Buildings energy retrofit valuation approaches: state of the art and future perspectives

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Abstract

The European Directives 2010/31/EU and 2012/27/EU identified the buiding sector as a key sector to achieve the 20-20-20 targets (and those set for 2030 and 2050) and identified existing buildings energy retrofit as a fundamental driver to promote development and create opportunities for employment in this sector which is still affected by a severe economic crisis.

Buildings energy retrofit is a complex process involving a great number of decision variables and issues related not only to technical and technological aspects, but also to environmental, social and cultural aspects. This topic is widely debated in literature. There are several contributions on energy consumption modeling and evaluation as well as many authors addressed the impacts of retrofit strategies on CO_2 emission reduction. There exists also a conspicuous strand of literature on the methodologies to evaluate different retrofit strategies according to their economic, environmental and social effects (e.g., multi-criteria analysis, life cycle costing and assessment, econometric models, etc.). Nonetheless, there is a lack of contributions that provide a systematic literature review and a classification of most relevant papers on the most innovative and multidisciplinary valuation approaches.

This paper presents a systematic literature review, and aims to define the state of the art on valuation approaches of existing buildings energy retrofit. According to a dynamic systematic review protocol, we identified the most relevant contributions and we provide a synoptic table, which summarizes methodological and descriptive aspects and allows for identifying potential gaps in the literature and future developments.

1. INTRODUCTION

The European Council of March 2007 identified energy efficiency as a key factor in the global strategy to reduce the impacts of climate change, and emphasized the need to increase energy efficiency in order to achieve the objective of reducing by 20% the European Union's energy consumption by 2020 (COM, 2008). Subsequently, in 2014 The European Commission set new EU-wide targets and policy objectives on pollutant emissions reduction for the period between 2020 and 2030 (2030 Framework for climate and energy). These objectives include: a 40% cut in greenhouse gas emissions compared to 1990 levels; at least a 27% share of renewable energy consumption; and at least 27% energy savings compared with the business-as-usual scenario.

As buildings accounts for 40% of total energy consumption in the European Union and 36% of CO_2 emissions (BPIE, 2015), they play a crucial role in the achievement of the above objectives.

According to the Building Stock Observatory of the European Commission, the European building stock accounts for 250 million residential properties (65% of which are single- family houses and the remaining 35% is represented by apartments): more than 40% of the existing assets were built before 1960, whereas 90% of the total stock was built before 1990, prior to the entry into force of the 2002/91/EU Directive on the energy performance of buildings.

The Italian Real Estate is the oldest in Europe and exhibit an energy demand, which amounts to 36% of overall national demand (about 133 Mtoe). 70% of existing buildings was built before 1970 (prior to the entry into force of laws and norms on energy efficiency of buildings) and 25% of the stock has never underwent maintenance or renovation. According to the 2017 annual report on energy efficiency published by the National Agency on new technologies, energy and sustainable development (ENEA), primary energy consumption recorded in 2015 in Italy was of about 156.2 Mtoe and demand/consumption in the residential sector was of about 32.5 Mtoe, registering a 10% increase in demand with respect to 2014.

The European and national policies on energy efficiency which were implemented after the entry into force of both the Directive 2010/31/EU, better known as Energy Performance of Buildings Directive - Recast (EPBD), and the Directive 2012/27/EU, better known as Energy Efficiency directive (EED), boosted energy retrofitting of existing buildings and recognized such retrofit interventions as key drivers to promote development and create job opportunities in the building sector which is slowly recovering from the severe global economic crisis started in 2007. Italy is expected to save on primary energy a minimum quota of 25.8 Mtoe in the period 2014-2020 (ENEA, 2017).

Nonetheless, existing buildings energy retrofit is a complex process involving a great number of decision variables and issues related not only to technical and technological aspects, but also to environmental, social and cultural aspects (Roberts, 2008). The topic is largely debated in literature. There are several contributions on energy consumption modeling and evaluation as well as many authors addressed the impacts of retrofit strategies on CO_2 emission reduction. There exists also a conspicuous strand of literature on the methodologies to evaluate different retrofit strategies according to their economic, environmental and social effects (e.g., multi-criteria analysis, life cycle costing and assessment, econometric models, etc.). Nonetheless, there is a lack of contributions that provide a systematic literature review and a classification of most relevant papers on the most innovative and multidisciplinary valuation approaches. In this respect, Martínez-Molina *et al.*, (2016) provided a literature review on technical issues related to improvement of energy efficiency and comfort for final users of historical buildings; Webb (2017) reviewed criteria, methods, and decision making processes used to assess energy retrofits in historic and traditional buildings; Šćepanović *et al.*, (2017) presented an overview and categorization of all major types of interventions in the residential sector and analyzed their effectiveness in specific contexts; Soares *et al.*, (2017) outlined the state of the art on strategies to improve energy and environmental performance of buildings; Doan *et al.*, (2017) provided a systematic review of the development of green rating systems, by analyzing BREEAM, LEED, CASBEE and Green Star NZ; Kivimaa and Matiskainen (2018) carried out a systematic review of case studies on low energy innovations in the European residential building sector and analyzed their drivers (e.g., design, environmental and social sustainability; political and financial drivers, etc.); Pomponi and Moncaster (2016) proposed a systematic literature review on strategies to tackle embodied carbon in built environment.

