POLITECNICO DI TORINO

MSc Program in
Architecture for the Sustainable Design

Master's Degree Thesis

Life cycle approaches for the green retrofitting of existent buildings

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Contents

Chapter 2. European regulatory context

Chapter 3. Methodological context:
Life Cycle Thinking

Chapter 4: Literature selection

ABSTRACT

The building sector has a key role in the fight against the climate change, since it is responsible of the largest share of energy consumption and CO_2 emissions both at global and at European levels. In Europe, the existing building stock represents a huge problem since its almost entire share is energy inefficient. Therefore, a green retrofit action is needed, that is not only meeting the minimum energy performance requirements and being financially beneficial to the building owners, but that also has a low environmental impact.

The aim of this Master's Degree thesis is to identify how the researchers have been figuring out a methodology for the economic evaluation of a green retrofit scenario in a life cycle perspective in the European context. The work is structured into four chapters related to the main macro research areas. The first one deals with a theoretical framework about the economic foundation of the sustainable thinking and it introduces the models of Circular Economy (CE) and Green Economy (GE), in which the green retrofitting can be identified. Then, the building energy performance regulation is defined into an European regulatory context in which the main strategies and legislation adopted in the construction sector are described, with a specific attention to the growing focus on the existing buildings. In addition, the Italian documentation related to the building energy performance is reported and analysed by highlighting the most innovative developed tools.

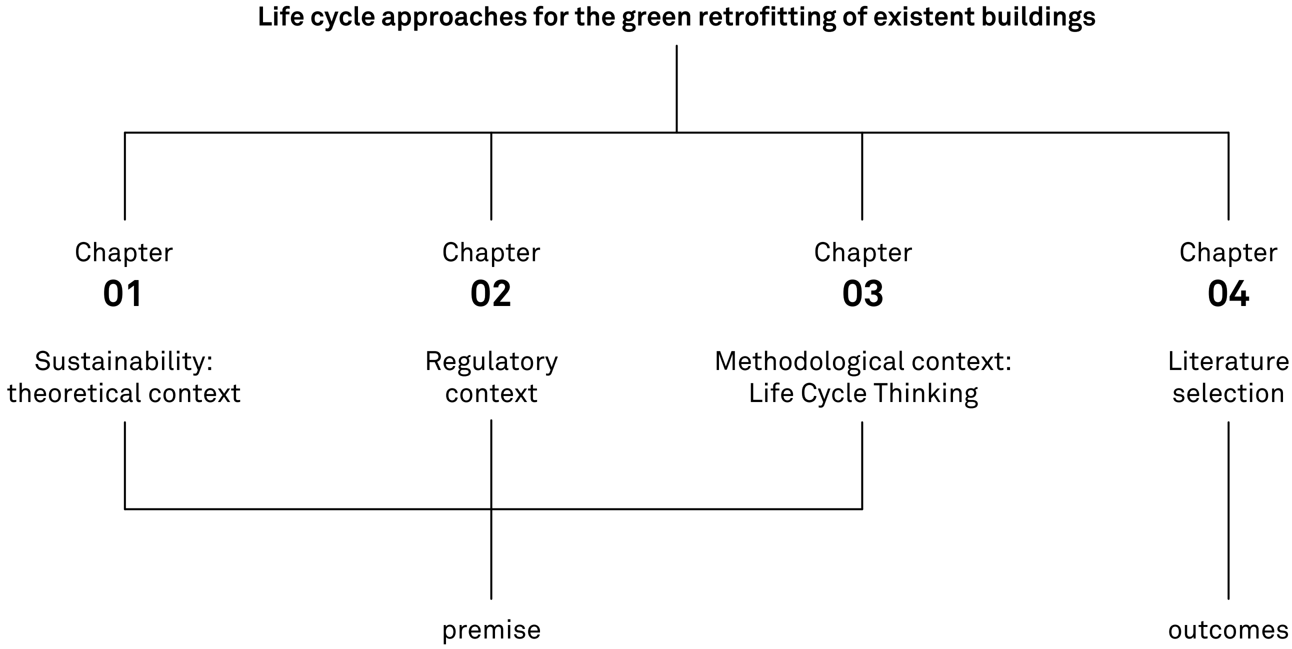
The third chapter introduces the methodological context of the Life Cycle Thinking (LCT), an approach that considers all the life cycle phases of a building, or a building component, and its related activities, and two derived techniques: the Life Cycle Assessment (LCA) and the Life Cycle Cost Analysis (LCCA) or Life Cycle Costing (LCC). The former is a method to assess the environmental impact of a product, or a building. The latter is a technique for the economic evaluation of a new or an existing asset which takes into account both immediate and long-term costs and benefits. LCCA is at the base of the literature selection presented in the fourth chapter, whose focus has been the application of the Life Cycle Cost Analysis for the economic evaluation of retrofit projects and the development of an integration between the economic and the environmental impact analysis, for the assessment of the most sustainable refurbishment scenario among alternative retrofit strategies.

The selection process represents a first innovative aspects of this thesis research. Moreover, the resulted limited number of articles and the adoption of a different methodological application in each of them have allowed the implementation of a new literature analysis method. Finally, the selected articles are analysed in order to identify the different approaches in which the economic and environmental analysis are performed, even through integrated applications.

INTRODUCTION

Over the last decades the climate change has been one of the most important issue at global level. The greenhouse effect is the main driver of the climate change, mainly caused by the human activity. Since fifties, the population has dramatically growth and it is predicted to rise to 9 billions by 2050. The related economic growth and the production-consumption chain have contributed to a correlated carbon dioxide emissions five-fold increase, from 5 billions of tonnes in 1950 to 35 billion of tonnes in 2019. These phenomena were faced in the Paris Agreement, the first-ever universal, legally binding international treaty on climate change, which laid down to limit global warming below 2, preferably to 1.5, degrees Celsius, compared to pre-industrial levels. The Agreement was adopted by 196 Parties at COP 21 in Paris, on 12 December 2015 and entered into force on 4 November 2016. In the same year, United Nations adopted the 2030 Agenda for Sustainable Development and set 17 Sustainable Development Goals (SDGs), which are an urgent call for action by all countries in a global partnership.
In line with its commitment with the Paris Agreement, Europe leads the global fight against the climate change and aims to become the first climate-neutral continent by 2050.
In the achievement of this goal, the building sector has a pivotal role since it is responsible of the largest share of energy consumption and CO_2 emissions both at global and at European levels. Indeed, buildings consume 35% of the world final energy and emit 38% of the global carbon dioxide. In Europe, 40% of energy consumption and 36% of CO_2 emissions come from the built environment.
In the recent years, the attention is mainly focused on the existing buildings, since 75% of the European building stock is energy inefficient and only 1% per year is renovated. The retrofit action has been considered crucial to reach the EU climate targets about the energy-efficiency improvement and greenhouse gases emission decrease. Indeed, 5/6% of the energy consumption would be lowered and 5% of CO_2 emissions would be cut after renovation.
In addition, the renovation of existing buildings is strategic for the continent economic growth and job opportunities since it would contribute to 9% of the EU GDP and add 18.000 new jobs in the construction sector. However, the question is: Is a retrofit action both cost-effective and environmental friendly than a new construction? And how this can be evaluated?
The aim of this research thesis is to identify how the researchers have been figuring out a methodology for the economic evaluation of a building retrofit scenario in a life cycle perspective, that is considering all the life cycle phases of a building, or a building component, from the design to end-of-life. The ultimate scope is the economic evaluation not only of a functional retrofit, that is financially beneficial to the owner while respecting the minimum energy performance requirements, but a green retrofit, which also considers the environmental impact and the indoor spaces comfort and quality for the occupants.

This thesis considers the European context and it is structured into four macro research areas, of which each is dealt in a chapter. The figure below shows the general framework.



The first one is related to the term "green" of the objective of this research and deals with an overview of the sustainable model and its connections. First, the introductory section aims to identify the main topics linked to the sustainable development, such as the economic foundation of the sustainable thinking. Later, two sustainable economic models are treated: the Circular Economy (CE) and the Green Economy(GE). The former faces one of the main topics of sustainability, that is the limitedness of the natural resources since it represents a business alternative to the actual linear production-consumption model; it is represented by a loop of a two-cycle flow system. The latter is not a business model but a branched strategy that extends and embraces all dimensions, at all scales, involving each Country and stakeholder without neglecting any field. Indeed, the CE model can be inserted in the GE strategy.
Both the two economic models are then related to the built environment, that is one of the key sectors, together with food and transport, and influences all three pillars of sustainability.
Finally, the focus is shifted on the existing buildings which have a central role in this research. Indeed, the circular economy model not only can be adapted to the construction sector, but can also be a tool for a circular recovery strategy in which all the existing buildings are energy retrofitted and/or spatially renovated. As regards the GE section, green buildings are treated since they represent one of the six sectors of a green economy. However, the greenest action is not building at all and the next phase of a green building is greening an existing one. Therefore, the green retrofitting, that is the innovative aspect of this research thesis, concludes the first chapter.

The second chapter reports an analysis of the regulatory framework and the main climate action adopted by Europe in the way of a unique ultimate scope that is to become the first climate-neutral continent by 2050. Therefore, the first section deals with the main climate targets on the greenhouse gases emission cutting, the increase of energy by renewable sources and the energy-efficiency improvement to reach by 2020 and by 2030 for the period 2013-2020 and 2021-2030 respectively.
Since the energy-efficiency is considered a key issue in the sustainable development, the next section focuses on this topic. First, the legislation and the main strategies on the energy-efficiency are presented. Then, the building role in the energy-efficiency strategies is analysed by reporting specific extracts of the documentation. Finally, by following the same logic of the chapter 1, the focus shifts on the existing buildings. Hence, the 2020 Renovation Wave Strategy, which has been adopted by the European Commission with the aim of refurbishing the EU building stock, is described.
The last section is totally about the regulatory framework process of the building energy performance. After a chronological report and description of the building energy performance Directives (EPBD 2002/91/EC; EPBD Recast 2010/31/EU; EED 2012/27/EU; Directive 2018/844), an analysis on the growing attention of the regulation on the existing buildings is described. In particular, the 2020 Energy Strategy is considered a turning point in the growing interest about the EU building stock.
The chapter ends with a report on the implementation of the European regulation in the Italian context by specifying the most important parts of the documentation analysed.
The third chapter identifies the methodological context on which the literature selection and analysis, described in Chapter 4, are based. This is the Life Cycle Thinking (LCT), an approach that considers all the life cycle phases of a building, or a building component, and its related activities that in the construction sector are raw material extraction, material processing, transportation, distribution and consumption, maintenance, reuse or recycling, and disposal. In particular, two approaches derived from LCT are described: the Life Cycle Assessment (LCA) and the Life Cycle Cost Analysis (LCCA) or Life Cycle Costing (LCC). The former is a method to assess the environmental impact of a product, or a building. The latter is a technique for the economic evaluation of a new or an existing asset which takes into account both immediate and long-term costs and benefits. In LCCA each cost component is related to each phase and, in particular, the use-maintenance-operation costs are discounted to the present. In order to develop a LCC methodology which also integrates environmental and social costs, the Society of Environmental Toxicology and Chemistry (SETAC) has defined three typologies of LCC: Conventional LCC (C-LCC or LCC), Environmental LCC (E-LCC) and Societal LCC (S-LCC). These three are described in the last paragraph of Chapter 3.

Finally, Chapter 4 presents the innovative research area of this master thesis, in which a selection of articles is described. The focus is the application of the Life Cycle Cost Analysis (LCCA) for the economic evaluation of retrofit projects and the development of an integration between the economic and the environmental impact analysis for the assessment of the most sustainable refurbishment scenario among alternative retrofit strategies. The selection process have started with the insertion of specific keywords in two open-data sources: Scopus and Web of Science. Then, the articles have been collected according to five criteria: the year of publication, the geographical area of the analysis, the application context, the scientific disciplinary sector and the type of publication. In particular, the first two criteria are related to the regulatory framework on the energy performance of buildings. Therefore, the articles are considered in the European context and over the period 2002-2012 that is from the first EPBD Directive 2002/31/EC.

The 17 selected articles have been divided in three groups on the basis of the focus of the research: manuscripts about LCC analysis, manuscripts about LCC analysis and environmental considerations and manuscripts about LCC analysis and Life Cycle Assessment (LCA). All have been scheduling in a table.

Then, each article has been described in detail on a layout pre-set by the author. The single study of each article has led to the analysis section of this research. Since a limited number of articles and a different methodology in each of them resulted from the research, a new analysis method is proposed. This is not based on the usually adopted typologies of analysis (temporal, geographical, etc...), considered inappropriate in this case, and not useful to a future development on this topic. Instead, the methodology used in each manuscript can be the base information to which link the others. Therefore, after the identification of the methodology used in each article, the documents have been analysed according the interrelation between each methodology of each article and different categories: year of publication, EU Country, building typology and Energy Efficiency Measures (EEMs). For a better comprehension and individuation of the related information, a scheme is used for each methodology-category analysis.

Finally, an environmental analysis is figured out in which the previous distinction of articles in three groups becomes a double distinction in indirect and direct environmental impact considerations. The former analyses how the environmental impacts are indirectly considered in LCCA , for instance through the adoption of the social or individual discount rate, or through the consideration of green technological solutions as alternative scenarios to which compare the base case in the LCCA. Instead, the second group articles are analysed to figure out how the results of LCA and LCCA are integrated in a single outcome, for instance through the eco-efficiency matrix. Therefore, all the considerations described in this last section could pave the way to as many research objects and could serve as a fertile ground for the development of new methodologies which integrate environmental impacts in LCCA in monetary terms.

01

Sustainability: theoretical context

INTRODUCTION

This chapter deals with a theoretical framework about some of the main economic models related to the sustainable development. Before entering the body of the chapter, it is necessary to retrace some dates and related treatises that have been the foundation of sustainable development and how these events clarify the correlation with various topics.
First among them is the economic foundation of the sustainable thinking.
In 1798 Thomas Malthus, in "*Principles of political economy*", states a first correlation between technology (economy), people and planet and about the limitedness of natural resources without using "sustainable" term yet:

"Technological development without regard for environmental and social impacts brings undesired consequences: degradation of air, water and land, loss of biodiversity, resource depletion and increasing inequality".[1]

In relation to the technological and economic growth, the topic of limitedness of natural resources arises.
In 1991 Herman E. Daly in "*Steady-State Economics"* deals with the relation between the use of resources and their limitedness in proportional terms:

"The rate of use of renewable resources must be no greater than the rate of regeneration;
The rate of use of non-renewable resources must be no greater than the rate at which renewable resources can be substituted for them;
The rate of emission of pollutants must be no greater than the rate at which they can be recycled, assimilated, or degraded by the environment". [2]

In1972 the Club of Rome published *"The Limits to Growth"*,[3] a report on the exponential economic and population growth in relation to a finite supply of resources, studied by computer simulation. The document was the first of a series of debates in the 20th century on the ultimate limits imposed by resource depletion and it required the necessity of a global governance.
In the same year, in fact, an Earth Summit was reunited in Stockolm; it was the first international conference by United Nations, which focused on the necessity to take international actions for protecting the environment.

(1) MALTHUS T (1798). *Principles of political economy.* Cambridge University Press .1 January 1989

(2) DALY H.E. (1991). *Steady-State Economics. The new paradigm.* The Johns Hopkins University Press

(3) CLUB OF ROME. (1972). *The limits to growth.* https://www.clubofrome.org/publication/the-limits-to-growth/

The result was the "Stockholm Declaration", which resulted in a declaration on the state of the global environment and 26 principles for protecting it. Other important international treaties followed the Stockolm Declaration, such as the Agenda 21 by the Earth Summit in Rio de Janeiro in 1992, the Alborg Charter and ICLEI foundation in 1994, the Kyoto Protocol in 1997.
In 1992 the same authors of *"Limits to Growth"* published "*Beyond the Limit of Growth"*,from which the well known IPAT equation derives:[4]

I = P x A x T
Impact = Population x Affluence x Technology
where
Affluence = consumption / per person
Technology = Impact / per consumption

A milestone of the sustainable development concept is the Brundtland Report in1987, also known as Our Common Future, released by the World Commission on Environment and Development (WCED). The first definition of sustainable development is attributed to this document:

"Sustainable development meets the needs of the present without compromising the ability of future generations to meet their own needs".[5]

Therefore, the social component is inserted in addition to the economic and environmental ones. The direct consequence is the born of PPP thinking (planet, people, prosperity) and, thus, the definition of three pillars of sustainability: economic, social and environmental.
1987 is also an important year for the awareness raising on another topic, the climate change. In fact, the Intergovernmental Panel on Climate Change (IPCC) is founded in 1987 to provide the world with a clear scientific view on climate change and its consequences.
Among various documentation, in 2007 the IPCC publishes a report in which the correlation between carbon dioxide in the atmosphere and climate change is established beyond any doubt. Since then, important strategic actions and international policies occur until to define the seventeen Sustainable Development Goals (SDGs) in 2015 by 2030 UN Agenda.
As concerns policies, norms and action plans in the European context refer to the second chapter of this research thesis.
Instead, in this chapter the theoretical sustainable context in Europe is treated.
After the excursus on the sustainable development and the delineation of the main topics, the chapter deals with two macro-economic models born to achieve the goals of a global sustainable development.

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(4) CLUB OF ROME (1992). *Beyond the limits to growth.* The Donatella Meadows project. https://donellameadows.org/archives/beyond-the-limits-to-growth/

(5) WCED (1987). *Our Common Future.* Brundtland Report.

In the first section, the model of Circular Economy (CE) is treated in depth. The CE model faces one of the main topics of sustainability, that is the limitedness of the natural resources, as it has been described in the excursus. It is based on an economic growth inversely proportional to the use and consumption of raw materials, which is possible thanks to the prolongation of the life span of resources.
The second section deals with the model of the Green Economy (GE), in which the CE model can be inserted. In fact, GE has a broader focus and it is described as:

"*an economy that can secure growth and development, while at the same time improving human well-being, providing decent jobs, reducing inequalities, tackling poverty and preserving the natural capital upon which we all depend*". (6)

The sustainable topic of climate change is correlated to both CE and GE economic models; the reduction of GHGs emissions is a direct effect.
The built environment has a central role in the fight against the climate change. Moreover, it affects all three pillars of sustainability.
At the end of each of the two sections, a focus on the built environment is dealt and, in particular, the application of the CE and GE models on existing building stock in Europe is treated.

(6) EUROPEAN COMMISSION (2011). *Rio+20.Towards a green economy and better governance*. Brussel. 20 June 2011. p 5.

1.1 CIRCULAR ECONOMY (CE)

In this section, the Circular Economy model is treated. Most of the information is taken from the average of reports written by the Ellen MacArthur Foundation over the years,(1) which has been the first to develop a business model from the concept of Circular Economy.
First, a description of the main aspects of the actual linear economy model is delineated, besides data showing its negative effects at global level; in this part it is also showed a circular scenario to allow a comparison with the linear one.
The second part deals with the Circular Economy model by explaining the basic principles and by detailing its system components; further, a detailed description of benefits and opportunities of the CE model is presented.
The next part deals with the CE application to the built environment, in which weakness points can be strengthened by new and developing strategies. The section ends by dealing with the opportunity of retrofitting the existing buildings in Europe to reach a sustainable society, primarily after the pandemic.

1.1.1 FROM A LINEAR TO A CIRCULAR MODEL

The circular economy is an alternative economic model to the actual "linear” model, which follows a ‘take-make-dispose’ pattern. In a linear economy, companies extract materials, apply energy and labour to manufacture a product, and sell it to an end consumer, who then discards it when it no longer serves its purpose. The circular model, instead, deletes the end-of-life phase by products life cycle and inserts the recycle-reuse-repair phase.

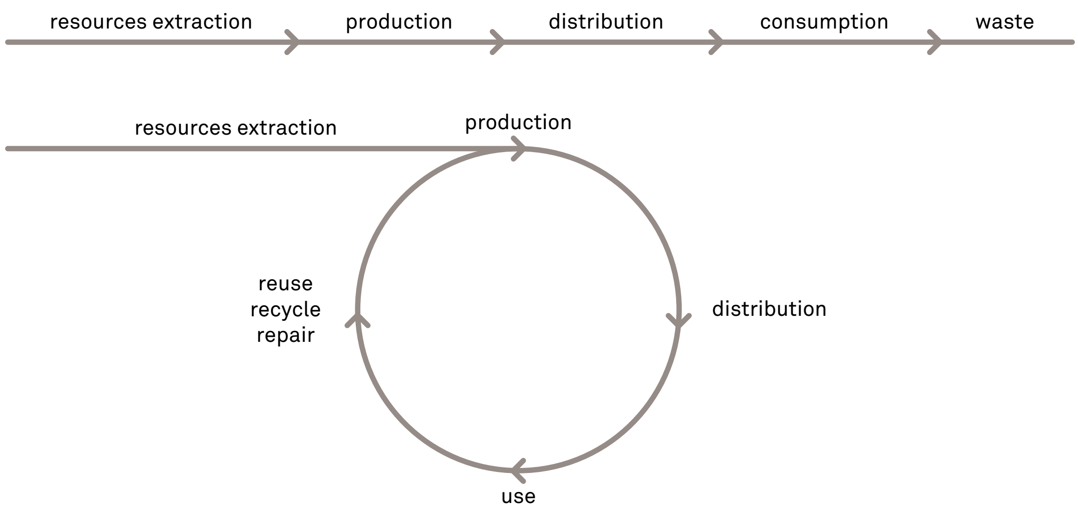

Figure 1 The linear and circular models
Source: Author elaboration

(1) ELLEN MACARTHUR FOUNDATION. *Publications.* Available online https://ellenmacarthurfoundation.org/publications

The linear economy had been convenient until 2000, when raw materials prices were quite low and accessible by business companies.[2]

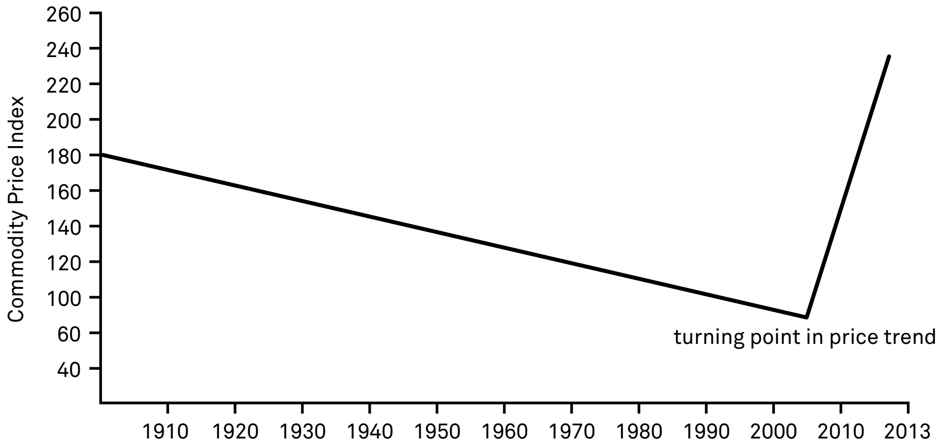

Figure 2 Commodities price trend in the last century
Source: Author re-elaboration from Ellen MacArthur Foundation (2014). *Towards the circular economy. Accelerating the scale-up across global supply chain*, Report. p.13

Figure 2 above shows a dramatic increase of resource prices after 2000, which carried the producers to start to quest for a decoupling of the revenues from material inputs.
The Circular Economy can meet this request and this is clear since the definition of the new model by Ellen MacArthur Foundation:

“The term ‘circular economy’ denotes an industrial economy that is restorative by intention and design. In a circular economy, products are designed for ease of reuse, disassembly and refurbishment, or recycling, with the understanding that it is the reuse of vast amounts of material reclaimed from end- of-life products, rather than the extraction of resources, that is the foundation of economic growth”. [3]

Figure 3 shows the benefits of a circular scenario compared to the actual linear model in economic terms in the European context.
In the figure a current development scenario, that is the actual linear model, and a circular scenario are compared with the situation at present (2014). The systems of three human needs - mobility, food and built environment - are analysed. At present, Europe spends € 7.2 trillion every year, out of which € 1.8 trillion are primary resource costs, € 3.4 trillion are other related cash-out costs and € 2.0 trillion are externalities, such as traffic congestion, CO_2 (€29/tonne), no monetary health impacts of noise and pollution, land opportunity costs, negative health effects caused by indoor environment and transport time.

(2) ELLEN MACARTHUR FOUNDATION (2014). *Towards the circular economy. Accelerating the scale-up across global supply chains.* Ellen MacArthur Foundation, Rethink the future. Report, p 13.

(3) ELLEN MACARTHUR FOUNDATION (2012). *Towards the circular economy. Economic and business rationale for an accelerated transition.* Ellen MacArthur Foundation, Rethink the future. Report, p 14.

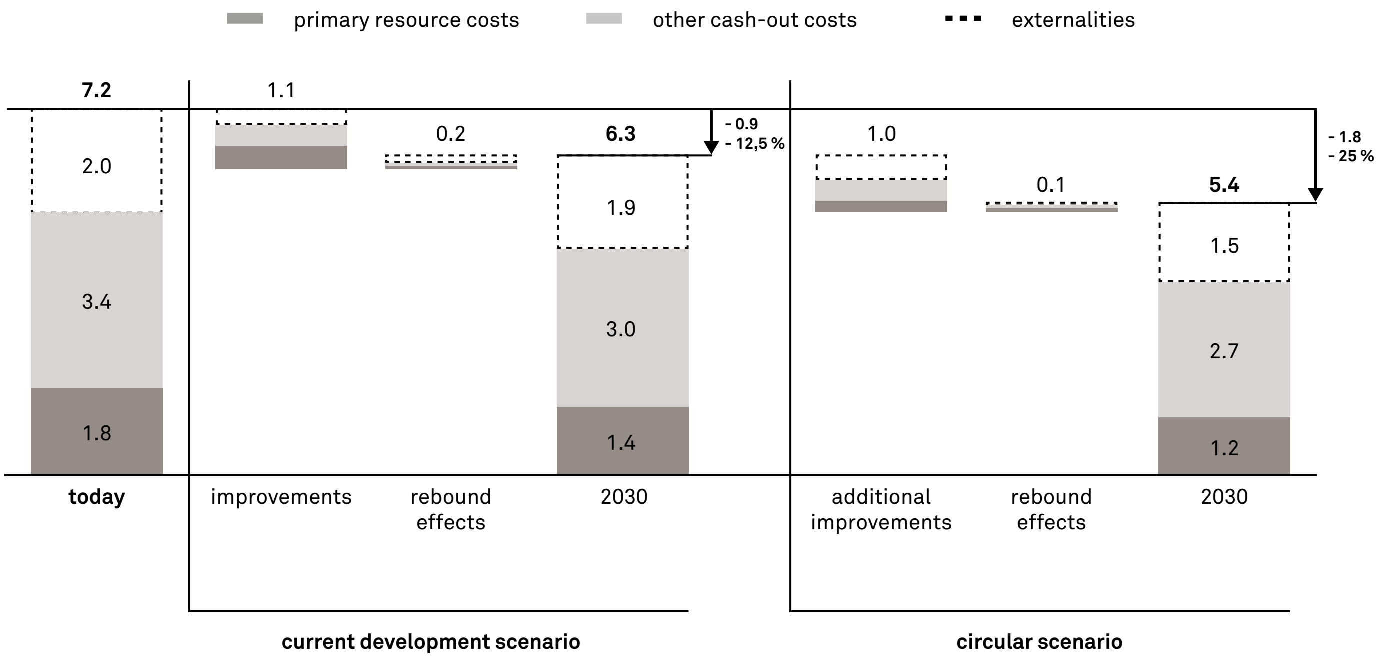

Figure 3 Mobility, food and built environment, EU-27, societal perspective 2030
Source: Author re-elaboration from Ellen MacArthur Foundation (2015). *Growth within: a circular economy vision for a competitive Europe.* Report, p.13

In a current development scenario, Europe would reduce its costs by € 0.9, that is 12.5 %, by 2030; instead, in a circular scenario Europe would reduce the expenditures by € 1.8, that is 25 %, by 2030. In the figure the rebound effect is considered, that is an utilization increase of goods after a decrease of the relative prices; this effect would increase prosperity, but, if not managed well, could exacerbate externalities and resource challenges.

As shown in Figure 3, externalities are considered both in the linear and in the circular scenarios. However, the linear model had been pursued so far (and it is carried on today as well) also because the indirect costs, precisely the externalities, have not been considered although its relevance in the production chain.

Moreover, business companies and producers have started to doubt on the production-consumption model because of the increased exposure to risk, since the resource prices will continue to increase (see Figure 2) as populations grow and urbanise and it will be more and more difficult to reach the extraction locations. Besides the prices increase, many consumers markets are facing a stagnating demand.

Further, the producers have started to account the large losses occurred all along the material chain. The Ellen MacArthur Foundation explains several ways through which the unnecessary losses occur in a linear model.[4]

(4) ELLEN MACARTHUR FOUNDATION (2012). *Towards the circular economy. Economic and business rationale for an accelerated transition.* Ellen MacArthur Foundation, Rethink the future. Report, pp 14-18.

Waste in the production chain	
	21 billion tonnes / year in OECD countries
End-of-life waste	
	+ 65 billion tonnes in 2010 **+ 82 billion tonnes in 2020** of raw materials entered in the world **+ 2.6 billion tonnes in 2010** of EU waste of which only 40% recycled/reused
Energy losses	
	In a linear model all the residual energy is lost because of the disposal of products. The extraction of raw materials is the most energy consumer part in a supply chain.
Ecosystem services erosion	
	Humanity now consumes more than the productivity of Earth's ecosystems can provide sustainably, and is thus reducing the Earth's natural capital.

Figure 4 The linear model losses.
Source: Author elaboration from Ellen MacArthur Foundation (2012). *Towards the circular economy. Economic and business rationale for an accelerated transition.* Ellen MacArthur Foundation, Rethink the future. Report, pp 14-18.

1.1.2 CE MODEL IN DETAIL

The circular economy is a system that is restorative by intention. It goes beyond the actual production-consumption chain. Products are designed to turn back their life cycle, not to be discarded. In this way manufacturers retain the ownership of the products that are sold to be “used” not just “consumed”and, consequently, “consumers” become “users”.
The circular economy is based on three principles:

DESIGN OUT WASTE AND POLLUTION

“What if waste and pollution were never created in the first place?

A circular economy reveals and designs out the negative impacts of economic activity that cause damage to human health and natural systems. This includes the release of greenhouse gases and hazardous substances, the pollution of air, land, and water, as well as structural waste such as traffic congestion”. [5]

KEEP PRODUCTS AND MATERIALS IN USE

“What if we could build an economy that uses things rather than uses them up?

A circular economy favours activities that preserve value in the form of energy, labour, and materials. This means designing for durability, reuse, remanufacturing, and recycling to keep products, components, and materials circulating in the economy. Circular systems make effective use of bio-based materials by encouraging many different uses for them as they cycle between the economy and natural systems”. [5]

REGENERATE NATURAL SYSTEM

“What if we could not only protect, but actively improve the environment?

A circular economy avoids the use of non-renewable resources and preserves or enhances renewable ones, for instance by returning valuable nutrients to the soil to support regeneration, or using renewable energy as opposed to relying on fossil fuels”. [5]

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(5) ELLEN MACARTHUR FOUNDATION. *What is the circular economy?* Official Website. https://archive.ellenmacarthurfoundation.org/circular-economy/what-is-the-circular-economy

Figure 5 below graphically shows the CE model. It is built on several school of thoughts, but it is perhaps most recognisably influenced by Cradle to Cradle's theory.
The figure below shows a system effectively working at every scale and composed of two cyclical flows: biological and technical.

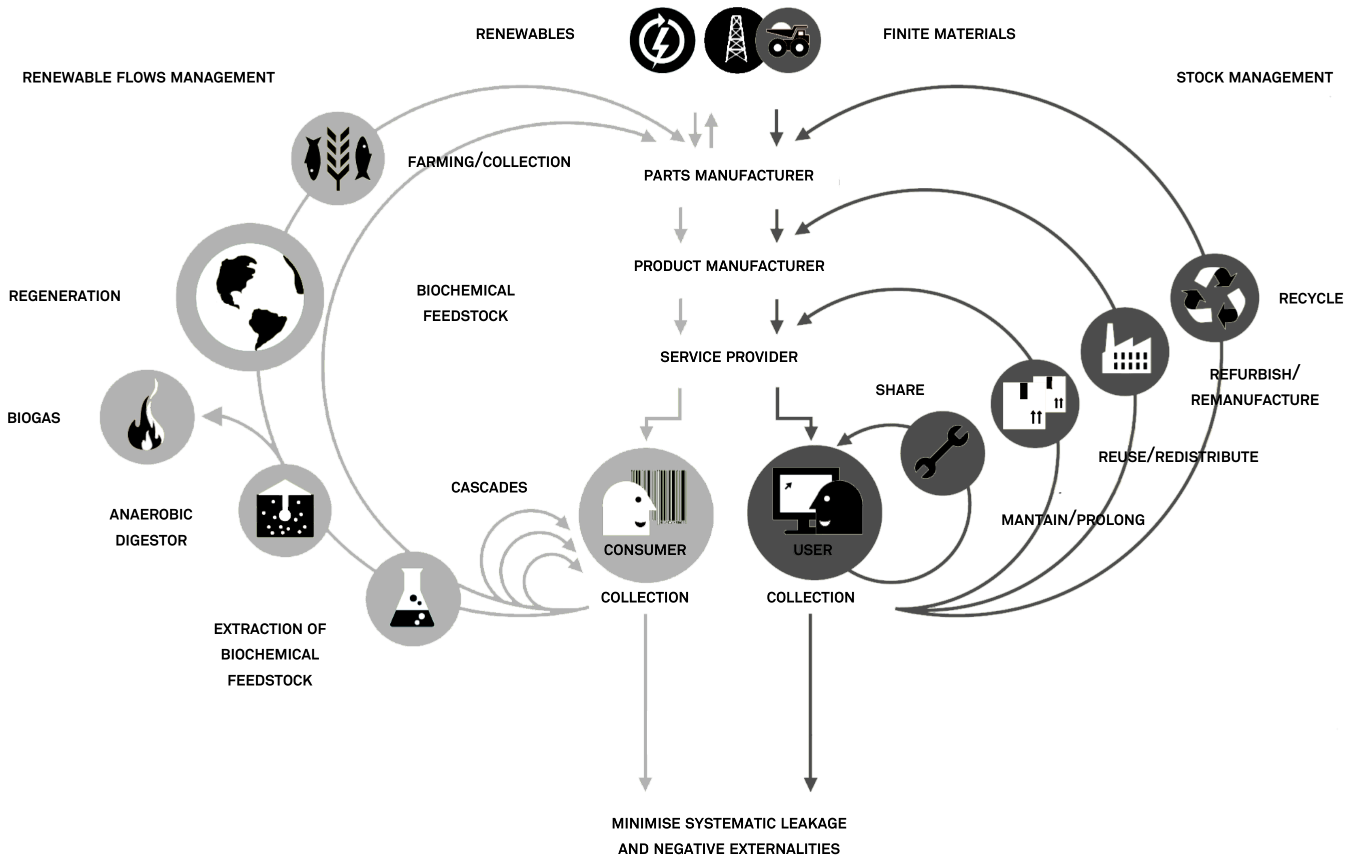


Figure 5 The Circular Economy system.
Source: Ellen MacArthur Foundation (2012). *Towards the circular economy. Economic and business rationale for an accelerating transition*. Report. p.24

Biological materials - represented in light grey on the left side of the figure - are those materials that can be reintegrated into the natural world,once they have gone through one or more use cycles. They will naturally become nutrients for the environment after a bio-degradation.

Technical materials - represented in dark grey on the right side - cannot re-enter the environment and must continuously cycle through the system so that their value can be captured and recaptured.

In a true circular economy, consumption is substituted by use, except in the biological cycle because of the natural degradation of the products and their transformation of nutrients for the Earth. However, even if natural degradation occurs in the biological cycle, the circular economy ensures a flow management so as not to exceed the carrying capacity of the Earth and allows the enhancement of natural capital through the regeneration.
Besides the biological cycle, in the technical cycle the value of the finite resources is maximized from the outermost to the innermost cycle with the huge contribution of the technological development.
The CE system is structured on the three basic principles of the circular economy, deeply described at page 22, and reported below:

1. Design out waste and pollution;
2. Keep products and materials in use;
3. Regenerate natural system.

Ellen MacArthur Foundations has tried to "measure" the circular economy through the utilizations of primary metrics. Further, EMF has translated CE principles into six business actions, representing the so-called ReSOLVE framework. (6)
Figure 6 below is a schematization of the three principles, the primary metrics for measuring them and the ReSOLVE framework actions.

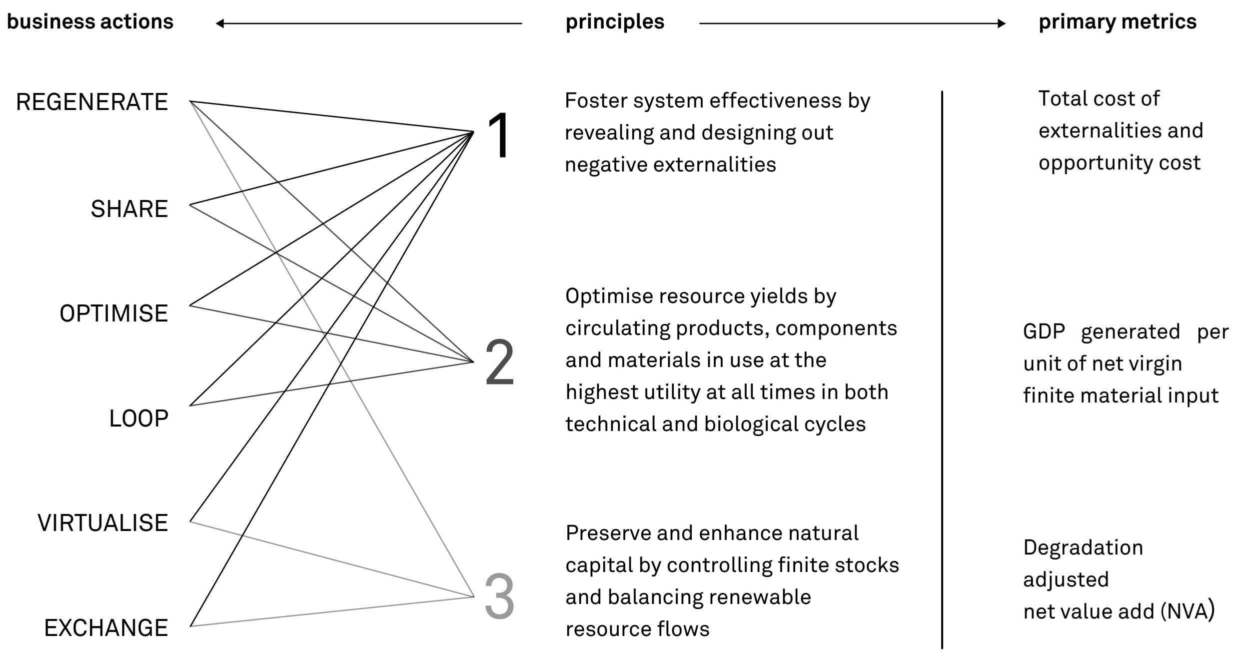


Figure 6 Measuring the Circular Economy.
Source: Author elaboration from
Ellen MacArthur Foundation (2015). *Growth within: a circular economy vision for Europe.*
Ellen MacArthur Foundation, McKinsey Center for Business and Environment. Report, pp 23-26.

(6) ELLEN MACARTHUR FOUNDATION (2015). *Growth within: a circular economy vision for Europe.* Ellen MacArthur Foundation, McKinsey Center for Business and Environment. Report, pp 23-26.

1.1.3 BENEFITS AND OPPORTUNITIES

Circular economy provides benefits for all three sustainable fields (economy, environment,society) and opportunities for the stakeholder involved. Ellen MacArthur Foundation clearly explains the benefits and opportunities of a circular economy scenario.(7)
These information are schematised below.

Economic benefits

economic growth	Europe GDP **+ 11% by 2030** **+ 27% by 2050**
substantial net material cost savings	medium-lived products **+ USD 630 billion** fast moving consumer goods **+ USD 700 billion**
job creation potential	job opportunities **+ 7.300-13.300 by 2035**
innovation	technological development improved materials labour energy-efficiency

Figure 7.1 CE Economic Benefits
Source: Author elaboration from
Ellen MacArthur Foundation (2015). *Towards the circular economy: business rationale for an accelerated transition.* Report, p 11.

(7) ELLEN MACARTHUR FOUNDATION (2015). *Towards the circular economy: business rationale for an accelerated transition.* Ellen MacArthur Foundation, Report, pp 11-15.

Environmental benefits

carbon dioxide emission	Europe CO_2 emission **- 48% by 2030** **+ 83% by 2050** across mobility, food system and built environment
primary material consumption	**- 32% by 2030** **+ 53% by 2050**
land productivity and soil health	avoid worldwide land degradation cost **USD 40 billion** Europe synthetic fertilizers consumption **- 80% by 2050**
negative externalities reduction	time lost to congestion cost **- 16% by 2030** **- 60% by 2050** for households

Figure 7.2 CE Environmental Benefits
Source: Author elaboration from
Ellen MacArthur Foundation (2015). *Towards the circular economy: business rationale for an accelerated transition.* Report, p 12.

