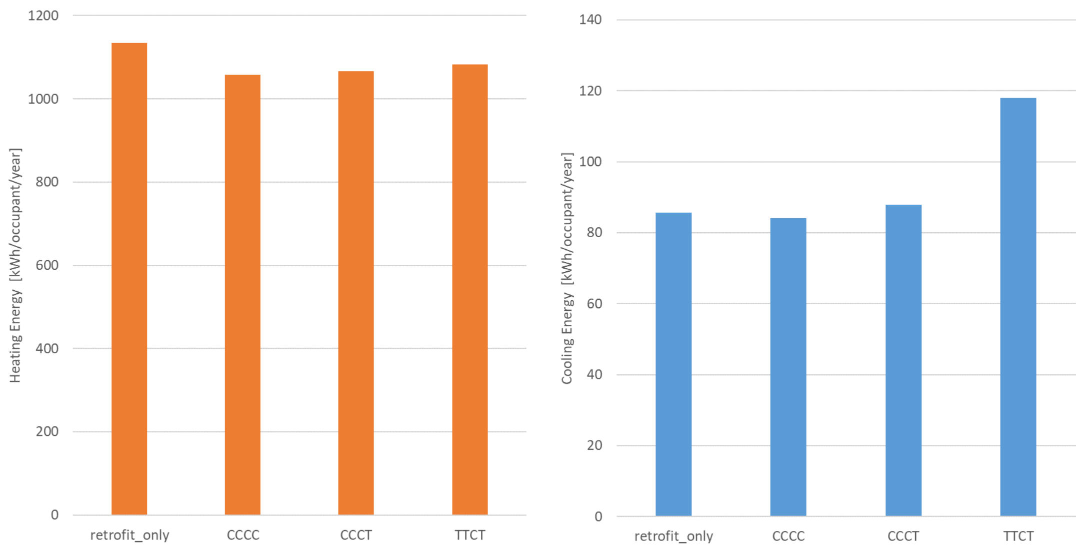


Figure 18: Annual operational emissions for heating and cooling per occupant calculated using CESAR-P. Heating energy demand on the left and cooling demand on the right.

5.6.2 Impact on solar potential

The solar potential of each reference design was aggregated for each surface direction. This takes into account the shading from the neighbouring buildings. The solar potential for each archetype and densification scenario are shown in Figure 19. Designs that have a greater proportion of unshaded high buildings with south-facing facades, such as A2, generally have a higher solar potential for the south-facing surfaces.

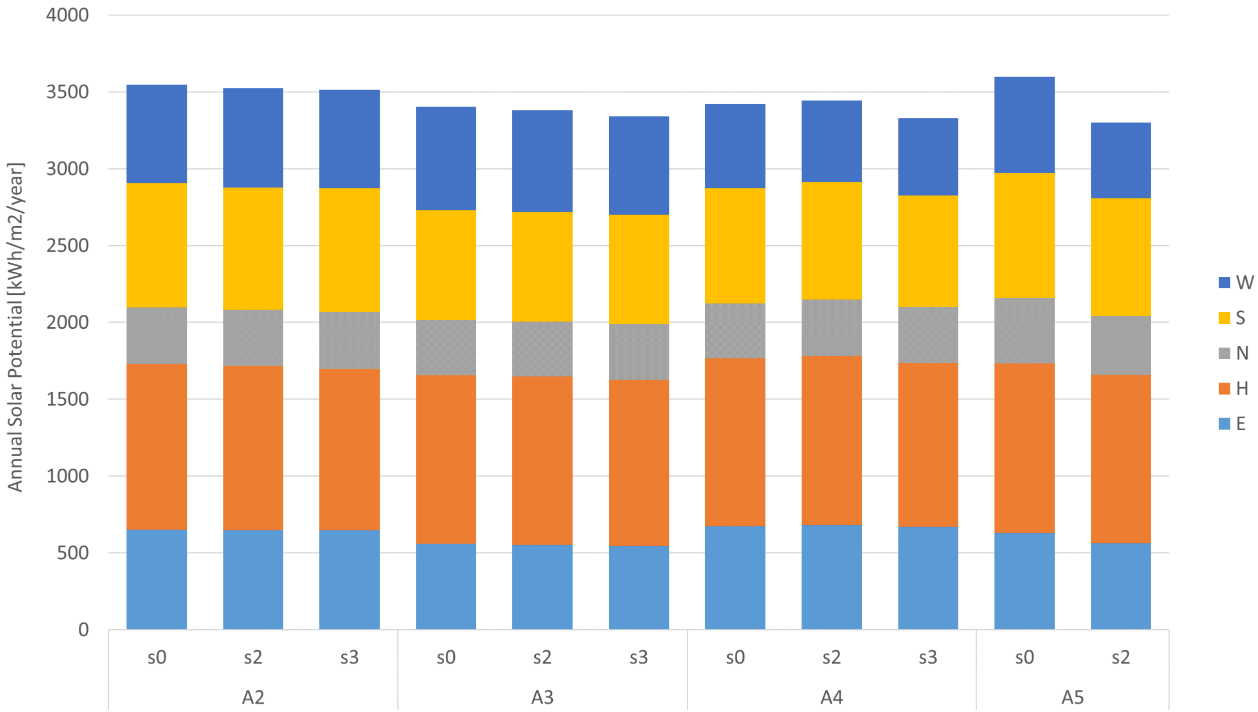


Figure 19: **Solar potential of each of the reference archetypes.**

The range of the average total solar potential 633 kWh/m^2 and 740 kWh/m^2 were found in designs belonging to the same neighbourhood archetype. This shows that the solar potential is influenced by the site conditions and design rather than being specific to a particular archetype.

