# Bio-based insulation materials: an opportunity for the renovation of European residential building stock

Evaluation of Carbon uptake benefits through a dynamic life cycle assessment (DLCA)

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The climate does not wait changing.
It continues changing.
The only way out, is for us to change as well.

*R. Rovers*

**Abstract**

European Union, as party to the Paris Agreement, shall contribute to hold the increase in the global average temperature to well below 2°C, that, according to the Fifth Assessment Report of IPCC, implies the Carbon budget shall not be exceeded. Building sector in Europe is responsible for 36% of the GHG emissions, and its renovation represents a priority. A common tendency dealing with energy efficiency is to focus only on operational energy, neglecting the impacts coming from materials production, on site construction, and disposal. Actually, such environmental burdens may result to be cumbersome, especially if a short-term perspective is considered. The task of the present work is to investigate and holistically assess the benefits deriving from the use of bio-based, renewable materials for the energy retrofit of the European residential building stock. Applying a dynamic LCA, that allow the consideration of a dynamic time horizon and a consistent accounting of the biogenic CO2, the work aims to show how much the choice of the insulation material can affect the overall Carbon balance. A simulation of 200 years starting from 2018 at the current renovation rate is performed. Five different external walls alternatives for the building retrofit, including fast-growing bio-based, wood, mineral and polystyrene solutions, for three different end of life scenarios, are investigated. Results show that, beside to the primary goal of increasing passive performances, a large-scale use of bio-based building insulation materials can lead to a climate mitigation effect, as the biomass regrowth induce a beneficial Carbon sink effect since the first years. Furthermore, renovation rate has proved to be by far the most important parameter to control; for achieving its rise, modular pre-assembled facades should be encouraged. Addressing rapidly the transition toward a zero-carbon society is the priority. In this perspective, bio-based materials represent an opportunity that should not be wasted.

**Abstract**

Il presente lavoro è frutto di un progetto congiunto tra Politecnico di Milano e ETH Zürich nell'ambito dell'accordo Swiss-European Mobility Programme. Le linee guida del lavoro sono state definite presso il Dipartimento di Architettura, Ingegneria delle Costruzioni e Ambiente Costruito del Politecnico di Milano, mentre il pieno sviluppo della tesi si è svolto presso la Chair di Sustainable Construction del dipartimento di Civil, Environmental and Geomatic Engineering presso ETH Zürich. Convinti che tale collaborazione tra gli istituti avrebbe portato a validi nuovi approfondimenti nel campo della ricerca della sostenibilità, essa è stata concepita con l'intento comune di comprendere i benefici ambientali dei nuovi prodotti isolanti naturali biogenici (bio-based) per la riqualificazione energetica dell'involucro dell'edificio. L'Unione europea, quale parte dell'accordo di Parigi, è tenuta a contribuire a mantenere l'aumento della temperatura media globale ben al di sotto dei 2°C. Secondo la quinta relazione di valutazione dell'IPCC il rispetto di tale limite ambientale globale implica l'imposizione di un tetto massimo al rilascio di gas clima-alteranti in atmosfera (Carbon budget). Con il potenziale emissivo rimanente dobbiamo avviare urgentemente la transizione verso una società a zero emissioni in modo da annullare l'interferenza antropogenica nel cambiamento climatico. Il settore dell'edilizia in Europa è responsabile del 36% delle emissioni di gas serra e la sua riqualificazione energetica rappresenta una priorità. Una tendenza comune in materia di efficienza energetica è quella di concentrarsi solo sull'energia operativa, trascurando gli impatti provenienti dall'energia grigia, cioè le emissioni prodotte nelle varie fasi di ciclo vita del prodotto: produzione, trasporto, costruzione, sostituzione, smaltimento. In realtà, tali oneri ambientali possono risultare ingombranti, soprattutto se si considera una prospettiva a breve termine. Il compito del presente lavoro è quello di indagare e valutare in modo olistico i vantaggi derivanti dall'utilizzo di materiali biogenici come paglia, canapa, legno, ecc. per la riqualificazione dell'edilizia residenziale europea. Il tratto distintivo di questi materiali naturali è da un lato di essere rinnovabili, dunque di avere un potenziale rigenerativo sufficientemente rapido, dall'altra di avere un'impronta ecologica negativa dovuta alla rimozione di importanti quantità di anidride carbonica per effetto della fotosintesi. Lo studio approfondito di soluzioni a base vegetale implica la necessità di modellare in maniera coerente il bilancio della $CO_2$ biogenica. Dunque viene rimossa la semplificazione secondo cui essa viene considerata nulla, in luogo di un modello che tenga conto dell'effettiva evoluzione delle emissioni/assorbimenti durante il ciclo di vita per poterne valorizzare lo stoccaggio temporaneo. Questa esigenza viene soddisfatta attraverso l'applicazione di una LCA dinamica, che inoltre permette di ottenere come output l'impatto ambientale come funzione del tempo, ovviando così alle incoerenze sulla considerazione degli orizzonti temporali insite in un LCA tradizionale. Con questo strumento il lavoro mira a mostrare quanto la scelta del materiale isolante possa influenzare l'equilibrio carbonico complessivo. Una volta delineate le principali problematiche ambientali e i principali target del settore edilizio europeo (cap.2). Viene proposta una panoramica sugli isolanti biogenici e sulla loro possibile applicazione in edilizia (cap.3). Nel seguito il parco residenziale europeo viene analizzato e caratterizzato facendo

rifermento a sette macro-aree (GeoClusters), in modo tale da modellare una possibile evoluzione del miglioramento delle prestazioni dell'involucro nel tempo considerando i tassi di rinnovo attuali (cap.4). Successivamente viene illustrato il modello di calcolo; esso riunisce e rielabora spazialmente e temporalmente dati concernenti sia il patrimonio edilizio europeo sia la valutazione di impatto ambientale delle tecnologie in esame; infine si applica un LCA dinamico da cui si ottengono i risultati finali in termini di forzante radiativo (cap.5). La simulazione copre un arco temporale di 200 anni a partire dal 2018 e comprende lo studio di cinque diverse alternative per l'isolamento delle pareti esterne, tra cui soluzioni bio-based a crescita rapida, legno, minerali e polistirene, per tre diversi scenari di fine vita. La stima dei benefici indotti dalla ricrescita della biomassa, è basata sull'ipotesi di base secondo cui a seguito dell'installazione di un componente edilizio biogenico contenente un certo quantitativo di Carbonio, una corrispondente quantità di anidride carbonica viene sequestrata dall'atmosfera e stoccata nella nuova biomassa che si rigenera a partire dall'anno successivo alla posa in opera dell'elemento. I risultati mostrano che un'utilizzazione su vasta scala di materiali da costruzione naturali può portare, accanto al soddisfacimento dell'obiettivo primario di migliorare le prestazioni passive dell'edificio, all'ulteriore effetto di trasformare i carichi ambientali, incorporati nella riqualificazione, in benefici. Tale effetto di mitigazione climatica viene attivata fin dai primi anni nel caso di materiali biogenici a crescita rapida, ed è dovuta al bilancio di Carbonio complessivamente negativo delle operazioni. A partire da questo concetto si possono aprire anche nuove prospettive di programmazione degli interventi di recupero, rispetto alle attuali normative: affiancando ad esempio i target energetici esistenti con dei target ambientali in cui il potenziale rigenerativo, e dunque di stoccaggio della $CO_2$ sia considerato. D'altra parte, il tasso di ristrutturazione annuo è risultato di gran lunga il più importante parametro da controllare infatti un suo incremento comporta un'amplificazione degli effetti indotti dagli interventi, siano essi benefici, isolanti naturali, o dannosi, isolanti convenzionali. Si ritiene inoltre che spingere la prefabbricazione elementi modulari di facciata per il retrofit possa contribuire alla velocizzazione transizione. Puntare senza sconti a una società a zero emissioni e farlo rapidamente nel rispetto del Carbon budget sono elementi centrali per poter mantenere viva la speranza di evitare danni irreversibili all'ecosistema. In questa prospettiva, l'uso di materiali biogenici (bio-based) per la riqualificazione energetica del patrimonio edilizio esistente, rappresentano un'opportunità che non dovrebbe essere lasciata incolta.

# Contents

# Chapter 1

# Introduction

This study was conducted in a joined project between *Politecnico di Milano* and *ETH Zürich* within the framework of the Swiss-European Mobility Programme. As master thesis exchange student, I had the chance to set the guidelines of the work at the Department of Architecture Built Environment Construction Engineering of Politecnico di Milano and to fully develop it at the Chair of Sustainable Construction of the Department of Civil, Environmental and Geomatic Engineering at ETH Zürich.

Convinced that this would have led to valuable new insights in the research field of sustainability, the collaboration between the institutes was conceived upon the common purpose understanding the environmental impact of novel bio-based insulation products for energy retrofit of the building envelope.

Among the motivations that moved me to devise this topic there are on one hand the strong will to give a contribution to the de-carbonization path the building sector, must cover within the next decades, for facing climate change; on the other hand, I was interested in combining the environmental awareness with a potentially valuable market share.

Nevertheless, I owe the company *Equilibrium - bioedilizia*, where I did my internship, that allowed me to gain a deeper outlook on natural building materials for improving the environmental compatibility in construction sector.

## 1.1 Foreword

Retrofitting the building envelope in European building stock represents a main concern, as they are responsible for 40% of energy consumption and 36% of CO2 emissions in the EU and about 35% of the EU's buildings are over 50 years old. Energy efficiency measures are therefore a priority for cutting the operational energy.

Nevertheless, the impacts coming from the implementation of the renovation strategies, particularly embodied energy and related carbon emissions, are often neglected in the equation. This could result to be a crucial mistake if we want to address sustainability consistently.

Therefore, the choice of the insulation material for instance could represent a turning point: it could either induce additional loads, like in the case of conventional materials, or it could generate a double benefit (operational and embodied) like in the case of bio-based. This crossroad could significantly divert the actual result especially a in the short term, that is our main concern for hasten the energy transition.

Another clue to be preliminarily pointed out for the understanding of the work is that current LCA methodologies are not equipped to give any value to temporary carbon storage, as the amount of sequestered carbon would be subtracted from the emission occurring at the end of the storage period to give a net zero emission.

Since we intend to deal with biogenic materials, where biogenic carbon is preponderant, the choice of traditional tools could strongly mislead the assessment, hence a dynamic LCA approach is adopted. So that the timing of every GHG emission, including biogenic carbon flows is accounted for and the benefits given for temporarily storing carbon or delaying GHG emissions, are considered (Levasseur et. al. 2013).

## 1.2 Goal and scope

The task of the present research is the investigation and quantitative assessment of the benefits deriving from the use of bio-based material for the renovation of the European residential building stock.

Specifically, development of a comparative assessment among bio-based and traditional solutions will be carried out. Thereafter a projection of the impacts at European scale is explored through the innovative dynamic approach to LCA, a new impact assessment tool that provide a function of time as output and a consistent way of accounting for biogenic $CO_2$.

In a conventional retrofit of the building envelope, the higher is the reduction of operational energy aimed, the higher is the amount of industrialized materials to be invested invested, the higher is the related embodied impact.

The final aim of this study is to demonstrate that implementing a bio-based renovation of the building envelope, it is possible to turn the weakness connected to the material impacts, into an opportunity for climate mitigation thanks to the Carbon sink capacity of the biomass regrowth.

## 1.3 Outline

The structure of the work can be staged in different sections. We firstly describe what are the environmental challenges we are called to answer in the next decades (chapter 2), then bio-based materials as insulation alternatives are presented (chapter 3), later an examination of the European building stock is conducted (chapter 4), the model adopted and the dynamic LCA approach is thus illustrated and detailed (chapter 5), and finally results are explored (chapter 6) and conclusion are remarked (chapter 7).

To be noticed that the projections made on the building stock cover always a time horizon of 200 years starting from January the 1st 2018, and that only global warming impact category is here controlled in terms of radiative forcing.

# Chapter 2

# Ecosystem and built environment

## 2.1 Global environmental limits

Awareness of climate change and the contribution of buildings to energy use, resource consumptions and CO2 emissions is widespread (Santamouris and Asimakopoulos, 2001)

> Human interference with the climate system is occurring. Climate change poses risks for human and natural systems. (IPCC, 2013)

Anthropogenic greenhouse gas emissions have dramatically increased in the last decades, figure 2.1, experiencing during the last years the highest annual emission rate ever achieved. Average global atmospheric $CO_2$ concentration, that depends on the cumulative emissions, during these months has touched 410 ppm, and currently it keeping rising at a rate of ~2 ppm/yr.

Global warming, is the temperature rise of the Earth's climate system across the centuries. Pre-industrial level of temperature is assumed as reference, and since then we have registered an unprecedented rise that is extremely likely to be dominantly caused by human influence.

This disproportionate polluting pattern must be drastically decreased within the next years as we are rapidly approaching our global environmental limit: a level in which warming become self-fuelling because of the triggering of several factors like Permafrost melting, release of Carbon stored in the soil, drop of albedo and crust reflectivity, see level rise due to thermal expansion, reduced $CO_2$absorption capacity of oceans, etc. The effects of this condition of irreversibility, also called "point of no return", have already being felt and the inertia of the phenomenon can make global warming proceed even after an emission stoppage (Frölicher et al., 2013). If it is fair to say that the fuse of such a dangerous loop cannot be avoided, but then it is even more important remarking that its consequences can significantly be dampened if we are able to keep the temperature rise under certain limits (2°C).

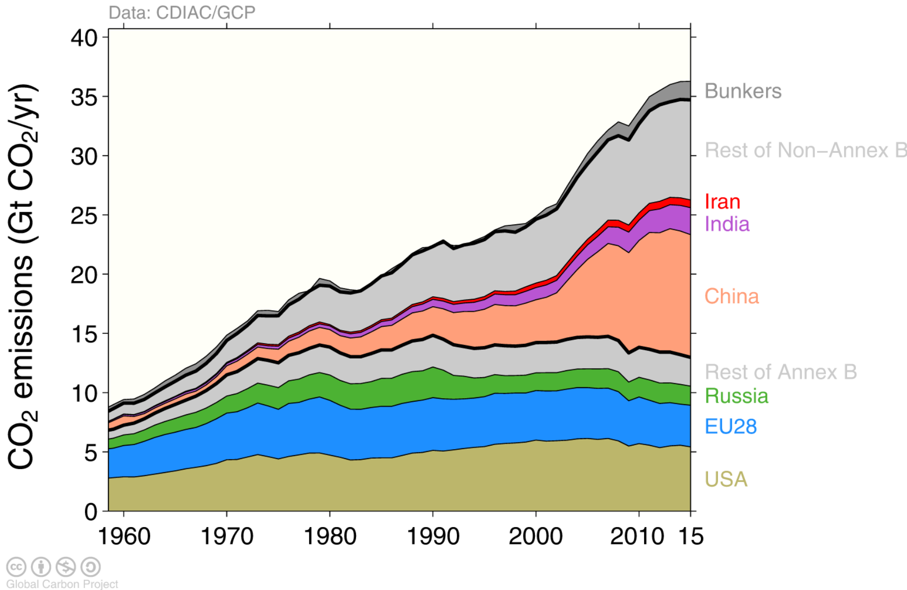



Figure 2.1: Global $CO_2$ emission rate. Source: Global Carbon Project

### 2.1.1 Carbon Budget

The respect of global environmental limit can be effectively interpreted through the concept of (cumulative) Carbon budget. It represents the the finite amount of greenhouse gases we can emit to limit global temperature rise to 2°C. With Carbon budget approach mitigation challenges are reframed as a stock problem, rather than the most frequent approach of focusing on the flow of $CO_2$ in atmosphere (Millar et al., 2016).

The 5th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) provides the latest assessment of evidence on the climatic effect of cumulative $CO_2$ emissions as follows: "Cumulative emissions of $CO_2$ largely determine global mean surface warming by the late twenty-first century and beyond", supporting the cumulative Carbon budget approach. Besides, and estimation of the amount of carbon dioxide the world can emit while still having a likely chance of limiting the global temperature rise to 2°C is provided and presented in figure 2.2. A left over of 1000 $GtCO_2$ is the quantification of the Carbon budget (2°C - 66%) as of 2011.

The Global Carbon Project has updated this figure to the year 2017 considering the emissions occurred between 2011 and 2016 yielding a number of 762 $GtCO_2$ as illustrated in figure 2.3.

In the present research the simulation starts on January the $1^{st}$ 2018, therefore the emission year 2017 has been also considered (assumed to be equal to the year 2016), and a global Carbon budget of 722 $GtCO_2$is finally taken as reference threshold.

Shifting to a temporal outlook, the Budget can be translated into time left. Namely if the rate of emissions is assumed to be unaltered in the next years evaluating the time remaining before the Carbon Budget is blown is straight forward, and can be see in figure 2.4 where different deadlines are presented, in function of the reference temperature rise and the probability of occurrence. As we can see if the "business as usual" condition is kept (emission of 2016), the 2°C Budget is blown in 19.1 yr, meaning at the beginning of the year 2036.

| Cumulative $CO_2$ emissions from 1870 in $GtCO_2$ | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Net anthropogenic warming [a] | <1.5°C | | | <2°C | | | <3°C | | |
| Fraction of simulations meeting goal [b] | 66% | 50% | 33% | 66% | 50% | 33% | 66% | 50% | 33% |
| Complex models, RCP scenarios only [c] | 2250 | 2250 | 2550 | 2900 | 3000 | 3300 | 4200 | 4500 | 4850 |
| Simple model, WGIII scenarios [d] | No data | 2300 to 2350 | 2400 to 2950 | 2550 to 3150 | 2900 to 3200 | 2950 to 3800 | n.a. [e] | 4150 to 5750 | 5250 to 6000 |
| Cumulative $CO_2$ emissions from 2011 in $GtCO_2$ | | | | | | | | | |
| Complex models, RCP scenarios only [c] | 400 | 550 | 850 | 1000 | 1300 | 1500 | 2400 | 2800 | 3250 |
| Simple model, WGIII scenarios [d] | No data | 550 to 600 | 600 to 1150 | 750 to 1400 | 1150 to 1400 | 1150 to 2050 | n.a. [e] | 2350 to 4000 | 3500 to 4250 |
| Total fossil carbon available in 2011 [f]: 3670 to 7100 $GtCO_2$ (reserves) and 31300 to 50050 $GtCO_2$ (resources) | | | | | | | | | |

Figure 2.2: Cumulative carbon dioxide ($CO_2$) emission consistent with limiting warming to less than stated temperature limits at different levels of probability, based on different lines of evidence. Source: Table 2.2 SYR IPCC2013.

| | <1.5C | | | <2C | | |
|---|---|---|---|---|---|---|
| **Budget** | **66%** | **50%** | **33%** | **66%** | **50%** | **33%** |
| Carbon budget as of 2011 (a) | 400 | 550 | 850 | 1000 | 1300 | 1500 |
| Total CO2 emissions from 2011 to 2016 (inclusive) | 237.98 | 237.98 | 237.98 | 237.98 | 237.98 | 237.98 |
| Carbon budget as of 2017 | 162.02 | 312.02 | 612.02 | 762.02 | 1062.02 | 1262.02 |
| Years left (at 2016 emissions) | 4.06 | 7.82 | 15.34 | 19.09 | 26.61 | 31.62 |
| As above, in years / months | **4 yrs / 1 mths** | **7 yrs / 10 mths** | **15 yrs / 4 mths** | **19 yrs / 1 mths** | **26 yrs / 7 mths** | **31 yrs / 7 mths** |

| **Emissions** | **2011** | **2012** | **2013** | **2014** | **2015** | **2016** | |
|---|---|---|---|---|---|---|---|
| Fossil fuels & cement production (GtC) (b) | 9.54 | 9.69 | 9.82 | 9.89 | 9.9 | 9.93 | |
| Land use (GtC) (b) | 0.91 | 0.97 | 0.92 | 1.1 | 1.32 | 0.96 | |
| Fossil fuels & cement production (GtCO2) | 34.95 | 35.5 | 35.98 | 36.24 | 36.27 | 36.4 | (c) |
| Land use (GtCO2) | 3.33 | 3.55 | 3.37 | 4.03 | 4.84 | 3.51 | (d) |
| Total CO2 from all human sources (GtCO2) | **38.29** | **39.06** | **39.35** | **40.27** | **41.11** | **39.91** | |

**Data sources**
(a) Taken from Table 2.2 in the IPCC AR5 Synthesis Report: http://www.ipcc.ch/pdf/assessment-report/ar5/syr/SYR_AR5_FINAL_full_wcover.pdf
(b) Global Carbon Budget 2016 emissions dataset v1.0 (Dec 2016): Excel file available here: http://cdiac.ornl.gov/GCP/
(c) For 2016 data only: Le Quéré, C. et al. (2016) Global Carbon Budget 2016, Earth Syst. Sci. Data, 8, 605–649: http://www.earth-syst-sci-data.net/8/605/2016/
(d) Data not yet available for 2016, so average taken of previous 10 years

Figure 2.3: Carbon budget 2017. Amount of Carbon dioxide still releasable in atmosphere as of 2011 and updated as of 2017, and correspondent time span, before the different thresholds are reached. Collection of the data Source: Global Carbon Project.