Opportunities for companies

profit opportunities	- input costs + new profit streams + medium-lived products and fast moving consumer good improvements
reduced volatility and greater security of supply	- virgin materials + recycled inputs + share of labour costs - exposure to price volatility + resilience
new demand for business services	+ companies that support end of life products + sales platform that reuse products + specialised knowledge on product refurbishment
improved customer interaction and loyalty	+ longer-term relationship with customers + quality of products + customers satisfaction

Figure 7.3 CE Opportunities for Companies
Source: Author elaboration from
Ellen MacArthur Foundation (2015). *Towards the circular economy: business rationale for an accelerated transition.* Report, pp 13-14.

Opportunities for individuals

increased disposable income

Europe households income
+ 3000 € or 11% by 2030

greater utility

+ products for customers real needs

reduced obsolescence

+ budget
+ quality of life

Figure 7.4 CE Opportunities for Individuals
Source: Author elaboration from
Ellen MacArthur Foundation (2015). *Towards the circular economy: business rationale for an accelerated transition.* Report, pp 14-15.

1.1.4 THE BUILT ENVIRONMENT

The built environment is one of three main sectors of interest of circular economy, together with mobility and food. In fact, buildings, infrastructure and food influence all three pillars of sustainability and have a global impact.
For Europe, the built environment is a crucial topic. Each European household spends a direct average annual cost of € 9.600, or 27 percent.The average rises to € 15.500 by including societal and opportunity costs. EMF specifies that:

"Direct user cash-out cost includes annualised rent or purchase price, maintenance, utility costs (energy and water), insurance, appliances, and accommodation services. Societal cash-out costs include office space and government expenses for social housing, community development, street lighting, and waste management. Opportunity costs include CO_2 emissions, health effects due to indoor air quality, and transport time to and from work as this is strongly related to urban design and virtual offices."[8]

Construction is one of the largest economic sectors of the European economy since it represents the 8.8 percent of Gross Domestic Product (GDP) and almost 14 million jobs.

9.600 - 15.000€
or
27% - 42%
per household / per year

8.8% EU GDP
14 million jobs

Although the energy efficiency of buildings has been at the heart of strategies and regulations for many years in Europe (see Chapter 2), they are responsible for approximately 40% of EU energy consumption and 36% of the GHGs emissions. Buildings are therefore the single largest energy consumer in Europe.[9]

40%
EU energy
consumption

36%
EU CO_2
emissions

(8) ELLEN MACARTHUR FOUNDATION (2015). *Growth within: a circular economy vision for Europe.* Ellen MacArthur Foundation, McKinsey Center for Business and Environment. Report, p 82.

(9) EUROPEAN COMMISSION (2020). *In focus: energy efficiency in buildings.* Official website. https://ec.europa.eu/info/news/focus-energy-efficiency-buildings-2020-feb-17_en

Moreover, the construction sector remains too wasteful. Four main factors accounting for most of this waste are schematised below: (10)

Low productivity in construction

10-15% wasted material

+0/0.5% production in some EU Countries
+2% in others

Under - or over - utilisation

60 % not used offices

but

50% overcrowded dwellers

Energy consumption

40 % energy consumption

20-40 % energy consumption reduction thanks to energy management

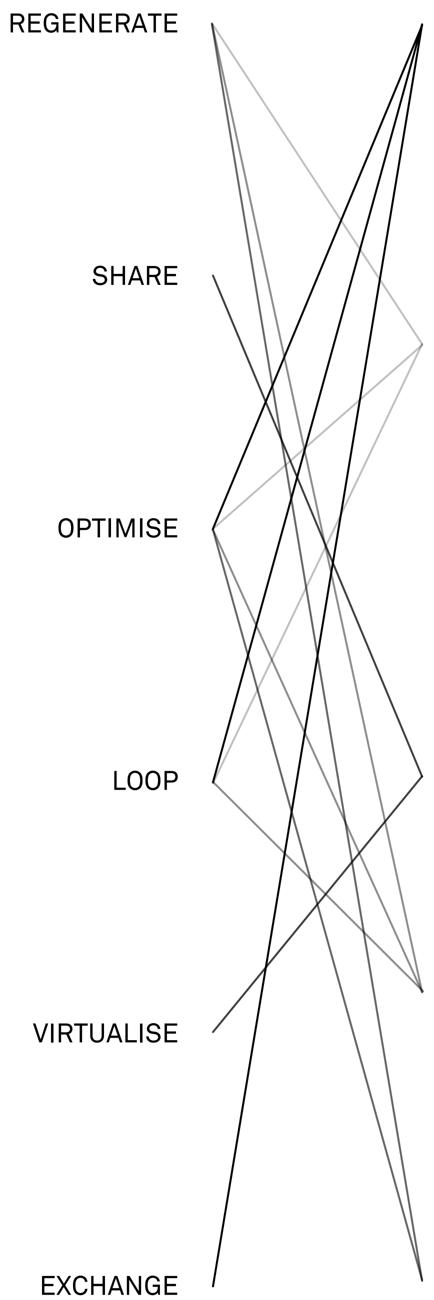
End-of-life waste and toxic materials.

54 % landifilled materials in some EU countries

6% in others

Figure 8 The main causes of waste in construction sector.
Source: Author elaboration from Ellen MacArthur Foundation (2015). *Growth within: a circular economy vision for Europe.* Ellen MacArthur Foundation, McKinsey Center for Business and Environment. Report, pp 82-83.

The six strategies of the “ReSOLVE Framework” of circular economy (see CE in detail) can be applied to the built environment. Figure 9 below shows six levers that could transform the built environment in a less wasteful sector and it links them to the the six business action of the ReSOLVE Framework.



1	Industrial production and 3D printing	**30 %** costs reduction **50%** delivery time reduction **30-60%** less material
2	Energy generation and use	up to **90 %** heating and cooling energy savings in passive houses for just **10%** more on investment costs **20-30%** energy consumption reduction after retrofitting of existing houses
3	Share residential and office spaces	sharing is more convenient and trusted **60 %** not used offices
4	Modularity and durability	more flexibility of space **80%** reused components of a building envelope 100 years durable
5	Urban planning	CO_2 emission reduction **75%** land use reduction

Figure 9 CE actions in the built environment
Source: Author elaboration from Ellen MacArthur Foundation (2015). *Growth within: a circular economy vision for Europe.* Ellen MacArthur Foundation, McKinsey Center for Business and Environment. Report, pp 84-86.

1.1.5 THE OPPORTUNITY OF THE BUILDING RENOVATION

As it has been described in the previous section, buildings are responsible for approximately 40% of Europe energy consumption and 36% of the greenhouse gas emissions. The built environment is therefore the single largest energy consumer in Europe.
At present, about 35% of the EU's buildings are over 50 years old and almost 75% of the building stock is energy inefficient. At the same time, only about 1% of the building stock is renovated each year. (11)

35% EU building is **50** years old	**75%** EU building is energy inefficient	only **1%**/year EU building is renovated

Moreover, the COVID19-Sars pandemic has showed the deep weaknesses of the built environment sector, bringing to light the prevalence of low-quality buildings, the difficult affordability of decent housing, and the lack of adaptability of the EU current building stock.
European Commission has looked to the renovation of existing buildings as an important sector on which to "recover" the whole continent. Indeed, the energy refurbishment of existing buildings could reduce the EU's total energy consumption by 5-6% and lower CO_2 emissions by about 5%. In addition, the energy efficiency investments positively influence the economy, especially the construction industry, which generates about 9% of Europe's GDP and directly accounts for 18 million direct jobs.

-5/6% energy consumption after renovation	**-5%** CO_2 emission after renovation	**+9%** EU GDP by the construction industry	**+ 18.000 million** of direct jobs by the construction industry

In this context, the European Commission has launched the Green Deal action plan to restart from a sustainable and green economy model (see chapter 2).
As an integral part of this European strategy, the circular economy is a framework for resilience and regeneration that delivers on multiple policy objectives.

(11) EUROPEAN COMMISSION (2020). *In focus: energy efficiency in buildings.* Official website. https://ec.europa.eu/info/news/focus-energy-efficiency-buildings-2020-feb-17_en

(12) ELLEN MACARTHUR FOUNDATION (2020). *The circular economy: a transformative Covid-19 recovery strategy.How policymakers can pave the way to a low carbon, prosperous future* Ellen MacArthur Foundation. Report.

The Ellen MacArthur Foundation highlights how policymakers can help pave the way towards a lowcarbon and prosperous future.[12] EMF has identified five key sectors on which act to start a "recovery" strategy after the pandemic; not for nothing, the first one is the built environment, followed by mobility, plastic, packaging , fashion and food. After that, two circular investment opportunities are highlighted for each sector for a total of ten attractive circular investment opportunities which address both the short and long-term goals of the public and private sectors.
Figure 10 below schematises two circular actions for the built environment.

1 Renovation and upgrade of the buildings	
	for every **EUR 1** invested in energy refurbishment, up to **EUR 5** in public finance returns **2 million** energy refurbished homes create **2 million** new jobs in EU Countries of 50-70 million people renovations lowering energy use by **40%** can reduce GHG emissions by **63%** in the residential sector
2 Building materials reuse and recycling infrastructure	
	GHG emissions in the G7 countries could be reduced by **14–18%** in 2050 by improved recycling of construction material processing recycled aggregates can reduce GHG emissions by **40%** or more compared to virgin materials designing steel elements for reuse could generate savings of **2–10%** for a whole building and up to **25%** savings in material costs

Figure 10 The Covid-19 Recovery Strategy in the Built Environment.
Source: Author elaboration from Ellen MacArthur Foundation (2020). *The circular economy: a transformative Covid-19 recovery strategy. How policymakers can pave the way to a low carbon, prosperous future* Ellen MacArthur Foundation. Report, pp 22-28.

1.2 GREEN ECONOMY (GE)

This section deals with an argumentation of the Green Economy model. First, a clarification of the term origins, the concept definition and the main strategic guidelines are explained both at global and at European level.
Then, a comparison between the Green Economy and the previous treated Circular Economy systems and their interest areas are analysed.
Finally, the Green Economy is specifically related to the built environment as well as it has been done with the circular model. Green buildings are treated by reporting information on the construction sector data about the environmental impact and their correlation with Sustainable Development Goals. Even this section deepens at the end the importance of the existing buildings in fight against the climate change and it deals with the green retrofitting action.

1.2.1 ORIGINS,DEFINITIONS AND GUIDELINES

The term "green economy" was first used in 1989 in the *“Blueprint for a Green Economy”* report for the Government of the United Kingdom written by a group of environmental economists. The report was commissioned to advise the UK Government if there was a correlated definition to the term “sustainable development” for the measurement of economic progress and the appraisal of projects and policies.
Therefore, the green economy concept derives from economy as the sustainable development concept, being the two closely related. Indeed, even if there is not an internationally agreed definition, the concept of green economy was carried out by UNEP (United Nations Environment Programme) since 2008 in relation to the financial crisis and the need for global initiatives to stimulate economic recovery and sustainability of the world economy.
One of the key reports was the flagship Green Economy Report released by UNEP in November 2011 under its Green Economy Initiative.
The Green Economy had been the main topic of Rio+20 United Nations Conference of Sustainable Development, held in 2012 in Rio de Janeiro.
After twenty years from the Rio Summit in 1992, the world was still facing two major and closely related phenomena: a global population set to grow by over a third by 2050, and the climatic crisis pressure. However, as described in the introduction of this chapter, the most influencing events for the sustainable development show the importance and efficacy of a global action.

As regards to the European context, the report *"Rio+20: towards the green economy and better governance"* held by European Commission in 2011 in occasion of the UNEP Summit, is considered the flagship of the Green Economy development in Europe. The report gives a clear definition of green economy:

"an economy that generates growth, creates jobs and eradicates poverty by investing in and preserving the natural capital offers upon which the long-term survival of our planet depends." (1)

The document is widely based on existing sustainable development strategies such as Europe 2020 (2010), with particular reference to the fourth flagship related to the resource efficiency and the aim to decouple the use of natural resources from the economic growth while starting a series of new actions on raw materials, energy efficiency, biodiversity, as well strategy to decarbonise the economy, energy and transport.
According to what it is described in the report, a green economy could attempt to this objectives but it is necessary preserve and invest in the assets of key natural resources, that is the natural capital.
An important characteristic of the green economy model is that offers opportunities to all Countries, regardless of their level of development because all have even common challenges and targets to reach.
A direct effect is an international cooperation for sharing the gained knowledge and experiences.
Although the green economy model is adaptable to all countries, it is particular interesting for the developing countries, which have the opportunity to grow their economies, by building on the sustainable management of their natural capital, making use of low-carbon solutions and promoting sustainable consumption and production paths.
Further, it is a model not totally new and it is not require the necessity to start from zero, because it can be built on a wide number of existing strategies and actions.
By following these already in place policies, the report identifies three policy dimensions for achieving a transition towards a green economy. Figure 1 is an Author elaboration that synthesizes the three policies.

(1) EUROPEAN COMMISSION (2011). *Rio+20.Towards a green economy and better governance*. Brussel. 20 June 2011. p 5.

1 What?	
Investing in the sustainable management of key resources and natural capital	key resources areas and strategies: **water** quality and efficiency **energy** renewable and efficiency **oceans and seas** global management **land** conservation and sustainable **agriculture** **forests** protection and management **materials** improvement and **waste management**
2 How?	
Establishing the right market and regulatory conditions	combination of **regulatory** and **market-based** instruments in a flexible and cost-effective way deleting of **environmentally harmful subsidies** that are the major obstacle to green economy transition mobilization of **large scale financial resources** to stimulate **eco innovation, environmental technologies and green SMEs** improvement of **new skills** and **know-how** for ensuring **new and decent jobs** improvement of **scientific and research cooperation** to build a sustainable future

	enhancing a **mutual supportiveness between trade and sustainable development** to support sustainable patterns of supply and demand at international level
	creation of new comparable metrics and indicators for **ensuring and measuring progress**
3 Who?	
Improving governance and private sector involvement	reinforce and mainstream **sustainable development governance** within the UN system and at the same time corresponding the attention to r**egional, national and local structures**
	reinforce **international environmental, economic and social governance** within the UN system
	stress the important role of **non-state actors** (women, youth, workers, farmers, local governments, business and industry, the scientific community and NGOs) by improving the **participation of business**

Figure 1 The Green Economy Guidelines
Source: Author elaboration from EUROPEAN COMMISSION (2011). *Rio+20.Towards a green economy and better governance*. Brussel. 20 June 2011. pp 6-10

1.2.2 GE AND CE MODELS IN COMPARISON

As it has been described in the first section of this chapter, in the circular economy the value of products, materials and resources is maintained in the economy for as long as possible, and the generation of waste is minimised. In this model, the economic growth is decoupled from raw materials depletion and waste management and reduction has a central role. It can be considered an alternative business model and represents a huge contribution to the achievement of sustainable development goals.

The green economy, instead, can be defined as the concretization of the sustainability in all its principles and interlinkages. It does not focus on the economic growth as the ultimate goal, but it is extended to the ecosystems resilience and human well-being.

According the European Environmental Agency (EEA), the green economy is represented by the intersection of ecosystem, economy and human well-being as well as sustainability is underpinned by the three pillars of environment, economy and society (or planet, prosperity and people). (2)

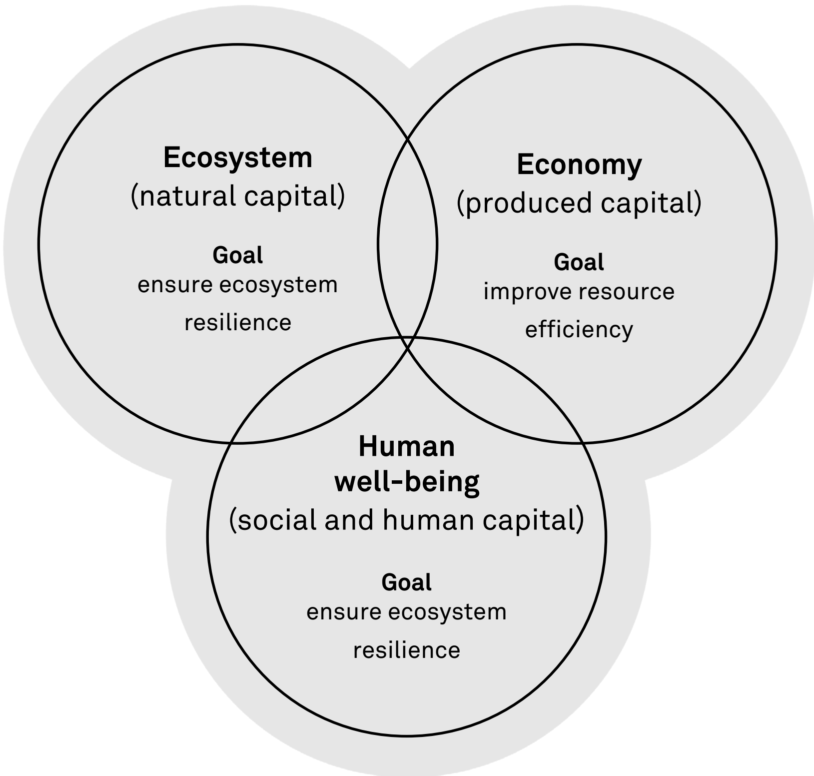


Figure 2 The Green Economy model according IEA
Source: Author elaboration from European Commission (2018). *The inclusive green economy in EU development cooperation. An innovative approach at the instersection at the EU Planet, People and Prosperity objectives*. Report. p.4

(2) European Commission (2018). *The inclusive green economy in EU development cooperation. An innovative approach at the instersection at the EU Planet, People and Prosperity objectives*. Report. p.4

In 2012 the International Chamber of Commerce (ICC) published the *"Green Economy Roadmap: a guide for business, policymakers and society"*, [3] to assist in the development and implementation of policies and actions towards a green economy.

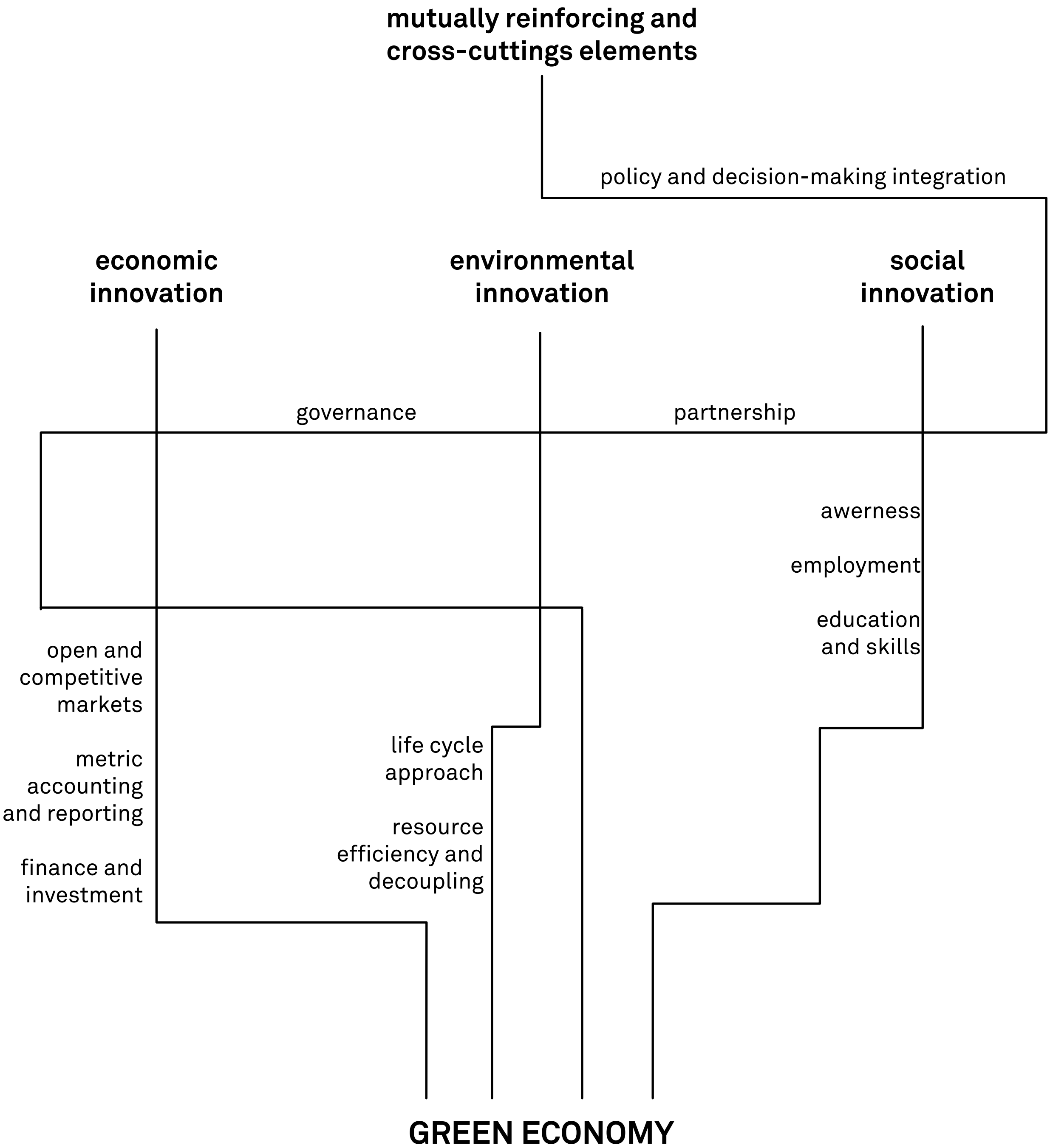


Figure 3 The Green Economy Roadmap
Source: Author elaboration from International Chamber of Commerce (2012). *Green economy roadmap: a guide for business, policymakers and society.*

(3) International Chamber of Commerce (2012). *Green economy roadmap: a guide for business, policymakers and society.*

The document explains the aim of the Green Economy Roadmap:

"The Roadmap highlights the essential role of business in bringing solutions to common global challenges and calls for innovation, collaboration and governance on ten key conditions to be worked on simultaneously, both bottom up and top down,as well as in the short and long term. These conditions recognize the interdependence of the economic, environmental and social dimensions in the sustainable development and seek to integrate them in a more holistic manner". (4)

This document was released after the report *"Rio+20: towards the green economy and better governance"* in which a quest for a Green Economy Roadmap was stated and the main guidelines were already described.
As it can be seen, the Green Economy is represented by a map and includes guidelines to reach a sustainable development according to a global perspective.
It is not a loop like the Circular Economy model, which is represented by two cyclical flows seeking to shrink their interest area more and more. It is rather a branched strategy that extends and embraces all dimensions, at all scales, involving each Country and stakeholder without neglecting any field.
For these reasons, the circular economy can be considered an essential component of the green economy because of the extension of their interest area.

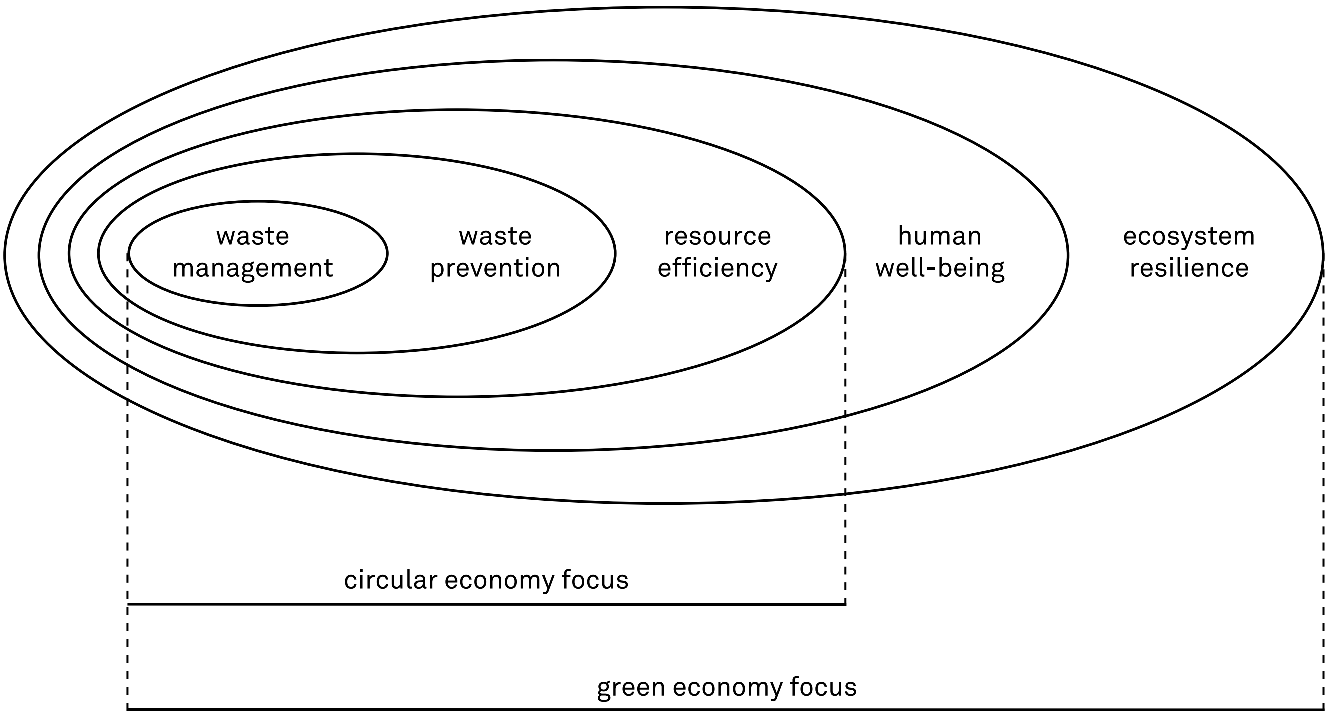


Figure 4 Circular economy focus and green economy focus
Source: Author elaboration from European Commission (2018). *The inclusive green economy in EU development cooperation. An innovative approach at the intersection at the EU Planet, People and Prosperity objectives*. Report. p.5

(4) International Chamber of Commerce (2012). *Green economy roadmap: a guide for business, policymakers and society.*

1.2.3 GREEN BUILDINGS

Architecture plays a pivotal role in the transition to a sustainable society. Buildings represent a dominant sector in the use of energy and are among the largest sources of GHG emissions in most countries. For these reasons, new buildings are an important source for future emissions, especially in developing countries with a high rate growing populations and a rapid economic growth.
The International Energy Agency (IEA) reports that in 2019 the building sector consumed the largest share of energy (35%) and produced the major amount of CO_2 emissions (38%) in relation to other industries, as showed in Figure 5 below. (5)

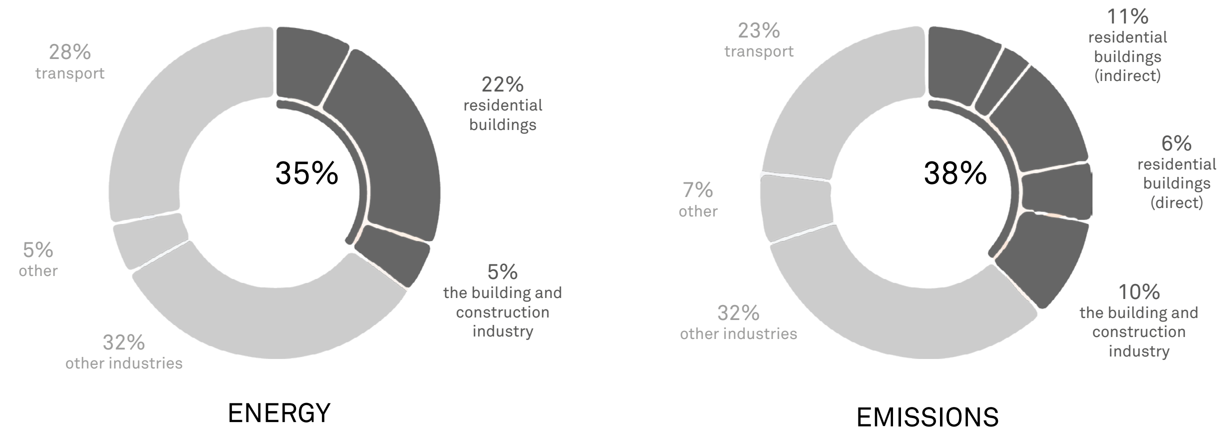


Figure 5. Global share of buildings and construction final energy and emissions, 2019
Source: Author re-elaboration from GlobalABC (2020). *Global status report for buildings and construction*. Report. p.20

However, since 2017 the building energy consumption remained quite stable, whereas the CO_2 emissions reached the highest level ever. Figure 6 below shows the relation with two important drivers of resource consumptions and emissions that are the population growth rate and the added floor space. A positive slightly decrease of the dependence of CO_2 emissions and energy demand from population growth and floor space can be noticed.

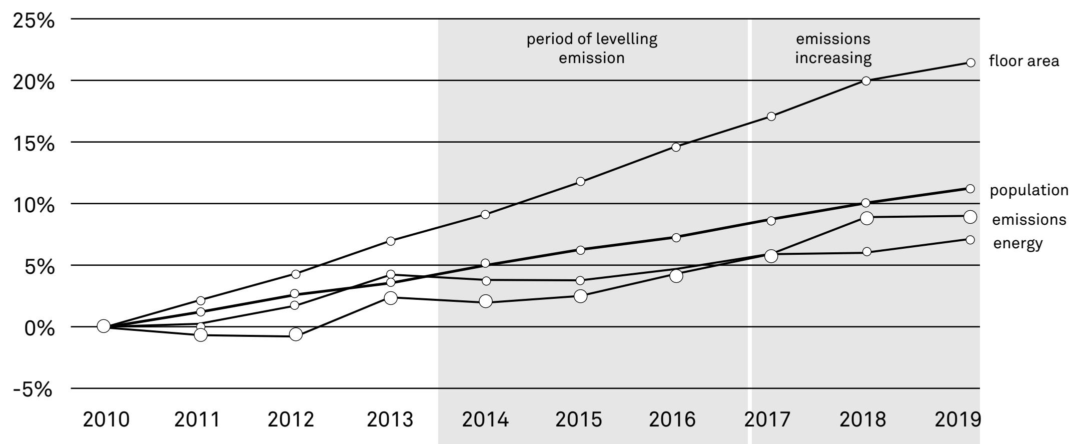


Figure 6. Change in global drivers of trends in buildings energy and emissions 2010-2019
Source: Author re-elaboration from GlobalABC (2020). *Global status report for buildings and construction*. Report. p.19

(5) GlobalABC (2020). *Global status report for buildings and construction*. Report. p.20

The previous data suggest how the built environment must be one of the main policy areas of the green economy strategy and the importance of the green buildings development.
The World Green Building Council is an independent, non-profit organisation made up of businesses and organisations working in the building and construction industry. It gives a clear definition of green building:

"a building that, in its design, construction or operation, reduces or eliminates negative impacts, and can create positive impacts, on our climate and natural environment; green buildings preserve precious natural resources and improve our quality of life". (6)

In relation to the definition of sustainability, a sustainable building should be a system able to keep constant its own performances with time with a limited consumption of energy and materials.
Building sustainability involves aspects connected to: environment, energy efficiency, water consumption, quality of life of its occupants, durability, costs/benefits ratio, and building materials.
There are a number of features which can make a building 'green'. These include:

- efficient use of natural resources (e.g. water, energy);
- use of renewable energy, such as solar energy;
- pollution and waste reduction measures, enabling of re-use and recycling;
- good indoor environmental air quality;
- use of no-toxic and sustainable materials;
- consideration of the environmental impact in all building life cycle phases;
- consideration of the quality of life of occupants;
- design according flexibility and adaptability criteria.

Any building designed according the above features can be considered "green", regardless any other type of structure.
However, since a green building is design in relation to the place where it will be built, not all green buildings can be designed following the same approach. Indeed, different countries and regions have a variety of characteristics such as distinctive climatic conditions, cultures and traditions, building types and ages besides a wide range of environmental, economic and social priorities; all these factors shape characterize the approach to green building design.
Besides the World Green Building Council, many countries host their own council, such as Green Building Council Italia.

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(6) WORLDGBC. *About green buildings*. What is a green building? Official website https://www.worldgbc.org/what-green-building

Green buildings can contribute to the achievement of some of the 17 Sustainable Development Goals (SDGs) for the decoupling of the economic growth from climate change, poverty and inequality.
In particular, nine of seventeen sustainable goals can be reached by a green architecture, as showed in Figure 7 below.

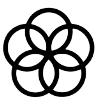
3	GOOD HEALTH AND WELL-BEING		green buildings can improve people health's and wellbeing
7	AFFORDABLE AND CLEAN ENERGY		green buildings can use renewable energy, becoming cheaping to run
8	DECENT WORK AND ECONOMIC GROWTH		building green infrastructure create jobs and boost the economy
9	INDUSTRY, INNOVATION AND INFRASTRUCTURE		green building design can spur innovation and contribute to climate resilience
11	SUSTAINABLE CITIES AND COMMUNITIES		green building are the fabric of sustainable communities and cities
12	RESPONSIBLE CONSUMPTION AND PRODUCTION		green building use circular principles where resources aren't wasted
13	CLIMATE ACTION		green building help to combat climate change using fewer emissions
15	LIFE ON LAND		green building can improve biodiversity, save water resources and help to protect forest
17	PARTNERSHIP FOR THE GOAL		green buildings are a way to create strong global partnership

Figure 7. Green Buildings and Sustainable Development Goals.
Source: Author elaboration from WGBC. *About green buildings. Green buildings and the sustainable development goals* . Official website.
https://www.worldgbc.org/green-building-sustainable-development-goals

To distinguish a “green” from a “conventional” building, certification and rating tools has been developed. Green or sustainable building certifications play an important role for building developers and owners to both distinguish their buildings within the market, but also to highlight their commitment to the principles of sustainable building construction and operation. Such certification represents a market transformation tool where it accelerates the movement of the market and all its stakeholders to a better quality construction practice.
2020 has seen continued growth in the number of green/ sustainable building certification standards and more buildings than ever are being certified. Below a list and a brief description of the best known rating systems in the world, in Europe and in Italy, are presented. (7)

LEED:
The “Leadership in Energy and Environmental Design” rating system is the most diffuse at global level. It has been developed by US Green Building Council in 2000 for rating both new and existing buildings. It has four certification level: certified, silver, gold and platinum. It is based on seven criteria: Sustainable Sites (SS), Water Efficiency (WE), Energy and Atmosphere (EA), Materials and Resources (MR), Indoor Environmental Quality (IEQ), Innovation in design (ID), Regional priorities (PR).
In Italy, GBC Italia adapted LEED system in the Country since 2009.

BREEAM:
The “Building Research Establishment Environmental Assessment Method”, created in 1990, is the oldest green building rating system and it is linked to over 560,000 certified projects in over 50 countries. The BREEAM is measured through 9 categories: management, health and well-being, transport, water, materials, land use and ecology, and pollution.

DGNB:
This green building certification program was created by the German Sustainable Building Council and focuses on promoting sustainable building practices across Europe. DGNB is based on 3 levels of certification - platinum, gold, and silver - defined after the building evaluation on ecological, socio-cultural and function, technical, and process qualities.

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(7) SUSTAINABLE INVESTMENT GROUP (SIG). *Top 12 Green Building Rating Systems* Official website https://sigearth.com/top-12-green-building-rating-systems/

GREEN STAR:

Green Star is an international green rating system, particularly popular in Australia and South Africa, which can be used in a variety of building types. It is assessed in categories (i.e. indoor environmental air quality, energy, transportation, water, materials, land use and ecology, emissions) and also include an innovation category for rewarding projects that created or utilised new approaches to sustainability. The main goal of Green Star is to guide project teams to make conscious decisions regarding energy usage and material selection

PASSIVEHOUSE:
Developed in Germany, Passivehouse is a voluntary standard for the building energy efficiency, which reduces the building's ecological footprint. It results in ultra-low energy buildings that require little energy for space heating or cooling. It can be applied to any structure.
The Passivhaus standard requires that the building fulfills the following requirements:
- use up to 15 kWh/m2 per year for heating and cooling as calculated by the Passivhaus Planning Package, or a peak heat load of 10 W/m2, based on local climate data.
- use up to 60 kWh/m2 per year primary energy (for heating, hot water and electricity).
- leak air up to 0.6 times the house volume per hour at 50 Pa as tested by a blower door.

By late 2008, estimates of the number of Passive house buildings around the world ranged from 15,000 to 20,000 structures. As of August 2010, there were approximately 25,000 such certified structures of all types in Europe.

ITACA:
Developed in 2004 by the Italian Institute for Innovation and Transparency of Procurement and Environmental Compatibility, the ITACA protocol, classifies a building according to the level of sustainability. The credits are 37, grouped within 19 categories in turn distributed in five thematic areas: Site quality, Resource consumption, Environmental loads, Indoor environmental quality, Quality of service. Based on the specific performance, for each criterion and sub-criterion the building receives a score that can vary from -1 to +5, where zero represents the minimum acceptable performance, determined by reference to Italian technical standards and current legislation, or standard construction practice.

1.2.3 GREEN RETROFITTING

The next phase of a sustainable development in the built environment is greening the existing buildings. Existing buildings consume more energy than used in the construction of new ones. For that reason, the greenest action is not build at all and make the existing building stock energy-efficient. As will be described in the second chapter, European Commission has put the building renovation at the centre of its EU Green Deal strategy, especially after the Covid-19 Sars pandemic.
Therefore, the existing building stock demands for a green retrofitting strategy.
The United States Green Building Council (USGBC) defines the green retrofit as:

> *"any kind of upgrade at an existing building that is wholly or partially occupied to improve energy and environmental performance, reduce water use, and improve the comfort and quality of the space in terms of natural light, air quality, and noise—all done in a way that it is financially beneficial to the owner. Then, the building and its equipment must be maintained to sustain these improvements over time".* (8)

Since green retrofitting is strictly connected to sustainability, Figure 8 below summarises the economic, environmental and social benefits and disadvantages of this green action.

economical benefits
- Retrofitting a building is often **less expensive** than to demolish and rebuild, or even to build new
- Since the construction phase is reduced, the **financial cost** is **reduced**
- Building adaptation increases the **building value**

economical drawbacks
- Often **retrofitting costs** are **higher** than new building construction costs

environmental benefits
- **Less energy utilization, pollution, transport energy and resource depletion** in the construction phase
- **No land utilization** which causes habitat degradation, altered ecosystems and bio-diversity, reduced air and water quality

social benefits
- Retrofitting preserves the societal and cultural assets embodied in existing built environment

social drawbacks
- Generally, social goals are not always realized in retrofitting

Figure 8. Green retrofitting sustainable benefits and drawbacks.
Source: Author elaboration from JAGARAJAN R. and others (2017). *Green retrofitting. A review of current status, implementations and challenges*. Renewable and Sustainable Energy Reviews. p 3

Moreover, as for green buildings, some rating systems can be applied for the increased performance of existing buildings as well. Below some certification for greening existing buildings are listed.

LEED EBOM [9]

The “Leadership in Energy and Environmental Design” (LEED) for Existing Buildings: Operation & Maintenance (O&M) Rating System provides a tool for property managers who want to decrase operating costs while increase occupant's productivity in a environmentally responsible manner. LEED EBOM is a set of voluntary performance standards for the sustainable ongoing operation for buildings not undergoing major renovations. It also provides sustainability guidelines for building operations. Moreover, it is based on the actual performance of building not on design expectations. Buildings can achieve four performance levels on the basis of the earned point (34-42 points Certificated; 43-50 points Silver; 51-67 points Gold; 68-92 points Platinum) in six performance fields: Sustainable Sites (SS), Water Efficiency (WE), Energy & Atmosphere (EA), Materials & Resources (MR), Indoor Environmental Quality (IEA) and Innovation in Operations (IO).

BREEAM IN USE (BIU) [10]

BREEAM In-Use is an environmental assessment method that enables property investors, owners, managers and occupiers to determine and drive sustainable improvements in the operational performance of their buildings. It provides sustainability benchmarking and assurance for all building types. Ratings are scored against nine key environmental categories that provide a comprehensive assessment of a building’s environmental performance and management: Management, Health & Well-being, Energy, Transport, Water, Resources, Resilience, Land Use & Ecology, Pollution. These categories are based on the most influential factors that affect a building’s environmental impacts and performance: energy and water efficiency, health and well-being benefits to occupants, management practices, circular economy principles (waste and materials), pollution management, sustainable transport access, support to local biodiversity and resilience to risks including from climate change.
The performance levels are: Acceptable, Pass, Good, Very Good, Excellent, Outstanding.

ENERPHIT [11]

"EnerPHit Standard is the Passive House certification for existing building. It uses Passive House components for all relevant structure elements in such buildings leads to extensive improvements with respect to thermal comfort, structural integrity, cost-effectiveness and energy requirements".

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(8) LOCKWOOD C.(2009). *Building retrofits.* Urban Land. November/ December 2009. p3

(9) USGBC (2008). *LEED for Existing Buildings: Operations & Maintenance.* US Green Building Council. September 2008

(10) BRE. *BREEAM in Use.* Official website. https://www.breeam.com/discover/technical-standards/breeam-in-use/

The certification can be achieved through the compliance of one among two criteria: the building component method or the energy demand method. The former set minimum U-values for opaque and transparent envelope and minimum ventilation rate percentages; the latter sets maximum heating and cooling demand. Moreover three Renewable Primary Energy (PER) performance levels can be achieved: Classic, Plus and Premium.

GREEN GLOBES EB (12)

Green Globes for Existing Buildings (EB) 2021 is a science-based, user-friendly benchmarking and certification program, evaluating the environmental sustainability, health and wellness, and resilience of an individual building or an entire portfolio. Eligible buildings must: be designed for occupancy; have conditioned space; has been occupied longer than 18 months and/or more than 12 consecutive months utility data available; be at least 400 gross square feet in size. The assessment process is composed of six phases. First, the interested user completes and submits EB questionnaire; later, GBI schedules onsite assessment, then, assor onsite review and final report; GBI reviews and issues final report; finally, the existing buildings is rated and certificated. The score can reach a total of 1000 on the basis of six factors: Environmental, Social and Governance (ESG) Management; Site, Energy, Water, Material, Indoor Environmental Quality.

