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ENERGY MODELLING OF CITY HOUSING STOCK AND ITS TEMPORAL EVOLUTION

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ABSTRACT

With very low rates of replacement of the existing somewhat dated housing stock a key challenge for nations to meet their emissions reduction targets during the coming years will be to improve the energy performance of existing buildings within their cities. In this paper we describe the preliminary form of a system dynamics model of the housing stock of the city of Basel in Switzerland and investigate how this may evolve up to the year 2050. In particular we model the renovation process of the stock, test the key parameters influencing this process (e.g. renovation cycle and future population change) and analyse the resulting energy performance of the stock (measured by energy consumption for space heating and domestic hot water as well as greenhouse gas emissions). Potential future technological improvements to energy performace standards and to the embodied energy associated with renovation activity are also taken into account. We close the paper by presenting the tested scenarios and discussing the results from applications of the model to the city of Basel.

INTRODUCTION

The vast majority of energy is consumed in urban settlements which are thus largely responsible for the currently excessive greenhouse gas emissions and associated symptoms of climate change. It is thus increasingly urgent that the energy performance of urban settlements be improved – a key component of which relates to existing buildings; suggesting the need for renovation measures to improve their energy performance. In Switzerland, the potential for energy-efficiency improvements remains nevertheless largely untapped; and the share of building components that have not yet been improved with respect to energy efficiency ranges between 30% and 80%, depending on the type of building component (Jakob, 2006).

In our case study, energy consumption for heating and hot water of the residential sector alone accounts for some 22% of the city of Basel's final energy consumption (Figure 1).

In consequence the renovation of residential buildings to minimise their thermal energy needs has been identified as one of the key priority areas of the city's Energy an Environment Department.

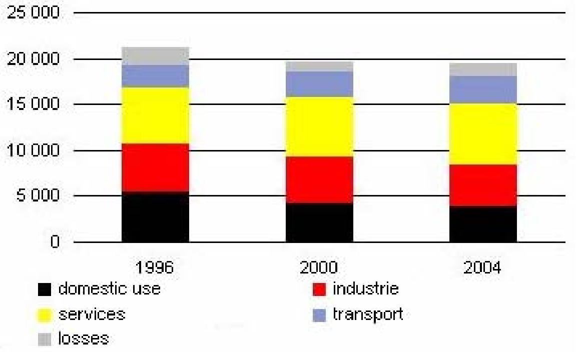

Figure 1 Energy use by consumer groups (in TJ per year), city of Basel (adapted from original diagram of StatA, 2007).

With this in mind we have developed a model of the temporal evolution of the urban built stock and its energy performance, to test strategies to improve this performance. In particular, we wish to explore the following questions:

- How can we achieve large-scale energy demand cuts in the housing sector?
- What is the impact of the urban building stock renovation dynamics on future energy consumption and associated CO_2 emissions?
- What are the different factors related to these dynamics and how do they influence indicators of sustainability?

In the following we present the methodology that we have employed to explore these issues as well as the corresponding results and discussions of them.

METHODOLOGY

To investigate the dynamics of the urban built stock we have used a system dynamics modelling (SDM) approach. SDM is widely applied in the study of dynamic systems by representing them as a set of interrelated stocks, flows and feedback mechanisms and simulating their temporal evolution (cf. Forrester, 1969; Coyle, 1996; Low et al, 1999; Heimgartner, 2005; He et al, 2006; Ulli-Beer and Groesser, 2007).

In our case the **system scope** is set to the residential built stock of the city and its energy-related renovation, i.e. refurbishment that improves building energy performance (in contrast to renovation without impacting on energy use, or simple maintenance). The buildings are classified according to four construction periods (pre-1947 [64%], 1947-1975 [27%], 1975-2000 [8%] and post-2000 [1%],). Each category corresponds to an average energy reference (<1975 = 410MJm^{-2}a^{-1}, 1975-2000 = 265-410 MJm^{-2}a^{-1} and >2000 = 265–210 MJm^{-2}a^{-1}) established from a desktop review of published studies (Siller, 2007; BFE & ecocept, 2007). The temporal scope of the model is set to the period 2005-2050.