### 2.1.2 Low-Carbon society Transition

Transition is a long-term structural change in resources provision and energy system that from the present situation leads toward a Carbon neutral society (and more in general climate neutral).

Overcoming the threats anthropogenic-driven climate change is posing on our society, is the greatest challenge of the century, and it can be effectively tackled only if a transition to a zero-carbon society is assumed as final target, without compromises for half measures. Actually it would be more correct to talk about Low-Carbon society inasmuch the bio-capacity of the Earth is able to compensate a certain amount of greenhouse gases. Namely after the transition

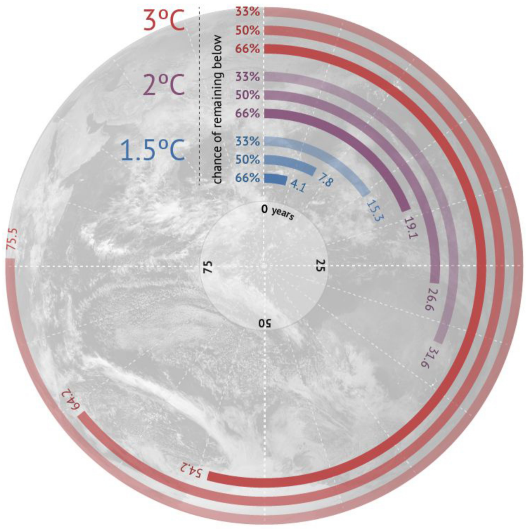



Figure 2.4: Carbon Countdown Clock. As of the start of 2017, they are reported the number of years of current emissions that would use up the IPCC's carbon budget for different level of warming. Source: Carbon brief.

is accomplished, people should live from a 1 ton $CO_2$ per capita per year limit (assumed as being within natural regeneration capacity) to maintain a balanced $CO_2$ level globally (Rovers et al., 2017); consider that the current average carbon dioxide emission is 6.9 $tCO_2/cap/yr$ in Europe, 16.1 in USA, 5.9 in Italy, 0.5 in Nigeria, 4.9 global (Olivier et al., 2016). A visualization of a possible transition scenario is illustrated in figure 2.5, where the steep reduction after the peak is a possible trend to be followed to stay under the Budget.

Another key concept that cannot be disregarded is the energy $CO_2$ intensity. As renewable penetrates in the market, energy gets cleaner, meaning that producing a unit of energy will become less impacting in the future; note that if embodied impacts from the production of solar panels, wind turbines, etc. this statements could be overturn, but let us assume that we will be able to built low impact organic PV and wooden turbines, then the decarbonization of energy is and advantage that we will benefit from while the transition is proceeding. As reference data we can mention the level of $CO_2$ intensity in the European Union that has dropped from a value of 3.4 (1960) to a value of 2.1 (2013) [$kgCO_2/kgoe$ of energy use] (Source: The World Bank Website). Due to this energy cleaning, it is important to shift energy based targets to impacts (emission) based targets.

Nowadays the tendency is to move toward a "greener" economy, but too often it is done only for pleasing new market trends, resulting into a good product make-up and a moderate GHG reduction. With this approach the real point is missed and the actual commitments disregarded. For avoiding major damages to the ecosystem the crucial factors to be assumed as background of every strategy are 1) that a complete decarbonization of the society is urgent (Transition) and 2) that the amount of emission we have left for accomplishing the task is limited (Carbon Budget).

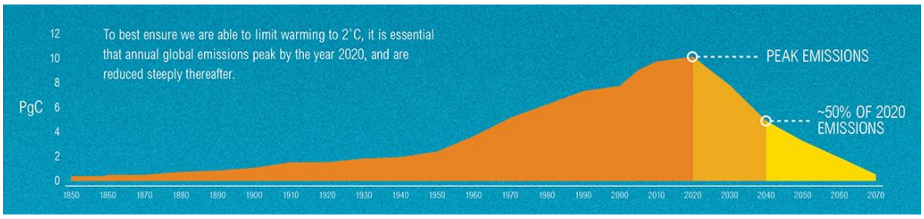



Figure 2.5: Evolutions of anthropogenic Carbon emission from the pre-industrial era and projection of an ideal reduction within the budget. The transition is the descending branch of the curve, from the peak emission to the carbon neutrality. Source: IPCC ichonography

## 2.2 Role of buildings in Europe

### 2.2.1 Households related impacts

One of the main key sectors where it is vital to reduce the energy consumption, is the existent building stock, where energy use has seen overall a rising trend over the past 20 years. Buildings are responsible for 40% of energy consumption and 36% of $CO_2$ emissions in the EU. With 250 million of dwellings of ≈100 $m^2$ each on average, residential buildings account for 75% of the total stock. In 2014, GHG emissions generated by industries and households in the EU-28 stood at 4.4 [$GtCO_2eq/yr$], housing sector holds a share near to one fifth with an emission rate of 0.85 [$GtCO_2eq/yr$] where space heating is by far the dominant player, see figure 2.6.

Currently, about 35% of the EU's buildings are over 50 years old, and around 87% of stock (by useful floor area) has been built before 2000. As we can see from figure 2.7 the age of the building is directly related with its consumptions. Therefore focusing on retrofitting the old building stock has substantial energy saving and thus avoided impacts potentials. This large share of energy swallower buildings is the stock portion we will concentrate our analysis on, see section 4.4.2. To be noticed that within this part of the stock is included also share of Architectural Heritage and historic buildings that will have to cope with the opposite requirement of being protected on one side and being renovated on the other (Mazzarella, 2015).

### 2.2.2 Mitigation and adaptation

Climate change policy has developed around two themes: *mitigation* and *adaptation*. Mitigation is tackling the causes of climate change through reduction of greenhouse gas emissions; adaptation is adjusting to the physical impacts of climate change, by reducing vulnerability and finding opportunity. Mitigation and adaptation should not be viewed as alternatives. Adaptation will be needed to deal with the unavoidable impacts of climate change even with mitigation. In the longer term, adaptation is likely to be insufficient to manage the most serious impacts of climate change should mitigation efforts fail. The building sector has a considerable potential for positive change both in mitigation and adaptation strategies, to become more efficient in terms of resource use and environmental impact. (Iannaccone et al., 2014).

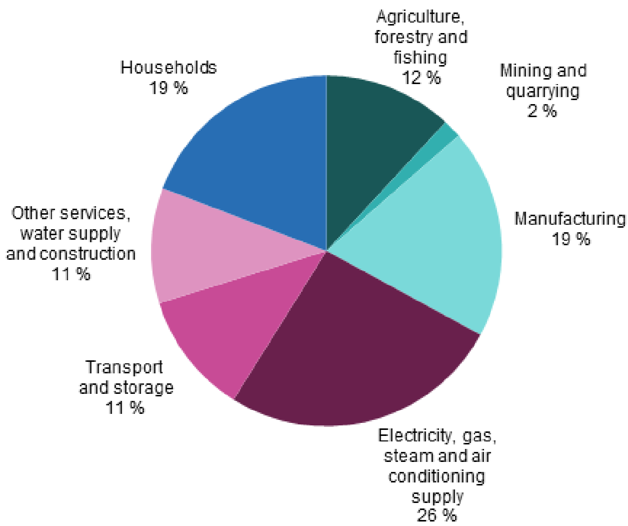



Figure 2.6: Greenhouse gas emissions by economic activity, EU-28, year 2014, % of total emissions in $CO_2$eq. Source: Eurostat

Adapting buildings to the effects of the climate change means renovation. If we consider new constructions as already adapted, the focus in on existing buildings that are not always equipped to face harder climatic conditions. In effect adaptation to climate change means also facing scarcity (resources depletion, water shortage etc.) so a special care to the materials used and embodied impacts is recommended, see section 3.2.1.

Mitigation in buildings comprises energy efficiency measures in general and phase out of fossil fuels through the use of renewable sources. Again the field of operational energy cut is largely discussed while embodied energy is often hidden.

In the present work we will concentrate on insulation intervention of existing walls in order to cope with renovation need for adaptation. But a special focus will be dedicated to the use of bio-based materials as insulation in order to gain an additional benefit thanks to their regeneration potential. One of the task of this study is to investigate and quantitatively assess the mitigation potential of the use of natural insulation materials instead of conventional ones, within the renovation intervention for the adaptation of the household sector.

### 2.2.3 European targets and dwellings related budget

The commitments of European union in the field of climate change see the implementation of different strategies for approaching the transition.

- Firstly we have to mention the 2015 United Nations Climate Change Conference, Conference of the Parties 21. The *Paris Agreement* at article 2 states:

  1. This Agreement, in enhancing the implementation of the Convention, including its objective, aims to strengthen the global re-

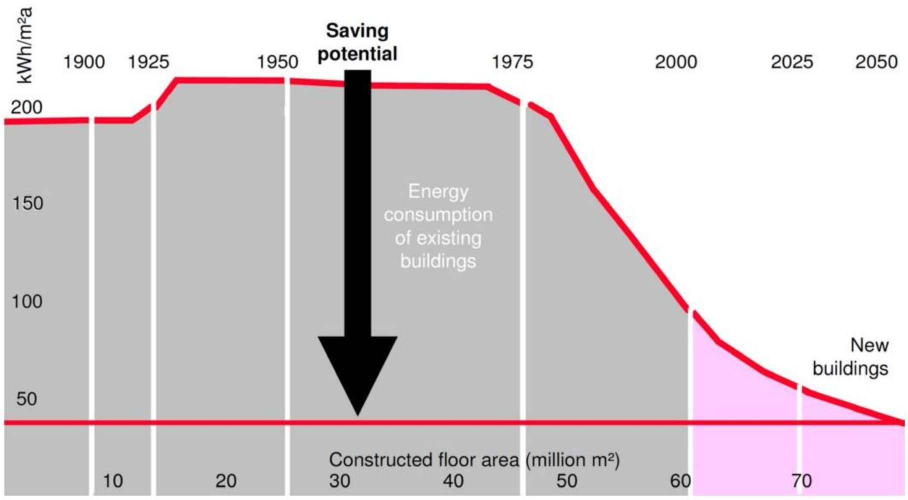



Figure 2.7: Constructed floor area and specific energy consumption for heating and hot water of existing buildings in Zurich and target value for sustainable renovation (Zimmermann, 2011).

> sponse to the threat of climate change, in the context of sustainable development and efforts to eradicate poverty, including by:
>
> (a) Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change;
>
> (b) Increasing the ability to adapt to the adverse impacts of climate change and foster climate resilience and low greenhouse gas emissions development, in a manner that does not threaten food production; and
>
> (c) Making finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development.
>
> 2. This Agreement will be implemented to reflect equity and the principle of common but differentiated responsibilities and respective capabilities, in the light of different national circumstances.

- Secondly as EU28 we have submitted the *Europe 2020 strategy* in which we aim to achieve:

  - greenhouse gas emissions 20% lower than 1990 levels
  - 20% of energy coming from renewables
  - 20% increase in energy efficiency

- And lastly the key legislation covering the reduction of the energy consumption of buildings can be recalled: The 2010 *Energy Performance of Buildings Directive* (EPBD) and the 2012 *Energy Efficiency Directive* (EED).

The framework of the Paris Agreement it has been highlighted the importance of containing temperature rise within 2ºC. In section 2.1.1 it has already been explained the link between the rise in temperature and the Carbon budget. If we want to apply this concept to the housing sector it is necessary to understand the share of the global budget that can be devoted to it. Being the global budget as of the beginning of 2018 correspondent to 722 [$GtCO_2eq$], the share allocated to European Union is calculated in proportion to the population. Since currently Europe accounts for less than 7% of the total population its budget will be of the order of 48 [$GtCO_2eq$]. As we know that European residential stock holds a share 19% of emission over the total economical activities (section 2.2.1), the budget to be considered within the present research is 9 [$GtCO_2eq$] (valid for the 2°C scenario, the same apply for the others). Note that a simple proportion criterion has been considered for allocating the budget to European union, because any other different criteria needs to have a specific justification to be used.

The prescriptions of the Europe 2020 strategy include a 20% by 2020 of energy cut, meaning either that we push energy efficiency up to save on average 1/5 of energy consumption, or that 1/5 of the dwellings become ZEB. It has been chosen the first strategy and currently it is being achieved the target, specifically: greenhouse gas emission in 2015 are 78% respect to 1990 (target 2020: $<$80%), share of renewable energy in 2015 is 17% (target 2020: $>$20%), primary energy consumption in 2015 is 1082 toe (target 2020: $<$1086 toe) (data Eurostat). From the monitoring it appears a good accomplishment but we have to consider that this strategy should be sustained (40% in 2030, 60% in 2040 and so on), and that it will be much more difficult push the agenda for the following 20% reduction.

Finally some words on the standards. They have rightly been so meticulous in the energy efficiency detailing and in the nZEB definition, but in a progressively cleaner energy supply the paradigm must shift from energy to impacts (e.g. Zero Carbon Building).

# Chapter 3

# Bio-based materials for renovation

## 3.1 What is bio-based

### 3.1.1 Definition(s)

The definition of bio-based is debatable. Commonly bio-based materials are perceived as "natural", but that is very broad concept. The definition could be linked to the origin of the material, "derived from living (or once-living) organisms" (Wikipedia); or to the renewal capacity, but even fossils and sand can be renewed in long time-span. Someone tried even to define bio-based economy: "production paradigms that rely on biological processes and, as with natural ecosystems, use natural inputs, expend minimum amounts of energy and do not produce waste as all materials discarded by one process are inputs for another process and are reused in the ecosystem" (European Commission, 2011). In the end the general outline may appear quite nuanced.

Thus we need to zoom on what really make the difference with other alternatives: the core feature of bio-base materials is that they are "re-growable" resources, implicitly implying they are regenerated in useful time to keep in balance the system. In other words bio-based does not mean necessarily sustainability but it is directly related to it.

Several application of bio-based materials can be related to building. Natural construction materials used for structural purposes like timber or bamboo, are known. But also the use of plant-based elements either as insulation or as infill, possess a huge potential.

Loose natural chips or fibres for insulation is one of the possible application; an alternative is the utilization of agro-concrete, defined as: "A mix between aggregates from lignocellular plant matter coming directly or indirectly from agriculture or forestry, which form the bulk of the volume, and a mineral binder" (Amziane et al., 2013).

### 3.1.2 Fast-growing biogenic materials

Scarcity or resources can be tackled effectively through the use of renewable materials. But also among bio-based there are differences. In effect, as above mentioned, it is central to point out the time needed for having back the biomass used in construction. Two categories can be mainly identified:

- Long-lived: basically wood, that can take from 50 up to more than 100 years to regenerate;
- Fast-growing: all the plantations, either yearly crop or grass-like plants

The benefits of dealing with materials that can be used today and regenerated 1 year time is immediately perceived in terms of resources, but it gains much more importance if we have to think, as we have, in a short perspective to avoid main consequences of global warming. In spite of the fact that within the present work we are not dealing with impact categories like resource depletion or land consumption (only global warming is considered), we sill want to qualitatively underline how not only global warming but other impact categories can benefit from the use of fast-growing biogenic materials.

## 3.2 Why rely on bio-based

### 3.2.1 Relevance of embodied

The main road followed up to now leads to energy efficiency: it is a wide topic that include several approaches as enhancing passive performances, rising building system efficiency, relying on adaptive control and demand side management, etc. If we leave apart the measures for enhancing comfort, the vast majority of the others is aimed to cut operational energy; a wise policy undoubtedly. But the shifting of the burden on materials is often underestimated.

As shown in section §2.2.3, in order to limit the rise of temperature within 2ºC, fast retrofitting of existing dwellings is inescapable, because breaking down operational energy is an absolute priority.

As a consequence, since the quantity of materials for carrying out such a large-scale operation is significant, it is necessary embodied impacts to be included in the equation (and related $CO_2$ footprint). If only operational energy is considered, and embodied excluded from the assessment (choosing for example EPS for retrofitting the building envelope), the risk is to ignore a big player worstening the situation instead of improving is likely to be (at least in the short term). This is because emissions for material production are immediate and can be high while energy savings are limited and spread in time.

Moreover if we look at figure 3.1 it is clear that rising building performances, embodied impacts of materials will gain more and more relevance up to the limit case of ZEB, in which they are the only burden to be considered.

### 3.2.2 Insulation material comparisons

Therefore, if we do have to renovate, and we do have to consider embodied impacts, the problem is shifted on the choice of the material. The choice has

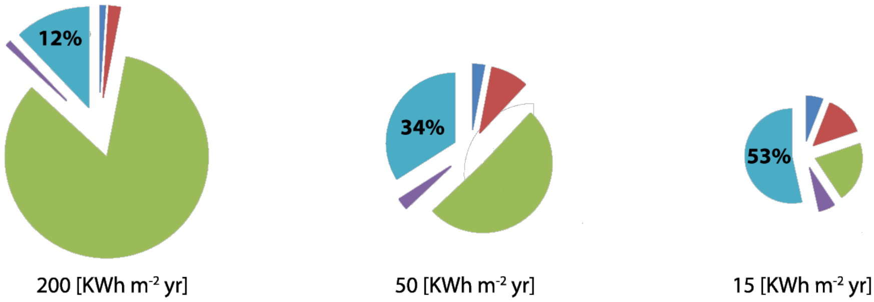



Figure 3.1: Relevance of embodied energy. Material related impacts gaining more and more importance going toward better performance buildings. Source: S. Amziane, M. Sonebi, RILEM Technical Letters (2016)

to guidelines: performance and environmental impact; specifically, thermal performance and carbon footprint.

At this regard, in figure 3.2 we propose a preliminary investigation. It is shown a comparison in terms of emissions per service provided (unitary thermal resistance). Data elaborated from IBO database and UNI 10351:1994 and UNI EN 10456:2008.

It is already visible from this chart how bio-based materials are considerably convenient compared to synthetic insulation and at least competitive, if not better with respect to mineral insulation. Note that here a steady state thermal resistance has been considered (conductivity times unitary length).

If we want to double check through the use of another tool we can look at the figure 3.3, a chart built up with the software CES Selector. The indicator chosen in this case are are $CO_2$ footprint [kg/kg] from primary production and thermal diffusivity [$m^2/s$], which provides information also on the dynamic thermal behaviour of the material.

This could already be sufficient for addressing choice toward bio-based, but as we can see in the followings chapters the dynamics of greenhouse gases with the use of bio-based provide another huge advantage: carbon sequestration and storage (CSS) phenomena, occurring after the production, during the service life of the building, due to regrowth of biomass employed, that effectively remove $CO_2$ from the atmosphere, opening to the carbon negative renovation perspective.

## 3.3 Retrofitting external wall

The purpose of this section is to explain the rationale behind the definition of the technologies we have adopted for depicting a large-scale renovation.We try to identify problems and possibilities of technical implementation of the bio-based renovation strategy. Now that we have stated clearly "why" we have to do it (reducing emissions), "what" (renovation with bio-based) and "when" (shortest time possible), we have to focus on "how" to do it.