Besides the above rating systems, in 2009 Jerry Yudelson in Greening Existing Buildings refers to the European Energy Performance of Buildings Directive (EPBD 2002/91/EC) as an important step toward the buildings labelling and a comprehensive program that should be also emulated in the United States. (13) Indeed, EPBD Directive sets five conditions for each Member State:

1. Energy Performance Certification (EPC) that the owner must provide to a prospective buyer of the building;
2. Inspection of all boilers and air-conditioning units to ensure proper operation;
3. Experts qualification for building inspection and for providing the analysis for the EPC;
4. Calculation methodology for the assessment of the energy use;
5. Minimum energy performance requirements in order to contain the energy utilization.

The EU Directive will be implemented over the years and will focus its attention on existing buildings. In Chapter 2 these considerations will be treated.

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(11) PASSIVE HOUSE INSTITUTE (2016). *Criteria for the Passive House, EnerPHit and PHI Low Energy Building Standard.* Darmstadt, Germany,

(12) GREEN BUILDING INITIATIVE (GBI). Green Globes for Existing Buildings 2021. Sensible solutions to reach your building's potential. Official Website https://thegbi.org/green-globes-certification/how-to-certify/existing-buildings/

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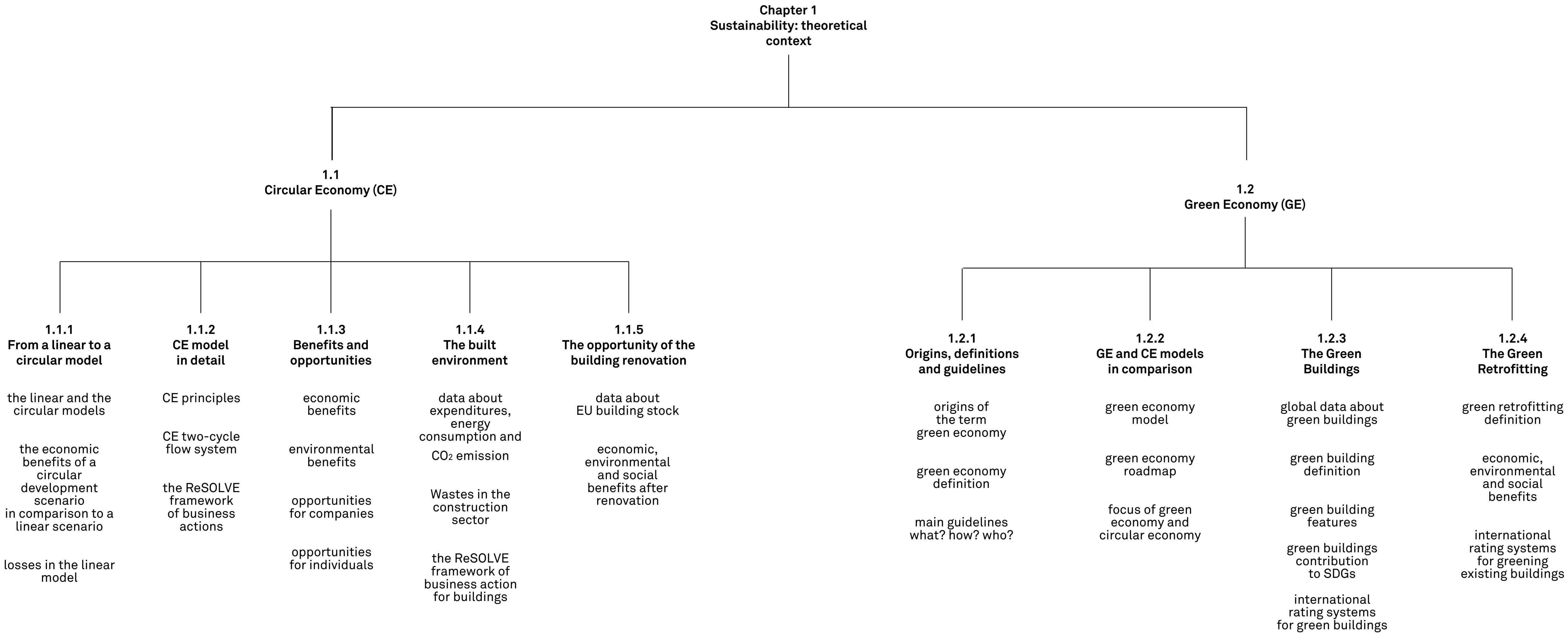
PASSIVE HOUSE INSTITUTE (2016). *Criteria for the Passive House, EnerPHit and PHI Low Energy Building Standard*. Darmstadt, Germany.

GREEN BUILDING INITIATIVE (GBI). *Green Globes for Existing Buildings 2021. Sensible solutions to reach your building's potential.* Official Website
https://thegbi.org/green-globes-certification/how-to-certify/existing-buildings/



Chapter 1 framework
Author elaboration

02

European regulatory context

INTRODUCTION

This chapter traces the most important strategies and regulations adopted in Europe to fight the climate change. The ultimate goal had been to reach the European climate neutrality by 2050; this aim is still pursued today. Indeed, the most recent actions plan and legislation,until 2021, have been treated.
The first section deals with the policies carried out for reaching the GHGs emission cutting, the energy-efficiency improvement and the increasing production of energy from renewable sources first by 2020, then by 2030. The Kyoto Protocol in 1997 had been the starting point for the adoption of long-term strategies and climate target as the only efficient way for the transition toward a low-carbon society.
The second section focuses on the energy topic and, in particular on the energy-efficiency strategies adopted, of which increasing was too slowly over 2020 climate energy package period, in contrast with the pace of the renewable energy improvement. However, the energy efficiency is considered a key issue in the sustainable development. After a trace of the energy-efficiency strategies adopted in Europe since 2008, the section analyses the attention given to the building sector over this excursus; as a result, the building sector is one of the most influential sectors in the fight against climate change. Not by chance, the paragraph ends with a report about the Renovation Wave strategy adopted in Europe starting from 2020 for the energy and technological refurbishment of all the EU building stock.
Finally, the third section deals with the European regulatory framework process for the building energy performance. The first sub-section reports the following legislations:
Energy Performance of Buildings Directive (EPBD) 2002/91/EC; Energy Performance of Buildings Directive (EPBD Recast) 2010/31/EC; Energy Efficiency Directive (EEC) 2012/27/EC; Directive 2018/844/EU amending Directives 2010/31/EC and 2012/27/EC. The second sub-section analysies how the attention given to the improvement of the energy performance of the existing buildings is developed over the years. Finally, the third section ends with a focus on the Italian regulatory framework context in relation to the European context. The Author has tried to report the most important steps of each regulation.

2.1 EU CLIMATE TARGETS AND MAIN POLICIES

This section reviews the main European strategic actions to fight climate change. The Kyoto Protocol in 1997 launched the strategy of setting long-term targets to tackle the climate change. Thus Europe imposed a long-term major goal to be achieved in 2050: the climate-neutrality. For achieving the 2050 main goal, Europe set a first target by 2020 for the 2013-2020 period and a second target by 2030 for the 2021-2030 period. The targets are related to greenhouse gases emission cutting, renewable energy improvement and the energy-efficiency increasing. This section is structured on two sub-sections, or paragraphs, treating the 2020 and 2030 strategy packages respectively.

2.1.1 2020 CLIMATE AND ENERGY PACKAGE

2007 marked a turning point for the European role in the global fight against the climate change. In that year, the European Council was reunited to set three key climate targets to meet by 2020[(1)]:

from 1990 levels	→	**-20% GHGs emission**	**+20% renewable energy**	**+20% energy-efficiency**

The GHGs cutting emission and energy from renewable sources production targets were enacted in legislation on 23 April 2009 through the Decision 406/2009/EC [(2)] and the Directive 2009/28/EC[(3)] of the European Parliament and of the Council. The former laid down binding limits to the greenhouse gases emission for the period between 2013 and 2020 for Member State by taking into account the relative per capita GDP of each State.
The Decision 406/2009/EC was a sort of sequel of the Council Decision 2002/358/EC of 25 April 2002[(4)] approving the 1997 Kyoto Protocol, in which participating countries committed to reduce their emissions by an average of 5% below 1990 levels for the period 2008-2012. The EU-15 (at that time) Member States committed to an 8% reduction for the whole continent. The Decision 2002/358/EC therefore set national binding targets on GHGs emission expressed in percentages and then translated in exact quantities (tonnes of CO_2-equivalent). The EU and its Member States met their commitments by achieving an overall cut of 11,7%.

(1) COMMISSION OF THE EUROPEAN COMMUNITIES (2008). *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. 20 20 by 2020 Europe's climate change opportunity.* European Commission. Brussels. p 2

(2) Decision 406/2009/EC of the European Parliament and the Council of 23 April 2009 on the effort of Member States to reduce their greenhouse gas emissions to meet the Community's greenhouse gas emission reduction commitments up to 2020. Off. J. Eur. Union.

(3) Directive 2009/28/EC of the European Parliament and the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. Off. J. Eur. Union.

(4) Decision 2002/358/EC of the European Council of 25 April 2002 concerning the approval, on behalf of the European Community, of the Kyoto Protocol to the United Nations Framework Convention on Climate Change and the joint fulfilment of commitments thereunder. Off. J. Eur. Communities

The Decision 406/2009/EC also defined two key tools,still in place today, for reaching 2020 climate and energy targets: Emission Trading System (ETS) and the Effort Sharing Decision (ESD).
On the basis of what is explained in the EU ETS Handbook(5), the former is the cornerstone of the European policy to tackle the climate change. The ETS is based on a pre-set total emission "cap", or threshold, and on a fixed number of carbon allowances accessible to companies each year. The system guarantees the possibility to trade the allowances. Indeed, companies who necessitate of extra allowances can reduce their emissions or buy allowances by emitters who have extra of them. In this way a financial incentive is given to the lowest emitters and this mechanism moves forward a "cap" falling. The figure below is a graphical schematization of the mechanism.

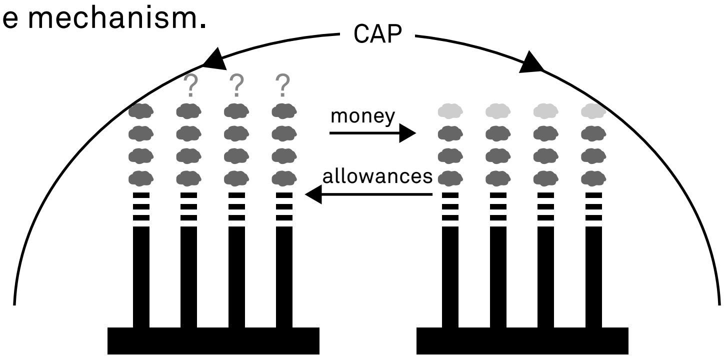


Fig.1 Emission Trading System
Source: Author re-elaboration from European Commission. The EU Emissions Trading System explained.
https://www.youtube.com/watch?v=fJrFSLfaeeE

The ETS was first adopted by the 2003/87/EC (6) Directive and introduced in 2005 after the legally-binding targets on GHGs emissions imposed by the 1997 Kyoto Protocol for the period 2008-2012. After a first phase from 2005 to 2007 for testing the new system, a second phase of ETS ran from 2008 to 2012, as the Kyoto Protocol commitment period. The third phase 2013-2020 was strategic for achieving the 2020 climate targets, by introducing in the "cap and trade" system the aviation companies as well.
The Effort Sharing Decision is also included in the Decision 406/2009/EC (7) and sets annual binding national emission limits for most sectors not included in the EU ETS, such as transport, buildings, agriculture and waste for the period 2013-2020. The annual targets are also known as annual emission allocations (AEAs).
According to what it is reported on European Commission website,(8) EU greenhouse gas emissions were reduced by 24% between 1990 and 2019, while the economy grew by around 60% over the same period.

In the 1990-2019 period	→	**-24%** **GHGs emission**	**+60%** **economic growth**

(5) EUROPEAN COMMISSION (2015). EU ETS Handbook. European Union. pp 4-10

(6) Directive 2003/87/EC of the European Parliament and the Council of 13 October 2003 establishing a scheme for greenhouse gas emission allowance trading within the Community and amending Council Directive 96/61/EC. Off. J. Eur. Union.

(7) Decision 406/2009/EC of the European Parliament and the Council of 23 April 2009 on the effort of Member States to reduce their greenhouse gas emissions to meet the Community's greenhouse gas emission reduction commitments up to 2020. Off. J. Eur. Union.

(8) EUROPEAN COMMISSION. *Progress made in cutting emission.* Official website of the European Union. https://ec.europa.eu/clima/policies/strategies/progress_en

The goals were achieved also thanks to the introduction of European funding programs, such as NER 300(9) and Horizion 2020(10), founded for improving sustainable technologies projects. The former took its name from the sale of 300 million emission allowances to companies for the third ETS phase. The funds from the sales were distributed to projects selected through two rounds of calls for proposals, one in 2012 and the other in 2014, covering 200 and 100 million allowances respectively.
Horizon 2020 was a funding program with nearly 80€ billion over the 2014-2020 period to invest in innovation and research.

2.1.2 2030 CLIMATE AND ENERGY FRAMEWORK

On 22 January 2014, the Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions(11), defines a new policy framework for achieving new three key targets by 2030:

from 1990 levels	→	**-40%** **GHGs emission**	**+32%** **renewable energy**	**+32,5%** **energy-efficiency**

The targets were set on the basis of the previous period progresses. The new goals led to another phase of Emission Trading System and an upgrading of the Effort Sharing Decision. The fourth phase (2021-2030) of ETS was introduced on 14 March 2018 by the Directive 2018/410(12) amending the Directive 2003/87/EC. The updated directive built on the basis of the third phase (2013-2020), which had changed the system considerably compared to the previous phases (2005-2007 and 2008-2012). Moreover, the EU ETS has proven to be a cost-effective tool in driving emissions reductions; installations covered by the ETS reduced emissions by about 35% between 2005 and 2019(13).
The ETS revision focused on several points among which the pace increasing of the annual cap reduction to 2.2% as of 2021 and the continuance of the carbon allowances free allocation to the companies (14).
As regards sectors not covered by the EU-ETS such as transport, buildings, agriculture and waste, the European Council established an emission reduction by 30% by 2030 compared to 2005. The Effort Sharing Regulation 2018/842 of 30 May 2018(15) laid down binding annual greenhouse gas emission targets on those sectors for each Member State for the period 2021–2030.

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(9) EUROPEAN COMMISSION. *NER 300 Programme.* Official website of the European Union. https://ec.europa.eu/clima/policies/innovation-fund/ner300_en

(10) EUROPEAN COMMISSION. *What is Horizion 2020?.* Official website of the European Union. https://ec.europa.eu/programmes/horizon2020/what-horizon-2020

(11) EUROPEAN COMMISSION (2014). *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. A policy framework for climate and energy in the period from 2020 to 2030.* European Commission. Brussels. 22 January 2014

(12) Directive (EU) 2018/410 of the European Parliament and of the Council of 14 March 2018 amending Directive 2003/87/EC to enhance cost-effective emission reductions and low-carbon investments, and Decision (EU) 2015/1814. Off. J. Eur. Union.

For each Member State was imposed a percentage in relation to 2005 levels. For instance, Italy was imposed a reduction of 33%.

The Regulation (EU) 2018/1999 of 11 December 2018 on the Governance of the Energy Union and Climate Action [16] set out the necessary legislative foundation for achieving the 2030 targets for energy and climate in concordance with the 2015 Paris Agreement [17]. The Regulation established a governance mechanism based on the following five dimensions:

1.energy security

2.internal energy market

3.energy efficiency

4.decarbonisation

5.research, innovation and competitiveness.

Moreover, the Regulation introduced the national energy and climate plans (NECPs) to be implemented by the Member State every ten years taking into account a long-term perspective. The first plan had to cover the 2021-2030 period and notified to the Commission by December 2019.

The alarming and accelerating effects of climate change and the urgent aim of becoming the first climate-neutral continent by 2050 have led to the European Green Deal [18], a new growth strategy presented by the Commission on 11 December 2019. Among several policies, the Communication about the EU Green Deal declared the willingness to increase the EU's greenhouse gas emission reductions target for 2030.

On 4 March 2020 the Commission published the Communication with the proposal of a new regulatory European Climate Law [19] for enacting in legislation the objective to become a net zero GHGs emission continent by 2050.

On 17 September 2020 the Commission presented the European 2030 Target Plan [20] to reduce EU greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels. The plan has shown how to achieve the new target is realistic and feasible.

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(13) EUROPEAN COMMISSION. *Progress made in cutting emission.* Official website of the European Union. https://ec.europa.eu/clima/policies/strategies/progress_en

(14) EUROPEAN COMMISSION. *EU Emission Trading System (EU-ETS).* Official website of the European Union. https://ec.europa.eu/clima/policies/ets_en

(15) Regulation (EU) 2018/842 of the European Parliament and of the Council of 30 May 2018on binding annual greenhouse gas emission reductions by Member States from 2021 to 2030 contributing to climate action to meet commitments under the Paris Agreement and amending Regulation (EU) No 525/2013. Off. J. Eur. Union.

(16) Regulation (EU) 2018/1999 of the European Parliament and of the Council of 11 December 2018 on the Governance of the Energy Union and Climate Action, amending Regulations (EC) No 663/2009 and (EC) No 715/2009 of the European Parliament and of the Council, Directives 94/22/EC, 98/70/EC, 2009/31/EC, 2009/73/EC, 2010/31/EU, 2012/27/EU and 2013/30/EU of the European Parliament and of the Council, Council Directives 2009/119/EC and (EU) 2015/652 and repealing Regulation (EU) No 525/2013 of the European Parliament and of the Council. Off. J. Eur. Union.

(17) The Paris Agreement of COP21 (2015) has established to mantain the global temperature below the 1,5 °C after the post-industrial level.

(18) EUROPEAN COMMISSION (2019). *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. AThe European Green Deal.* European Commission. Brussels. 11 December 2019

(19) EUROPEAN COMMISSION. *Committing to climate-neutrality by 2050: Commission proposes European Climate Law and consults on the European Climate Pact.* Official website of the European Union. https://ec.europa.eu/commission/presscorner/detail/en/ip_20_335

(20) EUROPEAN COMMISSION.State of the Union: Commission raises climate ambition and proposes 55% cut in emissions by 2030. Official website of the European Union. https://ec.europa.eu/commission/presscorner/detail/en/ip_20_1599

2.2 THE ENERGY-EFFICIENCY FOCUS IN THE EU AGENDA

In contrast with the pace of the renewable energy improvement, the energy-efficiency increasing was too slowly over the 2020 energy and climate package period.
Hence, after dealing with the targets set by the European Union to fight the climate change, this section focuses on the energy topic and, in particular, on the energy-efficiency as it is considered a key issue in the sustainable development.
The first paragraph deals with an excursus of the main strategies, action plans and laws on the implementation of the EU energy system since 2008 until today.
Then the focus shifts on the building sector by highlighting how the previous treated energy strategies acted on the building energy-efficiency.
Finally, the third paragraph focuses on the "Renovation Wave", the most recent strategy developed in 2020 regarding the refurbishment of the European building stock.

2.2.1 THE OVERALL NORMS AND STRATEGIES

The 2020 energy and climate package was implemented by the Energy 2020 Strategy [(1)], introduced by the European Commission on 10 November 2010. The strategy was started in order to ensure a tool for achieving the energy-efficiency improvement target of 20% by 2020 since the strategy at that time was inadequate to the longer time changes. The new energy strategy is explained in the document by defining five priorities and the relative actions:
1. Achieving an energy efficient Europe;
2. Building a truly pan-European integrated energy market;
3. Empowering consumers and achieving the highest level of safety and security;
4. Extending Europe's leadership in energy technology and innovation;
5. Strengthening the external dimension of the EU energy market;

The first priority is supported by the following statement:

> *"energy efficiency is the most cost effective way to reduce emissions, improve energy security and competitiveness, make energy consumption more affordable for consumers as well as create employment, including in export industries".* [(2)]

It is also interesting to report the strategic importance given to the existing building stock as a largest potential sector to make energy efficiency savings, as it will be treated in the next pages.

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(1) EUROPEAN COMMISSION (2010). *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Energy 2020. A strategy for competitive, sustainable and secure energy.* European Commission. Brussels. 10 November 2010

(2) EUROPEAN COMMISSION (2010). *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Energy 2020. A strategy for competitive, sustainable and secure energy.* European Commission. Brussels. 10 November 2010 p 6

The 20% energy efficiency target was not legally binding for the Member States in 2007, that is when the 2020 climate and energy package was introduced by the European Council.
The target was enacted with the adoption of the Energy Efficiency Directive 2012/27/EU of 25 October 2012[3]. The Directive imposed to lower the primary and final energy consumption to a specific average. To achieve this target, EU countries were required to set their own indicative national energy efficiency targets and publish three years national energy efficiency action plans (NEEAPs) and annual progress reports.
The NEEAPs set out estimated energy consumption, planned energy efficiency measures, long-term renovation strategies, and the improvements that individual EU countries expected to achieve to reach the EU 2020 target of 20%.
The necessity of an integrated energy market, as described in the second priority of 2020 Energy Strategy, led to the publication of the Energy Union Strategy [4] by the European Commission on 25 February 2015.
Since the Energy 2020 Strategy, Europe was still too fragmented in different national regulatory framework for each Member State. The European Commission defined five interrelated dimensions on which to build the new strategy:

1. Energy security, solidarity and trust;
2. A fully integrated European energy market;
3. Energy efficiency contributing to moderation of demand;
4. Decarbonising the economy;
5. Research, innovation and competitiveness.

The third dimension is related to the new energy-efficiency target of 32,5% set by the European Commission on 2014[5]. A special attention is given to the transport and building sectors.
The necessity of a cooperation among Member States led to the legally enacting of the Energy Union Strategy through the Regulation (EU) 2018/1999 of 11 December 2018 on the Governance of the Energy Union and Climate Action [6]. The Regulation set out the necessary legislative foundation for achieving the 2030 targets for energy and climate by establishing a governance mechanism based on the Energy Union Strategy five dimensions. The introduction of the national energy and climate plans (NECPs) (see the section 2.1.2) allowed the implementation of a long term national commitment and a European governance built on transparency.
The energy-efficiency target of 32,5% by 2030 was set as legally binding in the Directive on Energy Efficiency 2018/2002 of the 21 December 2018[7], amending the Directive 2012/27 EU. The amending Directive transformed the target percentage in the specific average limit of 1128 Mtoe for primary energy and 846 Mtoe for final energy consumption. Moreover, the amending Directive introduced an annual 0,8 % energy saving target for each Member State for the 2021-2030 period.

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(3) Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC. Off. J. Eur. Union.

(4) EUROPEAN COMMISSION (2015). *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee the Committee of the Regions and the European Investment Bank. Energy Union Package. A Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy.* European Commission. Brussels. 25 February 2015

(5) EUROPEAN COMMISSION (2014). *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. A policy framework for climate and energy in the period from 2020 to 2030.* European Commission. Brussels. 22 January 2014

The Directive 2018/2002 is part of the Clean Energy for all European Package [8], a energy strategic framework announced by the European Commission in March 2019.
The document of the new energy strategy is structured in seven chapters, each related to a policy:

1. Accelerating the clean energy transition in the EU;
2. Modernising the economy for the benefit of everyone;
3. Increasing energy security;
4. Bringing people and countries closer;
5. Consumers at the heart of the energy transition;
6. Europe as an energy and climate action leader in the world;
7. Moving towards a Clean Planet for All.

The first strategy is carried out by the target to be more efficient of 32,2 % by 2030 and by the new energy rulebook composed of the national energy and climate plans (NECPs). Moreover, the transition to a clean energy is accelerated by the energy from renewable energy sources target of 32 % by 2030.
A European clean energy transition requires a huge economic investment for such an economic transformation. The second chapter discusses the benefits gained from the investment, such as the 900.000 new jobs linked to the clean energy sector.

€180 billion
Mobilising up to **€**180 billion of public and private funds per year until 2021

1% increase
Generating up to 1% increase in economic growth over the next decade

900.000 new jobs
Creating around 900.000 new jobs linked to the clean energy sector

Moreover, investing in research and innovation will contribute to make the EU a global technology leader. Finally, a big importance is given to citizens as cleaner energy would improve health and a better quality of life and would allow citizens to manage their energy use by themselves.
The fourth point reports the five dimensions of the 2015 Energy Union Strategy: energy security, solidarity and trust; a fully integrated European energy market; energy efficiency; decarbonisation of the economy; research, Innovation and competitiveness.
Finally, the document highlights how a collaboration among EU Member States in a spirit of solidarity would be fundamental to carry out a safe and affordable energy system. The 2018 Governance of the Energy Union and the NECPs would allow the collaboration among EU countries and the local stakeholder participation.

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(6) Regulation (EU) 2018/1999 of the European Parliament and of the Council of 11 December 2018 on the Governance of the Energy Union and Climate Action, amending Regulations (EC) No 663/2009 and (EC) No 715/2009 of the European Parliament and of the Council, Directives 94/22/EC, 98/70/EC, 2009/31/EC, 2009/73/EC, 2010/31/EU, 2012/27/EU and 2013/30/EU of the European Parliament and of the Council, Council Directives 2009/119/EC and (EU) 2015/652 and repealing Regulation (EU) No 525/2013 of the European Parliament and of the Council. Off. J. Eur. Union.

(7) Directive (EU) 2018/2002 of the European Parliament and of the Council of 11 December 2018 amending Directive 2012/27/EU on energy efficiency. Off. J. Eur. Union.

(8) EUROPEAN COMMISSION (2019). Clean Energy For All Europeans. Luxembourg, Publications Office of the European Union.

Nine months later the publication of the Clean Energy for all European Package, the European Commission has announced the European Green Deal [9] on 11 December 2019. It is an on-going wide-spread strategy for the sustainable growth of the continent.
Among several strategic areas, the European Green Deal focuses on three key principles and eight actions for a clean energy transition, reported in the following by the author.

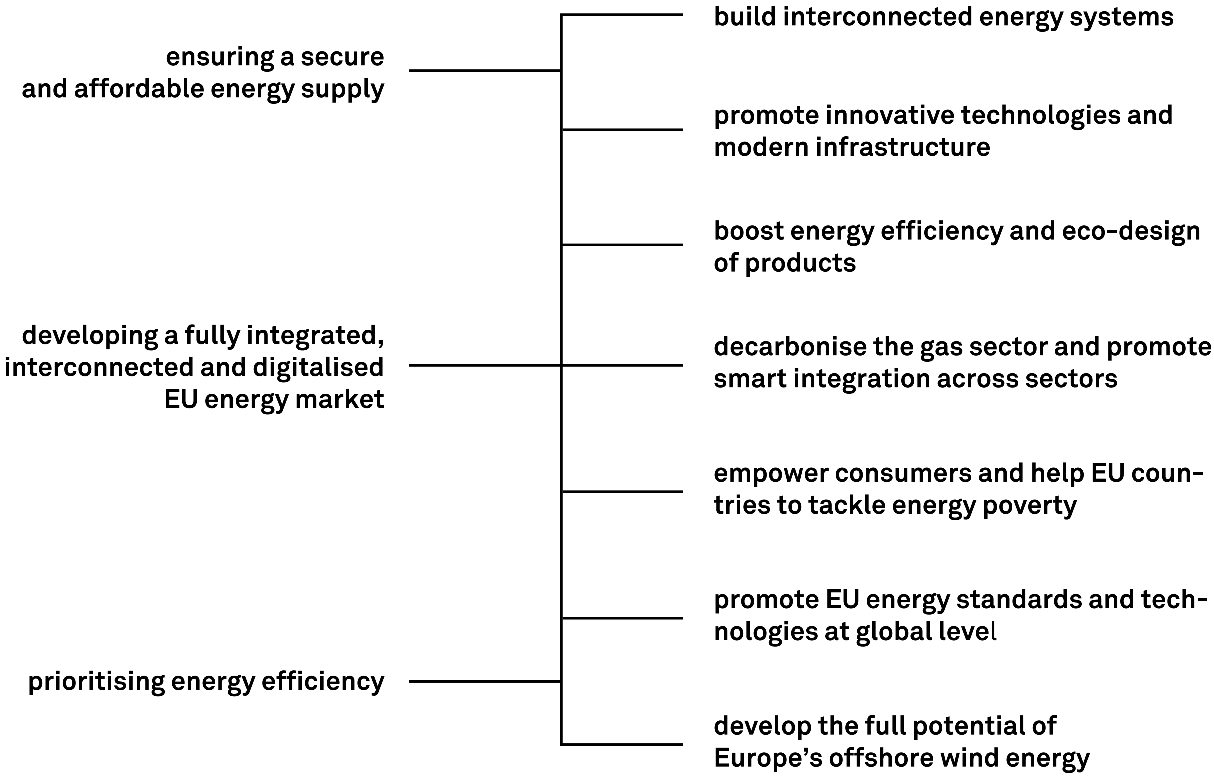

Fig.1 The European Green Deal
Source: Author re-elaboration from European Commission. An European Green Deal.
https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en#thematicareas

On 14 July 2021 the Commission has presented the Delivering the European Green Deal[10], a set of proposal for the economic transformation of all sectors with the aim of a climate neutrality Europe by 2050.
Since the target of cutting greenhouse gases emissions of 55% by 2030 requires higher shares of renewable energy and greater energy efficiency, the Commission proposes to increase the renewable energy target to 40% and the energy efficiency to 36% and 39% for the final and primary energy consumption respectively.

from 1990 levels	→	**-55% GHGs emission**	**+40% renewable energy**	**+36-39% energy-efficiency**

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(9) EUROPEAN COMMISSION (2019). *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. The European Green Deal.* European Commission. Brussels. 11 December 2019

(10) EUROPEAN COMMISSION. Delivering the European Green Deal. Official website of the European Union. https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/delivering-european-green-deal_en

The new targets are part of the proposal for a new Directive on energy efficiency [11]. The proposal contains entire parts of the Directive 2012/27/EU and Directive 2018/2001 and, after deleting them, adds the replacement text. A key element is doubling the annual energy saving obligation from 0,8 % to 1,5 % for each EU Member State from 2024 to 2030.

For the 2024-2030 period → **1,5% annual energy savings for each Member States**

The proposal for the revised directive also puts a stronger focus on alleviating energy poverty and empowering consumers, through strengthened requirements on awareness raising and information provision.

(11) EUROPEAN COMMISSION (2021). *Proposal for Directive of the European Parliament and of the Council on energy efficiency (recast).* European Commission. Brussels. 14 July 2021

2.2.2 THE BUILDING ENERGY-EFFICIENCY STRATEGIES

This section aims to reflect the importance given to the building sector in the strategies discussed in the previous paragraph, through a critical elaboration by the author. Section 2.2.3 then clearly treats the European regulatory framework that has been regulated the building sector.
Since the 2020 Energy Strategy, the existing building stock issue for achieving the energy-efficiency target has been considered. The document is structured on five sections corresponding to five priority for an energy strategy. The Priority 1 is "Achieving an energy-efficient Europe" and the related paragraph states that:

"Special attention should be given to the sectors with the largest potential to make energy efficiency gains, namely the existing building stock and transport sector.
(...)
In the residential sector, the issue of divided incentives between owners and tenants needs to be addressed. Regarding the substantial stock of public buildings, the authorities need to exploit all available opportunities to improve the energy efficiency and autonomy of the buildings." (1)

The 2015 Energy Union Strategy document describes five dimensions on the basis of which to built a new energy system. The third one is the energy-efficiency as a contribution to the moderation of energy demand; the building sector is identified among the sectors with a huge energy-efficiency potential. The title of the first paragraph of the energy-efficiency section is *"Increasing energy efficiency in the building sector"* and contains the following statements:

"Heating and cooling is the largest single source of energy demand in Europe and the majority of Europe's gas imports are used for these purposes. Huge efficiency gains remain to be captured with regard to district heating and cooling, which will be addressed in a Commission strategy.
(...)
Actions by Member States, particularly at the local and regional levels, are needed to exploit the energy efficiency potential of buildings.
(...)
The European Fund for Strategic Investments provides an opportunity to leverage major investments in renovating buildings. Investments in this area can provide great returns in terms of growth and jobs". (2)

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(1) EUROPEAN COMMISSION (2010). *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Energy 2020. A strategy for competitive, sustainable and secure energy.* European Commission. Brussels. 10 November 2010, p 6

(2) EUROPEAN COMMISSION (2015). *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee the Committee of the Regions and the European Investment Bank. Energy Union Package. A Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy.* European Commission. Brussels. 25 February 2015, pp 12-13

As described in the previous section, the 2019 Clean Energy for All European Package document is structured in seven paragraphs related to seven energy policies. The first policy is *"Accelerating the clean energy transition in the EU"* and the linked paragraph contains the following phrases:

"A particular emphasis is also given to improving energy performance in the building sector. This sector is crucial to the clean energy transition, as buildings are the largest energy consumers, accounting for 40% of final energy consumption and 36% of greenhouse gas emissions in Europe.
By accelerating the renovation rate of buildings and exploiting all smart technologies available, this sector can contribute to a carbon-neutral and competitive economy". (3)

Finally, the European Green Deal Communication of 11 December 2019 contains the EU Green Deal Roadmap illustrating the elements of the ongoing growth strategy. The fourth policy is *"Building and renovating in an energy and resource efficient way"*. The descriptive text of the policy is the following one:

"Buildings account for 40% of energy consumed. Today the annual renovation rate of the building stock varies from 0.4 to 1.2% in the Member States. In parallel, 50 million consumers struggle to keep their homes adequately warm. To address the twin challenge of energy efficiency and affordability, the EU and the Member States should engage in a 'renovation wave' of public and private buildings.
(...)
The Commission will rigorously enforce the legislation related to the energy performance of buildings.
(...)
In addition, the Commission will review the Regulation Construction Products. It should ensure that the design of new and renovated buildings at all stages is in line with the needs of the circular economy, and lead to increased digitalisation and climate-proofing of the building stock.
(...)
The Commission will also work to lift national regulatory barriers that inhibit energy efficiency investments in rented and multi-ownership buildings.
Particular attention will be paid to the renovation of social housing, to help households who struggle to pay their energy bills. Focus should also be put on renovating schools and hospitals, as the money saved through building efficiency will be money available to support education and public health". (4)

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(3) EUROPEAN COMMISSION (2019). Clean Energy For All Europeans. Luxembourg, Publications Office of the European Union, p 4

(4) EUROPEAN COMMISSION (2019). *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. The European Green Deal.* European Commission. Brussels. 11 December 2019, p 9-10

2.2.3 A RENOVATION WAVE FOR EUROPE

As it has been declared in the EU Green Deal Strategy, the European Commission has published its Renovation Wave Strategy (1) on 14 October 2020 for improving the energy performance of the existing buildings.
The Communication starts with data about the European building stock. More than 220 million building units, representing 85% of the EU's building stock, were built before 2001 and 85-95% of the existing buildings will still be standing in 2050.

85% of EU building units were built before 2001	**85-95% of EU existing buildings will be standing in 2050**

The main issue to resolve is that most of those existing buildings are not energy-efficient. The reason is that a large share of buildings was constructed before 1970 that is when the building code on thermal insulation of the building envelope started to appear. Moreover, the use and operation phase of buildings, representing the longest phase, is responsible for about 40% of the EU's total energy consumption, and for 36% of its greenhouse gas energy emissions from energy. Further, Covid-19 pandemic has laid bare the lacking affordability of the building stock, in a period in which homes have become the focus of people daily life.

from buildings use	→	**40% of EU's total energy consumption**	**36% of EU's GHGs emission from energy**

Beyond the basic necessity to make buildings more liveable, Europe urgently aims to become the first climate-neutral continent by 2050. The EU buildings' greenhouse gas emissions, final energy consumption and energy consumption for heating and cooling shoud be reduced respectively by 60%, 14% and 18% to achieve the 55% emission reduction target by 2030.

to achieve 55% GHGs emission reduction	→	**-60% of buildings GHGs emission by 2030**	**-14-18% of buildings energy consumption by 2030**

(2) EUROPEAN COMMISSION (2019). *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. A Renovation Wave for Europe - greening our buildings, creating jobs, improving lives*. Brussels.14 October 2020

On these basis and considering the social, environmental and economic benefits deriving form a renovation strategy, the European Commission has launched the following challenge:

"to at least double the annual energy renovation rate of residential and non-residential buildings by 2030 and to foster deep energy renovations. Mobilising forces at all levels towards these goals will result in 35 million building units renovated by 2030. The increased rate and depth of renovation will have to be maintained also post-2030 in order to reach EU-wide climate neutrality by 2050". (2)

To achieve the above objective, the Communication defines seven key principles, re-elaborated by the author in the following map:

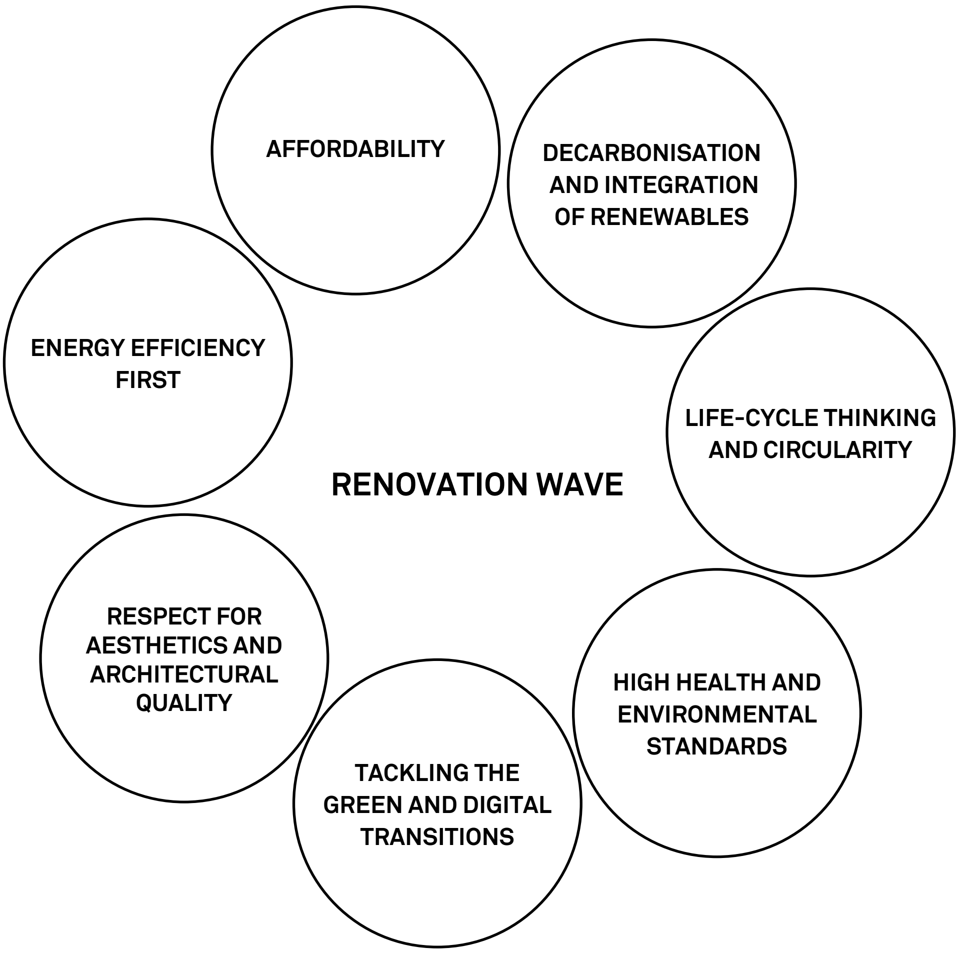

Fig.1 The Renovation Wave principles
Source: Author elaboration from: A Renovation Wave for Europe - greening our buildings, creating jobs, improving lives. European Commission, Brussels, p 3-4

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(2) EUROPEAN COMMISSION (2019). *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. A Renovation Wave for Europe - greening our buildings, creating jobs, improving lives*. Brussels.14 October 2020, p 3

Finally, the document lists the seven action areas identified by the Commission and explain them in seven chapter [(3)]. The map below is a schematized representation of the seven areas.