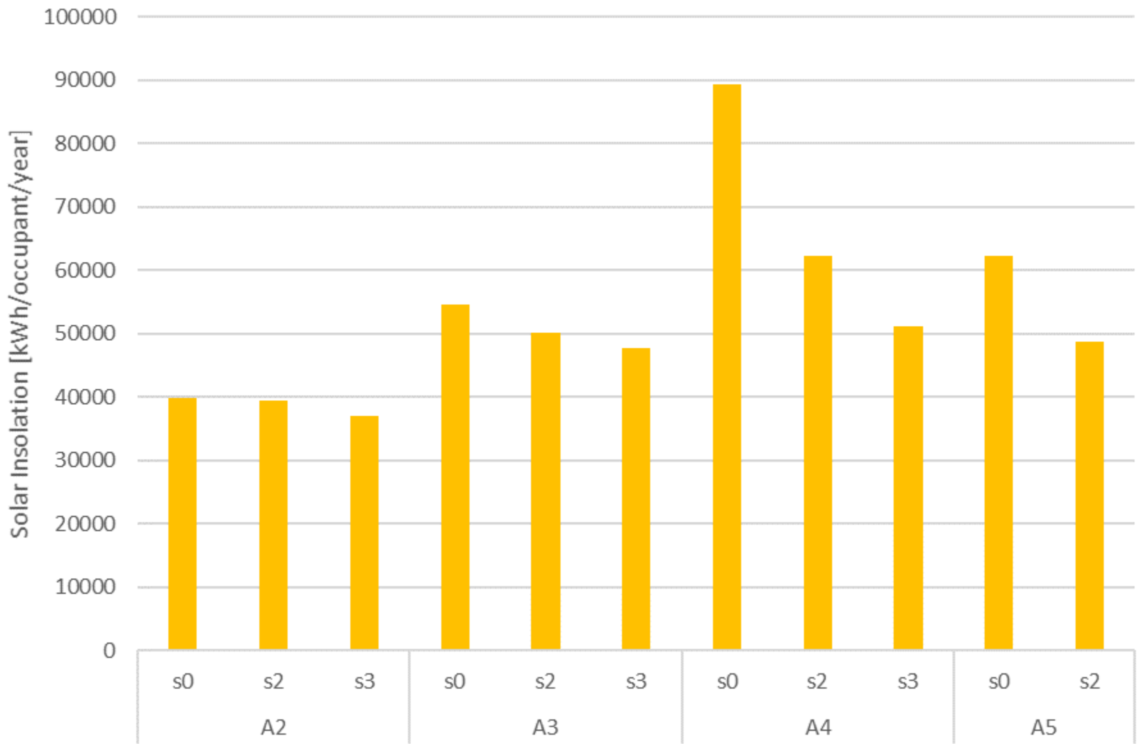


Figure 20: Solar insolation per occupant per year of each neighbourhood archetype and densification strategy.

Figure 20 shows that the solar insolation for all surfaces decreases across the densification strategies. This is because there is less building surface area per occupant for the densified strategies. This study only considers the potential of building-integrated and building-mounted solar energy systems. It does not consider the possibility of developing large-scale solar farms using rural sites that would otherwise be used for housing if a densification approach is not adopted. Densification may prove more favorable to medium-sized forms of renewable and efficient energy generation e.g. biomass, hydro, district heating, that are designed to supply at the community level; however, there was insufficient data on the reference designs or neighbourhood archetypes to establish how and where such supply systems could be implemented. Such an analysis is likely to be more strongly coupled to the centrality of a site, where regulatory factors are also considered. It is also important to establish resource availability as a factor of the neighbourhood or region.

The investigation of influencing factors found that significant savings in embodied energy of the new constructions can be achieved using materials with a low embodied carbon intensity. In this study, we have used the assumptions of carbon intensity for timber and concrete from SIA 2032; which offers a high-level analysis of the implications of using the materials to construct the main building elements across the densification scenarios. It is recommended that a more detailed analysis be carried out during the design and procurement stages because the origin and type of material will have a large implication on the final performance.

Addressing this research question also established that densification is not the ideal case for integrated solar technologies because its amount of surface area per occupant is reduced. More data would be required for a more detailed analysis of decentralised vs centralised energy supply of different densification scenarios.

5.7 Answer RQ7: The impact of densification on the total energy of the neighbourhood archetype across Switzerland

A previous controlled study of urban form showed that the specific cooling and heating demand decrease with the number of floors[48]. In this study, the built form of the reference urban designs varies considerably between the buildings in each archetype, see the summary in Table 4 and Table 5. In the future, operational demand will continue to be reduced by energy efficiency improvements and the demand will increasingly be supplied by renewable energy technologies[62]. Figure 21 shows the total annual energy averaged across the construction strategies, for each of the neighbourhoods. In all cases, there is an increase in total energy for each densification strategy. This is because the densified neighbourhoods have an increased quantity of and larger buildings.

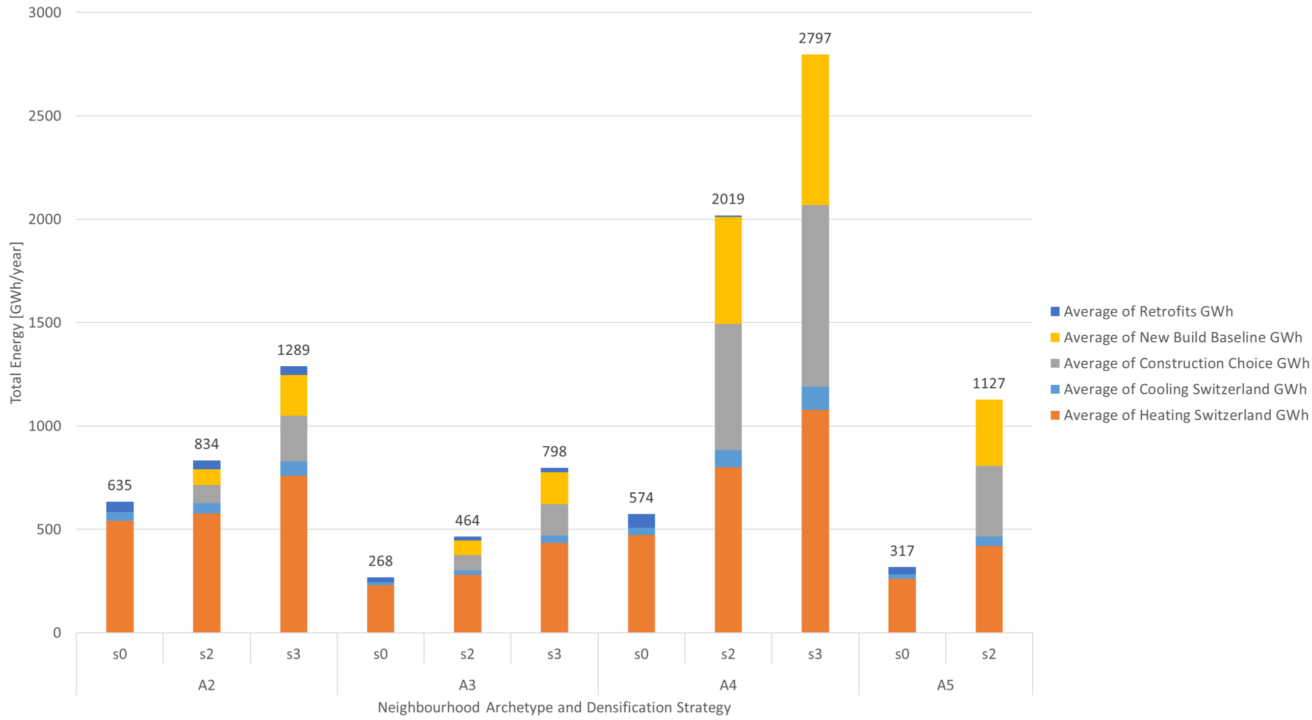


Figure 21: The upscaled energy demands for each neighbourhood archetype (A2-A5) and densification strategy (S1 – S3) averaged across the construction strategies.

