Judith Drouilles[a], Sergi Aguacil[ab], Endrit Hoxha[b], Thomas Jusselme[b], Sophie Lufkin[a], Emmanuel Rey[a]

Environmental impact assessment of Swiss residential archetypes: a comparison of construction and mobility scenarios

[a] *Laboratory of Architecture and Sustainable Technologies (LAST), School of Architecture, Civil and Environmental Engineering (ENAC), Ecole Polytechnique Fédérale de Lausanne (EPFL), Switzerland.*

EPFL – ENAC – IA – LAST, LE 1110, Station 18, 1015 Lausanne, Switzerland

[b] *Building 2050 Research Group, Ecole Polytechnique Fédérale de Lausanne (EPFL), Fribourg, Switzerland.*

EPFL – ANTEN – ANTFR – BUILD, HBL 0 42A (Halle Bleue), Passage du Cardinal 13b, 1700 Fribourg, Switzerland

Corresponding author: Endrit Hoxha, end.hoxha@hotmail.com

Abstract:

Life-cycle assessment of the built environment tends to focus mostly on operational final energy consumption of buildings located within a specific context. Such limited scope prevents a broader usability of findings in practice. In Switzerland, the "2,000-Watt society" vision provides a theoretical framework towards energy transition. Intermediate targets for 2050 relate to an extensive assessment incorporating environmental impacts of construction materials and use of a building, and of induced mobility of its occupants. Accordingly, it becomes crucial to gather information about the current building stock performance and its transition potential. The paper aims at contributing to the sustainability transition debate by providing a comparative assessment of retrofitted and new residential buildings representative of the Swiss building stock. A direct output could constitute in establishing a reliable reference dataset to support practitioners' or lawmakers' future decisions. The novelty of the study relies on two aspects: 1- on adopting an interdisciplinary approach to propose an overview of the current status and transition potential of the built environment; 2- on building a methodology able to extrapolate results for large-scale studies of neighbourhoods or larger built areas. Based on the definition of four building archetypes, this study assesses four scenarios decomposed into four to six variants. The scenarios consist in varying the building energy-performance, while the variants implement different locations – among urban, peripheral and rural areas – and different passive or active strategies. Results are expressed in terms of non-renewable primary energy consumption and global warming potential. They highlight in particular the performances of renovation projects, the effect of high-energy performance on embodied impacts, the low-level of performance of single-family houses and the significant impact of mobility related impacts.

Keywords: residential building archetypes, life-cycle assessment, operational impacts, embodied impacts, daily mobility, non-renewable primary energy.

Abbreviations

A_E	Energy reference area
bp	Best practice in construction
COP	Coefficient of performance
cp	Common practice in construction
DHW	Domestic hot water
E0	Current status
FSO	Federal statistical office
GWP	Global Warming Potential
HVAC	Heating, ventilation and air-conditioning
MFH	Multi-family house
MFH.n	Multi-family house – new building
MFH.r	Multi-family house – retrofitting project
NRPE	Non-renewable primary energy
RE	Renewable energy
S0	Scenario 0, using Swiss regulation as reference (SIA norms)
S1	Scenario 1, using MINERGIE® requirements as reference
S2	Scenario 2, using MINERGIE-P® requirements as reference
S3	Scenario 3, using MINERGIE-A® requirements as reference
SFH	Single-family house
SFH.n	Single-family house – new

SFH.r	Single-family house – retrofit
SFOE	Federal office for energy
SIA	Swiss society of engineers and architects
Wpeak	Photovoltaic power for standard conditions test

Acknowledgements

This article presents the results of the LOW CARBON HOUSING research project, supported by the Smart living Lab, a research and development centre for the built environment of the future whose ambition is to bridge the gap between research and industry. This study was also conducted in the framework of the LIVING PERIPHERIES research project, supported by the Swiss National Science Foundation (SNSF) (Project n°100013_152586/1), and the ACTIVE INTERFACES interdisciplinary research project, part of the National Research Programme "Energy Turnaround" (NRP 70) of the SNSF. Further information on the National Research Programme can be found at www.nrp70.ch.

The authors also acknowledge the participation of Angela Clua Longas from the Laboratory of architecture and sustainable technologies (LAST) of the Ecole Polytechnique Fédérale de Lausanne (EPFL) for providing information and data about the new multi-family house archetype.

1. Introduction

1.1 Research framework and limitations

In most post-industrial European countries, including Switzerland, enabling sustainability transition of the built environment by reducing its environmental footprint is a priority. Considering energy consumption in their daily life, Swiss households appear as highly energy demanding due to materials needed for the building construction, to the dwelling operation and to the induced mobility (Novatlantis et al. 2011). Based on the “2,000-W society” vision (Suisse Energie 2017), Switzerland has updated its energy strategy aiming at a sustainable use of resources (SFOE 2015a). Within the context of this vision, by 2100, the annual global warming potential (GWP) indicator is limited to 1 ton of CO_2 equivalent (CO_2e) per person and a maximum primary energy (PE) power of 2,000 watts per person, including 500 watts of non-renewable primary energy (NRPE). This represents a reduction of 88% (GWP) and 78% (PE) with respect to 2005 when the mean power per person was about 6,000 watts. In 2014 and 2015, it was already reduced to less than 5,000W (Suisse Energie 2017). Swiss authorities (SFOE 2015a; SIA-2040 2017) have defined intermediate targets for 2050 for the built environment, which consider a broad environmental assessment of the building, including its construction and operation, as well as the occupant-induced mobility.

The conducted literature review highlights the lack of reference data concerning the environmental impacts in terms of non-renewable primary energy consumption and global warming potential owing to construction process, use of the dwelling by occupants and induced daily mobility in Switzerland (Jusselme et al. 2015). Considering the growing impacts of materials, which can account up to 40 to 60% of the global environmental impacts of energy efficient buildings, conducting detailed assessments of embodied impacts is urgent (Sartori and Hestnes, 2007; Cabeza et al, 2014). Nevertheless, data of construction material impacts emerge from analysing the building scale (SIA-2032 2010) and depend on specific building features (Gustavsson and Joelsson 2010). For that reason, it is difficult to find average and reliable reference values by square meter of dwelling or based on site-specific climate and applicable on a large scale to assess a whole set of buildings (John 2012).

1.2 Preliminary studies and remaining challenges

The paper directly addresses limitations detected in a preliminary step of the research, which conducted an energy assessment of the dwelling stock of urban centres, suburbs, peripheries and rural areas and questioned the theoretical capacity of Swiss dwellings to achieve the energy performances required by the “2,000-W society” vision (Drouilles et al. 2017). Based on the analysis of statistics and literature, the previous study highlighted the limitations of conducting large-scale energy assessments.

Aguacil *et al*. (2017a) summarize both possible approaches to conduct an energy assessment or life-cycle assessment (LCA), at large-scale (top-down or bottom-up) and expose their main applications. The top-down approach is based on real energy consumption of a large area (i.e. city or country) provided by energy suppliers. Based on global data, this approach tries to estimate the energy consumption of a specific area (i.e. a neighbourhood): the global consumption is proportionally attributed to the chosen measure unit (built area, dwelling, building types) (Steskens et al. 2015). The bottom-up approach begins with a detailed study at building scale (using representative buildings). It consists in analysing the construction details to obtain specific energy consumptions using a simulation software. The environmental impacts are calculated based on the results of the energy simulation and the study at the level of constructive detail. The energy assessment of a specific area, i.e. composed of different buildings classified in representative buildings or archetypes, proceeds from up scaling results obtained at building scale. Through this up scaling process, by multiplying the results by the total number of buildings, dwellings or square meters of the studied area (Swan and Ugursal 2009) it is possible to estimate the energy consumption and GWP of a wider building stock fitting the archetype features.

Most of existing research aiming to assess energy performance at the scale of built areas implement either large-scale modelling (Ratti et al. 2005; Stephan et al. 2012) or statistical analyses based on household consumptions (Holden and Norland 2005; Rey et al. 2013). Therefore, the results depend on the studied area and are usually focused on final energy consumptions. Since specific building features are necessary to make these calculations, this kind of approach can assess neither the primary energy consumption nor the embodied impacts owing to the building construction.

The Typology Approach for Building Stock Energy Assessment (TABULA) project (IEE 2016) involving twenty European countries has focused on the elaboration of a harmonized database of existing buildings to allow energy assessment of the building stock (Loga et al. 2016). Unfortunately, TABULA only focuses on operational energy consumption and the database applies to countries part of the European Union, which does not include Switzerland. Other researchers have limited the study boundary to only one material (Kunič 2017), one built element (Slavkovič 2015), one case study (Citherlet and Defaux 2007; Paganin et al. 2017) or a specific area (Xu et al. 2016). None of them have studied buildings in their totality, including also different locations through the variable impacts of daily-mobility. Research focussing on European countries highlights the influence of considering specific climate conditions using hourly weather data in the simulation process to evaluate properly the dwelling operational impact and the embodied impacts (Rossi et al. 2012; Aguacil et al. 2017a). Hence, an adequate database built within a specific context is required to conduct a reliable LCA.

At large-scale, research on energy consumption tends to focus mainly on dense urban areas. Nevertheless, some authors have started to assess the energy performance of peripheral residential areas in order to evaluate the effect of centrality on the overall energy balance (Heinonen et al. 2013a; Rey et al. 2013; Ottelin et al. 2015). The main factor that conditions the variation of the overall energy performance is the daily mobility of the inhabitants (Rickwood et al. 2008). In a context of increased concentration of equipment, services and activities in urban centres, the inhabitants of the urban periphery rely on commuting to access work and leisure places. The energy and environmental impacts of induced daily mobility represent a considerable cost for households (Desjardins and Mettetal 2012; Drouilles et al. 2017). New developments about these questions consider the occasional mobility related to holidays (Nessi 2012; Munafò 2016) because it implies a rebalancing of travelled distances between centre and periphery (Holden and Norland 2005). However, the direct effects are unclear since mobility practices are also highly dependent on lifestyles, which are spread unevenly among each territorial entity (Heinonen et al. 2013a; 2013b).

1.3 Overview of the study

The research described in this article tries to overcome the identified limitations by generating a reliable methodology adapted to the Swiss dwelling stock in order to conduct large-scale life-cycle assessments. It aims at exploring some possible evolution strategies of the residential building stock according to a variety of representative features. The novelty of this research lies in expanding the boundary of common studies by evaluating the environmental performance of buildings (construction and operation) and induced mobility. Not only does it assess the related environmental impacts for a singular building; it also takes into account several energy performance objectives, construction typology, energy source and heating, ventilation and air-conditioning (HVAC) and domestic hot-water (DHW) systems, assuming different locations, private parking types and assessment horizons for induced daily mobility. As a result, this research provides new reference data available for strategic planning with a twofold perspective. First, it can inform decision-makers, government or non-government organizations on where to put their efforts while developing solutions with low environmental impacts. Second, it can provide an assessment framework to conduct LCA at neighbourhood or city scale based on the combination of several alternative scenarios.

The methodology follows in a systematic way for the database to become as informative and reusable as possible. It uses the concept of archetype that defines a theoretical model able to represent each of the different building typologies of a specific building stock (Oliveira Panão et al. 2013). Hence, according to the Swiss housing stock current constitution, the study considers four residential archetypes: single- and multi-family buildings, implementing both new and renovation projects. Afterwards, the method consists in analysing and comparing scenarios and variants of each archetype by considering the whole LCA according to the “2,000-W society” vision framework. Environmental impacts, expressed in terms of non-renewable primary energy (NRPE) and global warming potential (GWP), first relate to the operation of buildings and of induced motorized daily mobility depending on location and building type. Then, they consider the construction materials on a lifespan of 60 years. The definition of variants includes (1) energy performance objectives, (2) construction typology, (3) energy source and HVAC/DHW systems, (4) induced daily mobility assuming two different performances of motorized conveyances and (5) private parking types (Fig. 1).

Section 2 presents the chosen residential archetypes based on the analysis of territorial organisation and composition of the housing stock in the Swiss context. It also describes the comparative scenarios and the LCA framework for the elaboration of the different variants. *Section 3* presents the LCA results, which are summed up and discussed in *Section 4*.

2. Material and method

2.1 Selection of residential building archetypes

The method chosen to analyse the existing building stock implements a bottom-up approach. The strength is to consider a specific building in order to estimate in a more accurate way its NRPE and the resulting GWP for (1) material and construction (embodied impacts), (2) use of the building (operation impacts), and (3) daily mobility of building users (operational impacts owing to the induced daily mobility). The remaining issue consists in choosing some buildings representative of the Swiss housing stock to provide a valid and reliable reference framework.

Sustainable urban planning raises many challenges in terms of building retrofit or construction of energy-performing new buildings, which has been tackled by abundant research on low energy construction (Ruiz et al. 2012; Lasvaux et al. 2017). According to available data from the Federal Statistical Office (FSO), the share of new dwellings in the Swiss building stock was 1% in 2015. However, it differs between the single-family houses stock – 0.96% – and the multi-family houses stock – 1.45% (FSO 2017a). Following this trend, 65% of the 2050 building stock already exists. Therefore, in order to follow the guidelines set by the intermediate targets for the horizon of 2050, it is necessary to take into account not only new-construction projects but also the retrofit potential (Eames et al. 2013; Jones et al. 2013; Riera Pérez and Rey 2013).

Single- and multi-family houses represent about 82% of the Swiss dwellings and buildings (FSO, 2017a) (Tab. 1). The remaining 18% gather mainly mixed-use buildings (residential and non-residential). The two periods of 1946-1979 and 1980-2015 gather 70% or more of the residential building stock. This threshold is interesting as new policies have targeted, since the 1980s and in response to the oil crises, a reduction of energy consumption in new buildings, through improving building envelope, increasing insulation and implementing double-glazing windows (SFOE 2015b).