Aim of this paper is to implement a systematic review based on Scopus database to provide a state of the art literature on valuation approaches of buildings energy retrofit. By implementing a dynamic protocol of systematic review, we firstly identify relevant keywords. Secondly, we perform preliminary statistical analysis (meta-analysis), we examine for each relevant keywords, major contributions or most cited papers and we provide synoptic table, which summarizes methodological and descriptive aspects, and allows for identifying potential gaps in the literature and future developments.

The reminder of the paper is organized as follows. In Section 2, we illustrate the systematic review process, present and discuss meta-analyses, and provide a synoptic table, which summarizes major contributions on Life Cycle Cost (LCC) approaches to the valuation of buildings energy retrofit. In Section 3 we discuss results and identify potential gaps in the literature. Section 4 concludes.

2. SYSTEMATIC REVIEW

In this section, we propose a systematic literature review (Fink, 2005) which aims at updating the state of the art literature and present a reference theoretical-methodological framework to valuate optimal retrofit strategies of existing buildings and identify evidence and experiences that can be useful in providing guidelines.

According to the systematic review protocol proposed by Brown (2007), starting from a specific research question, in a systematic review relevant literature is identified, selected and discussed; in addition results illustrated and discussed in the selected contributions are analyzed following a three-stage procedure: planning, conducting and reporting the review.

In the first stage, we verified the novelty of the research question and carried out literature scoping and mapping to survey existing literature on valuation approaches, potential overlapping and future developments. In addition we defined a "dynamic protocol" that allows for a flexible approach during the review process by introducing in-itinere changes on research criteria and parameters as well as on research setting, to optimize review and increase its flexibility and objectivity.

In the second stage (conducting of the review), we conducted the systematic review by forming firstly a group of experts who provided feedbacks on the process optimization. In the following phase we: *a)* identified relevant keywords and search strings; *b)* constructed and developed dynamically selection criteria to fine-tuning the research according to a sequential approach; *c)* assessed selected contributions quality and excluded those which were not considered as relevant. We then constructed a database in which we catalogued and classified contributions further investigated by title, author/s, publication date, source, main motivation for inclusion in the database.

In the third stage (reporting of the review) we provided thematic and descriptive analyses, discussed results to update the state of the art and outline study limitation and gaps in the literature.

2.1 Systematic search

The systematic search here illustrated focuses on valuation approaches of investments in buildings energy retrofit.

Improvement of buildings energy performances is a complex process which requires theoretical advances and innovative research on design and building practice, use of non-conventional construction materials, implementation of innovative and cost-effective regulatory policy and mechanisms (e.g. standard setting and enforcement), interaction with renewables and increased awareness by designers, practitioners and final users (Soares *et al.,* 2017).

Reduction in both energy consumption and environmental impacts of built environment represent globally a challenge, which calls for in-depth knowledge of key drivers of energy needs and demand. In the specific, retrofitting is usually and heterogeneous and articulated process which requires several different expertise and specializations to be integrated in dynamic contexts, often affected by great uncertainties. The analysis and evaluation of existing buildings energy retrofit are therefore arduous tasks because buildings are complex systems in which technical, technological, social, environmental and aesthetic aspects are closely interconnected and each sub-system influences the overall energy performance and consequently plays a fundamental role (Kaklauskas *et al.,* 2005; Antoniucci *et al.,* 2015). In this respect, Ma *et al.,* (2012) identified six key factors on which the success of retrofit program depends: policies and regulations, client resources and expectations, retrofit technologies, building specific information, human factors and uncertainty. Investment decisions in energy retrofitting of buildings require to be analyzed according to different perspectives: we cannot prescind from technical, economic, environmental and social factors analysis but at the same time, we have to take into consideration end users' cultural view and behavior.

