IOP Conference Series: Earth and Environmental Science

PAPER • OPEN ACCESS

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To cite this article: V Göswein *et al* 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **323** 012172

IOP Conf. Series: Earth and Environmental Science **323** (2019) 012172 doi:10.1088/1755-1315/323/1/012172

Fleet-based LCA applied to the building sector – Environmental and economic analysis of retrofit strategies

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Abstract. CO_2 emissions need to be reduced by 40% in 2030 in Portugal as an intermediate target of the Paris Agreement. This challenging goal is expected to be achieved through incentive-based regulations and voluntary actions. This study improves the understanding of renovation strategies to reduce emissions caused by the built environment. A fleet-based Life Cycle Assessment (fb-LCA) is adapted and applied to the building sector. Fb-LCA integrates LCA and a fleet model to describe stocks and flows associated with a class of products over time. The method is tested for a neighbourhood in Lisbon, Portugal. The analysis compares 3 scenarios of dynamic renovation rates for the next 30 years: business as usual, a public economic incentive to renovate, and mandatory renovation. Different technology scenarios including bio-based ones, are compared. Among the latter, alternative material solutions, e.g. insulation cork boards, are emerging, providing carbon sequestration. Results highlight the environmental benefits of bio-based materials considering the temporal profile of renovation activity. Furthermore, the cost and sensitivity analysis help stakeholders to justify retrofit actions from an environmental and economic point of view. The adaptation of a fb-LCA approach proves to be an easy-to-use method to assess technology options and policy scenarios at a neighbourhood scale.

1. Introduction

1.1. The built environment as a cause of pollution and as an opportunity to tackle climate change

The Paris Agreement aims to tackle climate change by limiting global temperature rise this century well below 2° Celsius above pre-industrial levels, or even limit it to 1.5° Celsius. The ambitious goal is an 80% reduction of CO_2 emissions by 2050 compared to the year 1990. By ratifying the agreement in October 2016, Portugal and many other countries have committed themselves to comply with the intermediate targets of reducing the national CO_2 emissions at least by 40% in 2030 [1]. This challenging goal is expected to be achieved by means of incentive-based regulations and voluntary actions.

The built environment consumes 62% of final energy and is a major source of greenhouse gas emissions (55%) [2]. In Portugal, almost 70% of the buildings were built before 1990, when the first Portuguese regulation regarding thermal comfort in buildings was published. In 2010, 35% of the buildings in Portugal needed major retrofit works and about 3% presented a high level of degradation

[3]. According to 2014/15 European work program, the renovation of buildings represents more than 17% of the primary energy savings potential of the EU for 2050 [4].Therefore, the renovation of buildings has a high capacity to influence the environmental impacts and global objectives of climate change mitigation.

1.2. Bridging the gap between embodied and operational energy

In the existing literature, direct emissions during the use phase of buildings and indirect emissions in the production, construction and waste management phases, are usually disconnected. To achieve climate sustainability goals, we need to find a way to understand the dynamics of the built environment by bridging these two levels. Low-impact solutions, on both levels, for example through thermal refurbishment of the façade, are needed. In this regard, traditional insulation materials for retrofit might not always be the best solution in terms of impacts, but alternative material solutions, e.g. insulation cork boards, are emerging [5]. Bio-based products offer the opportunity to account for carbon sequestration, which offers an environmental benefit that might compensate for the impacts caused during production and construction [6].

The objective of this study is to explore potentials of greenhouse gases (GHG) and other emissions reductions associated with the renovation of buildings. It wants to improve the understanding of renovation dynamics in relation to achieving climate targets. For this purpose, a method called fleet-based Life Cycle Assessment (LCA) will be adapted and, in a simplified way, applied to the building sector.

1.3. Technology diffusion

The question if "a product-centred approach to LCA is always the best" was answered by Field *et al.* [7] by introducing the "fleet-based" LCA (fb-LCA). This approach deals with effects distributed over time, and integrates LCA and a fleet model that describes the stocks and flows associated with a class of products over time. Instead of making use of a single element for the declared unit, it looks at a set of units in service. Fb-LCA is able to model temporal changes and effects of technology diffusion because it considers the dynamics of replacing products that reached their end-of-life with new ones. And because it considers how resource consumption and environmental impacts change over time, it is a useful method to analyse technological transitions.