Table 1 Number of buildings and dwellings for single- and multi-family houses in 2015 in Switzerland, per construction period. Source: FSO 2017a

Indicators	Single-family houses		Multi-family houses	
	quantity	ratio	quantity	ratio
Building stock	983’210	58%	449’936	26%
Dwelling stock	983’210	24%	2’455’997	56%
Construction period (buildings)				
< 1946	236’568	24%	140’770	31%
1946 - 1979	326’904	33%	162’026	36%
1980 - 2015	419’738	43%	147’140	33%

To be representative of the existing residential building stock, this study proposes four archetypes: both types of residential buildings (single- and multi-family houses) of two construction periods (existing buildings to be refurbished and new constructions) to reflect the evolution of practices. The chosen archetypes for the existing building to be refurbished (SFH.r and MFH.r) consider the construction features of the 1940s-1970s, according to the eREN research project (HEIA 2016). New buildings (SFH.n and MFH.n) are designed according to common example found nowadays in Switzerland. Tab. 2 sums up the main features of the four residential archetypes.

Table 2 Main features of the four residential archetypes: single-family house – new (SFH.n), single-family house – retrofit (SFH.r), multi-family house – new (MFH.n) and multi-family house – retrofit (MFH.r).

Archetype	Number of dwellings per building	Total living area / per dwelling	Total number of floors / heated	Windows to wall ratio [%]

SFH.r	1	135 m^2	3 / 2	8%
SFH.n	1	135 m^2	2	13%
MFH.r	48	2,532 m^2 / 53 m^2	7 / 6	22%
MFH.n	30	1,870 m^2 / 62 m^2	6	33%

2.2 Scenarios definition

To clarify the amount of simulations, Fig. 1 shows in a schematic way the combinations of the different parameters for each archetype (SFH.r, SFH.n, MFH.r, MFH.n) and synthetizes each scenario and variant with the codification used in this article. The different energy performance scenarios are based on variable features and targeted performances. In this scope, we used Swiss regulation and labels as reference framework to set energy performance targets. Scenario *E0* represents the current pre-renovated status of the 50s-70s buildings (including double-glazing windows). Scenario *S0* represents the baseline, for which the building performance is at least compatible with the current Swiss regulation SIA 380/1:2016 (SIA 2016b). Scenario *S1* uses the requirements set by the MINERGIE® label as performance targets. Scenarios *S2* and *S3* respectively follow at least the requirements of MINERGIE-P® and MINERGIE-A® labels commonly used in Switzerland (Hall et al. 2014; Minergie 2017).

The strategies for improving the building envelope (e.g insulation thickness, fenestration type) are defined in order to achieve the different performance targets of each scenario (*S0*, *S1*, *S2*, *S3*). Afterwards, several inflexion parameters imply the elaboration of a series of different variants. They are related to:

a. Considering different construction systems, *common practice* (cp.) or *best practice* (bp.), including variations of material quality, insulation thickness, façade finishing, etc.
b. Considering different HVAC and domestic hot water (DHW) systems from *oil boiler* to *electric heat pump* using.
c. Increasing the use of renewable energies by implementation of *solar thermal* (ST) or *photovoltaic panels* (PV).
d. Adjusting the results of embodied impacts according to the parking type: *underground parking*, *individual garage* and *outside parking*.
e. Considering five locations: *urban centres*, *suburban, peri-urban, rurban* and *rural* areas (Drouilles et al. 2017).
f. Considering, for the mobility aspects only, two hypotheses to include *current performance* and assumptions about the *future improvements* of mobility technologies achieved by 2050 (SIA 2039:2016).

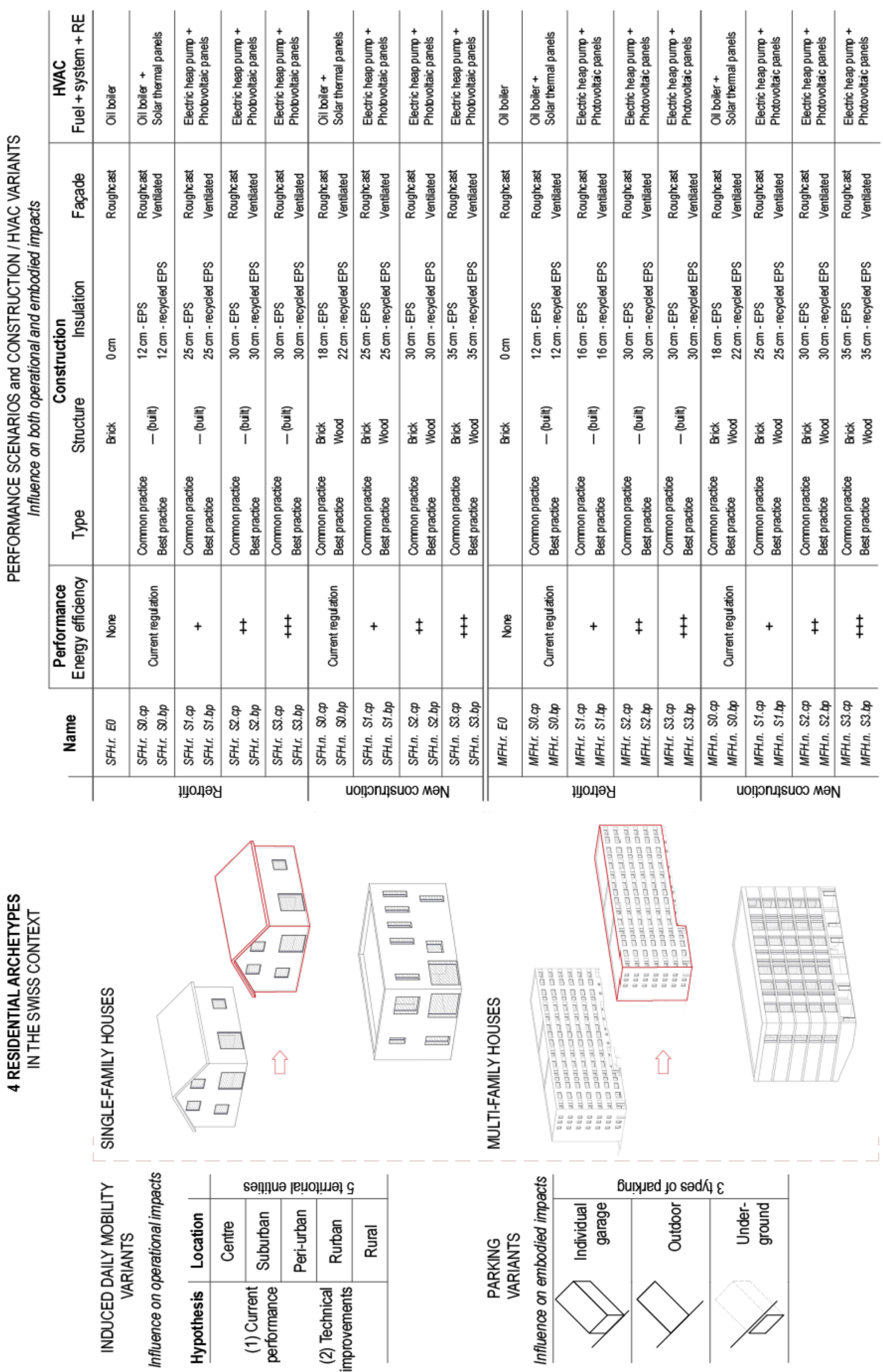


Fig.1 Synthesis of scenarios and variants for the environmental impacts estimation of the four archetypes

Regarding the energy source to cover heating and DHW demands, FSO provides data about the repartition per type of buildings and construction period (FSO 2017b). According to the data in Tab. 3, oil is by far the most important heating energy source used in buildings. About 70% of all residential buildings form the 40s-70s period, use oil boilers. Since 1980, oil is still the principal heating energy source along with natural gas and electric heat pump. Hence, scenarios *E0* and *S0* use oil for heating and DHW, and scenarios *S1* to *S3* implement heat pumps as it is the major heating system installed in certified MINERGIE® (-, P, A) buildings, for both new and retrofitting projects (Minergie 2017). This broad use is due to the simplicity of the installation, the low-level of energy demand, and the good combination with on-site energy production.

Table 3 Energy sources used for heating (representation higher than 3%) by building type (FSO 2017b)

Energy sources or HVAC for heating	1946-1979		1980-2015	
	SFH	MHF	SFH	MHF
Oil - Boiler	**65.44%**	**73.01%**	**30.63%**	**34.56%**
Gas - Boiler	8.26%	10.76%	**19.58%**	**24.27%**
Electricity – Joule effect	13.56%	6.26%	10.51%	5.75%
Electricity – Heat pump	3.81%	2.36%	**30.91%**	**22.23%**
Wood - Boiler	7.24%	3.44%	5.43%	6.53%
District heating	1.04%	2.82%	1.76%	3.93%

2.2.1 Retrofitting approach

The existing single-family house archetype – *SFH.r* (Fig. 1, 2a) has been defined according to Swiss buildings and housing statistics (FSO 2017a), and real estate information. The house is composed of three storeys. Living areas are situated on ground and first floors while the underground floor is an unconditioned area.

The existing multi-family house archetype – *MFH.r* (Fig. 1, 2b) has been adapted from a real six-storey building built in 1968 in Neuchâtel. The semi-underground level has unconditioned non-residential spaces.

For the energy retrofitting projects, we relied on the eREN research project to define the archetypes proposed in this article (HEPIA 2016). The most common wall type of buildings from 40s-70s is a 20 cm brick wall without thermal insulation. The outer layer of the façade is roughcast plaster. Horizontal slabs are built in reinforced concrete. The roofs are sloped (wooden structure) or flat (concrete structure) and not insulated. The windows present double-glazing and wooden frame without thermal bridge rupture (Fig. 2a, 2b).

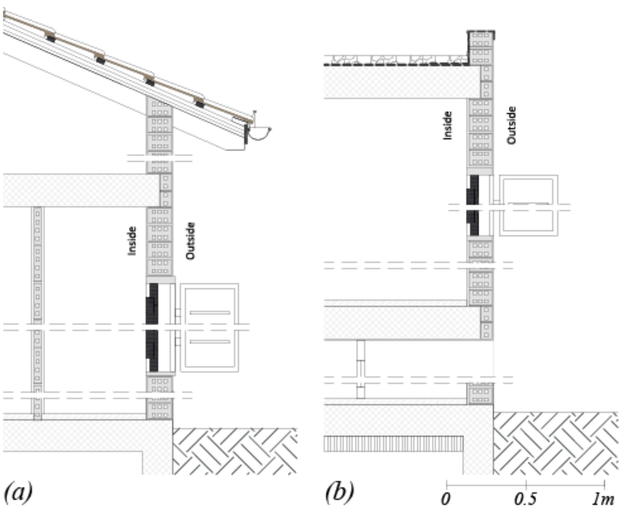


Fig.2 Main façade section for 40s-70s archetypes in their current status *E0.* (a) SFH.r (b) MFH.r

Retrofitting variants *S0* to *S3* qualified as *common practice* implement a traditional and affordable construction system, with most commonly used material and methods in Switzerland (HEPIA 2016; SFOE 2017). An external insulation façade system is implemented on the existing façade. According to the energy performance target, each scenario implements a specific thickness of insulation using expanded polystyrene (EPS) for roof and façade (Tab. 4). The renovation includes the replacement of the frame and glazing of existing windows (Fig. 3a, 3b).

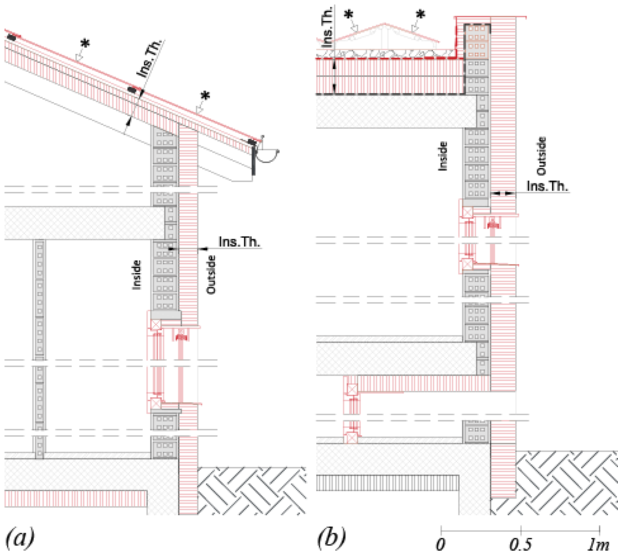


Fig.3 Section of the main façade for 40s-70s archetypes, applicable for *common practice* variants: *S1.cp*, *S2.cp*, *S3.cp*. (a) SFH.r and (b) MFH.r (*: ST or PV panels)

Qualified as *best practice*, retrofitting variants (*S0.bp to S3.bp*) seek to implement a lighter and low-impact construction system based on wood with an external insulated ventilated façade (with 100% recycled EPS, wood structure and solid panels) (Tab.4, Fig. 4a, 4b).Wooden frame with thermal bridge rupture windows are installed with improved U-*values*, from 0.98 to 0.7 W/m^2.K depending on scenario.

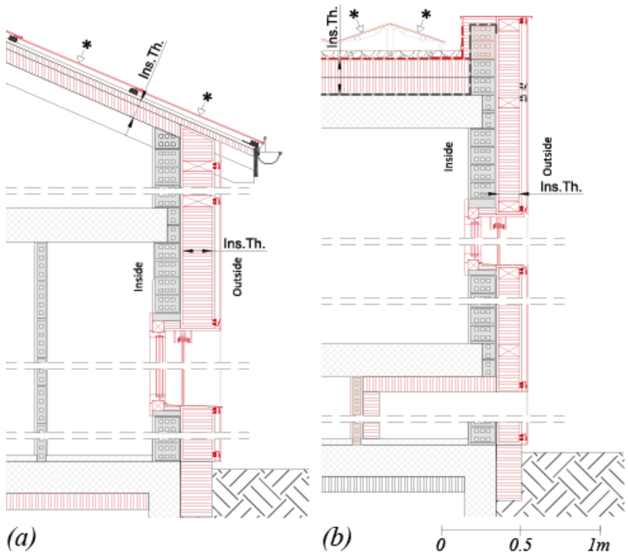


Fig.4 Section of the main façade for 40s-70s archetypes, applicable for *best practice* variants: *S1.bp*, *S2.bp*, *S3.bp*. (a) SFH.r and (b) MFH.r (*: ST or PV panels)

Table 4 Insulation thickness, HVAC system and renewable energy implemented for each scenario in 40s-70s buildings.

