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Energy transition challenges in under-occupied homes
Assessment of two peri-urban neighbourhoods of single-family houses

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ABSTRACT: Current planning policies aim at putting a stop to urban sprawl by favouring densification processes. In this context, future developments are more likely to happen in strategic urban areas than in existing peri-urban neighbourhoods of single-family houses. There, a possible path of development is the inertia and the submission to demographic evolutions of population ageing and reduction of household sizes. Under those unfavourable conditions, the evolution of two case-studies located in the Swiss context is measured by 2050. The paper investigates the energy transition potential of two off-centred residential areas by assessing the environmental impacts owing to construction/retrofit and operation of dwellings, and to the induced daily mobility of the inhabitants. The innovative methodology implemented for this research project supports a spatiotemporal data management that allows establishing an annual assessment throughout the 35-year period of study (2015-2050). The results highlight the submission of the transition potential to the alternation of household's life-cycles. This study underlines the importance of considering over-time assessments for a more reliable prospective evaluation, and it questions the transition slowness of owner-occupied dwellings.

KEYWORDS: Energy transition, single-family homes, under-occupation, retrofit, life-cycle analysis

1. INTRODUCTION

1.1 Context and challenges

Facing climate change issues, cities appear as one of the major energy consumers. Transport and households are particularly responsible for this high urban energy footprint, especially in off-centred low-density residential areas [1].

Energy-retrofitting of single-family houses, which are mostly heated with fossil fuels, represent a major topic for coming years. The issue is even more urgent in peri-urban areas highly dependent on individual car mobility. Under those conditions, inhabitants are vulnerable to potential future crisis. Therefore, investigating straight away the energy transition potential of areas of single-family houses is important, since them too have a role to play in meeting global emission targets. Locally, exploring the possibility of more resilient peri-urban communities would help mitigate future socioeconomic downsides.

However, among multiple challenges faced by peri-urban residential areas, the paper addresses: 1) the low energy-efficiency of their building stock, mainly built between the 1960s and 1980s, 2) the issues of the mismatch between single-family houses typologies and current demographic and societal evolutions towards population ageing and reduction of household size [2].

1.2 Research framework

The findings presented in this paper are part of a broader research [3] which investigated the future of peri-urban neighbourhoods of single-family houses in light of five prospective scenarios. The research questioned the sustainability transition potential of car dependent residential areas created mainly in the second half of the 20th century.

The first step of the research identified *peri-urban residential municipalities* according to several criteria recurrent in European and Swiss definitions. They gather towns that are physically separated from the compact central urban fabric, but connected to them through functional relationships (commuting). They also present significative population density and proportion of single-family houses in their building stock. Finally, they met a strong demographic growth between 1950 and 2000 [4]. The main body of research was the conception, application and assessment of the following prospective scenarios, presented in depth in [5]. Two scenarios – *Caducity* and *Exclusivity* – investigate a future inertia of neighbourhoods and the preservation of current lifestyles. The scenario *Opportunity* focuses on effects of emerging soft-densification practices. *Urbanity* and *Mutuality* propose deeper transitions based on weak signals of mentality and society changes. The scenarios are systematically applied in real case-studies and assessed according to all aspects of sustainability and to their implementation feasibility. Altogether, the research outcomes help anticipating how future planning decisions might maintain or improve the situation of existing peri-urban neighbourhoods.

1.3 Aim and structure

The present paper however focuses only on the *Caducity* scenario and investigates more deeply the effect of a *status quo*, which may concern some of the neighbourhoods less integrated within metropolitan dynamics, which are not considered as future land resources. Hence, the paper aims at assessing the energy transition potential of such areas submitted to unfavourable conditions of development. The novelty of the approach lies in part in considering the effects of inertia or negative trends [6], also in conducting a prospective analysis at neighbourhood scale based on a research by design methodology combined with an extensive data management. It results in the spatiotemporal assessment of the scenarios implementation process and outcomes.

The following section of the paper presents the material and methods used for the implementation of the *Caducity* scenario into two existing case-studies, located in the urban region of Lausanne. Starting from a theoretical basis, it sets the conditions for attractiveness and value losses, then it gives the hypotheses selected for the scenario implementation at neighbourhood scale and for the assessment of its environmental impacts.

The next section provides the results in terms of demographic trend, building transformations and environmental assessment. The results highlight the impacts of a wide spread under-occupation of single-family houses on the energy transition extent and speed.