This analysis shows that densification of the A4 archetype incurs the greatest amount of energy. This is because this archetype has the greatest densification potential, in terms of population, see Figure 6. This archetype also has one of the highest total energy per occupant, see Figure 13. The densification approach for this archetype primarily involves the construction of new buildings, the majority of the total energy is embodied. This means that sustainable construction solutions for the densification of this archetype could yield the greatest energy and emission savings across Switzerland.

5.8 Answer RQ8: The factors with the greatest impact on total energy across Switzerland.

The annual upscaled results are shown in Figure 22 for total emissions and Figure 23 for total energy for each construction strategy. The data used to plot these tables is provided in Appendix Section 9.4.

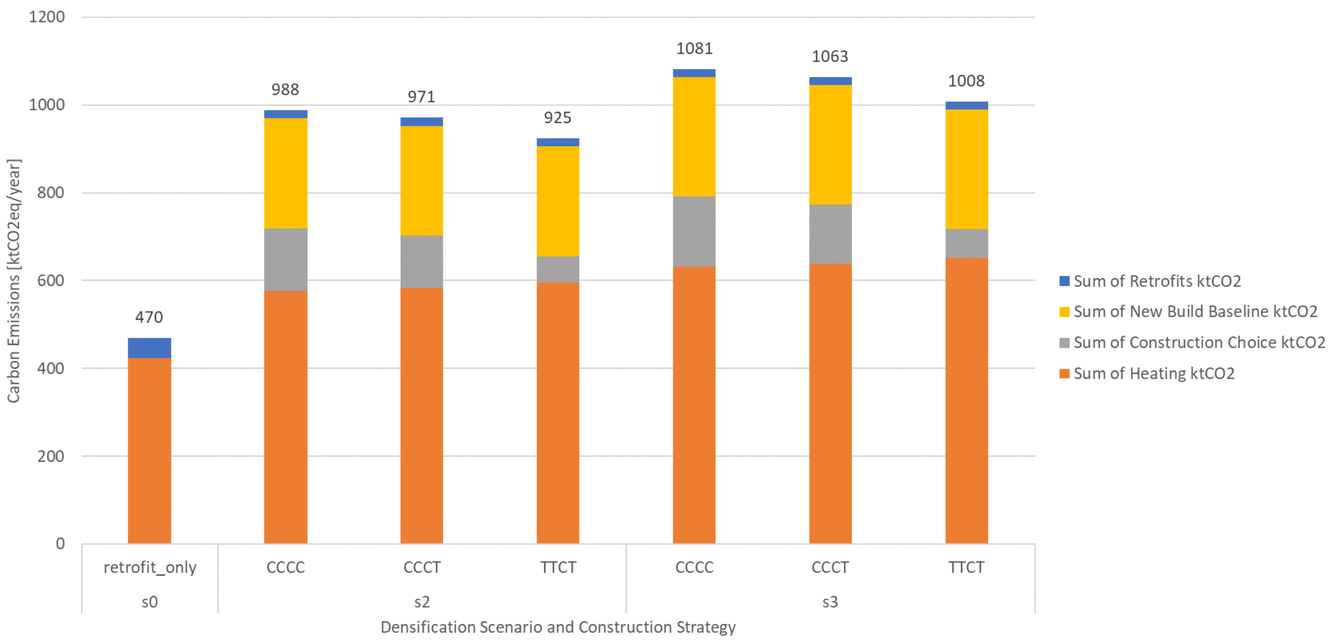


Figure 22: Upscaled values of total carbon emissions for the post-war neighbourhoods across Switzerland (CCCC: concrete scenario TTCT: timber intensive scenario).

Figure 22 shows that the S3 densification strategy has the highest emissions. In this strategy, the all-concrete construction strategy (CCCC) has the highest emissions at 1’081 ktCO_2eq. By replacing concrete and using timber in the construction of the walls, internal floors and the roof (scenario TTCT) a saving of 6.4% (63 ktCO_2eq) for the S2 strategy and 6.8% (73 ktCO_2eq) for the S3 strategy can be achieved. The construction choice can be reduced by about 50% between concrete and timber, however, some of this positive effect is compensated by a slight increase in operational emissions. The embodied emissions savings due to material choice are relatively insignificant based on the assumptions made in this study. A more detailed assessment of the carbon and energetic intensity of the assumptions made in the baseline emissions may yield further savings.

Figure 23 shows that the S3 densification strategy is the most energy-intensive strategy. When comparing total energy, there is less difference across construction strategies (4%). This is due to concrete having a favourable energy performance compared to timber due to its higher density. In the future, due to a warming climate, timber buildings may have a greater requirement for air conditioning or ventilation strategies.

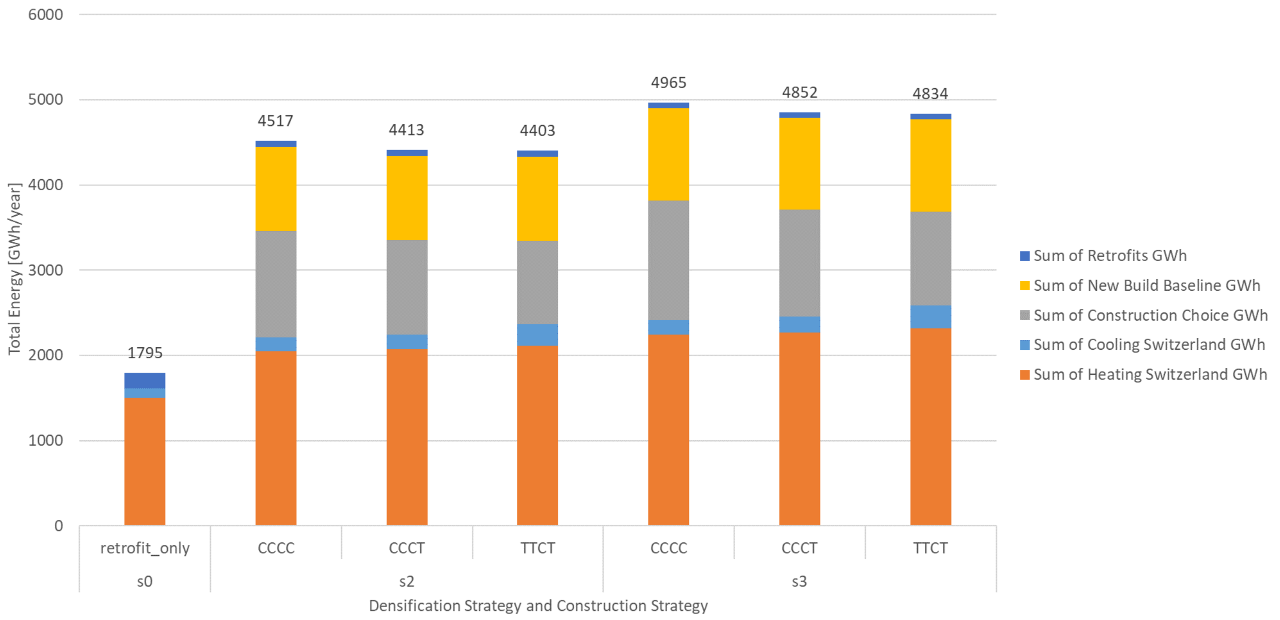


Figure 23: Upscaled values of total energy for the post-war neighbourhoods across Switzerland (CCCC: concrete scenario TTCT: timber intensive scenario).