Scenario	SFH.r	MFH.r	HVAC (heating and DHW)	Renewables
	Thickness [cm] (*U-value* [W/m^2.K])			
E0	0 (1.21)	0 (1.13)	oil boiler	-
S0	12 (0.25)	12 (0.25)	oil boiler	solar thermal
S1	25 (0.24)	16 (0.20)	heat pump	photovoltaics
S2	30 (0.12)	19 (0.17)	heat pump	photovoltaics
S3	30 (0.12)	30 (0.12)	heat pump	photovoltaics

2.2.2 New construction

According to statistics (FSO 2017a) and the trend of Swiss single-family house design, through the comparison online projects (Bautec SA, Mistral construction SA, Prologis Sàrl, Renggli AG, Villvert SA), the single-family house archetype – *SFH.n* (Fig. 1, 5) is a two-storeys building with flat roof, which design avoids openings on the north façade.

Statistics (FSO 2017a) and Swiss construction current practice gave the design framework for the multi-family house archetype – *MFH.n* (Fig. 1, 5). The design seeks compactness, airtightness, good daylighting potential and natural ventilation. The entrance level is situated on a semi-buried floor, with non-residential uses.

Qualified as *common practice*, the proposed construction system follows the one of retrofitting variants and implements bricks for all bearing walls and reinforced concrete for all horizontal elements including the flat roof. A roughcast plaster protects the external insulation (EPS) (Tab. 5). The partitions are built with a plasterboard sandwich system with metallic structure and acoustic insulation (rock wool) (Fig. 5a).

The variants qualified as *best practice* implement a wooden construction system for each horizontal and vertical element of the building (Fig. 5b). The insulation also has a lower environmental footprint, being 100% recycled EPS (Tab. 5).

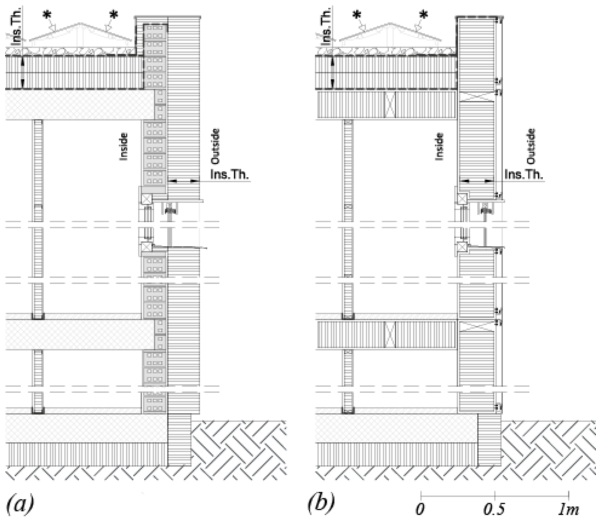


Fig.5 Section of the main façade for new construction archetypes. (a) *Common practice* variants – *S1.cp, S2.cp, S3.cp*, (b) *Best practice* variants – *S1.bp, S2.bp, S3.bp* (*: ST or PV panels).

Table 5 Insulation thickness, HVAC system and renewable energy implemented for each scenario in new buildings.

Scenario	SFH.n	MFH.n	HVAC (heating and DHW)	Renewables
	Thickness [cm] (*U-value* [W/m^2.K])			
S0	22 (0.16)	20 (0.17)	oil boiler	solar thermal
S1	25 (0.14)	25 (0.14)	heat pump	photovoltaics
S2	30 (0.12)	30 (0.12)	heat pump	photovoltaics
S3	35 (0.10)	35 (0.10)	heat pump	photovoltaics

Tab. 4 and 5 sum up both, *common practice* and *best practice* variants, in terms of HVAC systems and renewable energy integration. For the current status (*E0*), the existing HVAC system is maintained without implementing renewables. For baseline scenario *S0*, an oil boiler is considered in addition to solar thermal panels to cover about 30% of DHW demand. For scenarios *S1* to *S3*, an electric heat pump system partially fed by a photovoltaic installation is proposed. Regarding the energy performance simulations, the coefficient of performance (COP) is of 0.85 for the oil-boiler and of 2.8 for the electric heat pump system. It includes the losses due to supply elements (wall radiators) and facility distribution.

2.2.3 Private parking places

Apart from the material associated to the renovation of existing buildings or new construction, the calculation of embodied impacts includes the construction materials of different parking types. The single-family house archetypes include two parking places. For multi-family houses, 1 place per dwelling plus 10% for visitors is counted on average. As shows figure 1, three types of parking places are assessed: (1) underground parking, (2) individual garage, (3) outside parking. The type of outdoor flooring differs according to the construction quality: asphalt is implemented in *common practice* scenarios while a prefabricated concrete mono bloc paving is used in *best practice* variants.

2.3 Energy assessment framework

2.3.1 Calculation method and targets

According to the Swiss regulation for buildings (SIA 2015b), energy requirements are evaluated based on the energy reference area (A_E). A_E considers all living and conditioned areas within the thermal envelope of a building including all construction elements, i.e. it is measured from the external perimeter of the considered area. As a result, A_E changes according to the wall thickness. The impact is significant for new buildings, in particular between *common practice* and *best practice* variants. Hence, it was necessary to adjust the insulation thickness in order to comply with final energy limits (Tab. 6).

Table 6 Energy reference area (A_E) for each scenario depending on the construction variant (*common practice* or *best practice*) and its level of insulation.

Scenarios for new buildings	Common practice (cp.)		Best practice (bp.)	
	SFH.n	MFH.n	SFH.n	MFH.n
S0	145 m^2	2,832 m^2	138 m^2	2,754 m^2
S1	150 m^2	2,869 m^2	140 m^2	2,790 m^2
S2	153 m^2	2,895 m^2	143 m^2	2,816 m^2
S3	156 m^2	2,922 m^2	147 m^2	2,842 m^2

To define a comparison basis to assess the performance of each scenario, the study considers the intermediate targets set by SIA-2040 (2017) for 2050, in the framework of the "2,000-W society" vision (Novatlantis et al. 2011). Tab. 7 presents the targets for residential buildings in terms of non-renewable primary energy (NRPE) and global warming potential (GWP).

Table 7 Intermediate targets for 2050, including environmental impacts related to operation, construction and induced daily mobility, expressed in non-renewable primary energy (NRPE) and global warming potential (GWP) (SIA-2040 2017).

	kWh/m²·yr (NRPE)		$kgCO_2e/m^2$.yr (GWP)	
	Retrofitting	**New construction**	**Retrofitting**	**New construction**
Operational	70	60	5	3
Embodied	20	30	5	9
Induced mobility	30		4	
Total	**120**		**14**	**16**

2.3.2 Environmental impacts

Embodied impacts are assessed according to the European standard (EN-15978 2012) for an assumed building reference study period of 60 years (SIA-2040 2017). The functional unit of a square meter of A_E (m^2.yr) is considered for the assessment of the non-renewable primary energy consumption and global warming potential indicators. The boundary of the whole building LCA includes stages of production, construction, use and end of life. The hypotheses for distance of transport, construction, lifespan of building elements necessary for the assessment of the embodied impacts are similar to those presented in Hoxha et al. (2016b). Environmental impacts of construction stage for different previously described macro components are evaluated based on the corresponding quantity employed in each scenario and on impact factors of the KBOB database (KBOB 2016). This database contains information about environmental impacts of building materials for the Swiss context and is in accordance with the CEN standard (EN 15804 2012). The transport of building elements and components to the construction site is made by truck (16-32t) for an assumed distance of 50km. Within the boundary of the assessment are also considered the environmental impact of building components replacement – according to assumed service life (Hoxha 2015). The impacts of end-of-life stage are evaluated in accordance with the Swiss practice translated in the KBOB database.

The assessment of the operational impacts, are based on final energy consumption for heating, cooling, DHW, lighting and appliances that are evaluated following the Swiss regulation for buildings SIA-380/1:2016 (SIA 2016b). The simulations rely on a definition of the building envelope using an iterative process through hourly-step simulation using Energy Plus (*DesignBuilder* 2018) and Neuchâtel region weather file generated using Meteonorm software (Remund et al. 2010; *Meteonorm* 2017). The energy model has been configured using the normative assumptions and user profiles for multi- and single-family buildings provided by the SIA 2024:2015 (SIA 2015a), including occupancy schedules, standard utilisation profiles, etc. Using these normative assumptions the results can be compared with the 2'000-Watt society targets for 2050 defined by the SIA 2040:2017 (SIA 2017).

Performance targets of the scenarios depend on the building size and the average temperatures in their location. For scenario *S0,* according to the SIA-380:2016 (SIA 2016Bb) the target is fixed on a limit of heating energy demand (Qh,li) that takes into account the energy reference area (A_E) and thermal envelope area (A_{th}).

$$Qh,li = \left(13 + 15 \cdot \frac{A_{th}}{A_E}\right) \cdot fcor \quad (1)$$

Where

$$fcor = 1 + (9.4 - AMT) \cdot 0.06 \quad (2)$$

Qh,li: Limit of heating energy demand [kWh/m^2.yr]
A_{th}: Thermal envelope area [m^2] evaluated according SIA 380, (2015).
A_E: Energy reference area [m^2] evaluated according SIA 380, (2015).
fcor: corrector factor related to the weather of the building location, and calculated with formula 2 [✎].
AMT: real annual mean temperature of the building location (9.7 °C for Neuchâtel (Switzerland)) [°C].

Scenarios *S1*, *S2* and *S3* are designed to be compatible with MINERGIE® (-, P, A) labels. Within this framework, the energy performance targets take into account the whole energy balance of the building expressed in final energy in kWh/m^2.yr (Tab. 8). According to the requirements set by MINERGIE® (-, P, A) labels, installing a minimum of 10Wpeak of PV power per each square meter of energy reference area is mandatory in new buildings. The scope of the study not being on the implication of PV installation, the resulting PV production - the self-consumption part only - is accounted for in the final energy results. The assumption is that the PV production reduces the energy consumption of lighting, appliances and HVAC using an electric heat pump.

Table 8 Final energy limit consumption for *S1-S3* scenarios, for new and renovation projects (MINERGIE 2017).

Scenario	**Energy label taken as reference**	**New constructions**	**Renovation of existing buildings**
		kWh/m^2.yr	
S1	MINERGIE®	55	90
S2	MINERGIE-P®	50	80
S3	MINERGIE-A®	35	35

2.3.3 Induced daily mobility operational impacts

The technical specification SIA-2039 provides a calculation framework to assess the environmental impacts owing to induced daily mobility (SIA 2016a). The document presents two methods to estimate the energy needs related to daily mobility of building occupants, whether the current mobility and location are known. When neither is known, the method relies on FSO's micro census on mobility and transport (FSO and ARE 2012), which represents the most complete data source about mobility practices in Switzerland.

In our archetype model, mobility and location are unknown. Hence, we looked for a way to attribute mobility values by building type and territorial entity. Based on a classification of Swiss municipalities between centre, suburban, peri-urban, rurban and rural areas (Drouilles *et al*. 2018). We analysed the micro census results and obtained a repartition of travelled distances and transportation types per territorial entities (FSO and ARE 2012). The induced daily mobility considers only the incoming mobility. In the case of residential buildings, 47% of daily mobility is counted (SIA 2039:2016).

This calculation method questions the integration of the impacts due to the construction and availability of parking spots in a residential project. According to SIA-2039, "the primary energy consumption clearly increases if parking places are available" because use of individual motorised transport is easy. Data from the micro census are dependent on households' characteristics rather than buildings'. Hence, the presence of parking places affects neither the results of travelled distances nor the conveyances repartition. This is one limitation of this approach. In further work, the implantation of the modelled building on a specific existing plot should allow the assessment of environmental impacts owing to daily mobility of inhabitants in a more precise way.

The method to estimate these impacts considers, in addition to territorial entities, the housing occupancy status ("tenant", "house owner", "apartment owner" and other less representative types). Crossing those results with the repartition of housing occupancy status by territorial entity, specific mobility data came out for single- and multi-family houses as well as for each territorial entity. Table 9 shows the repartition between occupancy status and territorial entity. It also provides the daily travelled kilometres. The daily mobility is highly influenced by the repartition of owners and tenants, which is inverted between single- and multi-family houses. Distances also tend to be longer in peripheral areas.

Table 9 Daily mobility, individual motorized transport (IMT), public transport (PT) and soft mobility (SM) data for induced daily mobility estimation, in function of location and the type of user (owner or tenant).

			Single-Family Houses			
Territorial entity	**House owners**	**Tenants**	**Daily mobility [km]**	**IMT**	**PT**	**SM**
Centre	70%	30%	36.22	60.14%	27.29%	12.57%
Suburban	72%	28%	38.78	68.34%	20.49%	11.17%
Peri-urban	73%	27%	45.54	73.12%	20.02%	6.86%
Rurban	71%	29%	42.21	75.00%	17.40%	7.60%
Rural	67%	33%	37.85	79.17%	14.66%	6.17%
			Multi-Family Houses			
Territorial entity	**Apartment owners**	**Tenants**	**Daily mobility [km]**	**IMT**	**PT**	**SM**
Centre	7%	93%	30.35	52.05%	34.51%	13.44%
Suburban	11%	89%	35.12	65.86%	23.90%	10.24%
Peri-urban	12%	88%	41.92	72.35%	19.58%	8.07%
Rurban	14%	86%	40.75	74.68%	19.06%	6.26%
Rural	13%	87%	36.76	78.24%	14.77%	6.99%

Table 9 also shows conveyance shares. The use of public transport and soft mobility is higher in central areas. The share of individual motorized transport on the other hand is higher in the peripheral and rural areas. 82% of distances travelled by public transport use the train while the rest (18%) resorts to buses and trams. SIA-2039 provides conversion factors for each selected transportation mode, as well as reference values assume future environmental impacts related to mobility, in the framework of the "2,000-W society". As stated in (Drouilles et al. 2017), the current environmental impacts due to induced mobility are far from achieving the intermediate targets for 2050. Consequently, an alternative variant explores future potential impacts based on SIA's hypothesis (Tab. 10).