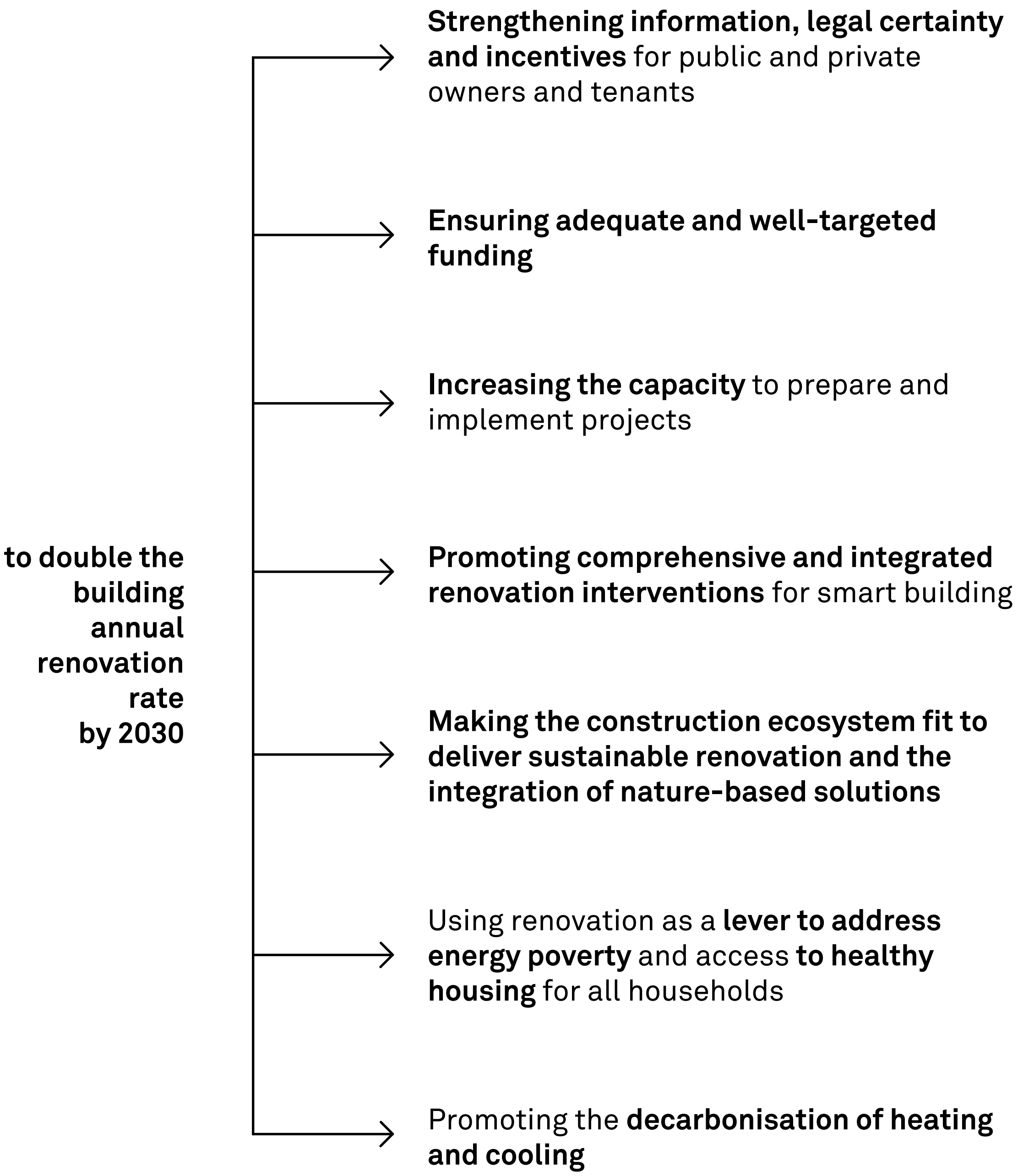

Fig.2 The Renovation Wave action areas
Source: Author elaboration from: A Renovation Wave for Europe - greening our buildings, creating jobs, improving lives. European Commission, Brussels, p 5-6

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(2) EUROPEAN COMMISSION (2019). *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. A Renovation Wave for Europe - greening our buildings, creating jobs, improving lives*. Brussels.14 October 2020, p 5-19

2.3 THE BUILDING ENERGY PERFORMANCE LEGISLATION

The last section of the second chapter is entirely dedicated to the energy performance of buildings. The first part deals with the regulatory framework process which has concerned the management and maintenance of buildings until today.
The following paragraph analyses how the focus on existing buildings and the need for energy retrofitting has increased over the years in the European legislation. In particular, the author has individuated a turning point in that focus development.
Finally, the Italian regulatory framework process is discussed and the normative is analysed in relation to the European level.

2.3.1 THE REGULATORY FRAMEWORK PROCESS

The first directive of the energy performance of buildings was the 2002/91/EC of 16 December 2002, also known as EPBD Directive [(1)]. It was implemented to tackle the limits imposed by the 1997 Kyoto Protocol, enacted in the Decision 2002/358/EC [(2)] of 25 April 2002.
The document is structured on seventeen articles and contains general information on what Member States should do to improve the energy performance of new and existing buildings taking into account indoor and outdoor climate conditions and cost-effectiveness.
The directive introduces the obligation of a methodology for the calculation of the energy performance of buildings and list which measures the framework should include in the calculation and which different building categories it should consider.
The most important part is the Article 7 which introduces the Energy Performance Certificate (EPC) to be reviewed every 10 years.
The 2002/91/EC Directive was amended by the 2010/31/EU Directive, also known as EPBD Recast [(3)], on 19 May 2010. The document is structured on thirty-one articles; the new parts will be described below.
As in the 2002/91/EC Directive, the Article 3 of the EPBD recast is about the adoption of a methodology for calculating the energy performance of buildings and it is more deeply described than in the previous Directive. The Annex I implementing the Article 3 contains more precise information such as the necessity of a previous calculation of the annual energy consumption, of the heating and cooling energy needs, of an energy performance indicator and a of a numeric indicator of primary energy use.

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(1) Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the energy performance of buildings. Off. J. Eur. Communities.

(2) Decision 2002/358/EC of the European Council of 25 April 2002 concerning the approval, on behalf of the European Community, of the Kyoto Protocol to the United Nations Framework Convention on Climate Change and the joint fulfilment of commitments thereunder. Off. J. Eur. Communities

(3) Directive 2010/31/EC of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings. Off. J. Eur. Communities.

In the Article 4, the Directive introduces the concepts of "minimum" and "cost-optimal"; the title becomes *"Setting of minimum energy performance requirements"* and contains the following statement:

"Member States shall take the necessary measures to ensure that minimum energy performance requirements for buildings or building units are set with a view for achieving cost-optimal levels". (4)

Moreover, the "building unit" is considered in addition to the only entire building, that is any part of a building capable of producing its own income such as a single flat, an office, a shop, a storage area or a laboratory.
The new Article 5, *"Calculation of cost-optimal levels of minimum energy performance requirements"*, set the obligation by the Commission to establish by 30 June 2011 the following:

"a comparative methodology framework for calculating cost-optimal levels of minimum energy performance requirements for buildings and building elements". (5)

and the related Annex III explains how the new methodology framework should be structured. In addition to the new and existing buildings considered in 2002/91/EC, the amending Directive introduces the application of minimum energy requirements to "building elements" that form part of the building envelope and that have a significant impact on the energy performance of the building envelope when they are retrofitted or replaced, and the " technical building system" whenever they are installed, replaced or upgraded. Consequently, in addition to the Article 6 and 7 for new and existing building respectively, the Article 8 for technical building system is introduced.
The Article 9 introduces for the first time the Nearly Zero Energy Buildings (NZEB). It states that:

"by 31 December 2020, all new buildings are nearly zero-energy buildings and after 31 December 2018, new buildings occupied and owned by public authorities are nearly zero-energy buildings". (6)

Moreover, the article contains the obligation for Member States to draw up national plans which should include a detailed application in practice of the NZEB definition, a numerical indicator of primary energy use, intermediate targets for improving the energy performance of new buildings by 2015 and information on the policies and financial or other measures adopted for the promotion of nearly zero-energy buildings.

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(4) Directive 2010/31/EC of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings. Off. J. Eur. Communities. p 7-8

(5) Directive 2010/31/EC of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings. Off. J. Eur. Communities. p 8

(6) Directive 2010/31/EC of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings. Off. J. Eur. Communities. p 9

It is introduced an obligation also for the Commission to report the progress of Member States in increasing the number of nearly zero-energy buildings. The obligation started by 31 December 2012 and the report has to be written every three years thereafter.
Moreover, the Article 10 forces Member States to list, by 30 June 2011, the existing and proposed measures and instruments including those of a financial nature for achieving the objectives of the Directive. The list had to be updated every three years.
The Energy Performance Certificate in the Article 7 of the EPBD was updated in the Article 11 of EPBD recast together with the Article 12 "Issue of energy performance certificates", explaining to which buildings and building elements the Member States should require the EPC, and the Article 13 "Display of energy performance certificates", which explain when and where the EPC should be clearly showed.
Finally, the Article 14 and 15 forces the Member States to a regular inspection of heating and air-conditioning systems. The two articles are very similar to Article 8 and 9 of the EPBD but the Directive 2010/31/EU introduces the Article 16 that is the obligation to issue a report after each inspection.
The comparative methodological framework introduced by the EPBD Recast has been implemented by the Guidelines accompanying Commission Delegated Regulation (EU) No 244/2012[7] of 16 January 2012 for the calculation of cost-optimal levels of minimum energy performance requirements for buildings and building elements. The "Optimal Cost" concept has been explained by Elena Fregonara in 2015 as

"the lowest cost that may guarantee the quantity of energy necessary to meet the energy needs of the building during its estimated economic life cycle". [8]

and it is expressed in a simplified form in the figure below.

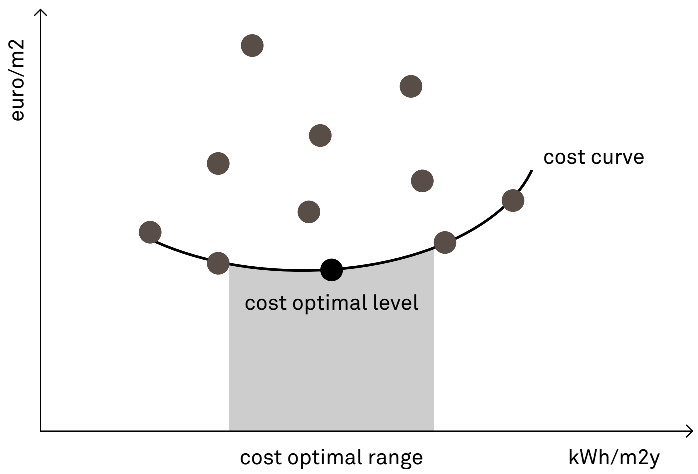

Fig.1 The Optimal Cost
Source: FREGONARA E., (2015). *Evaluation sustainability design. Life Cycle Thinking and international orientation*, Franco Angeli, Milano, p 16

(7) EUROPEAN COMMISSION (2012). *Guidelines accompanying Commission Delegated Regulation (EU) No 244/2012 of 16 January 2012 supplementing Directive 2010/31/EU of the European Parliament and of the Council on the energy performance of buildings by establishing a comparative methodology framework for calculating cost-optimal levels of minimum energy performance requirements for buildings and building elements.* Off. J. Eur. Union.

(8) FREGONARA E., (2015). *Evaluation sustainability design. Life Cycle Thinking and international orientation*, Franco Angeli, Milano, p 16

The figure shows on the x-axis the necessary primary energy, expressed in kWh/m2 year and on y-axis the global cost value, expressed in €/m2; each point correspond to an energy "package", that is a building type reference. The black point represents the Cost Optimal level and the grey band includes the Cost Optimal range. By joining the packages at the bottom of the graph, a cost curve can be obtained.
The Directive 2012/27/EU (9) on energy efficiency of 25 October 2012 (see section 2.2.1) contains information only about existing buildings which will be treated in the next section.
Finally, the Directive 2018/844(10) of 30 May 2018 modifies both Directive 2010/31/EU and 2012/27/EU. The document is structured in five articles: Article 1 *"Amendments to Directive 2010/31/EU";* Article 2 *"Amendments to Directive 2012/27/EU";* Article 3 *"Transposition";* Article 4 *"Entry into force";* Article 5 *"Addresses".*
The replaced parts that it is interesting describe in this research are mainly about the renovation of the existing buildings and will be treated in the next section.

2.3.2 THE GROWING ATTENTION ON THE EXISTING BUILDINGS

This section focuses on the European building stock and how the energy refurbishment of existing buildings has been placed at the heart of the European legislation over the years.
The 2020 Energy Strategy of 2010, treated in the section 2.2.2, can be considered a turning point in the attention given to the existing buildings renovation since they are considered a key issue for achieving the energy efficiency target for the EU climate-neutrality by 2050. Hence, the energy performance of the building normative can be divided in two periods: before and after 2010, or before and after 2020 Energy Strategy.
The EPBD Directive of 2002 and the EPBD recast of 2010 are part of the first period. Indeed, although the existing buildings are treated in their own specific article in both directives, the action to be taken on their refurbishment are limited to a minimum energy performance requirement. Moreover, the actions have to be taken for buildings, or buildings units, or building elements, undergoing major renovation, but it is not clear what exactly "major renovation" means and which are the burdens for considering a renovation at low or high impact.
In the second period it can be noticed the development of the focus of the existing buildings energy-efficiency in the European regulatory framework.
In the Directive 2012/27/EU on energy efficiency of 25 October 2012, the only parts related to buildings are the Articles 4 and 5. The former is entitled *"Building Renovation"* and its content is reported hereafter:

(9) Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC. Off. J. Eur. Union.

(10) Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency. Off. J. Eur. Union.

(1) Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC. Off. J. Eur. Union. p 13

"Member States shall establish a long-term strategy for mobilising investment in the renovation of the national stock of residential and commercial buildings, both public and private. This strategy shall encompass:
(a) an overview of the national building stock based, as appropriate, on statistical sampling;
(b) identification of cost-effective approaches to renovations relevant to the building type and climatic zone;
(c) policies and measures to stimulate cost-effective deep renovations of buildings, including staged deep renovations;
(d) a forward-looking perspective to guide investment decisions of individuals, the construction industry and financial institutions;
(e) an evidence-based estimate of expected energy savings and wider benefits." [(1)]

The Article 5, *"Exemplary role of public bodies' buildings"* contains the following statements:

"(...) each Member State shall ensure that, as from 1 January 2014, 3 % of the total floor area of heated and/or cooled buildings owned and occupied by its central government is renovated each year to meet at least the minimum energy performance requirements that it has set in application of Article 4 of Directive 2010/31/EU."
(...)
Member States shall require that central government buildings with the poorest energy performance be a priority for energy efficiency measures, where cost-effective and technically feasible.
(...)
by 31 December 2013, Member States shall establish and make publicly available an inventory of heated and/or cooled central government buildings.
(...)
Member States shall encourage public bodies, including at regional and local level, and social housing bodies governed by public law, to:
(a) adopt an energy efficiency plan containing specific energy saving and efficiency objectives and actions
(b) put in place an energy management system, including energy audits, as part of the implementation of their plan;
(c) use, where appropriate, energy service companies, and energy performance contracting to finance renovations and implement plans to maintain or improve energy efficiency in the long term." [(2)]

(2) Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC. Off. J. Eur. Union. p 14-15

Finally, the Directive 2018/844[3] of 30 May 2018 plays a central role in the energy refurbishment of existing building. It basically consists in an amending Directive of both 2012/27/EU and 2010/31/EU directives. However, one of the new articles introduced in the document is the Article 2a, entitled *"Long term renovation strategies"*, and represents an important step in the process of the renovation of the European building stock. The text below is extracted by the article with the aim to explain what the new strategies adoption means.

"Each Member State shall establish a long-term renovation strategy to support the renovation of the national stock of residential and non-residential buildings, both public and private, into a highly energy efficient and decarbonised building stock by 2050, facilitating the cost-effective transformation of existing buildings into nearly zero-energy buildings.

Each long-term renovation strategy shall be submitted in accordance with the applicable planning and reporting obligations and shall encompass:
(a) an overview of the national building stock and expected share of renovated buildings in 2020;
(b) the identification of cost-effective approaches to renovation relevant to the building type and climatic zone
(c) policies and actions to stimulate cost-effective deep renovation of buildings and to support targeted cost-effective measures and renovation
(d) an overview of policies and actions to target the worst performing segments of the national building stock and an outline of relevant national actions that contribute to the alleviation of energy poverty;
(e) policies and actions to target all public buildings;
(f) an overview of national initiatives to promote smart technologies and well-connected buildings and communities, as well as skills and education in the construction and energy efficiency sectors;
(g) an evidence-based estimate of expected energy savings and wider benefits, such as those related to health, safety and air quality.

In its long-term renovation strategy, each Member State shall set out a roadmap with measures and domestically established measurable progress indicators, with a view to the long-term 2050 goal of reducing greenhouse gas emissions in the Union by 80-95 % compared to 1990
(...)".[4]

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(10) Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency. Off. J. Eur. Union.

(10) Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency. Off. J. Eur. Union. p 7-8

2.3.3 THE ITALIAN REGULATORY FRAMEWORK OF THE BUILDING ENERGY PERFORMANCE

The last paragraph of this second chapter deals with the implementation in the Italian context of the European legislation on the building energy efficiency.
By following a chronological order, the first European Directive 2002/91/EC on the energy performance of the buildings (EPBD) was implemented by the Legislative Decree 192/2005 [1] of 19 August 2005. This last contains seventeen articles divided in three main parts. The first part is entitled "Overall Principles" and is extended from Article 1 to Article 10. The title of the second part is "Transitional Rules" and contains the Articles 11 and 12. The last part is "Final Provision", included between the Article 13 to 17. In addition, ten annexes, from A to L letter, enforce the Decree.
The document structure is quite similar to the EPBD Directive but it is obviously more specific and adapted to the Italian Country. This is evident from the purpose defined in Article 1 reported hereafter:

"The present Decree establishes the criteria, the conditions and ways to improve energy performance of buildings in order to promote development, enhancement and the integration of renewable sources and energy diversification, contribute to the achievement of the national limitation targets on greenhouse gases emissions set by the Kyoto Protocol, promote the competitiveness of the most advanced compartments through technological development". [2]

Article 3 defines the "Areas of intervention" that is specific indications of the building typologies on which act to improve their energy-efficiency. In contrast to the EPBD Directive distinction of new and existing buildings in two articles, Article 3 is related to both. In the case of existing buildings renovation, the law defines a gradual refurbishment in relation to the kind of intervention. The following scheme explains the different areas of intervention.

total refurbishment of the whole building in case of	complete renovation of the envelope in existing buildings with A > 1000m2 demolition and reconstruction under extraordinary maintenance of existing buildings with A > 1000m2	**partial refurbishment of**	building enlargement when its volume is 20% greater than building volume specific intervention such as thermal installation or replacement of heat generators

(1) Legislative Decree D.lgs 192/2005 by the President of Republic of 19 August 2005. *Implementation of the Directive 2002/91/EC on the energy performance of buildings.* Gazzetta Ufficiale, Ordinary Supplement n.222, 23 September 2005.

(2) Legislative Decree D.lgs 192/2005 by the President of Republic of 19 August 2005. *Implementation of the Directive 2002/91/EC on the energy performance of buildings.* Gazzetta Ufficiale, Ordinary Supplement n.222, 23 September 2005, p 2.

Article 4 sets the "Adoption of general criteria, a methodology calculation and energy performance requirements"within 120 days from the entry into force of the Decree. Until that date, in the "Transitional Rules" section the Articles 11 and 12 respectively provide: the calculation of the energy performance of buildings in winter air conditioning and, in particular, the annual primary energy demand in the Annex I; the reduction of energy consumption by the use and maintenance of thermal systems for winter heating, regular inspections and minimum requirements for external commissioned for inspections in the Annex L.
The aspects to consider in the methodology calculation are listed in the Annex B added to the Article 4 of the Legislative Decree, in the same way and with the same listed factors of the European EPBD Directive. In addition, the D.lgs 192/2005 sets to consider another important factor, that is the use of renewable energy. Indeed, the Annex D contains the provisions for the integration of the solar thermal and photovoltaic systems on building roofs.
The promotion of the renewable energy use is also enhanced by "Cooperation Mechanism" in Article 5 and by "Accompanying measures" defined in Article 13 as information,education and training programmes on that topic.
Finally, it is interesting to report that, as in Article 7 of EPBD Directive, Article 6 lays down the obligation of the Energy Performance Certification (EPC) for the interventions defined in Article 3 within one year from the entry into force of the Decree.
The Legislative Decree 311/2006 *(3)* of 29 December 2006 provides corrective and supplementary provisions to D.lgs 192/2005. The updated Decree is composed of ten articles, eight of which are modifies related to the previous Decree articles. This section reports only the most interesting parts.
Article 1 modifies the previous Article 3 by adding the existing systems replacement and the installation of new systems in new or existing buildings to the areas of intervention.
Article 2 sets new obligation about the energy certification on the transfer for certification of buildings by 1 July 2008 and of building units by 1 July 2009. In addition, the article introduces the EPC obligation for accessing to incentives and for public management of system installations by 1 July 2007.
Finally, to Article 9 of "Functions of regions and local authorities" of the previous Decree, Article 3 adds the obligation to provide an awareness and energy retrofitting programme of the territorial real estate by 31 December 2008.
Article 4, comma 2, letters a) and b) of the Legislative Decree 142/2005 about the adoption of a calculation methodology and minimum requisites for the building energy performance is implemented by the Decree of the President of Republic D.P.R. 59/2009 *(4)* of 2 April 2009.
This last is composed of eight articles, of which Article 4 contains twenty-seven commas. The most important information are reported below.

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(3) Legislative Decree D.lgs 311/2006 by the President of Republic of 29 December 2006. *Corrective and supplementary provisions to Legislative Decree 19 August 2005, n. 192, implementing Directive 2002/91/EC, on the energy performance of buildings.* Gazzetta Ufficiale, Ordinary Supplement n.26, 1 February 2007.

(4) Decree of the President of Republic 59/2009 of 2 September 2009. *Regulation implementing Article 4, paragraph 1, letters a) and b), of the Decree19 agosto 2005, n. 192, on the implementation of the Directive 2002/91/EC on the energy performance of buildings.* Gazzetta Ufficiale, n.132, 10 June 2009.

First of all, the following definitions are introduced in Article 2: "filtering systems for transparent surfaces", "periodic thermal conductivity" and "green roof".
In Article 3, "Calculation methodology for the energy performance of buildings and installations", the national technical standards, defined in the context of EN norms to support the EU Directive 2002/91/EC, are adopted. In particular, the following norms of the UNI/TS 11300 series are adopted:
a) UNI/TS 11300 - 1 Energy performance of buildings - part 1: Determination of the building's thermal energy needs for summer and winter air conditioning;
b) UNI/TS 11300 - 1 Energy performance of buildings - part 2: Determination of primary energy need and returns for winter air conditioning and for the production of domestic hot water.
Article 4 lays down the determination for all categories of new and existing buildings of Index of Winter Heating Performance (EPi) and the verification of its lower value than limits set by Annex C of D.lgs 142/2005. In addition, the article defines that the summer cooling energy performance is equal to the ratio between the annual thermal energy need for summer cooling and the building area and its value must be higher than:
1) 40 kWh/m2 in climatic zones A and B and 30 kWh/m2 in climatic zones C,D,E and F for residential buildings;
2) 14 kWh/m2 in climatic zones A and B and 10 kWh/m2 in climatic zones C,D,E and F for other buildings.
It is important to clarify that the building categories are defined in Article 3 of D.P.R. 412/1993[(5)] which is often specified in the D.P.R. in question.
Then, Article 4 provides specific indications for the thermal transmittance calculation and the heat generators installations as well, with reference to the Annex C of D.lgs 192/2005. Moreover, it specifies that the installations have to ensure a measurement error lower than more or less 5%.
Finally, the obligatory use of renewable sources for thermal and electrical energy is highlighted and, in particular, the energy production system has to be design in order to cover at least 50% of annual primary energy need for domestic hot water production.
The implementation of Articles 4,5,6 and 9 of D.lgs 192/2005 occurred by the Ministerial Decree of 26 June 2009 through the publication of the "National guidelines for the energy performance certification of buildings"[(6)]. The D.M. is composed of eight articles and two annexes, A and B; the Annex A, in turn, is composed of seven annexes, from 1 to 7.
The aim of the D.M. in question is to define an energy certification system able to:

a. provide information on the energy quality of buildings and tools for clear and immediate understanding:

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(5) Decree of the President of Republic 412/1993 of 26 August 1993. *Regulation laying down rules for design, installations, operation and maintenance of thermal installation in buildings reduction of energy consumption by implementing Articl 4, comma 4, of the law 10 of 9 January 1991.*Gazzetta Ufficiale, n.96, 14 October 1993.

(6) Ministerial Decree D.M. by the Ministry of Economic Development of 26 June 2009. *National guidelines for the energy performance certification of buildings.* Gazzetta Ufficiale, n.158, 10 July 2009.

(7) Ministerial Decree D.M. by the Ministry of Economic Development of 26 June 2009. *National guidelines for the energy performance certification of buildings.* Gazzetta Ufficiale, n.158, 10 July 2009, p 10.

- to assess the economic convenience of energy refurbishment projects;
- for purchases and leases of real estate by considering the energy performance of buildings;
b. to contribute to an homogeneous application of the energy performance certification of buildings (...) trough the definition of a national procedure containing:
- the indication of a buildings classification system;
- the individuation of alternative energy performance calculation methodologies in relation to different characteristic of the building (...);
- the availability of simplified methods for minimising the citizens burdens". [(7)]

The sub-paragraph 3 of Annex A shows the formula for the total energy performance calculation: [(8)]

EPgl=EPi + EPacs + EPe + EPill

where
EPgl is the global energy performance index;
Epi is the energy performance index for winter heating;
EPacs is the energy performance index for the domestic hot water production;
EPe is the energy performance index for summer cooling;
EPill is the energy performance index for the artificial lighting.
The indexes are expressed in kWh/m2 for residential buildings and in kWh/m3 for other buildings.
Moreover, the sub-paragraph 4 of Annex A defines two main methodologies for the determination of the energy performance: the "Calculated method by project" and the "Calculation method by building survey or standard". The former is based on the project data considered as constructed; the latter is based on surveys carried out on the existing building by survey procedures, by comparison with other similar buildings or by climatic, typological, geometrical and installation data.
Finally, an important point is the institution of a national board among State, Regions, and local authorities for the coordination of the Energy Performance Certification (EPC) normative.
The Annex A will be modified by the Ministerial Decree of 22 November 2012[(9)]; however, the modifies are only related to few adjustments.

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(8) Ministerial Decree D.M. by the Ministry of Economic Development of 26 June 2009. *National guidelines for the energy performance certification of buildings.* Gazzetta Ufficiale, n.158, 10 July 2009, p 12.

(9) Ministerial Decree D.M. by the Ministry of Economic Development of 22 November 2012. *Modify of Decree 26 June 2009 laying down "National guidelines for the energy performance certification of buildings" .* Gazzetta Ufficiale, n.290, 13 November 2012.

The Directive 2010/31/EU of 19 May 2010, also known as EPBD recast, was implemented in Italy by the Legislative Decree 63/2013 [(10)] of 4 June 2013, composed of twenty articles.
The Decree is based on modifications of the D.lgs 192/2005 articles and addition of the new European Directive. In particular, Article 5 is the implementation of Article 9 of EPBD recast about the introduction of the Nearly-Zero Energy Buildings (NZEB).
The text below is extracted from Article 5:

"After Article 4 of the Legislative Decree 19 August 2005, the following are added:
Article 4-bis, "Nearly-Zero Energy Buildings".
1. From 31 December 2018, new buildings occupied and owned by public authorities, including school buildings, must be nearly-zero energy buildings. From 1 January 2021, this provision will be extended to all new buildings.
2. From 30 June 2014, the Action Plan (...) to increase the NZEB number is defined. This Plan, which may include targets differentiated by type of building, will be sent to the European Commission.
(...)
4. From 31 December 2013, (...) a list of financial measures to promote energy efficiency in buildings and the transition to nearly zero-energy buildings. This list will be updated every three years (...)." [(11)]

Article 9 modifies Article 11 of D.lgs 192/2005 by adopting national standards for the calculation methodologies of the building energy performance. To the UNI/TS 11300-1 and UNI/TS 11300-2 specified in D.P.R 59/2009, the following norms are added:
a. Recommendation CTI 14 2013 "Energy performances of buildings - Determination of the primary energy and the Energy Performance EP for the building classification";
b. UNI/TS 11300 - 1;
c. UNI/TS 11300 - 2;
d. UNI/TS 11300 - 3 - Energy performances of buildings - Part 3: Determination of the primary energy need and the summer cooling returns;
e. UNI/TS 11300 - 4 - Energy performances of buildings - Part 4: Usage of the renewable energy and other methods for heating generation and domestic water production;
e bis. UNI EN 15193 - Energy performances of buildings - energy needs for lighting.
The D.lgs 63/2013 became Law 90/2013 [(12)] on 3 August 2013.

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(10) Legislative Decree D.lgs 63/2013 by the President of Republic of 4 June 2013. *Urgent provisions for the transposition of Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010, on the energy performance of buildings for the definition of infringement procedures initiated by the European Commission, as well as other provisions on social cohesion.*
Gazzetta Ufficiale, n.181, 3 August 2013.

(11) Legislative Decree D.lgs 63/2013 by the President of Republic of 4 June 2013. *Urgent provisions for the transposition of Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010, on the energy performance of buildings for the definition of infringement procedures initiated by the European Commission, as well as other provisions on social cohesion.*
Gazzetta Ufficiale, n.181, 3 August 2013, p 17-18.

(12) Law 90/2013 by the President of Republic of 3 August 2013. *Conversion into law, with modifications, of the Decree 4 June 2013, n. 63, containing urgent provisions for the transposition of Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010, on the energy performance of buildings for the definition of infringement procedures initiated by the European Commission, as well as other provisions on social cohesion.* Gazzetta Ufficiale, n.181, 3 August 2013.

The European Energy Efficiency Directive 2012/27/EU was implemented in Italy by the Legislative Decree 102/2014 (13) of 4 July 2014, composed of twenty articles and eight annexes.
It will have been modified in a few parts by the D.lgs 141/2016 (14) of 18 July 2016.
The structure of the document and the articles are the same of the European Directive with specification to the Italian context. In particular,the aim improve the national energy efficiency is related to the achievment of the national target that is the reduction of 20 million of tonnes of oil for energy production by 2020.

Italian target starting from 2010	→	**- 20 million tonnes of oil for energy production by 2020**

The D.M 26/6/2009 "National guidelines for the energy performance certification of buildings" for the implementation of Article 6 of D.lgs 192/2005 was modified by the Ministerial Decree of 26 June 2015 in "Adaptation of national guidelines for energy certification of buildings"(15).
The Decree is composed of ten articles and the Annex 1, integrated by four appendix A-D.
The aim is the same of the previous one: the determination of a homogeneous certification system for the energy performance of buildings. For achieving this goal, in addition to the definition of national guidelines and of cooperation tools between State and Regions, the present Decree aims to:

"realize a national information system for the management of a national register of the energy performance attestations and thermal installations". (16)

Article 4 introduces the national Energy Performance Attestation (APE) as a new essential element in the national guidelines for the building energy performance certification. APE is considered a orientation-market tool towards more qualitative buildings.
Each APE must obligatory contains:
a. the global energy performance index;
b. the energy class, determined by the global energy performance index;
c. the thermal performance indexes for heating and cooling of the building;
d. the minimum requisites of energy performance by law;
e. CO_2 emissions;
f. the exported energy;
g. the proposal of important and economic convenient intervention for an energy-efficiency improvement.

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(13) Legislative Decree D.lgs 102/2014 by the President of Republic of 4 July 2014. *Implementation of Energy Efficiency Directive 2012/27/EU amending Directives 2009/125/EC and 2010/30/EU and repeals Directives 2004/8/EC and 2006/32/EC.* Gazzetta Ufficiale, n.165, 18 July 2014.

(14) Legislative Decree D.lgs 141/2016 by the President of Republic of 18 July 2016. *Integrative provisions to Legislative Decree 4 July 2014, n. 102, implementing Directive 2012/27/EU on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC.* Gazzetta Ufficiale, n.172, 25 July 2016.

Appendix B shows the APE format which is composed of five pages. Appendix C shows an essential APE format for commercial advertisements with the more important information. This last is reported below.

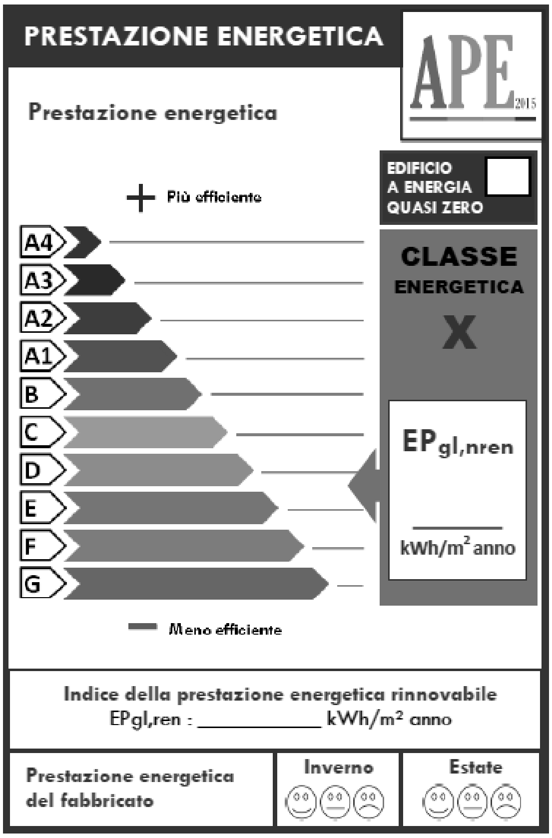

Fig.1 APE format for commercial advertisements
Source: Ministerial Decree D.M. by the Ministry of Economic Development of 26 June 2015. *Application of energy performance calculation methodologies and definition of provisions and minimum requirements of buildings.* Gazzetta Ufficiale, n.162, 15 July 2015, p 31.

Article 6 sets that, within ninety days from the entry into force of the Decree, ENEA must institute SIAPE, the national Information System of the Energy Performance Attestations.

Finally, the last European Directive 2018/844/EU, amending the 2010/31/EU and 2012/27/EU directives, has been implemented by the Italian Legislative Decree 48/2020 [(17)] of 10 June 2020. The document is composed of fourteen articles , the most of which add some modifies to the D.lgs 192/2005 articles.
The most important parts of this last Decree on energy-efficiency of buildings are Article 5 and Article 8.

(15) Ministerial Decree D.M. by the Ministry of Economic Development of 26 June 2015. *Application of energy performance calculation methodologies and definition of provisions and minimum requirements of buildings.* Gazzetta Ufficiale, n.162, 15 July 2015.

(16) Ministerial Decree D.M. by the Ministry of Economic Development of 26 June 2015. *Application of energy performance calculation methodologies and definition of provisions and minimum requirements of buildings.* Gazzetta Ufficiale, n.162, 15 July 2015, p 2.

(17) Legislative Decree D.lgs 48/2020 by the President of Republic of 10 June 2020. *Implementation of Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018, amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency.* Gazzetta Ufficiale, n.146, 10 June 2020.

The former adds the Article 3-bis to Article 3 of D.lgs 192/2005. The article is entitled "Long-term renovation strategy" and is explained by the following statements:

"(...) within thirty days of the entry into force of this provision, the long-term strategy to support the national building stock of residential and non-residential buildings, both public and private, in order to obtain a decarbonised and high efficiency real estate by 2050, by allowing a cost-effective transformation of the existing buildings in nearly zero-energy buildings

(...)

the strategy provides for the setting of periodic indicative targets for 2030, 2040 and 2050, including the achievement of an annual restructuring rate for improving the energy performance by at least 3%(...)." (18)

Article 8 introduces the Article 4-quater in the D.lgs 192/2005 that is "National portal on the energy performance of buildings" and it is clarified below:

"the National Portal on the energy performance of buildings is instituted with the aim of providing citizens, businesses and the public administration information on the energy performance of buildings, on best actions for cost-effective energy renovations, on existing tools for improving the energy performance of buildings, including the replacement of fossil fuel boilers by more sustainable alternatives, and energy performance attestations". (19)

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(18) Legislative Decree D.lgs 48/2020 by the President of Republic of 10 June 2020. *Implementation of Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018, amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency.* Gazzetta Ufficiale, n.146, 10 June 2020, p 5-6.

(19) Legislative Decree D.lgs 48/2020 by the President of Republic of 10 June 2020. *Implementation of Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018, amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency.* Gazzetta Ufficiale, n.146, 10 June 2020, p 12-14.

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Gazzetta Ufficiale, n.181, 3 August 2013.

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Gazzetta Ufficiale, n.146, 10 June 2020.

Chapter 2
Regulatory context

2.1
EU climate targets and main policies

2.1.1
2020 climate and energy package

Period:
2013-2020

Targets from 1990 levels:
-20% GHGs emission
Decision 406/2009/EC

+ 20% renewable energy
Directive 2009/28/EC

+20% energy-efficiency
no directive

Key tools:
Emission Trading
System(ETS)

Effort Sharing Decision
(ESD)

Funding programs:
NER 300
Horizon 2020

2.1.2
2030 climate and energy framework

Period:
2021-2030

Targets from 1990 levels:
-40% GHGs emission

+ 32% renewable energy

+32,5% energy-efficiency

updated ETS and ESD
Regulation (EU)2018/1999
NECPs

European Climate Law 2020

2030 Target Plan:
-55% GHGs emission

2.2
The energy-efficiency focus in the EU agenda

2.2.1
The overall norms and strategies

the strategic importance of
the energy- efficiency
in
Energy 2020 Strategy (2010)

+ 20% energy-efficiency
binding target adoption
in
Energy Efficiency Directive
2012/27/EU
in which NEEAPs

Energy Union Strategy (2015)

+ 32,5% energy-efficiency
binding target adoption
in
Energy Efficiency Directive
2018/2002
as part of the
Clean Energy for All European
Package (2019)

European Green Deal
Strategy (2019)

Delivering the
European Green Deal (2021),
a set of proposal and
new targets
from 1990 levels by 2030:

-55 % GHGs

+40% renewable energy

+36-39% energy-efficiency

2.2.2
The building energy-efficency strategies

Energy 2020
Strategy
Priority 1

2015 Energy
Union Strategy
3rd dimension

2019 Clean Energy
for All
European Package
1st policy

2019 European
Green Deal
4th policy

2.2.3
A Renovation Wave for Europe

data about EU
building stock

aim:
to double the
annual energy
renovation rate
by 2030
35 billions units
renovated by 2030

Renovation Wave
7 key principles

Renovation Wave
7 actions

2.3
The building energy performance legislation

2.3.1
The regulatory framework process

EPBD
Directive 2002/91/EC
Article 7: EPC

EPBD Recast
Directive 2010/31/EC
Article 5:
calculation of cost-optimal
levels of minimum energy-
performance requirements
Article 9: NZEB

EED 2012/27/EU

EPBD Recast and EED
modified by
Directive 2018/844

2.3.2
The growing attention on existing buildings

2020 Energy Strategy (2010)
as a turning point in the
attention given to the
existing buildings

Low attention given to the
existing buildings before
2020 Energy Startegy
in 2002/91/EC
and 2010/31/EU

High attention given to the
existing buildings after
2020 Energy Startegy

in Article 4
"Building Renovation"
and Article 5
"Exemplary role of public
bodies' buildings"
both in 2012/27/EU

in Article 2a
"Long Term
Renovation Strategies"
in 2018/844

2.3.3
The Italian regulatory framewok

implementation of
2002/91/EC

L.D. 192/2005
modified by
L.D. 311/2006
and implemented by
D.P.R. 59/2009
and by
D.M. 26 June 2009,
which is modified by
D.M. 26 June 2015

implementation of
2010/31/EU

L.D. 63/2013

implementation of
2012/27/EU

L.D. 102/2014

implementation of
2018/144

L.D. 48/2020

Chapter 2 framework
Author elaboration

03

Methodological Context:

Life Cycle Thinking

INTRODUCTION

This chapter deals with two very diffuse methodologies in the construction sector, the Life Cycle Assessment (LCA) and Life Cycle Cost Analysis (LCCA) or Life Cycle Costing (LCC). Both derive from the Life Cycle Thinking (LCT) approach, which is even considered prior to the circular economy and strictly linked to the sustainable development concept. In addition, there are many approaches, programmes and activities in the Life Cycle Thinking basket that are essential in the green economy. These have been developed to assist in decision-making at all levels regarding product development, production, procurement, and final disposal. They can be used in all sectors, and offer the possibility to examine a range of key impact categories and indicators.

The main goals of LCT are to reduce a product's (or a building) resource use and emissions to the environment as well as improve its socio-economic performance through its life cycle. This may facilitate links between the economic, social and environmental dimensions within an organization and through its entire value chain. Therefore, Life Cycle Thinking is an effective tool which integrate the principles of circular economy, it is also included the human well-being as in green economy, and embraces the environmental, economic and social perspectives of the sustainable principles.

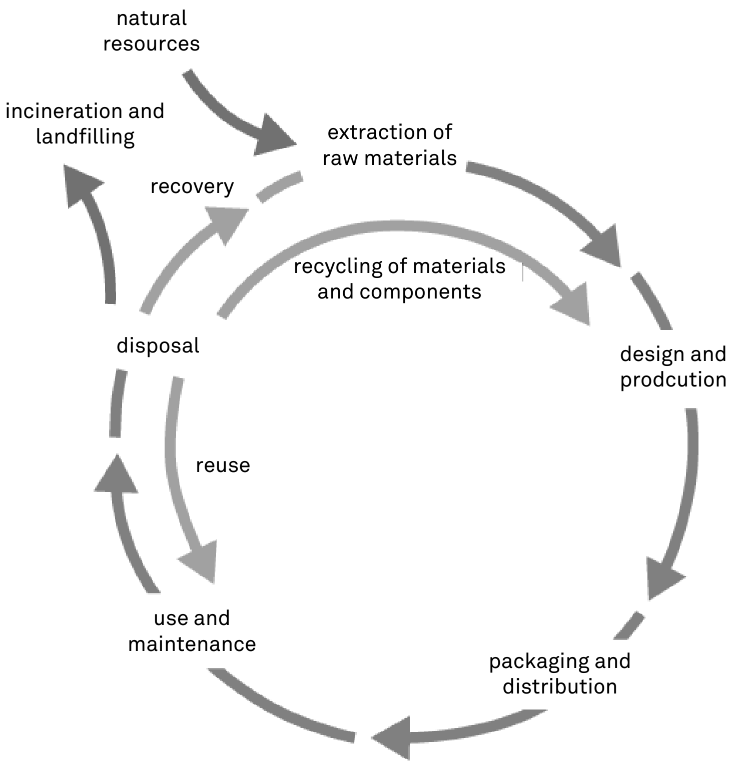

Figure 1 LCT approach for a product life cycle.
Source: Author re-elaboration from LIFE CYCLE INITIATIVE. *What is Life Cycle Thinking?* Official website.
https://www.lifecycleinitiative.org/starting-life-cycle-thinking/what-is-life-cycle-thinking/

3.1 LIFE CYCLE ASSESSMENT (LCA)

This section briefly deals with the Life Cycle Assessment (LCA) that is one of the most consolidated approach in the context of Life Cycle Thinking. The section is divided in two sub-sections. The first sub-section describes the LCA reference standards and its linkage to other regulations; in particular the environmental labelling regulations are treated.
The second sub-paragraph deals with the LCA methodological framework and the four steps are briefly described by highlighting the most important ones.