Findings of the preliminary literature review show that there are several valuation methods and methodologies of buildings energy retrofit, which have been investigated in literature and they can be classified into single-criteria approaches, such as economic evaluations based on LCC and Net Present Value (NPV) rule (Verbeeck e Hens, 2005; Kaynakli, 2012; Ma *et al.,* 2012; Fumo, 2014; Krarti e Dubei, 2018), and multiple-criteria or multiple-objective approaches (Soares *et al.,* 2017; Webb, 2017). In detail, from a preliminary literature review it emerged that there are a number of models and methods to assess conditions and support investment decisions in building retrofit. These models can be grouped into two main categories (Soares *et al.,* 2017): models in which alternative solutions are known "a priori" (Jaggs e Palmer, 2000; Flourentzou e Roulet, 2002; Rey, 2004), and models in which alternative solutions are defined by optimization modeling (Diakaki *et al.,* 2008; Diakaki *et al.,* 2010; Krarti e Bichioua, 2011; Asadi *et al.,* 2012; Petersen e Svedsen, 2012; Wu *et al.,* 2017), where genetic algorithms are often implemented to optimize the decision process (Eisenhower *et al.,* 2011; Shao *et al.,* 2014; Delgam et al.,2016; Motuzien *et al.,* 2016; Nowak *et al.,* 2016; Si *et al.,* 2016; Lu *et al.,* 2017; Pal *et al.,* 2017; Wu *et al.,* 2017; Jafari e Valentin, 2018). Among multiple criteria approaches, the Analytic Hierarchy Process (AHP), proposed by Saaty in the Eighties (Saaty, 1980), is one of the most frequently adopted (Mohsen e Akash, 1997; Alanne, 2004; Lizana *et al.,* 2016; Si *et al.,* 2016; Roberti *et al.,* 2017; Re Cecconi *et al.,* 2017; D'Alpaos e Bragolusi, 2018). There exists indeed a lack in literature of contributions focusing on the marginal value and the willingness to pay for energy efficiency and performance improvements in buildings (Banfi *et al.,* 2008; Kwak *et al.,* 2010; Farsi, 2010; Michelsen e Madlener, 2012; Phillips, 2012; Achtnicht e Madlener, 2014; Syahid e Zaki, 2016; Carrol *et al.,* 2016; Prete *et al.,* 2017). It is exiguous, as well, the strand of literature on the analysis and valuation of indirect and/or not-market benefits generated by improvements in buildings energy efficiency, such as increase in occupants' comfort (Wu *et al.,* 2017; Galassi e Madlener, 2017), increase in market value of retrofitted buildings (Jakob, 2006; Marmolejo-Duarte e Bravi, 2017), improvement in buildings aesthetics (Vanstockem *et al.,* 2018) and CO_2 emissions reduction (Alberini *et al.,* 2018).

Once completed the above preliminary literature review, thanks to which we identified the general aspects more frequently analyzed and most commonly adopted valuation approaches (Table 1), we conducted a systematic literature review on Scopus database in order to identify the most relevant articles on efficiency and energy retrofit of buildings. We therefore filtered the database with respect to language (i.e., English), publication date (within the period 2000-2017), title, abstract and keywords and "*Engineering*", "*Energy*" and "*Environmental Science*" as subject areas.

By adopting a pyramidal search structure, we complemented primary keywords and search strings ("*valuation*" OR "*assessment*" OR "*assessments*" AND *"approach"* OR *"approaches"* AND *"building"* OR *"buildings"* AND *"energy"* AND *"efficiency"*) with additional keywords and search strings considered as relevant to the specific research field under investigation (*"economic"* AND *"technical"* *"social"* AND *"environmental"* AND *"policy"* AND *"uncertainty"* *"life cycle cost"* OR *"LCC"* AND *"cost"* OR *"costs"* AND *"Analytic Hierarchy Process"* OR *"AHP"* AND *"decision making"* AND *"tool"* OR *"tools"* AND *"willingness to pay"* OR *"WTP"*), which in turn emerged from the preliminary literature review (Table 2).

Table 1 - *General aspects and multidisciplinary approaches which emerged in the preliminary literature review*

GENERAL ASPECTS	Economic
	Environmental
	Technical
	Social
	Uncertainty
VALUATION APPROACHES	Life Cycle Cost (LCC)
	Economic analysis
	AHP
	Decision Making
	Discrete Choice

Table 2 - *Research question-RQ, keywords and search strings*

RQ: *Which are relevant valuation approaches with respect to buildings energy retrofit?*	
First level Key words and search strings	"valuation" OR "assessment" OR "assessments" AND "approach" OR "approaches" AND "building" OR "buildings" AND "energy" AND "efficiency"
Second level keywords and search strings	"economic" AND "technical" "social" AND "environmental" AND "policy" AND "uncertainty" "life cycle cost" OR "LCC" AND "cost" OR "costs" AND "Analytic Hierarchy Process" OR "AHP" AND "decision making" AND "tool" OR "tools" AND "willingness to pay" OR "WTP"

We then limited our search to journal articles and selected the most significant according to specific keywords and number of citations. In detail, we identified 882 documents in the SCOPUS database, which we limited to 682 by introducing filters relative to year of publication within the period January 2010 (when the EPD entered into force) and December 2017.

In a subsequent phase, on the one hand, we included in our selection other contributions, which had been cited in most cited documents or were considered significant with respect to second level keywords and search strings, and on the other hand, we excluded from our database those articles, which we considered as not relevant after reading abstract or full text.