Even though until now the application of purely fb-LCAs is relatively restricted to fields that underlie high technology innovations, e.g. cars, the method shows advantages that seem beneficial also for assessing building stocks and scenarios for retrofitting. This method can be used to assess the dynamics of introducing or increasing the share of a specific type of insulation material, considering different retrofitting rates depending on the location. In a study on the development of residential building stocks [8] used an approach that reminds of fb-LCA. The authors estimated country-wide future renovation activities on the residential building stock that needs retrofitting by defining building cohorts. However, a Europe-wide analysis would require generalized parameters to model the composition of the building stock.

1.4. Building stock modelling

A model is always a simplification of reality. A complex system like a building stock needs an appropriate model to be analysed. There are two general approaches in building stock modelling: top-down and bottom-up models. Top-down models work with aggregated data. Bottom-up stock accounting uses material intensity coefficients to estimate the material quantity in a single unit of the examined end-use objects at a specific moment in time. With simple typologies, it is already possible to obtain interesting results regarding future policy and technology scenarios for a building stock at the urban scale [9].

This study will make use of a bottom-up approach and will focus on a defined set of buildings and materials to explore the opportunities of a fb-LCA applied to the diffusion of retrofit strategies.

2. Data and Methods

The framework for the model, presented in figure 1, reminds of a typical LCA, but it uses an up-scaled declared unit that is the whole opaque façade area of all buildings under study. The product stages A1 "Raw material supply", A2 "Transport", A3 "Manufacturing", and construction process stages A4 "Transport" and A5 "Construction installation process", as well as the use stage B6 "Operational Energy Use", are taken into account to estimate environmental impacts. The analysis focuses on the impact categories Global Warming Potential (GWP) and Primary Energy Non-Renewable (PE-NRe), but Abiotic Depletion Potential (ADP), Acidification Potential (AP), Eutrophication Potential (EP), Ozone Depletion Potential (ODP) and Photochemical Ozone Creation Potential (POCP) are also considered to be in line with the European recommendation for the application of LCA to construction products and services [10]. Moreover, the study also estimates the economic costs associated to Life Cycle (LC) stages A1 to A5, cradle to gate, and the energy cost of heating and cooling during the study period related to LC stage B6.

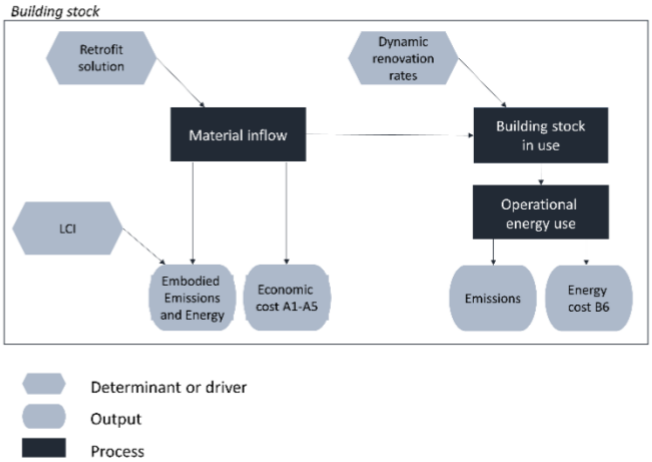

Figure 1. Framework of the model

The developed method is tested for one type of construction typology in the Lisbon neighborhood Alvalade. This neighborhood is of particular interest since it was built within a short period, between the 1940s and the 1960s, promoted by an urban expansion plan of the Lisbon municipality in 1944. Here, a specific type of construction called "Placa", mixed masonry-reinforced concrete, is particularly prominent. In total, 230 buildings were identified to be similar to that type and considered in the present study. The declared unit is the total opaque façade area of all buildings: 124,577 m^2.