Table 10 Conversion factors according to SIA-2039 (SIA 2016a)

	Current conversion factors		**Hypothetical future conversion factors**	
	NRPE (kWh/km)	**GWP (kgCO_2e/km)**	**NRPE (kWh/km)**	**GWP (kgCO_2e/km)**
IMT	0.897	0.197	0.461	0.083
PT - bus	0.456	0.104	0.340	0.076
PT - train	0.141	0.008	0.125	0.007

Conversion factors combine both consumption and embodied impacts due to manufacturing vehicles including the necessary infrastructures. The estimation of conversion factors by 2050 relies on technologies and methods that already exist. Therefore, it is reasonable to think these values will progressively decrease (Zachariadis 2006; Thiel et al. 2016). Regarding the individual motorized transport, SIA-2039 hypothesis for 2050 is 3 litres of gasoline per 100 km. Regarding buses the variant considers the implementation of cleaner and more efficient fuel (hydrogen and electricity). For trains it implements more efficient technologies and thermal insulation to reduce the air-conditioning demand (SIA 2016a).Considering the low impact of the embodied energy of soft modes (e.g. bikes) in comparison to other transportation types, they are not included in the assessment.

3. Results

3.1 Scenario performances with current induced mobility impacts

Environmental impacts of all assessed combinations, classified in three categories (embodied, operational and induced mobility impacts) are shown in Fig. 6 and 7 for non-renewable primary energy (NRPE) and global warming potential (GWP) indicators. Graphs also include the reference value of the intermediate targets for 2050 to evaluate the specific performances of each scenario and variant.

3.1.1 Performance comparison

Regarding annual NRPE consumption of the baseline scenario *S0*, the comparison of new building variants shows a reduction up to 36% between single-family houses (*SFH.n.S0)* and multi-family houses (*MFH.n.S0)*. In the case of retrofitting scenarios, the NRPE consumption in multi-family houses (*MFH.r.S0)* is also about 37% lower than in single-family houses (*SFH.r.S0)*. As a result of compactness and higher dwelling occupation, the retrofitted multi-family house located in the *centre* with *individual garage (MFH.r.S0.cp.)* is 23% more efficient than the corresponding single-family house (*SFH.r.S0.cp.)*. For equivalent new constructions, the performance gap rises to 36%.

Although the overall results tend to be of the same magnitude, the performance results between retrofitting and new construction present different repartitions of the energy consumption. The results emphasize the weight of embodied impacts in new construction scenarios. In the case of scenarios *S1* to *S3* applied to single-family houses, embodied impact is nearly 4 times higher in new buildings than in retrofitting projects. However, new buildings tend to be more efficient in terms of operational impact: for *S1* the performance of renovation project (*SFH.r.S1)* is 30% higher, compared to new building (*SFH.n.S1)*. Regarding scenarios *S2*, operational impact is also reduced by 52% from renovation project (*MFH.r.S2)* to new building (*MFH.n.S2).*

Results show that a new single-family house has a higher overall NRPE consumption than a house retrofitted to comply to the same energy standard. The performance gap between those archetypes varies from 5% (*S1.bp*) to 19% (*S3.cp*). For example, a new house of the variant *SFH.n.S2.cp* has an annual NRPE consumption of about 195 kWh/m^2.yr, the same variant achieved through retrofitting actions will reach an annual NRPE consumption of about 172 kWh/m^2.yr (12% lower). The results are not as clear regarding multi-family houses: until *S2*, new buildings (*MFH.n*) perform better than renovation projects (*MFH.r*). Then, in scenarios *S3*, a retrofitted multi-family house (*MFH.r.S3*) is more energy efficient than a new one (*MFH.n.S3*). It terms of GWP, all retrofitting scenarios *S1* to *S3* present lower values both in single- and multi-family houses (*SFH/MFH.r*) than new buildings (*SFH/MFH.n*).

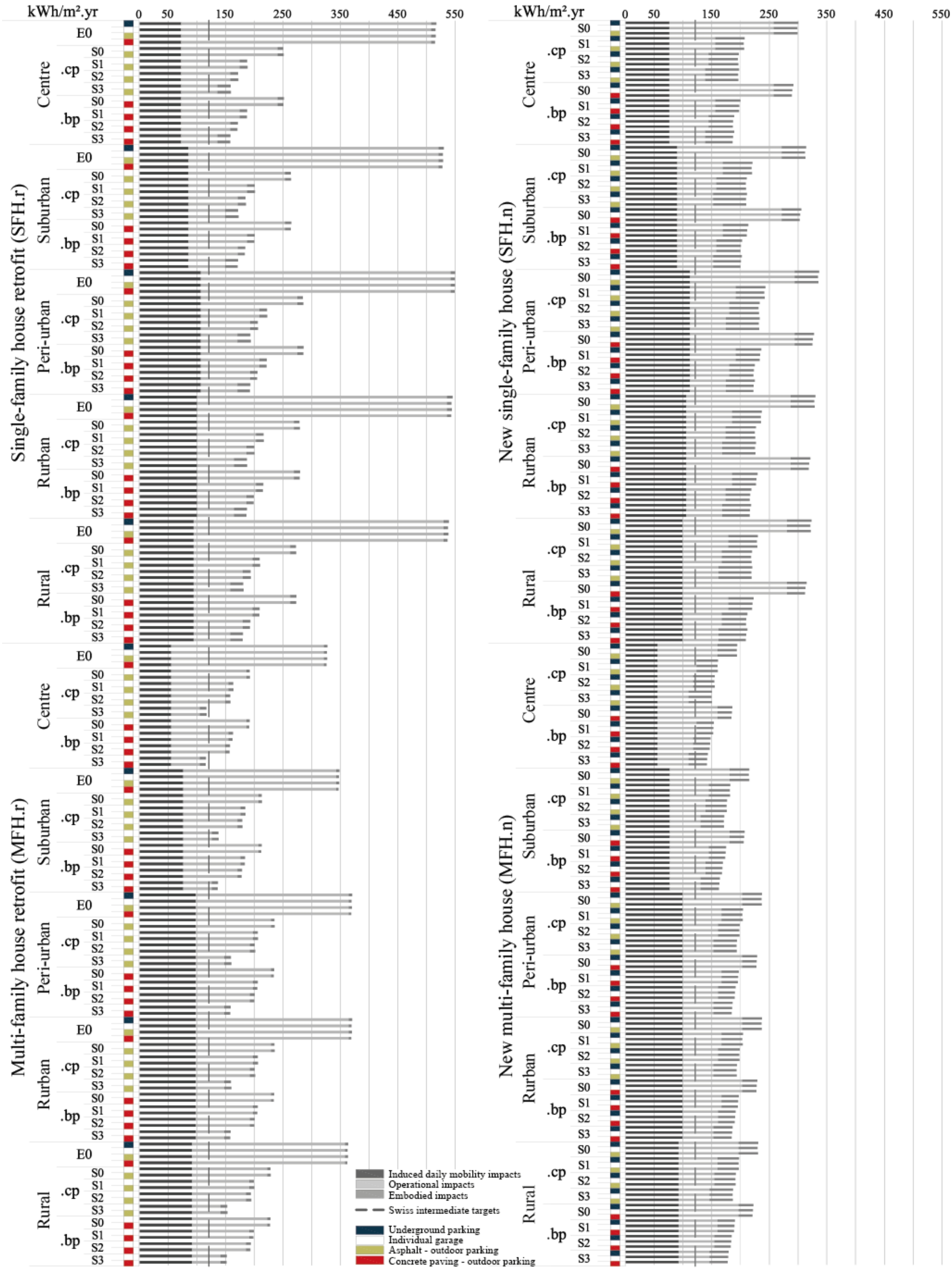
Results of the energy assessment for the retrofitting scenarios emphasize the performances of current construction standards in comparison with current status of residential buildings (*SFH.r.E0* and *MFH.r.E0)* constructed between 1940s and 1970s. Renovation projects of single-family houses according to the Swiss regulation (*SFH.r.S0)* achieve a reduction of 55% annual NRPE consumption, which goes up to 74% in case of a house retrofitted to the highest energy standard (*SFH.r.S3*). Between single-family houses following the regulation (*SFH.n/r.S0)* and other *SFH.n/r.S1-S3*, a 30 to 40% reduction is achieved through increasing insulation and implementing on-site renewable energy production. Regarding multi-family houses, the NRPE consumption reduction is also significant but limited to 45% between current status (*MFH.r.E0*) and scenarios *S0* (*MFH.r.S0*), or to 20% to 30% between (*MFH.n/r.S0)* and other (*MFH.n/r.S1-S3)*.

Results of new buildings emphasize the weak performances of single-family houses. Unlike the other archetypes, none of the new variants of single-family houses (*SFH.n)* reaches any targets (Tab. 7). Retrofit actions highly affect the GWP and achieve reductions up to 85% between current status (*SFH/MFH.r.E0*) and *S1* to *S3* scenarios (*SFH/MFH.r.S1-S3*). Between the baseline *S0* scenario and the following *S1-S3*, GWP indicator is reduced by 40% to 60%.

3.1.2 "2,000-W society" vision as a demanding framework in Switzerland

The overall reading of the results implies that the intermediate targets are very demanding since only 4 variants out of 440 (1%) reach the NRPE targets, and none of them complies with the GWP targets. It is nevertheless encouraging that the retrofitted multi-family house (*MFH.r.S3)* achieves lower NRPE results than the intermediate targets, and 16 other variants are only less than 25% higher than the target. The results emphasize the impact of mobility results, since the (nearly) complying results apply to variants located in the *centre* where travelled distances and use of individual motorized transport are lower (Tab. 9).

Fig.6 Current induced daily mobility, operational and embodied impacts in non-renewable primary energy consumption (NRPE)


kWh/m².yr
0
50
150
250
350
450
550
Single-family house retrofit (SFH.r)
Multi-family house retrofit (MFH.r)
New single-family house (SFH.n)
New multi-family house (MFH.n)
Centre
Suburban
Peri-urban
Rurban
Rural
.cp
.bp
E0
S0
S1
S2
S3
Induced daily mobility impacts
Operational impacts
Embodied impacts
Swiss intermediate targets
Underground parking
Individual garage
Asphalt - outdoor parking
Concrete paving - outdoor parking

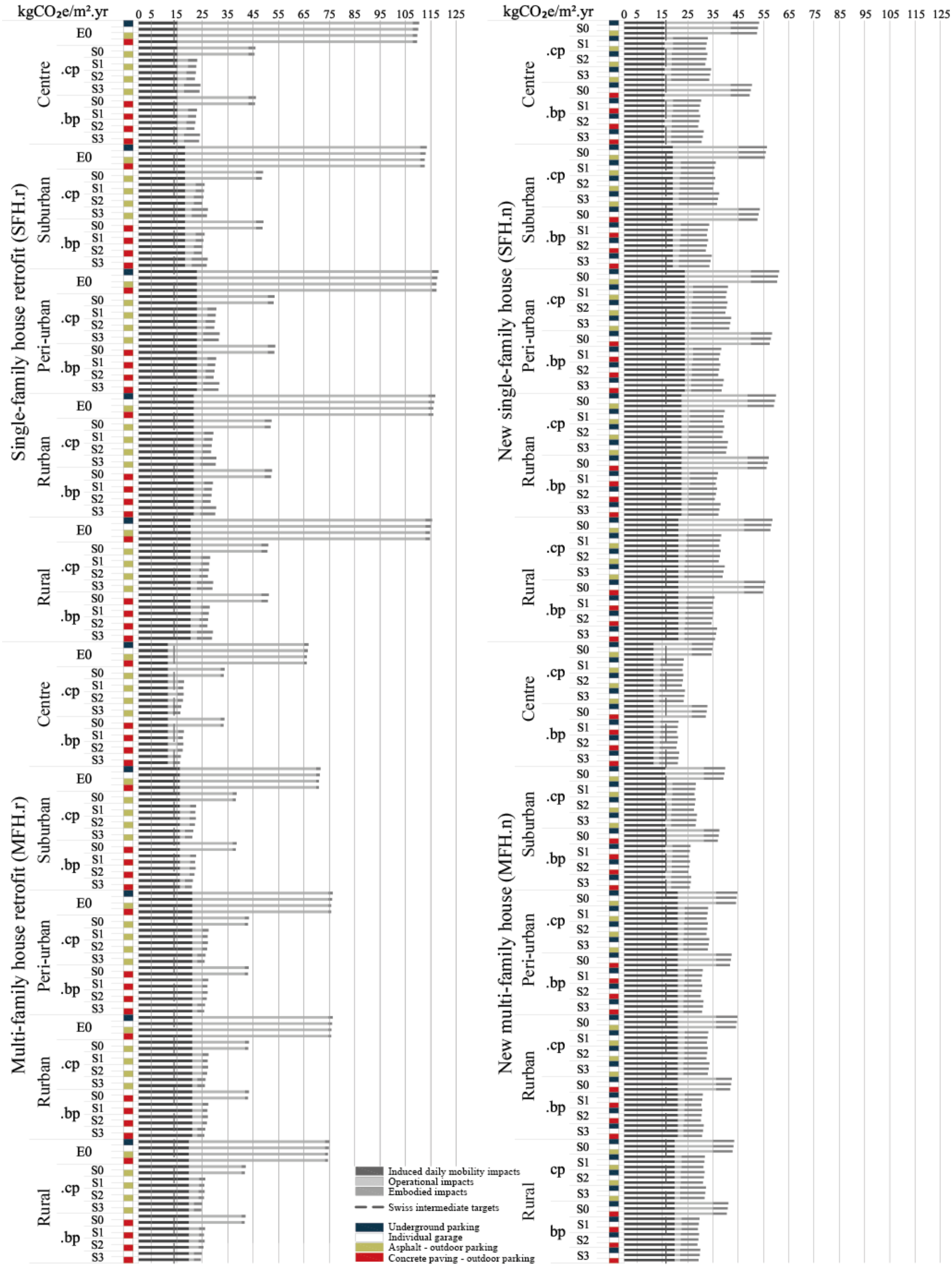

kgCO₂e/m².yr
0 5 15 25 35 45 55 65 75 85 95 105 115 125
Single-family house retrofit (SFH.r)
Multi-family house retrofit (MFH.r)
New single-family house (SFH.n)
New multi-family house (MFH.n)
Centre
Suburban
Peri-urban
Rurban
Rural
.cp
.bp
E0
S0
S1
S2
S3
Induced daily mobility impacts
Operational impacts
Embodied impacts
Swiss intermediate targets
Underground parking
Individual garage
Asphalt - outdoor parking
Concrete paving - outdoor parking

Fig.7 Global warming potential (GWP) for current induced daily mobility, operational and embodied impacts

3.2 Building related results

3.2.1 Detailed results in terms of operational impacts

This section focuses on the results in terms of energy consumed by electric appliances, lighting, heating and DHW. Results presented in Fig. 8 show that complying with the Swiss regulation SIA-380/1:2016 offers a considerable reduction of NRPE consumption and GWP. However, it is not enough to achieve intermediate targets for 2050 (Tab. 7). The most important reduction, up to 70% when considering GWP of *SFH.r*, is achieved between current status (*SFH/MFH.r.E0*) and scenarios complying with Swiss regulation (*S0)*. Current regulation focuses on limiting the heating demand (according to the Formula 1 and 2, section 2.3.2) and requires covering at least 30% of the DHW annual demand with renewables. The application of those requirements results in a greater energy performance of the building envelope and, in this case, in the implementation of ST panels (EnDK, 2014), which cover 4% of the NRPE consumption.