3.1.1 ORIGINS, DEFINITIONS AND REFERENCES

Life Cycle Assessment, or LCA, is a decision support tool for evaluating the environmental impact of a product, or building, or building component, all over its life cycle, from "cradle to grave". Nowadays, LCA is defined and regulated by Standard ISO 14040:2006, *Environmental Management – Life Cycle Assessment – Principles and Framework*,(1) drafted by the Technical Committee ISO/TC 207. ISO 14040 is part of the ISO 14040/44 series included in "Environmental Management" published by ISO/TC207 team in 1993 and explained in the figure below.(2)

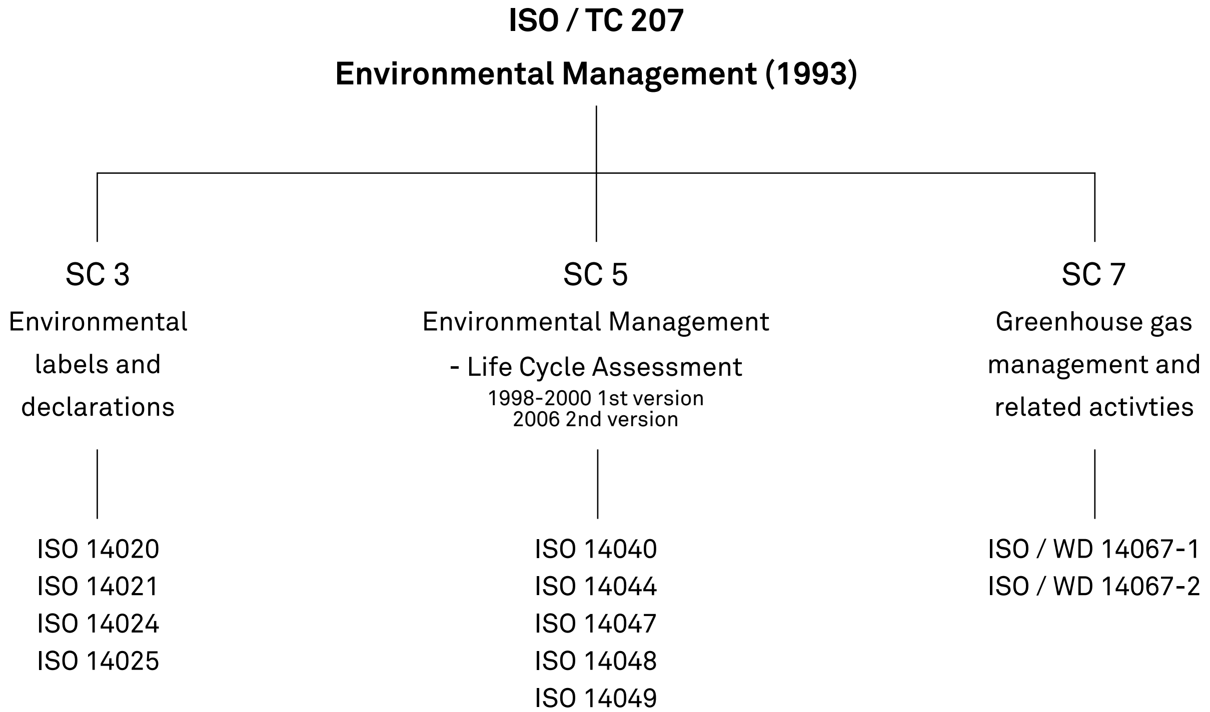

Figure 1 ISO-TC207-Environmental Management (SC 3, SC 5 and SC 7).
Source: THIEBAT F., (2019). *Life Cycle Design: an experimental tool for designers*, Politecnico di Torino, Springer Series, Torino, p 33

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(1) International Organization for Standardization, ISO 14040:2006, *Environmental Management - Life Cycle Assessment - Principles and Framework*, ISO/TC 207/S05, International Organization for Standardization, Geneva, Switzerland, 2006.
International Organization for Standardization, ISO 14044:2006, *Environmental Management - Life Cycle Assessment - Requirements and Guidelines*, ISO/TC 207/S05, International Organization for Standardization, Geneva, Switzerland, 2006.

(2) THIEBAT F., (2019). *Life Cycle Design: an experimental tool for designers*, Politecnico di Torino, Springer Series, Torino, p 33

The standard group includes three Subcommittees that are SC3, SC5 and SC7. The first one (SC3) identifies three broad types of voluntary label declarations:

• ISO Type I environmental labelling, regulated by UNI EN ISO 14024:2001, defines a voluntary, multiple-criteria based, third party program that awards a license, based on the fulfilment of a set of criteria, that authorises the use of environmental labels on products indicating an overall environmental preferability of a product within a particular product category based on life cycle considerations.

• ISO Type II environmental labelling, also known as self-declared environmental labelling and regulated by UNI EN ISO 14021:2016, reports the environmental information of a product which can be declared by the producer without a third-party intervention. It also describes selected terms commonly used in environmental claims and gives qualifications for their use.

• ISO Type III environmental labelling, also known as Environmental Product Declaration (EPD) and regulated by ISO 14025:2010 reports statements based on established parameters and contains a quantification of environmental impacts associated with the life cycle of the product calculated through the LCA system and are subject to an independent control.

The SC 5 regulates the LCA standard series ISO 14040-44 and SC 7 introduces regulations about the greenhouse gas emission management and related activities.
Life Cycle Assessment bases its origins in the late sixties and early seventies when industrial companies started to focus on the whole production chain, instead of the single product, to assess the energy-environmental impact of different food and beverage containers. In 1979, Ian Boustead published the "Handbook of Industrial Energy Analysis"(3) in UK in which an energy-used calculation methodology is applied to the production of different kinds of materials. This text is considered crucial in the LCA development by many experts. (4)
In1990, the Society of Environmental Toxicology and Chemistry (SETAC) coined the term Life-Cycle Assessment for the first time during a congress held in Vermont, USA.
Later, the International Standard Organization published the first standard series ISO 14040/44 on Environmental Management - Life Cycle Assessment in 1998, revised in 2006 and confirmed in 2016, as reported in the figure 1.

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(3) BOUSTEAD I., (1979). *Handbook of Industrial Energy Analysis*, Ellis Horwood Ltd , Publisher, New York.

(3) EUROPEAN ENVIRONMENTAL AGENCY EEA, (1997). *Life Cycle Assessment. A guide to approaches, experiences and information sources*, EEA, Environmental Issues Series No 6, p 13-14.

3.1.2 THE METHODOLOGICAL FRAMEWORK

The Standard UNI EN ISO 14040:2006 defines the Life Cycle Assessment as:

"a *compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle". (6)*

The LCA framework proposed by the ISO can be summarised in four stages showed in the figure below.(7)

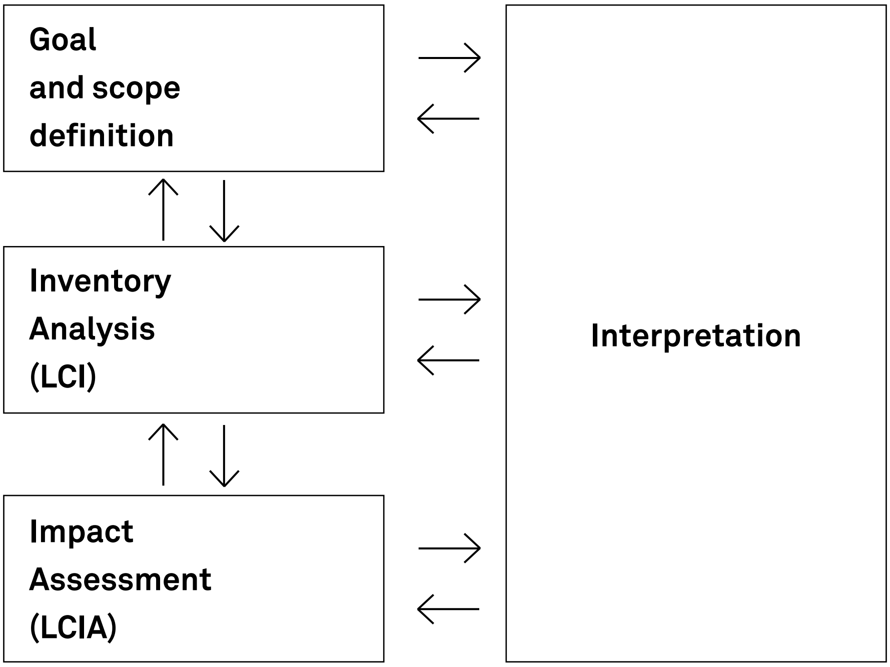

Figure 2 Diagram of the structure of the LCA based on ISO 14040.
Source: THIEBAT F., (2019). *Life Cycle Design: an experimental tool for designers*, Politecnico di Torino, Springer Series, Torino, p 33

The first step, "Goal and scope definition", is introduced by ISO 14040 and defines three elements for the final application of the system :

1. Definition of the objectives of the analysis;
2. Choice of functional unit that is a quantified reference unit on which the analysis is set;
3. Delimitation of the system boundaries that is the life cycle stages considered in a period.

(6) International Organization for Standardization, ISO 14040:2006, *Environmental Management - Life Cycle Assessment - Principles and Framework*, ISO/TC 207/S05, International Organization for Standardization, Geneva, Switzerland, 2006.

(7) THIEBAT F., (2019). *Life Cycle Design: an experimental tool for designers*, Politecnico di Torino, Springer Series, Torino, p 33

The second step is the Life Cycle Inventory Analysis or LCI and is regulated by ISO 14041. It represents the LCA most complex phase since it reproduces an analytical system of the real application through the data collection and calculation procedures to quantify the inputs and outputs of the system. The process is iterative because of its development in parallel with data collection. The data can be classified into three main categories:

1. Energy input elements, input raw materials, support materials or other physical entities in input;
2. Products, co-products and wastes;
3. Emissions to air and discharges to water and soil;
4. Other environmental aspects.

The third step is the Life Cycle Impact Assessment or LCIA, regulated by ISO 14042. This phase analyses the environmental impacts of the LCI results by associating them with defined environmental impact categories and category indicators. This stage is articulated into four main steps:

1. Classification of the impact categories;
2. Characterization of each substance in relation to its impact on a specific environmental issue through a weighted average of inputs and outputs;
3. Normalization of the values in relation to a reference value;
4. Valuation of the environmental impact of a product through a numerical factor.

The last step is the "Results interpretation and analysis" and it is introduced by ISO 14043. It combines the results of LCI and LCIA with the pre-established goals of the first step and is articulated in the following steps:

1. Identification of the strong and weak points of the results;
2. Comparison of the results with the pre-established goals;
3. Addition of eventual data for reaching the objectives of analyses.

3.2 LIFE CYCLE COST ANALYSIS (LCCA)

This section deals with Life Cycle Cost Anlysis (LCCA) methodology. First, its standard definition and calculation formula are described with a focus on the cost componenets linked to life cycle phases. Then, the methodological framework is treated and the economic indicators are described; a particular attention is given to the eventual synergy with LCA. Finally, the three typologies of LCC are defined.

3.2.1 DEFINITION AND THE COST COMPONENT CONCEPT

Life Cycle Cost Analysis (LCCA) or Life Cycle Costing (LCC) is an economic evaluation tool that allows the calculation of the total cost of a project by considering all the life cycle period, from the design to the end-of-life phase.
It has its origins in the early seventies to support US Department of Defense in the purchase of the expensive military equipment.
The tool is defined by Standard ISO 15686-5:2008,(1) revised by ISO 15686-5:2017.An Author reports the following LCCA definition, based on the literature:

"a technique which enables the systematic appraisal of life cycle costs over a period of analysis; an approach for the quantification of costs and benefits with particular reference to component costs during the entire life cycle of the building, so that it can support the decisions between project design solutions/components/specific materials based on the criteria of efficacy and economic efficiency; it is a technique for the economic evaluation of a new construction or an existing asset taking into account both immediate and long-term costs and benefits." (2)

The above definition needs to be integrated with an explanation of "cost-components" and "life cycle phases" terms. The Life Cycle Cost Analysis is based on the life cycle concept of a building and it considers all the phases from "cradle to grave". The phases are the following ones:

1. Briefing;
2. Planning;
3. Design;
4. Construction;
5. Use - Maintenance - Adaptation;
6. End of life - Disposal.

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(1) International Organization for Standardization, ISO 15686-5:2008, *Buildings and constructed assets - Servicelife planning, Part 5: Life Cycle Costing*, ISO/TC 59/CS 14, International Organization for Standardization, Geneva, Switzerland, 2008.

(2) FREGONARA E., (2015). *Evaluation sustainability design. Life Cycle Thinking and international orientation*, Franco Angeli, Milano, p 78

The following figure shows the life phases in the construction sector related to Whole Life Cost and Life Cycle Cost, further distinguishing Life Cycle Cost in construction and Life Cycle Cost in use.(3)

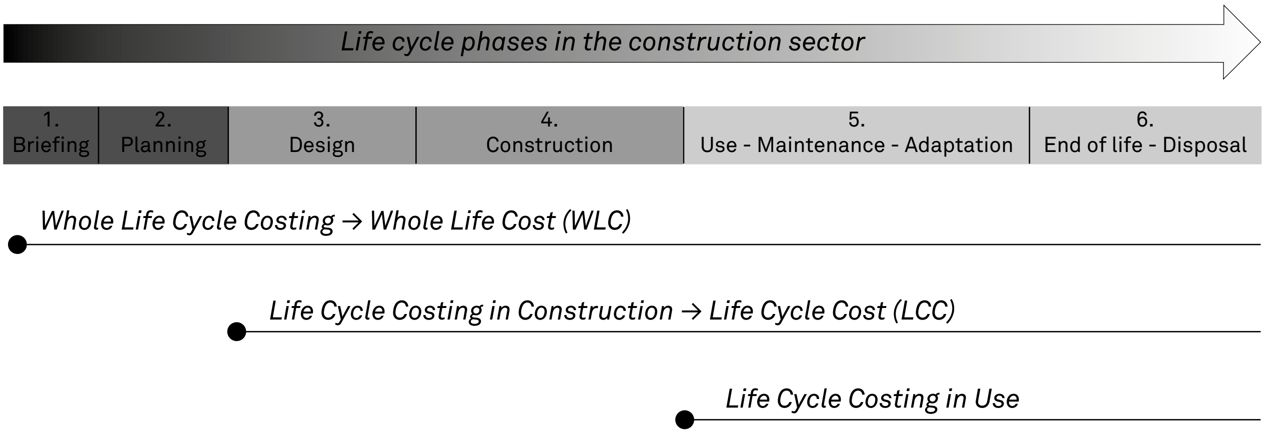

Figure 1 Building Process phases and Life Cycle Costing.
Source: Author's re-elaboration from FREGONARA E., (2015). *Evaluation sustainability design. Life Cycle Thinking and international orientation*, Franco Angeli, Milano, p 83

The Cost concept of the life cycle (Life Cycle Cost) is fundamental in LCCA methodology. The Life Cycle Cost derives from the Global Cost formulation that is defined by Standard EN 15459:2007 - *Energy performance of buildings - Economic evaluation procedure for energy systems in buildings*.(4) It represents an essential support to EPBD recast 2010/41/EU in the definition of a calculation methodology of the energy performance of buildings.
The Global Cost formula is the showed below:

$$C_G(\tau) = C_i + \sum_j \left[\sum_{i=1}^{\tau} \left(C_{a,i}(j) \times R_d(i) \right) - V_{f,\tau}(j) \right]$$

where:
$C_G(\tau)$ represents the Global Cost, referred to in the initial year τ_0;
C_i stands for initial investment costs;
$C_{a,i}(j)$ the annual cost at year i, for the j component (including running costs and the periodic or replacement costs);
$R_d(i)$ is the discount factor at year i;
$V_{f,\tau}(j)$ is the final value of the j component at the end of the calculation period.

(3) FREGONARA E., (2015). *Evaluation sustainability design. Life Cycle Thinking and international orientation*, Franco Angeli, Milano, p 83

(4) European Committee for Standardization (CEN), Standard EN 15459:2007, *Energy Performance of Buildings - Economic evaluation procedure for energy systems in buildings*., European Committee for Standardization, Brussels, Belgium, 2007.

The discount factor R_d may be expressed as:

$$Rd = 1 / (1 + Rr)^{p}$$

where R_r is the real discount rate and p is the reference period.
The Global Cost formula takes into account all the "relevant" costs in LCC methodology. The formula can be re-written as the following one:

$$LCC = \sum_{t=0}^{N} Ct / (1 + r)^{t}$$

where:
C_t is the sum of the relevant costs;
N is the number of the years of the period;
r is the discount rate.
Among the relevant cost components, it is also possible to distinguish between investment, operational and maintenance costs and to write again the formula as:

$$LCC = Ci + \sum_{t=0}^{N} \left[(C0 + Cm)/(1 + r)^{t}\right] \pm Vr\left[1 /(1 + r)^{N}\right]$$

where:
LCC stands for Life Cycle Cost;
C_i are the initial investment costs;
C_0 are the operational costs;
C_m are the maintenance costs;
t is the year when the cost is incurred;
N stands for the number of years of the entire period considered for the analysis;
r is the discount rate;
V_r is the residual value of a component at the end of the period and it can be positive if the component retains a value at the end of the period, or negative if it has to be disposed.
It can be noticed as in the formula the discount factor takes a key role since it allows to calculate the future costs at the present and evaluate if the initial investment costs will be repaid later. In the next page, in Figure 2 each cost component is related to each life cycle phase and in Figure 3 is explained which costs need to be actualized.[(5)]

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(5) FREGONARA E., (2015). *Evaluation sustainability design. Life Cycle Thinking and international orientation*, Franco Angeli, Milano, p 89

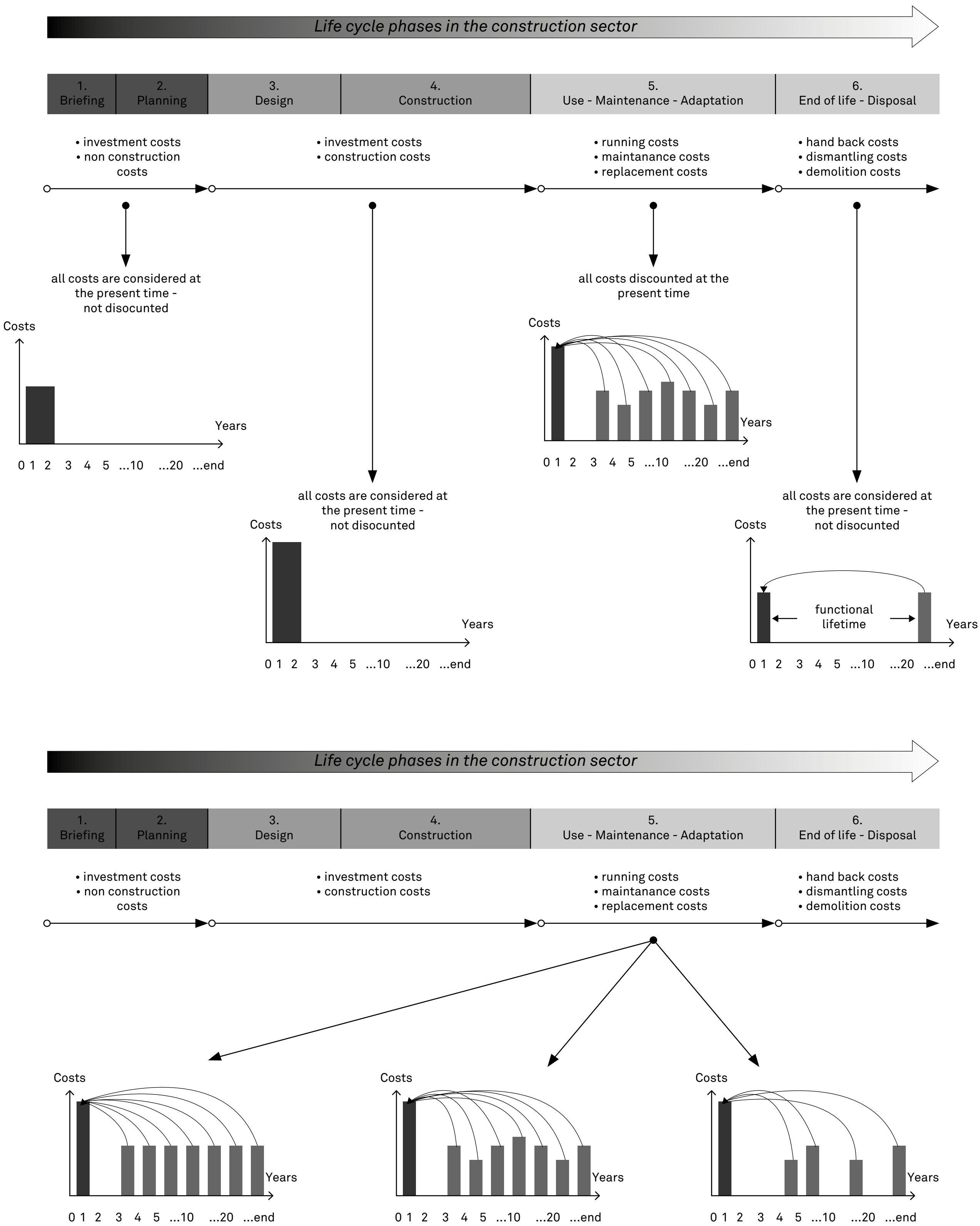

Figure 2 Categories of cost along the life cycle of a building and its discounting.
Source: Author's re-elaboration FREGONARA E., (2015). *Evaluation sustainability design. Life Cycle Thinking and international orientation*, Franco Angeli, Milano, p 89

3.2.2 THE METHODOLOGICAL FRAMEWORK

The LCC analysis, as mentioned before, it is based on ISO 15686-5:2008 - *Building and constructed assets - Service life Planning - Part 5 - Life Cycle Costing*. This Standard provides a procedure for the application of the methodology on new buildings, existing buildings or their components. LCCA can be considered a decision-making support tool for choosing among projects or technological alternatives and to individuate the most convenient solution. The chosen solution usually has higher initial investment costs and lower operational and maintenance costs.
The methodology is articulated in the following fifteen steps:(6)

- **Step 1** identifies the main purpose of LCC analysis;

- **Step 2** identifies the initial purpose of the analysis;

- **Step 3** identifies the relationship between sustainability analysis and LCC;

- **Step 4** identifies the analysis period and economic evaluation methods;

- **Step 5** identifies the necessary additional analysis, such as risk, uncertainty and sensitivity analysis;

- **Step 6** identifies the requisites of the asset and project;

- **Step 7** identifies the options that need to be included in the LCC analysis and cost items to consider;

- **Step 8** collects the cost and schedule data to be used in the LCC analysis;

- **Step 9** verifies financial parameters and period of analysis;

- **Step 10** reviews risk strategies and produces a preliminary analysis of risk and uncertainty (optional);

- **Step 11** draws up an economic evaluation plan;

- **Step 12** applies the detailed risk/uncertainty analysis (optional);

- **Step 13** applies the sensitivity analysis (optional);

- **Step 14** interprets and presents initial results;

- **Step 15** presents results and prepares the final report.

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(6) LANGDON D., (2007). *Life cycle costing (LCC) as a contribution to sustainable construction: a common methodology*. Davis Langdon Management Consulting. Final report.

Step 4 is one of the most important stage in which the identification of economic evaluation methods happens through the definition of the following economic indicators that represent the outputs of LCC analysis:

• Net Present Value (NPV) is used to calculate the total discounted cash flow including costs and revenues/benefits. In LCC analysis the revenues correspond to savings and NPV can be also named NPC (Net Present Cost). The NPV formula is written below:

$$NPV = \sum_{t=0}^{N} Ct / (1 + r)^t$$

where Ct is the total of relevant costs; N is the number of years of the period considered; r is the discount rate.

• Payback Period (PBP), in the non-discounted version (Simple PB-SPB) or in the discounted version (Discounted PB-DPB), represents the time necessary to recover initial investment costs, given a certain annual saving. The SPB is written below:

$$SBP = Oi / Rmy$$

where Oi represents the initial outlays or the investment and Rmy the mean yearly revenue.

• Net Savings (NS) and Net Benefits (NB) represent the present value of the savings/benefits during the year, net of the additional discounted investment costs, needed to have the same returns/savings. NS are expressed in the following formula:

$$NS = LCC_{BC} - LCC_{A}$$

where LCC_{BC} is the base case and LCC_{A} is the alternative case. If NS is positive the alternative case is better that the base one.

• Savings to Investment Ratio (SIR) expresses the relationship between what is saved in the operational phase and the additional investment costs without considering any residual value. It is calculated through the following formula:

$$SIR = Os / Ai$$

where Os are the operational savings and Ai are the additional investment costs.

• Adjusted Internal Rate of Return (AIRR) measures the annual performance of a project over a reference period taking into account intermediate reinvestments. The AIRR calculation implies the same assumptions previously made for the calculation of NS and SIR. It is formally expressed as:

$$AIRR = (1 + r)(SIR)^{1/N} - 1$$

In the table below the acceptability conditions are expressed for each indicator:

INDICATOR	ACCEPTABILITY CONDITION
NPV	the lowest possible
PBP	lower than the asset service life
NS / NB	acceptable (cost-effective) if > 0
NS	the highest possible
SIR	> 1
AIRR	> r (applied discount rate)

Figure 3 Economic evaluation measures: synthetic indicators and acceptability conditions.
Source: Author re-elaboration from: FREGONARA E., (2015). *Evaluation sustainability design. Life Cycle Thinking and international orientation*, Franco Angeli, Milano, p 94

The next Step 5 considers the integration of a Risk and Sensitivity Analysis of the outcomes because of the variations might be happen over the period of the analysis.
Step 3 is also interesting because it considers a synergy between the economic (LCC) and environmental (LCA) analysis. It is a complex point since it is difficult to integrate environmental aspects in the LCC analysis. Although LCC and LCA are two different processes applied in different disciplinary sectors, the two methodologies can interact both if applied separately, if conducted in parallel or applied jointly. In particular:

- the LCC and LCA approaches used as two separate methodologies to assess a single investment option;
- the LCC and LCA approaches used as assessment methods between different alternatives of investment;
- the LCC analysis used to provide an economic assessment of options previously identified through an LCA analysis;

- LCA analysis as a method to identify alternatives with a good environmental impact on which an LCC analysis should subsequently be carried out;
- LCC analysis to identify the best cost-effective options on which then perform an LCA analysis.

The possible synergies between the LCC methodology and the LCA methodology are illustrated in the figure below.

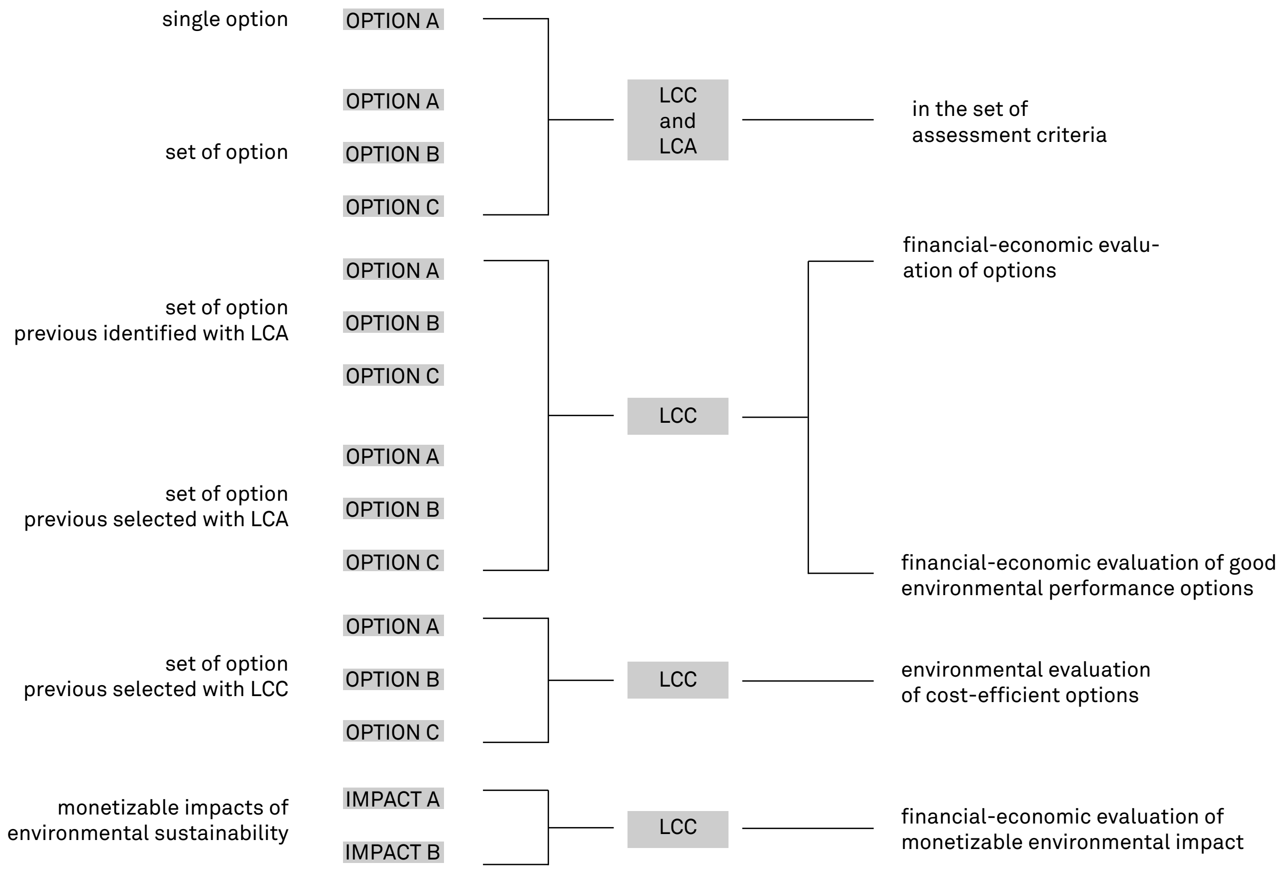

Figure 4 Synergies between LCC and LCA.
Source: Author re-elaboration from: FREGONARA E., (2015). *Evaluation sustainability design. Life Cycle Thinking and international orientation*, Franco Angeli, Milano, p 117

From an operational point of view, tools for joint modelling of economic and environmental aspects for the assessment of project alternatives include, on the one hand, widespread commercial software and, on the other, tools in-house based on calculation sheets.
For instance, the Building for Environmental and Economic Sustainability (BEES) is a software developed by the National Institute of Standards and Technology (NIST). It is a support tool for the eveluation of building projects on the basis of cost-efficiency and environmental criteria through the application of LCC and LCA. After each calculation methodology, LCC and LCA are combined in a Multi-Attribute Decision Analysis.

3.2.3 DEFINITION OF THE LCC TYPOLOGIES

There are different types of LCC, which differ significantly from each other. The various models have been developed to meet the need of a complete sustainable evaluation of a building/ product/component in which economic, environmental and social aspects can be included.
The Society of Environmental Toxicology and Chemistry (SETAC) defines three LCC typologies: Conventional LCC (CLLC or LCC), Environmental LCC (ELCC) and Societal LCC (SLCC).(7)
The first one is the consolidated Life Cycle Cost Analysis methodology described in the previous section. This type of LCC does not take into account, in its typical structure, elements such as pollutant emissions from the production process or labour costs, and for this reason it is considered somewhat limiting, unable to provide an overall view of the life process of a product.
The Environmental LCC, instead, represents an important step towards a more accurate and sustainable inclusive methodology. Indeed, the ELCC takes also into account external relevant costs and benefits anticipated to be privatized. In other words, the environmental externalities of the Whole Life Costs are considered in monetary terms and discounted at present.
Finally, the Societal Life Cycle Costing includes, like the other two typologies, the assessment of all the costs associated to the life cycle of a product from an economic and environmental point of view, further considering the assessment of social impacts (e.g. using the "willingness to pay" or "willingness to pay" method).(8) Indeed, the Societal LCC aims to go beyond the concept of externality at a strictly environmental level, including those relating to human health and those deemed difficult to assess from an economic point of view; and which are taken into account only qualitatively. In other words, the SLCC is used to quantify the environmental impacts resulting from the production of a given product on society and in monetary terms. The figure below shows the system boundaries of the three LCC typologies:(9)

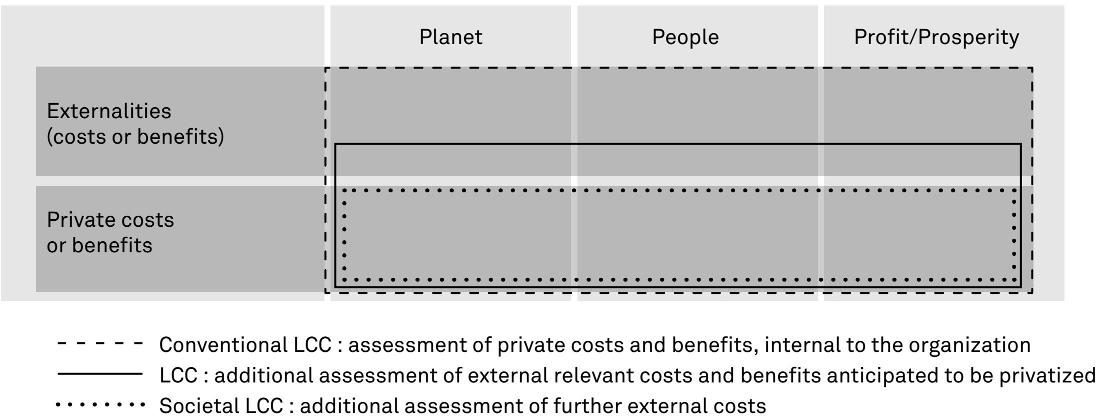

Figure 5 Scope of application of three flavours of life cycle costing.
Source: Author re-elaboration from: UNEP, SETAC, (2011). *Towards a Life Cycle Sustainability Assessment. Making informed choices on products*, UNEP/SETAC Life Cycle Initiative, p.15

(7) UNEP, SETAC, (2011). *Towards a Life Cycle Sustainability Assessment. Making informed choices on products*, UNEP/SETAC Life Cycle Initiative, p.14

(8) HUNKELER D., (2008). *Environmental Life Cycle Costing*, Taylor & Francis Inc.

(7) UNEP, SETAC, (2011). *Towards a Life Cycle Sustainability Assessment. Making informed choices on products*, UNEP/SETAC Life Cycle Initiative, p.15

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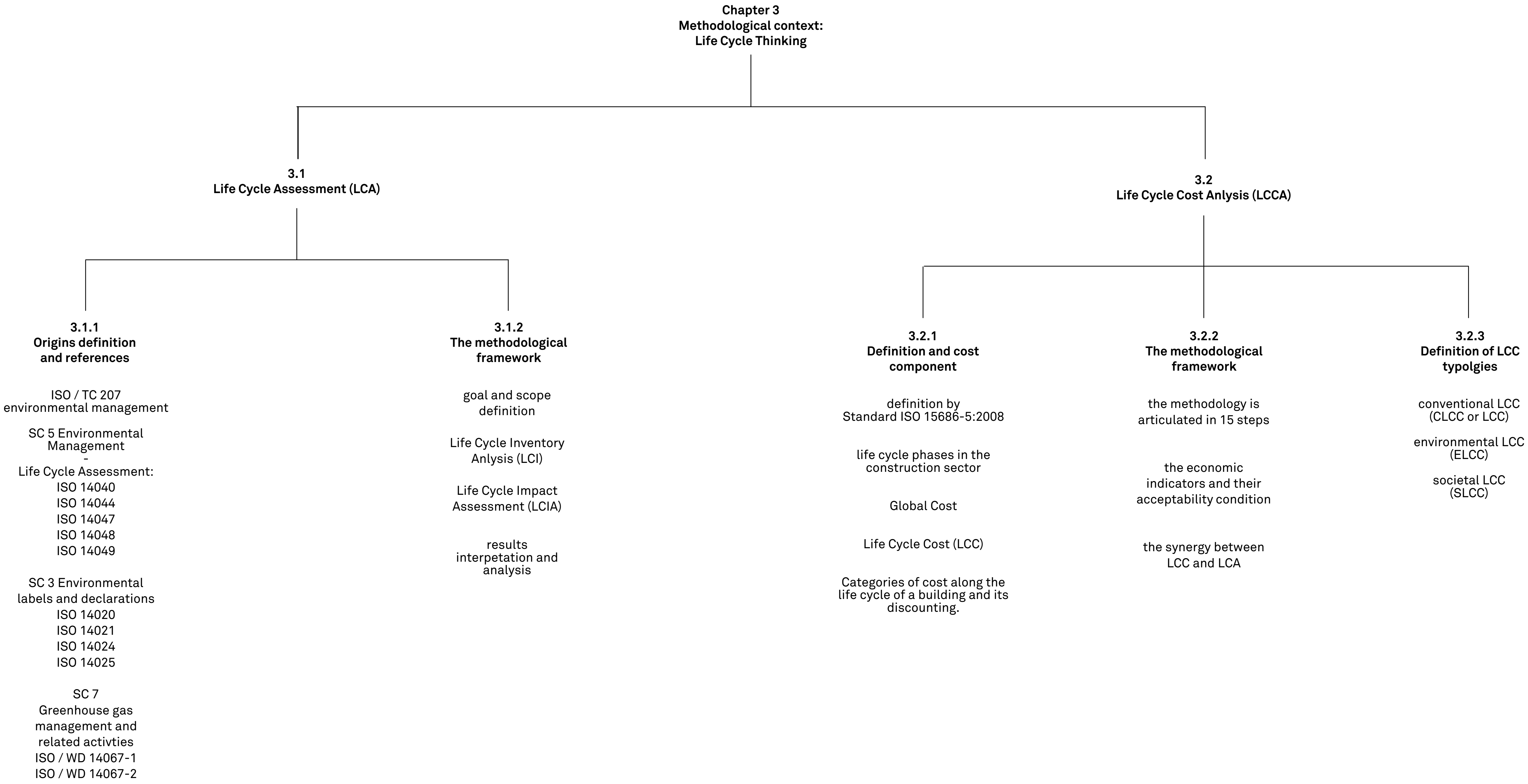

Chapter 3 framework
Author elaboration

04

Literature selection

INTRODUCTION. RESEARCH AND SELECTION PROCESS

This chapter covers a literature selection of articles dealing with energy efficient retrofitting case studies in Europe. The focus of this research is the application of the Life Cycle Cost Analysis (LCCA) for the economic evaluation of retrofit projects and the development of an integration between the economic and the environmental impact analysis for the assessment of the most sustainable refurbishment scenario among alternative retrofit strategies.
The open-source databases used for the research are Scopus and Web of Science, in which the following keywords have been inserted:
(LCC) OR (LCCA) OR (life cycle cost*) OR (life-cycle cost*) OR (life cycle cost analysis) OR (life-cycle cost analysis) OR (life cycle costing) OR (life cycle cost assessment)
AND (retrofit*) OR (refurbishment*) OR (renovation*).
The keywords sequence has been fundamental for the selection and it is the result of numerous previous combination proofs.
The next step has been the selection of the collected articles according to five criteria:

1. Year of publication;
2. Geographical area of the analysis;
3. Application context;
4. Scientific disciplinary sector;
5. Type of publication.

The year of publication has been considered in a time period from 2002 at present (2021). It has been set on the basis of the European regulatory framework related to the energy refurbishment of existing buildings of which the first normative was the Energy Performance of Building Directive 2002/91/EC. The geographical area has been also considered in relation to the regulatory framework in Europe and only European countries have been selected.
Since the aim of this research is to deal with the LCCA methodology related to retrofit projects and verify the presence and the development of environmental considerations, three application context have been identified:

1. Manuscripts about LCC analysis;
2. Manuscripts about LCC analysis and environmental considerations;
3. Manuscripts about LCC analysis and Life Cycle Assessment (LCA).

In order to limit the selection to the energy refurbishment in the built environment, the following scientific disciplinary sectors have been considered: Engineering, Energy, Environmental Science, Business Management and Accounting, Mathematics, Economics and Finance.
Finally, the type of publication selection has been restricted to only open-access articles.
It is important to clarify that multi-criteria and optimization methods have been excluded from the analysis.
The selected articles are 17 and they have been scheduled in a table presented in the first section of this chapter.
After the scheduling, all the articles have been individually detailed on the basis of a layout pre-set by the author.