Model formulation

The distribution is given by $\{x_1(t), x_2(t), x_3(t), x_4(t)\}$, where x_i stands for the number of buildings in the *i*-th category. The evolution of this distribution is described by two states $\{x_{11}(t), x_{21}(t), x_{31}(t), x_{41}(t)\}$ and $\{x_{12}(t), x_{22}(t), x_{32}(t), x_{42}(t)\}$, which represent the number of buildings of the *i*-th category that are renovated once and twice respectively. As “renovated once” we denote buildings that undergo one renovation within the simulation time period or underwent one renovation within a period of 30 years of the start of the simulation (i.e. since 1971). In the same vein, the term “renovated twice” refers to buildings that undergo two renovations within the simulation time or underwent two renovations within a period of 30 years before the simulation start year.

The model core is built on the basis of an aging chain (Forrester, 1969; Sterman, 2000). The renovation stages correspond to cohorts (or vintages) of the main aging chain and the energy requirements represent its attribute. The processes of construction and demolition imply that the flows in the system are non-conserved. The whole system can thus be described as a non-conserved 3-vintage aging structure with co-flows. Figure 2 presents the model in conceptual form.

In generalized form the state $C_i(t)$ of each stock (cohort) is calculated as follows:

$$C_i(t) = \int \left[I_i(t) + T_{i-1,i} - O_{i,i+1} - T_{i,i+1}(t) \right] dt \ , \qquad \text{[Eq.1]}$$

Where $I_i(t), O_i(t), T_{i-1,i}(t)$ denotes the *i*-th inflow, the *i*-th outflow and the transition from the *(i-1)*-th to *i*-th cohort respectively. In our case, $I_i(t)$ and $O_i(t)$ represent construction (indeed only of x_4) and demolition (of each x_i) respectively. The transition flow from one cohort to another due to renovation is given by:

$$T_{i,i+1}(t) = C_i(t) / \tau_t \ ; \qquad \text{[Eq.2]}$$

The transition rate is thus $1/\tau_i$, where τ_i (years) refers to the average residence time per *i*-th cohort.

The boundary conditions for this n-vintage chain (in our case 3-vintage) are set by $T_{-1,0} = T_{n-1,n} = 0$.

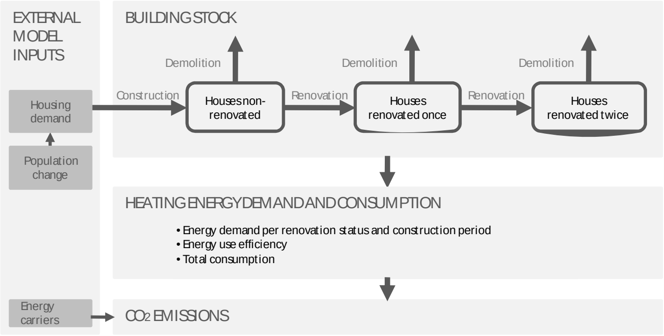

Figure 2 Conceptual model structure

The building stock evolution module is linked with a module that calculates the buildings’ energy demand for space heating and domestic hot water (DHW). When a dwelling is renovated, its energy demand decreases to an amount equal to the difference between its pre-renovation and post-renovation energy standard $\left(e_j - e_{j+1}\right)$, in MJm^{-2}a^{-1}, where *j* is the cohort number in the aging chain.

The total energy demand (in TJ/a) is then given by:

$$E_{tot}(t) = \sum_{i=1,\, j=0}^{4,2} x_{ij}(t) s_i e_{ij} \cdot 10^{-6} \qquad \text{[Eq.3]}$$

where s_i is the average energy reference area per house and the sum is taken over all building types (*i*) and renovation statuses (*j*=0,1,2). The total energy consumption (TJ/a) for heating and DHW is then calculated as follows:

$$E_{cons}(t) = \sum_{i=1,\, j=0}^{4,2} x_{ij}(t) s_i e_{ij} \Big/ \eta_{ij} \cdot 10^{6} \qquad \text{[Eq.4]},$$

where η_{ij} is the efficiency of the heating system for the *j*th renovation status of the *i*th building type.

Calibration

The model was calibrated using data for Basel, aggregated to the level of the city (building stock characteristics, renovations taken place since 1970 and energy consumption 1990-2004/2007). Basel is an historical city in northern Switzerland, located at the border with Germany and France. Its population is around 189 600 people. The city is peculiar in the sense that a reasonably large majority of its buildings are old: the largest part of Basel’s housing (64%) was built before 1947 and a significant part (27%) was erected in the after-war period before the oil crisis in the 1970s. About a half of its dwellings were renovated at least once in the period 1971-2000; however, only a small part of this entailed energy-relevant improvements.