Regarding GWP, the shift to heat pumps and more energy-performing scenarios (*S1* to *S3*) allows all scenarios to meet the intermediate targets. Regarding NRPE consumption, only the *S3* scenarios respect the targets, but only for three archetypes (*SFH.r.S3*, *MFH.r.S3* and *MFH.n.S3*). To meet the targets for this indicator, the impacts of new single-family houses (*SFH.n.S3*) should still be reduced by 4%. This includes the fact that the overall operational impacts are lowered thanks to self-consumption of renewable energy produced on site by PV installation in all *S1*-*S3* scenarios. In new multi-family houses for instance, the PV production allows a 14% (*MFH.n.S1*-*S2*) to 20% (*MFH.n.S3*) reduction of operational impacts.

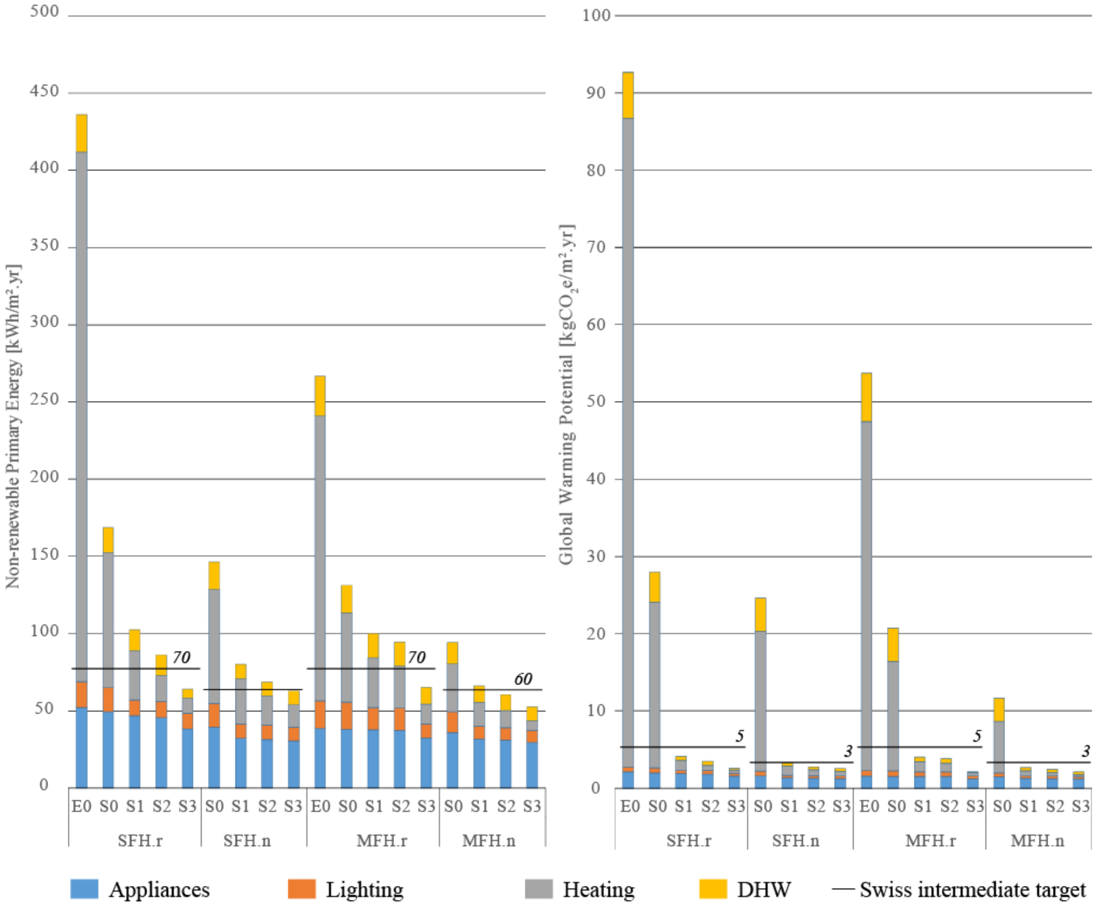


Fig.8 Results in terms of NRPE and GWP due to the final energy balance between consumption (Electric appliances, lighting, heating and DHW).The results include the reduction due to renewable energy production (ST and PV panels), for each archetype and performance scenario, compared to the intermediate targets (Tab. 7).

3.2.2 Detailed environmental impact results

For *common practice* variants, the results presented in Fig. 9 show lower environmental impacts for retrofitting scenarios – only *SFH.r.S3* does not reach the intermediate targets. The situation for new constructions is more disadvantageous since none of the variants reaches the targets for both indicators simultaneously. However, *MFH.n.S0* scenario reaches the targets for GWP indicator. According to the data in Fig. 9, the environmental impacts of multi-family houses are lower than those of single-family houses. It confirms the positive shape effect in the minimisation of impacts.

Vertical elements present the largest impacts for the majority of new construction scenarios. For retrofitting however, the elements bearing the largest share of responsibility differ according to indicators and construction typology. Another interesting result is the trend of impact within one scenario and between scenarios (*E0* to *S3*). Within one scenario, we can observe the influence of parking places in the overall impact for the GWP indicator: an underground (*un.*) parking presents the highest values and an outdoor parking place (*out.cp*) the lowest. For the NRPE consumption, results are different. Individual garage (*in.*) presents lower impacts in multi-family houses and outdoor parking (*out.cp*) in better in single-family houses, while underground (*un.*) have always the largest impact.

Between scenarios, results in the case of retrofitting present an increment of impacts that vary from 300-350% for new constructions and 15-35% for single- and multi-family houses and for both indicators. This result shows the consequences of materials in terms of environmental impact in case Swiss building energy performance is improved. Those observations underline the benefits of building retrofit: their label improvement allows reaching the intermediate targets even though their embodied impacts increase. Regarding new constructions, whatever the label, the techniques of current practice do not allow reaching the targets.

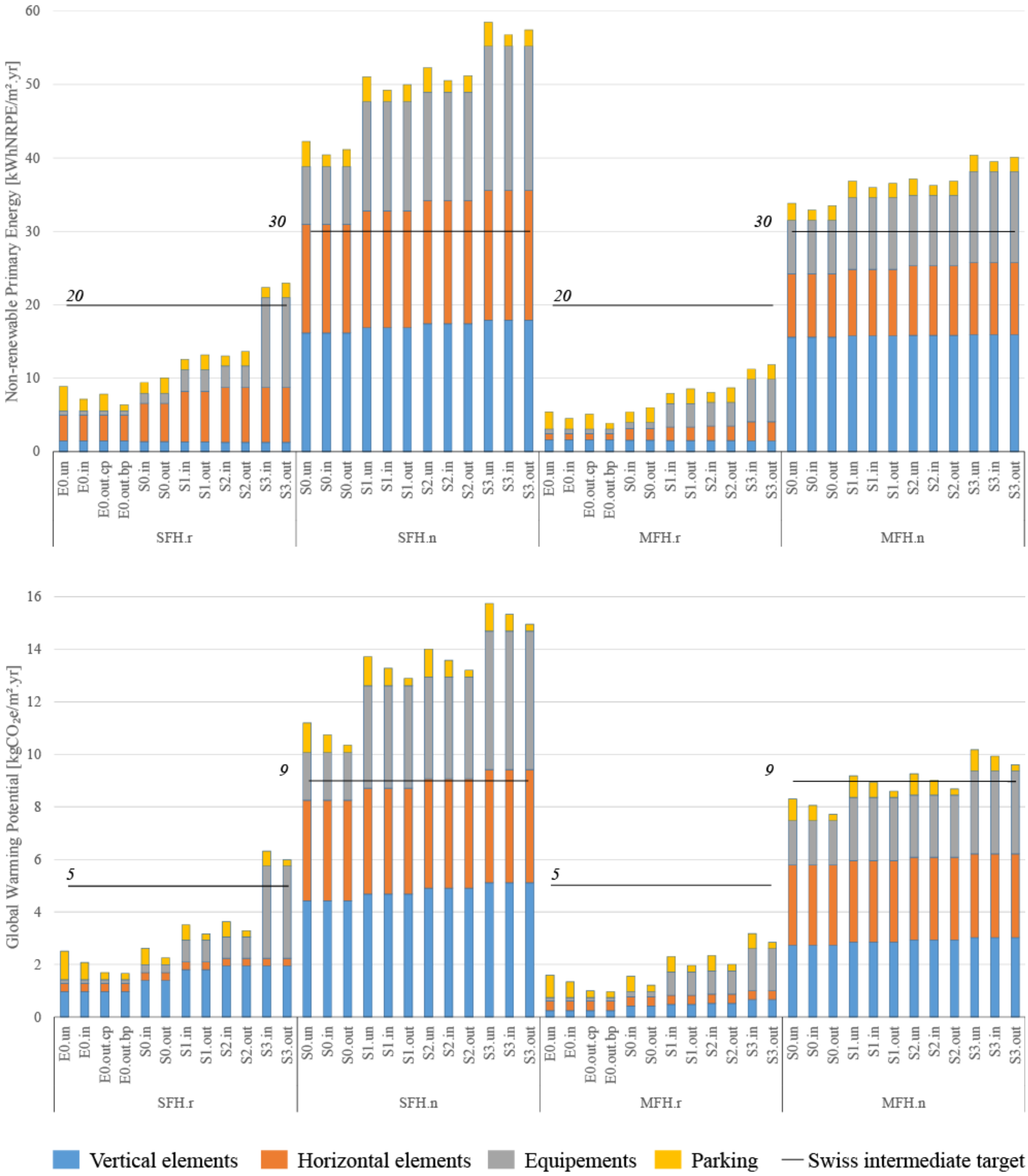


Fig. 9 Embodied impacts for *common practice* (cp) variants in terms of NRPE and GWP – different variants according to type of parking: *un.* – underground, *in.* – individual garage, *out.* – outside parking. In existing buildings, the underground parking is only accounted for at the *E0* stage, i.e. the initial construction. *E0* scenario only implements *common practice* variants. That is why both types of outside parking spaces – *out.cp*: asphalt, *out.bp*: concrete mono bloc paving – are presented.

For *best practice* (*.bp*) variants, the results presented in Fig. 10 are moderately improved. Environmental impacts of new buildings are in average minimized by 20% for NRPE and 25% for GWP. Although for retrofitting the conclusions are similar to those of current practice, the overall impacts are minimized with 9% for NRPE and 4% for GWP. Similar conclusions are also obtained for the largest contributors and trend of impacts within scenarios and between them. The advantage of *best practice* remains the achievement of targets for new constructions. Observations drawn from data in Fig. 10 lead to the conclusion that new single-family houses complying with the Swiss regulation (*SFH.n.S0*) and all variants for new multi-family houses (*MFH.n*) reach the intermediate targets for both indicators.

Based on the observation of retrofitting projects and new constructions we conclude on the possibility to reach easily the intermediate targets in renovation. Regarding new constructions, it is possible to reach the targets only by implementing best practices for multi-family houses and less insulation for single-family houses.