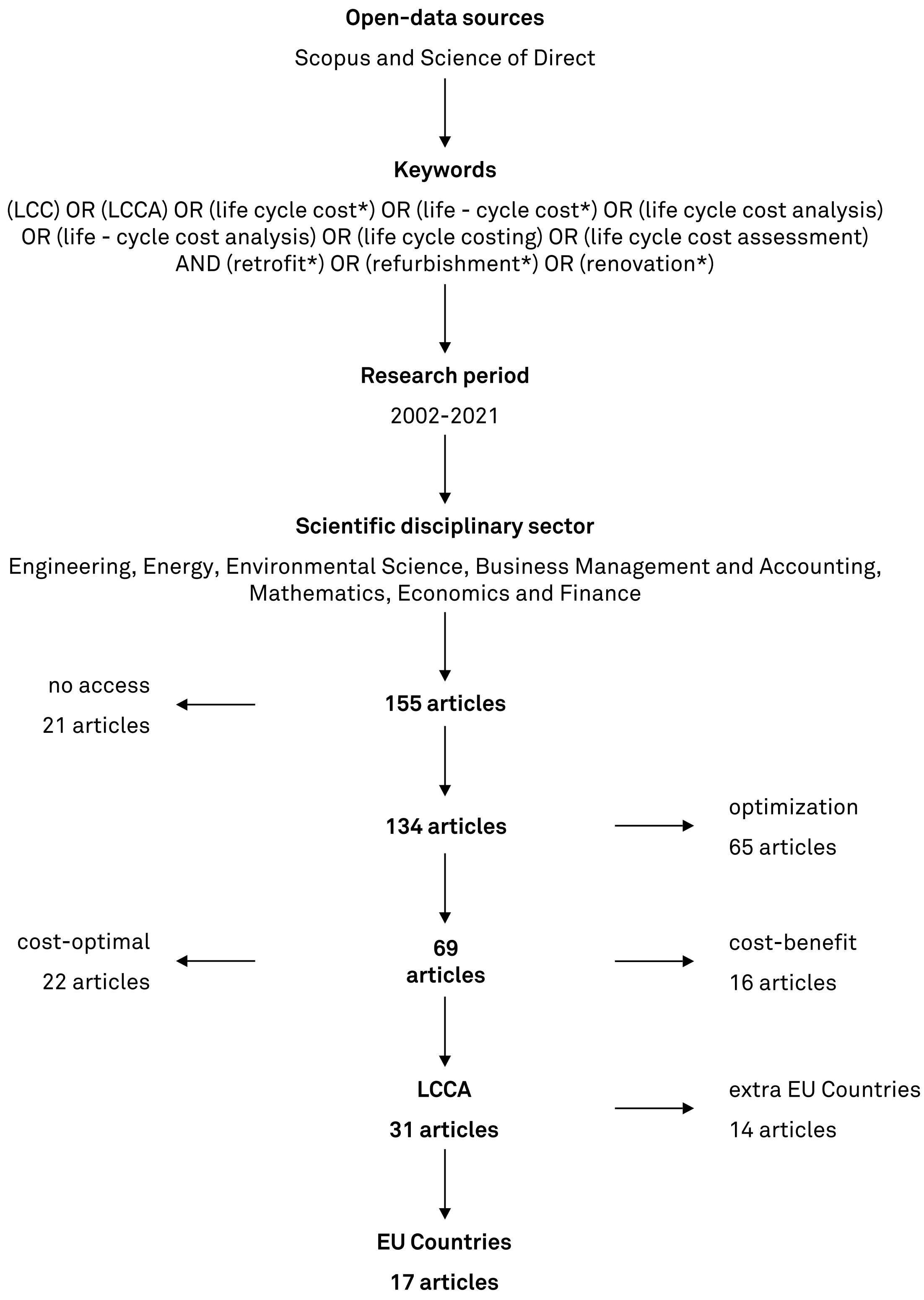

Figure1. Research selection process.
Source: Author elaboration

4.1 CLASSIFICATION OF THE SELECTED ARTICLES

In this section the 17 articles selected for this research have been scheduled in a table and divided in three sections:

17 articles → n°1-8 LCCA
→ n°9-10 LCCA + environmental considerations
→ n°11-17 LCCA + LCA

Figure 2. Methodological categorization of the articles.
Source: Author elaboration

The articles are listed in descending order from the most recent to the least, in each of the three sections.
The table has been structured in order to give the most important information about each article:

- N° article;
- Title;
- Year of publication;
- Author;
- EU Country;
- Methodology;
- Building typology;
- Energy Efficiency Measures (EEMs).

In particular, five building typologies have been specified:

- Residential;
- Commercial;
- Office;
- Educational;
- Historical;

Finally, the following Energy Efficiency Measures (EEMs) have been extracted from the articles and inserted in the table:

- Lighting retrofit
- Envelope refurbishment
- Windows replacement
- HVAC system
- DHW system

N° Article	Title	Publication Year	Authors	Publisher	EU Country	Methodology	Building Type	EEMs
1	*Economic performance assessment of three renovated multi-family buildings with different HVAC systems*	**2020**	A. Khadra, M. Hugosson, J. Akander, J. A. Myhren	Energy & Buildings	**Sweden**	**LCCA**	Residential	HVAC System
2	*Life cycle cost of building energy renovation measures, considering future energy production scenarios*	**2019**	M. S. Gustafsson, J. A. Myhren, E. Dotzauer, M. Gustafsson	Energies	**Sweden**	**LCCA**	Residential	HVAC System
3	*Evaluation of energy retrofit in buildings under conditions of uncertainty: The prominence of the discount rate*	**2017**	S. Copiello, L. Gabrielli, P. Bonifaci	Energy	**Italy**	**LCCA**	Residential	Envelope refurbishment Windows replacement Ventilation system
4	*Cost-effective passive house renovation packages for Swe-dish single-family houses from the 1960s and 1970s*	**2017**	T. Ekströma, R. Bernardoa, Å. Blomsterberg	Energy and Buildings	**Sweden**	**LCCA**	Residential	Envelope refurbishment New HVAC system New DHW system
5	*Retrofitted Solar Domestic Hot Water Systems for Swedish Single-Family Houses—Evaluation of a Prototype and Life-Cycle Cost Analysis*	**2016**	L. R. Bernardo,*, H. Davidsson, E. Andersson	Energies	**Sweden**	**LCCA**	Residential	DHW system
6	*Retrofit Scenarios and Economic Sustainability. A Case-study in the Italian Context*	**2016**	E. Fregonara, V. R.M. Lo Verso, M. Lisac, G. Callegaria	Energy Procedia	**Italy**	**LCCA**	Residential	Envelope refurbishment Windows replacement New HVAC system New DHW system
7	*Life cycle costing as an early stage feasibility analysis: The adaptable transformation of Willy Van Der Meeren's student residences*	**2015**	W. Gallea, M. Vandenbrouckeb, N. De Temmermanc	Procedia Economics and Finance	**Belgium**	**LCCA**	Residential Office Commercial	Envelope refurbishment
8	*Towards a methodology to include building energy simula-tion uncertainty in the Life Cycle Cost analysis of rehabilitation alternatives*	**2014**	R. Almeida, N. Ramos, S. Manuel	Journal of Building Engineering	**Portugal**	**LCCA**	Educational	Windows replacement
9	*Combination of lighting retrofit and life cycle cost analysis for energy efficiency improvement in buildings*	**2021**	P. Belany, P. Hrabovsky, Z. Kolkova	Energy Reports	**Slovakia**	**LCCA** + environmental impact considerations	Educational	Lighting retrofit

N° Article	Title	Publication Year	Authors	Publisher	EU Country	Methodology	Building Type	EEMs
10	*Techno-economic analysis of energy renovation measures for a district heated multi-family house*	**2015**	M. Gustafsson, M. S. Gustafsson, J. A. Myhren, C. Bales, S. Holmberg	Applied Energy	**Sweden**	**LCCA + environmental impact analysis**	Residential	Envelope refurbishment Windows insulation HVAC system
11	*Investigating eco-efficiency procedure to compare refurbishment scenarios with different insulating materials*	**2020**	C. Colli, A. Bataille, E. Antczak	Procedia CIRP	**France**	**LCCA + LCA**	Residential	Envelope refurbishment
12	*Statistical method to identify robust building renovation choices for environmental and economic performance*	**2020**	A. Galimshina, M. Moustapha, A. Hollberg, P. Padey, S. Lasvaux, B. Sudret, G. Habert	Building and Environment	**Switzerland**	**LCCA + LCA**	Residential	Enevelope refurbishment HVAC system
13	*Energy Retrofitting of a Buildings' Envelope: Assessment of the Environmental, Economic and Energy (3E) Performance of a Cork-Based Thermal Insulating Rendering Mortar*	**2019**	J. D. Silvestre, A. Castelo, J. Silva, J. L. de Brito, M. D. Pinheiro	Energies	**Portugal**	**LCCA + LCA**	Residential	Enevelope refurbishment
14	*Combining Life Cycle Environmental and Economic Assessments in Building Energy Renovation Projects*	**2017**	R. Moschetti, H. Brattebø	Energies	**Norway**	**LCCA + LCA**	Residential	Enevelope refurbishment Windows replacement New HVAC system New DHW system
15	*Economic and environmental analysis of energy renovation packagesfor European office buildings*	**2016**	M. Gustafsson, C. Di Pasquale, S. Pioppi, A. Bellini, R. Fedrizzi, C. Bales, F. Ochs, M. Siè, S. Holmberg	Energy and Buildings	**EU countries**	**LCCA + LCA**	Office	Enevelope refurbishment Windows replacement New HVAC system New DHW system
16	*Building retrofit addressing occupancy: An integrated cost and environmental life-cycle analysis*	**2016**	C. Rodrigues, F. Freire	Energy and Buildings	**Portugal**	**LCCA + LCA**	Historical Residential Office	Enevelope refurbishment
17	*Adaptive reuse of buildings: Eco-efficiency assessment of retrofit strategies for alternative uses of an historic building*	**2016**	C. Rodrigues, F. Freire	Journal of Cleaner Production	**Portugal**	**LCCA + LCA**	Historical Residential Office	Enevelope refurbishment

4.2 DESCRIPTION OF THE ARTICLES

In this section each article has been detailed in an individual board of which the layout has been per-set by the author.
The board is basically composed of two main columns. The bigger column on the left side contains the descriptive information of the document:

- Title;
- Author;
- Keywords (by the document);
- Content summary.

The grey column on the right side contains a top-down sequence of the most important information of the article.

- N° article;
- Year of publication;
- EU Country;
- Methodology;
- Energy Efficiency Measures (EEMs);
- Building typology;
- Case study;
- Period of the analysis;
- Functional unit;
- System boundaries.

At the top of the column there are information on the basis of which the article has been selected and scheduled in the table of the previous section (year, Country, methodology).
The EEMs and the building typology information are essential to understand which retrofit project it is dealing with.
The last four information make the article more or less accurate among the other papers.
The case study description, the building service life, the functional unit and the system boundaries are data on the basis of which the Life Cycle Cost Analysis has been applied.
The papers in which both LCCA and LCA are considered present a double description in some items of the grey column.
The specific boards of each article are listed below. (1)

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(1) In each article the Author's keywords are reported.

Economic performance assessment of three renovated multi-family buildings with different HVAC systems

A. Khadra, M.Hugosson,
J. Akander, J. A. Myhren. published on Energy & Building

Keywords (by document) Building renovation; Life cycle cost; Life cycle cost analysis; Discount rate; Energy price escalation; HVAC systems.

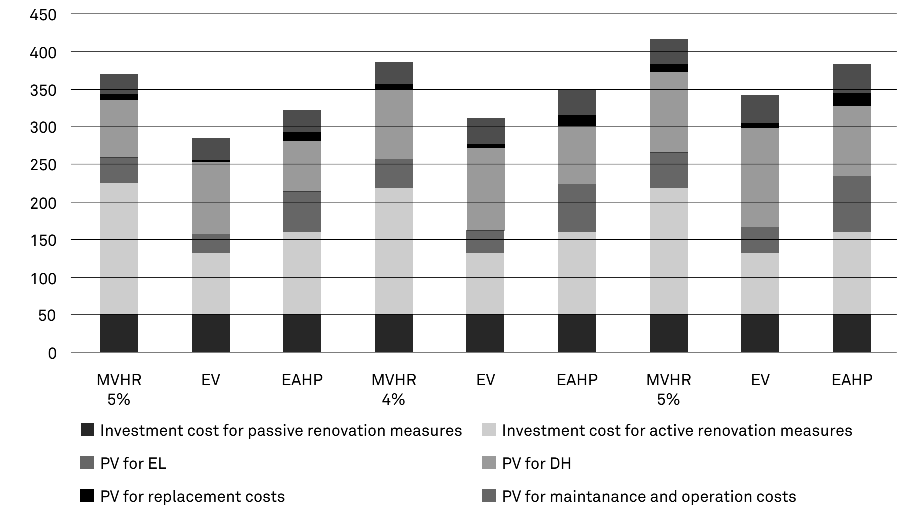
Content summary The aim of this study is the economic comparison of three different HVAC systems in three multi-family buildings in the Tjärna complex built between 1969 and 1971 in Borlänge, Sweden. Each building has 36 apartments and they are originally district heated and equipped with exhaust ventilation without heat recovery, operating with the constant flow.
The three HVAC renovation packages are:

- Building 1: MVHR system (mechanical ventilation with heat recovery)

- Building 2: EV system (exhaust ventilation system with pressure-controlled fans)

- Building 3: EAHP system (exhaust ventilation with pressure-controlled fans and exhaust air heat pump for heat recovery

The first step of the study is the production of a LCCA analysis based on real and measured data (investment costs, energy use, energy price) to understand which of the three options is the most economically convenient.
The second step is to verify the results through a sensitivity analysis in which different discount rate and energy prices are performed.
Three different values of discount rate (3%,4%,5%) and two district heating and electricity price escalation values (1% DH and 2%El; 2%DH and 1%El) are performed in the sensitivity analysis.
The results show that the EV system is the most economically convenient.
In the figure below LCC for the renovation packages using different discount rates and 1% real energy price escalation is represented.



Author re-elaboration from Fig. 7. *LCC for the renovation packages using different discount rates and 1% real energy price escalation*. p 8

Article n°1
Pub. Year 2020
Sweden

Methodology

LCCA
+
energy simulation
+
sensitivity analysis

EEMs

HVAC system

Typology

Residential

Case Study

3 multi-family houses

Analysis period

40 years

Functional Unit

heated floor area 3879 m2

System Boundaries

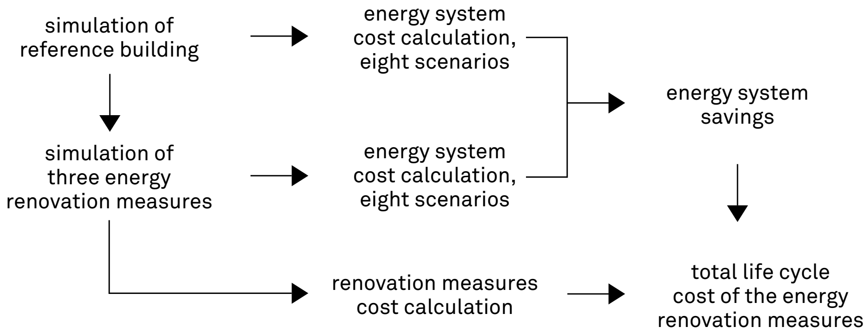
Use-maintenance -end of life

Life cycle cost of building energy renovation measures, considering future energy production scenarios

M. S. Gustafsson, J. A. Myhren,
E. Dotzauer, M. Gustafsson published on Energies

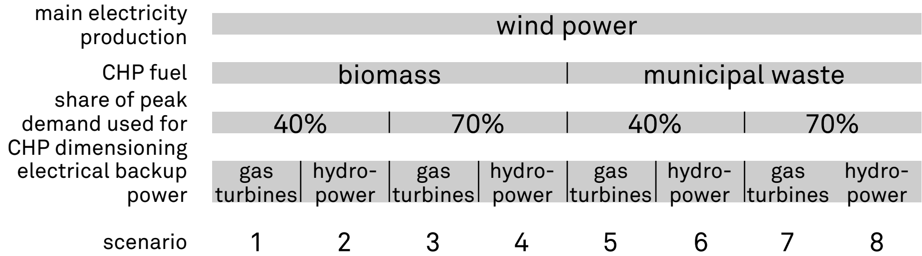
Keywords (by document) Life cycle cost; Energy system; District heating; Energy renovation measures; Heat pump; Mechanical ventilation with heat recovery; Combined heat and power; Wind power.

Content summary In this study, a Life Cycle Cost Analysis (LCCA) is performed for different energy efficiency scenarios.
The important characteristic of this article is that LCCA is calculated by considering the whole energy system rather than just the building.
The methodological framework is the following one:



Author re-elaboration from Fig 1. *Flowchart describing the methodology.* p 3

A reference building simulation is performed in order to get hourly values of the energy demand which is used to calculate the energy system cost for eight energy system scenarios. Three energy renovation measures are also simulated, and the energy system costs are calculated for the eight energy system scenarios for each energy renovation measure. The cost for the energy renovation measures are calculated, and the total LCC is achieved by adding the energy system savings.
The three studied renovation measures are the following:
A) mechanical ventilation with heat recovery (MVHR) system
B) exhaust air heat pump (EAHP) for heating system
C) exhaust air heat pump (EAHP) for heating and domestic hot water system
Simulations of the building with the different renovation measures were done in TRNSYS 17. The output from the simulations were used as an input for the energy system cost calculation.
The eight energy system scenarios regarding electricity and district heating production are defined as follows:



Author re-elaboration from Fig. 2. *The eight different energy system scenarios regarding electricity and district heating production.* p.5

LCC calculation demonstrates that none of the renovation measures result in a lower LCC than the reference building for any energy system scenario.

Article n°2
Pub. Year 2019
Sweden

Methodology

LCCA

+

energy simulation

EEMs

HVAC system

Typology

Residential

Case Study

three storey multi-family building

A=4700 m2

60 apartments

Analysis period

30 years

Functional Unit

energy system

System Boundaries

Production

Operation

Maintenance

Evaluation of energy retrofit in buildings under conditions of uncertainty: The prominence of the discount rate

S. Copiello, L. Gabrielli, P. Bonifaci. published on Energy

Keywords (by document) Residential buildings; Energy efficiency; Uncertainty; Life-cycle cost;Monte Carlo simulation; Discount rate.

Content summary The case-study of this document is an eight-story residential building in the city of Bologna, Italy. It presents a poor energy efficiency. Therefore the aim of the study is the thermo-economic appraisal of six retrofit scenarios through a LCC-MC (Life Cycle Cost Analysis and Monte Carlo simulation) integration model. The six scenarios are:

s1=wall insulation; s2=roof and floor insulation;
s3=s1+s2=whole building envelope insulation;
s4=windows replacement;
s5=s3+s4=envelope insulation and windows replacement;
s6=new ventilation system installation;
s7=s5+s6=envelope insulation, windows replacement and new ventilation system.

In order to apply the method to each of the six scenarios, the LCC equation:

$$Lcc = Bc + \sum_{i=1}^{n} (Mc+Oc) / (1+r)^{i}$$

where Bc are the building costs, Mc are the maintenance costs, Oc are the operating costs, becomes:

$$Lcc = Ic(j) + \sum_{i=1}^{n} (q(j) \cdot p) / [(1+r) / (1+e)]^{i}$$

where are the Ic(j) are the investment costs to implement each of the j scenarios, assumed incurred at time 0. The period of analysis n is considered equal to the useful life of the works (30 years). Hence, the maintenance costs (Mcj) are assumed to be equal to zero. The operating costs (Ocj) are limited to the energy expenses, given by the product of the energy requirement subsequent to the implementation of works (qj) and the energy price (p); e is the energy inflation rate.
In the equation Ic(j) and q(j) are internal factor (dependent on stakeholder) and assumed as given whereas p, e, and r are external factor allowed to vary and, for that reason, considered in the LCC-MC equation:

$$Lcc = \overline{Ic}(j) + \sum_{i=1}^{n} (\overline{q}(j) \cdot p) / [(1+r) / (1+e)]^{i}$$

$p \sim U(p_{min},\dots,p_{max})$ $r \sim U(r_{min},\dots,r_{max})$ $e \sim U(e_{min},\dots,e_{max})$

where the bar on Ic(j) indicates a constant (or internal factor).
Under the framework of the MC simulation, one hundred thousand iterations are performed for each scenario. Lcc grows with the increase of energy price and energy inflation rate. On the contrary, it falls with the increase of the discount rate, which resulted to be the most influential parameter.

Article n°3

Pub. Year 2017

Italy

Methodology

LCCA

+

energy simulation

+

Monte Carlo simulation

EEMs

Envelope refurbishment

Windows replacement

New ventilation system

Typology

Residential

Case Study

A building of 4.700 m2 divided into blocks hosting in total 550 dwellings

Analysis period

30 years

Functional Unit

single residential block of 1651m2

System Boundaries

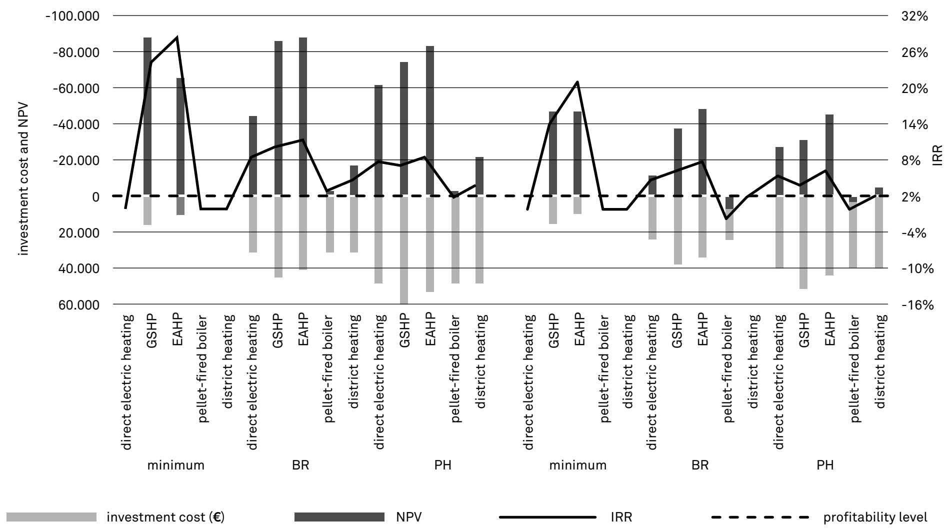
Construction to use phase

Cost-effective passive house renovation packages for Swedish single-family houses from the 1960s and 1970s

T. Eksträma, R. Bernardoa,
Å. Blomsterberg published on Energy and Buildings

Keywords (by document) Cost-effective; Energy efficiency measures; Passive house; Renovation packages; Single-family houses; Renewable energy production.

Content summary This paper evaluates the cost-effectiveness of renovating single-family houses in Sweden to Passive House level based on the Swedish Passive House standard.
The housing stock was built between 1961 and 1980. Two reference houses (RH1 and RH2) are considered because of the heating cost increase after 1975 and because the PH requirements are specific for climate zone and type of heat generation.
A life cycle cost analysis is used to evaluate the cost-effectiveness of different EEMs in relation to three renovation levels:
minimum or a functional and no energy-efficiency renovation level; a building renovation level; a Passive House (PH) renovation level.
The output are calculated through NPV and IRR higher than r=2%.
The figure below shows the input and output of the LCC analysis that is the investment costs and NPV and IRR, for different type of heat generation at three renovation levels. Negative NPV and IRR>2% are required for the renovation package profitability.



Author re-elaboration from Fig. 6. *Investment cost and results from the LCC analysis, presented as NPV and IRR, for different types of heat generation at different renovation levels for the referencehouses.* p.12

The most cost-effective combination of type of heat generation and renovation package was shown to be with an exhaust air heat pump (EAHP), which resulted in the highest IRR.
The paper also presents building energy simulations of renovation packages for RH1 and RH2 at three renovation levels and for each level the results are divided into two categories: final energy use and the energy savings potential of the energy efficiency measures (EEMs) in the renovation packages.

Article n°4
Pub. Year 2017
Sweden

Methodology

LCCA

+

energy simulation

EEMs

Envelope refurbishment

New HVAC system

New DHW system

Typology

Residential

Case Study

single-storey house
RH1 230 m2
RH2 142 m2

Analysis period

40 years for building envelope
20 years for installation

Functional Unit

RH1 230 m2
RH2 147 m2

System Boundaries

All life cycle phases

Retrofitted solar domestic hot water systems for Swedish single-family houses. Evaluation of a prototype and life-cycle cost analysis

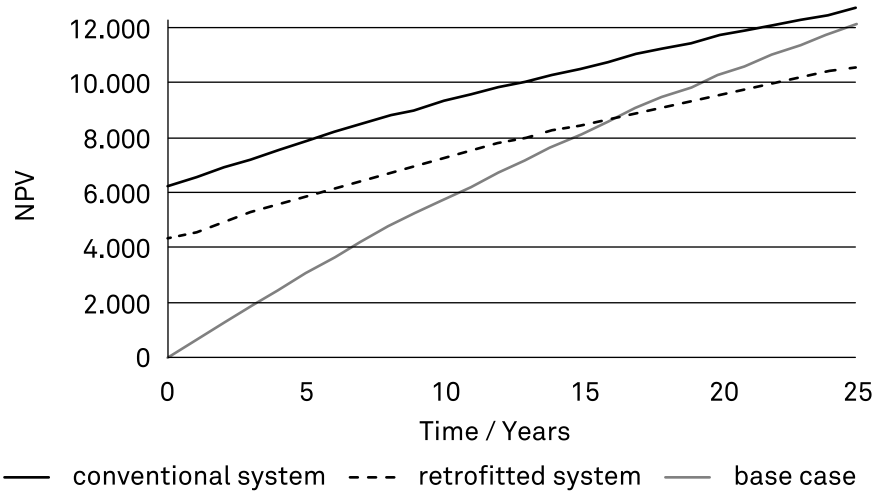
L. R. Bernardo, H. Davidsson, E. Andersson published on Energies

Keywords (by document) Retrofit; Solar thermal; Single-family houses; Life cycle cost; Domestic hot water.

Content summary This article describes the installation, measured performance and cost effectiveness of a retrofitting solution that re-uses the existing domestic hot water heater system in a new solar domestic hot water system. The existing system is integrated into the new one instead of being entirely replaced.
A Life Cycle Cost Analysis is performed for three cases: the retrofitted solar domestic hot water solution, a conventional solar domestic hot water system and the base case without any solar heating system.

NPVtotal = Ic + NPVdhw + NPV maintenance

where NPV dhw, takes into account C0, that is the annual running costs for domestic hot water production, and how these costs are accounted over time by the influence of i and g. that respectively are the rate of return on investment and a linear increase on the yearly electricity price. The following graph shows the NPV values of three scenarios during the 25 years period.



Author re-elaboration from Fig. 9a. *Life cycle cost based on net present value for the base case (without solar energy), retrofitted system and a conventional solar domestic hot water system*. p.10

The retrofitted system become profitable in approximately seventeen years while the conventional system never becomes profitable.
The study also considers the life cycle profit value used to evaluate the impact of the sensitivity analysis and consists on the difference between the net present value with and without a solar domestic hot water system.

LCP = NPVtotal - NPVwithout dhw

In the Sensitivity Analysis the input variation is ±20% and considers the cost of electricity, the investment cost, the electricity price growth, the lifetime, and the rate of return. The results shows that LCP calculation of the retrofitted is always positive but mainly negative for the conventional system.

Article n°5
Pub. Year 2016
Sweden

Methodology

LCCA

+

energy and thermal performance calculations

+

sensitivity analysis

EEMs

DHW system

Typology

Residential

Case Study

Service Life

25 years

Functional Unit

5 m2 of flat plate solar collectors

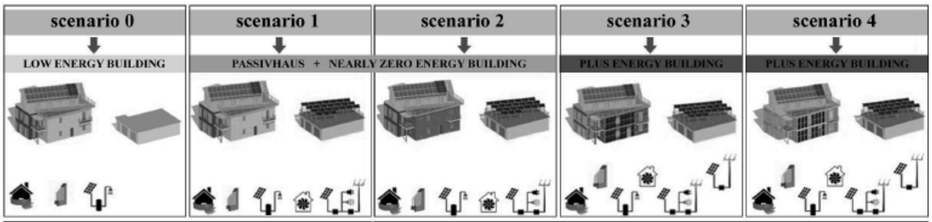
System Boundaries

Retrofit Scenarios and Economic Sustainability. A Case-study in the Italian Context

E. Fregonara; V.R.M. Lo Verso;
M. Lisa; G. Callegari published on Energy Procedia

Keywords (by document) Energy Retrofit; Energy Efficiency Scenarios; Economic Sustainability; Life Cycle Costing; Global Cost.

Content summary This article presents a innovative multidisciplinary approach for the energy and economic evaluation of alternative retrofit scenarios for a double-family single house,located in Turin, Italy. Different EEMs and technological solutions are combined to obtain five retrofit scenarios with different energy consumption and cost values, as shown in the figure below.



Author re-elaboration from Fig. 3. *Summary of different energy efficiency measures.* p.6

The scenario 0 is a low energy building with a energy performance slightly better than the existing situation. Scenario 1-2-3-4 are configured in accordance with "Passivahous" and "NZEB" criteria through a greater thermal insulation e HVAC system and the use of renewable sources. Furthermore, the scenario 3 and 4 are configured as "plus energy building" because the energy produced is beyond the needs.
First, a energy simulation is conducted to know the energy consumption and relative costs of each scenario.
Then, a economic analysis is conducted through a simplified LCC approach.

$$LCC = Ci + \sum_{t=0}^{N} (Co + Cm) / (1 + r)^{t}$$

where Ci are the investment costs; Co are the operational costs; Cm are the maintenance costs; t the year in which the cost occurred and N the number of years of the entire period considered
for the analysis (30 years); r the discount rate (2.5%).
In this analysis all the economic indicators of LCCA are calculated. The NPV was calculated for every scenario, while other economic indicators – Net Savings (NS), Discounted Pay Back Period (DPB), Saving to Investment Ratio (SIR), Adjusted Internal Rate of Return (AIRR), Simple Pay Back Period (SPB)- were calculated only for the alternative scenarios, compared to the base case 0.

	NPC	NS	SIR	AIRR	SPB	DPB
accettability conditions	as low as possible	acceptable >0 not acept. <0	acceptable >1 not acept. <1	acceptable >2.5 not acept. <2.5	as low as possible	
Scenario 0	265869	-	-	-	-	-
Scenario 1	265321	548	1.02	2.6	10	13.2
Scenario 2	253539	12330	1.3	3.5	10.7	14.6
Scenario 3	328044	-62175	0.5	0.1	19.5	>30
Scenario 4	302920	-37052	0.6	0.8	19	21.5

Author re-elaboration from Table 2. *Summary table of results of economic evaluation.* p.9

The most viable trade-off between energy and economic constraints was the scenario 2 with the lowest NPC.

Article n°6
Pub. Year 2016
Italy

Methodology

LCCA

+

energy calculations

EEMs

Envelope refurbishment

Windows replacement

New HVAC system

New DHW system

Typology

Residential

Case Study

Two-storey family building. Two flats for a total floor area of 204 m2
Energy class E

Service Life

30 years

Functional Unit

Floor area=204 m2

System Boundaries

construction-use-maintenance phase

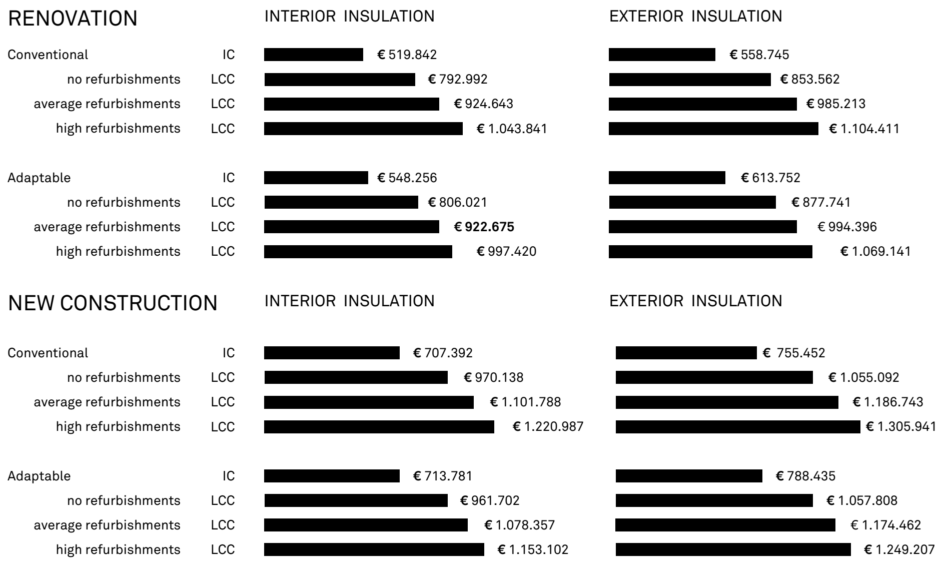
Life cycle costing as an early stage feasibility analysis: the adaptable transformation of Willy Van Der Meeren's student residences

W. Gallea,
M. Vandenbrouckeb,
N. De Temmermanc

published on
Procedia Economics and Finance

Keywords (by document) Sustainable building; Design for Change; Future value of buildings; Life Cycle Costing.

Content summary The purpose of this study is to assess the economic convenience to transform and reuse 352 student residencies rather than to demolish them.
A conventional life cycle cost analysis is performed both at component and at element building level.
First, the Initial Cost (IC) and Life Cycle Cost (LCC) are presented for each building element separately. Each element cost item is calculated in relation to renovation or new construction strategies and in relation to interior or exterior wall insulation. Furtherly, the conventional or adaptable design of each element is considered in the calculation as well.
Comparing the interior and exterior insulation strategies shows differences in initial costs and life cycle cost only for the exterior walls both for renovation and new construction.
An adaptable element is convenient if the savings obtained by the reuse compensate the labor costs for the element replacing.
The results also show that renovation is more convenient than new construction, except for the interior walls.
Second, the initial cost (IC) and life cycle cost (LCC) are calculated strategy by strategy at building level. Total costs are calculated for the transformation of a cluster of student residences into an information hub with offices and a restaurant. No-refurbishment, average refurbishment and high refurbishment options are considered. In this case, the comparison is more correctly because for each strategy different elements as well as different amounts of elements are needed.
Indeed, the results are different; the exterior insulation strategy results to be more expensive than the interior one; the adaptable design is always convenient; as at element level calculation, the new construction is more expensive than renovation at building level as well.
The figure below shows IC and LCC of the building level analysis.



Author re-elaboration from Table 2. *Comparing the initial cost (IC) and life cycle cost (LCC) of each transformation strategy shows that those strategies that are built with adaptable building elements are less sensitive to the number of refurbishments compared to conventionally realized transformations.* p 6

Article n°7

Pub. Year 2015

Belgium

Methodology

LCCA

EEMs

Envelope refurbishment

Typology

Residential /

Office /

Commercial

Case Study

352 student residences

Service Life

78 years

Functional Unit

1 m2 at element level

444 m2 at building level

System Boundaries

existing demolition

+

All life cycle phases

Towards a methodology to include building energy simulation uncertainty in the Life Cycle Cost analysis of rehabilitation alternatives

R. Almeida,
N. Ramos,
S. Manuel

published on Journal of Building Engineering

Keywords (by document) Energy simulation;Uncertainty;Monte Carlo method;Life Cycle Cost

Content summary In this paper an energy conservation project of a school building is studied. The aim is to consider the uncertainty of the energy simulation and its effect on LCC analysis.
First, a school building model is simulated with EnergyPlus and five input parameters are considered as variables with an associated uncertainty, namely: occupation, metabolic rate, lighting, ventilation and envelope thermal resistance.
Then, the uncertainty of the five parameters is defined through the Monte Carlo method in which the simulations are performed for 25, 50, 100, 200 and 500 cases. A sensitivity analysis of the results is also performed.
Finally, the simulation output (school building heat demand) is then used as a stochastic input in the LCC analysis for the economic evaluation of the cost effectiveness of the windows replacement.
The integrated approach methodology is represented below.

occupation
metabolic rate
lighting
ventilation
enevelope thermal resistance

→

EnergyPlus simulation
+
Monte Carlo simulation
+
sensitivity analysis

→

Heat demand
+
economic parameters:
investment cost,
discount rate,
period of analysis

→ LCCA

Author re-elaboration from Fig. 1. *The integratedapproachmethodology.* p.4

The life cycle cost analysis is based on deterministic parameters. Hence,only energy simulation inputs were defined as uncertain, which does not allow fora holistic uncertainty analysis.This approach, however, is useful when the focus is set on the influence of the technical solutions.
The LCC analysis is performed through the equation below.

$$LCC = I + Repl - Res + E + OM\&R$$

where I are the investment costs, Repl are the replacement costs, Res are the residual value minus disposal costs, E are the energy costs and OM&R are the non-fuel operating, maintenance and repair costs. For this example the following assumptions are considered: initial investment of 9000 €; discount rate of 3%; energy cost of 0.15 €/kWh and two periods of analysis, 15 and 20 years.
The economic effect of replacing the windows is estimated in a reduction of 10% on the annual heating demand.

Article n°8
Pub. Year 2014
Portugal

Methodology

LCCA

+

stochastic energy simulation

EEMs

Windows replacement

Typology

Educational

Case Study

Two-storey school building:
classroom 545m2
circulation 212m2
storage 130mq
toilet 63m2
total = 950m2

Anlysis period

15 and 20 years

Functional Unit

System Boundaries

Combination of lighting retrofit and life cycle cost analysis for energy efficiency improvement in buildings

P. Belany,
P. Hrabovsky, Z. Kolkova
published on Energy Reports

Keywords (by document) Life cycle cost analysis; Lighting systems; Economic; Consumption of electricity; Measurement; Lighting retrofit

Content summary The aim of this article is to propose a LCCA methodology for the lighting retrofit. The study considers two retrofit scenarios with two different LED systems, one controlled by movement and the other controlled by daylight and movement. First, the electricity consumption of the original and two retrofit systems is calculated. The outcomes show that LED2 system consumes less energy than the original and LED1 systems.
In the next step the results are verified through the LCCA methodology in which:

total cost(€) = ∑investment(€) + ∑Fpv • maintenance(€)

+ ∑Fpv • annual energy(€)

where Fpv is a factor of present value.

investment cost (€) = Nrst •(Nl•(Pl+Mll)) + Cecd

where Nrst is the number of rooms of the same type; Nl is the number of luminaires; Pl is the price per luminaire (€); Mll is the material and labour cost per luminaire; Cecd is cost of external control device (€)

annual energy (€) = (Ep •(Nrst•Nl•El•TRFc•Ho)) / 1000

where Ep is the electricity price; El is the power of luminaires; TRFc is the total reduction factor for control (influence of different degrees of lighting control);
Ho is the operation hour

The environmental impact is also included in this analysis:

climate impact (kg•CO_2) = ∑energy usage (kWh) • CLeu (Kg•CO_2•kWh-1)

where energy usage is the energy consumption of individual rooms;-CLeu is the climate impact electricity usage

energy usage = (Nrst •Nl • El • TRFc • Ho) / 1000

Another important parameter is the LENI (Lighting Energy Numeric Indicator) number:

LENI =∑ energy usage / A(m2), where A is the area of the room.

The following are the results for the three system:

energy consumption (€)	601	399	547
climate impact (kg•CO_2/year)	681	55	28

Article n°9

Pub. Year 2021

Slovakia

Methodology

LCCA

+

environmental impact considerations

+

sensitivity analysis

EEMs

Lighting retrofit

Typology

Educational

Case Study

195 m2 of common space of a university department

Analysis period

one year

Functional Unit

-

System Boundaries

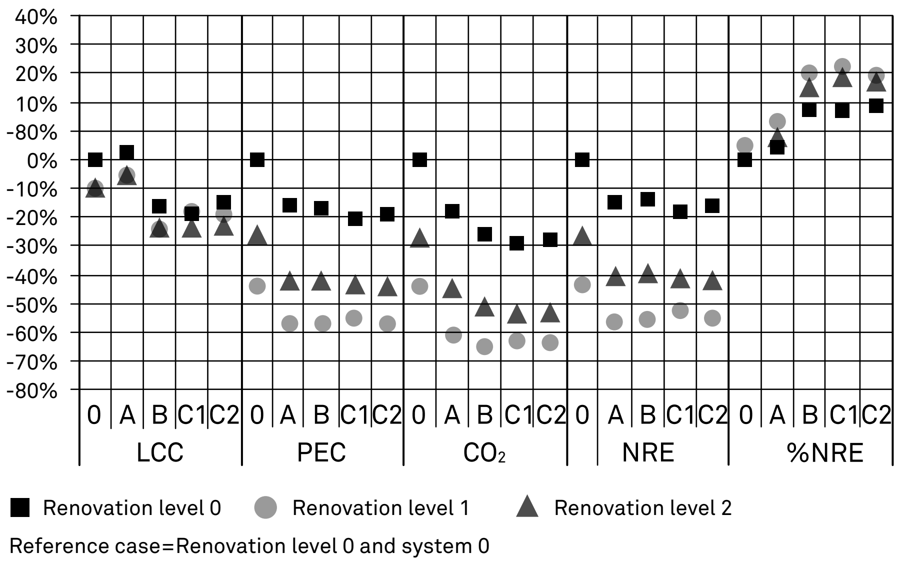
All life stages

Techno-economic analysis of energy renovation measures for a district heated multi-family house

M. Gustafsson, M. S. Gustafsson,
J. A. Myhren,C. Bales, S. Holmberg published on Applied Energy

Keywords (by document) District heating; Air heat recovery; Heat pump; LCC Primary energy; Low-temperature heating

Content summary The present study investigates the environmental and economic aspects of a retrofit scenario in which to a district heating (DH) multi-family house are added different combinations of HVAC systems and renovation levels.
In addition to the existing HVAC system, denoted ‘‘0”, four other system combinations were studied:
(A) 0 + MVHR;
(B) 0 + EAHP for heating;
(C1) 0 + EAHP for both heating and DHW;
(C2) C1 + some radiators converted to ventilation radiators.
Furthermore, three renovation level are considered: level 0 includes basic renovation and repairs to maintain functionality of the building, such as change of windows, façade repairs, tuning of radiator system and change of water taps.
Levels 1 and 2 included changing to triple glazed windows and balcony doors rather than double glazed. For level 2, insulation of façade (80 mm) and roof (195 mm) was added.
After a energy performance simulation, a life cycle cost analysis is conducted in which NPV and DPB are calculated considering a discount rate of 4%. The energy price growth rate, for both electricity and district heating, was set to 3%/year for the whole period, including a 1% inflation rate.
Besides the economic analysis, a environmental impact analysis is conducted and limited to the use phase, assuming the contribution of embodied energy would be relatively small in the life cycle perspective.
Finally, an economic sensitivity analysis is conducted in which investment and maintenance costs are varied by ±20%, while interest rate and energy price growth were changed by ±1 percentage point.
Life cycle costs, primary energy consumption, CO_2 emissions and non-renewable energy consumption for all systems and renovation levels are shown in the figure below. The best combination altogether was renovation level 2 and system B, closely followed by C1 and C2. The DPB for that combination is 19.2 years.