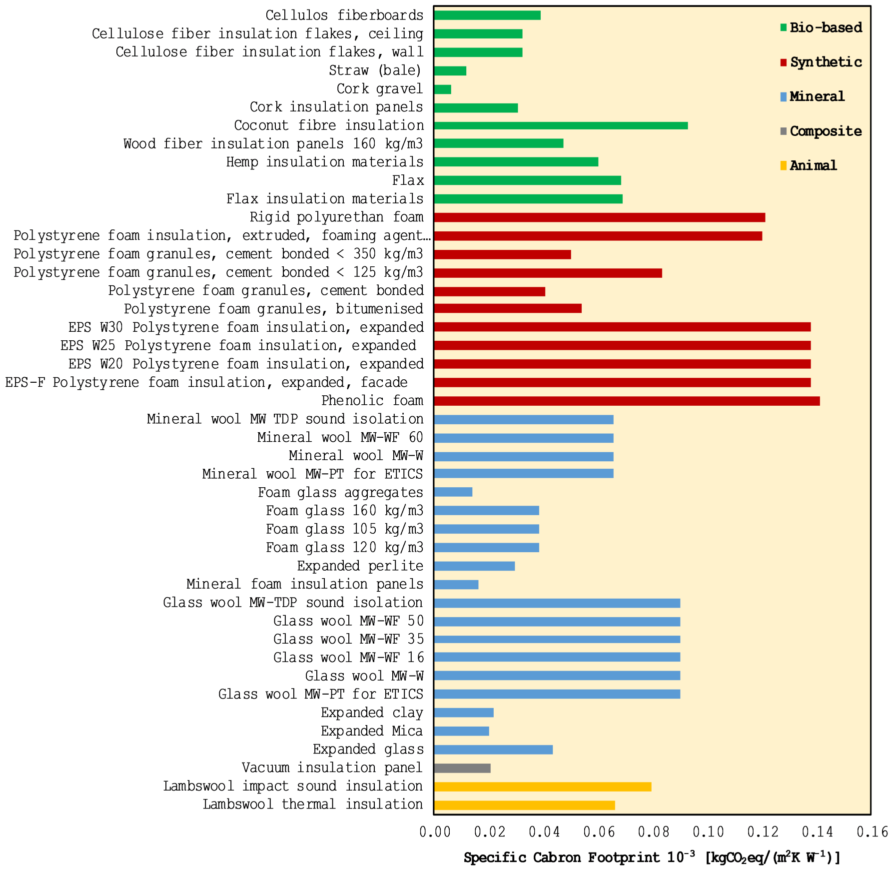



Figure 3.2: Insulation material comparison. Range of low density products with possible application in construction compared through the specific carbon footprint: environmental indicator normalized over the performance (amount of green house gas released per unitary thermal resistance). Source: IBO database

### 3.3.1 Availability of biogenic materials

An important issue to be taken in consideration is the availability of the bio-biomass. Namely one can ask if a sufficient supply to satisfy the potential demand coming from European large scale renovation is present or not. The answer is different product by product:

Timber: the production of sawn-wood in Europe is over 100 [$Mm^3/yr$] (Eurostat, 2017a), handsomely able to cover the need for framing of prefabricated panels and insulation fibres.

Straw: a by-product from cereal plants that are abundant in Europe. Considering the yield varying in the range 3.1-4.8 [t/ha] (Konvalina et al., 2014), a cultivation area of 57 [Mha] (Eurostat, 2017b) and a share of wheat over total cereal of 48% (Eurostat, 2016), we can estimate the availability of straw to about 100 [Mt/yr]. Even if other

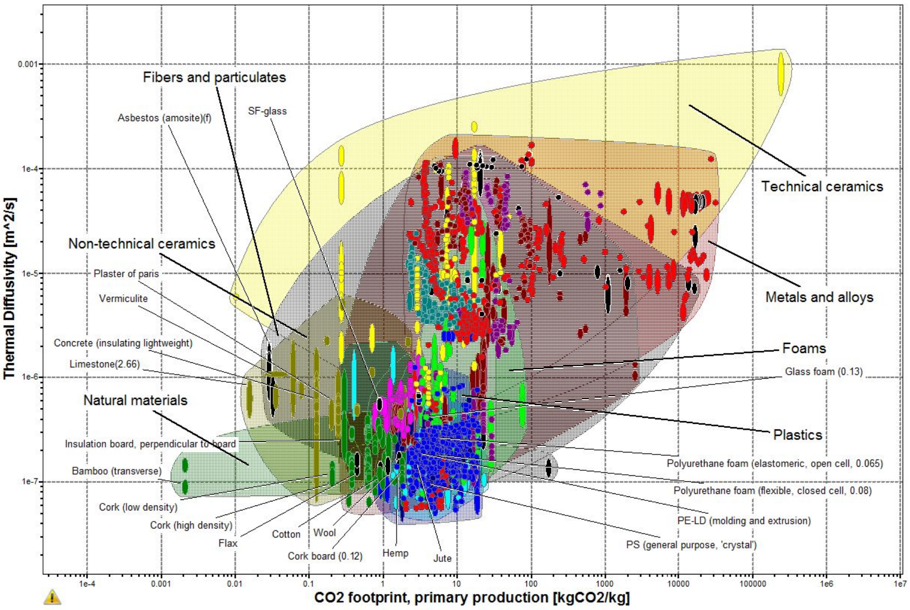



Figure 3.3: Insulation material comparison with thermal diffusivity. On x-axis we have emissions of $CO_2$ during production per unit mass of product, combined with thermal diffusivity on y-axis for giving an indication about dynamic thermal performances. Logarithmic scale. Natural materials on the bottom left part of the chart.

uses has to be considered this figure is far larger than the demand for retrofitting, around 1.5 [Mt/yr].

Hemp — hemp shiv in particular, the woody core, a by-product of hemp crop (that represents the majority of the biomass). Currently the supply of hemp shiv is insufficient, 43000 [t/yr], but the market is in rapid expansion because of the multiple products can be produced out of hemp plant, (Carus et al., 2016).

Flax — with 81000 [ha] of fibre flax cultivated and 130000 tons of long fibres, Europe is responsible for 80% of global production (Green et al., 2015); but it is unlikely to get a share of the market for construction.

Reed — a grass-like plants that can be employed in substitution of the first coat for plaster finishing; several criticalities could appears if used as insulation material Miljan et al. (2013).

Bamboo — the absolute winner in terms of carbon footprint, suitable for structural application.

Cork — very low impact material but available in low quantities and not always easy to get.

Juta — cheap bio fibre, produced mainly in India not in Europe.

For simplicity we have presented here only a limited variety of products, but enough for support our research. Therefore, also on the basis of availability constraints we can narrow the focus. Particularly we have chosen to test the environmental behaviour of 5 different technologies: 3 bio-based, insulation layer made out of straw chips, hemp-lime concrete and reed mat; 1 mixed with mineral insulation and wood fibres; 1 conventional with e.t.i.c.s. in expanded polystyrene.

### 3.3.2 Durability and end of life

Dealing with bio-based materials, as we have seen in 3.2.2 bio-based materials are good thermal insulator. What is important is to maintain this ability hindering their tendency to degrade, in other words assuring durability. Fire, water, frost, insects, rodents and biological decomposition may turn to be a threat for the bio-based construction component. For extending the service-life of the bio-material we can on one side acting on its protection: confining it into a tight cavity, e.g. loose straw chips in a prefab sandwich panel; and on the other side working on its composition: we can rely on the fact that the biogenic component is mineralized by a binder, e.g. lime or clay, that acts as a protection on bio-fibres. In hemp concrete for example, thanks to the action of lime, hemp shives slowly mineralize, becoming inert and reducing the risks of rot and mould formation Arrigoni et al. (2017).

As regard the end of life scenarios for bio-based building products, we have to clarify that the map is rather unknown since reliable range of real cases of disposals are not available yet. Being a relatively new market, information about the end of life are yet to be collected, therefore assumptions will be made as we will see in section 5.2.3.

### 3.3.3 Large-scale renovation

As already formerly stated, fossil fuel energy consumption must be significantly reduced for stabilizing greenhouse gas emissions. If we take figures calculated in section §2.2.3 as reference values for housing sector, and try to translate them in technical feasibility terms we have to fit the following framework: total stock of 250 million dwellings (EU Buildings Database), with a percentage around 87% (see section 4.4.2) of high consumption buildings. If we match these figures with the 2 agendas we are involved in as Europe (section §2.2.3) we obtain:

- Europe 2020 Strategy: over 40 million houses have to be retrofit to zero-energy (zero-emission) by 2020.
- Paris Agreement: all the residential building stock has to be zero-carbon within 2037 for staying below 2ºC temperature rise.

For fulfilling these targets, renovation rates have to be strongly enhanced respect to the current 1%. Involvement of industry, government, tenants and stakeholders should drive the residential transformation. Large-scale renovation implies massive coordinated programs to be sustained for several years, and represent the only plausible strategy to respect housing sector commitments.

A key element for succeeding is prefabrication. If we take as reference the massive retrofit scenario described, prefabrication is in fact the only approach that allow to break down time, costs, and risks. Prefab facade modules, mechanically anchored to the existing structure, depress as much as possible the invasiveness of the intervention, allow to speed up the installation and increase the level of safety in the construction area.

Currently only the principle of cost-optimality is followed, identifying what intervention can produce a better result at a lower price. But if we seriously want to tackle climate change, new guidance principles have to be introduced, as to seek the environmental optimum considering the regeneration potential of bio-based materials.

### 3.3.4 Case studies

Among the the variety of existing case studies of partial and full prefabrication for renovation of building envelope we mention here three of them that are meaningful:

IEA_EBC_Annex_50 "Prefabricated Systems for Low Energy Renovation of Residential Buildings". This project focuses on typical apartment blocks (representing approximately 40% of the European dwelling stock) and concentrates mainly on minimizing the primary energy consumption . See figure 3.4.

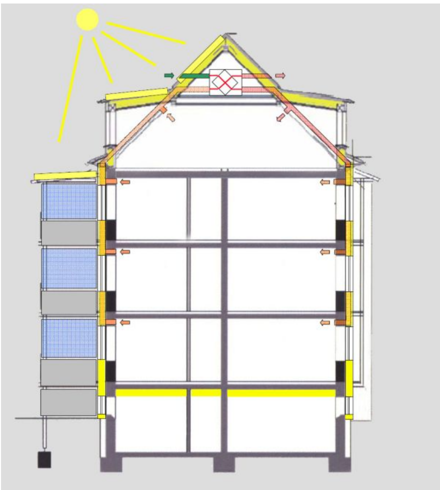


Figure 3.4: IEA EBC Annex 50. Prefabricated facade modules used to construct a new building envelope outside the existing building. (Miloni et al., 2011)

Stroomversnelling Dutch project for energy retrofit of 150 terraced single-family houses (representing approximately 40% of the European dwelling stock), within a district redevelopment plan that comprises the installation of prefab facade and roof modules in ten days per house and without the need of the inhabitants to leave their house during works . See figure 3.5.

TES_EnergyFacade "Prefabricated timber based building system for improving the energy efficiency of the building envelope". Research project

Figure 3.5: Stroomversnelling - Implementation of prefabricated facade modules and final result after renovation. (Rovers, 2014)

aimed to develop a façade renovation method (TES method) based on large scale, timber based elements for the substantial improvement of the energy efficiency of a renovated building, which would be applicable throughout Europe . See figure 3.6.

## 3.4 External insulation systems: 5 alternatives

In the light of all the considerations illustrated above, in this section we present five technologies. These solutions are designed with the aim of being representative for a potential projection of their use a at European level. External insulation systems that could answer to the requirements of performance, durability, and prefabrication is being compared: particularly we can identify 2 groups:

- On-site installation systems
- Off-site prefabrication

Thermal features and layering description is presented in 3.2.

All the solutions has been built with the same thermal resistance - $R_{gap}$=2.2 [$m^2K/W$] - in order to make them comparable; it has been chosen this number because it represents the European average weighted thermal resistance to be added to the existing envelope in order to cover the performance gap, see section 4.6.1. In the table are presented the reference thickness, but in the model the insulation layer of each system varies according to the Geocluster to which it corresponds, in order to take into account variability of climate and thus of material amount. Densities of materials has been chosen according to either suggestions from Ecoinvent® database, or technical sheets or UNI EN 10456:2008.

### 3.4.1 EPS - Expanded polystyrene external insulation

As e.t.i.c.s. with polystyrene can be considered representative of current intervention practice, EPS solution has been chosen as our baseline. Basically consists in on site installation of synthetic insulation. Specifically we have foreseen the demolition of the existing plaster and the restoration of 1 cm of cement mortar for giving regularity. Then, the EPS panel is applied and finished with a thin protection layer again cement based.

### 3.4.2 HCB - Hempcrete block external insulation

Bio-based version among on-site installed system. Again demolition and restoration of the existing plaster is needed. Then, precast predried hemp-lime concrete blocks are laid in order to wall up an insulation layer against the existing structure. A lime based plaster and render is applied as finishing. As reference hempcrete blocks we have assumed to use the commercial product Biomattone®, relying on the specification provided by the Italian company Equilibrium Bioedilizia s.r.l.

### 3.4.3 TIM - Timber frame with mineral insulation

Moving to the prefabrication category, we define the conventional reference system as a timber frame with double layer of insulation, glass wool and wood fibres. It is a mixed timber-mineral composite panel that can represent the class of prefab facade module currently available on the market.

### 3.4.4 HCF - Timber frame with injected hempcrete

Bio-based prefab solution. A timber frame is filled with a mixture of hemp shives and lime (proportion 1 to 1 by weight), and water. Assembly and drying process is carried out off-site. Anchoring and plastering are executed on the construction site. As reference hempcrete mixture we assumed to use the commercial product Natural Beton ®200, relying on the specification provided by the Italian company Equilibrium Bioedilizia srl.

### 3.4.5 STR - I-joist frame with pressed straw

Bio-based prefab solution. An engineered I-joist frame is filled with loose straw chips, sealed with a layer of light clay-straw mortar off-site. A reed mat is fixed to the external side of the panel for simplifying the plastering. After the assembly the module is transported on the construction area and, once installed is finished with a lime plaster. As reference prefab panel we assumed to adapt for retrofit purposes the commercial product Zöe®, relying on the specification provided by the Swiss company Zöe Circular Building GmbH.

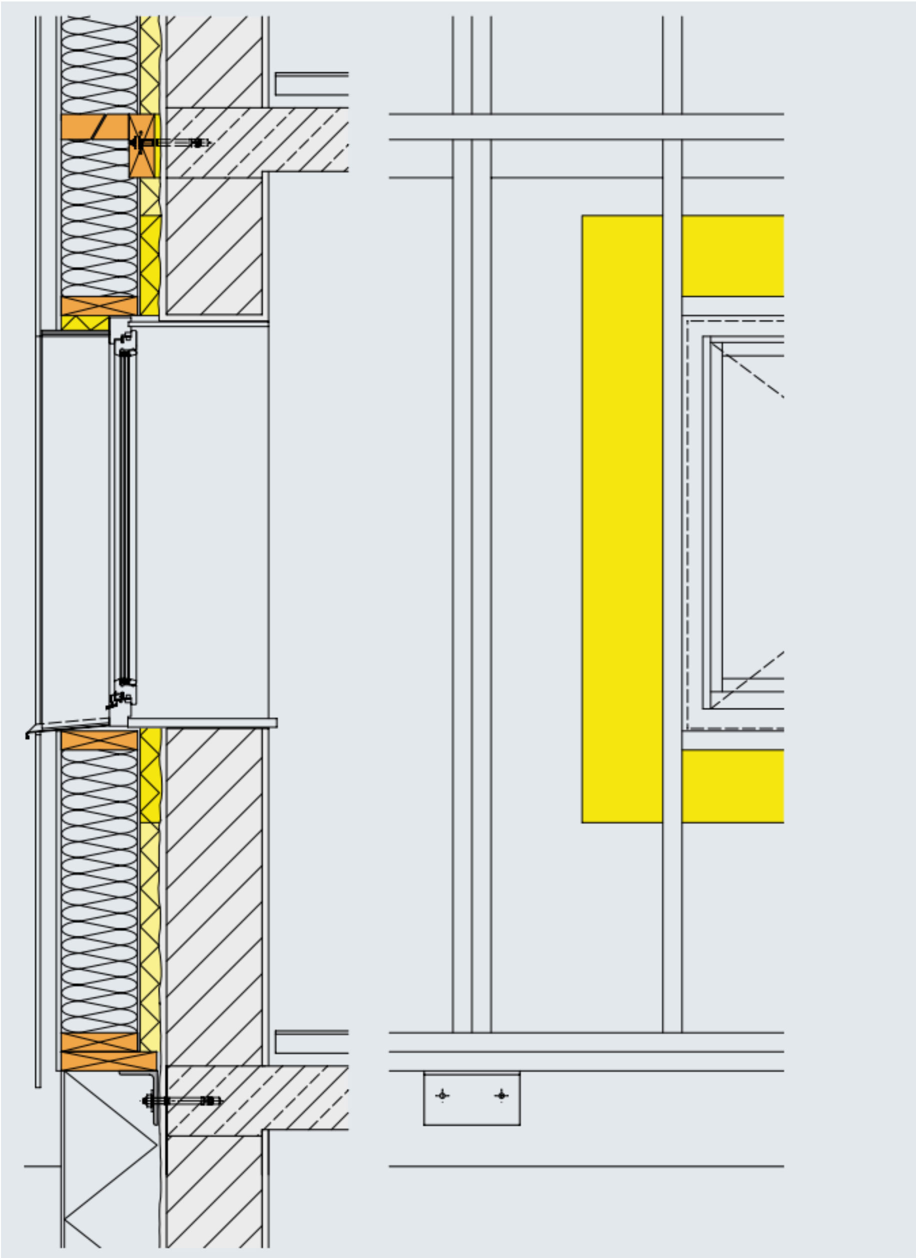


Figure 3.6: TES EnergyFacade - Window detail. Anchorage of the prefab module at the structural existing external beams; adaptation layer and mineral wool in yellow; cellulose fibre insulation; timber frame studs; airtight connection to the window. Technische Universität München. (Technische Universität München, 2010)

| | | Thick. | Dens. | Conduct. | Mass |
|---|---|---|---|---|---|
| | | $mm$ | $kgm^{-3}$ | $Wm^{-2}K^{-1}$ | $kgm^{-2}$ |
| *On-site installation* | | | | | |
| **EPS - Expanded polystyrene external insulation** | | | | | |
| 1 | Cement mortar | 10 | 1800 | 0.80 | 18 |
| 2 | EPS* | 90 | 20 | 0.04 | 2 |
| 3 | Base plaster | 2 | 1800 | 0.80 | 4 |
| *Tot* | *size* | *102* | - | - | *24* |
| **HCB - Hempcrete blocks external insulation** | | | | | |
| 1 | Lime plaster | 10 | 1800 | 0.80 | 18 |
| 2 | Hempcrete blocks* | 165 | 330 | 0.07 | 51 |
| 3 | Lime mortar* | - | 500 | 0.16 | 6 |
| 4 | Lime plaster | 20 | 1800 | 0.67 | 36 |
| *Tot* | *size* | *195* | - | - | *111* |
| *Off-site prefabrication* | | | | | |
| **TIM - Timber frame with mineral insulation** | | | | | |
| 1 | OSB | 18 | 650 | 0.13 | 12 |
| 2 | Glass wool* | 60 | 20 | 0.04 | 1 |
| 3 | Timber frame* | - | 500 | 0.12 | 3 |
| 4 | Wood fibreboard sof | 60 | 130 | 0.05 | 8 |
| 5 | Cover plaster | 6 | 1800 | 0.8 | 11 |
| *Tot* | *size* | *144* | - | - | *34* |
| **HCF - Timber frame with injected hempcrete** | | | | | |
| 1 | OSB | 18 | 650 | 0.13 | 12 |
| 2 | Hempcrete injected* | 100 | 200 | 0.05 | 18 |
| 3 | Timber frame* | - | 500 | 0.12 | 5 |
| 4 | Reed mat | 20 | 145 | 0.06 | 3 |
| 5 | Lime plaster | 20 | 1800 | 0.67 | 36 |
| *Tot* | *size* | *158* | - | - | *74* |
| **STR - I-joist frame with pressed straw** | | | | | |
| 1 | OSB | 18 | 650 | 0.13 | 12 |
| 2 | Light clay straw | 45 | 600 | 0.16 | 27 |
| 3 | Timber I-joist* | - | - | - | 11 |
| 4 | Straw chips* | 60 | 100 | 0.05 | 6 |
| 5 | Light clay straw | 45 | 600 | 0.16 | 27 |
| 6 | Reed mat | 20 | 145 | 0.06 | 3 |
| 7 | Lime plaster | 20 | 1800 | 0.67 | 36 |
| *Tot* | *size* | *208* | - | - | *122* |

Table 3.2: Alternative external insulation systems for energy retrofit of external walls. A traditional construction method - on-site installation, with 2 solutions: EPS (synthetic), HCB (bio-based); and an advanced construction method, prefab facade modules, with 3 solutions: TIM (mixed mineral + wood), HCF (bio-based), STR (bio-based) have been considered. Identical thermal performance provided $R_{gap}$=2.2 [$m^2K/W$]. *indicates that the thickness is variable cluster by cluster.