The analysis incorporates the fleet-based approach by analysing dynamic renovation rates (see figure 2). It describes the next 30 years in accordance with the EU energy directive [11], which is also a commonly chosen time frame in Economic and Energy LCA. The Business as Usual (BAU) is compared to two scenarios: one assumes that a public economic incentive is introduced to promote the renovation of exterior walls. For the public economic incentive scenario, a Weibull probability density function is applied. The other scenario is that of a legislation that makes renovation of exterior walls within the next 30 years mandatory. For the mandatory renovation scenario, a Normal distribution is assumed, which is often used in building stock modelling.

Furthermore, different technology scenarios are analyzed: the building stock as it is without any retrofit action is compared to two different scenarios with an external thermal insulation composite system (ETICS) applied to a single leaf wall: one with the commonly used insulation material extruded polystyrene (EPS); and the other one with the bio-based insulation cork board (ICB). The technology scenarios are paired with the dynamic renovation rate scenarios described before. Also, a sensitivity analysis on heating and cooling use is carried out. The default value for the consumption of energy during the B6 sub-stage is assumed to be only 10% of the heating and cooling needs, in accordance with the national use pattern. This value is compared to fulfilling 20%, 30%, 40% and 50% of heating and cooling needs.

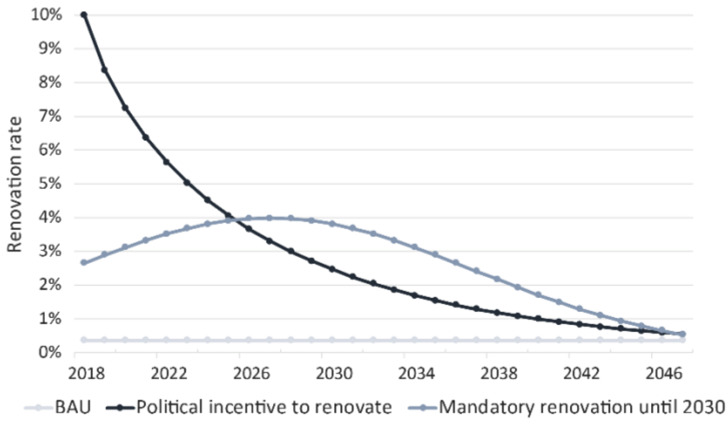

Figure 2. Renovation rates under study.

The costs of LC stages A1 – A5, that include the installation of the ETICS system in the building, in units of m^2 of wall, were taken from various sources [12–14]. The calculation of the energy cost in each year, per m^2 of external wall, relates to the energy use for heating and cooling, based on the method given in the national regulations [15].

3. Results

3.1. Environmental impacts - Renovation all at once

As a first step, the cradle to gate impacts for the declared unit were calculated for the hypothetical case that everything is renovated at this moment in time. The alternative of not renovating has 0 impacts for LC stages A1 to A5. The impacts for the two technology alternatives, an ETICS with ICB and an ETICS with EPS, in both cases 0.08 m thick, are compared in figure 3. GWP is negative for the ICB solution since biogenic carbon capture is considered based on a recent Environmental Product Declaration [16].

Furthermore, the embodied energy related to heating and cooling needs, for the default value of 10%, was estimated for the reference case and the two retrofit scenarios. The U-values are 2.41W/m^{2}K for no retrofit, 0.42 W/ m^{2}K for the ICB solution and 0.38 W/ m^{2}K for the EPS solution. The results for PE-NRe and GWP can be seen in figure 4. In both impact categories, the reference case "no retrofit" performs the worst. The differences between the two ETICS scenarios are small with 2,202 kg CO_2 eq. for the ICB solution vs. 2,176 kg CO_2 eq. for the EPS solution, and 34,040 MJ vs. 33,639 MJ respectively.

During LC stages A1-A5 and B6 for 30 years the ETICS with ICB causes less 53% GWP and less 28% PE-NRe compared to no retrofit. ETICS with EPS has a smaller reduction potential than the one with ICB with 19% less for GWP and 17% less for PE-NRe compared to no retrofit.

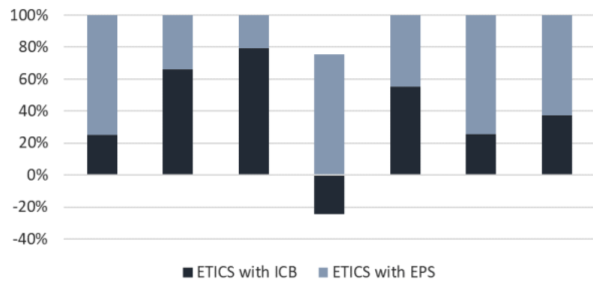

Figure 3. Comparison of environmental impacts for LC stages A1 – A5.