2. METHOD

A panel of eighteen academy and industry experts was consulted to gather arguments supporting diverse future perspectives for neighbourhoods of single-family houses. The five scenarios resulted from the identification of coherent future visions for an application in the Swiss context. They are representative of the issues discussed in the interviews and collected across the literature. The *Caducity* scenario, is therefore, representative of the current and foreseen evolution of some peri-urban areas [7]. It considers the following context and hypotheses.

2.1 Loss of attractiveness

According to current trends, neighbourhoods of single-family houses are likely to face stagnation or decay in the coming years [8,9]. Arguments supporting this hypothesis are owing to external circumstances such as the global demographic transition known in European countries. The growing proportion of small households and elderlies questions the maintenance of the attractiveness of single-family houses typologies [2,10,11]. As shown in a Dutch study, population ageing and the reduction of household size is highly corelated to an over-consumption of housing, i.e. to dwelling under-occupation [12]. The authors indicate how older households tend to stay in their homes after children departure and that the phenomenon is more common in owner-occupied homes.

Regarding peri-urban neighbourhoods of single-family houses a higher risk of inertia exists due to the high dependence to individual motorized transport [8], and to the common political opposition to change meant to preserve the electorate’s living environment [13]. Moreover, current trends in urban and territorial planning tend to reorient future developments in strategic urban areas well connected to public infrastructures. This inward densification is a guiding principle of current Swiss planning policies [14]. Those evidences witnessed at large scale suggest that some dynamics relating to the shrinking city phenomenon (such as population decrease) could apply to some peripheral or off-centred built areas [15].

2.2 Loss of value

At a closer scale, the *Caducity* scenario embraces those hypotheses, which induce a loss of economic value of existing buildings due to the conditions of low attractiveness and of delayed retrofits.

1. As a direct consequence of longer occupation periods, many small elderly households, with limited resources live in single-family houses. Retrofit actions are delayed until new occupants get involved.
2. Living in central areas close to a richer offer of local amenities becomes more appealing than the landscape qualities of peri-urban areas. Hence, a slight disarticulation of the real-estate market in those areas induces longer vacancies between owners: prices drop and insertion time of houses in the market increases.
3. For a similar reason, the scenario assumes that the demand is not sufficient for the empty plots to be built. It only allows the refurbishment of existing houses.

2.3 Implementation in two case studies

Further than identifying those theoretical hypotheses, the added value of the research lies in implementing the scenario into existing case-studies in order to observe actual effects on the building stock. To do so, the study is focused on the urban region of Lausanne, Switzerland.

Selected among a typology of peri-urban neighbourhoods of single-family houses [16], the case-studies presented here belong to two contrasted types, showing opposite features. The neighbourhood located in Chavornay (CHA) (Fig. 1a) is close to a regional train station, its urbanisation started long before 1975. Quite large, with an area of nine hectares, it gathered in 2015, 213 inhabitants in 93 dwellings. The neighbourhood located in Jorat-Mézières (MEZ) (Fig. 1b) is only accessible by bus. Its urbanisation started around 1975. It is a small neighbourhood, with an area of three and a half hectares. It was composed in 2015, of 29 dwellings occupied by 72 persons.

Figure 1: L: Neighbourhood in Chavornay (CHA) VD-CH (2015) R: Neighbourhood in Jorat-Mézières (MEZ) VD-CH (2015)

The evolution of owner-occupied houses is very dependent on the inhabitant's evolving needs along the different life-stages. It is especially conditioned by the entry into the family phase, since the purchase of a house usually precedes or follows the birth of the first child [2]. By considering neighbourhoods of owner-occupied houses built in the second half of the 20th century, many houses are still occupied by their initial owners. Simulating the house occupation, and the alternance of cycles (Fig. 2) is possible thanks to the definition of turning points and pivotal ages when changes are more likely to happen. Two elements have significative effects on the assessment of environmental impacts:

- The departure of the children. Afterwards, the house is occupied by a small household of retired people.
- Life expectancy [17]. Even though local data have shown that some households wish to relocate, the scenario assumes that 100% of them stay as long as possible in their houses. Indeed, in this scenario, the real-estate market lengthens the insertion time of houses and prevents a fast and easy rotation of households.