For the latter, i.e. the fraction of energy-efficiency improving renovation, we used the data from a survey on energy-related refurbishments conducted in 2003 (Jakob and Jochem, 2004; POLIS, 2003). Swiss census data capture all renovation activity (energy-relevant as well as energy-irrelevant) in one number (so that for example façade renovation more often means repainting than insulating); thus not providing the resolution desired for our purposes. As Jakob (2006) states, "the empirical basis of refurbishments with regard to thermal insulation in the past...is relatively weak in Switzerland (and in most countries)", such that most renovation studies are seriously limited by the absence of reliable statistical data (Kohler and Hassler, 2002).

Thus for our residence times τ_i , we use Swiss reference data for the average lifetime of specific building components (Table 1), under normal building usage conditions.

Table 1. Average economic lifetimes of typical energy-relevant refurbishment measures (adapted from Lachat, 2008)

BUILDING COMPONENT		RENOVATION MEASURE	AVERAGE LIFETIME, YEARS
1	Envelope	Façade insulation	30 (25-40)
		Roof, attic and basement insulation	30
		Windows replacement	25
2	Heat production system	Heating system replacement (boiler, burner, central heating convertor, circulation pump, electric heating installation)	20
	DHW production	Replacement of DHW installation (combined or electric boiler)	20
3	Heating regulation system	Heating system regulation Thermostatic baths replacement (for water radiators)	20
4	Solar panels	Solar panels installation	20

Based on a desktop review of existing renovation standards with respect to energy performace (BAFU 2006; Siller et al, 2007; Pfeiffer et al , 2005), we set 200 $MJm^{-2}a^{-1}$ and 100 $MJm^{-2}a^{-1}$ as default values for specific energy (heating and DHW) demand of buildings renovated once and twice respectively.

CO_2 emissions due to residential heating and DHW are calulated based on the actual split of energy supply systems to the residential sector in Basel, together with their respective emissions factors (Table 2).

Table 2. Supply split for residential heating and respective CO_2 emissions factors (from BFE, 2007 and StatAg,2004)

ENERGY CARRIER, DOMESTIC SPACE HEATING	FRACTION, IN %, 2000 (BASEL)	FRACTION, IN %, 2000 (SWITZER-LAND)	EMISSION FACTOR, TONNES CO_2/TJ
Heating oil	41.0	56.0	73.7
Gas	28.9	13.8	55.0
District heating	26.6	1.4	12.8
Electricity	1.1	11.4	0
Solar	1.0	0.1	0
Wood/carbon	0.9	13.1	0
Heat pumps	0.3	4.1	0
Other	0.1	0.1	-

RESULTS AND DISCUSSION

Our initial Business As Usual (BAU) scenario corresponds to the above assumptions, with rates of construction of new buildings and demolition of existing ones (assumed to be the oldest) following the trends of the calibration period, i.e. 60 and 25 houses per year respectively.

The resulting development of Basel's housing stock up to the year 2050 is shown in Figure 3, predicting a 0.187% - 0.171% annual growth rate for the total number of buildings. This figure is on a par with the average Swiss dynamics of construction, according to which in Swiss cities of the size of Basel (>100 000 citizens) the number of apartments grows by 0.2-0.3% per year. Furthermore, due to systematic renovation the number of non-renovated dwellings decreases by a factor five, while up to a half of the dwellings are expected to undergo two renovations by 2050.