2.2 Meta-Analysis

To structure the review we performed meta-analyses that have shown a growing interest for the evaluation and assessment of buildings energy retrofit (Figure 1). Starting from 2010, when the Energy Performance of Buildings Directive recast entered into force, there is evidence of an increase in the number of documents, which in turn was followed by a further increase in 2012, when the Energy Efficiency Directive (EED) entered into force. This trend confirm the robustness of our hypothesis relative to filtering searched documents by publication date, comprised within the time-period January 2010-December 2017.

According to our meta-analyses, it can be easily shown that, the most relevant subject areas are Engineering (64.4%), Energy (47.9%) and Environmental Sciences (39.0%). This reveals that published articles are interdisciplinary and multi-sector (Figure 2).

It is worth noting the Country of origin of such contributions (Figure 3), according to which we can conclude that in the United States the issue of buildings energy retrofit is in-depth investigated due to both the large number of real estate assets and the growing

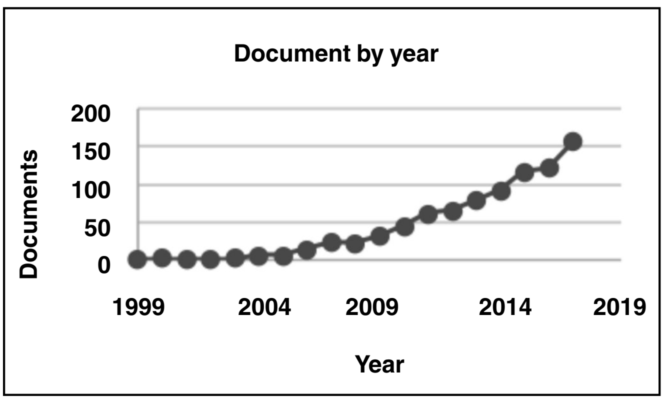

Figure 1 - *Documents by year (Our Processing)*

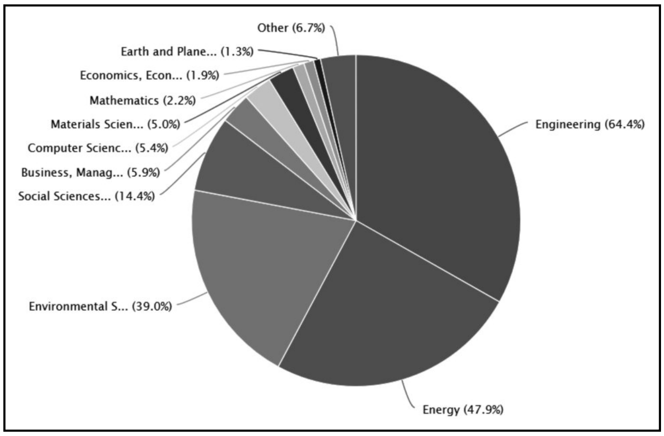

Figure 2 - *Documents by area (Source: Scopus)*

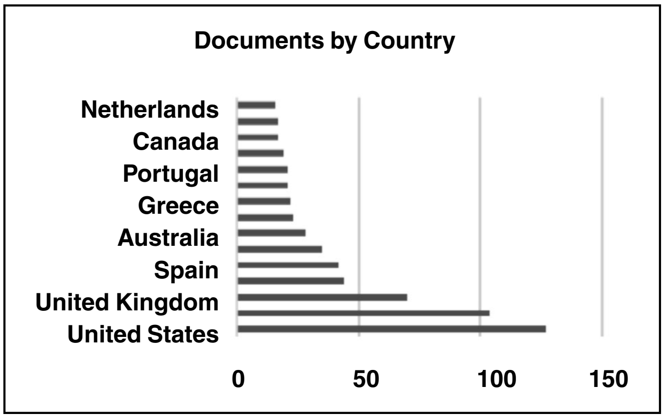

Figure 3 - *Documents by Country (Our Processing)*

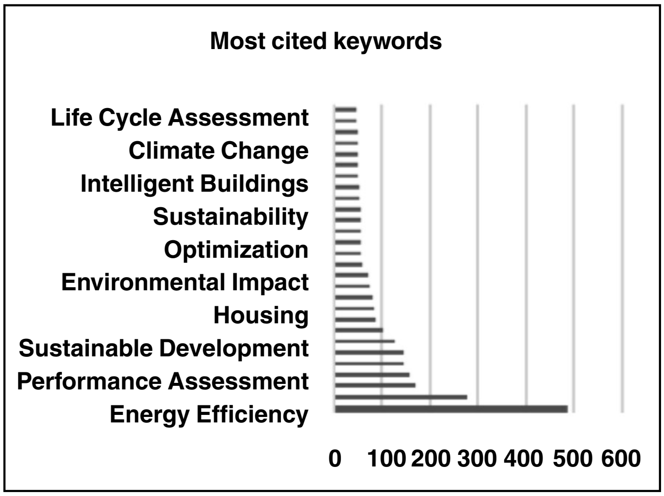

Figure 4 - *Most cited keywords (Our Processing)*

awareness and consciousness on climate change effects of greenhouse gas emissions. Italy is second in the ranking by number of publications. This confirms that in Italy the issue of buildings energy retrofit is of paramount importance. The Italian real estate, in fact, is among the oldest and one of the least energy-efficient in Europe: 49% of the stock was built more than fifty years ago (76% of the whole stock was built before 1981) and 90% exhibits an excessive energy demand (ISTAT, 2012).