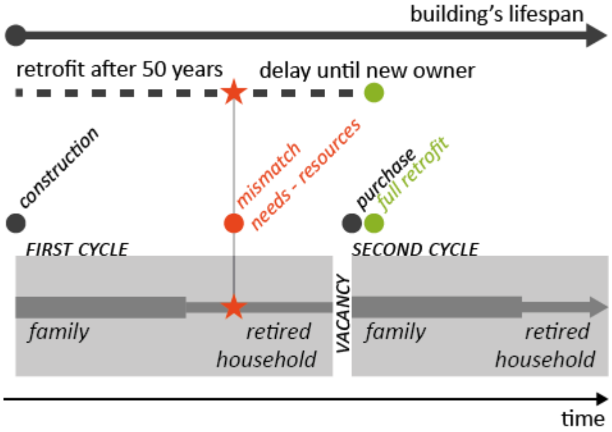

Figure 2: Occupation cycles in owner-occupied single-family houses, and effect on building's state. Hypotheses considered for the entire building stock in Caducity scenario.

2.4 Environmental impact assessment

The environmental impact assessment is built at neighbourhood scale according to the framework set by the Swiss 2000-watt society concept applied to the built environment [18]. Non-renewable primary energy (NRPE) demand and subsequent greenhouse gas (GHG) emissions for construction/retrofit and operation of the buildings, as well as for induced daily mobility of the dwelling's occupants are considered within the assessment. Global targets for those three items are set for 2050 at 7,200 kWh.pers.yr and 960 kgCO$_2$e.pers.yr.

Considering the complexity of conducting environmental assessments at larger scales than the building's, the evaluation relies on reference values provided by [1]. The latter gives a reference database to establish indicative large-scale energy assessments. This work provides reference values in square-meter per year for operation and construction/retrofit of representative Swiss residential buildings of the late 20th century (Tab. 1).

Table 1: Indicative and non-exhaustive reference data used to estimate the environmental impacts at neighbourhood scale. Values expressed in kWh(NRPE).sqm.yr and in kgCO2e.sqm.yr. OI: Operational impacts, EI: embodied impacts assessed for a 60 years lifespan, SFH: single-family houses, MFH: multi-family house. Whole tables in [1]'s complementary files.

OI	**As built (E0)**		**Retrofit S0**		**Retrofit S1**	
	NRPE	**CO$_2$e**	**NRPE**	**CO$_2$e**	**NRPE**	**CO$_2$e**
SFH	435.98	92.65	175.58	29.67	102.65	4.15
MFH	266.78	53.72	138.83	22.61	99.93	4.04

EI	**As built (E0)**		**Retrofit S0**		**Retrofit S1**	
	NRPE	**CO$_2$e**	**NRPE**	**CO$_2$e**	**NRPE**	**CO$_2$e**
SFH	5.58	1.42	7.93	1.99	11.17	2.92
MFH	3.09	0.74	4.00	0.97	6.56	1.72

According to the hypotheses mentioned in figure 2, the state of both case-studies' building stock is assessed throughout the 2015-2050 period. The external circumstances considered for this particular prospective scenario provide other clues such as the household's limited resources and their lower capability to retrofit their house to highly efficient energy standard. Consequently, this scenario considers that 90% of retrofitted buildings will simply comply with legal requirements in terms of energy efficiency that are progressively more restrictive i.e. S0 before 2015 and S1 until 2050 (Tab. 1). The remaining buildings (10%) are retrofitted to higher standards towards passive or positive energy buildings.

The proposed assessment considers all residential buildings in the neighbourhood according to their heating fuel, gross floor area (GFA) and mean occupation. Unlike what Table 2 presents, the assessment is conducted annually for each individual building. Consequently, every variation in occupation or energy performance induced by principles shown in Figure 2 are precisely accounted for.

Table 2: Aggregated data representative of each case-study's building stock. Mean gross floor area (GFA), majority heating fuels in 2015; in 2050, heat-pumps are mostly used. The last two columns show the mean building occupation in 2015 and 2050, considering under-occupation by small households and transitional vacancy.

Case-study	**Nb. buildings**	**Mean GFA**	**Heating fuels**	**2015 occup.**	**2050 occup.**
CHA	75	251sqm	oil/gas	2.8	2.5
MEZ	20	319sqm	oil	3.6	3.8

The assessment of mobility related environmental impacts rely on the method detailed in [19]. Based on mean annual impacts established for 2015 and 2050 car fleets, the method considers nine adjustment factors related to location and other project features. Half of them are stable among case-studies and/or scenarios. Table 3 presents impacts and factors used for *Caducity* scenario.