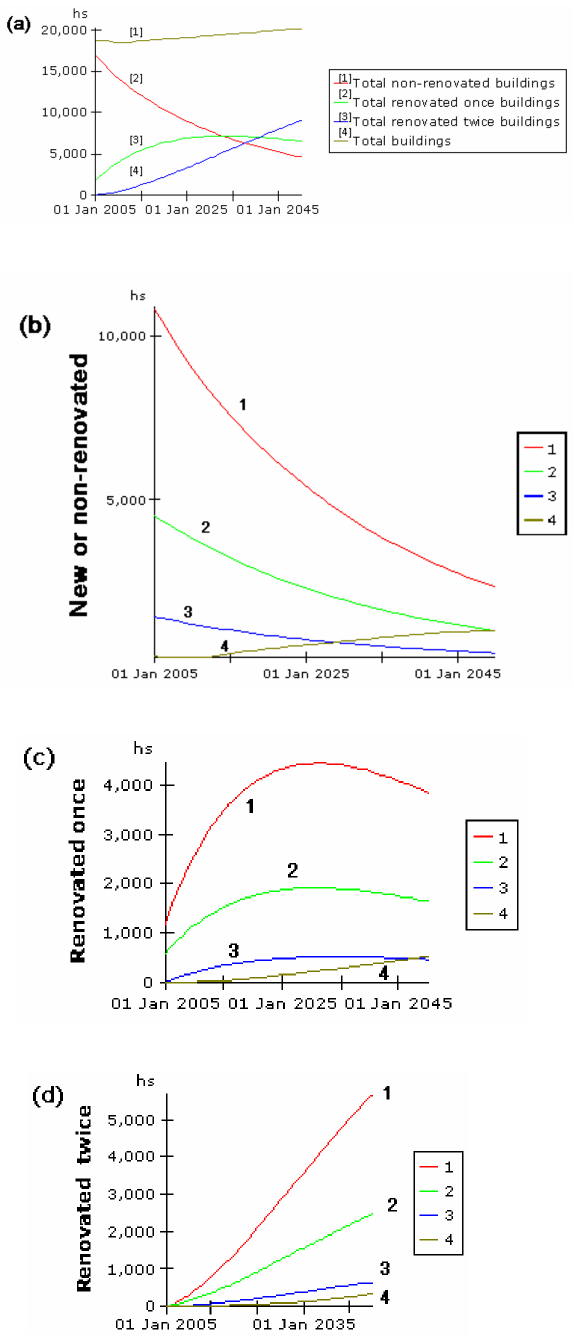

Figure 3 Evolution of Basel's housing stock, 2005-2050, BAU, in aggregated presentation (a) and disaggregated representation (b-d). (b) denotes the stock of new and non-renovated buildings, (c) the one of buildings renovated once and (c) the one of buildings renovated twice. ['hs'=houses; numbers 1-4 correspond to construction periods pre-1947, 1947-1975, 1975-2000 and post-2000 respectively]

The energy consumption implications of this evolution of the building stock are presented in Figure 4. From this it is clear, provided that the model assumptions are reasonable, that with systematic renovation to currently available energy performance standards (and without significant improvements of these standards), the energy consumption of the residential building stock during the next half century is expected to halve.

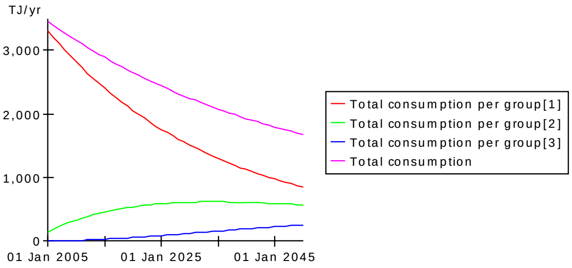

Figure 4 Residential energy consumption in TJ/yr for space heating and DHW, BAU (Buildings categories: [1]-new or non-renovated, [2]-renovated once, [3]-renovated twice)

However, this alone is unlikely to satisfy our objectives if we are to achieve a 2000W/Ca society (a sustainability-like concept developed in Switzerland which requires a reduction of annual per capita primary energy use from ~6000W to 2000W). For this we need to reduce residential energy consumption by a factor of three to four; inclusive of the embodied energy content of new or additional constructional materials. To achieve this we may need to (I) further increase the rate of renovation of the existing stock, (II) to improve the energy performance of these measures, whilst (III) also being mindful of the energy consequences of the materials used. These options will be discussed below.

Rate of renovation

To examine this issue we have first tested the model's sensitivity to renovation rate, and the implications of an enhanced renovation rate on total energy consumption. Based on Binz et al (2000), the options of minimal, average and maximal residence time per cohort were tested, with τ_i equal to 20, 30 and 40 years respectively. Each case corresponds to one of the following assumptions respectively: 1) complete renovation might be triggered once the shortest of building components' lifetimes (20 years) is achieved (cf. Table 1); or 2) the complete renovation cycle in Switzerland has a period of 30 years (POLIS, 2003; Jakob and Jochem, 2004); or, 3) the maximal residence time (40 years) applies if complete renovation is triggered by the need to change the envelope insulation, hence the maximal duration of usage determines the delay of subsequent renovation in this case.