5.9 Answer RQ9: The impact on total energy when all existing buildings are refurbished and extended to meet the densification quotas

The original reference designs are based on typical approaches for the neighbourhoods (see Appendix 10.2). After reviewing the results of the first simulation, we wanted to know the environmental impact when all existing buildings are kept and the additional densification quota is achieved by extending the existing buildings vertically by one floor. This approach is typically avoided due to the expense; however, we were keen to know the environmental performance in case a cost trade-off is needed in the future. The calculation methodology for this approach is detailed in Section 3.5.

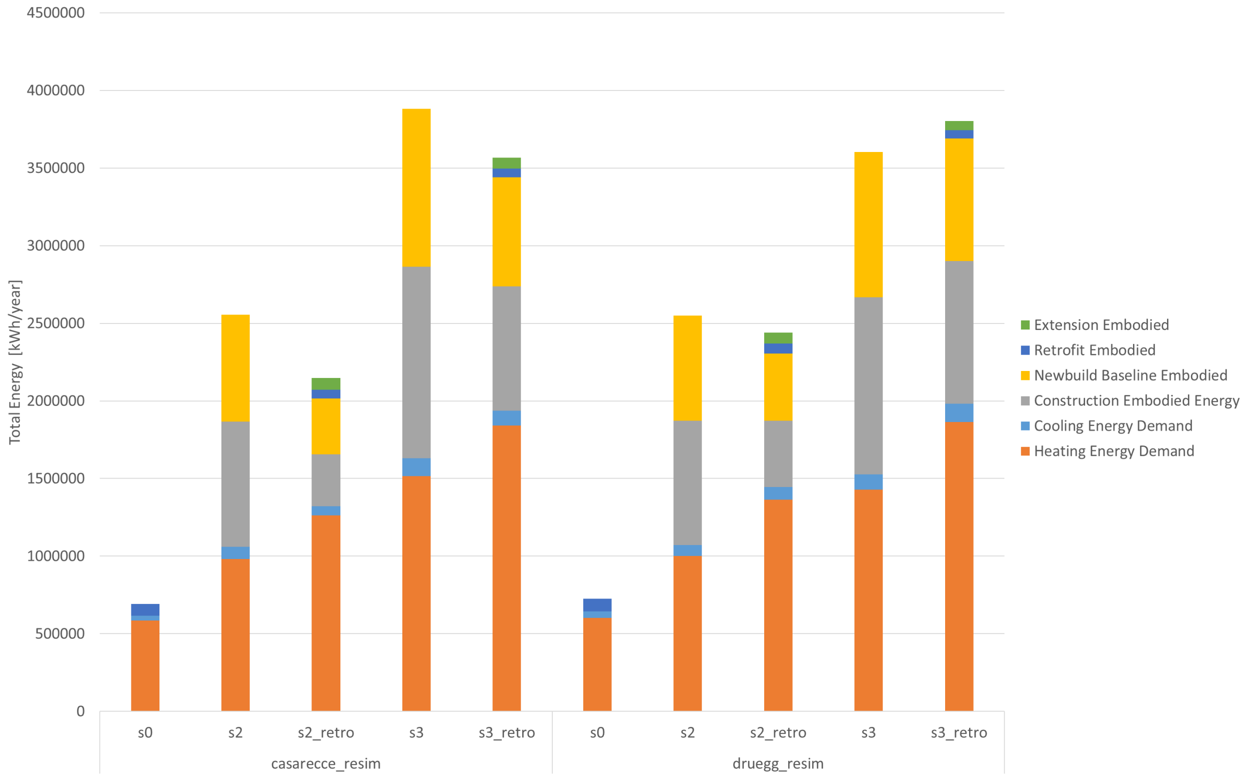


Figure 24: Result of retro-plus strategy where all existing buildings are kept. New builds are kept to a minimum and additional occupant capacity is achieved by extending the existing buildings by one floor.

Figure 24 shows the results of keeping the existing buildings in the retro-plus designs of the A4 archetype. In both cases, there is a significant reduction in the embodied energy associated with new buildings; however, this improvement is partly offset by the older buildings having higher operational energy than designs consisting of all new buildings. This means that to be effective, the retro-plus strategy must also address the performance gap between new and retrofitted buildings. In the case of Drüegg, the higher operational energy from the retrofitted buildings completely outweighs the reduction in embodied energy from minimizing the construction of new buildings. The difference in these results for designs from the same neighbourhood archetype highlight the challenge of generalizing a particular strategy to a specific archetype.

6 Key conclusions, recommendations and further research needs

Based on this research project, the following key conclusions and recommendations can be made. They also indicate gaps in knowledge and identify future fields of research:

Post-war residential neighbourhoods offer a high potential for densification…

Urban densification of entire neighbourhoods is an opportunity to tackle multiple environmental challenges whilst addressing current urbanisation trends. Our analysis reveals that there is considerable densification potential in post-war neighbourhoods in Switzerland. These are neighbourhoods that are already built-up and inhabited. This finding is promising for countries such as Switzerland where the transformation potential of former industrial sites for densification is becoming increasingly scarce. Therefore, we recommend a stronger focus of the densification discourse on already existing buildings and neighbourhoods, i.e. post-war neighbourhoods, instead of new development areas. However, the implementation possibilities are not always ideal, depending on location, ownership structure, building condition and economic constraints. There is a need for further research on how these potentials can be reaped, which includes studying the economic feasibility as well as how to densify in the context of multiple ownerships.

…but this potential is highly dependent on their location within the existing infrastructure systems.

We simulated densification potentials for a business-as-usual densification strategy and a strategy where current policies would allow for higher neighbourhood densities (concentrated strategy). Depending on the pursued strategy, an additional 0.35 – 1.4 million people (4 – 15% of the current Swiss population) could be accommodated in Switzerland within post-war urban neighbourhoods. A densification potential of around 0.7 million people was estimated for a business as usual densification strategy and about 1.4 million people for the concentrated densification strategy. Across all scenarios, more than half of this potential is located in favourable locations (central and medium centrality), which we recommend to be considered first to densify. We have argued that as opposed to greenfield land development, sustainable densification should take into account the existing building stock as well as other infrastructure systems such as transportation and mobility.