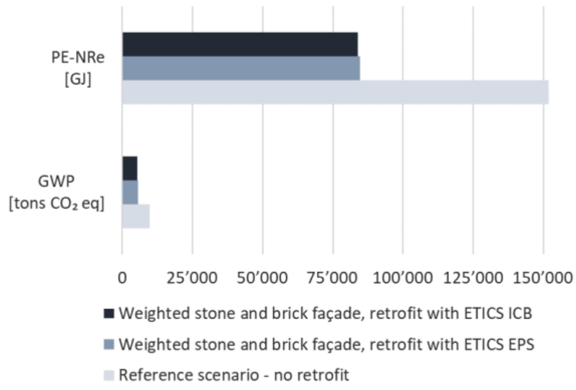

Figure 4. Heating and cooling impacts during 30 years (LC stage B6) for the declared unit.

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3.2. Economic and energy costs

The economic cost for LC stages A1-A5, and the energy cost in LC stage B6 with the default value of 10% consumption of energy needed to fulfil the heating and cooling needs during the next 30 years, were estimated for all scenarios. The assumed discount rate was 3%. The economic performance considers market prices, e.g. the acquisition cost including manufacturing, transport to site and installation in the building, as well as the economic savings potential that the thermal retrofit solutions offer. This includes the potential improvements of energy performance of the building envelope after the installation of the ETICS system and the related energy saving potential. The economic costs and energy costs for the three different options are shown in figure 5. It highlights than none of the suggested retrofit solutions offers economic savings compared to the reference case “no retrofit”.

The energy costs are € 22.63 for the energy use for heating and cooling after 30 years study period for 1 m^2 of non-retrofitted wall, compared to €12.64 for 1 m^2 of wall with ETICS with ICB and €12.50 for 1 m^2 of wall with ETCS with EPS. Moreover, EPS has a lower market price than ICB. These values scale linearly with the opaque façade area. However, the energy cost was calculated based on the assumption that only 10% of heating and cooling needs in LC stage B6 are fulfilled. Since in many cases more than 10% needs need to be fulfilled, a sensitivity analysis on this parameter was conducted. Figure 6 shows the results of the sensitivity analysis. Illustrated are the relative differences of the sum of economic and energy cost, compared to the reference case “no retrofit”. One can see that, with an increased value of 40-50% heating and cooling needs fulfilled, the two ETICS solution became equally cheap or even slightly cheaper than the reference case.

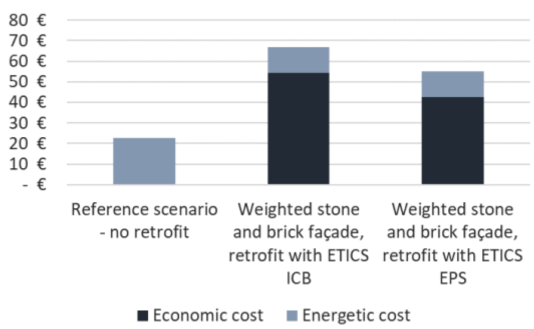

Figure 5. Comparison of the economic cost for LC stages A1-A5, and energy cost for the LC stage B6, after 30 years for 1 m^2 of exterior wall.

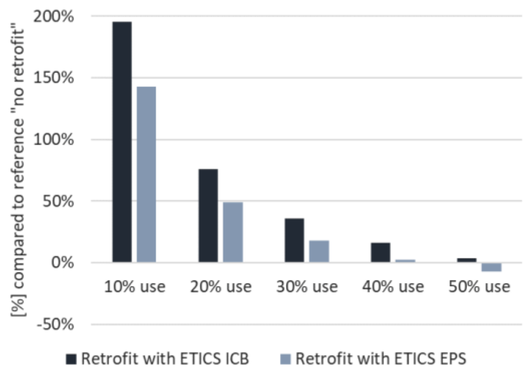

Figure 6. Sensitivity analysis of heating and cooling needs. Based on the total economic cost for LC stages A1-A5 and energy cost for B6.