Keywords analysis (Figure 4) reveals that among second-level keywords more closely related to economic valuation of buildings energy efficiency and retrofit, the more frequently cited are "Life Cycle", "Costs" and "Energy Performance". This makes it evident the cross reference to the Life Cycle Cost methodology, which turned out to be the most frequently investigated and adopted approach in the economic evaluation of buildings energy retrofit strategies. By direct inspection of Figure 1 and Figure 3, it emerges that the entry into force of EPBD and EED favored the focusing on LCC of a large quota of the academic community. Indeed EPBD and EED introduced the concept of optimal energy performance level and of cost-optimal solution. Article 5 of EPBD established in fact that Member States calculate cost-optimal levels of minimum energy performance requirements, by using the comparative methodology framework established in accordance with Annex III and relevant parameters (e.g., climatic conditions and the practical accessibility of energy infrastructure), and subsequently they compare the results of this calculation with the minimum energy performance requirements in force.

In detail, the comparative methodology framework requires Member States to calculate the NPV of energy efficiency measures according to the LCC approach. In addition the above mentioned Directives make explicit reference to the possibility for Member States of introducing incentive schemes to boost investments in buildings energy performance improvements.

2.3 Life Cycle Cost

In accordance to the results of our meta-analyses and in the light of the above considerations on the effects of the EBPD and EED implementation, we decided to further investigate and focus our systematic review on articles in which the LCC approach had been adopted (127 documents).

Among the contribution identified according to a systematic search based on the so called PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) guidelines (Liberati *et al.*, 2015), and taking into consideration either the most cited contributions or those explicitly adopting LCC as valuation method, we selected for reporting 18 articles, whose findings and results are summarized in Table 3.

The above 18 core articles were selected according to the number of citations and the following keywords "Lyfe Cycle Cost" or "LCC" and "Costs". They consider different construction typology and use, different climatic zones

Table 3 - *Synopytic table of core articles on LCC*

Reference	Building type	Retrofit measures	Method	Major results
Kneifel, 2010	Commercial buildings	HVAC system (heating, ventilation and air conditioning), different types of thermal insulation of the building envelope; low-emissivity windows, LEC (low Energy Case) design.	LCC method	The proposed measures allow for reducing energy consumption by 20-30%; LEC system is profitable; carbon emissions will decrease by 32% in 10 years
Hamdy *et al.*, 2013	Single-family house (two-storey house) in cold climate (Finland)	Different types and thickness of wall, roof, and floor insulation; two window types; four shading options; three heat recovery units; two cooling options; four heating systems; on-site solar systems of different size	LCC method by three-stage optimization	The ranking of cost-optimal measures depends on installed heating/cooling systems and the escalation rate of energy prices. Photovoltaic (PV) sizes up to 20 sq m are preferable cost-optimal options for houses with electrical demand; mechanical cooling is not a cost-optimal option due to investment and operating costs; economic feasibility of mechanical cooling becomes close to optimal when integrated with PV systems; achievement of NZEB targets is feasible with primary energy consumption up to 70 kWh/m^2a; incentives are required to boost investments towards NZEB; solar-thermal system is not a cost-optimal solution
Risanek and Choudhary, 2013	5-storey office building	Thermal insulation of roof and facade; upgraded external glazing; condensing boilers; improved lighting control; thermostatic electronic radiator valves	LCC and NPV (net present value), optimization algorithms and sensitivity analysis	Analysis of economic and technical uncertainty of data and parameters; economic uncertainty affect results much more than technical uncertainty; demand-side measure are most cost-effective and offer greenhouse gas (GHG) mitigation potential of about 10-40%; demand-side measure with a condensing boiler and a mini CHP system are the most cost-effective solutions to maximize GHG emissions reduction
Ferrara *et al.*, 2014	Two-story high-performance single-family house	Different insulation thickness of building envelope; low-emissivity windows; mechanical ventilation unit with heat recovery, air-to-air reversible cycle heat pump; cooling fans; gas condensing boiler; wood-pellet boiler; electric radiators	LCC method and Particle Swarm Optimization Algorithm	The light wooden envelope is the best choice in reaching good energy performances at limited costs; the pellet boiler is the best solution in terms of costs; high-performing all-in one system allows to reach better performances with a little cost increase; cost-optimal design options are related to low-performance envelope systems