A holistic and interdisciplinary approach is required for drawing conclusions on the trade-off between energy, densification and impacts on other sectors.

We have only focused on the energy performance of buildings. A more detailed study integrating the impact of different sectors (e.g. mobility, infrastructure) would provide a more holistic view of the impact of each strategy. We recommend for future studies to not consider densification in isolation but do a cross-sectorial consideration. Further projects should not only consider the spatial dimension of densification but also take on a multi-disciplinary perspective and particularly consider sector coupling. Densification projects evaluating the sustainability of densification should particularly include the transportation sector as well as other infrastructure systems to be able to deduce more robust conclusions. This study can serve as a basis to continue working on this topic in a more transdisciplinary way.

The densification potential of post-war neighbourhoods in highly central locations is limited but substantial in medium central locations. In both cases, it should be more actively promoted.

We find that the overall densification potential in highly central locations is limited. However, we have identified considerable potential in locations with medium centrality and accessibility. We believe that it would be an opportunity lost to pursue a business-as-usual densification strategy instead of realising higher densities in these neighbourhoods. We recommend a concentrated densification strategy particularly in well-connected and highly suitable locations. These potentials are not distributed evenly across Switzerland and substantial population growth from densification in medium or highly central locations would therefore be focused on few communities (see Figures 10, 11 and 12).

The floor area used per occupant is a critical consideration for sustainable densification.

Whenever a new building is constructed the embodied energy and emissions can be spread across the occupants. If it is possible to accommodate more people in fewer buildings it improves the energy and emissions on a per occupant basis. We have assumed a constant floor area per person (cf. Section 3.1.2). We find that the most critical influencing factor for densification as well as for energy use is the floor area per person, which should, therefore, besides locational considerations, receive most policy attention when improving the sustainability of densification.

More research is required to determine the full impact of material choice on total energy and emissions.

The choice of construction material, based on the assumptions made in this study, had a relatively small impact on the performance in terms of total energy and emissions. The savings from choosing timber over concrete ranged from 6.4% to 6.8% for the densification strategies considered and assumptions made in this study. A more detailed study where more information on the baseline assumptions and the specific types of materials and their origin may yield greater savings. This could also work towards quantifying the uncertainty in the results due to the assumptions. Due diligence on all assumptions is required during the detailed design phase and procurement phase. The authors recognise that there is not a single type of timber and concrete and care must be taken when specifying assumptions for a particular project.

Reducing the reliance of new buildings should also address the performance of retrofitted buildings.

In the revised retrofit-plus scenarios, the number of new buildings was minimised and existing buildings were extended to accommodate the additional occupants from densification. This achieved a saving in the embodied emissions. However, this resulted in an increase in operational demand due to the higher percentage of old retrofitted buildings. This means that any strategy that adopts this approach must tackle both the embodied energy and operational aspects to achieve a reduction in the total emissions.

The current socio-economic and institutional framework conditions are challenging for densification that optimises for energy and emissions perspective.

While our assessment allows for the simulation of densification potentials, fully reaping these potentials may require considerable institutional and policy innovation to facilitate neighbourhood transformations at larger scales. We found that neighbourhoods are often heterogeneous in terms of existing buildings (building age, building type etc.) and in terms of ownership structure. This may complicate a coordinated transformation and densification of entire neighbourhoods.

Depending on the developed neighbourhood and envisioned densification, making the most use of existing buildings can lower embodied emissions and should be carefully evaluated. For a case study example, the S2-retro-plus and S3-retro-plus densification strategies achieved the same densification as the S2 and S3 strategies but saw a reduction in embodied energy ranging between 20% and 50% for the neighbourhoods and densification strategies considered. We note that the economic framework conditions may hinder the pursuit of suggested densification strategies as they are unrealistic from today's economic perspective.

Energy and emission aspects should systematically have an early influence on the urban design process to foster sustainability.

There is to date no systematic approach concerning energy and emissions integrated into the development of the urban designs for each reference neighbourhood we analysed. This raises the need for a tool that enables the consideration of embodied and operational emissions during the early design phase of densification strategies. For densification strategies, this should be combined with an occupant centric evaluation of performance i.e. kWh/occupant/year. For example, if architects had a tool that could give them feedback on their design decisions, they could optimise their designs based on the specific constraints and requirements they are working with.

Further investigations for a more detailed parameterisation of urban designs could allow for a more comprehensive evaluation.

The reference neighbourhoods used in the evaluation and scaling of the energy and embodied performance only contained the building geometries. All other assumptions were made based on standards and statistics. If more data could be collected about the urban design regarding the specific use of individual buildings, construction specifications, surrounding infrastructure etc. then a more comprehensive evaluation could be carried out.

The data needed for such analyses is not harmonised at the national level.

The detailed and realistic estimation of densification potentials would be improved with better data availability. Densification analysis would be facilitated by releasing data at the national scale, such as e.g. a national database with all protected buildings and zones. We also recommend a national database with detailed information on the building refurbishment status, current floor area ratio as well as maximum legally allowed floor area ratios at a plot level. For the energy analysis, more information about the current material properties of buildings would be required.

The uncertainty of exact figures concerning grey energy should not be underestimated.

The estimation of energy and embodied emissions have been based on standards. These do not provide a range of uncertainty for the figures. We recommend that this uncertainty should at least contain the variation in the embodied emissions of variation in types of timber and concrete used in construction.

7 Publications

The findings of this research project have been published as follows:

- Eggimann S., Wagner M., Ho Y.N., Züger M., Schneider U., Orehounig K. (2021): Geospatial simulation of urban neighbourhood densification potentials. Sustainable Cities and Society, 72, 103068. https://doi.org/10.1016/j.scs.2021.103068
- Eggimann S., Wagner M., Chen T., Ho Y.N., Schneider U., Orehounig K. (2020): Sustainable urban densification potentials: a geospatial analysis of Swiss post-war neighbourhoods. IOP Conference Series: Earth and Environmental Science, 588, 1.01–1.05. https://doi:10.1088/1755-1315/588/2/022040