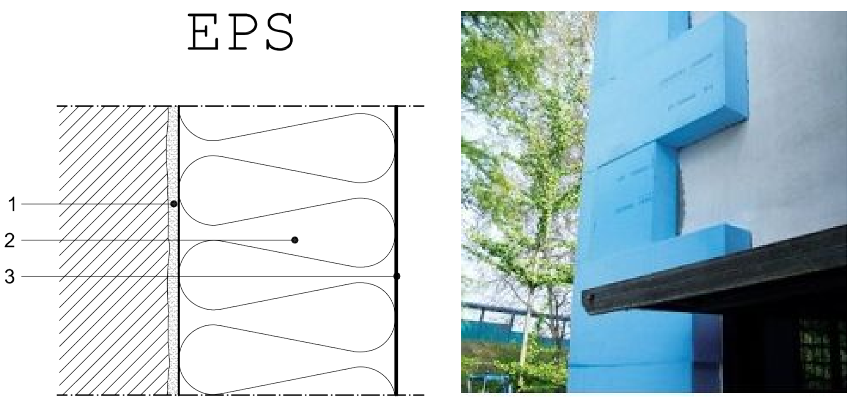



Figure 3.7: EPS - External thermal insulation composite system

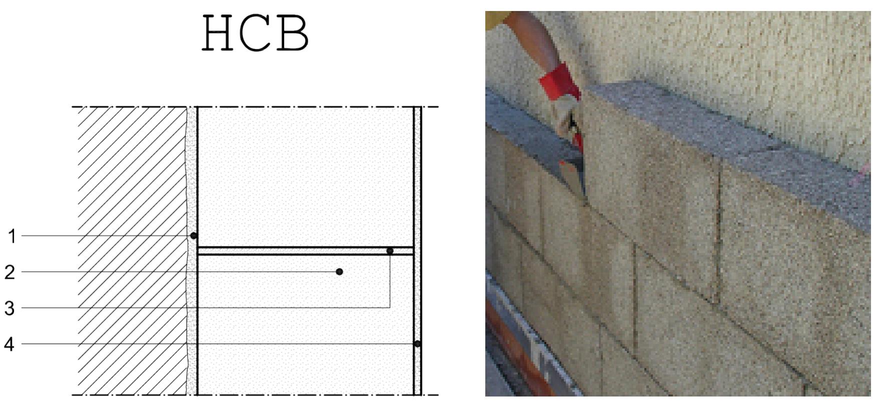



Figure 3.8: HCB - Hempcrete block external insulation

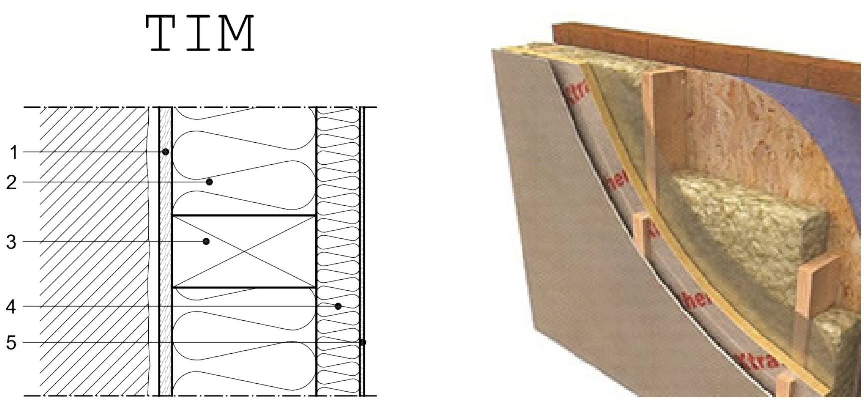



Figure 3.9: HCB - Hempcrete block external insulation

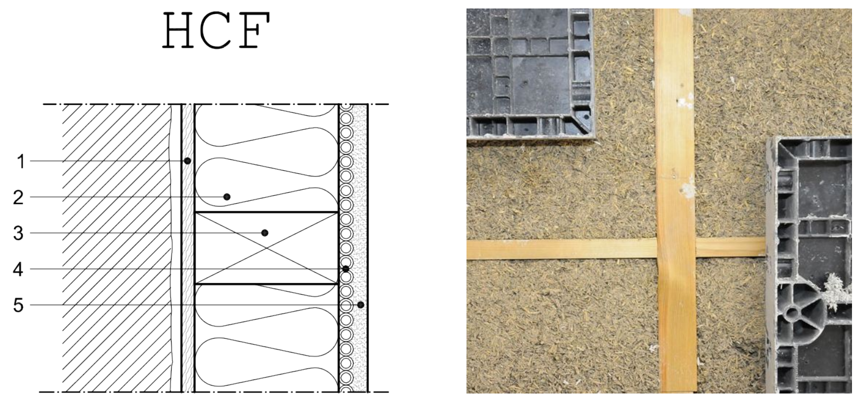



Figure 3.10: HCB - Hempcrete block external insulation

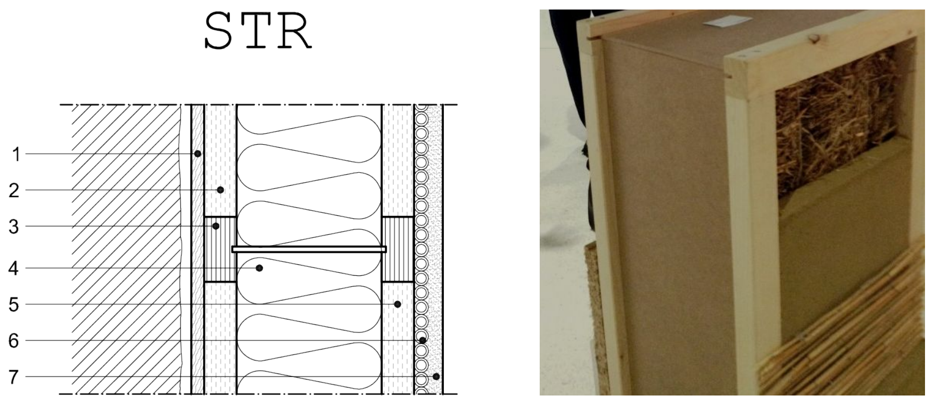



Figure 3.11: HCB - Hempcrete block external insulation

# Chapter 4

# European building stock

## 4.1 Introduction

For gaining awareness about benefits of renovation using bio-based materials at European level, the description of the residential stock is a necessary step. In addition it allows to fully exploit the dynamic LCA potential. Within this chapter a characterization of the EU28 housing sector is presented.

A variety of sources were consulted including databases and European project such as: Tabula, Entranze, Enerdata and Odyssee.

We intend to figure out which role the residential built environment can play for reduction of the GHG emissions within a European context, the extent of the effort to be done, what are the potential advantages or drawbacks and what are the parameters we have to adjust for renovating staying within the budget. If we choose energy efficiency as major player we necessarily have to have a community perspective to evaluate its benefits.

Beside this unitary approach, it is not possible to forget the heterogeneity of our community. Flattening all the diversities characterizing the European built environment would be a too strong approximation; and referring only to global average indicators, would mislead in terms of results and would give a unreliable picture of the future scenarios.

On the other hand, dealing with 28 countries separately would turn to be cumbersome. Missing data or different indicators among the State Members would impose constraints the will end up to hindering the main scope of the analysis of this chapter: The collection and elaboration of data about consistency and features for building up a model of the European residential sector, with the final aim of simulating a large-scale retrofit.

Therefore we choose an intermediate approach. Grouping countries according to specific criteria, allow us to handle a relatively low number of actors (seven) but still keeping approximations sufficiently small not to distort the examination's meaning. In this way it is possible to keep track of the different architectural heritages, that in fact reflect the deep diversities among European cultures, codes, habits and peculiarities. But a wide enough view for gaining awareness about the big picture is kept.

The investigation carried out is focusing mainly on dimension, renovation rates, and thermal performance of the EU28 residential existing building stock.

## 4.2 Boundary of the analysis

Outlining the European building stock is a wide topic that involve huge number of variables. This is the reason why, in function of the aim of analysis, we set some constraints for the definition of the system's borders.

### 4.2.1 EU-28

The geographical extent of the analysis correspond to the political one at the current time: 28 member states of the European Union (EU28).

### 4.2.2 Residential stock

With respect to building categories, only residential stock is included. This choice comes primarily from the lack of organized data on non-residential stock and secondly from the fact that however dwellings represent the largest share of built environment both in terms of squared meters (figure 4.1) and consumption.

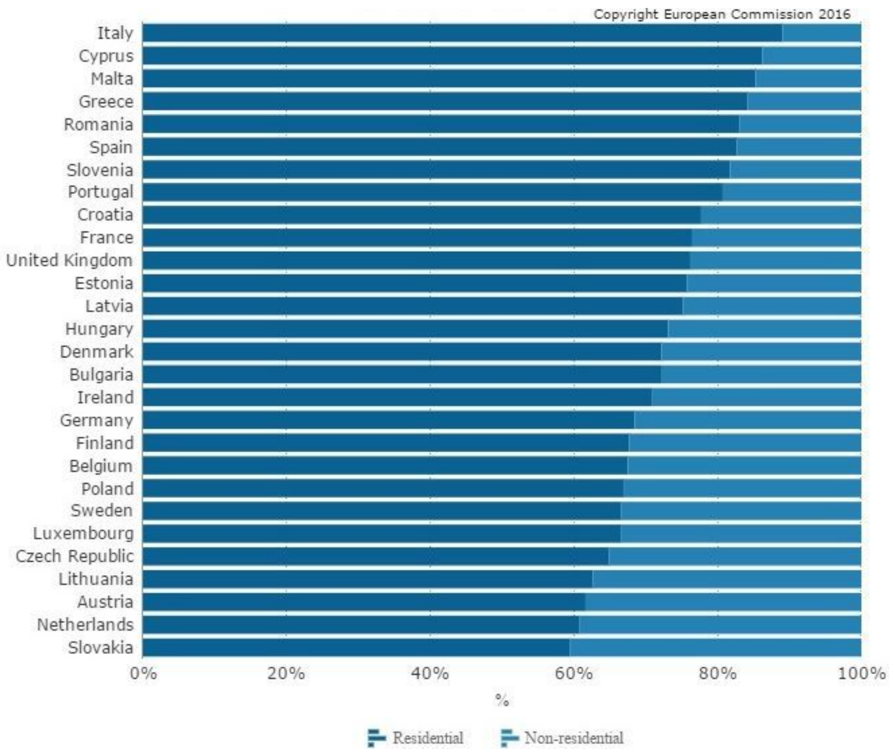



Figure 4.1: Breakdown of building floor area. (European Commision, 2016)

### 4.2.3 Only external walls

As regard renovation, the purpose of the dissertation is focusing on external walls. First because opaque vertical building envelope is playing a big role in energy losses; then because retrofitting external walls is a direct way to involve in the simulation a massive use of bio-based insulation materials, to be compared with traditional ones. It is to be clear that the renovation we refer to all over the work is hence a partial operation: windows, roof, ventilation are excluded from the analysis; but still it has to be considered a deep renovation as will be better explained in section §4.5.

### 4.2.4 Construction age

The age of the building is another factor that has to be considered if we deal with renovation. Buildings in Europe are on average old, almost the totality of the state members has got a share of dwellings built before 1980 greater than 50%, while some populated countries such as Germany, Italy or United Kingdom exceed 70% of the total residential stock. See figure 4.2.

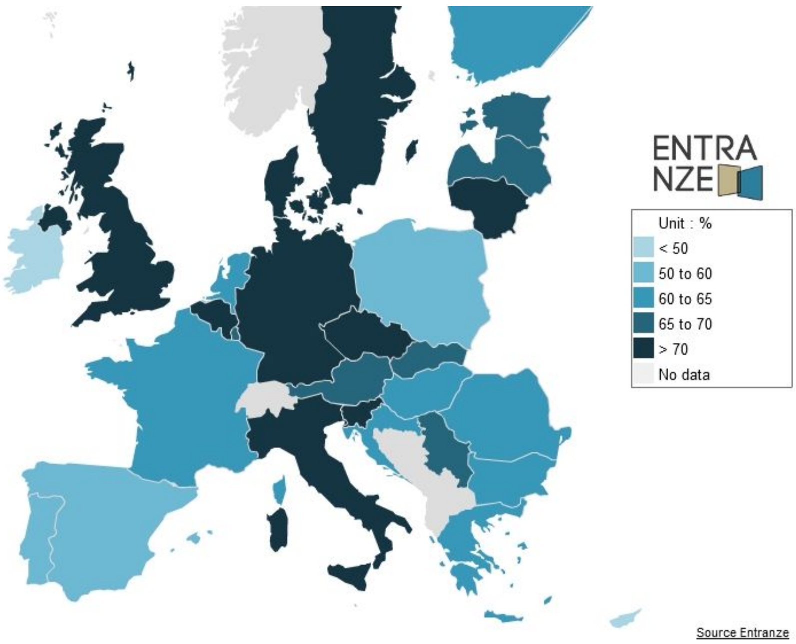



Figure 4.2: Share of dwellings built before 1980. (Entranze, 2016)

## 4.3 Geoclusters

Geocluster are virtual trans-national areas where strong similarities are found in terms of climate, culture and behaviour, construction typologies, economy, energy price and policies and gross domestic product, to name a few.

For avoiding to deal with 28 countries separately, European nations have been clustered into 7 areas according to the above mentioned definitions:

1. Southern Dry (ES, PT)
2. Mediterranean (IT, EL, CY, MT)
3. Southern continental (FR, BG, HR, SI)

4. Oceanic (UK, IE, BE)

5. Continental (DE, NL, AT, HU, CZ, LU)

6. Northern continental (PL, DK, RO, SK, LT)

7. Nordic (SE, FI, LV, EE)

Specifically, in the present work we follow (Birchall et al., 2014) who suggests a grouping criterion based mainly on climatic conditions. A representation of the climatic regions adopted is presented in figure 4.3. In this way we are doing nothing but locating similarities across the EU countries by using climatic parameters, thus we fit into the nomenclature suggested by (Sesana et al., 2015) who call such aggregation Geocluster.

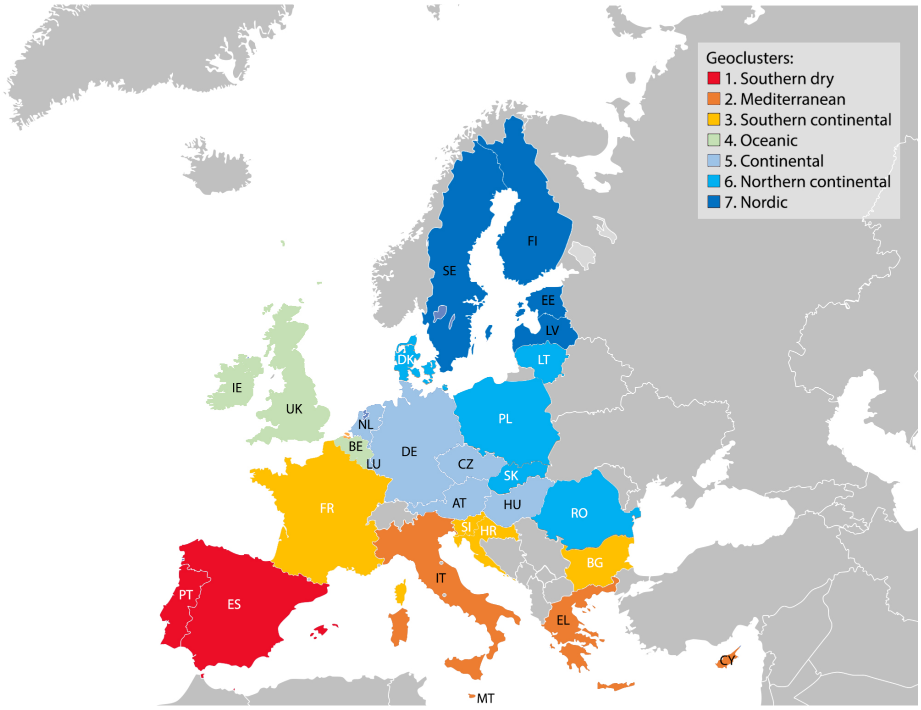



Figure 4.3: Mapping of the Geoclusters. EU28 members grouped in 7 macro-area. Criteria of clusterization based on similarities in climatic conditions. (Birchall et al., 2014)

For simplicity, one nation is never split between Geoclusters. It is an approximation inasmuch across some state, climatic differences can also be significant. Another caveat is that clusters are not meant for being comparable with the others in terms of floor area, but to be internally coherent in order to validate the hypothesis to renovate in the same way (e.g. same thickness of insulation), within one Geocluster.

## 4.4 Residential building stock characteristics

### 4.4.1 Consistency of the household sector

The dimension of the residential building stock in Europe accounts for 22.6 billions of squared meters of floor area divided in 250 millions of dwellings (a physical structure, a house, an apartment, a group of rooms, intended for occupancy by the member of a household) (EU Buildings Database) distributed among the Geoclusters as shown in table 4.2.

| | **<'45** | **45-'69** | **70-'79** | **80-'89** | **90-'99** | **>'99** | **TOT** |
|---|---|---|---|---|---|---|---|
| | $[Mm^2]$ | $[Mm^2]$ | $[Mm^2]$ | $[Mm^2]$ | $[Mm^2]$ | $[Mm^2]$ | $[Mm^2]$ |
| #1_(ES) | 421 | 594 | 517 | 423 | 450 | 689 | 3095 |
| #2_(IT) | 640 | 1086 | 660 | 495 | 321 | 461 | 3664 |
| #3_(FR) | 939 | 728 | 583 | 461 | 348 | 622 | 3681 |
| #4_(UK) | 1183 | 829 | 432 | 304 | 231 | 387 | 3366 |
| #5_(DE) | 1445 | 1815 | 895 | 709 | 535 | 576 | 5974 |
| #6_(PL) | 397 | 556 | 345 | 298 | 179 | 226 | 2001 |
| #7_(SE) | 182 | 253 | 157 | 120 | 69 | 90 | 871 |
| **EU-28** | 5140 | 5932 | 3620 | 2841 | 2116 | 3004 | 22652 |

Table 4.2: Share of dwellings built in different periods. (European Commision, 2016)

### 4.4.2 Age distribution of building stock

As construction techniques for installing insulation are strictly dependent on the condition and typology of the existing support, we have to deal with the age distribution across the building stock. We define our target share for the renovation as the entire building stock with the exclusion of the dwellings built after 1999.

This hypothesis has been made according to multiple factors:

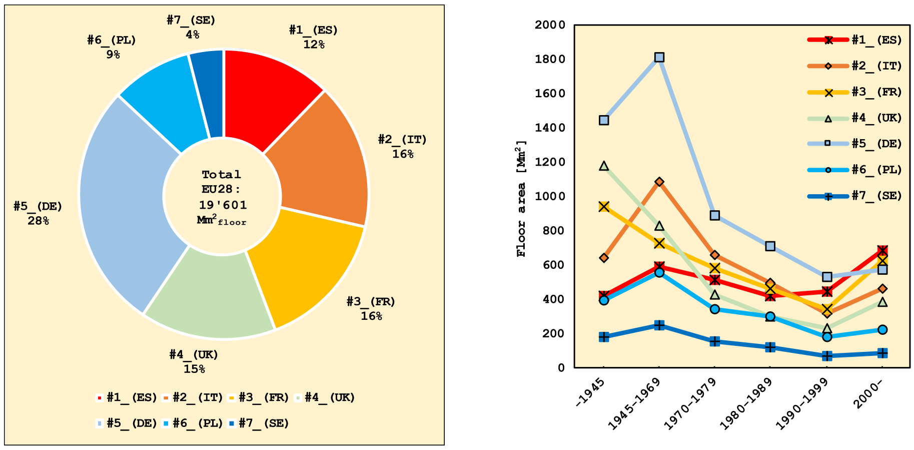
>'99 External envelope of newest building is supposed to be good enough not to undergo a major renovation: weighted average U-value of walls for buildings built after 1999 is estimated to be 0.55 W/(m^2 K), data elaborated from (Entranze, 2016). Therefore we decided to exclude this share from the analysis.

'45-'99 Buildings in this category are considered the priority for renovation because they represent the largest share of buildings and the are the main cause of the huge energy waste within our built environment. Certainly included in the analysis.

<'45 Within this band we can locate at least three typologies of building: 1) historic buildings, in this case there will be a number of additional constraints (e.g. landscape conservation) that would impose to rise the complexity during renovation and so the temptation should be

to exclude them; 2) ancient buildings, for this typology it is not likely to think that ordinary retrofit techniques (like the ones we are presenting, see section §3.4 could be applied, but it is reasonable to think that similar alternative solutions could be adopted); 3) abandoned buildings, the rising demand of houses in the next decades will probably impose their make over. Since it was not possible to split these category, we decided to include in the analysis the whole share.

Hence, it can be summarized that the share of dwellings we suppose will be renovated in the future represents around the 87% of the total residential building stock, figure 4.4.




(a) (b)

Figure 4.4: (a) Floor area of EU28 residencial buildings by geocluster. (b) Share of dwellings built in different periods. Weighted average in EU28. Buildings later than 1999 are excluded from the analysis.