Author re-elaboration from Fig.4. *Life cycle cost, primary energy consumption, CO_2 emissions and absolute and relative non-renewable energy consumption of all studies cases.* p 6

Article n°10

Pub. Year 2015

Sweden

Methodology

LCCA

+

environmental impact analysis

+

sensitivity analysis

EEMs

Envelope refurbishment

Windows insulation

HVAC system additions

Typology

Residential

Case Study

Four-storey building with a heated area of 4700m2.
15 apartments for each floor.

Anlysis period

30 years

Functional Unit

whole house

System Boundaries

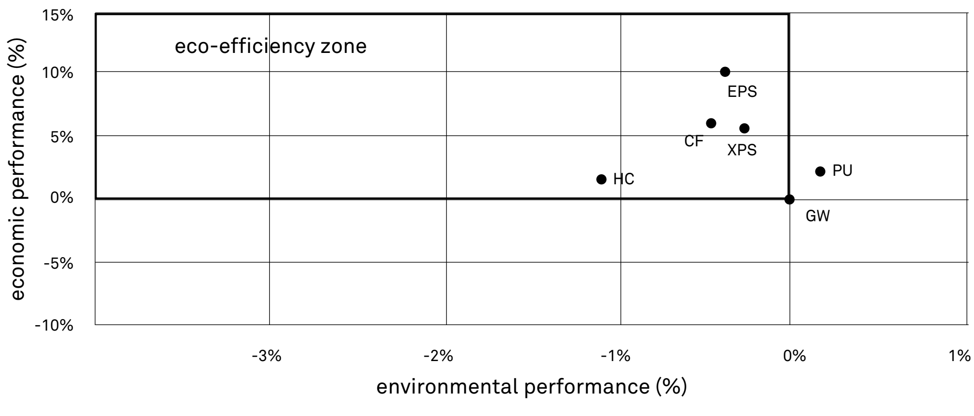
from design to use-maintenance phase

Investigating eco-efficiency procedure to compare refurbishmentscenarios with different insulating materials

C. Colli, A. Bataille, E. Antczak published on Procedia CIRP

Keywords (by document) Eco-efficiency; Life cycle assessment; Whole life costing; Building Refurbishment

Content summary The paper investigates the eco-efficiency of six refurbishment scenarios considering different insulating materials: glass wool (GW), hemp concrete (HC), cellulose fiber (CF), rigid foam of polyurethane (PU), expanded polystyrene (EPS) and extruded polystyrene (XPS).
First, a LCA analysis is performed and the results are aggregated ina single score ILCD midpoint indicator according to which the refurbishment scenario using PU is the worst one whereas the scenario using HC is the best one.
The second stemp is the WLC analysis which also considers the externalities, the non-construction costs, and the income. The economic indicators used in this analysis is the net present value (NPV) and the discounted payback time.
The results show a variation related to the reference scenario (building refurbishment scenario with GW insulating material) from –6 % up to + 16%. The best economic refurbishment scenario is the one using EPS, and the worst economic scenario is the one using HC.
The environmnental and economic impact analyses obtain opposite results.
Finally, an eco-efficiency analysis is performed through a matrix composed of score percentage of environmental performance in x-axis and economic one in y-axis. The matrix shows the best performance of EPS even after a sensitivity analysis and an eco-efficiency ratio method.



Author re-elaboration from Fig.6. *Eco-efficiency matrix for different insulating material scenarios of refurbish- ment (ILCD single score –100 years RSP).* p 5

Article n°11
Pub. Year 2020
France

Methodology

LCA

+

LCCA

+

sensitivity analysis

EEMs

Envelope refurbishment

Typology

Residential

Case Study

60 mq living area in a social single-family house

Analysis period

50 years

Functional Unit

total living area per year

System Boundaries

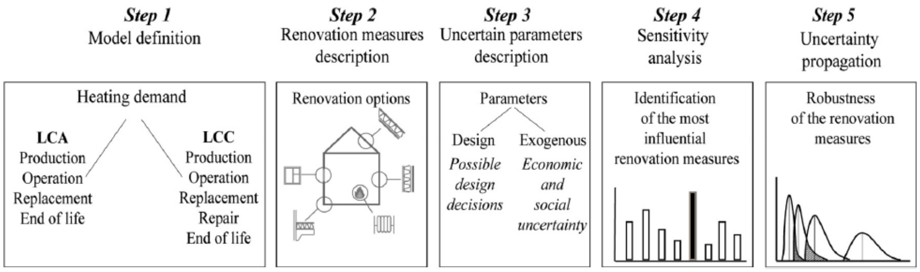
All life cycles

Statistical method to identify robust building renovation choices for environmental and economic performance

A. Galimshina, M. Moustapha,
A. Hollberg, P. Padey,
S. Lasvaux, B. Sudret,
G. Habert published on Building and Environment

Keywords (by document) Life cycle assessment; Life cycle cost; Uncertainty quantification; Building renovation

Content summary The aim of this study is to quantify the uncertainty components of a renovation scenario after it has been analysed through an integrated workflow of LCA and LCCA.
The methodology is shown in the graph below.



Author re-elaboration from Fig.1. *Proposed methodology.* p 2

First, the heating demand of the building and a combined LCC and LCA is conducted. Secondly, possible renovation measures are selected. Thirdly, the uncertain parameters are identified and described. This is followed by the global sensitivity analysis (GSA), which is performed in several screening assessments to define the most influential parameters for the renovation.
Finally, the uncertainties are propagated for the selected renovation measures and the solution robustness is compared to that of the non-renovated baseline case.
To evaluate the applicability of the method, three buildings from different construction periods are selected. Three construction periods are chosen as representatives of the majority of the building stock in Switzerland:1939,1960,1972.
The possible renovation measures are defined by renovation of the envelope and replacement of the heating system. The envelope is represented by the exterior wall, roof, ground slab, windows and surfaces facing unheated areas. The heating system can be chosen among a boiler, an air-to-water heat pump or district heating.
The individuated uncertain parameters are divided into the following categories:
•components types
•embodied emissions and investment costs
•operational emissions and costs
•reference service life (RSL) of components
•system performance
•user-oriented parameters
The sensitivity analysis shows that the heating replacement is the most influential parameter for the renovation.
The final step of uncertainty quantification calculated though the MC method shows that the environmental or economic performance over the life cycle after applying a renovation measure is worse than it would be without that renovation, probably due to various uncertainties.

Article n°12
Pub. Year 2020
Switzerland

Methodology

LCA

+

LCCA

+

sensitivity analysis

EEMs

Envelope refurbishment

New HVAC system

Typology

Residential

Case Study

A1= 2445 m2

A2=1475 m2

A3= 1446 m2

Analysis period

60 years

Functional Unit

building use for the entire period

System Boundaries

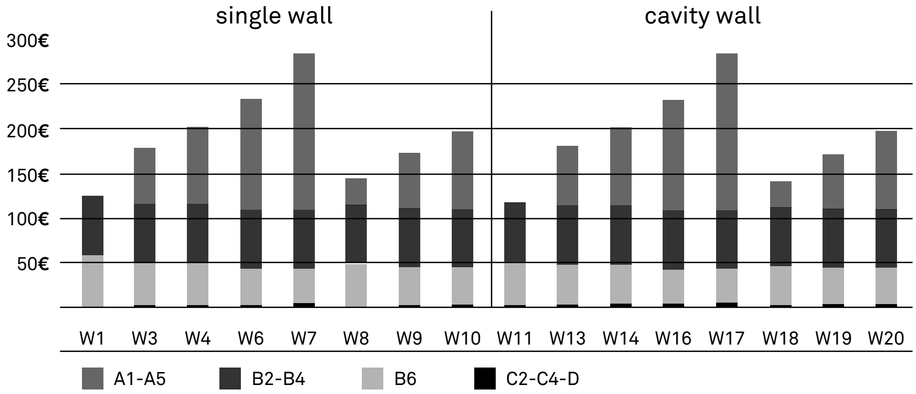
All life cycle phases

Energy retrofitting of a building envelope: assessment of the environmental, economic and energy (3E) performance of a cork-based thermal insulating rendering mortar

J. D. Silvestre, A. Castelo, J. Silva,
J. L. de Brito, M. D. Pinheiro published on Energies

Keywords (by document) cork; energy retrofitting; life cycle assessment; life cycle costs; thermal insulating; rendering mortar

Content summary This research studies the economic, environmental and energy (3E) assessment of an energy retrofitting of an external wall of a flat by considering a cork-based TIRM (Thermal Insulating Rendering Mortar).
This paper is an application of the 3E-C2C methodology developed by the University of Lisbon. The method assess the 3E impacts in all life cycle stages (from cradle-to-cradle).
A life cycle assessment is used for the energy and environmental impact and a life cycle cost analysis for the economic impact.
For the analysis, two solutions are considered as base case-studies: a single-leaf wall of hollow fired-clay bricks and a cavity walls with two leaves of the same material. Then, twelve alternative TIRM insulation solutions are considered internally, externally and on both. Furthermore, three values of heating and cooling needs are considered: 10%, 30%, 50%.
The LCA analysis shows that the W9 solution (single wall-external 10 cm TIRM) has the lowest primary energy consumption from non-renewable sources for satisfying 10% of heating and cooling needs. If the value increases to 30% and 50% the W10 (single wall-external 15 cm TIRM) solution becomes the best alternative.
Within the cavity wall group, the LCA shows that W18 (cavity wall-external 4 cm TIRM) has the lowest PE-NRe, considering the consumption of energy necessary to fulfil 10% of the heating and cooling needs. If this value is increased to 30% or 50%, then W20 (cavity wall-external 15 cm TIRM) becomes the best alternative.
The LCC analysis outcomes (NPV) are given in the next figure.



Author re-elaboration from Fig.5. *NPV of the economic (including A1-A5, B2-B4, and C2-C4 and D stages) and energy (for B6 substage) costs of each external wall alternative.* p 9

The best economic alternative considering the consumption of energy needed to fulfil 10% of the heating and cooling needs is W1 (no renovation) but, when the energy consumption increases to 30% or 50%, the best alternative becomes W8 (single wall-external 4 cm TIRM).
The best economic alternative considering the consumption of energy needed to fulfil 10% or 30% of the needs is W11 (no renovation) but, when the energy consumption increases to more than 50% (53%), the best alternative becomes W18 (cavity wall-external 4 cm TIRM).

Article n°13
Pub. Year 2019
Portugal

Methodology

LCA

+

LCCA

EEMs

Envelope refurbishment

Typology

Residential

Case Study

south and north facades of a building intermediate flat

Analysis period

50 years

Functional Unit

1 m2

System Boundaries

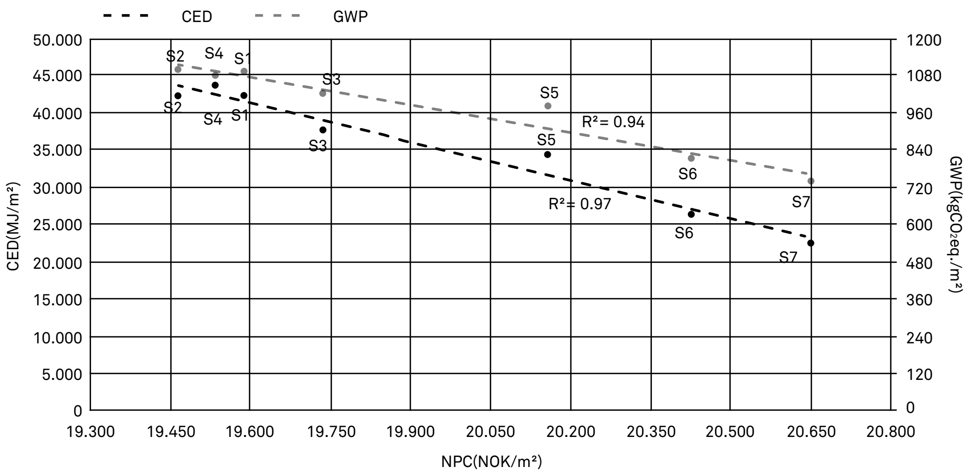
All life cycle phases

Combining Life Cycle Environmental and Economic Assessments in Building Energy Renovation Projects

R. Moschetti,H. Brattebø published on Energies

Keywords (by document) buildings; energy renovation; dynamic energy simulation; life cycle assessment (LCA); life cycle costing (LCC); sensitivity analyses

Content summary This paper clearly describes an integrative environmental and economic assessment methodology of a renovation scenario of a single-family house in Oslo, Norway.
In this article, seven alternative scenarios (S) are defined and explored, in addition to the reference scenario (S1) that concerns the renovation project as it was already implemented for the case building. In particular, the scenarios S2–S7 present all the renovation measures of S1 with some differences in terms of the space heating system and the renewable energy technologies (RETs).
For the environmental impact assessment, a LCA is calculated and the outcomes are expressed by global warming potential (GWP) and cumulative energy demand (CED) indicators.
The results shows that S7 (S1 + multi-split air-to-water heat pump with water radiators, PV system, and solar thermal system) is the scenario with the lowest GWP and CED value, mainly due to the RETs integration. In all scenarios, the energy use-operation phase is the highest contributor to the environmental impact.
The economic analysis is carried out by the LCCA and the NPC is the performance indicator. S7 presents the highest value of NPC, 6% higher than the lowest value of S2.
In all scenarios, the investment costs constitute the leading component, ranging from 76% in S1 to 79% in S7.
The results of LCA and LCCA are given below in the same graph.



Author re-elaboration from Fig.6. *Global warming potential and cumulative energy demand results plotted against the net present cost results.* p 11

The graph shows that a modest increase of NPC value gives large reductions of GWP and CED values, due to the slight difference among NPC values. For instance, S7 presents the highest NPC and the lowest GWP while S2 presents the opposite results. However, S7 has a NPC 6% higher than S2 but a GWP 32% lower than S2.
At the end of the paper, a sensitivity analysis is conducted by changing the building life span and the electricity mix of the energy use during the operation phase in LCA and the building life span after the renovation and the real discount rate in LCC.

Article n°14

Pub. Year 2017

Norway

Methodology

LCA

+

LCCA

+

sensitivity analysis

EEMs

Envelope refurbishment

Windows replacement

New HVAC system

New DHW system

Typology

Residential

Case Study

single-family house
3 floors
gross internal floor areal=176.7 m2

Analysis period

50 years + different lifespans with EAC

Functional Unit

1 m2 of GIFA

System Boundaries

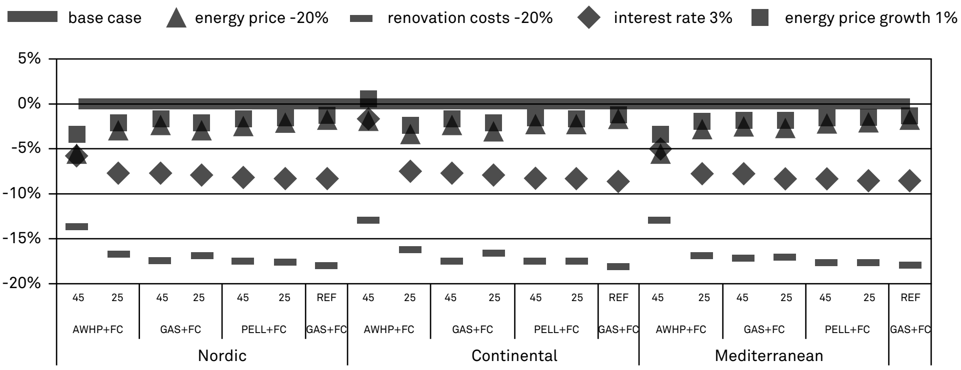
All life cycle phases

Economic and environmental analysis of energy renovation packages for European office buildings

M. Gustafsson, C. Di Pasquale,
S. Pioppi, A. Bellini,
R. Fedrizzi, C. Bales, F. Ochs,
M. Siè, S. Holmberg published on Energy and Buildings

Keywords (by document) Energy renovation; Office buildings; LCA; LCC; TRNSYS

Content summary The aim of this study is to assess the economic and environmental aspects of renovation packages for typical European office buildings. The building models used in this study are defined as typical European office buildings from the period 1945–1970 in the Nordic, Continental and Mediterranean regions. Climate data for Stockholm, Stuttgart and Rome are used in simulations.
In addition to a reference case, denoted “REF”, two different renovation standards, “25” and “45”, are investigated. These labels signify an ideal heating demand of 25 kWh/(m2y) and 45 kWh/(m2y),respectively. Envelope insulation and windows replacement are considered together with three centralized energy generation systems and two distribution systems: air-to-water heat pump (AWHP), gas boiler and pellet boiler in combination with radiant ceiling (RC) panels or fan coils (FC). Installation of solar PV panels on the roof or on the facade, facing south-east, is investigated in combination with all systems.
The economic and environmental evaluation of the renovation measures is performed through the Life Cycle Cost analysis and the Life Cycle Assessment methodologies, respectively.
In the LCC calculations, Net Present Values (NPV) of future costs are considered with an interest rate of 4%, including 1% inflation. The total costs for “25” and “45” are lower than for “REF”, except for the “45” case in the Nordic climate with boiler systems and FC. The total annualized costs are reduced, compared to the reference, by up to 9% for the Mediterranean climate, 19% for Continental and 11% for Nordic, with the AWHP and radiant ceiling system showing the largest reductions.
Regarding the environmental assessment, the lowest impact, for all climates, is seen for the “25” case and the systems with pellet boilers. Both LCA and LCC parameters are varied in a sensitivity analysis
The figure below shows a sensitivity analysis of the economic assessment indicating the relative impact on the total annualized costs by reduced investment and installation costs, energy price, interest rate and energy price growth. Energy prices and energy price growth have larger impact on the “45” than the “25” case, and particularly on the AWHP systems.



Author re-elaboration from Fig.5. *Changes in total annualized costs for variation of renovation costs, energy price growth, energy price and interest rate, compared to the base-case scenario (default values).* p 6

Article n°15
Pub. Year 2016
Eu countries

Methodology

LCA

+

LCCA

+

sensitivity analysis

EEMs

Envelope refurbishment

Windows replacement

New HVAC system

New DHW system

Typology

Office

Case Study

five-floor building type

Analysis period

30 years

Functional Unit

to provid comfortable conditions regarding indoor temperature, ventilation and lighting

System Boundaries

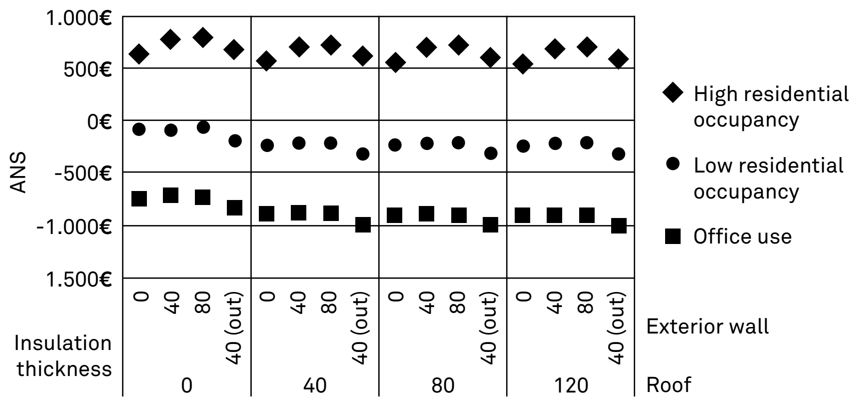
All life cycle phases in LCA; from design to use-phase in LCCA

Building retrofit addressing occupancy: an integrated cost andenvironmental life-cycle analysis

C. Rodrigues, F. Freire published on Energy and Buildings

Keywords (by document) Building retrofit; Environmental impacts; Life-cycle assessment (LCA); Life-cycle costing (LCC); Occupancy patterns

Content summary This study presents an integrated approach combining environmental life-cycle assessment (LCA), life-cycle costing (LCC) and thermal dynamic simulation to assess the impact of different retrofit strategies in a early 1900 single-family house in Coimbra, Portugal. Besides the retrofit strategies, this study combines different insulation levels and occupancy patterns. Moreover, the present work shows how occupancy influences the analysis outcomes.
Three occupancy scenarios (low-residential; high-residential; office) are combined to three alternative roof insulation levels (40-80-120 mm) and to two alternative exterior wall insulation levels (40-80mm). The base-case occupancy scenario is defined by a four-person family with low occupancy, and set-points fixed at 20°C (heating) and25°C (cooling).
First, a thermal dynamic simulation model is implemented to calculate the energy needs of the whole building.
The environmental impact is defined by 5 indicators (CC, OD, TA, FE, ME) plus the nor-renewable primary energy (NRPE).
The LCA analysis shows that high residential occupancy has greater environmental impacts than low residential occupancy or office use due to higher heating and cooling needs. Moreover, additional insulation levels lead to considerably higher benefits (10–45% of impact reduction) for high occupancy than low occupancy (5–24%).
The LCC analysis is performed by using the Equivalent Annuity Cost method and 2% discount rate is considered.
The annual net savings of each retrofit strategy are calculated by comparing the EAC of retrofit with the EAC of no-retrofit, as follows:
ANS = EAC no-retrofit - EAC retrofit strategy
In the figure below, annual net savings of exterior-wall and roof retrofit insulation strategies (relative to no-retrofit), assuming alternative occupancy scenarios and office use, are shown.



Author re-elaboration from Fig.4. *Annual net savings of exterior-wall and roof retrofit insulation strategies (relative to no-retrofit) assuming alternative occupancy scenarios: residential low and high occupancy, and office use.* p 8

The figure shows that high residential occupancy presents higher net annual savings. In low residential occupancy and office use, none of the retrofit strategies present positive savings.

Article n°16
Pub. Year 2016
Portugal

Methodology

LCA

+

LCCA

+

sensitivity analysis

EEMs

Envelope refurbishment

Typology

Historical /

Residential /

Office

Case Study

three floors single family house

Analysis period

50 years in LCA
EAC method in LCCA

Functional Unit
1 m2 of living A

System Boundaries

existing demolition phase

+

retrofit construction and maintenance phases

Adaptive reuse of buildings: eco-efficiency assessment of retrofit strategies for alternative uses of an historic building

C. Rodrigues, F. Freire   published on Journal of Cleaner Production

Article n°17
Pub. Year 2016
Portugal

Methodology
LCA
+
LCCA
+
sensitivity analysis

EEMs
Envelope refurbishment

Typology
Historical /
Residential /
Office

Case Study
three floors office
A= 438 m2

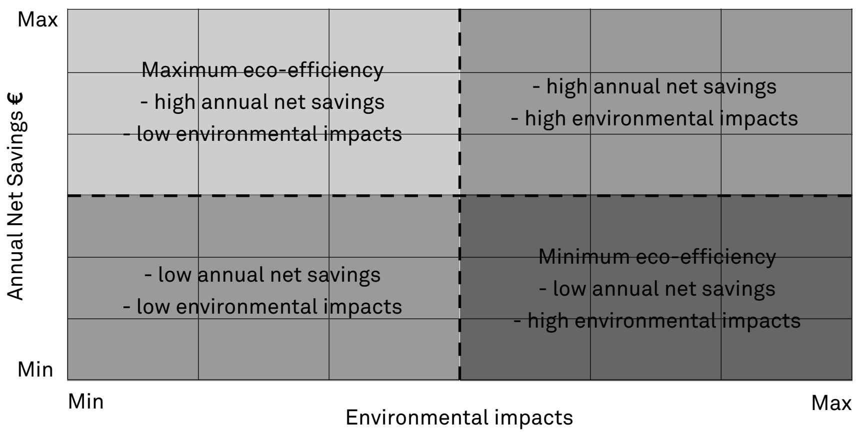
Analysis period
50 years in LCA
EAC method in LCCA

Functional Unit
1 m2 of living A

System Boundaries
existing demolition phase
+
retrofit construction and maintenance phases

Keywords (by doument) Building retrofits; Environmental impacts; Life-cycle assessment; Life-cycle costing; Occupancy pattern; Thermal insulation

Content summary This paper represents a more accurate and defined work of the previous one.
The same case study, that is a historic residential building adaptively reused as an office, is based on both residential and office use layout design (in the previous paper only the residential use is considered).
As in the n°14 article, nine occupancy scenarios are considered by combining alternative insulation levels (0-40-80-120 mm roof insulation levels; 0-40-80 mm exterior wall insulation levels) and usage levels (office use; high and low residential occupancy).
After an energy need calculation of the whole building in EnergyPlus, a life cycle assessment (LCA) and a life cycle cost analysis (LCCA) are calculated in this work as well. The environmental indicators are NRPE, CC, OD, TA, FE and ME and the LCCA is performed by using the Equivalent Annual Cost (EAC) method.
However, the environmental and economic assessment are not singularly studied but they are integrated in the so-called eco-efficiency matrix, that is defined to goal to maximise annual net savings while reducing environmental impacts.
It is represented in the figure below.



Author re-elaboration from Fig.2. *Eco-efficiency analysis (based on (Ferrandez-García et al., 2016; Iba~nez-Fores et al., 2013)).* p 7

As it can be seen in the figure, the plot is divided into four areas individuated on the basis of the environmental impact on x-axis and the annual net savings in the y-axis. The light shaded grey area on the upper left side defines the better option of an eco-efficiency analysis which contains high economic value and low environmental impact.
This matrix is repeated for each of nine scenarios. In low residential occupancy the most eco-efficiency scenario combines
no roof insulation and exterior wall insulation 80mm (R0EW80).
In high residential efficiency the best strategies are R40EW40, R40EW80, R80EW40 and R80EW80).
Office use presents the same results in all categories.

4.3 ANALYSIS OF THE DIFFERENT METHODOLOGICAL APPROACHES IN THE SELECTED LITERATURE

The criterion followed for selecting the articles is the presence of Life Cycle Cost Analysis, and related methodologies. The consideration of the environmental impacts of the renovation measures has allowed to divide the 17 articles in three main groups, as explained in Figure 2 in Section 4.2 and reported below:

1. LCCA : Articles 1 to 8;
2. LCCA + environmental considerations : Articles 9 and 10;
3. LCCA +LCA : Articles 11 to 17.

In the description of each article other information about calculation are specified after a deep study of each manuscripts. Figure 2 of Section 4.2 becomes:

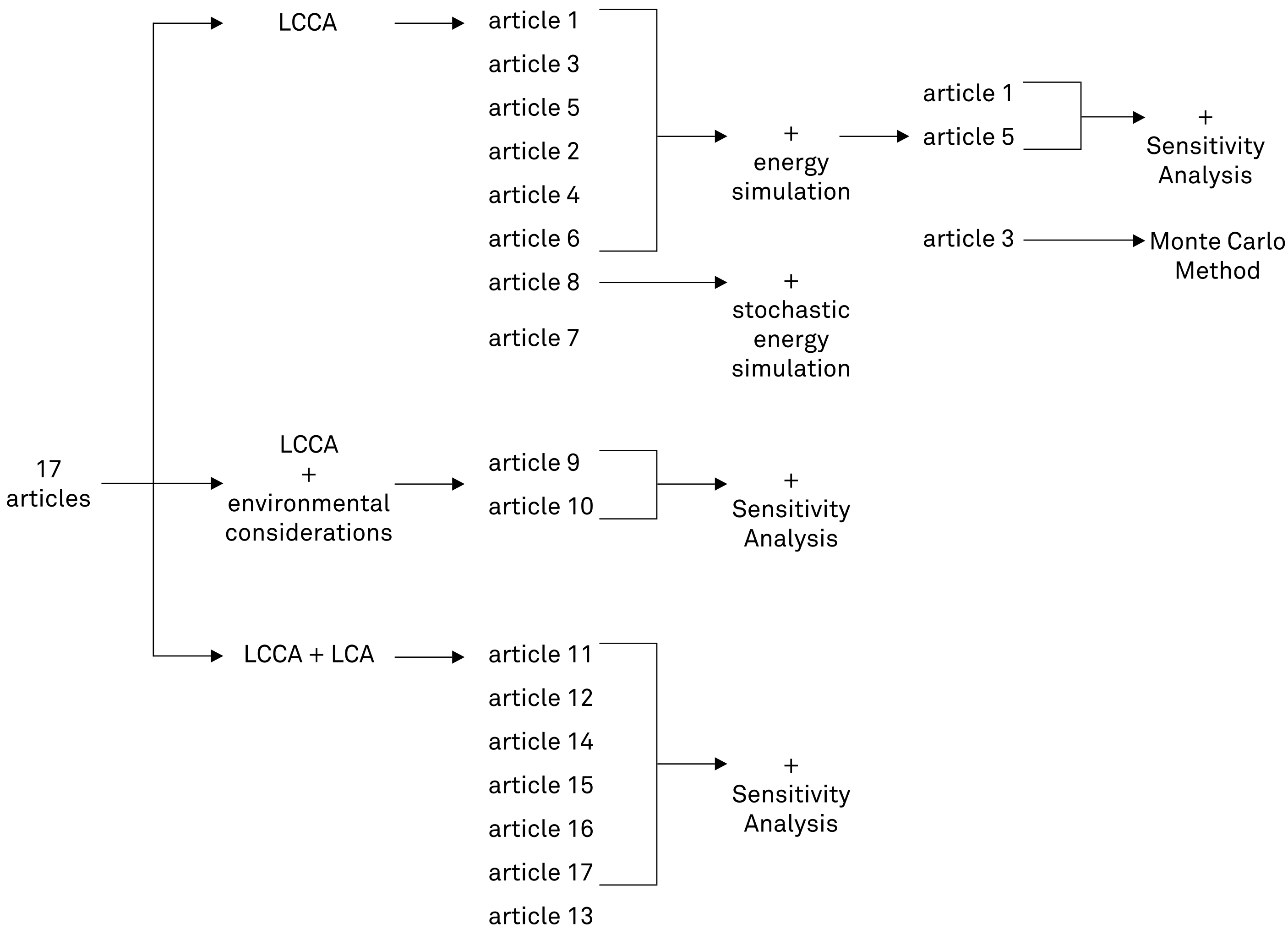


Figure 3. Methodological categorization of the articles and specific calculation tools.
Source: Author elaboration

Given the limited number of articles considered in this research, the usually adopted typologies of analysis (temporal, geographical, etc...) have been considered inappropriate and not useful to a future development on this topic.
Instead, the methodology used in each manuscript can be the base information to which link the others. In the detailed description of each article, the grey column on the right side contains the main information about the analysis works. The figures below shows the linkage of the methodology with the publication year, EU Country, building typology, Energy Efficiency Measures (EEMs).

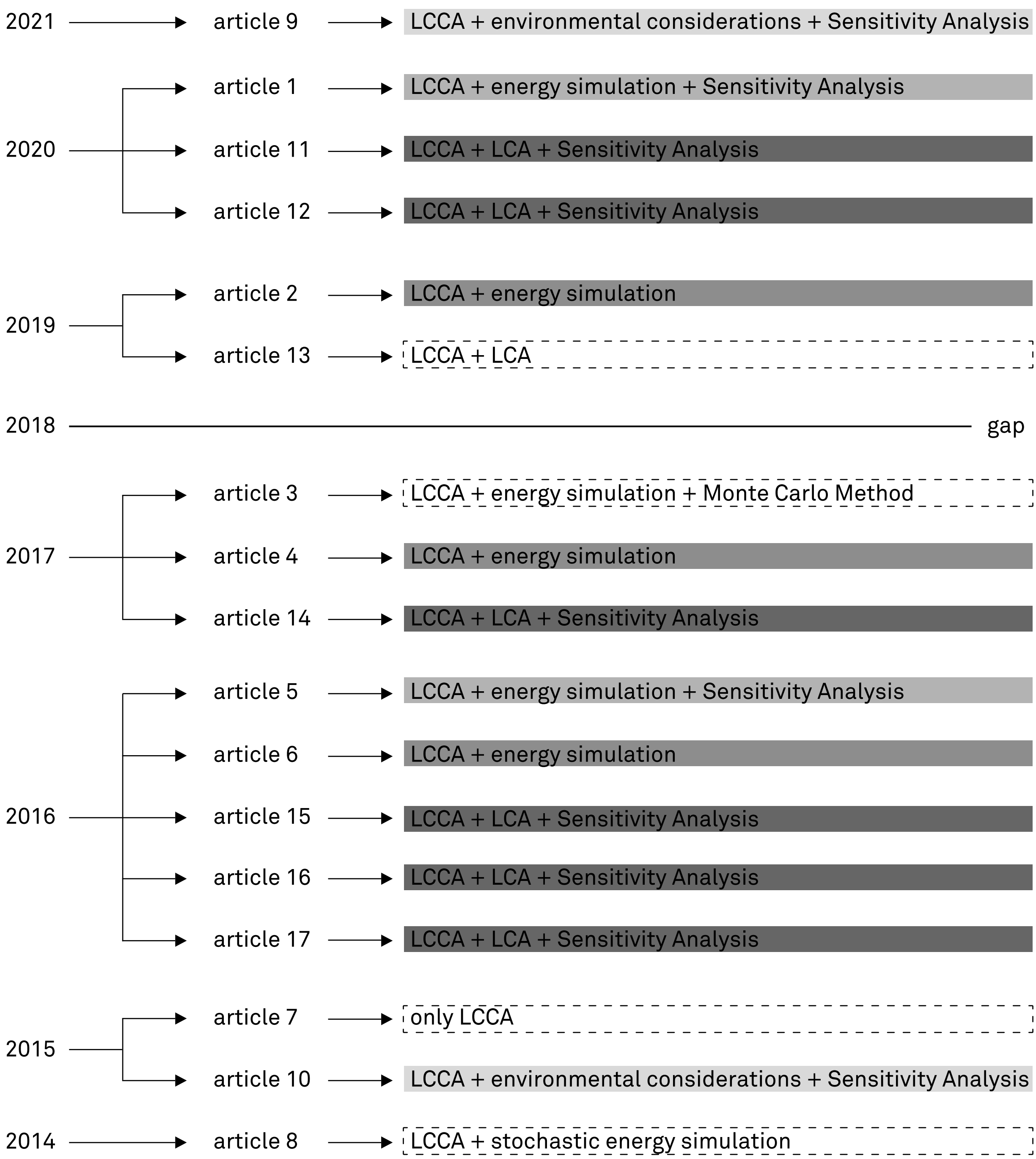


Figure 4. Publication year categories.
Source: Author elaboration

In the previous figure the same methodologies are highlighted by the same colour. The dotted box is linked to single case-methodologies. It can be seen that 2016 in the fullest year of articles and that only 2020 and 2014 present just one article. In addition, the "LCA + LCCA + Sensitivity Analysis" is the most diffuse methodology (5 articles) followed by "LCCA + energy simulation" (3 articles). However single-case methodology articles are 5 as well. Finally, the "LCCA+ energy simulation" methodology is the one repeated for the highest number of different years (4 years: 2019, 2017, 2016 and 2014 by considering the stochastic energy simulation as well).

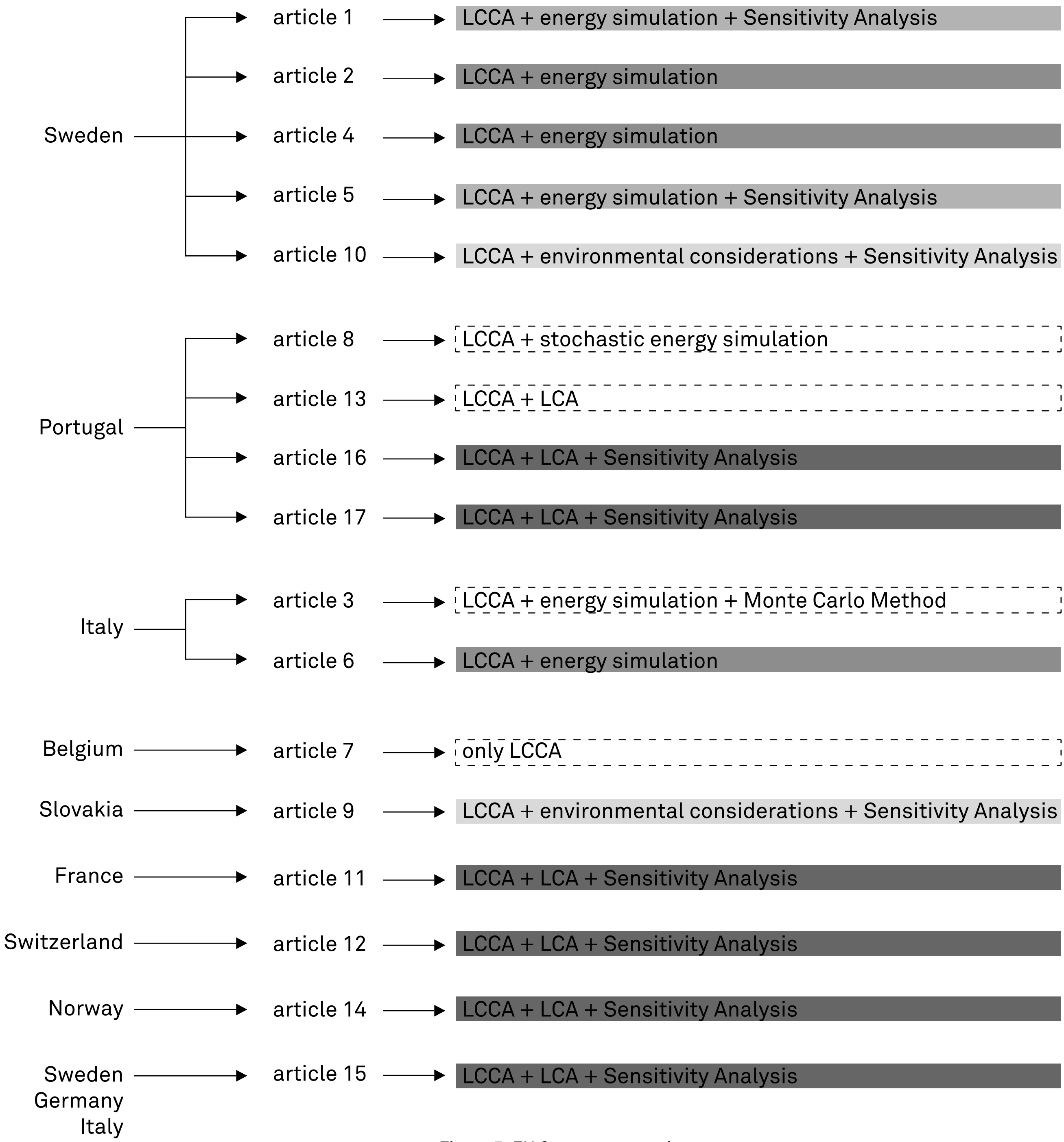


Figure 5. EU Country categories.
Source: Author elaboration

The EU Country categories map clearly shows that Sweden hosts the highest number of articles (6 since it is also considered in Article 15). It is immediately followed by Portugal with 4 articles. This numbers can seem not relevant. However, although this research is focused on the European context, the selection process in Figure 1 shows that at international level the numbers of articles are limited as well. Hence it has been considered interesting to report the results of the other Countries. The figure below shows the number of articles for each Country at global level.

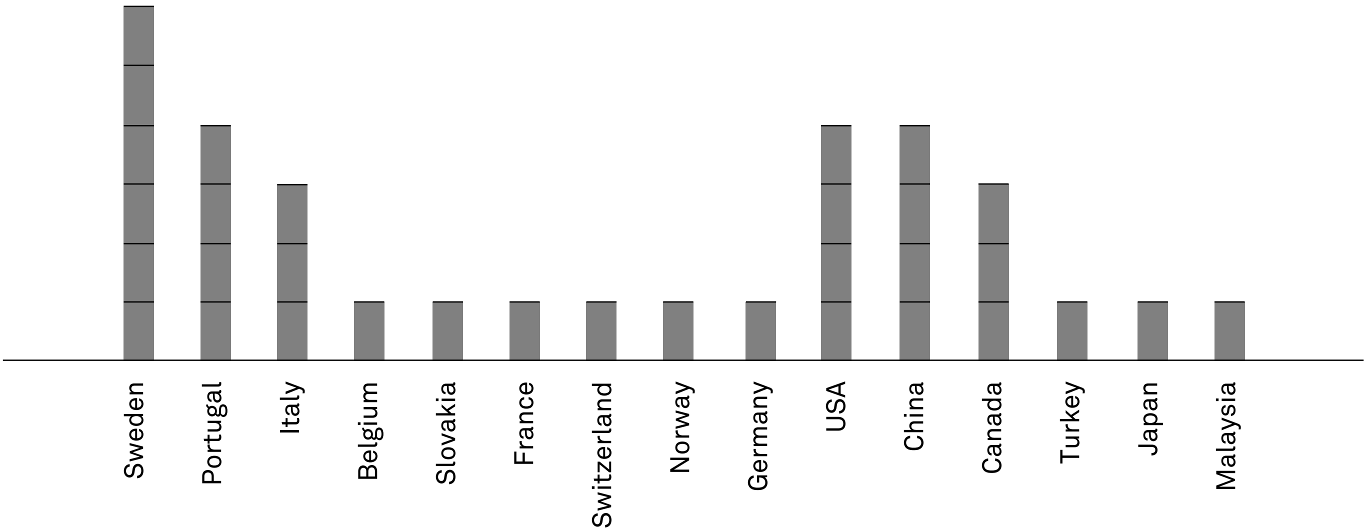


Figure 6. Numbers of article for each Country at global level. One rectangle is one article.
Source: Author elaboration from Scopus

The figure above shows how the limited number of the selected articles is actually relevant at global level. Eight out of fifteen Countries presents only one article. Sweden is in top position both at European and global level. Portugal has the same number of articles of USA and China. Italy and Canada host among the highest numbers of articles as well.
However, as explain at the start of Chapter 4, only EU Countries continue to be considered beacuse of the same regulatory framework and unit of measures used in the calcuations.