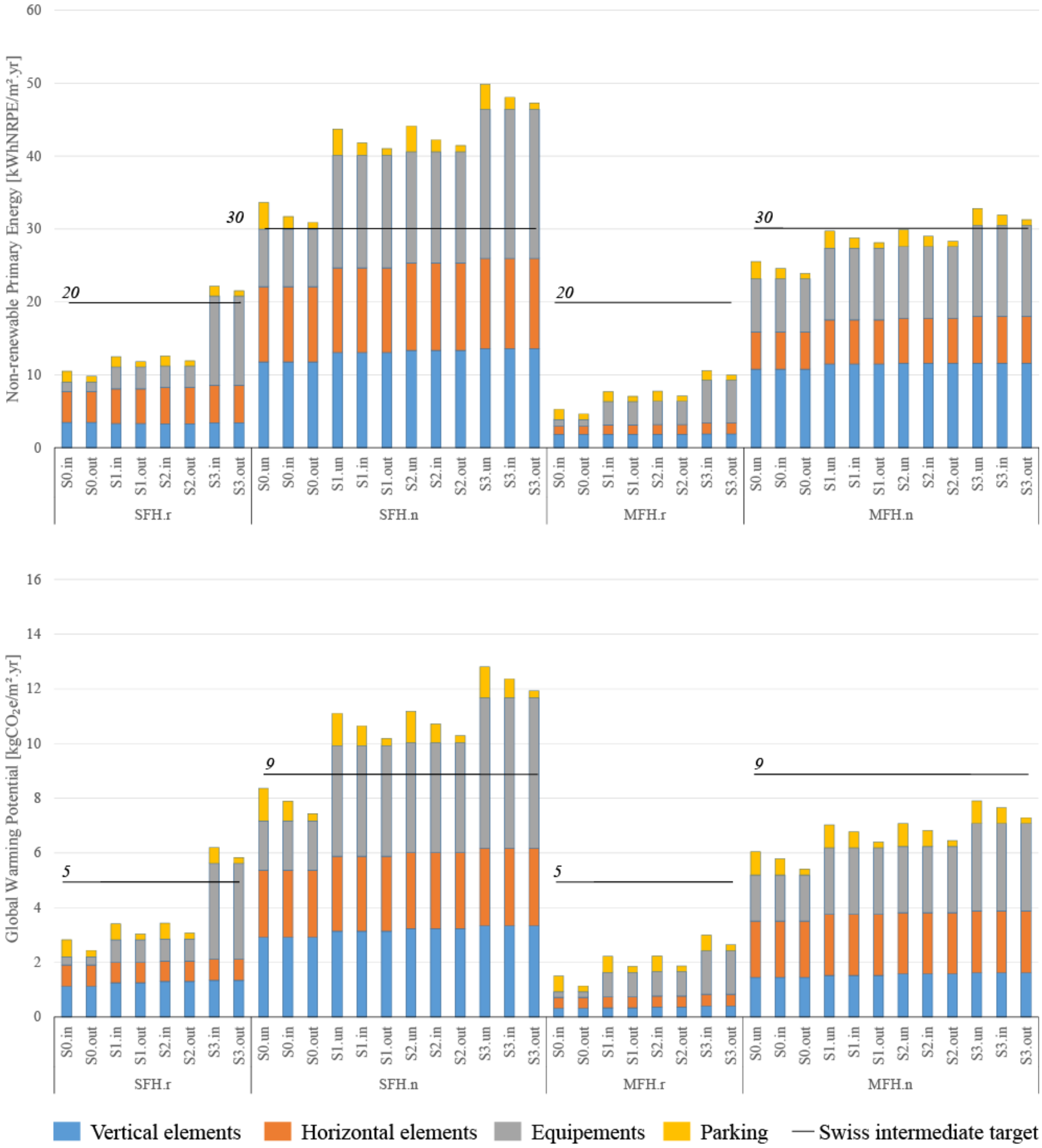


Fig.10 Embodied impacts for best practice (bp) variants in terms of NRPE and GWP – different variants according to type of parking: un. – underground, in. – individual garage, out. – outside parking: concrete monobloc paving.

3.3 Mobility related results

The divergent proportion of tenants and owners (Tab. 9) explains the results variation between single- and multi-family houses, which are 10% to 25% higher for single-family houses in *central*, *suburban* and *peri-urban* areas (Fig. 11). GWP results follow a similar trend as NRPE results but are 4 to 6 times higher than the intermediate target, except in multi-family houses located in the *centre* which show the lower results. Those results emphasize the extent of the carbonation of current mobility as well as the demanding nature of the GWP target.

The highest results for single- and multi-family houses are those of the *Peri-urban* areas where the travelled distance is the longest among all the territorial entities. In terms of NRPE consumption, induced daily mobility of multi-family houses inhabitants is 44% higher in *peri-urban areas* than in the *centre* (55.6 kWh/m^2.yr), and for single-family houses, results (109.5 kWh/m^2.yr) rise by one third in comparison to results obtains in *central areas* (74.3 kWh/m^2.yr).

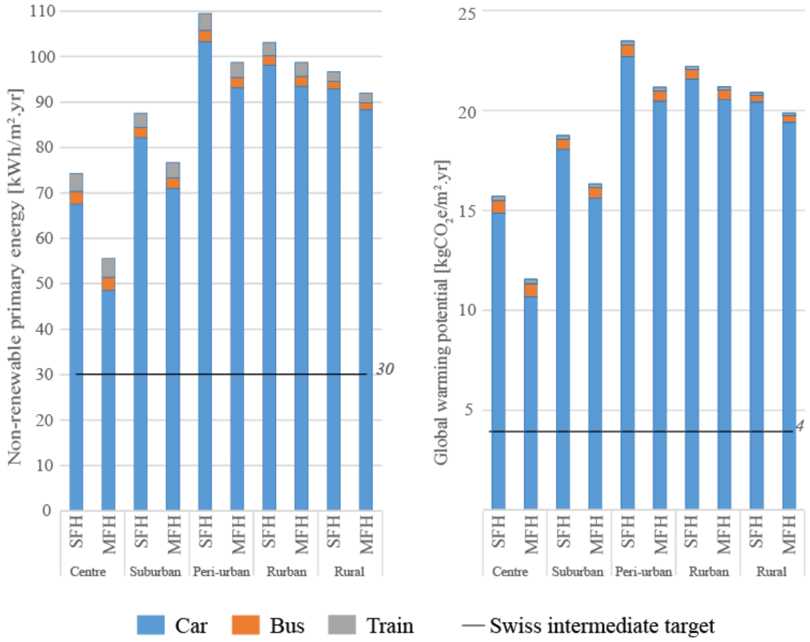


Fig.11 Results in terms of NRPE and GWP owing to current daily mobility induced by the building use, according to building type and territorial entity.

Considering the gap between the current mobility results and the intermediate targets, a projection is proposed assuming a potential future reduction of mobility related impacts (Fig. 12) (SIA 2016a). Results are halved between both assessments. The methodology considers only technical improvements; changes assume neither a redistribution of dwelling owners nor a different recourse to conveyances. According to the results, a technically improved mobility is not sufficient to meet the intermediate targets. Only one option complies with the goals. Results in *peri-urban areas* remain almost twice as high as the 30 kWh/m^2.yr target.

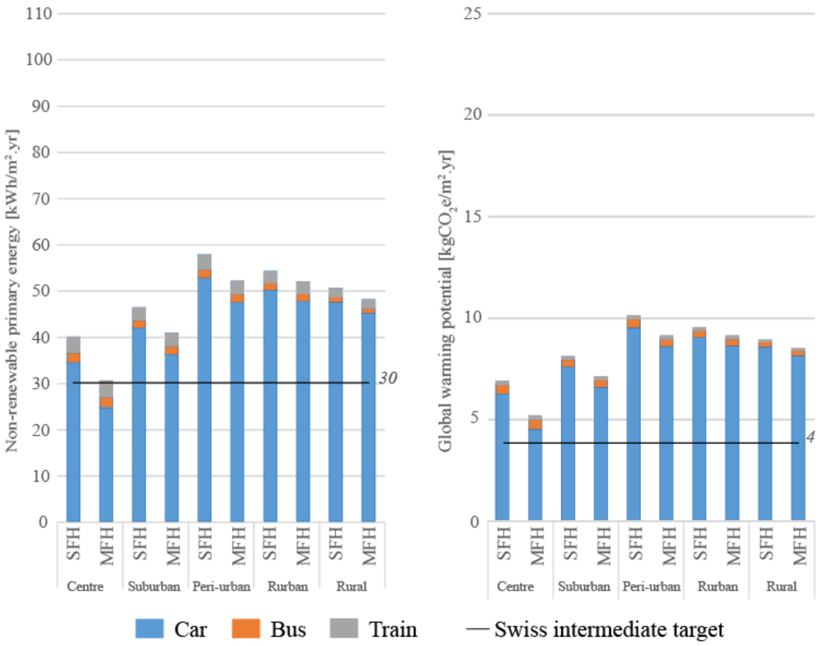


Fig.12 Results in terms of NRPE and GWP owing to a hypothetical reduced daily mobility induced by the building use, according to building type and territorial entity.

3.4 <u>Scenario performances with reduced IDM impacts</u>

The improved mobility results are combined with the previous operational and embodied impacts in Fig. 13 and 14. These figures show future performances achievable according to the information and practices known and available today. Under those conditions, some variants meet the intermediate targets set for the horizon of 2050.

A general overlook of multi-family house results shows that all *S1* to *S3* scenarios (*MFH.n/r.S1-S3*) are below or close to achieving the target. The best-case corresponds to central *MFH.r.S3.bp.*, with a NRPE consumption of 107.4 kWh/m^2.yr and a GWP of 10 kgCO_2e/m^2.yr. Regarding retrofitted single-family houses, although the *SFH.r.S3* scenarios are bordering the NRPE target, none of them meets the intermediate target of 120 kWh/m^2.yr. Nevertheless, some of the *SFH.r.S1/S2/S3* scenarios in the *centre* and s*uburban* areas reach the GWP goal. Due to the amount of CO_2e embodied in the necessary material for the *S3* scenarios, especially in the equipment (Fig. 9, 10), *SFH.n/r.S3* shows higher GWP than *SFH.n/r.S1-S2*.

SFH.n performs the worst among the assessed archetypes. None of the studied scenarios and variants meets the targets of both indicators. The best performing new single-family house shows results between 25% and 30% higher than NRPE targets and 40% above GWP goals.

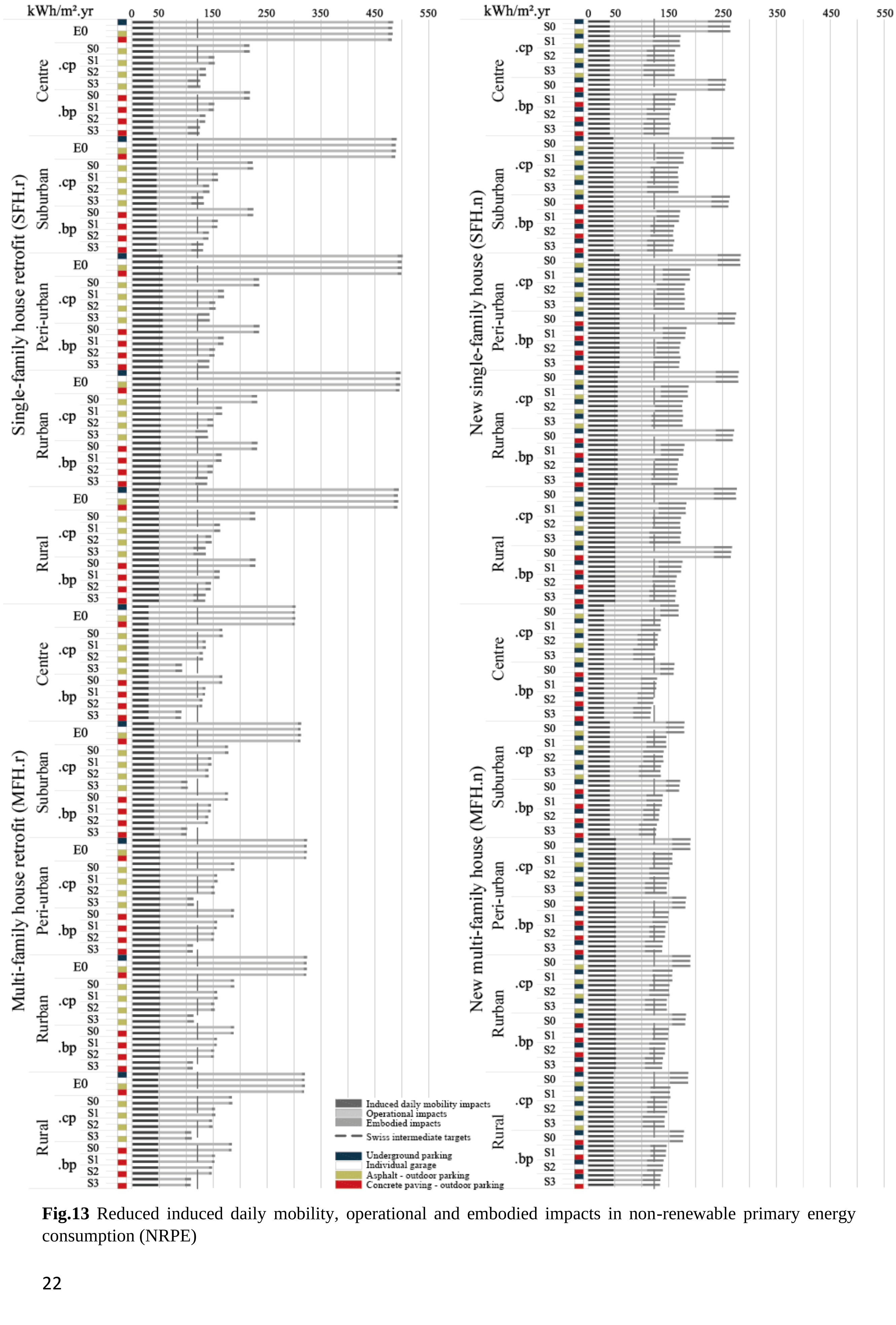


Fig.13 Reduced induced daily mobility, operational and embodied impacts in non-renewable primary energy consumption (NRPE)