Note that we are excluding by the analysis new constructions along the period 2018-2218, and demolitions that have a very low, between 0.02% and 0.23% (Meijer et al., 2009).

In a dynamic perspective, considering also the buildings that will be built in the next years (hopefully low impact good performances) and the ones that will be demolished, we have to see the stock under our analysis (around 19.6 billion of squared meters) as the only real group of buildings that we have to focus our attention on before completing the transition, because they are and will be the real responsible of too high carbon emissions. The figure we aforementioned, 87%, therefore is going to converge to zero over time, but is interesting to understand at what speed it will happen.

### 4.4.3 Floor-Wall correlation

Since our concern is the insulation of the external walls, we need to build up a correlation between the floor area, and the external wall area.

Modeling the building stock is an operation that can be affected by great uncertainties, and trying to model the configuration of the European buildings with reference geometries, have resulted to incorporate too high approximations compared to the effort needed to have such an estimation. Therefore we rely on statistical data collected by the European project TABULA, (Loga et al., 2010). In their report measures of floor area and external walls are provided, by country, and for each building typology.

Reducing the typologies of buildings in 2 main categories (1) single family and (2) multi-family, and extending the information where missing, we have come out with correlation coefficients that link the floor area to the wall area. Such coefficients are provided for every cluster and for every building category, and are presented in table 4.4.

| | **Single family** | **Multi family** | **SF coeff.** | **MF coeff.** | **Correlation factor** |
|---|---|---|---|---|---|
| | [%] | [%] | [-] | [-] | [-] |
| #1_(ES) | 42% | 58% | 1.34 | 1.00 | 1.15 |
| #2_(IT) | 31% | 69% | 1.34 | 0.98 | 1.09 |
| #3_(FR) | 67% | 33% | 1.38 | 0.85 | 1.20 |
| #4_(UK) | 85% | 15% | 0.76 | 0.60 | 0.74 |
| #5_(DE) | 66% | 34% | 1.03 | 0.64 | 0.90 |
| #6_(PL) | 61% | 39% | 1.00 | 0.49 | 0.80 |
| #7_(SE) | 60% | 40% | 1.13 | 0.62 | 0.93 |
| **EU-28** | 58% | 42% | 1.17 | 0.78 | 1.00 |

Table 4.4: Floor-Wall correlation coefficients. Share (by floor area) of single family and multi family buildings across the Geoclusters (Entranze, 2016); correlation coefficient per Geocluster, elaboration data from TABULA, (Loga et al., 2010).

## 4.5 Building renovation rate

### 4.5.1 Equivalent major renovation

Article 2 of EPBD (EU, 2010) gives the following definition:

> 10. 'major renovation' means the renovation of a building where: (a) the total cost of the renovation relating to the building envelope or the technical building systems is higher than 25 % of the value of the building, excluding the value of the land upon which the building is situated; or (b) more than 25 % of the surface of the building envelope undergoes renovation; Member States may choose to apply option (a) or (b).

As we can see a certain freedom is left to Member States for the interpretation of "major renovation", both in terms of definition and monitoring. Therefore a way to overcome the different interpretations across the country has to be adopted.

In this work we refer to indicator of "major renovation equivalent", as defined by Zebra2020 (2014):

> The ZEBRA consortium assumes that with major renovations, a building's final energy demand for heating can be reduced by 50 to 80% (range depending on the country defined by national experts according to the current efficiency of the building stock).

In this way have a uniform indicator to ease comparisons. A plot of the equivalent major renovation rate by Geocluster can be seen in figure 4.5.

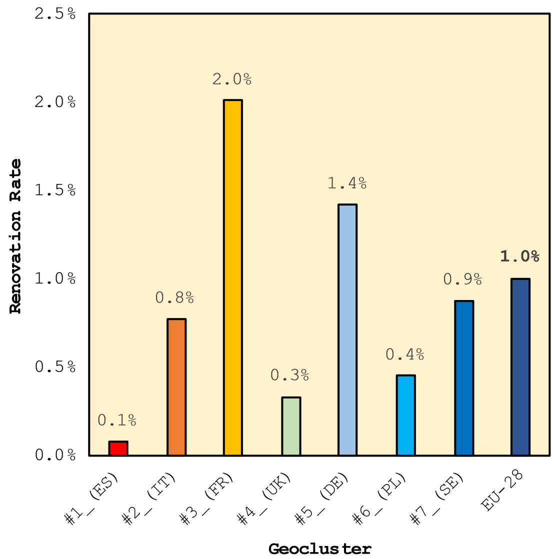



Figure 4.5: Renovation rate by Geocluster. In order to consider a normalized type of intervention, equivalent major renovation has been considered. Zebra2020 (2014)

### 4.5.2 Current rates

Currently the renovation rate in Europe is nearing 1.0%, which implies that after the first year, 99% of stock still consumes considerable amount fossil fuel for operational energy, and after second year 98%, and so on. If we look at this number within the framework of the transition, it is an exceedingly low value.

Moreover, 1.0% is a community average, but actually among the cluster we detect values significantly different, that can range from 0.1% to 2.%. Only looking at this non-uniformity it's easy to figure out the importance of pushing toward a common policy.

Renovation rate it's a fundamental parameter because the share of energy-intensive buildings, if far too high (87%) and every year it cut a significant amount of budget that we could invest instead of deplete paying the bill of energy. So, qualitatively, it would be better to have absurdly high renovation rates at the beginning (start of our analysis 1st January 2018), when it matters, and then decrease it when the share of consumer buildings has been drastically reduced. Obviously this scenario is only theoretical because actually renovation rate is a parameter that suffer of big inertia, because the construction sector by definition is not flexible and very low to incorporate changing.

### 4.5.3 Time-span for completing the renovation

It is important to keep separate renovation rates, at least by Geocluster, because in this way it is possible to keep track of different speeds. In a certain moment each cluster will experience the "saturation"; the ones with high renovation rates, while others will keep going forward with their low rates even beyond thousand years; namely within the 200 years of our projection only some of the cluster will have used up all the building stock to under analysis, while others will had got still a considerable share of energy consumer buildings. A numeric quantification is illustrated intable 4.6.

| | **External walls** | **Walls yearly renovated** | **Renovation total time** |
|---|---|---|---|
| | $[Mm^2]$ | $[Mm^2yr^{-1}]$ | $[yr]$ |
| #1_(ES) | 2752 | 2 | 1307 |
| #2_(IT) | 3519 | 27 | 130 |
| #3_(FR) | 3679 | 74 | 50 |
| #4_(UK) | 2199 | 7 | 301 |
| #5_(DE) | 4926 | 70 | 73 |
| #6_(PL) | 1410 | 6 | 490 |
| #7_(SE) | 722 | 6 | 114 |
| **EU-28** | 19208 | 193 | – |

Table 4.6: Renovation total time. A projection of the time needed to completely saturate each cluster, namely cover all the share of buildings to be retrofitted within that cluster, considering the actual rate of renovation.

## 4.6 Building envelope performance

### 4.6.1 Performance gap

An important driver is the performance gap between the current thermal insulation and the target insulation given by the national building codes.

Specifically we can retrieve from literature current values of thermal transmittance of the buildings walls considered, (Entranze, 2016). Beside it is possible to couple these values with the ones required by the codes, first nation by nation, then aggregated by cluster, (Zebra2020, 2014). Converting into thermal resistance and subtracting we obtain the thermal resistance to be added for being compliant to the current building standards.

The average weighted additional thermal resistance for EU28, represents around 2/3 of the resistance after renovation and will lead to have an average $U_{gap}$=0.42 [W/m$^2$/K] for the retrofitted wall. Single values cluster by cluster can be seen in figure 4.6.

### 4.6.2 Performance target

Coping with the performance gap could already appear an achievement, but if we compare the performance after the (compliant) renovation with standard value of nZEB buildings in Europe, $U_{nZEB}$=0.17 [W/m$^2$/K] (Zebra2020, 2014) it is evident that we are still far. And if we also consider that the transition we are trying to address has as final target a carbon neutral built environment (thus net zero energy necessarily), it is reasonable suppose that insulation levels should be pushed more.

Therefore we have assumed to set the performance target at the double of what is needed to cover the performance gap, in order to be not too far from zero-energy envelope performances. Namely doubling the additional thermal resistance we get to a final $U_{tar}$=0.19 [W/m$^2$/K] weighted average. To be recognized also the presence of big uncertainties at this level: unknown possible evolution of building codes in the future, unavailability of a range of reliable energetic simulations that could directly correlate insulation thickness with potential savings, partiality of the renovation intervention (as explained in section 4.2.3).

### 4.6.3 Model adjustment

For taking into account the requirements difference among the cluster, (climatic variability is considered within the performance target that varies), an adjustment in the model is needed.

The external insulation kit is divided into variable (insulation itself) and constant part (finishing, plastering etc.). Then, according to the need, the variable part is increased/decreased while the constant part is fixed.

In this way each of the 5 technologies proposed (see section §3.4) can fit the 7 different climatic regions, allowing to an accurate assessment of the impacts coming from the use of the materials employed in the renovation across the different areas. Without this device, the impacts coming from the constant component would have adjusted as well as insulation part, misleading the analysis both in terms of environmental impact (plaster burden is not negligible) and performance.

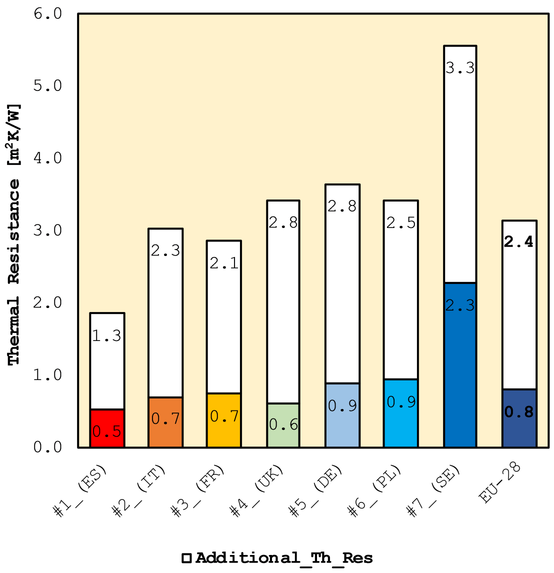



Figure 4.6: Building envelope performance. Actual and additional thermal resistance for being compliant to the national building code, weighted by Geocluster.

# Chapter 5

# Model and Dynamic LCA application

Investigation on environmental burden induced by European housing sector energy retrofit, in terms of global warming is the primary goal of this study.

In this chapter we present first the model outline, then the emission and sequestration life cycle inventory is discussed, addressing both: release into the atmosphere of greenhouse gases due to construction materials and possibly uptake processes of carbon dioxide. Finally the model of dynamic LCA is contextualized and detailed. The time-span considered is 200 years.

## 5.1 Model

The model flow chart is represented in figure 5.1.

The two pillars of the model are the EU28 residential building stock (EU28) on one side, widely discussed in chapter 4, that provide time and space dynamic amplifiers coefficients; and on the other side, the emissions and sequestrations Life Cycle Inventory (LCI) of the different technological solutions, namely the atmospheric loads profiles that provide the 1-sqaured-meter impacts to be scaled up. Both these data set are combined into time and space dependent Aggregation Matrix (AM) that accounts also for the cumulative effects of the overlapping renovations occurring shifted year after year, for progressively obtaining a dynamic Inventory Result (IR), that eventually feed a Dynamic LCA code (DLCA) with the final goal of achieving an outlook on large-scale renovation alternatives effects on climate change.

### 5.1.1 LCA approach

With reference to the LCI portion of the model, we have followed a cradle-to-grave approach. The structure of LCA we have adopted is in compliance with EN ISO 14040:2006 and EN 15804:2012 standards. Life cycle stages and modules for the building assessment are reported in figure 5.2. Since the objective is to focus only on the carbon footprint of the European "make over" (operational energy not considered, see section §1.2), within this study the following modules are included: A1 (raw material supply), (A2 Transport) A3 (manufacturing),

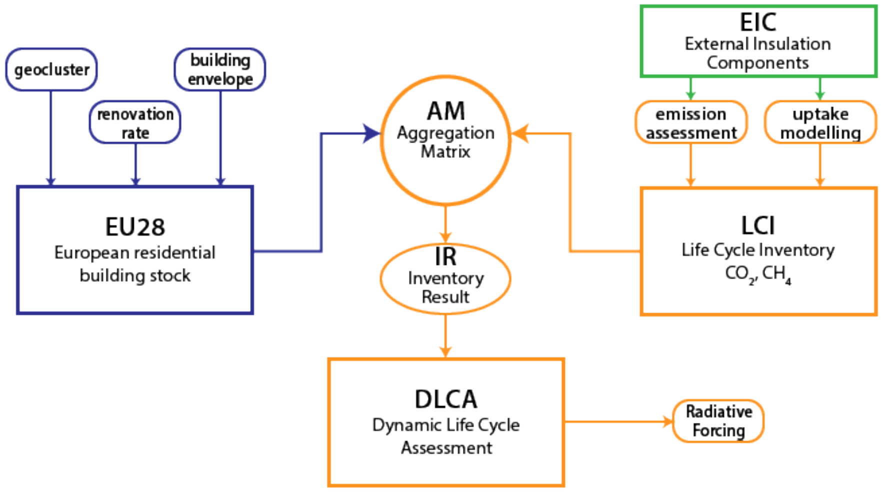



Figure 5.1: Model flow chart. The left branch, representing the European residential building stock (EU28), and the right branch, representing the emission and sequestration inventory (LCI), are converging into a time and space depending aggregation matrix that feed the dynamic LCA model for obtaining the final results in terms of radiative forcing.

A4 (transport), A5 (construction), B1 (use), B4 (replacement), C1 (deconstruction demolition), C2 (transport), C3 (waste processing), C4 (disposal). Other modules are excluded.

As regard to the last part of the model, the implementation of the DLCA is carried out as presented by the developer in Levasseur et al. (2010) and Levasseur et al. (2012).

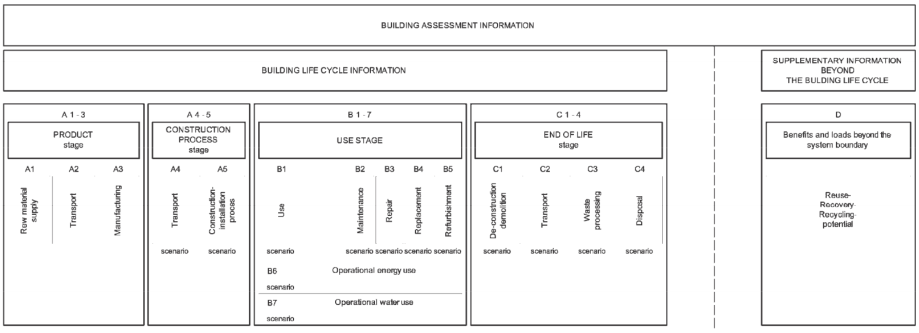



Figure 5.2: Life cycle stages and modules for the building assessment. From EN 15804:2012

## 5.1.2 Functional unit

The functional unit is 1 [m$^2$] of products system for insulation. Specifically it presents the following features:

- 1 [m$^2$] of external insulation by a variable thickness according to the need and to the layering, see section §3.4.

- R = 2.2 [$m^2K/W$]
- 60 years life span

Note that this unitary FU applies until LCI is provided; then, after the aggregation with the EU28 data, it becomes dynamic. In effect in DLCA impact assessment can be performed not necessarily on a fixed unit, but also on quantity that is changing year by year. In our case the dynamic functional unit is the time and space dependant surface of walls under renovation. So it represent a portion of the building stock (correspondent to to the renovation rate share), that is internally differentiated according to the climatic zone.

### 5.1.3 Impact category and assessment

Within the present study, one impact category is treated, climate change, and two greenhouse gases are considered, $CO_2$ and $CH_4$.

Within the framework of the DLCA, the impact assessment (LCIA) methodology utilized rely on the research of Levasseur et al. (2010). The dynamic indicator Global Warming Impact (GWI) is used for characterize the the instantaneous atmospheric load in terms of radiative forcing [$W/m^2$]. Note that until DLCA is used, we are only handling, "raw" GHGs quantities (LCI); once the DLCA is performed, the above mentioned methodology is applied, and a life cycle impact assessment is obtained in terms of radiative forcing.

### 5.1.4 Static LCI

In table 5.2 and table 5.4 a preliminary synthesis of the LCI in aggregated form is illustrated: tables show emissions and sequestrations of $CO_2$and $CH_4$in a static aggregated form. Here the dynamics is not present because all the inventory's contributions are summed up and grouped according to the life cycle module.

| | $[kgCO2]$ | **STR** | **HCF** | **TIM** | **EPS** | **HCB** |
|---|---|---|---|---|---|---|
| **A** | prod. | 37.1 | 28.6 | 9.7 | 10.2 | 36.6 |
| **B** | bio. | −34.0 | −24.0 | −12.4 | 0.0 | −27.9 |
| | carb. | −9.2 | −13.7 | −0.1 | −0.8 | −27.7 |
| | prod. | 9.5 | 9.5 | 4.4 | 6.1 | 8.4 |
| | ds1 | 2.7 | 2.7 | 1.6 | 0.2 | 0.9 |
| | ds2 | 1.9 | 1.9 | 0.2 | 6.3 | 0.9 |
| | ds3 | 1.9 | 1.9 | −0.8 | 6.3 | 0.9 |
| **C** | ds1 | 18.0 | 10.2 | 6.8 | 0.7 | 2.6 |
| | ds2 | 40.5 | 26.9 | −0.1 | 6.6 | 2.6 |
| | ds3 | −3.6 | −9.6 | −5.0 | 6.6 | −19.6 |
| **D** | ds2 | −7.6 | −3.9 | −1.1 | −0.2 | 0.0 |
| | ds3 | −24.3 | −21.5 | −14.0 | −0.2 | −21.8 |

Table 5.2: LCI for $CO_2$, aggregated form. Modules: production and construction (A), use (B), end of life (C), benefits beyond the system boundaries (D). Phases: production and construction (prod.), biomass regrowth (bio.), carbonation (carb.), disposal scenario (ds#).

| | $[10^{-2}kgCH4]$ | **STR** | **HCF** | **TIM** | **EPS** | **HCB** |
|---|---|---|---|---|---|---|
| **A** | prod. | 5.2 | 3.1 | 4.1 | 6.8 | 1.3 |
| **B** | bio. | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | carb. | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | prod. | 0.4 | 0.4 | 1.9 | 6.4 | 0.0 |
| | ds1 | 20.6 | 20.6 | 1.4 | 0.7 | 0.0 |
| | ds2 | −2.5 | −2.5 | 0.0 | 0.0 | 0.0 |
| | ds3 | −2.5 | −2.5 | −0.4 | 0.0 | 0.0 |
| **C** | ds1 | 76.1 | 28.4 | 6.7 | 0.7 | 0.2 |
| | ds2 | −8.6 | −2.9 | −0.2 | 0.1 | 0.2 |
| | ds3 | −11.2 | −4.9 | −2.1 | 0.1 | −0.7 |
| **D** | ds2 | −11.8 | −5.8 | −0.4 | −0.1 | 0.0 |
| | ds3 | −17.1 | −9.8 | −5.3 | −0.1 | −0.9 |

Table 5.4: LCI for $CH_4$, aggregated form. Modules: production and construction (A), use (B), end of life (C), benefits beyond the system boundaries (D). Phases: production and construction (prod.), biomass regrowth (bio.), carbonation (carb.), disposal scenario (ds#).

## 5.2 Modelling greenhouse gases emissions (LCI)

The emission life cycle inventories (half of the LCI) are 200 element vectors that collect the values of emissions of greenhouse gases due to production installation and disposal of our five alternative construction technologies for wall insulation. Values are obtained through the use of the software SimaPro® with Ecoinvent v3.3 database if possible. If no data are available new processes have been defined referring to specific building product's related study, in particular: for modelling the straw-based prefab module (STR) we rely on the work of Krause et al. (2017); for modelling the hempcrete-based prefab module (HCF) we referred to Arrigoni et al. (2017) as well as for modelling the hempcrete block (HCB).

In a dynamic perspective, the outputs from the software, namely rough value of atmospheric loads [$kg_{GHG}$], corresponding to the various phases of the life cycle (production, replacement, end of life), represent instantaneous impulses. The construction of the 200-years emission profiles consists of collecting the impulses and locating them in the temporary right position according to the assumptions made on the different building product life cycle.

### 5.2.1 Stage A - Product and construction process

All carbon dioxide and methane emissions occurring until the insulation system is installed on the building facade are here accounted, purposely, modules A1, A2, A3, A4, A5. These emission are assumed to occur all at time 0, with reference to the unitary emission profile. A quantification of the production inventory is presented here in figure 5.3 and in table 5.2 and table 5.4. For further information about the processes see Annex A.