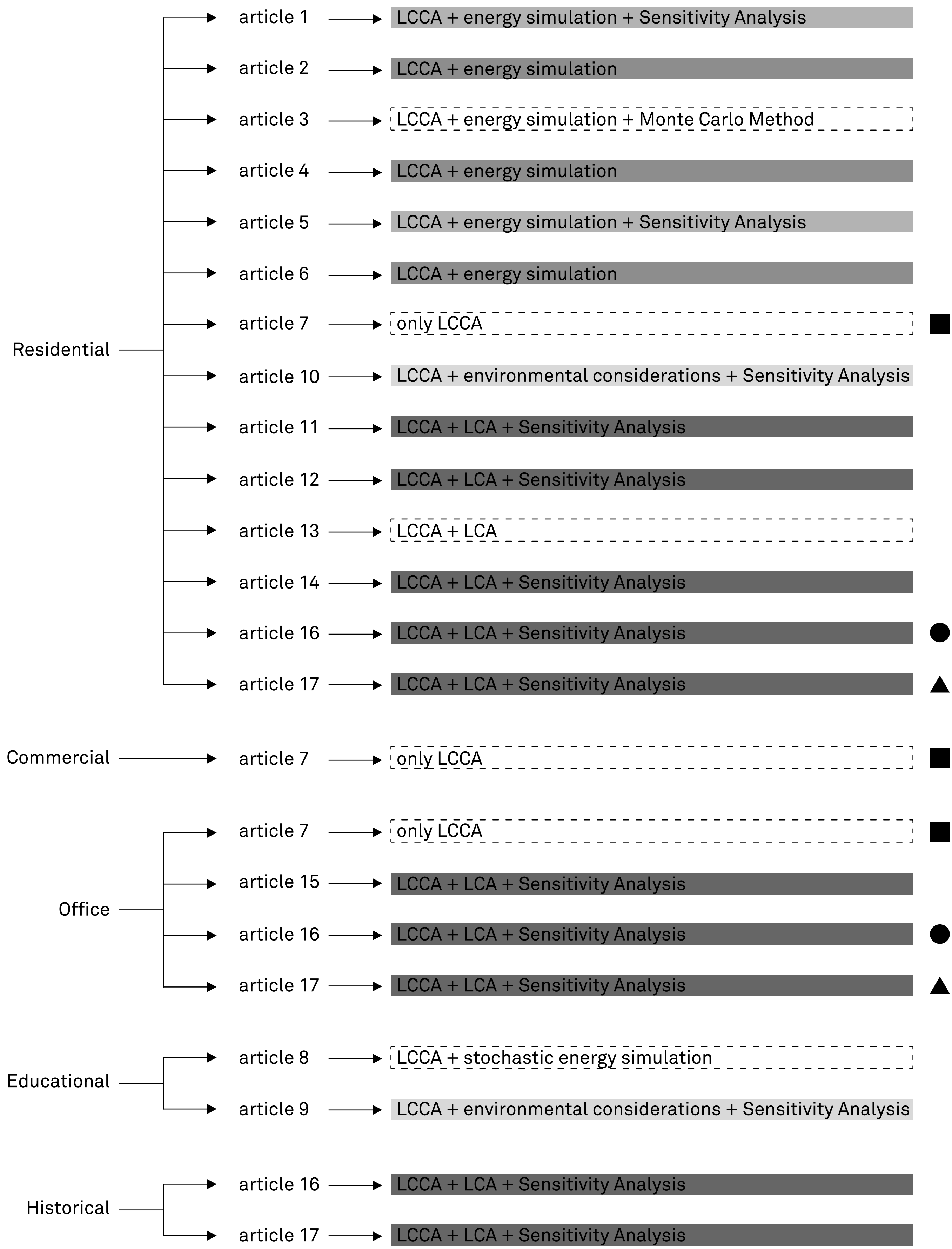


Figure 7. Building typology categories.
Source: Author elaboration

Figure 7 clearly shows that the residential building are the most studied typology in Europe. Fourteen articles out of seventeen, that is 82% of the total, are residential buildings. A few of the selected articles has studied more typologies so the same article is repeated in more groups. In order to recognize this repetition, a symbol has been associated to the repeated articles. It is interesting to notify that office buildings are mainly studied by considering both an economic and an environmental perspective verified by a Sensitivity Analysis.

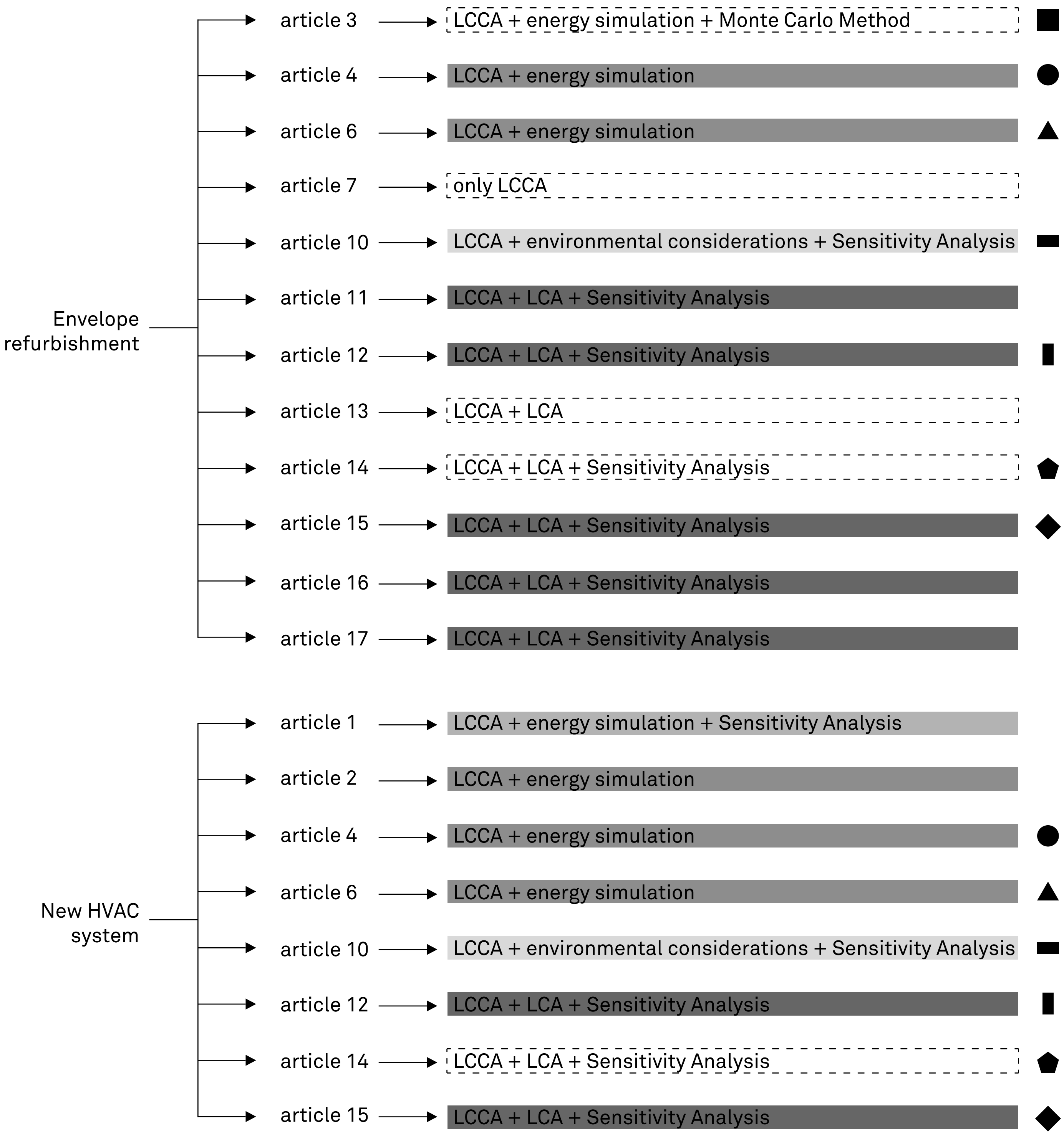


Figure 8. Continue...

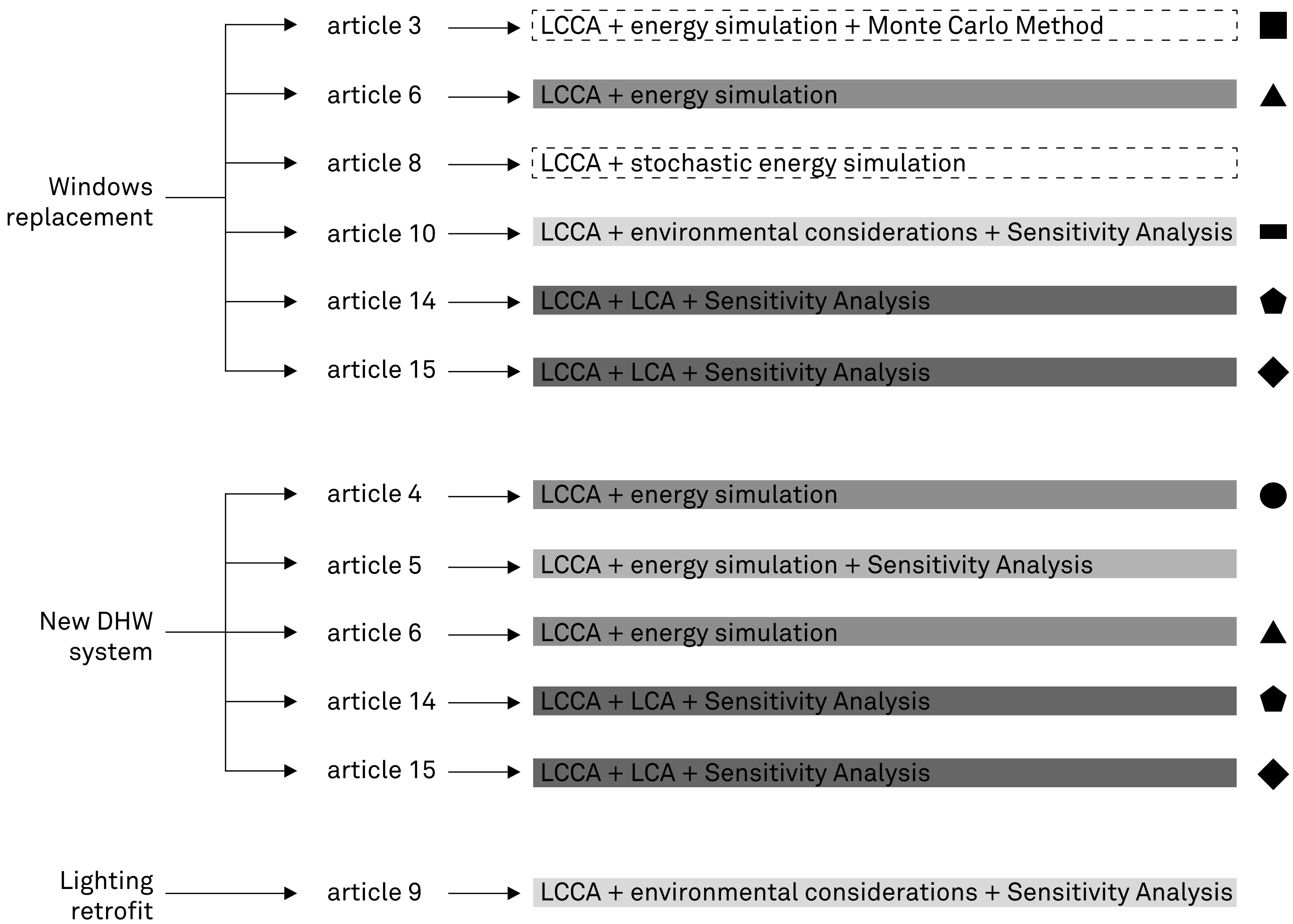


Figure 8. Energy Efficiency Measures (EEMs) categories.
Source: Author elaboration

The last analysed category is the Energy Efficiency Measures (EEMs). The envelope refurbishment is the most used EEM to improve the energy performance or for the energy conservation of a building. Seven of the twelve articles in the envelope refurbishment group are performed together with other measures then are repeated in other EEMs group, mainly with the intervention of a new HVAC system. The most repeated articles are 6, 14 and 15. Since the former applies the "LCCA + energy simulation methodology" and the last two consider the same methodology, it can be concluded that "LCCA +LCA + Sensitivity Analysis" is associated to the highest number of EEMs.

4.4 THE ENVIRONMENTAL ANALYSIS IN THE SELECTED LITERATURE

The aim of this research is not only to deal with the Life Cycle Cost Analysis (LCCA) or Life Cycle Costing (LCC) methodology applied to energy retrofit projects but also to look at the development of considerations and analysis of the environmental impact, linked or integrated to the economic evaluation of a energy refurbishment scenario. Indeed, the articles have been divided in three groups (Figure 1) by considering that the first category takes into account only the economic perspective (LCCA), the second group adds some environmental considerations to the economic analysis (LCCA + environmental considerations) and the third one integrates or adds a complete environmental impact analysis to the economic one (LCA + LCCA) according to the different synergies explained in Figure 4 in Section 3.2.2.
However, the studies of the first group can indirectly contribute to environmentally sustainable targets such as the greenhouse gases emissions reduction or the energy-efficiency improvement. This is explained by the reduction of the energy consumption because of the objective to reduce the expenses related to the Use - Maintenance - Operation phase. In other words, if one wants to spend less, he/her needs to consume less energy with the consequent reduction of GHGs emission by energy. Further, most of the articles refer to the EPBD recast Directive 2010/31/EU which set sustainable targets for the energy performance of the existing buildings. Hence, Figure 2 becomes:

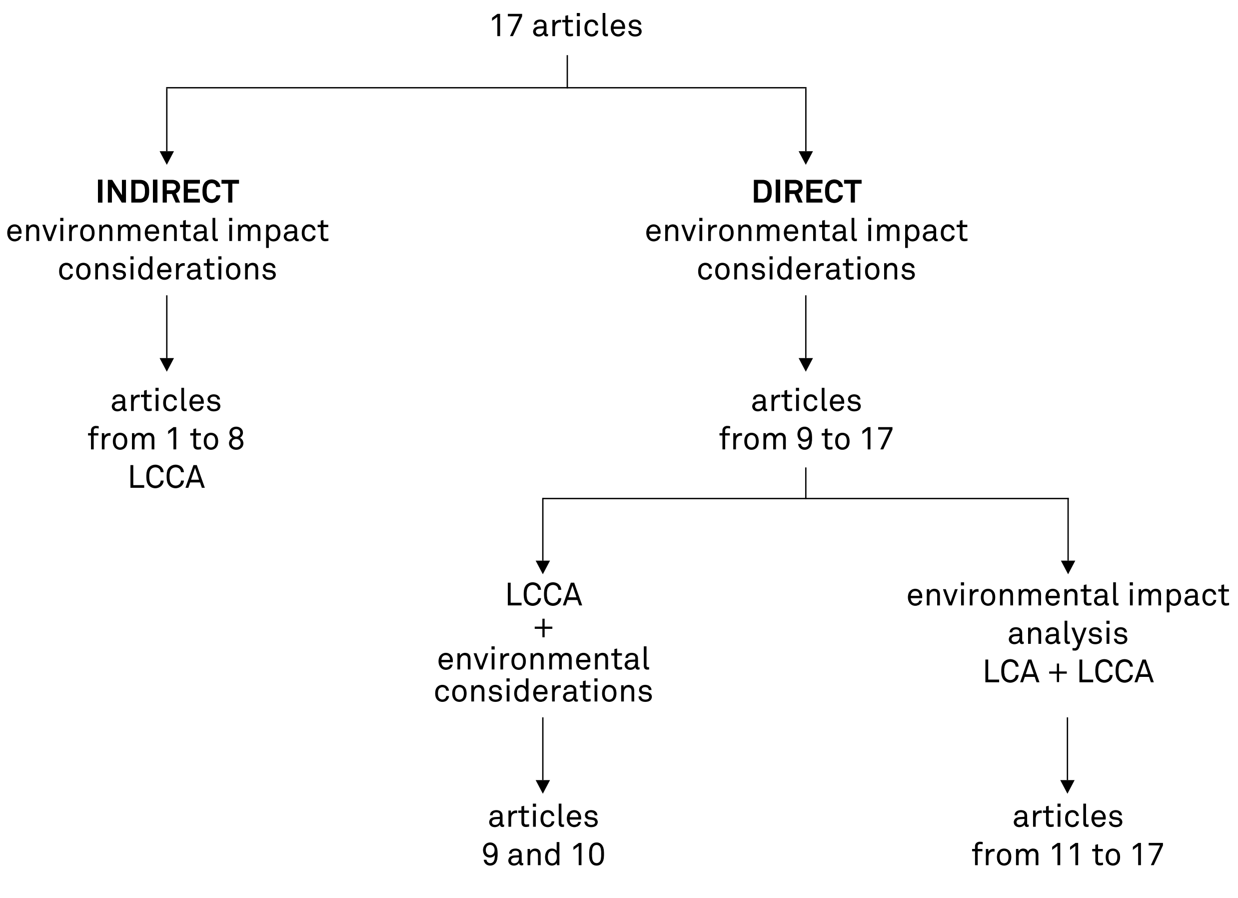


Figure 9. Indirect and direct environmental impact considerations.
Source: Author elaboration

4.4.1 INDIRECT ENVIRONMENTAL IMPACT CONSIDERATIONS

The articles from 1 to 8 differently contribute to the environmental sustainability of the explored retrofit scenarios.
Articles 1 and 3 are based on the huge impact of the discount rate on the assessment of the energy-efficiency potential of the considered renovation solution. The Building Performance Institute Europe (BPIE) considers the role of the discount rate according to two perspectives:[(1)]

1. Social discount rates are applied for evaluating total costs and benefits of energy systems from a societal perspective (range 1-7 %);
2. Individual discount rates are applied to model investment decision-making, reflecting the expected return of an investor (range 3-6 % for households; 6-15% for commercial or industrial investors).

Article 1 "Economic performance assessment of three renovated multi-family buildings with different HVAC systems" applies three values of discount rate and two value of energy escalation rate to three different HVAC system scenarios. Besides the LCCA results, environmental impact data are given as well. Indeed, the best solution reduces LCC by 24%, Primary Energy Consumption (PEC) by 58%, CO_2 emissions from energy by 65% and the energy consumption from non-renewable energies by 56%.
Article 3 "Evaluation of energy retrofit in buildings under conditions of uncertainty: The prominence of the discount rate" studies an integration between Life Cycle Cost Analysis (LCCA) and Monte Carlo Method (MCM) . The following methodological steps are taken from the article:

$$LCC = Bc + \sum_{i=1}^{n} (Mc + Oc) / (1 + r)^{i}$$

where LCC is precisely the life-cycle cost, Bc is the building cost, Mc represents the maintenance cost, and Oc stands for the operating cost. MCc and Oc are discounted. To apply the LCC model to the energy retrofit scenarios, the previous equation becomes:

$$LCCj = Icj + \sum_{i=1}^{n} (qj \cdot p) / [(1 + r)/(1 + e)]^{i}$$

where Icj are the investment costs to implement each of the j scenarios, assumed incurred at time 0. The period of analysis n is considered equal to the useful life of the works (30 years). Hence, the maintenance costs (Mcj) are assumed to be equal to zero. The operating costs (Ocj) are limited to the energy expenses, given by the product of the energy requirement subsequent to the implementation of works (qj) and the energy price (p).

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(1) BPIE (2015). *Discount rate in energy system analysis*, BPIE p 1-2

The energy inflation rate is (e). At this point the analysis distinguishes the LCCA parameters between internal, or endogenous, and external, or exogenous.
Internal factors are directly under control of the stakeholders involved in the project. External factors, on the contrary, are beyond the control of the stakeholders, they do indeed depend on the prices of goods and services. Icj and qj are considered endogenous and assumed as given, while the macroeconomic parameters p, e, and r are considered exogenous and allowed to vary within predetermined ranges. The previous equation becomes a Life Cycle Costing - Monte Carlo (LCC-MC) integration method:

$$LCCj = \overline{Ic}j + \sum_{i=1}^{n} (\overline{q}j \cdot p) / [(1 + r)/(1 + e)]^{i}$$

$$p \sim U(p_{min},\ldots, p_{max}),\ r \sim U(r_{min},\ldots, r_{max}),\ e \sim U(e_{min},\ldots, e_{max})$$

where the bar denotes the constants, namely, the internal factors.
In a MCM analysis intervals instead of values are considered. A wide interval (0-15%) is applied for the discount rate r in order to consider a societal perspective according to what it has been explained before. The analysis shows that r is four times more influential than p and e in the assessment of the best energy-performance solution. The article states that:

"Although it (the specific uncertainty) may seem intrinsic to the evaluation methods founded on the discounting principle, we should conclude that it is more properly intrinsic to the setting of the energy efficiency solutions and the presence of multiple stakeholders (...) diverging rankings may characterize the different stakeholders". (2)

Another way to implicitly consider the environmental impact in the economic analysis is the cost-effectiveness evaluation of sustainable technological solutions. For instance, the articles 4 and 6 compare a reference case to a Passive House level scenario and to a simple functional renovation scenario. Hence, in the LCCA calculation for the Passive House scenario are considered costs related to environment-friendly technological solutions since Passive House is a label for green buildings.
Article 4 demonstrates the cost-effectiveness of Passive House renovation level associated with a specific HVAC system.
Article 6 also considers a plus energy buildings option which produces energy beyond the needs but it is demonstrated to be not cost-effective. Even in this study the Passive House and NZEB renovation level solutions is demonstrated to be the best scenario.
In articles 2 and 8 the implicit environmental consideration stands in a more accurate Life Cycle Cost Analysis for reaching the energy conservation of a building.

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(2) COPIELLO S. GABRIELLI L. BONIFACI P. (2017). *Evaluation of energy retrofit in buildings under conditions of uncertainty: The prominence of the discount rate*, ENERGY p 7

The former considers the whole energy system in LCCA not only the energy price or the savings obtained from the less energy bought for the building system.
The energy system consists of both the District Heating (DH) system and the electricity system delivering energy to the building. Costs for both the production and distribution are considered. The DH distribution includes the cost for the pipes and the substation in the building, as well as the distribution losses. In order to expand the system boundaries, the energy system supplying the building is assumed to be 100%. All renovation measures result in a lower DH demand, at the expense of an increased electricity demand. All renovation measures also result in an increased LCC, compared to the reference building. When aiming for a transformation towards a 100% renewable system in the future, this study shows the importance of having a system perspective.
article 8 considers a stochastic energy simulation for a more accurate definition of energy consumption costs inputs in a LCCA calculation. The variables performed in a Monte Carlo analysis are: occupancy, metabolic rate, lighting, ventilation, envelope thermal resistance. The output is Eannual that is the heating annual energy demand. However, in this example case, uncertainty is not considered in the base costs and discount rate applied in the LCC analysis is setting those parameters as deterministic. Hence, only energy simulation inputs are defined as uncertain, which does not allow for a holistic uncertainty analysis.
Finally, article 5 studies the cost-effectiveness of a new solar Domestic Hot Water (DWH) in which the existing heater system is reused. Hence, beyond the improvement of the renewable energy use, wastes are avoided. In article 7 the LCCA calculation is performed for different envelope refurbishment scenario and conventional or adaptable system; the study shows that the "Design for Change" solution, which considers elements that can be assembled and disassembled, is the most cost-effective scenario.

4.4.2 DIRECT ENVIRONMENTAL IMPACT CONSIDERATIONS

From article 9 to 17 the environmental perspective is explicitly taken into account in the economic evaluation of a building retrofit scenario.
Articles 9 and 10 do not perform a complete Life Cycle Assessment (LCA) analysis but clearly link the cost-effectiveness to the less environmental impact solution.
The former performs an interesting application of LCCA to the lighting retrofit scenario for the energy-efficiency of an educational space. The study shows the flexibility and adaptability of the Life Cycle Cost Analysis methodology to any case. Further, the same factors used in the LCCA calculation are used for the Climate Impact formulation, but not in monetary terms.
The following methodology steps are taken from the article:

$$\text{Total cost} = \sum \text{investment} + \sum \text{Fpv} \times \text{maintenance} + \sum \text{Fpv} \cdot \text{annual energy}$$

where Total cost is a total price of life cycle (€); investment is an investment price (€); annual energy is an annual price of electricity (€); maintenance is price for maintenance (€), Fpv is a factor of present value (-).

$$\text{Fpv} = 1 / \text{Dr} \cdot (1 - \left[(1 + \text{Eapch}) / (1 + \text{Dr})\right]^{t_u})$$

where Fpv is a factor of present value (-), Dr is a discount rate (%), Eapch is an annual electricity price change (%), t_u is a usage time (year).

$$\text{Investment cost} = \text{Nrst} \cdot (\text{Nl} \cdot (\text{Pl}+\text{MLl}))+\text{Cecd}$$

where Investment cost is price of investment (€), Nrst is a number of rooms of the same type (-), Nl is a number of luminaires (-), Pl is a price per luminaire (€), MLl is a material and labor costs per luminaire (€), Cecd is cost of external control device (€).

$$\text{Annual energy} = \left[\text{Ep} \cdot (\text{Nrst} \cdot \text{Nl} \cdot \text{El} \cdot \text{TRFc} \cdot \text{ho})\right] / 1000$$

where Annual energy is an annual price of electricity (€), Ep is a price of electricity (€), El is a power of luminaries (W), TRFc is a total reduction factor for control (-), ho is an operation hour (hour).
At this point the Authors states that:

"Because of LCCA also provides information on the impact of a system on the environment, it is possible to calculate the overall impact of its operation. The value of this effect depends on the current composition of the energy sector producing electricity(...)" [3]

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(3) BELANY P. HRABOVSKY P. KOLKOVA Z. (2017).Combination of lighting retrofit and life cycle cost analysis for energy efficiency improvement in buildings, ENERGY REPORTS, p 8

Indeed,El, TRFc and ho can be used in the Climate Impact formulation as well:

$$\text{Climate Impact} = \sum \text{Energy Usage} \cdot \text{Cleu}$$

where Climate impact is related to the system (kg $\cdot CO_2$), Energy usage is the energy consumption of individual rooms (kWh), CIeu is a climate impact electricity usage (kg$\cdot CO_2 \cdot$kWh−1).

$$\text{Energy usage} = (\text{Nrst} \cdot \text{Nl} \cdot \text{El} \cdot \text{TRFc} \cdot \text{ho}) / 1000$$

Article 10 analyses both the economic and environmental perspective for a multi-family house in Sweden. The study reports the values of Life Cycle Costs (LCC), Primary Energy Consumption (PEC), CO_2 emissions and Non-Renewable Energy consumption for three renovation levels associated to five system combinations (0 is the reference scenario). The outcomes are showed in the figure below.

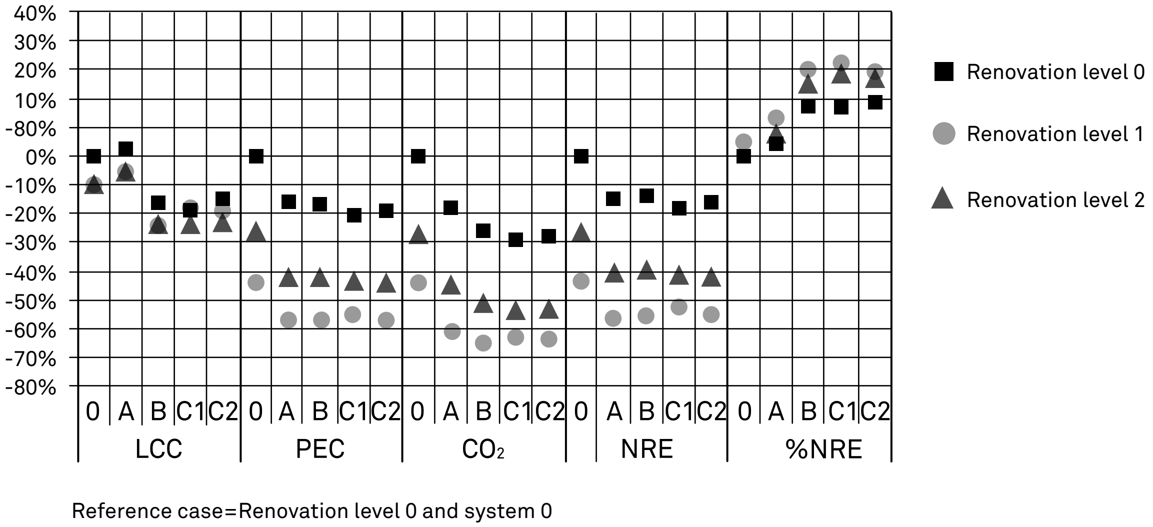

Figure 10. Life cycle cost, primary energy consumption, CO_2 emissions and absolute and relative non-renewable energy consumption of all studies cases. Source: Author re-elaboration from: GUASTAFFON M.(2015). *Techno-economic analysis of energy renovation measures for a district heated multi-family house.* APPLIED ENERGY.

Articles from 11 to 17 analyse both the economic (LCCA) and environmental (LCA) perspectives. However, only some articles try to integrate the two analyses into a single outcome. The most interesting study is article 11 "Investigating eco-efficiency procedure to compare refurbishment scenarios with different insulating materials". The study performs an eco-efficiency methodology defined by ISO 14045: 2012, developed for the first time by chemical industry BASF in 2002. The methodology considers two different scores: an environmental one and an economic one. These scores are represented in a matrix where a "best option" zone can be located. The methodology can be used in comparing different scenarios, in order to define the best eco-efficient scenario between the analysed ones.

In this study six refurbishment scenarios are analysed. In LCA analysis 16 International System Life Cycle Data (ILCD) midpoint environmental impact indicators are considered; in order to produce data for eco-efficiency analysis, environmental results are aggregated into a single score ILCD midpoint indicator.
Then, a Whole Life Cycle Costing analysis is performed which considers the life cycle costing of the building life cycle, as well as the externalities, the non-construction costs, and the income. However, the externalities taken into account are vacancy rate and unpaid rent rate and no environmental cost is computed. The economic indicator used in this analysis is the NPV and the discounted payback period.
The outcomes integration occurs through four steps:
1. eco-efficiency matrix with scores in percentage;
2. eco-efficiency ratio NPC(€) / EP(mPt);
3. eco-efficiency sensitivity analysis;
4. eco-efficiency ratio for each variable.
About the first step, it is not clear the transformation of the outcomes in percentage.
Step 1 and 2 are reported below. In step 2 are considered only two refurbishment solutions.

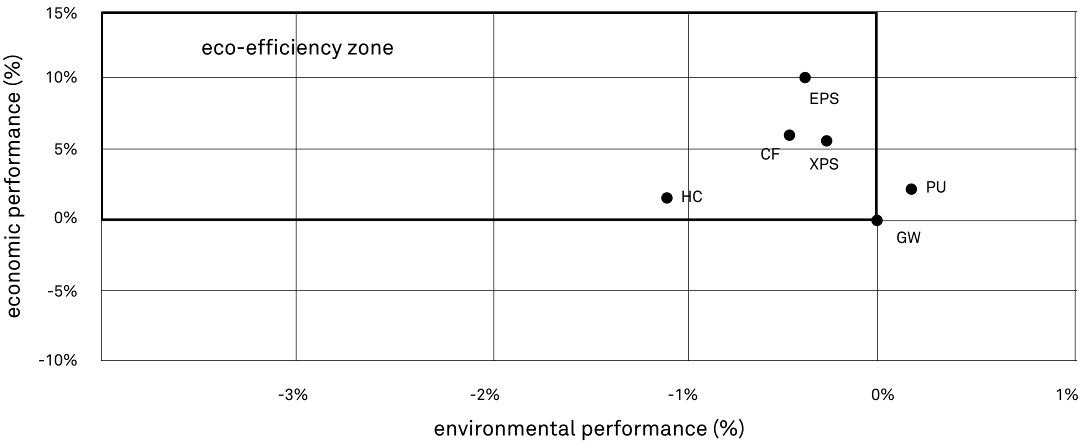

Figure 11.Eco-efficiency matrix for different insulating material scenarios of refurbish.ment
Source: Author re-elaboration from:
COLLI C. BATAILLE A. ANTCZAK E. Investigating eco-efficiency procedure to compare refurbishment scenarios with different insulating materials. PROCEDIA CIRP

Insulating materials	NPC (€)	EP (mPt)	Ratio (€/mPt)
CF	119308	1059,06	112,65
EPS	118590	1060,22	111,85

Figure 12.Eco-efficiency ratio results for the EPS and CF. Source: Author re-elaboration from:
COLLI C. BATAILLE A. ANTCZAK E. Investigating eco-efficiency procedure to compare refurbishment scenarios with different insulating materials. PROCEDIA CIRP

Article 17 applies the eco-efficiency matrix as well. Twelve renovation solution are associated to three occupancy levels and three different indoor temperature conditions. The twelve solutions are inserted in each of nine eco-efficiency matrix. Indeed, in this case the eco-efficiency matrix is not used to reach a single outcome but a better illustrative way to choose between alternative solutions.

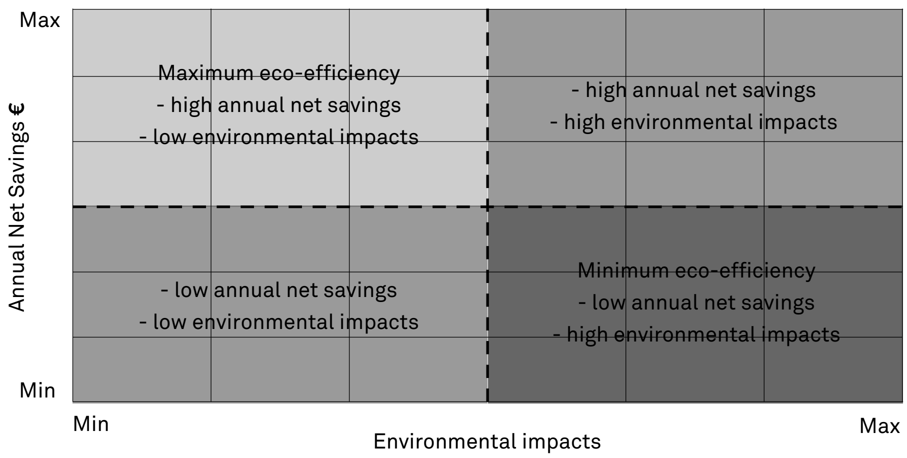

Figure 13. Eco-efficiency analysis. Source: Author re-elaboration from:
COLLI C. BATAILLE A. ANTCZAK E. Investigating eco-efficiency procedure to compare refurbishment scenarios with different insulating materials. PROCEDIA CIRP

The top left-side area contains the best solution and the maximum eco-efficiency level because it presents high Annual Net Savings and low environmental impacts. The economic indicator is per year because the LCCA is performed through the Equivalent Annual Cost (EAC) method.

Although is not an eco-efficiency matrix, Article 14 integrates LCCA and LCA indicators in the same graph as well. In this case the results of two environmental indicators (CED and GWP) are plotted against the NPC scenarios.

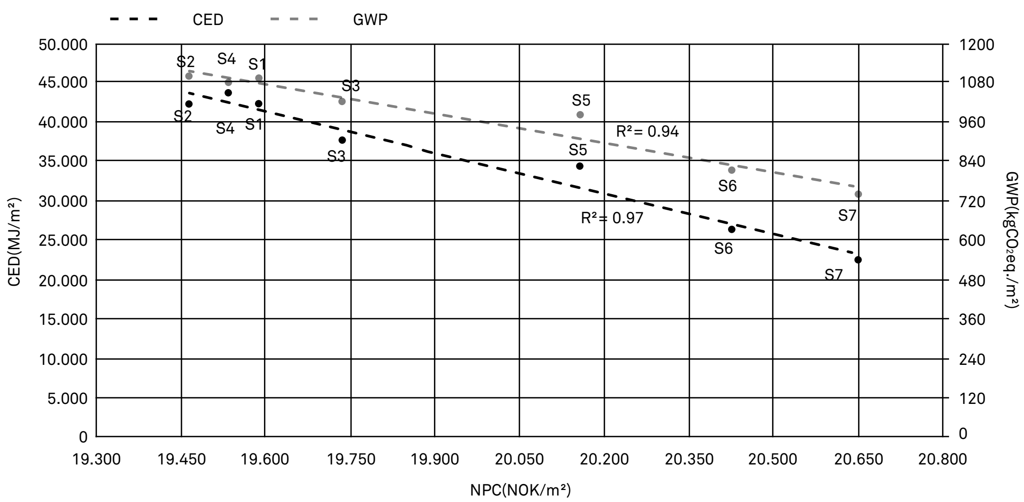

Figure 14. Global warming potential and cumulative energy demand results plotted against the net.
Source: Author re-elaboration from:
MOSCHETTI R. Combining Life Cycle Environmental and Economic Assessments in Building Energy Renovation Projects. ENERGIES

Figure 14 shows the GWP and CED trends. The economic and environmental impact have opposite trends; however, the graph shows that to a modest increase of NPC value correspond large reductions of GWP and CED values, due to the slight difference among NPC values.
In Article 12, "Statistical method to identify robust building renovation choices for environmental and economic performance", both LCA and LCCA are performed thorugh two equations run in parallel. The study does not report a single outcome but some parameters of the two analysis are performed together in a Global Sensitivity Analysis.
Finally, Article 13 reports the results of the Portuguese 3E-2C2 methodology, that performs the energy, economical and environmental analysis all along the building life-cycle, by also considering the dismantling cost of the reference scenario (cradle-to-cradle). However, the three analysis outcomes are presented in different graphs.

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Chapter 4

Literature selection

4.1
Introduction.
Research and selection process

selection by keywords

selection by 5 criteria:

1.Year of publication;

2. Geographical area of the analysis;

3. Application context;

4. Scientific disciplinary sector;

5. Type of publication.

Exclusion selection process:

- no access;
- optimization;
- cost-optimal analysis;
- cost-benefit analysis;
- extra EU Countries.

4.1
Classification of the selected articles

17 articles classified by:

- N° article;
- Title;
- Year of publication;
- Author;
- EU Country;
- Methodology;
- Building typology;
- Energy Efficiency Measures (EEMs).

4.2
Description of the selected articles

17 articles described by:

- Title;
- Author;
- Keywords (by the document);
- Content summary.

and

- N° article;
- Year of publication;
- EU Country;
- Methodology;
- Energy Efficiency Measures (EEMs);
- Building typology;
- Case study;
- Period of the analysis;
- Functional unit;
- System boundaries.

4.3
Analysis of the different methodological approaches in the selected literature

17 articles analysed by categories:

1.

year
+
methodological application;

2.

EU Country
+
methodological application;

3.

building typology
+
methodological application;

4.

EEMs
+
methodological application.

4.4
The environmental analysis in the selected literature

17 articles analysed according:

1.

indirect environmental impact considerations;

(if indirectly, how?)

2.

direct environmental impact considerations.

(if directly, how the economic results and the envirionmental results in a single outcome?)

Chapter 4 framework
Author elaboration

CONCLUSIONS

The objective of this study was the application of the Life Cycle Costing methodology through the selection of articles about the economic evaluation of green retrofit scenarios for the energy refurbishment of existent buildings. Although in the literature the term "green retrofitting" is not totally developed yet, some studies which integrate the environmental impact considerations to the economic evaluation of an energy refurbishment scenario can be found. By only considering articles in which the LCCA methodology is adopted, or in which the LCCA is correlated to environmental considerations, or in which both LCCA and LCA analysis are calculated, a limited number of manuscripts (17) was selected. However, each article presented a specific methodological application. This last aspect was the input to propose a new literature analysis method, that is to consider the application methodology as the base information to which link the other categories, that are the year of publication, the EU Country, the building typology and the Energy Efficiency Measures (EEMs). Moreover, the specificity of each study opened the way to many considerations starting from an environmental perspective.

First, the indirect considerations of the environmental impacts in the LCCA calculation through different ways, by starting from the premise that to make a building energetically efficient means to reduce its energy consumption and indirectly contribute to the cut of CO_2 emission from energy. The most interesting way is the adoption of a wide range of discount rate values in order to integrate societal factors in the calculation since the discount rate was found to have the hugest impact on the assessment of the energy-efficiency potential of the considered renovation solution. Another way to indirectly consider the environmental impact in the economic analysis is to consider pre identified sustainable technological solution in the alternative scenarios. Therefore, the costs considered in LCCA for the alternative scenario are already related to green retrofit solutions.

Secondly, how researchers tried to integrate the results from LCCA and LCA calculations into a single outcome, for instance through the adoption of the eco-efficiency matrix.

Therefore this research thesis could support future researchers about the application of the LCC analysis even with the integration of the environmental analysis in monetary terms.