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10 Appendix

10.1 A – Urban areas

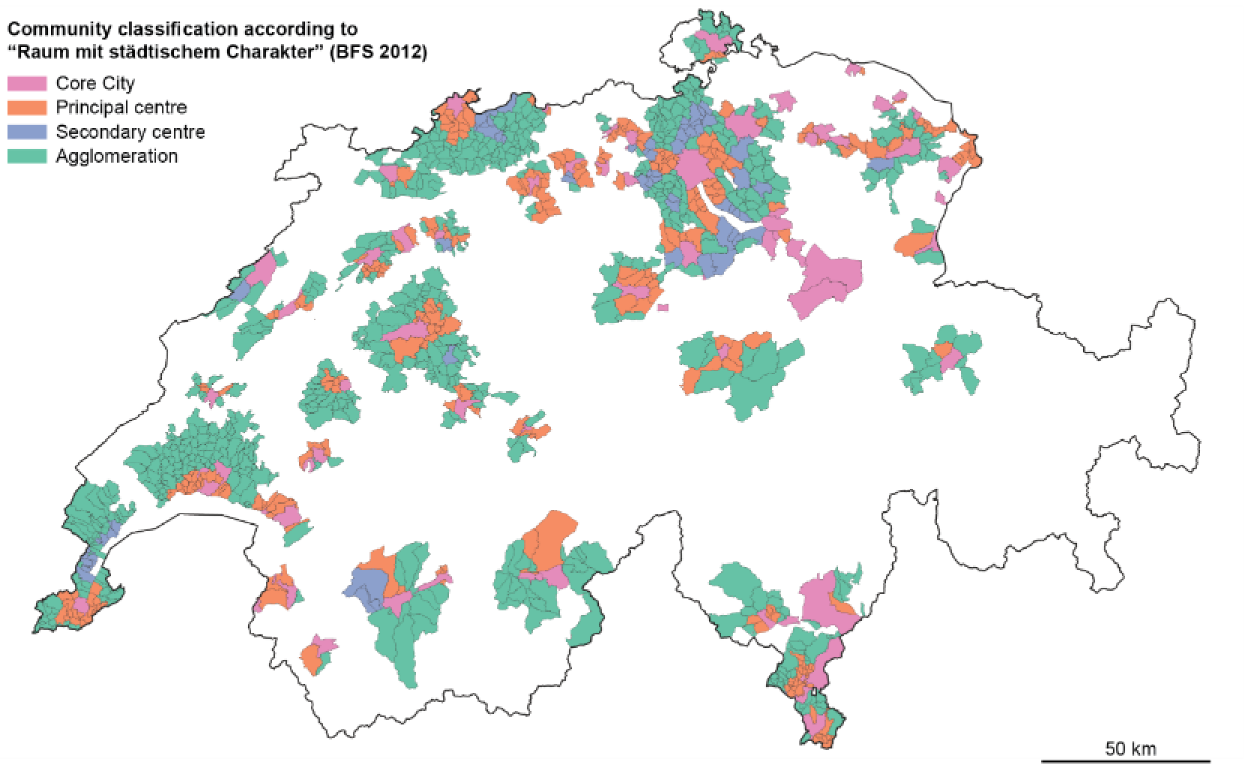
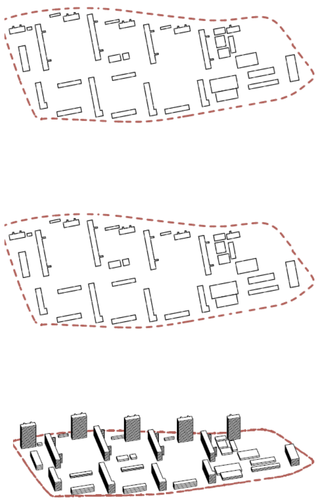
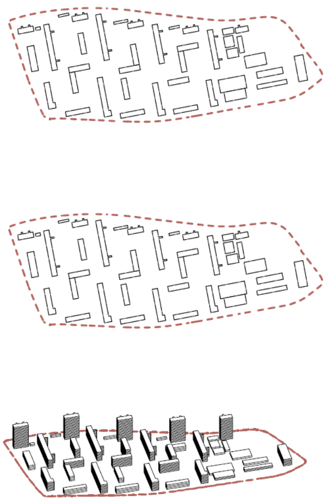
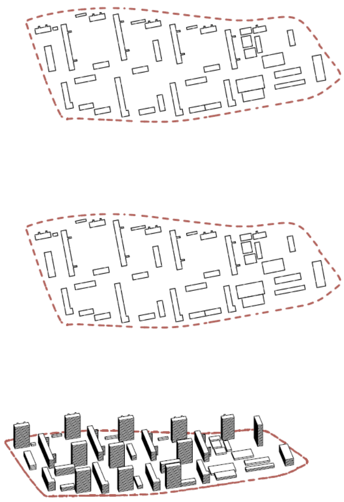
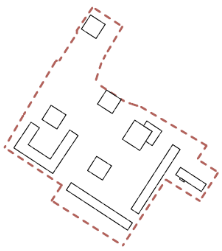
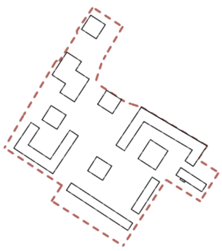
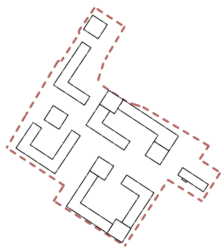
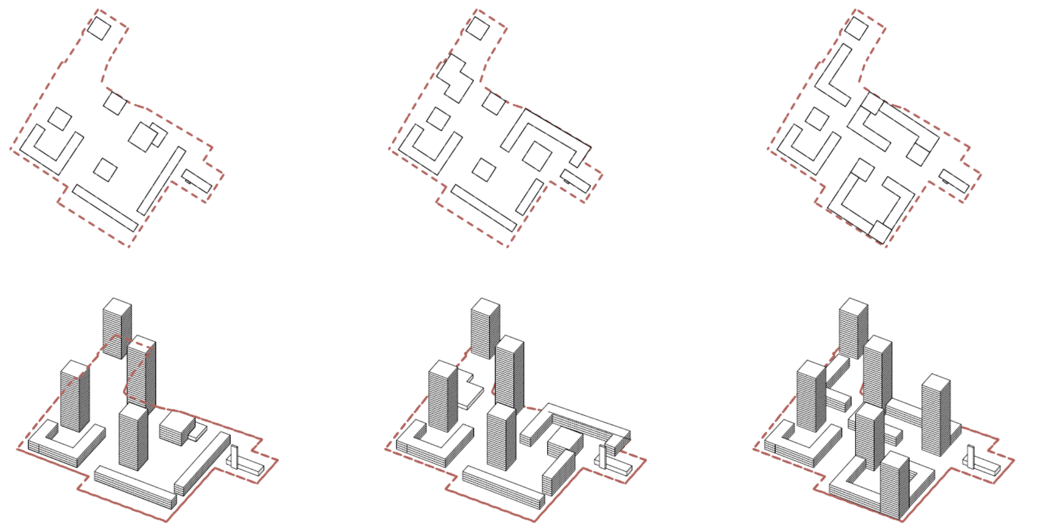


Figure A1: Communities considered to define areas with urban character in Switzerland.