### 5.2.2 Stage B - Use

Represents only the module B4 (replacement), as the module B1 (use) is null in terms of emissions. Replacement module can be read as a composite stage inasmuch it comprises a phase of production of the material to replace and a phase of disposal of the replaced elements. Replacements of building products occur at different time that have been defined according to Mayer (2005). However the simplifying hypothesis has been consider either 30, 40 or 60 years of service life, see table 5.6. Both production and end of life phases of the replacement has been modelled through SimaPro on the basis of what explained in section 5.2.1 and section 5.2.3. Further information can be found in table 5.2 and table 5.4 and in the Annexes.

### 5.2.3 Stage C - End of life

Modules C1-C4 are here considered. In SimaPro processes for demolition (C1), transport (C2) and waster processes (C3) have been defined. On top of that, since no reliable information about the end of life are available, 3 different end of life (EoL) scenarios are hypothesized: landfill, energy recovery, recycling. Differently from other modules, in C4 this multiple pathways separation is needed because results are sensitive to the method of waste disposal as shown by Levasseur et al. (2013).

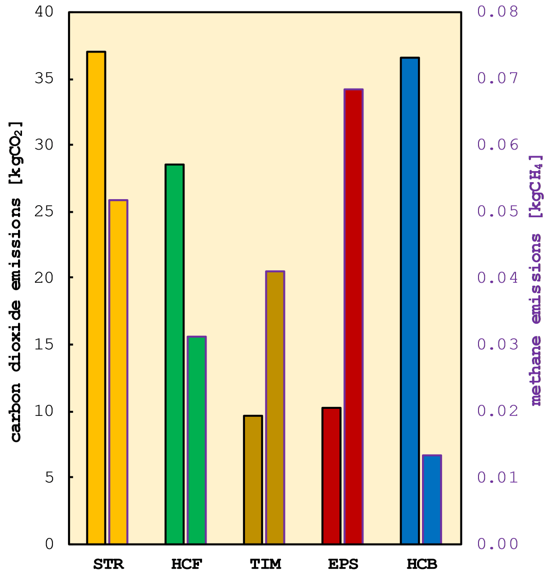



Figure 5.3: GHG emissions - Stage A. Emission of $CO_2$ and $CH_4$ due to production and construction phases (stage A1-A5). In the LCI these emission are supposed to occur at time 0. Note that no equivalence have yet applied, raw numbers have been retrieved by the SimaPro simulation.

In order to properly define the waste scenarios, two steps are necessary:

- products has to be grouped into five different material categories: among non bio-based we find *no potential*, *combustible*, *recyclable*; among bio-based instead we find *fast decomposing*, *wooden*. Waste material categories are specified in table 5.6

- according to the material category the each product will undergo different waste treatment, and will be sent to different facilities in particular we have considered: *inert landfill*, *municipal incineration facility*, *sanitary landfill*, *composting facility*, *recycling facility*.

Matching both the material categories with the correspondent waste treatment facilities it is possible to define the 3 disposal scenarios (ds):

**Landfill (ds1)** All material categories are put to landfill, *inert landfill* for non-bio-based, *sanitary landfill* for bio-based.

**Energy recovery (ds2a ds2b)** Feedstock energy is recovered from materials, when possible. *Combustible* and *wooden* materials are sent to *municipal incineration facility*, *fast decomposing* ones to the *composting facility*, remaining ones are put to landfill. This scenario splits in two for considering whether benefits beyond the system will be considered (a) or not (b).

**Recycling (ds3a ds3b)** Materials are recycled, when possible. Mean that wooden and recyclable materials are sent to recycling facility, the others are treated in the same way of energy recovery scenario. Also this scenario splits in two for considering whether benefits beyond the system will be considered (a) or not (b).

Each waste scenario is considered independent and the 3 paths are illustrated in figure 5.4. For further information see Annex C.

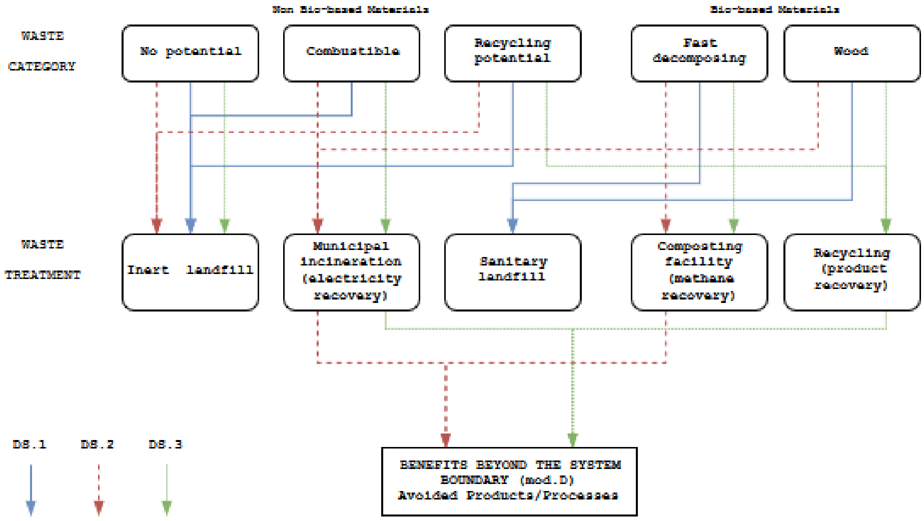



Figure 5.4: Disposal scenarios flowchart - 3 pathways of materials according to their related waste material category.

### 5.2.4 Additional assumptions

- All transport processes are lorry transports.
- Transport to the construction area (A4 module), is supposed always to cover 50 km as average distance.
- Prefabrication process is assumed not to induce additional transport, but only additional energy and machine use.
- Energy recovery from municipal incineration, occur in the form of electricity (not heat).
- In straw and reed composting process we assume that 50% of the bound carbon is emitted into the air while 50% remains bound as humus.
- In straw and reed sanitary landfill process we assume that 25% of the bound carbon is emitted into the as $CO_2$, 25% as $CH_4$, while 50% remains bound as humus.
- Hempcrete products are considered inert materials because the biogenic part is mineralized by the binder, see section 3.3.2.
- The recycling of wood products always happens as down-cycling to wood chips.

## 5.3 Modelling carbon sequestrations (LCI)

The sequestration life cycle inventory (the other half of the LCI) is obtained by modelling the $CO_2$ uptake phenomena occurring after the implementation of the building element. The chemical processes we have considered are basically 2:

**Biomass regrowth** occurring through the photosynthesis after the production of bio-based building products.

**Carbonation** occurring during the life time of lime-containing building products.

Both phenomena are considered within the Stage B, module B1 (Use).

### 5.3.1 Biomass regrowth

The use of bio-based building products implies temporary carbon storage in the biomass, a great benefit usually underestimated with the net-zero emissions assumption of the traditional LCA. In this work biogenic carbon is considered, and it's done in a consistent time framework, as we will see better in section §5.5.

There are two way of accounting for carbon dioxide exchanges due to biomass regrowth as illustrated by Peñaloza et al. (2016):

1. *before* - either we assume that the regrowth of the plant have occurred already beforehand respect to the use of the building product
2. *after* - or that after the production of the bio-based construction element, an equal amount of biomass is starting to grow again (implicit assumption of sustainable management of plantations and forests is adopted)

As shown by Levasseur et al. (2013), the choice can lead to significant differences. In this work we choose the option 2 for a couple of reasons: on one hand we want to consider nature is providing some resources that can be used as raw material in construction, not that biomass were necessarily meant to be used as raw material; on the other hand we want to set the initial temporal boundary at time zero because otherwise the resulting benefits are disproportionated in comparison with the actual carbon balance (initially we want to read an emission not a negative value).

In this framework, an carbon sequestration profile for each product along the years is needed. With reference to 3.1.2 we assume that:

- Fast growing biogenic materials are totally regenerated 1 year after their consumption, with a negative impulse.
- Timber starts its regeneration the year after the production but the forest cycle is supposed to last 90 years to be completed.

When we talk about regeneration we mean that the exact amount employed in the building product i.e. in kg of biomass, is regrowing nearby performing carbon sink processes through the photosynthesis.

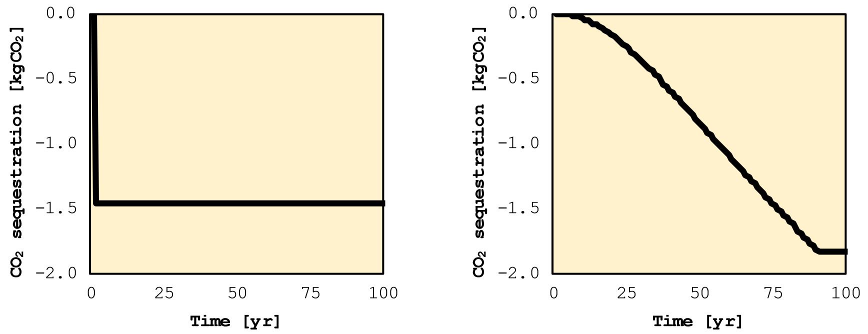
For modelling the carbon sequestration process:

- In the case of fast-growing an impulse function is chosen, therefore the only input information needed is the intensity of the impulse

- In the case of timber the growth trend suggested by Masera et al. (2003) for the even-aged Norway spruce of Central Europe has been taken as a reference. Rotation is supposed to happen at 95 years therefore a polynomial equation fitting the given curve from in the time-span 0-95 is calculated and presented here: $b = 0.000004t^4 - 0.0011t^3 + 0.1065t^2 - 0.2367t \; \left[m^3_{biomass}/ha\right]$

In order to eventually obtain the quantity of atmospheric $CO_2$ fixed by the plant thanks to the photosynthesis we first assumed the Carbon content for each species, namely: 0.4 [$kgC/kg_{straw}$] (Guine, Raquel de Pinho Ferreira Correia, 2013), 0.45 [$kgC/kg_{hemp}$] (Hempnewstv, 2009), 0.5 [$kgC/kg_{wood}$] (Thomas and Martin, 2012). Finally using stoichiometry and knowing the molar mass of Carbon to be 12 [kg/kmol] and of Carbon Dioxide 44 [kg/kmol], it is possible to achieve the mass-$CO_2$ conversion factors that are: -1.47 [$kgCO_2/kg_{straw}$], -1.65 [$kgCO_2/kg_{hemp}$], -1.83 [$kgCO_2/kg_{wood}$].

As an example, in figure 5.5 we illustrate the carbon uptake profiles of 1 [kg] of straw and timber regrowth after the use of 1 [kg] of raw material during the manufacturing.




(a) Straw (b) Timber

Figure 5.5: $CO_2$ uptake cumulative profiles for fast-growing and long-lived materials. It is shown how the absorption trend evolves in time after the production of 1 kg of straw (a) and 1 kg of timber (b). Only carbon sequestration is represented (negative values), emissions due to the production at time 0 are not accounted for in this charts.

### 5.3.2 Carbonation

Carbonation refers to chemical process that binds $CO_2$ to substrates. In constructions it can affect a wide range of materials. In the present study we suppose that its effects can be relevant in presence of lime. The release of $CO_2$ during the calcination is partially compensated through the carbonation process; the natural tendency of portlandite $Ca(OH)_2$, is to react with carbon dioxide in presence of water for coming back to the original state of limestone $CaCO_3$ (calcite) and closing the cycle, reported in 5.6.

Uses include lime mortar, lime plaster, lime render, lime-ash floors, tabby concrete, whitewash, silicate mineral paint, and limestone blocks which may

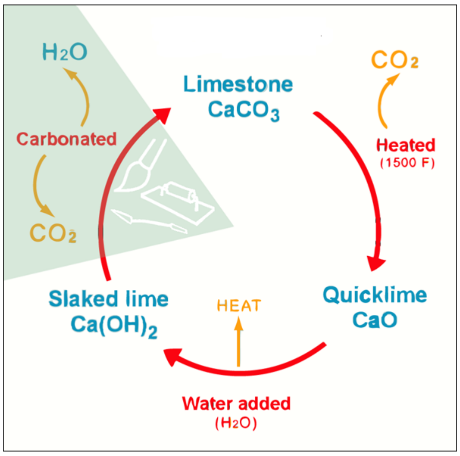



Figure 5.6: Lime cycle. Source: www.FrescoSchool.org

be of many types. With reference to our cases, see 3.2, we have made a basic differentiation between:

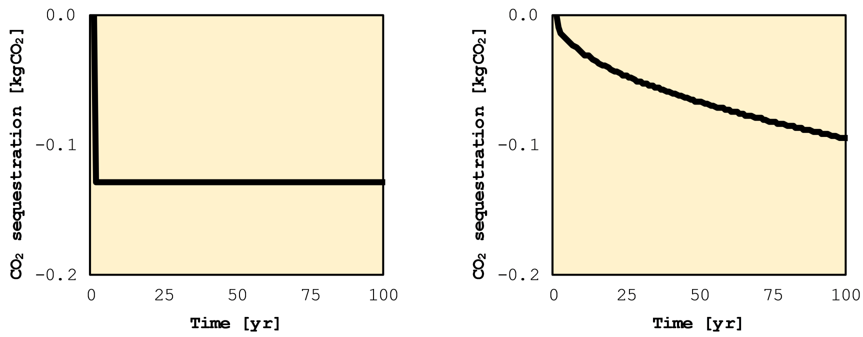
- Fast carbonation: for exposed thin layer, e.g. lime plaster, the assumption that carbonation is complete after 1 year time.

- Slow carbonation: for all the other lime-containing materials, e.g. lime mortar, hempcrete, etc. where portlandite is sheltered but still accessible to $CO_2$ diffusion process. Specifically we have assumed three values of carbonation rate to be used according to the material: 19.6 [mm/yr$^{0.5}$] for mortars, suggested by Xi et al. (2016), 6.2 [mm/yr$^{0.5}$] for hempcrete products, derived from calculations based on experimental tests of Arrigoni et al. (2017), 4.0 [mm/yr$^{0.5}$] for concrete based-materials, again suggested by Xi et al. (2016).

The carbonation model is based on other assumptions like: the mono-directional progression; a completeness threshold equal to 86% of the layer thickness thickness for fast carbonation (Eleni et al., 2014), and to 75% for slow carbonation (arbitrary). Moreover, if carbonation is not complete before the end of life of the element, in both end of life scenarios, landfill and recycling, as soon as the material is disposed, it behave as a fast carbonation material; this happens because, undergoing crushing process in both cases, carbonation rate is significantly risen.

Again, in order to eventually obtain the quantity of atmospheric $CO_2$ fixed by the lime thanks to the carbonation, it is necessary calculate the stoichiometric ratio between the molar masses of calcium hydroxide 74 [kg/kmol] and carbon dioxide 44 [kg/kmol] obtaining a value of -0.59 [$kgCO_2/kg_{lime}$]. Of course the right proportion of lime within the materials has to be considered for calculations.

As an example, in figure 5.5 we illustrate the carbon uptake profiles of 1 [kg] of straw and timber regrowth after the use of 1 [kg] of raw material during the manufacturing.




(a) Lime plaster

(b) hempcrete mixture

Figure 5.7: $CO_2$ uptake cumulative profiles for fast and slow carbonation process. It is shown how the absorption trend evolves in time after the production of (a) 1 kg of lime plaster, with a lime potion of 25%; and 1 kg of hempcrete mixture (b) corresponding to a virtual block with an exposed face of 0.0225 $m^2$ and a thickness of 0.2 m. Only carbon sequestration is represented (negative values), emissions due to the production at time 0 are not accounted for in this charts.

## 5.4 Aggregation Matrix (AM) and dynamic Inventory Result (IR)

With the definition of LCIs we have the unitary emission/uptake profiles referred to 1 $m^2$ of technology. Now it is needed to spatially scale and temporarily shift these profiles in order to depict the actual evolution in time of the $CO_2$ and $CH_4$atmospheric load (or unload), related to EU28 residential building stock insulation system production and installation.

The device we use to cope with this task is the aggregation matrix (AM), the result of the aggregation is the dynamic inventory result (DIR).

The elaboration that is performed in the AM spreadsheets is bridging LCI with the EU28, specifically the unitary profiles of each technology, 200 elements vectors measured in [$kg_{GHG}/yr/{m^2}_{wall}$] (LCI) are multiplied by the yearly renovated external wall building stock measured in [${m^2}_{wall}$] (EU28) combining independently the clusters, that means 7 different insulation thicknesses and 7 different renovation rate, with the 5 technologies, with the 3+2 end of life scenarios. Obviously dealing with different renovation rates it could happen that, some Geoclusters saturate their stock soon while others keep going for long time, and this is also accounted within the AM.

The calculation end up in another matrix that collects and sum up every year all the ghg emission/uptake records from the European building stock: this matrix is called dynamic inventory result (DIR) and represent the input table for running the dynamic LCA.

## 5.5 Dynamic LCA (DLCA)

> Releasing [or sequestering (editor's note)] a big amount of pollutant instantaneously generally does not have the same impact as releasing [or sequestering] the same amount of pollutant at a small rate over several years.

Is one of the basic concepts behind the development of a dynamic LCA (DLCA) formulation (Levasseur et al., 2010).

Traditional LCA methods bring with them some issues that in certain circumstances can reduce significantly representativeness of results:

- Invariant time horizon is the more evident. The selection of time horizon is equivalent to giving a weight to time and is one of the most critical parts of carbon accounting process (Fearnside, 2002) .
- Inconsistency in temporal assessment. e.g. if GWP100 is chosen, building service life is shorter than 100 years, and we have emission occurring near to the end of our time horizon, several inconsistencies are met within these time frames; as all emissions are typically collected into a single aggregate emission, and then characterized as they had occurred at time 0 and as they had lasted 100 years, independently from their actual timing.
- Exclusion of biogenic $CO_2$. The assumption is that the same amount of $CO_2$ that was previously sequestered by the biomass would be subtracted from the emission occurring at the end of the storage period to give a net zero emissions.

Coping with these criticalities through the use of a DLCA even is more relevant if we deal with bio-based materials, where biomass regrowth time and biogenic CO2 balance can play a big role (Levasseur et al., 2012), and may be relevant to consider actual positive and negative $CO_2$ emissions

Since we are interested to understand the dynamics of the renovation in terms of emission for staying under the budget, a DLCA approach is here adopted. In effects highlighting carbon storage benefits of using bio-based materials for the retrofit of EU28 building stock can be better achieved through the application of a dynamic LCA.

Although in principle applicable to all impact category in this formulation we are concerned only about global warming, based on radiative forcing concept.

A visualization of the comparison between a traditional and dynamic LCA can be found in figure 5.8.

### 5.5.1 Radiative forcing

> A change in average net radiation at the top of the troposphere because of a change in either solar or infrared radiation, is defined [...] as a radiative forcing. A radiative forcing perturbs the balance between incoming and outgoing radiation (IPCC, 1997)

Some of the outgoing infrared radiation is trapped by the anthropogenic occurring greenhouse gases emissions (principally carbon dioxide $CO_2$, bur also methane $CH_4$ and nitrous oxide $N_2O$) leading to a perturbed unbalanced state.

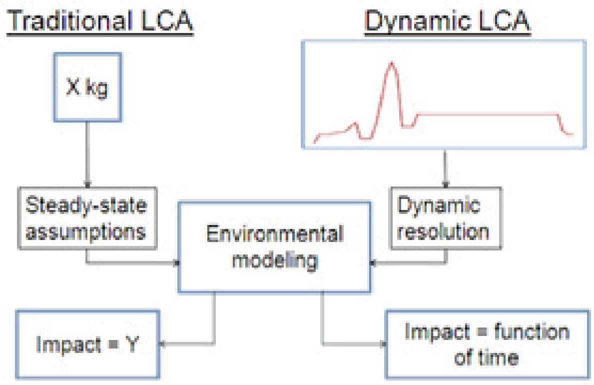



Figure 5.8: Traditional and Dynamic LCA comparison. The dynamic resolution (for each year) leads to a function of time as a result instead of a single number that in our case, having considered only global warming as impact category, is in terms of radiative forcing.

> Radiative forcing provides a convenient first-order measure of the climatic importance of perturbations to the planetary radiation balance (Joos et al., 2001).

In effect it quantifies the energy imbalance between the radiation absorbed by the planet from the sunlight and the power radiated back to the space.

Disequilibrium condition is the consequence of time lags in climate-system due to thermal inertia of the Earth. The temperature of the planet that does not instantaneously respond to the rise in temperature of the warmer surrounding atmosphere, caused by anthropogenic greenhouse effect, and therefore does not achieve a new equilibrium situation, in which incoming energy is equal to outcoming. It is such a disequilibrium that allow us to quantify global warming through the definition of radiative forcing (RF).