3.3. Environmental impacts – dynamic renovation rates

Renovation rate as a driver of the model has direct impact on the emissions released over time. The translated GWP for the three different renovation rates under study, as described before, are shown in figure 7. The values in the figure were obtained by holding the renovation technology fix, which is ETICS with ICB, and comparing the different policy scenarios. The chart shows renovation with ICB compared to doing nothing. Only LC stages A1-A5 are considered. If compared to a renovation scenario with EPS the CO_2 saving potential of ICB would be even bigger. In fact, only with bio-based construction materials such as ICB, carbon can be stored in the building. This needs to be considered when analysing the policy scenarios: not only renovation activity as such needs to be promoted but also bio-based materials. The CO_2 savings related to LC stage B6 follow the shape of figure 7.

The BAU has a linear trend line that does not offer a significant potential regarding negative CO_2 emissions. In contrast to that are the two hypothetical policy scenarios, where renovation is either mandatory or promoted with an economic incentive. The first critical step regarding the intermediate goals of the Paris agreement is the year 2030. In that year, the estimated cumulative negative CO_2

emissions will be only -40 tons CO_2 eqv. for the BAU scenario compared to -383 tons CO_2 eqv. for the mandatory renovation scenario and -546 tons CO_2 eqv. for the public economic incentive to renovate.

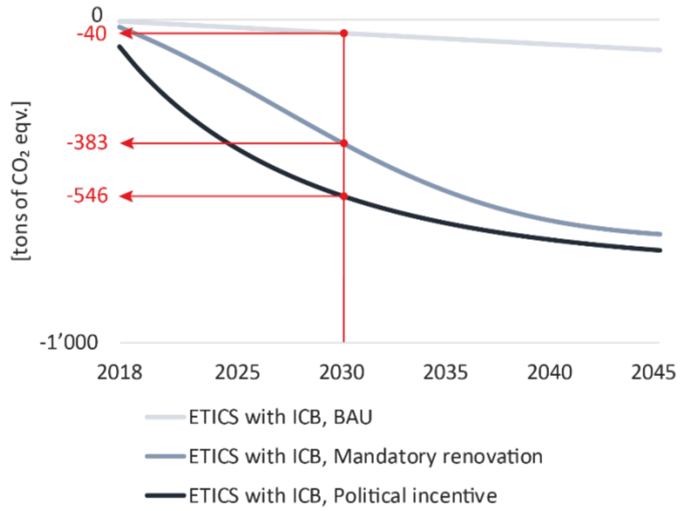

Figure 7. Dynamic cumulative GWP in kg CO_2 eqv. for the declared unit for cradle to gate impacts.

4. Discussion

The purpose of the present study is to improve the understanding of possibilities to reduce emissions caused by the built environment given the fact that binding global climate deals set targets that need to be fulfilled by every participating member. Based on the literature, we propose to use a fb-LCA with a bottom-up building stock modelling that helps to assess the combined potential of technology and policy scenarios. The technology aspect stands for different exterior wall insulation systems and the policy aspect for different renovation rates.

4.1. Technological retrofit options

The present study analysed different retrofit scenarios from an environmental and economic point of view. It was found that, regarding the cradle to gate impacts arising during A1-A5 and the operational energy use in B6, an ETICS system with EPS required slightly less PE-NRe than the one with ICB, 33.9 MJ vs. 34.2 MJ. However, cork as a bio-based insulation material offers the advantage of capturing carbon during its growth which can be accounted for as a negative GWP during construction stage. Both solutions caused significantly less GWP and PE-NRe than the reference scenario "no retrofit". Other researchers have tried to translate that environmental advantage into monetary units by applying weighting factors to make the different dimensions of sustainability easier comparable in a decision making process [17]. Yet, the monetization of impacts is a controversial topic [18] and many scholars argue that is very subjective to trade between economic, social and environmental dimensions sustainability. An option here would be to weigh costs and emissions from different point of views, for example a "green" approach vs. a cost-saving vs. a focus on the service life vs. architectural aspects etc. [19,20]