Table 3 shows the effect of various renovation periods (and their combinations) on the average system's energy conversion efficiency together with the relative emissions reduction arising from combined (system and fabric) upgrades.

Table 3. Model sensitivity to renovation period

RENOVATION PERIOD, YEARS	AVERAGE ENERGY USE EFFICIENCY, (2005: 0.71)	RELATIVE $C0_2$ REDUCTION, IN %
20	0.82	66%
30	0.78	54%
40	0.77	44%
20 for pre-1947; 30 for other ages	0.80	62%
20 for 1st renovation; 30 for 2nd renovation	0.81	63%

By way of example, a reduction in average residence time per renovation status from 30 years to 25 years (also suggested by Siller et al, 2007, following Wüest & Partner, 2006) would lead to an additional 13% reduction in energy consumption and an additional 6% reduction in CO_2 emissions (i.e. from 54% to 60% with respect to 2005 levels).

In addition to the stock dynamics simulated in the BAU scenario, we have tested alternative construction and demolition rates arising from different future population growth projections. In particular we have used the three official population forecasts for the period 2005-2050: “high” with 6% population growth, “medium” and “low” with about 9% and 29% population decline by 2050 respectively (BFS, 2007). It was further assumed that population growth creates a positive demand for housing (this is based on the Swiss average residential area of 44m2/person; and assumes that average occupancy density remains constant); whereas population decline leads to a negative demand, i.e. demolition (in this, we assume that old and non-renovated buildings are demolished first, as the available data does not contradict this assumption). The simulated energy consumption for these three population scenarios is shown in Figure 5.

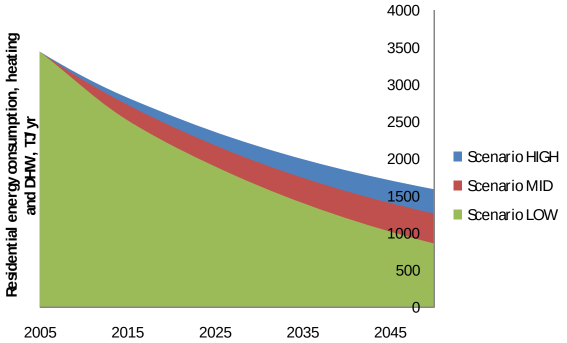

Figure 5 Energy consumption for low, medium and high population change scenarios.

Energy performance

As mentioned above, technological progress and future construction technologies are likely to offer further potential for energy-saving in buildings (Pfeiffer et al, 2005). To emulate this technological (or regulatory) progress we have assumed, following Siller et al (2007), a 10% improvement in residential energy performance every 15 years (beyond 2005). Such an improvement, as shown in Figure 6 below, would lead to a further 30% reduction of energy consumption by 2050 (this however ignores the possible embodied energy implications).

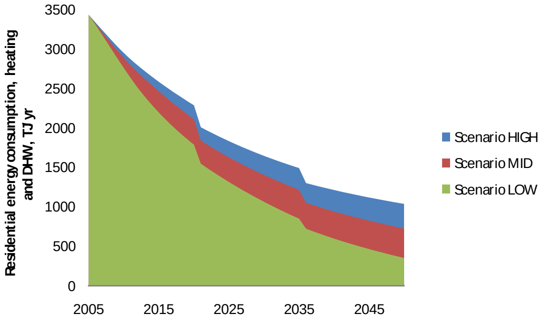

Figure 6 Energy consumption under assumption of further improvements to buildings’ energy performance standards.

Embodied energy

As noted above, it is of interest to consider the impact of materials’ embodied energy content on the overall consumption of energy. Embodied energy (energy that is consumed in the process of manufacturing, transportation and installation of materials used for construction or renovation) typically plays a rather secondary role in comparison with the total primary energy requirements for normal house maintenance such as heating, electricity and warm water (accounting for about 10% to 16% of total primary energy use (Binz, 2000). However, it may becomemore significant in the context of renovation.

Based on figures for the embodied energy content of materials for renovation and new construction from existing studies (Binz et al, 2000; Pfeiffer et al, 2005), our model predicts that, depending on the population change scenario, some 200 to 300 TJ/yr of embodied energy due to renovation could be accumulated during our simulation period of 45 years (Figure 7).