Nevertheless in Forster and Ramaswamy (2007), an approximately linear relationship between the global-mean radiative forcing at the troposphere and the equilibrium global mean surface temperature change is provided:

$$\Delta T_s = \lambda \Delta F \; [K]$$

Where $\lambda$ is a climate sensitivity parameter with a wide variability $0.3 \div 1.4 \; [K \, W \, m^2]$ (IPCC, 1997)

One of the main reasons to use radiative forcing as indicator for anthropogenic interference with the climate system and mitigation stringency is that it integrates across different radiative forcing agents. It allow to compare how much climate change different factors are responsible for, so to make them comparable. In effect we can compute the forcing of different players like GHG, aerosols, land use change, solar output, etc. Radiative forcing is a simple measure for both quantifying and ranking the many different influences on climate change.

In this work we are interested in GHG: how much each of them contribute to radiative forcing we will see in section 5.5.2, and eventually we will be able to sum them up throughout the dynamic LCA in section 5.5.3, keeping in mind that positive forcings lead to warming of the climate and negative forcings leads to a cooling.

A plot of the radiative forcing of climate from pre-industrial is found in figure 5.9.

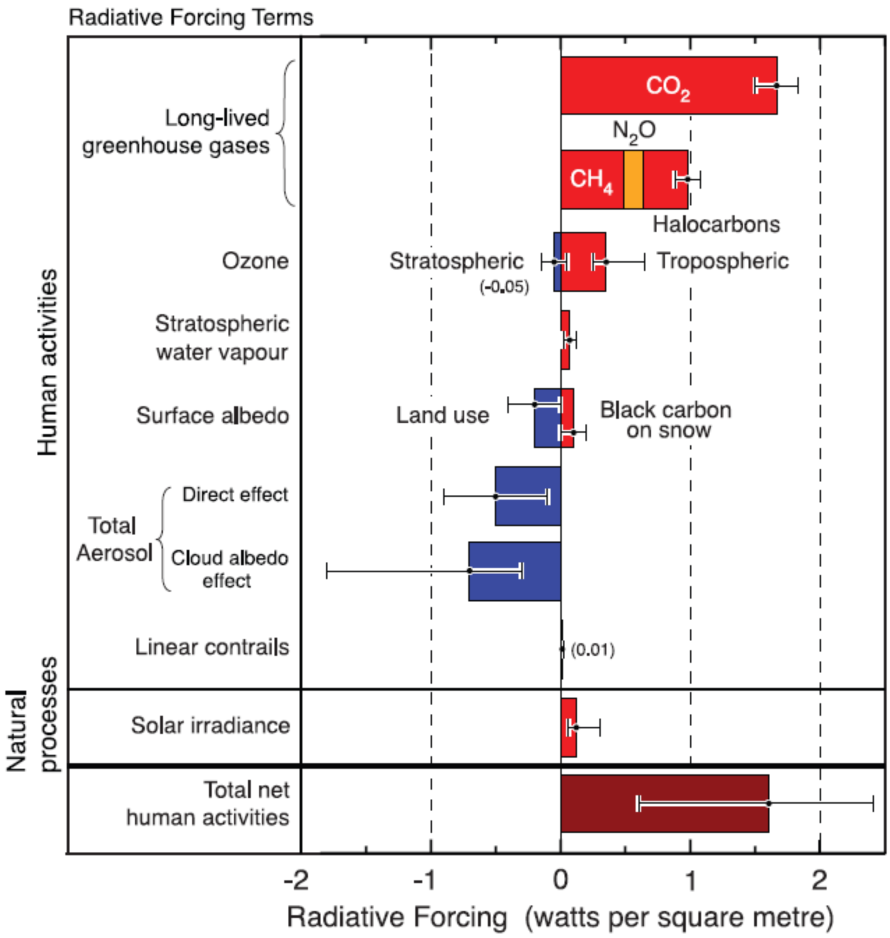



Figure 5.9: Radiative forcing of climate between 1750 and 2005. Summary of the principal components of the radiative forcing of climate change. The values represent the forcing in 2005 relative to the start of the industrial era (about 1750). Human activities cause significant changes. Positive forcings lead to warming of the climate and negative forcings leads to a cooling. Source: IPCC (2014).

### 5.5.2 Decay functions and AGWPs

A pulse emission of a greenhouse gas has an atmospheric load that can be described through a decay function.

The $CO_2$ response function used by Forster and Ramaswamy (2007) is based on the revised version of the Bern Carbon cycle model (Joos et al., 2001) using a background $CO_2$ concentration of 378 ppm. The decay of a pulse of $CO_2$ with the time t is given by:

$$C(t)_{CO_2} = a_0 + \sum_{i=1}^{3} a_i \cdot e^{-t/\tau_i} \; [-]$$

where:
$a_0 = 0.217$ $[-]$ $a_1 = 0.259$ $[-]$ $a_2 = 0.338$ $[-]$ $a_3 = 0.186$ $[-]$
$\tau_1 = 172.9$ $[yr]$ $\tau_2 = 18.51$ $[yr]$ $\tau_3 = 1.186$ $[yr]$

For $CH_4$ the time-dependent atmospheric load is given by:

$$C(t)_{CH_4} = e^{-t/\tau} \; [-]$$

where:
$\tau = 12$ $[yr]$

The GHG *radiative efficiencies* (RE) reported in table 2.1 by Hartmann et al. (2013) are:

$$RE_{CO_2} = 1.37 \cdot 10^{-5} \; \left[W\, m^{-2}\, ppb^{-1}\right]$$

$$RE_{CH_4} = 36.30 \cdot 10^{-5} \; \left[W\, m^{-2}\, ppb^{-1}\right]$$

Then, using the conversion factor of 2.12 $\left[PgC\, ppm^{-1}\right]$, from Ciais et al. (2013), and the GHG molar masses, we can transform concentration into mass through the factors 7.78 $\left[Gt_{CO_2}\, ppm^{-1}\right]$ and 2.83 $\left[Gt_{CH_4}\, ppm^{-1}\right]$, obtaining the *instantaneous radiative forcing per unit mass increase* in the atmosphere for each gas:

$$a_{CO_2} = 1.76 \cdot 10^{-15} \; \left[W\, m^{-2}\, kg_{CO_2}^{-1}\right]$$

$$a_{CH_4} = 128.10 \cdot 10^{-15} \; \left[W\, m^{-2}\, kg_{CO_4}^{-1}\right]$$

Finally the *absolute global warming potentials* (AGWP) for the two gasses are completely defined for whatever time horizon (TH) as:

$$AGWP_{CO_2}(TH) = \int_0^{TH} a_{CO_2} C(t)_{CO_2} dt \; \left[W\, yr\, m^{-2}\, kg_{CO_2}^{-1}\right]$$

$$AGWP_{CH_4}(TH) = \int_0^{TH} a_{CH_4} C(t)_{CH_4} dt \; \left[W\, yr\, m^{-2}\, kg_{CH_4}^{-1}\right]$$

A plot of the arguments of the integrals can be found in figure 5.10.

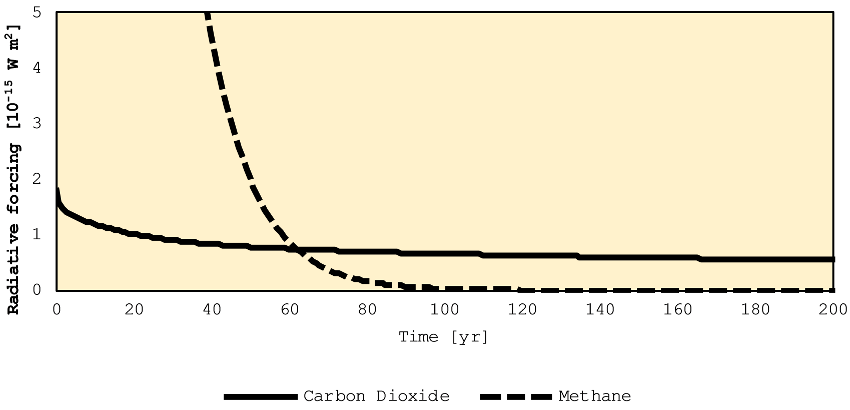



Figure 5.10: Decay functions of $CO_2$ and $CH_4$. Time dependant instantaneous radiative forcing of a unit mass pulse emission at time zero for carbon dioxide and methane.

### 5.5.3 Methodology

The formulation conceived by Levasseur et al. (2010) is based on the combination of a flexible instantaneous dynamic characterization factor (DCF), accounting for the decay of the greenhouse gases in time, with a dynamic inventory result (DIR), accounting for the evolution of GHG emission in time, and it is expressed by the following set of equations:

$$DCF_{inst,GHG}(t) = \int_{t-1}^{t} a_{GHG}\, C(t)_{GHG}\, dt \ \left[W\, yr\, m^{-2}\, kg_{GHG}^{-1}\right] \tag{5.1}$$

$$GWI_{inst}(t) = \sum_{GHG} \sum_{i=0}^{t} [g_{GHG}\,(t_i)] \cdot [DCF_{inst,GHG}(t - t_i)] \ \left[W\, m^{-2}\right] \tag{5.2}$$

$$GWI_{cum}(t) = \sum_{i=0}^{t} [GWI_{inst}(t_i)] \cdot [t_{i+1} - t_i] \ \left[W\, yr\, m^{-2}\right] \tag{5.3}$$

- $DCF_{inst,GHG}(t)$ : Dynamic characterization factor of a specific GHG emission that occurred $t$ years before with:
  - $C(t)_{GHG}$: Response function of the GHG as defined in section 5.5.2.
  - $a_{GHG}$: Instantaneous radiative forcing per unit mass increase in the atmosphere for the specific GHG defined in section 5.5.2.
- $GWI_{inst}(t)$ : Instantaneous global warming impact at a given time $t$ with:
  - $[g_{GHG}\,(i)]$: Dynamic inventory result (DIR) for the given GHG for year $i$.

  - $[DCF_{inst,GHG}(t-i)]$: Dynamic characterization factor as defined in equation (1) for given GHG for the time gap between occurrence of impact $[g_{GHG}(i)]$ and $t$.

- $GWI_{cum}(t)$ : Sum of all $GWI_{inst}(t)$ from 0 to time $t$.

In DLCA the life cycle impact can be assessed at whatever time elapse, through $GWI_{cum}(t)$. The cumulative global warming impact represents the amount of radiant energy that has been trapped into the atmosphere up to that moment due a specific GHG introduction trend. Moreover a coherent account of the dynamics of GHGs decay is done without losing information about timing.

This formulation has been implemented in a MATLB code (Krause et al., 2017) that close the model (DLCA) with the final output.

In order to have the results in terms of radiative forcing converted back in global warming potential units, for each chosen time horizon (TH) a conversion can be done. It is given by:

$$GWP(TH) = \frac{GWI_{cum}(TH)}{AGWP_{CO_2}(TH)} \ [kgCO_2eq]$$

The global warming impact at a given time is normalized over the cumulative radiative forcing of a 1kg $CO_2$ pulse emission occurring at time zero.

## 5.6 Uncertainties

### 5.6.1 Boundary analysis

The actual source of uncertainties we are trying to control is the set of parameters used for describing carbon sequestrations. Namely we have defined a variability range of some parameters considering best, worst and mode cases. The approach we adopt is *boundary analysis* because all uncertain parameters will be varied to worst and best case contemporary, enveloping the baseline into a variability range.

The set of parameters we have varied are illustrate in table 5.8.

Additional source of uncertainty that we are not going to quantify is in the model, especially the mathematical model of the sequestrations (biomass regrowth and carbonation). Sources of uncertainties are also the choice of the insulation system, but as we are dealing with explorative analysis we have designed them to be representative of specific category.

### 5.6.2 Sensitivity analysis

In order to study how certain important parameters contribute to overall model uncertainty we perform a sensitivity analysis. Specifically we have selected as driver parameters:

**Renovation rate** increasing renovation rate means scaling up the surface of external wall retrofitted every year. It is a relevant parameter because amplifying the effect of our simulation gives a measure on how dynamic cumulative effects evolve if pushed beyond the current rate. Three scenarios has been investigated: x1 scenario (baseline), x2 scenario, x4 scenario; with baseline r.r. $\approx$1%.

**Service life** it is interesting to see how shortening service life affect global behaviour. Generally it implies that end of life related impacts are anticipated and replacement phase is skipped. It needs to be précised that the boundary of our analysis exclude new building, so the impacts due to the potential new construction are not considered. Three alternatives has been investigated: 60 years (baseline), 30 years, 20 years.

To be noticed that throughout the sensitivity analysis an average end of life scenario has been considered, due to the unavailability of frequency statistical data that would have allowed to weight the different scenarios.

| | | Life Span [yr] | Waste material category |
|---|---|---|---|
| *On-site installation* | | | |
| **EPS - External Thermal Insulation Composite System** | | | |
| 1 | Cement mortar | 60 | *No potential* |
| 2 | EPS* | 40 | *Combustible* |
| 3 | Base plaster | 40 | *No potential* |
| **HCB - Hempcrete blocks** | | | |
| 1 | Cement mortar | 60 | *No potential* |
| 2 | Hempcrete blocks* | 60 | *Recyclable* |
| 3 | Lime mortar* | 60 | *Recyclable* |
| 4 | Lime plaster | 40 | *No potential* |
| *Off-site prefabrication* | | | |
| **TIM - Timber frame with mineral insulation** | | | |
| 1 | OSB | 60 | *Wooden* |
| 2 | Glass wool* | 40 | *No potential* |
| 3 | Timber frame* | 60 | *Wooden* |
| 4 | Wood fibreboard soft | 40 | *Wooden* |
| 5 | Cover plaster | 40 | *No potential* |
| **HCF - Timber frame with injected hempcrete** | | | |
| 1 | OSB | 60 | *Wooden* |
| 2 | Hempcrete injected* | 60 | *Recyclable* |
| 3 | Timber frame* | 60 | *Wooden* |
| 4 | Reed mat | 30 | *Fast decomposing* |
| 5 | Lime plaster | 30 | *No potential* |
| **STR - I-joist frame with pressed straw** | | | |
| 1 | OSB | 60 | *Wooden* |
| 2 | Light clay straw | 60 | *Recyclable* |
| 3 | Timber I-joist* | 60 | *Wooden* |
| 4 | Straw chips* | 60 | *Fast decomposing* |
| 5 | Light clay straw | 60 | *Recyclable* |
| 6 | Reed mat | 30 | *Fast decomposing* |
| 7 | Lime plaster | 30 | *No potential* |

Table 5.6: Materials inventory - service life and waste treatment

| | | WORST | MODE | BEST | |
|---|---|---|---|---|---|
| 1 | Forest rotation management | 100 | 90 | 70 | $[yr]$ |
| 2 | Fast carbonation completeness | 80% | 86% | 92% | $[-]$ |
| 3 | Slow carbonation rate for mortars | 6.1 | 19.6 | 36.8 | $[mmyr^{-0.5}]$ |
| 4 | Slow carbonation rate coefficient for hempcrete | 0.8 | 1.0 | 1.2 | $[-]$ |
| 5 | Slow carbonation completeness | 50% | 75% | 100% | $[-]$ |
| 6 | Share of portlandite in concrete | 2.3% | 6.4% | 8.8% | $[-]$ |

Table 5.8: Uncertainty parameters. Sources: 1.Eriksson et al. (2007), 2. Eleni et al. (2014), 3) Xi et al. (2016), 4) arbitrary 20% fluctuation, 5) arbitrary 25% fluctuation 6)Xi et al. (2016).

# Chapter 6

# Results

## 6.1 Instantaneous Global Warming Impact

The instantaneous global warming impact indicator ($GWI_{inst}$) in terms of radiative forcing [W $m^{-2}$] for the 5 technical solutions for the 3 disposal scenarios is shown in figure 6.1. In this charts is possible to read the evolution of climate warming response in time. Every atmospheric load or unload of gas released or sequestered during the life-cycle of the building product is scaled up according to the building stock renovation progression, reduced according to the decay function, and registered in the chart.

The production use and disposal of synthetic insulation (EPS) for retrofitting results to have, has expected a positive radiative forcing all the cycle around. Fast-growing bio-based materials (STR, HCF, HCB) on the contrary show the capacity of being immediately beneficial giving a negative forcing, so giving a contribution to mitigation. A middle-way behaviour is shown by the mixed technology (TIM); here the long time needed for timber to regrow shifts the moment biomass uptake will overcome emissions, in effect for the first 50 years impacts of mineral insulation are comparable to the ones of polystyrene, and only after 100 years they reach the neutrality; in the long term the effect of the forest will prevail and cooling effect will eventually start.

The instantaneous GWI is particularly useful also for the identification of the turning point in terms of emissions during the life-cycle.

For example in a) a peak is detected after 60 years in the STR technology because the landfill of straw chips has started, releasing methane (very harmful in the short term); in b) a sharper inflexion of EPS and TIM curve is met, because it corresponds to the beginning of the incineration process; in c) are clear the benefits of the recycling that avoid the emissions due to the production of the material recycled; in addition from the dotted lines is well visible the effort recycling process involve in comparison with the benefits it produce.

## 6.2 Cumulative radiative forcing

Through the progressive integration of the instantaneous radiative forcing profiles we obtain the cumulative global warming impact indicator ($GWI_{cum}$) in terms of cumulative radiative forcing [W yr $m^{-2}$] (figure 6.2). It is the most

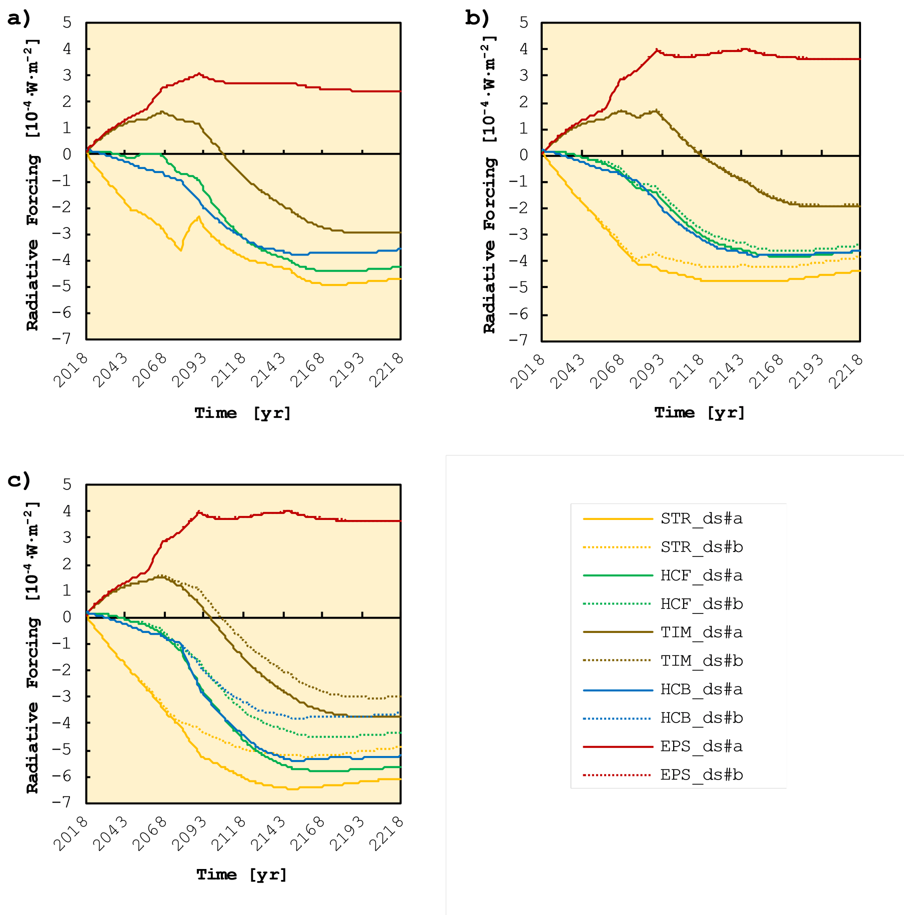



Figure 6.1: Climate warming response to the implementation of 5 insulation systems in terms of instantaneous radiative forcing $GWI_{inst}$ for 3 disposal scenario: a) Landfill b) Energy recovery c) Recycling. Bio-based renovation solutions induce a negative radiative forcing (cooling) with the synthetic one represent an environmental burden (warming) all the simulation around.

powerful indicator because at every time it represents the effects that a given choice has had up to that moment. In effect cumulative radiative forcing at a certain time indicates energy in the form of heat entered in the system (the atmosphere) up to that moment due to a certain emission history occurred beforehand.