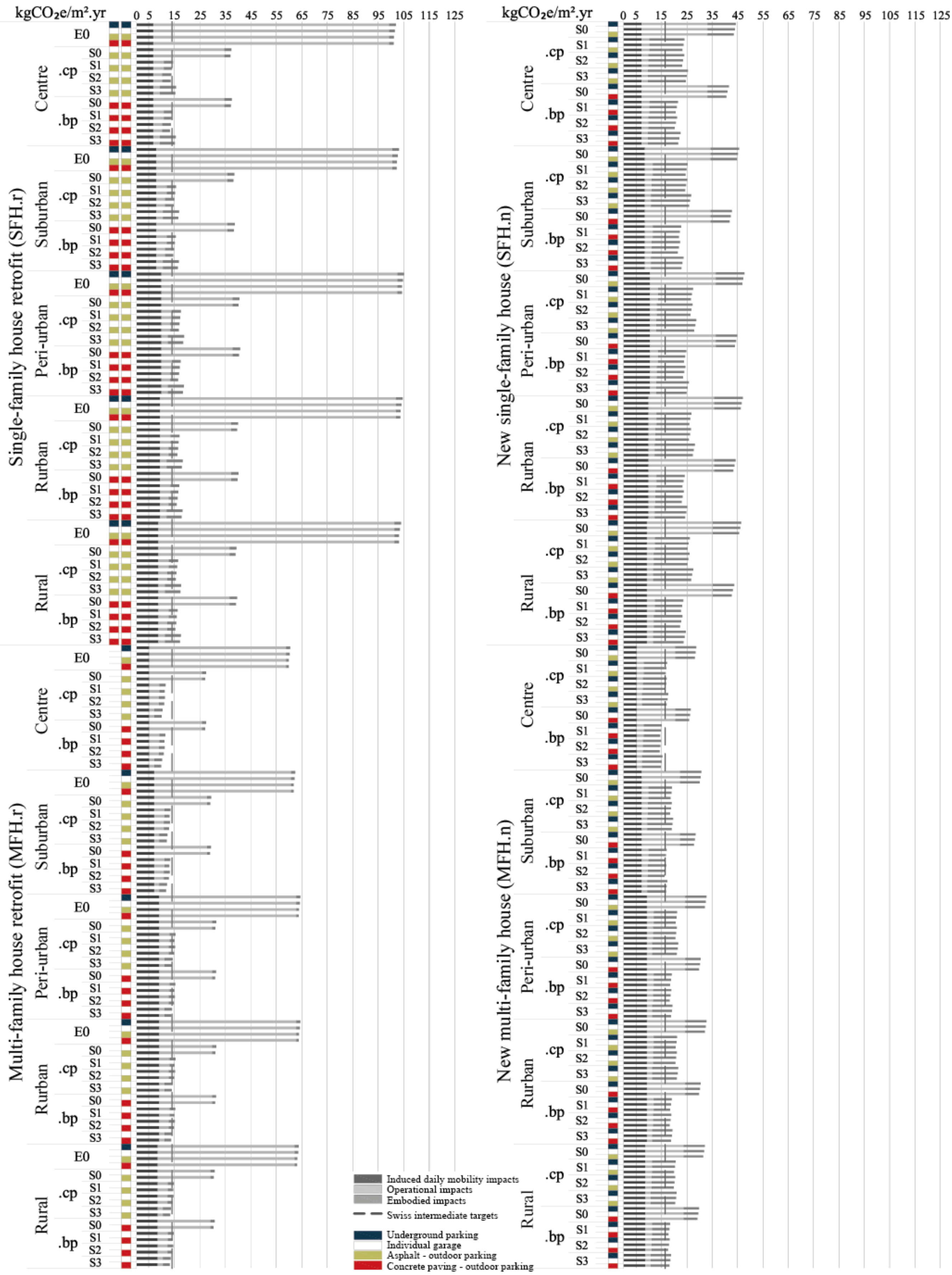


Fig.14 Global warming potential (GWP) for current induced daily mobility, operational and embodied impacts

4. Discussion

The detailed results presented as appendix provide the data for the residential archetypes adapted to the Swiss context. In order to choose the archetypes, we looked for the most common representative features for each building type and each construction period. Although buildings are never identical (e.g. different climate conditions, orientations, shapes…), this method provides a reference framework and basic database useful to illustrate current issues related to the environmental impact weight of the built environment, and especially the residential sector.

The gap among single- and multi-family houses results underlines the influence of compactness and occupation on the energy performance of a building. In the framework of the "2,000-W society", the intermediate targets for the built environment aim at an annual mean power per person of 840 W and 960 kgCO_2e of GWP. Therefore, the occupation and the resulting living area per person affect the overall per capita performances of the dwellings. In this scope, the current issue of under-occupation of single-family houses, which increases the living area per person, needs to be addressed in order to improve the environmental impacts of their inhabitants (Drouilles et al. 2017). In Switzerland, 75% of single family houses have at least a living area of 100 m^2 (FSO 2017a) and about half of the stock is occupied by one or two persons (Beyeler 2014).

This study highlights the overall environmental efficiency achieved within the current certification framework, given by the MINERGIE® labels, and reference targets. The results show that only the most requiring scenario, *S3* (energy positive buildings), is able to bring the performances close to the intermediate targets. Hence, in order to engage the built environment energy turnaround and meet the long-term targets set by the "2,000-W society" vision, the current certifications should be reconsidered to provide a framework about the whole building LCA. The current MINERGIE® labels mainly focus on operational final energy and they should include requirements about embodied impacts and operational impacts owing to the induced daily mobility, which tend to weight up to 70% in the overall LCA of the most performing buildings.

Starting from buildings of the 40s-70s in their current status (E0), the study underlines the benefits of building retrofits. Thanks to a very low investment in material and construction, environmental impacts are generally far below the targets and limited to less than 15% of the overall results in case of retrofitting projects. There is an immense improvement of energy performance and reduction of operational impacts: operational impacts go from representing more than 80% of the NRPE consumption to 30% in the more performing scenarios, which also consume about three times less energy. Therefore, energy wise and without taking into consideration density aspects, there should be no doubt about engaging a renovation process instead of a demolition/reconstruction one (Wastiels et al. 2016). Those results however raise some issues linked to the aspects of economic investment, timeline and technical feasibility of retrofit works (Jones et al. 2013; Fawcett 2014).

Another element identified with the study is the performance gap between the new construction of very low energy buildings (*S2* scenarios) and energy positive buildings (*S3* scenarios). When we focus on the operational and embodied impacts of new buildings, the overall performance is similar (+/- 5 kWh/m^2.yr). Those results raise the question of the benefit of achieving the best energy label when the added investment in material and construction erases the improvements made in reducing the operational impacts. Especially, when considering new single-family house archetype, which obtains the same overall results for *S2* and *S3* scenarios despite an improvement of operational impacts. The results presented by this archetype remain at least more than 25% higher than the intermediate targets. In order to comply with the energy performance requirements to aspire to a MINERGIE-A® label certification, it would be still necessary to increase the insulation, the HVAC systems performance, the PV installation or the self-consumption potential using storage systems (Aguacil et al. 2017b); that is, to increase the amount of material and thus the overall embodied impacts. Therefore, despite a high environmental footprint owing to embodied impacts, a further step of this study would be to analyse the balance between drawbacks and benefits of PV installations in terms of operational energy savings and embodied impacts, in terms of renewable energy production, self-consumption and sharing by injection to the local network, and in terms of economic investments and long-term payback.

The study underlines the central influence of operational impacts owing to the induced daily mobility within the overall buildings LCA. Considering the most performing scenarios, that of 2015 represents about half the NRPE consumption and up to 80% of the GWP. The results show that vehicle technical improvement is not sufficient to meet the intermediate targets. Some studies have explored the conditions for operational impacts owing to the induced daily mobility to meet the targets, (Scarinci et al. 2017), investigating the needed conveyance shift to be able to travel the same distance as today but meeting the intermediate targets. Through theoretical prospective scenarios, the preliminary study to this article states that operational impacts owing to the induced daily mobility will meet the targets only when low carbon individual motorized transport is used and trips and transportation are optimized, i.e. when the scenario assumes technical improvements at the same time as an optimization of practices and individual behaviours (Drouilles et al. 2017).

More precisely, the results underline how location and building type influence the operational impacts owing to the induced daily mobility. In particular, the study confirms the weak performances associated to the induced daily mobility of single-family houses' inhabitants living in peri-urban areas (*SFH.P*). Those results raise the issue of an adaptation of the targets to the location or building type: following their reduced induced daily mobility, people living in multi-family houses in central urban areas could afford to live in less energy-performing dwelling. Another option could be the implementation of energy equalization between the urban centre and its periphery. It would allow peripheral inhabitants to have higher environmental impacts than inhabitants of the centre, where the immediate living environment and amenities make the reduction of the environmental footprint an easier task to achieve.

5. Conclusions

The main findings of the study concern the benefits of renovation projects, which bring the environmental impacts of the building construction and operation down to the targets. Retrofit approaches are questionable regarding economic and feasibility aspects, but energy-wise they tend to offer better performances than new buildings. The results also confirm the expected weak performances of single-family houses in comparison to both multi-family houses and the intermediate targets. They underline the positive effects of compactness for reducing environmental impacts due to building construction and operation. Those findings support the argument that in the scope of urban renewal projects, densification and energy efficiency actions must be coupled to comply with the "2,000-W society" framework and achieve reduced per capita environmental footprints.

Results highlight the influence of each aspect in the whole life-cycle assessment of the four analysed archetypes. Consequently, it underlines the benefit of conducting interdisciplinary approaches considering different assessment scales – from the architectural object to the integration at urban and territorial level – to achieve a higher degree of sustainability. In perspective of this research, for increasing the robustness of conclusions, further uncertainty analyses are necessary by assessing the uncertainty in environmental impacts of buildings that derives from uncertainty in inputs.

The major output of this study relies in the implementation of a bottom-up methodology that provides reference values for the assessment of non-renewable energy and global warming potential indicators in the built environment in Switzerland. Based on the modelling and assessment of four building archetypes, the study provides 880 variants that can be combined for implementing an assessment on a larger scale. This database represents a consistent framework for professionals to make informed decisions by simultaneously considering the environmental impacts of building and the influence of location and territorial context. It especially offers the possibility to (1) run some preliminary environmental assessments from an isolated building to a group of residential buildings, i.e. a neighbourhood; (2) arbitrate pros and cons, in terms of environmental impacts, of a retrofit or new construction project; (3) provide a decision support on the type of action to engage depending on the location and archetype; (4) revise the regulation in use from the perspective of its impact on current practice; (5) assess current performance of buildings targeting high energy efficiency certifications (e.g.: *MINERGIE®* labels) or current regulation (e.g.: SIA) in comparison with the intermediate targets for 2050; (6) consider the extent of the improvements needed regarding the environmental impacts owing to the induced daily mobility (IDM). The results support the fact that practitioners need to be aware of the current performances achievable in the built environment and of the remaining challenges to meet the targets for 2050, which are still intermediate goals towards the achievement of the "2,000-W society" by 2100.

6. References

Aguacil, S., Lufkin, S., Rey, E., Cuchi, A. (2017a). Application of the cost-optimal methodology to urban renewal projects at the territorial scale based on statistical data—A case study in Spain. *Energy and Buildings*, 144, 42–60. https://doi.org/10.1016/j.enbuild.2017.03.047.

Aguacil, S., Lufkin, S., Rey, E. (2017b). Influence of energy-use scenarios in Life-Cycle Analysis of renovation projects with Building-Integrated Photovoltaics – Investigation through two case studies in Neuchâtel (Switzerland). *Proceedings of the International Conference for Sustainable Design of the Built Environment 2017*, London, UK, 1101–1112.

Beyeler, M. (2014). *Métamorphouse : transformer sa maison au fil de la vie*. Presses Polytechniques et Universitaires Romandes, Lausanne.

Cabeza, L.F., Rincon, L., Vilarino, V., Perez, G.,Castella, A. (2014). Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review. Renewable and sustainable energy reviews, 29. pp. 394-416.

Citherlet S., Defaux T. (2007). Energy and environmental comparison of three variants of a family house during its whole life span.*Building and Environment* 42(2), 591–598.https://doi.org/10.1016/j.buildenv.2005.09.025.