Table 3: NRPE demand and subsequent GHG emissions for 2015 and 2050 car fleets. Indicative adjustment factors used to assess 2050 GHG emissions owing to induced daily mobility in both case-studies PT: public transport.

Car fleet	**NRPE kWh.pers.yr**	**GHG kg.CO2e.pers.yr**
2015	4060	860
2050	2190	390

Adjustment (e.i. 2050 GHG)	**CHA**	**MEZ**
Location	1.04	1.04
Quality of access by PT	0.99	0.99
Intensity of PT use	1	1
Intensity of car use	1.28	1.28
Access to leisure	0.99	1.06
Access to supermarket	1.08	1.1
Access to car-sharing	1.12	1.16
Parking spot per dwelling	1.02	1.01
Income	0.72	0.72

3. RESULTS

3.1 Neutral or decreasing demographic trend

The conditions of implementation of *Caducity* scenario induce an overall demographic stability between 2015 and 2050 (Fig. 3). In CHA (grey line), the population steadily decreases, while newer houses are under-occupied. Contrary to MEZ, the building stock has grown regularly since the 1960s. It allows a continuous renewal of the population, and a limitation of the under-occupation to 17% to 50% of the building stock. In MEZ (black line), a demographic trough between 2015 and 2042 is related to the progressive under-occupation of 70% of houses. They were built in a short 10-year period and they follow similar occupation cycles. The vacancy reaches its highest level in 2036 with seven unoccupied homes. The increase in population noticed from 2040 on, corresponds to the beginning of new occupation cycles, and the reduction to 5% of under-occupation.

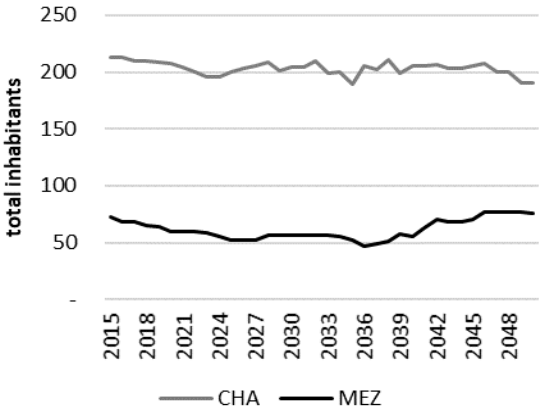

Figure 3: Demographic evolution in number of persons, in both case-studies (CHA: grey, MEZ: black line) between 2015 and 2050, according to the above-mentioned hypotheses.

3.2 Slow transition

The evolution of the building stock is submitted to these demographic conditions. Both case-studies present different features in terms of transition slowness. In CHA, only 47% of the building stock is retrofitted by 2050. It relates to the fact that the neighbourhood is composed of many houses built after the year 2000. In MEZ however, the slowness is due to the homogeneity of the neighbourhood since 95% of the houses are retrofitted in fifteen years, but the process starts in the second half of the considered period.

Table 4: Building retrofit process in both case-studies.

	CHA	MEZ
Retrofits before 2015	13%	0%
Retrofits 2015-2050	33%	95%
As built houses in 2051	53%	5%
Theoretical retrofit time limit	50 yr	
Actual mean retrofit timeout	60.68 yr	62.53 yr
First retrofit 2015-2050	2023	2033
Last retrofit 2015-2050	2050	2048

3.3 Environmental impacts in 2050

The assessment by 2050 aims at showing the transition potential and at what extent *Caducity* scenario achieves complying to 2050 requirements in energy efficiency. Figure 4 shows the average NRPE demand and GHG emissions per person in 2015 and 2050. In 2015, the assessment shows a very low average performance across the building stock of both case-studies. NRPE demand is at least 3.5 times higher than targets. In MEZ, GHG emissions exceed by 6.4 tons the annual target. The high reliance on fossil fuels for heating is clear throughout those results. By 2050, demand and emissions are significantly reduced in both case studies. In the case of CHA, environmental impacts in 2050 are still more than 10,000 kWh and one ton of CO_2e per person per year higher than targets. The improvement is more obvious in MEZ, with a reduction of about 25,000 kWh and 5.5 tons per person between 2015 and 2050.