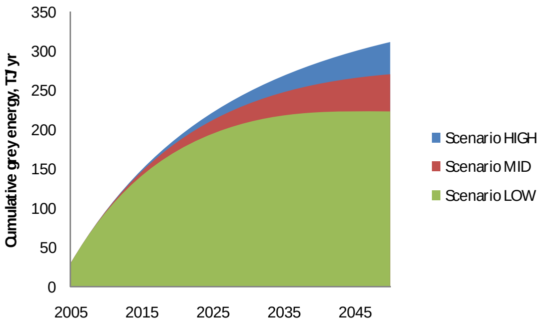

Figure 7 Cumulative embodied energy due to renovation for low, medium and high population change scenarios.

The result of this added dimension is non-negligible, leading to an effective increase in energy consumption of around 25% (cf. Figures 5 and 8).

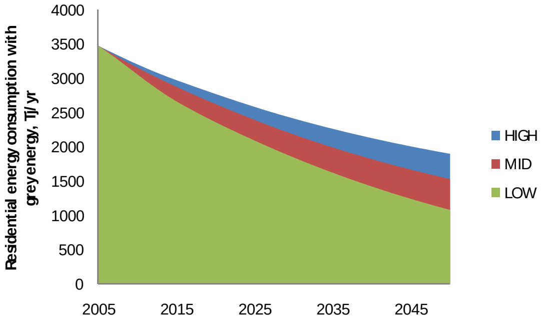

Figure 8 Energy consumption including grey energy due to renovation.

To conclude this preliminary work on residential building stock modelling, we have considered one final issue. In studies on renovation, protection of historically important buildings ranks amongst the most important barriers to renovation (Jakob and Madlener 2004). The number of such protected objects and ensembles varies from country to country, but probably does not exceed 1–2% of the [national building] stock (Kohler and Hassler 2002). Basel however is peculiar in the sense that a reasonably large majority of its buildings are old, and many of them are located in zones designated for protection or preservation. In consequence, and under current legislation, the scope for improving their energy performance is limited. Indeed, at some point in the future it is not unlikely that these inefficient but nevertheless important buildings (in terms of safeguarding historical heritage) come to dominate residential building energy consumption.

Based on the number of buildings that are designated for protection alone (i.e. excluding preservation) (Basler Denkmalpflege, 2005), assuming that their energy performance remains unchanged during the simulation period (a worst case scenario) and based on the BAU scenario, these buildings would consume 500 TJ/y by 2050 and account for some 30% of total energy consumption. However, this should be considered as no more than an estimation of the order of magnitude; to reduce the uncertainty in these predictions further data regarding the current energy performance of these buildings as well their corresponding heated surface area would be required.

CONCLUSIONS

In this paper we describe a simple model of the dynamics of urban residential building stock and its associated energy performance, based on an aging chain representation. From application of this model to the city of Basel in Switzerland, we conclude that:

- With no special improvements to building regulations or the rates of buildings' renovation, the energy consumption of Basel's residential stock is expected to halve by 2050; by virtue of expected demolition, construction and renovation trends.
- A further reduction of energy consumption of about 20-30% can be expected if likely future technological progress with respect to renovation standards is taken into account.
- As expected, average renovation rates influence reasonably significantly our residential buildings' energy consumption. Indeed, a reduction in average residence time per renovation from 30 years to 25 years would lead to an additional 13% reduction in energy consumption and an additional 6% reduction in CO_2 emissions. Further work with respect to parameters influencing the renovation rate itself would therefore seem to be merited.
- The forecasted energy consumption reduction is around 25% less if we take into account the embodied energy involved in extensive renovation.
- If we assume that the energy performance of buildings designated for protection and/or preservation remains unchanged, the energy consumption of these buildings could represent as much as 30% of the total (~500 TJ/y).
- Irrespective of the treatment of heritage buildings, the target to achieve a 2kW society by 2050 will not be realised without further improving upon rates of renovation and the energy performance of these measures whilst also being mindful of the energy consequences of the materials used. Further work is required here.

This paper represents a sound starting point in the modelling of urban built stock dynamics and associated energy performance. However, further work is required to reduce modelling uncertainties; but this would require that data describing the stock and its renovation be available at far finer granularity. Finally, it would be very useful to develop a model in which the stimuli for decisions to renovate buildings were modelled, to test strategies for increasing renovation frequency and improving the energy performance consequences of these renovation events.

ACKNOWLEDGMENT

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