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Corrado *et al.*, 2014	Apartment block	Wall insulation; upper and lower floor insulation; low-emittance windows; solar shading devices; thermal solar system; PV system	LCC method and sequential search technique	The cost-optimal level obtained involves a primary energy consumption for cooling, heating and hot water production equal to 115 kWh/m^2 and the related LCC is equal to 676 €/m^2
Pikas *et al.*, 2014	Generic single office floor model divided into 5 zones	Different building envelope insulation thicknesses; different low-emittance window/glazing type and size; different PV size, district heating with radiators; air-cooled chiller and balanced heat recovery ventilation with chilled beams	LCC and NPV method	Due to Estonia cold climate, cost-optimal measures result considering smaller window to wall ratio, triple glazing and argon filling and 200 mm thick insulation of walls; the cost-optimal level of the building provides for an energy consumption lower than 130 kWh/m^2
De Angelis et al. 2014	Social housing apartments block building	Walls insulation technologies; roof and floor insulation; window or glass replacement; condensing heat generator; thermostatic valve;, heat pumps; PV panels	LCC method	Net of heating systems costs, costs of renovation are in the range of 160-210 €/m2 and the related energy saving is of about 70% and 80% for the B and A energy rating respectively; by considering also heating systems, heat pumps are the best cost-optimal measures; tax incentives are fundamental in reducing investment payback time
Tadeu *et al.*, 2015	Historic five-story building	Thermal insulation options roof, exterior walls and floor; different low-emittance window solutions; alternative heating and domestic hot water (DHW) systems	LCC method	The maximum cost-optimal thickness of thermal insulation is 140 mm and the use of high insulation levels is not cost-effective; there is a correlation between the discount rate and energy price in offsetting investment costs; high discount rates and low energy prices do not favor investments in retrofit measures with low primary energy consumption; climatic zone affects the ranking of cost-optimal measures
Krarti and Ihm, 2016	Single-family residential building	Building orientation; different exterior wall and roof insulation thickness; different window-to-wall ratio and glazing; alternative air leakage levels; cooling temperature setting; refrigerator energy efficiency level setting, different types of boiler; different cooling systems; PV systems	LCC and optimization techniques (genetic algorithm, particle swarm technique)	Optimal annual energy use savings range between 35% and 55% and allow for LCC minimization; ranking of cost-optimal measures varies depending on climate zone; compared to minimum energy requirements, cost-optimal measures provide 30% energy savings; in order to maximize energy savings initial investment costs increase by 42%; energy-efficient lighting systems and refrigerators and high cooling set-points are cost-effective measures

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de Vasconcelos *et al.*, 2016	7-storey apartment	Different thermal insulation thicknesses; ventilated façade; application of drywall; windows substitution	LCC method	The best cost-effective measure is roof insulation; the thickness of thermal insulation strongly influences primary energy consumption; insulation of internal walls provide better results than external walls insulation
Mangan and Oral, 2016	16-storey residential building	Thermal insulation of external walls; green roof; low-emittance windows	LCC, LCA (Life Cycle Analysis) and $LCCO_2$ (cost of CO_2 emissions)	Climate zones affect the ranking of cost-optimal energy retrofit measures; the paper reports for each climatic zone the optimal solutions for the design of the insulating elements and relative technical characteristics. Results of LCE, $LCCO_2$ and LCC analyses indicate differences dependent on energy efficient improvement measures and climate zones
Barthelmes *et al.*, 2016	*CorTau* House (a building that reaches the NZEB target)	HVAC systems (Heating, Ventilation and Air Conditioning); interventions on the building envelope; thermal insulation of walls and roof; low-emittance doors and windows	LCC method	Investments to achieve NZEB targets are profitable; over the years, the high initial investment costs are offset by benefits due to reduced energy consumption that, in turn, reduces energy costs. The cost-optimal measure provides an annual energy consumption of <20.25 kWh/m^2a.
Copiello *et al.*, 2017	Public housing residential building	Thermal insulation of walls and roof; low-emittance windows; ventilation systems	LCC and Monte Carlo simulations	Uncertainty on discount rate affects LCC results much more than uncertainty on energy prices (i.e., four times as much as energy prices); cost-optimal measures vary according to macroeconomic parameters and discount rate
Jones *et al.*, 2017	5 dwellings houses in Galles	External wall insulation; loft insulation; low-e double glazing; LED lighting; gable cavity wall insulation; gas boiler and hot water tank; PV systems; positive pressure ventilation supply from loft space	LCC method	CO_2 reduction of 50-75%; cost savings of £402 to £621 per year, 56% reduction in energy consumption used for heating and 84% for electricity
Zangheri *et al.*, 2017	Single-family house; apartment block; office building; school	Building envelope, space heating; domestic hot water system; ventilation systems; cooling system; solar systems; lighting	LCC method and preliminary search-optimization techniques	Cost-optimal measures provide for a reduction in primary energy use that varies between 36-88%; for buildings that achieve NZEB targets, global costs are lower than in minimum energy requirements refurbishment