Regarding the cost analysis, the overall cheapest option was not to renovate. In that case there is no economic cost related to life cycle stages A1 to A5, and the overall cost, economic cost plus energy cost during the 30 years under study (B6), was lower than for the two technological retrofit scenarios with ETICS. The cheapest energy cost was obtained with an ETICS with EPS. The difference to the ETICS with ICB however is small, not even 1%. Moreover, the default value for consumption of energy for all these values was only 10% of the heating and cooling needs and therefore very low. The sensitivity analysis revealed that, with an increased amount of consumption of energy, the energy cost gains importance compared to the economic cost. By assuming that the consumption of energy is around 40-50% of the heating and cooling needs, the two ETICS systems under study had an equally low total cost, economic plus energy for 30 years, as the reference case "no retrofit". An energy consumption in that range is becoming more realistic, considering that people stay at or work from home more often, that

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some of the apartments are used as, for example, medical practices, or that the cost of electricity might increase in the future [21].

4.2. Dynamic renovation rates

A fb-LCA approach, which has not yet been applied to the building sector, was used to assess technology transitions over time. The model was simplified such that neither changes in background processes nor technological improvements over time were considered. Both are characteristics that are important in the fb-LCA in sectors with fast technological innovation, such as the electric car industry, but not so much in the construction industry, which is traditionally a rigid sector and little prone to technology innovation. In that way the method is well suited to answer the given question. The renovation rates were modelled dynamically because buildings have a long lifespan and should be understood as service providers with different future scenarios. Therefore, it is important to consider the temporal profiles of emissions so that the LCA result for each emission is a function of time rather than a single number. The results of the present study showed that, firstly, the emission profile is directly related to the assumed dynamic renovation rate, as was shown with the linear BAU projection compared with the policy scenarios (vs. the normally distributed renovation rate of legally mandatory renovation and vs. a public economic renovation incentive based on a Weibull distribution). Secondly, the difference between a linear rate and a dynamic one is big regarding the cumulative emissions and the emissions at each moment in time, which was shown in figure 7 regarding the critical year 2030. In that year, given the assumptions made for the public economic scenarios, a public economic incentive to renovate proves to be more effective than a law that makes renovation mandatory. Even though after 30 years these two scenarios reach basically the same cumulative negative GWP value, the incentive proves to be more effective at the time step 2030, which is an interesting finding regarding how to translate climate goals into action-making.

The model helps understanding the temporal profile of emissions. However, it is needed to understand how much GHG emissions CO_2 eqv. Are the actual target by 2030 and, further down the road, this needs to be known by sector and geographic boundary, e.g. for Portuguese building stock.

4.3. Limitations of the study and future research

There is a high uncertainty of the renovation rates and dynamics. The here presented rates should be understood as such. However, they can provide policy-makers with the relevant figures to make informed choices on how to achieve climate targets. There is also uncertainty in the heating and cooling needs. For this reason, a sensitivity analysis was performed. Yet, these interesting dynamics of operational energy needs should be included in future studies, such as the one done by Peuportier *et al.* [22] who already modelled the energy demand of buildings and districts with a dynamic LCA approach that accounts for the temporal variation of electricity production, and of its consumption in buildings.

5. Conclusion

The present study used a specific type of building in a well-defined geographical area to test the effects of retrofit actions of exterior walls of residential buildings considering LC stages A1 to A5 and B6. The results highlight the environmental savings potential of bio-based material to support reaching national and global GHG emission targets. The cost and sensitivity analysis provides information for stakeholders to justify retrofit actions from an environmental and economic point of view. The adaptation of a fb-LCA approach and its application to the building sector has not been done before and proves to be an easy-to-use method to assess different technology options and policy scenarios at a neighbourhood scale.

Acknowledgements

We would kindly like to thank Rita Bento, Alexandre Gonçalves and Ana Paula Flor for their support with the GIS data. The authors also acknowledge the support of the CERIS Research Centre, Instituto

Superior Técnico, Universidade de Lisboa to this research, and also of FCT (Foundation for Science and Technology) that supports the PhD work of the first author with the PD/BD/127854/2016 scholarship.

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