From this chart we can easily understand that the only insulation systems that can be applied in large scale without loading the atmosphere are bio-based ones (STR, HCF, HCB); actually we can see that they are doing more than simply not harming (neutrality), they are effectively contributing to mitigation with a cooling effect (negative radiative forcing). Outstanding is the performance of straw-based solution (STR) that is able to immediately take advantage by the regrowth; the two hemp-based technologies (HCF, HCB) suffer of a bigger inertia because of the use of lime as binder that, at least in the short term is able to counterbalance the benefits from the regrowth.

An intermediate result is provided by the mieral-timber solution (TIM) where the presence of the wooden frame and panels are able to dump the trend; the peak is reached around 100 years and is followed by a smooth decrease that allow to approach neutrality. To be noticed the large variability of the end of life that can lead to significant advantages in the case of recycling, and to much higher impacts in the case of incineration for the sudden evacuation of the $CO_2$ storage contained in the wood.

An irrecoverable warming effect is induced by the choice of conventional insulation for the building envelope. Its a nose-up trend that implies an additional burden to the environment in the short that will be compensated only by later operational energy savings (not accounted for in this work). Inappropriateness of synthetic solution (EPS) is here clearly illustrated, especially if a incineration disposal scenario is chosen.

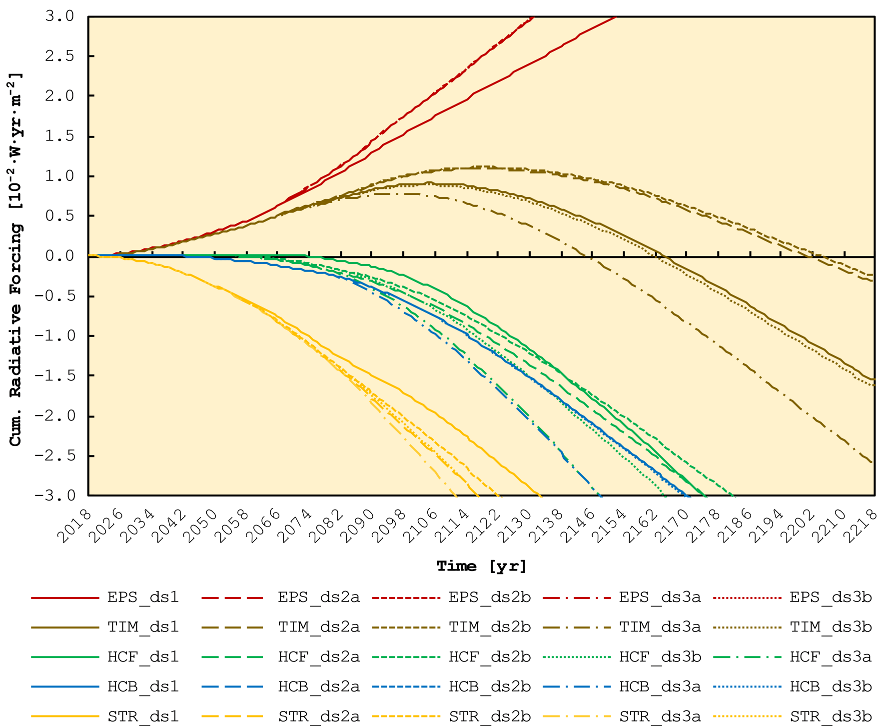



Figure 6.2: Cumulative radiative forcing $GWI_{cum}$ of five building insulation systems by five disposal scenarios. The dynamic climate-warming performance of each alternative is plot. At every year the amount of heat accumulated into the atmosphere due a certain emission history record can be read in the chart. Bio-based solutions (STR, HCF, HCB) provide climate-mitigation effect whatever time horizon is chosen, mixed wood-mineral solution (TIM) reach the climate neutrality only after more that hundred years, polystyrene (EPS) implementation represents a inappropriate choice from a global warming perspective.

## 6.3 Uncertainties

Combining together all the sources of uncertainties explained in section §5.6, and taking a picture of cumulative global warming impact at the year 2100 of all the alternatives, the situation is the one depicted in figure 6.3.

The bars represent the baseline, while the error bar represent the envelope of all uncertainties considered, namely best and worst performance is sought across all scenarios and reported together with the mode values. As we can see bio-based solutions are more affected by uncertainties, while the TIM and especially EPS solutions, beside being climate-altering, result more definite. Particularly high the potentiality shown by STR, HCB and HCF that with the right combination of factors can more that double their performance. Normally the highest degree of uncertainty far from the neutrality (much negative for negative, much positive for positive), because not in all the parameters considered the baseline coincide with an intermediate value (see section 5.6.2).

Note that even the end of life can be considered as a degree of uncertainty, but we prefer here to keep disposal scenarios separate to have a more detailed perception. For example we can detect that for TIM the choice of incineration can lead increase of emission near to 100% compared to the other waste scenarios; for HCB recycling is strongly recommended; while for EPS it does not imply significant difference choosing landfill or the other scenarios.

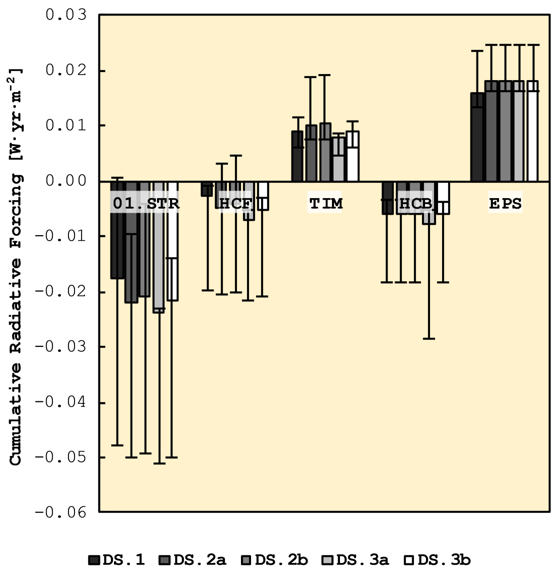



Figure 6.3: Uncertainties in the year 2100. They play a significant role especially for renewable solutions, also different end of life can be considered as uncertainties. Baselines are always negative (climate-beneficial) for fast-growing bio-based solution (STR, HCF, HCB), and always positive (climate-altering) for the other two (TIM, EPS).

If we now focus on the effects induced by renovation rate variation (sensitivity analysis), we can figure out that it represent by far the more important parameter to control. Raising renovation rate in particular produce the overall effect of amplifying the consequences a solution would have implied in baseline condition, whether they be benefits or harms for the environment.

In particular moving from the current rate (≈1%) to higher rates (x2, x4) the profiles are all pushed toward left, that means that whatever effect was supposed to have that solution, that effect will occur in advance: straw is giving benefits earlier, polystyrene is no longer dumped but shows a linear warming tendency, mixed timber-mineral solution anticipate the peak of 30, 40 years but increase the carbon capture potentiality in later stages. Note that an average end of life scenario has been considered for this analysis.

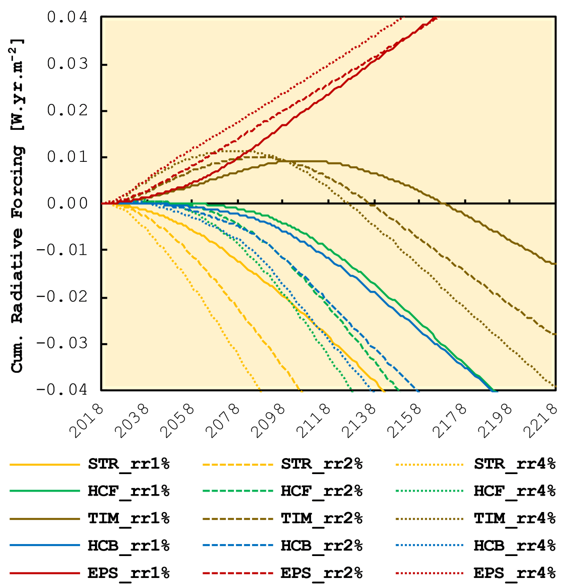



Figure 6.4: Sensitivity to renovation rate variation. An increase of renovation rate from baseline (≈1%) to higher rates (x2, x4), amplify the impacts whether they be benefits or harms for the environment. STR, HCF, HCB anticipate their carbon capture capacity, installation EPS results to be immediately climate-altering with a linear trend, TIM shifts the highest burden toward left, but produce higher benefits later on.

Expected service life parameter has an inferior influence compared to renovation rate in terms of sensitivity analysis, but still notable. In general, shortening the service life bring to a worsening of environmental performances because disposal impacts are forwarded, see STR, HCF and TIM; this is not true for EPS and HCB that have a heavier production phase compared to the disposal process, so it turn to be an advantage.

We have to precise that the shortening of the service life is not completely characterized through this analysis because within the boundary of our system we does not consider the new construction that is expected to be build after one end of life, so also related impacts are excluded.

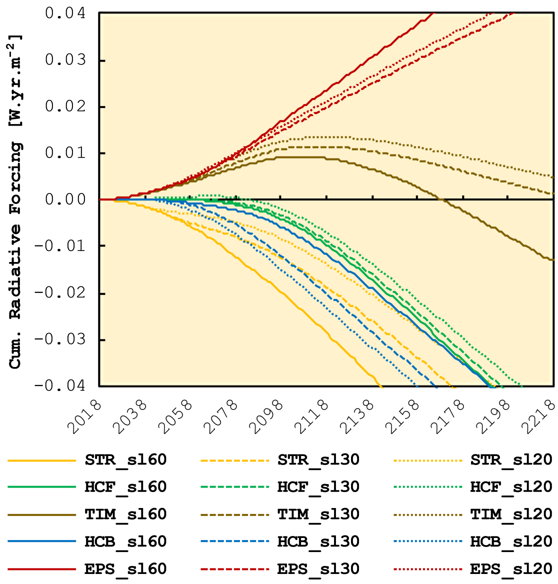



Figure 6.5: Sensitivity to service life variation . Shortening service life induce an improved performance where impacts due to end of life are on average heavier than manufacturing and installation ones (STR, HCF, TIM), and a worsening where the opposite applies. Impacts due to new construction after the end of life not considered.

## 6.4 Renovation and carbon budget

If we want to have an insight into a policy perspective, we can get the meaning of our analysis for staying under the 2°C temperature rise limit.

The chart presented in figure 6.6, shows the evolution of cumulative household emissions during the transition. We can see that the decreasing slope trend is due to the reduction of operational energy due to renovations, while the choice of the insulation system is responsible of the divergence of each family of lines.

The transition is considered to be over when the plateau is reached. Results are presented for different renovation rate. The horizontal limits represent the IPCC carbon budget share relative to European household sector (section §2.1.2).

### 6.4.1 Assumptions

For comparing the results of our analysis with the carbon budget we have to make assumptions on operational energy reduction. Since we didn't perform any energy simulation within this research, the only assumption we can rely on is considering renovation to ZEB: namely every building that undergoes energy retrofit becomes 0-energy. It is a strong assumption because we are dealing with a partial renovation of the building envelope (see section 4.2.3); with a whole retrofit we should include also windows substitution, that would represent an additional load, and the insulation of basement and roof, that in the case of bio-based would represent a benefit. On the other hand the value of transmittance considered for the opaque part are aligned with standard value of European nZEB (see section 4.6.2).

Another assumption is that carbon intensity of energy stays constant. Currently the value of $CO_2$ emitted per unit energy produced in European Union is 2.1 (kg$CO_2$ per kg of oil equivalent energy use), data 2013 from World Bank website. This value is supposed to decrease in time due to decarbonization measures, implying a lower rate of emission per unit of energy consumed; also in our chart this should push the bending down of the curves, enlarging the chances of staying under the budget.

Note finally that the carbon budget considered, is equally divided according to population and activity sector, rejecting other allocation criteria that could lead to grab carbon shares to less responsible counties.

### 6.4.2 Considerations on renovation rate

As we can see it represents the fundamental parameter for keeping the 2°C target in sight.

With "business as usual" (current) rates (~1%) the budget is blown in 2040 and the transition progress is only a fraction of the total. Things are slightly better doubling the rate, but still far from the target. With a triple or four times rate we can perceive the flattening of the curve but still missing the objective. We have to rise up to 5 times the current rate to be sure that the transition will be completed with conventional insulation systems. Note that with business as usual rates insulation system choice does not change the big picture.

### 6.4.3 Considerations on bio-based

The choice of the insulation material and can sensitively change the impact of renovation.

In a vertical perspective we can read the effect of bio-based as discount on the carbon fee we have to pay for adapting the building sector, in effect as of 2050 we could have achieved avoided emissions in the order of 0.2-0.5 Gt$CO_2$eq that could be invested elsewhere in other transitions (rise efficiency, produce solar panels wind turbine, etc.).

In an horizontal perspective the benefits are even more evident, because we read them in terms of time gaining. Namely using bio-based instead of conventional, with a rate of 2%, 3%, 4% the overrun of the budget can be delayed respectively of 2yr, 6yr, 24yr. That means buying precious time for tackling inertia of building industry to acknowledge changing.

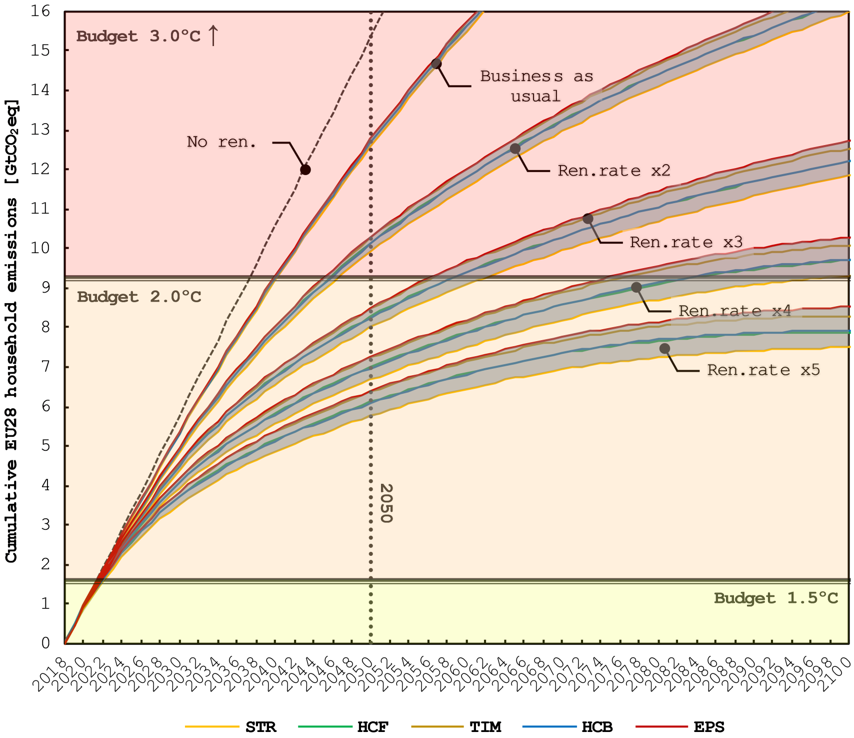



Figure 6.6: European carbon budget scenarios

# Chapter 7

# Conclusions

## 7.1 Main remarks

The need of addressing rapidly the transition toward a zero-carbon society is a priority, in this perspective bio-based materials represent a opportunity that should not be wasted.

Residential sector is one of the main emitter and if we want to meet the Paris Agreement commitments, massive interventions for improving the passive performances of the European building stock is inescapable. Therefore at least in the short term, when the energy is still highly carbon intensive, a renovation of the building envelope for containing losses is needed. Nevertheless the impacts coming from the implementation of the retrofit solutions can be cumbersome, difficult to compensate in few years, and exacerbating the atmospheric load in the first period. Thus, our focus is the assessments of the impacts coming from the whole life cycle of the building elements. Operational energy is excluded from the calculations as a homogeneous thermal transmittance of the walls is considered and therefore an equal share of energy savings can be assumed.

In this study we have verified that substituting conventional with bio-based insulation materials can overturn the perspective changing the threat of the production impacts into an opportunity for mitigation. Besides the importance of addressing a fast large scale renovation has been pointed out.

Specifically the remarks we want to underpin can be systematized in 4 stages:

1. Bio-based as an opportunity for climate change mitigation:
   Moving from synthetic/mineral to bio-based insulation materials is a chance for cancel out renovation related burden, and even achieving climate cooling effects. Results have shown that a massive installation of bio-based insulation materials can lead to a carbon negative (net) balance. In effect a negative radiative forcing means a reduction of the GHG amount in the atmosphere. Since renovation is already happening, even though very slowly, the substitution of conventional insulations with bio-based ones is an occasion that should not be wasted. Quantitatively, the choice of the material can originate significantly different scenarios: being 0 the case with a carbon neutral retrofitting, we register in the year 2100 a range varying from -2.1 [$10^{-2}$W yr $m^2$] in the best case (STR) to +1.8 [$10^{-2}$W yr $m^2$] in the worst case (EPS) (average end of life scenario).

2. Fast-growing for enhancing sequestration:
Short term massive Carbon uptake from the regrow in the fields of biomass employed as insulation in constructions prove to be by far the greatest benefit. These can be significantly amplified if fast growing materials are preferred as net atmospheric CO2 removals are performed in short time. Only fast growing bio-based materials show the capacity of removing from atmosphere all the carbon stored in the building in 1 year time. Wood for example has the same sequestration capability of straw and hemp due to photosynthesis, but it takes the whole life of the tree (90 years) for being completed while plantations can be regrown and cut again 90 times in the same time-span. If we move at European scale, this translates in a heavy delay of the TIM (long-lived) solution compared to STR, HCF, and HCB (fast-growing) in producing a net advantage. We have to wait year, 2108 ± 10 for reaching a 0 [W $m^{-2}$] instantaneous radiative forcing, while the break even comes only after 180 years ± 20 if we look at the global performance in terms of cumulative radiative forcing.

3. Transition within the Budget:
Our global environmental limit is the Carbon Budget. It represent the finite amount of greenhouse gases we can emit to limit the global temperature rise to 2°C, namely to fulfil the Paris Accord COP21. Since the scientific reasons for choosing such a threshold are widely illustrated by the scientific community (IPCC 2013), and accepted (almost) worldwide, it is important that whatever sustainable strategy for facing climate change respect this environmental limit. In our research we have adjusted the global limit to the European share corresponding to the building sector, establishing the figure of 9 [$GtCO_2eq$]. In this framework being the budget our spending power for the transition toward Zero Carbon Buildings, the bio-based effect can be seen as a discount in the environmental cost of renovation. In other words only the choice of bio-based respect to polystyrene insulation can originate budget savings equal to $0.2 \div 0.6$ [$GtCO_2eq$] depending from the renovation rate. In another perspective we can visualize instead that installing natural insulation the budget overrun can be delayed from 1 to 20 yr, depending on the renovation rate.

4. Prefabrication to speed up renovation:
Pre-assembled, pre-cast, fast installation technologies are crucial to shorten renovation time, especially dealing with external walls insulation. European residential building stock is old and energy swallower; as long as energy does not become completely clean, it is important to contain this energy flow as much as we can. And since transition in the energy system is not going to happen shortly, beside reducing end-user demand, policies should push toward a fast renovation of the existing stock. To achieving such a result designers, manufacturers, construction industry, and above all policies should bend the market proposing pre-fabricated facade (but also roof and basement) modules and panels. Making installation time drop, assuring reliable performance, and enhancing safety level in the construction area are crucial factors for addressing the adaptation of the building sector as fast as possible.

5. Environmental optimality

Beside the current tendency of following a cost-optimality principle to enhance the effectiveness of the unitary cost of intervention, the use of bio-based building elements can define new strategies and new priorities in the renovation practice. With respect to the current building standards that focus mainly on energetic targets, a timing of the interventions for instance could be introduced in function of the regenerative capability of the biomass utilized. In this way the sink potential of bio-based solutions and embodied impacts pertaining to conventional solution would be taken into consideration.

## 7.2 Outlook

If the present research has given a contribute in widening the awareness on some aspects, many other fields needs to be enlightened by further investigations, as can be:

- Implementing large scale energy simulation for modelling also operational energy evolution in time.
- Extending to whole building envelope retrofit, including impacts/benefits coming from windows substitution, roof and basement insulation.
- Deepening the design of technical solutions of prefab bio-based insulation systems for fast implementation.
- Refining environmental assessment with enhanced uncertainties.
- Approaching to a multi-option perspective for optimization of the renovation strategies including the cost perspective.
- Involving land-consumption impact category since it can result to be relevant dealing with bio-based materials.

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# List of Figures

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