DesignBuilder Software v.5 (2018). DesignBuilder Software Ltd. UK. https://www.designbuilder.co.uk/. Accessed 10 October 2018.
Desjardins, X., Mettetal, L. (2012). L'habiter périurbain face à l'enjeu énergétique. *Flux* 2012/3, 46–57.
Drouilles, J., Lufkin, S., Rey, E. (2017). Energy transition potential in peri-urban dwellings: Assessment of theoretical scenarios in the Swiss context. *Energy and Buildings*, 148, 379–390. https://doi.org/10.1016/j.enbuild.2017.05.033.
Drouilles, J., Rey, E. (2018). L'avenir des quartiers résidentiels périurbains dans le contexte helvétique, in. Léger J.-M., Mariolle B. *Densifier dédensifier, Penser les campagnes urbaines*, Parenthèses, Marseille.
Eames, M., Dixon, T., May, T., Hunt, M. (2013). City futures: exploring urban retrofit and sustainable transitions. *Building Research & Information*,41, 504–516. https://doi.org/10.1080/09613218.2013.805063.
EN 15804-2012, 2013. EN 15804-2012 Sustainability of construction works, Environmental product declarations, Core rules for the product category of construction products. CSN EN Standard.https://www.en-standard.eu/din-en-15804-sustainability-of-construction-works-environmental-product-declarations-core-rules-for-the-product-category-of-construction-products-includes-amendment-a1-2013/. Accessed 17 October 2017.
EN 15978-2012, 2013. EN 15804-2012 Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method. CSN EN Standard.https://www.en-standard.eu/csn-en-15978-sustainability-of-construction-works-assessment-of-environmental-performance-of-buildings-calculation-method/. Accessed17October 2017.
EnDK, C. des directeurs cantonaux de l'énergie (2014). *Modèle de prescriptions énergétiques des cantons* (MoPEC).
Fawcett, T. (2014). Exploring the time dimension of low carbon retrofit: owner-occupied housing. *Building Research& Information* 42, 477–488. https://doi.org/10.1080/09613218.2013.804769.
FSO, ARE (2012). *La mobilité en Suisse. Résultats du microrecensement mobilité et transports 2010* (No. 841–1000). FSO (Federalstatistical office), Neuchâtel.
FSO (2017a). Statistiques 2015 des bâtiments et logements. https://www.bfs.admin.ch/bfs/fr/home/statistiques/construction-logement/logements.html. Accessed27 July 2017.
FSO, (2017b). Energy field. Federal Statistical Office.https://www.bfs.admin.ch/bfs/en/home/statistics/construction-housing/buildings/energy-field.html. Accessed 11 October 2017.
Gustavsson, L., Joelsson, A. (2010). Life cycle primary energy analysis of residential buildings. *Energy and Buildings* 42, 210–220. https://doi.org/10.1016/j.enbuild.2009.08.017.
Hall, M., Geissler, A., Burger, B.(2014). Two Years of Experience with a Net Zero Energy Balance – Analysis of the Swiss MINERGIE-A® Standard. *Energy Procedia*, 48, 1282–1291.https://doi.org/10.1016/j.egypro.2014.02.145.
Heinonen, J., Jalas, M., Juntunen, J.K., Ala-Mantila, S., Junnila, S. (2013a). Situated lifestyles: II. The impacts of urban density, housing type and motorization on the greenhouse gas emissions of the middle-income consumers in Finland. *Environmental Research Letters*, 8, 035050. https://doi.org/10.1088/1748-9326/8/3/035050.
Heinonen, J., Jalas, M., Juntunen, J.K., Ala-Mantila, S., Junnila, S. (2013b). Situated lifestyles: I. How lifestyles change along with the level of urbanization and what the greenhouse gas implications are—a study of Finland. *Environmental Research Letters*, 8, 025003. https://doi.org/10.1088/1748-9326/8/2/025003.
Holden, E., Norland, I.T. (2005). Three Challenges for the Compact City as a Sustainable Urban Form: Household Consumption of Energy and Transport in Eight Residential Areas in the Greater Oslo Region. *UrbanStudies*, 42, 2145–2166. https://doi.org/10.1080/00420980500332064.
Hoxha, E. (2015). *Amélioration de la fiabilité des évaluations environnementales des bâtiments* (Doctoral dissertation). Université Paris-Est.
Hoxha, E., Jusselme, T., Brambilla, A., Cozza, S., Andersen, M., Rey, E. (2016a). Impact Targets as Guidelines towards Low Carbon Buidlings : A preliminary concept.*PLEA 2016 - Cities, Buildings, People: Towards regenerative environments, Proceedings of the 32rd PLEA International conference*, Los Angeles, 938–945.
Hoxha, E., Jusselme, T., Andersen, M., Rey, E. (2016b). Introduction of a Dynamic Interpretation of Building LCA Results: The Case of the Smart Living (Lab) Building in Fribourg, Switzerland. *Expanding Boundaries*. https://doi.org/10.3218/3774-6_25.
IEE (2016). TABULA WebTool. TABULA – Typology Approach for Building Stock Energy Assessment. http://webtool.building-typology.eu/#bm. Accessed 13October 2017.
Institut d'architecture TRANSFORM (Ed.) (2016). *Approche globale pour l'enveloppe du bâtiment : Rénovation énergétique*. Haute Ecole d'Ingénierie et d'Architecture (HEIA) Fribourg, Fribourg.

John, V. (2012). *Derivation of reliable simplification strategies for the comparative LCA of individual and "typical" newly built Swiss apartment buildings*. (Doctoral dissertation). ETH Zurich.https://doi.org/10.3929/ethz-a-007607252.
Jones, P., Lannon, S., Patterson, J. (2013). Retrofitting existing housing: how far, how much? *Building Research & Information*,41, 532–550. https://doi.org/10.1080/09613218.2013.807064.
Jusselme, T., Brambilla, A., Hoxha, E., Jiang, Y., Vuarnoz, D., Cozza S. (2015). *Building 2050-State-of-the-arts and preliminary guidelines*. Swiss Federal Institute of Technology Lausanne. EPFL-REPORT-214871. Switzerland.
KBOB (2016). Liste des écobilans dans la construction 2009/1 (v. 2014). https://www.kbob.admin.ch/kbob/fr/home/publikationen/nachhaltiges-bauen/oekobilanzdaten_baubereich.html. Accessed 15 June 2017.
Kunič, R. (2017). Carbon footprint of thermal insulation materials in building envelopes. *Energy Efficiency*, 10(6), 1511-1528. https://doi.org/10.1007/s12053-017-9536-1.
Lasvaux, S., Lebert, A., Achim, F., Grannec, F., Hoxha, E., Nibel, S., Schiopu, N., Chevalier, J. (2017). Towards guidance values for the environmental performance of buildings: application to the statistical analysis of 40 low-energy single family houses' LCA in France. *The International Journal of Life Cycle Assessment*,22, 657–674. https://doi.org/10.1007/s11367-016-1253-z.
Loga, T., Stein, B., Diefenbach, N. (2016). TABULA building typologies in 20 European countries—Making energy-related features of residential building stocks comparable. *Energy and Buildings*, 132, 4–12. https://doi.org/10.1016/j.enbuild.2016.06.094.
Meteonorm Software v7.2.2 (2017). Meteotest.Switzerland.http://www.meteonorm.com/en/. Accessed 10 October 2017.
Minergie (2014). Minergie – Home. http://www.minergie.ch/home_fr.html.Accessed 24 July 2017.
Minergie (2017). Liste des bâtiments. MINERGIE Schweiz.https://www.minergie.ch/fr/btiments/. Accessed 24 July 2017.
Munafò, S. (2016). *La ville compacte remise en cause ?: formes urbaines et mobilités de loisirs*. Editions Alphil Presses universitaires suisses. Neuchâtel.
Nessi, H. (2012). *Influences du contexte urbain et du rapport au cadre de vie sur la mobilité de loisir en Ile-de-France et à Rome*. Université Paris-Est, Paris.
Novatlantis, SIA, Swissenergy (2011). *Smarter Living: moving forward to a sustainable energy future with the 2000 Watt society* (No. 805.200.e). Bern.
Oliveira Panão, M.J.N., Rebelo, M.P., Camelo, S.M.L. (2013). How low should be the energy required by a nearly Zero-Energy Building? The load/generation energy balance of Mediterranean housing. *Energy and Buildings*,61, 161–171. https://doi.org/10.1016/j.enbuild.2013.02.031.
Ottelin, J., Heinonen, J., Junnila, S. (2015). New Energy Efficient Housing Has Reduced Carbon Footprints in Outer but Not in Inner Urban Areas. *Environmental Science & Technology*, 49, 9574–9583. https://doi.org/10.1021/acs.est.5b02140.
Paganin, G., Angelotti, A., Ducoli, C., Lavagna, M., Talamo, C. and Luccietto, S. (2017). Energy performance of an exhibition hall in a life cycle perspective: embodied energy, operational energy and retrofit strategies. *Energy Efficiency*, 10(6), 1343-1364.https://doi.org/10.1007/s12053-017-9521-8.
Ratti, C., Baker, N., Steemers, K. (2005). Energy consumption and urban texture. *Energy and Buildings*, 37, 762–776.https://doi.org/10.1016/j.enbuild.2004.10.010.
Remund, J., Müller, S., Schilter, C., Beat, R.(2010). The use of Meteonormwheather generator for climate change studies, *EMS Annual Meeting Abstracts*. Bern.
Rey, E., Lufkin, S., Renaud, P., Perret, L. (2013). The influence of centrality on the global energy consumption in Swiss neighborhoods. *Energy and Buildings*, 60, 75–82. https://doi.org/10.1016/j.enbuild.2013.01.002.
Rickwood, P., Glazebrook, G., Searle, G. (2008). Urban Structure and Energy—A Review. *Urban Policy and Research*,26, 57–81. https://doi.org/10.1080/08111140701629886.
Riera Pérez, M.G., Rey, E.(2013). A multi-criteria approach to compare urban renewal scenarios for an existing neighborhood. Case study in Lausanne (Switzerland). *Building and Environment*, 65, 58–70. https://doi.org/10.1016/j.buildenv.2013.03.017.
Rossi, B., Marique, A.-F., Reiter, S. (2012). Life-cycle assessment of residential buildings in three different European locations, case study. *Building and Environment*, 51, 402–407. https://doi.org/10.1016/j.buildenv.2011.11.002.
Ruiz, R., Stephane Bertagnolio, Lemort, V. (2012). Global Sensitivity Analysis applied to Total Energy Use in Buildings, *International High Performance Buildings Conference*. Purdue. USA. https://doi.org/10.13140/2.1.3178.7209.
Sartori, I., Hestnes, A.G. (2007). Energy use in the life cycle of conventional and low-energy buildings: A review article. *Energy and Buildings*, 39, 249–257. https://doi.org/10.1016/j.enbuild.2006.07.001.

Scarinci, R., Rast, F., Bierlaire, M. (2017). Needed reduction in mobility energy consumption to meet the goal of a 2000-watt society. *Transportation Research Part A: Policy and Practice*, 101, 133–148. https://doi.org/10.1016/j.tra.2017.05.010.
SFOE (2015a). Energy Strategy 2050.Société à 2000 watts. https://www.uvek.admin.ch/uvek/en/home/energie/energy-strategy-2050.html/. Accessed 15 November 2017.
SFOE (2015b).*Isolation thermique et technique du bâtiment - combien et dans quels cas*. Swiss Federal Office of Energy SFOE. Bern.
SFOE (2017). Catalogueconstruction.ch.Swiss Federal Office of Energy SFOE. Bern.http://www.bauteilkatalog.ch/ch/fr/21.asp?lng=FR&navid=1. Accessed 10October 2017.
SIA (2010). *L'énergie grise des bâtiments, Cahier technique SIA-2032*. Swiss society of engineers and architects SIA, Zurich.
SIA (2015a). *Données d'utilisation des locaux pour l'énergie et les installations du bâtiment - Cahier technique SIA-2024*. Swiss society of engineers and architects SIA, Zürich.
SIA (2015b). Base pour les calculs énergétiques des bâtiments. Norme SIA-380. Swiss society of engineers and architects SIA, Zurich
SIA (2016a). *Mobilité : consommation énergétique des bâtiments en fonction de leur localisation, Cahier technique SIA-2039*. Swiss society of engineers and architects SIA, Zurich.
SIA (2016b). *Besoin de chaleur pour le chauffage. Norme SIA 380/1*. Swiss society of engineers and architects SIA, Zurich.
SIA (2017). *La voie SIA vers l'efficacité énergétique - Cahier technique SIA-2040*. Swiss society of engineers and architects SIA, Zürich.
SIA (2018). *La voie SIA vers l'efficacité énergétique - Compléments et exemples relatifs au cahier technique SIA-2040, Documentation SIA D 0258*. Swiss society of engineers and architects SIA, Zürich.
Slavkovič, K., Radivojevič, A. (2015). Evaluation of energy embodied in the external wall of single-family buildings in the process of energy performance optimisation. *Energy efficiency*, 8(2), 239–253. https://doi.org/10.1007/s12053-014-9285-3.
Stephan, A., Crawford, R.H., de Myttenaere, K. (2012). Towards a comprehensive life cycle energy analysis framework for residential buildings. *Energy and Buildings,* 55, 592–600. https://doi.org/10.1016/j.enbuild.2012.09.008.
Steskens, P., Vanhellemont, Y., Roels, S., Van Den Bossche, N. (2015). A Decision Making Tool for the Energy Efficient Refurbishment of Residential Buildings. *EnergyProcedia,* 78, 997–1002. https://doi.org/10.1016/j.egypro.2015.11.043.
Suisse Energie (2017). La Suisse, sur la voie de la Société à 2000 watts: bilan des éneregies primaires en Suisse de 1980 à 2015. Société à 2000 watts. http://www.2000watt.ch/fr/societe-a-2000-watts/facts-figures/. Accessed 19 October 2017.
Swan, L.G., Ugursal, V.I. (2009). Modeling of end-use energy consumption in the residential sector: A review of modeling techniques. *Renewable and Sustainable Energy Reviews*, 13, 1819–1835. https://doi.org/10.1016/j.rser.2008.09.033.
Thiel, C., Nijs, W., Simoes, S., Schmidt, J., van Zyl, A., Schmid, E.(2016). The impact of the EU car CO2 regulation on the energy system and the role of electro-mobility to achieve transport decarbonisation. *Energy Policy,* 96, 153–166. https://doi.org/10.1016/j.enpol.2016.05.043.
Wastiels, L., Janssen, A., Decuypere, R. (2016). Demolition versus Deep Renovation of Residential Buildings: Case Study with Environmental and Financial Evaluation of Different Construction Scenarios. *Expanding Boundaries*. https://doi.org/10.3218/3774-6_76.
Xu, P., Shen, Y., Chen, L., Mao, J., Chang, E. and Ji, Y. (2016). Assessment of energy-saving technologies retrofitted to existing public buildings in China. *Energy Efficiency*, 9(1), 67–94.https://doi.org/10.1007/s12053-015-9350-6.
Zachariadis, T. (2006). On the baseline evolution of automobile fuel economy in Europe. *Energy Policy* 34, 1773–1785. https://doi.org/10.1016/j.enpol.2005.01.002.

7. Appendix

A separate excel file is provided. The dataset expresses results in terms of non-renewable primary energy (NRPE) consumption: kWh.m^2.yr; and of global warming potential (GWP): kgCO_2e/m^2.yr. Each category is divided into five columns: (1) induced daily mobility, (2) operational, (3) embodied, (4) total and (5) target.

1- *Induced daily mobility* refers to impacts owing to incoming mobility of building users. It considers distances travelled by individual motorized transport and public transport (train and bus).

2- *Operational* refers to operational impacts due to appliances, lighting, heating and domestic hot water (DHW).

3- *Embodied* refers to the embodied impacts owing to vertical elements (windows and doors, walls, insulation and façade), horizontal elements (slabs, insulation and roof), equipment (HVAC system and renewables: solar thermal (ST) or photovoltaics (PV) panels), and parking.

4- *Total* is the sum of induced daily mobility, operational and embodied.

5- *Target* refers to the framework of the “2,000-W society” (Novatlantis et al. 2011) for which SIA-2040 sets intermediate targets for 2050 (SIA 2017). Table 5 gives the detailed targets set for renovation projects and new constructions, and for each of the previous assessed categories (induced daily mobility, operational and embodied).