10.2 B – Urban design catalogue

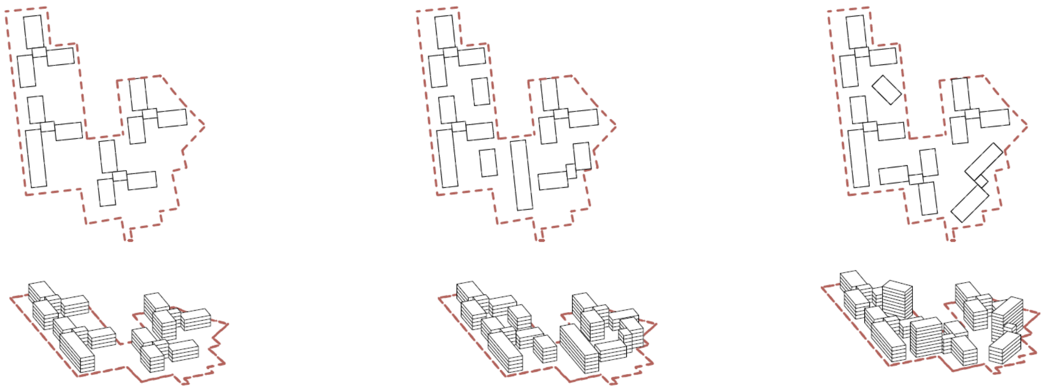
Table B1: Urban design catalogue for the different neighbourhood archetypes (A2 – A5)

	Current	**Strategy S2**	**Strategy S3**
A2	Tscharnergut, Bern		
			
	FAR: 0.971	**FAR: 1.19**	**FAR: 1.432**
A2	Siedlung Hardau II, Zürich		
			



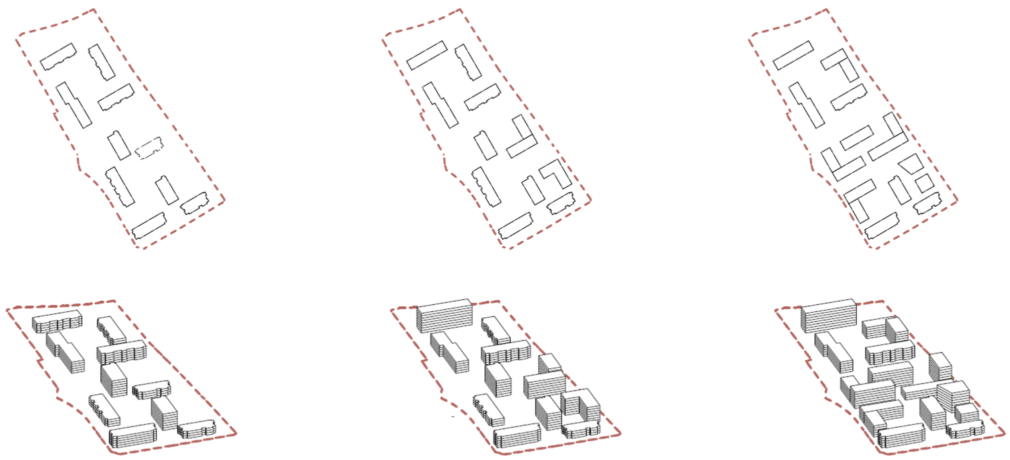
FAR: 2.011 | FAR: 2.285 | FAR: 3.091

A3 | Alterssiedlung Irchel, Zürich



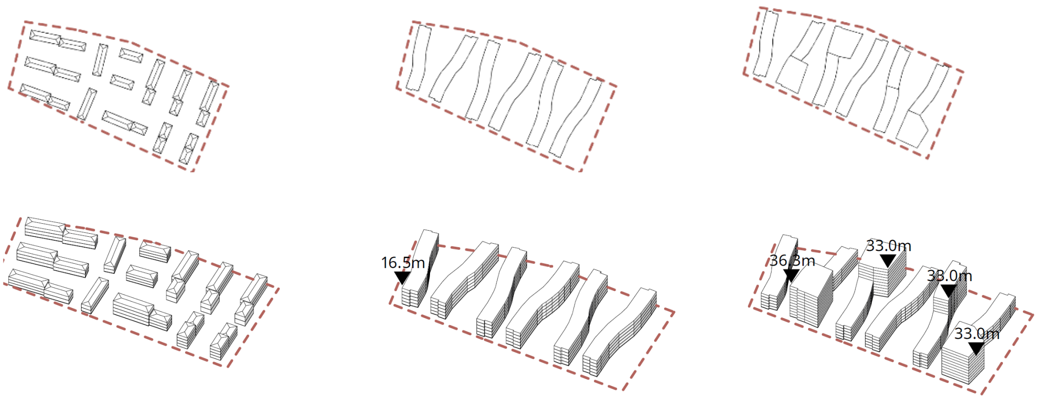
FAR: 1.068 | FAR: 1.385 | FAR: 1.689

A3 | Köniz-Buchsee, Bern



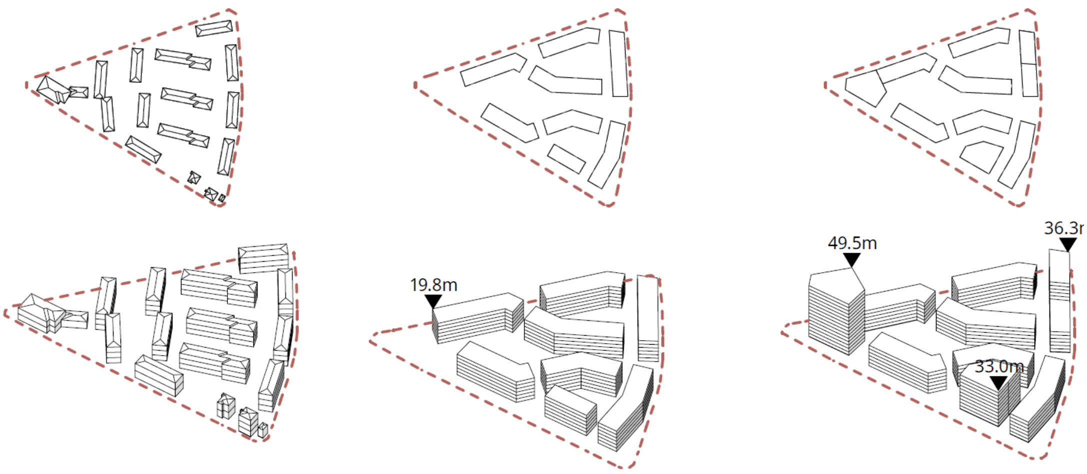
FAR: 0.866 | FAR: 1.016 | FAR: 1.41

A4 Casarecce, Zürich



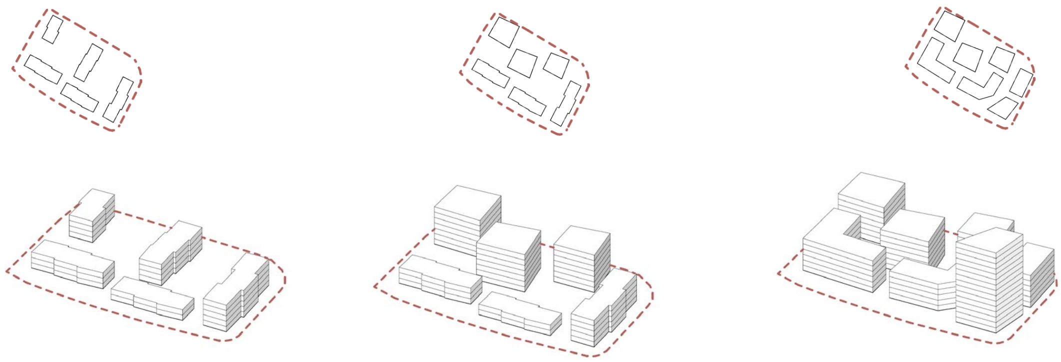
FAR: 0.718 **FAR: 1.923** **FAR: 2.839**