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Di Giuseppe *et al.*, 2017a	Single-family detached house	High performance envelopes; reversible high efficient heat pumps and/or condensing boiler for heating and hot water; PV panels and solar collectors; high performance distribution; emission and control systems for heating; Mechanical Extraction Ventilation (MEV) systems	LCC method and Monte Carlo simulation	With regard to buildings that reach the NZEB target, initial investment costs are predominant, over operating and maintenance costs; super-insulating envelope materials increases significantly investment costs; scenarios involving more efficient measures result in higher uncertainty on global costs; for NZEBs the payback time is greater than 30 years
Fregonara *et al.*, 2017	Two-storey family residential building	External thermal insulation of opaque walls; low-emittance highly insulating windows; decentralized controlled mechanical ventilation units; dual-flow with heat recovery system; solar panels; PV panels	LCC method	Retrofit measures allow for achieving A class energy rating; retrofit interventions on the building envelope are the most cost-effective compared to others (no maintenance costs and no performance level decrease over time)
Bottero *et al.*, 2018	*CorTau* House, (a building that reaches the NZEB target)	HVAC systems (heating, ventilation and air conditioning); interventions on the building envelope; thermal insulation of walls and roof; low-emittance doors and windows	LCC method and NPV	Investments to achieve NZEB targets are profitable compared to minimum energy requirements with no incentive schemes; when NZEBs are concerned incentives are over-estimated and favor free-riding opportunistic behavior

and strategies of intervention. Veerbeck and Hens (2010) presented the results of an analysis of the life cycle inventory of four typical Belgian residential buildings and demonstrated that the embodied energy of a building is marginal compared to energy consumption during usage phase. This result holds if we compare embodied energy of energy retrofit measures with the energy consumption reduction they generate. According to our review of the literature (Tadeu *et al.*, 2015; Mangan e Oral, 2016; Krarti e Ihm, 2016), the climatic zone is a key factor in identifying cost-optimal solutions in different locations, as the annual trend in temperature, is closely related to energy consumption of a building. The main retrofit interventions investigated in literature (Kneifel, 2010; Corrado *et al.*, 2014; Ferrara *et al.*, 2014; Pikas *et al.*, 2014; Tadeu *et al.*, 2015; Dilara Mangan and Koclar Oral, 2016; Krarti and Ihm, 2016; de Vasconcelos *et al.*, 2016; Di Giuseppe *et al.*, 2017a; Fregonara *et al.*, 2017; Jones *et al.*, 2017; Zangheri *et al.*, 2017;) concern building envelope and insulation thickness of walls, roofs and floors, as well as installation of low-emittance windows. This strategy of intervention (Fregonara *et al.*, 2017) allows for (almost completely) reducing maintenance costs and maintaining energy performance over time, thus reducing energy consumption. De Angelis et al. (2014) emphasized the importance of properly design thermic insulation, whose optimal thickness is determined by parametric analyses in order to avoid the construction of excessively large and cost-effective insulation. Krarti e Him (2016) showed that in climatic zones in which day-time temperatures are high, it is sufficient to design a small insulation thickness, and thus favor heat exchange at night. From the analysis of literature, it emerged that there is an increasing research interest in identifying cost-optimal solutions for Nearly Zero Energy Buildings (NZEBs). In this respect, Zangheri *et al*. (2017) applied a cost-optimal calculation method for identifying proper retrofit measures to reach cost-optimal and NZEB levels in various types of residential buildings built between the Sixties and the Seventies in representative European climatic conditions, and they demonstrated that in many cases the obtained NZEB refurbishments proved to be profitable when incentive schemes had been implemented. Hamdy *et al*. (2017) and Di Giuseppe *et al*. (2017a) confirmed results by Zangheri *et al*. (2017) and showed that investment costs to achieve NZEB energy performance levels are extremely high and the payback is greater than 30 years for single-family houses, therefore in order to undertake investments incentive schemes are required. Whereas, Barthelmes *et al*. (2016) analyzed various alternative scenarios of refurbishment and energy retrofitting of a single-family house, located in Piedmont Region in Italy, and showed that retrofit interventions towards NZEB targets are profitable and incentives are not required to undertake investments, due to high integration of renewable energy sources in the project. In line with the above findings, Bottero et al. (2018) outlined that additional investments required with respect to the baseline scenario (i.e., minimum energy performance requirements) are profitable per se (i.e., without incentive payments). Incentive schemes are therefore not key factors in boosting investments as NZEB solutions are positive NPV investments due to significant energy and cost savings and incentives may in turn favor free riding. The issue of uncertainty is largely debated in literature as well: uncertainty affects return on investment, energy prices, energy demand and investment and maintenance costs. To tackle this issue Monte Carlo simulations and sensitivity analyses on probability distribution of stochastic variables are usually implemented (Risanek *et al.*, 2013; Di Giuseppe *et al.*, 2017; Copiello, 2017). In the specific, uncertainty over discount rates affects significantly (and much more than uncertainty over future energy prices) cost-optimal solutions based on LCC and investment decisions (Tadeu, 2015; Copiello, 2017).