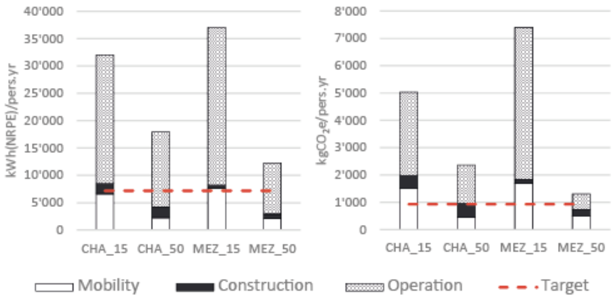

Figure 4: Evolution of NRPE demand and GHG emissions per person between 2015 (15) and 2050 (50), in both CHA and MEZ, owing to induced daily mobility of inhabitants, construction/retrofit of dwellings and their operation. Comparison with 2000-watt society targets for 2050.

3.4 Annual assessment and evolution trends

Figure 5 highlights the reduction trend of GHG emissions on an annual basis between 2015 and 2050, according to the assumptions of *Caducity* scenario. Whereas emissions are steadily decreasing in CHA, in MEZ average individual emissions increase until 2025 when a first dwelling is left vacant. The bell-shape distribution is linked to the drop of about one-third of the neighbourhood's population in the first years of the considered period. The decrease of GHG emission is very fast once the building renovation process starts in the neighbourhood.

An illustration of those distinct trends also appears in the comparison of cumulated GHG emissions during the whole 2015-2050 period. On average, a resident of CHA emits 3.8 tons of CO_2e per year, whilst in MEZ the annual individual average emissions for the 35-year period are of 6.1 tons of CO_2e.

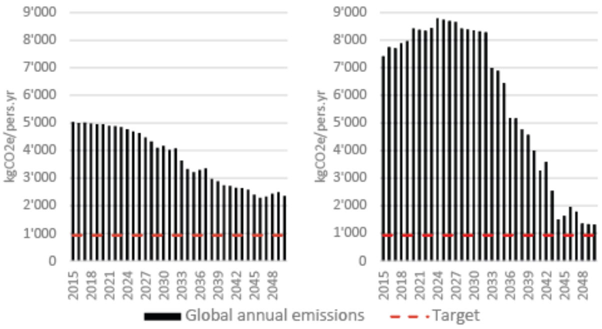

Figure 5: Annual evolution of GHG emissions for both neighbourhoods between 2015 and 2050. L: CHA, R: MEZ.

4. DISCUSSION

In line with international objectives to mitigate carbon emission by 80% to 90% by 2050, it is crucial that single-family houses located in remote areas also engage into building retrofit processes. Average environmental impacts in 2015 in both case-studies are far from meeting the targets set in the framework of the 2,000-watt society concept. Although, results show a clear improvement by 2050, they remain above targets. Optimizations should concern mobility practices and building occupation in priority.

The results of the implementation of the *Caducity* scenario highlight the importance of considering over-time assessments for a more reliable prospective sustainability evaluation. Focusing on the starting and finishing points of the assessment suggests that MEZ performs much better than CHA, and that it is more efficient in its renovation process. Nonetheless, the annual results over the 35-year period underline the steady improvement of the situation in CHA and its lower cumulated GHG emissions. The slowness of the energy transition appears clearly in this assessment and it raises the questions of ways to speed-up the process in owner-occupied buildings.

This study finally points out the need of further studies on turnkey real-estate developments in order to mitigate and better anticipate the alternation of occupation cycles in such homogeneous neighbourhoods. Energy efficiency is only one of the affected topics. On a sociodemographic level, small residential municipalities must also face an evolving demand for equipment such are child care facilities, schools or nursing homes.

5. CONCLUSION

This paper outlines conditions and effects of future stagnation or decay of peri-urban neighbourhoods of single-family houses. It underlines how those existing built areas might be submitted to losses in attractiveness and real-estate value due to a mismatch between single-family houses typologies and the growing proportions of small households and elderlies. The dynamic assessment of the scenario implementation highlights that inhabitants' life cycles determine the amplitude of the transformations engaged. Based on specific restrictive assumptions for *Caducity* scenario, the considered 35-year period (2015-2050) is nevertheless sufficient to witness a population renewal and the retrofit of most dwellings.

Because single-family houses are usually owner-occupied dwellings, similar energy transition trends are witnessed for more proactive scenarios. Even in cases of higher municipal implication (*Urbanity* scenario), transformations are submitted to the life cycles of households and to the temporality of their needs. To play their part in achieving the energy transition challenge globally, neighbourhoods of single-family houses must engage in retrofitting processes despite the complexity related to land fragmentation and to individual property.

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