A4 Drüegg, Zürich



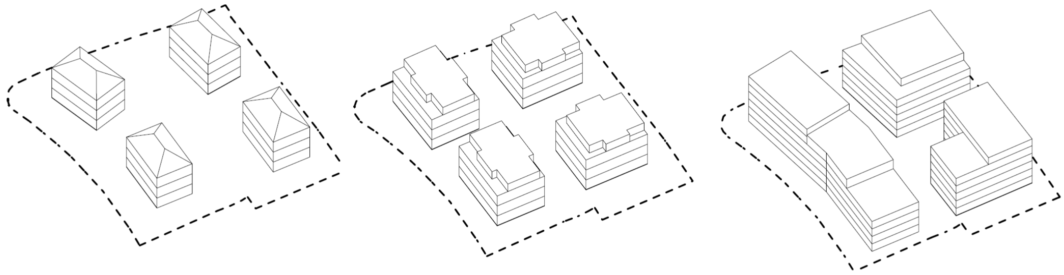
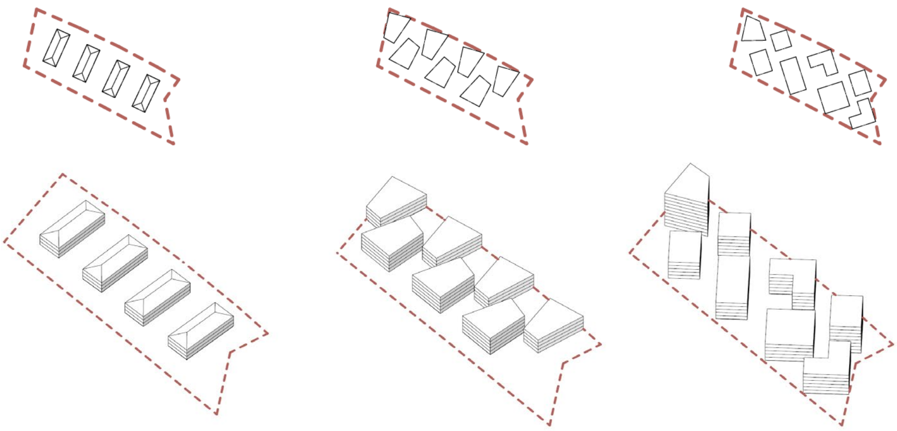
FAR: 0.718 **FAR: 1.923** **FAR: 2.839**

A4 Lochäcker, Zürich



FAR: 0.899 **FAR: 1.663** **FAR: 2.767**

FAR: 0.899 **FAR: 1.663** **FAR: 2.767**

A5	Goldbach, Zürich  **FAR: 0.52** **FAR: 1.08** **FAR: 2.26**
A5	Winzerhalde, Zürich  **FAR: 0.634** **FAR: 1.552** **FAR: 2.367**

10.3 C – SIA 2032 assumptions

1.1 C – SIA 2032 assumptions

TABLE C1: SIA 2032 assumptions. The yellow highlighted cells indicate the options investigated in the construction scenarios.

Elementgruppe	Bezeichung	Calculation Value	Ausführungsvariante
B 6.2 / 6.3	Aushub	10% Building Volume	ohne Grundwasser
C 1	Bodenplatte, Fundament	Footprint Area	gedämmt
C 2.1A / E 1	Aussenwand unter Terrain	Perimeter*Excavation Depth	gedämmt
C 4.4 / F1.1	Dach unter Terrain	NA	gedämmt
C 2.1B	Aussenwandkonstruktion über Terrain	Outer wall area	Timber/Beton
E 2	Äussere Wandbekleidung über Terrain	Outer wall area	Bekleidung leicht, hinterlüftet
E 3 / F 2	Fenster	Window Area	= 0 für Vollverglasung; Mittelwert 2-fach /3 -fach
C 2.2 / G 3	Innenwand	Gross Area	Mittelwert tragend und nicht tragend
C 4.1 / G 4	Deckenkonstruktion (inkl. Deckenbekleidung)	Footprint Area*number of floors	Timber/Beton
	Dämmung gegen unbeheizt	Roof Area	
G 2	Deckenaufbau	Footprint Area	Fertiger Bodenbelag (ohne Unterkonstruktion)
C 4.3	Balkon	NA	
C 4.4	Dachkonstruktion	Roof Area	Betondecke/Holzdecke
F 1.2 / F 1.3	Dachaufbau	Roof Area	gedämmt (Flachdach)
D1	Elektroanlage	Gross Area	Wohnen
D5	Wärmeanlage	Gross Area	Wärmeerzeugung und Verteilung
D7	Lufttechnische Anlage	NA	Lufttechnische Anlage
D8	Wasseranlage	Gross Area	Wohnen

10.4 D – Upscaling Results

Densification strategy	Construction code	Sum of Heating ktCO2	Sum of Construction Choice ktCO2	Sum of New Build Baseline ktCO2	Sum of Retrofits ktCO2	Grand Total ktCO2
S0	retrofit_only	423	0	0	47	470
S2	CCCC	577	142	250	19	988
S2	CCCT	583	119	250	19	971
S2	TTCT	595	60	250	19	925
S3	CCCC	632	160	273	17	1081
S3	CCCT	638	135	273	17	1063
S3	TTCT	652	66	273	17	1008

Densification strategy	Construction code	Sum of Heating Switzerland GWh	Sum of Cooling Switzerland GWh	Sum of Construction Choice GWh	Sum of New Build Baseline GWh	Sum of Retrofits GWh	Sum of Grand Total GWh
S0	retrofit_only	1503	116	0	0	176	1795
S2	CCCC	2048	165	1248	986	70	4517
S2	CCCT	2071	175	1110	986	70	4413
S2	TTCT	2114	253	980	986	70	4403
S3	CCCC	2242	177	1402	1078	65	4965
S3	CCCT	2265	188	1255	1078	65	4852
S3	TTCT	2314	276	1101	1078	65	4834

10.5 E – New-Build Energy Impacts