3. DISCUSSION OF RESULTS AND FUTURE DEVELOPMENTS

As previously mentioned, there several contributions in literature on the analysis of alternative measures of buildings energy retrofit (Roberts, 2008) and related costs, whereas there are few studies on the evaluation of benefits generated by buildings efficiency and energy retrofit interventions. The comparative methodology framework for calculating cost-optimal levels of minimum energy performance requirements for buildings and building elements set by the Commission Delegated Regulation (EU) No 244/2012 supplementing EPBD, makes explicit reference to the calculation of global cost and LCC for the valuation of energy retrofit strategies. The valuation approach set by the commission Delegated Regulation is indeed focused on cost minimization and costs, in most of the cases, coincides with avoided costs due to energy savings and CO_2 emission reduction. According to the so-called cost-optimal method, it is the responsibility of Member States to identify reference buildings, which are representative of the local market, and compare alternative energy efficiency measures with respect to primary energy demand and costs (LCC) of these measures. Alternative solutions are then ranked according to their energy performance and not to interests and preferences of investors (building industry or end users).

Nonetheless, some investors may be less concerned with economic performance than environmental performances (Araújo *et al.*, 2016; Jafari e Valentin 2018; Alberini *et al.*, 2018). Benefits due to increased comfort and indoor air quality and better protection against external noise, may amount to the same order of magnitude as energy-related benefits (Jakob, 2006; Prete *et al.*, 2017; Galassi e Madlener, 2017). Investments in buildings energy retrofit may reduce environmental costs and increase environmental performance, by implementing solutions, which take into account both energy efficiency and cost optimality (Becchio *et al.*, 2015; Pikas *et al.*, 2014). Cost-effectiveness of such interventions should considered and it should be identified different performance levels and trade-offs between costs and direct, indirect, tangible and intangible benefits of retrofit solutions. The market value of an energy-efficient building may be greater than a low performing one and this price premium may exceed the present value of future energy saving costs (Achtnicht, 2011; Popescu *et al.*, 2012; Banfi *et al.*, 2008; Zalejska J.A., 2014; Bonifaci e Copiello, 2015). Nonetheless, information asymmetry may induce risk-adverse consumers to underestimate those benefits that arise from the adoption of energy efficiency measures (Farsi, 2010). From this, it descends the importance of introducing energy efficiency ratings to correct the "market lemon" problem (Akerlof, 1970) which can cause a market failure. Public consensus and acceptance are fundamental for successful implementation of both investments in buildings energy retrofit and innovation processes (van Rijnsoever *et al.*, 2015).

In a nutshell, from a preliminary literature review, it emerges that stakeholders may be willing to pay more for sustainable solutions due for example to intrinsic value, environmental awareness and (ego-driven vs. social-oriented) warm glow. Nonetheless, there is a lack of comparative methodologies, which accounts for individuals' willingness to pay in identifying cost-effective energy retrofit measures.

Stakeholders' preferences with respect to alternative energy efficiency solutions may, de facto, play a crucial role in their selection and effective implementation. This may contribute to fill the gap between scientific research and actual undertaking of investments.

4. CONCLUSIONS

In this paper, we provide a systematic literature review on valuation approaches to buildings energy efficiency and retrofit strategies.

The preliminary review and meta-analyses, showed that there is a number of valuation and decision support models and methods applied in buildings energy retrofit, but the most frequently used is economic valuation is LCC. According to our analysis, the entry into force of both EPBD and EED induced academics and practitioners to focus on LCC method. We then focused our review by selecting as core articles those referring to LCC. Our search produced 127 articles, which reduced by filtering to 18 core articles for reporting (i.e., data synthesis and analysis). The main findings of core articles were reported in a synoptic table and can be summarized as follows: 1) interventions on building envelope (insulation of external walls, roofs and floors, windows, etc.) are the most effective in increasing energy performance, nonetheless it requires proper design in order to be cost-optimal; 2) the ranking of cost-optimal energy efficiency measures is strongly dependent on climate zone, due to the close relation between temperature and energy consumption; 3) the achievement of NZEB targets involves high investment costs and in order to be profitable, generally, incentives are required; 4) uncertainty that affects decision variables (e.g., discount rate, investment and maintenance costs, energy prices, energy demand) is a key factor for successful identification of robust energy efficient solutions.

In addition, our meta-analyses reveal that there is a limited number in literature on the monetary valuation of direct, indirect, tangible and intangible benefits arising from buildings energy retrofit. Usually, alternative retrofit solutions are ranked according to energy performance, not to investors' interests and preferences. Investors may be more interested in comfort increase or improvement of environmental performance, rather than in economic performance. The price premium of a high-energy performance building may offset *de facto* the present value of energy cost savings. It emerges therefore a potential gap to be filled with respect to stakeholders' willingness to pay. Stakeholders may be willing to pay non-negligible amounts for sustainable solutions as they may account for intrinsic value, environmental awareness and warm glow, besides saving on energy costs.

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