Life Cycle Cost Analysis of Nearly-Zero Energy Buildings: An Introduction to the Methodologies

Hashem Amini Toosi, Jacopo Famiglietti, and Mario Motta

1 Introduction

The building sector is responsible for around 40% of the final energy use and has a 6.5% share of the world economy (Elkhayat et al., 2020). The necessity of reducing energy consumption in the building sector to achieve the Sustainable Development Goals (SDG) became a consensus and has been reflected in national and international programs these days. The economic dimension is also known as a critical aspect of the sustainability concept, where the nearly-zero energy buildings (nZEBs) can contribute significantly due to their high relevancy to the country's economic programs (Amini Toosi et al., 2020).

Therefore, nZEBs are considered promising solutions to improve the performance of the building sector, and they are basically defined as buildings with extremely high energy efficiency, and the very low amount of energy required should be provided to a significant extent by renewable energy, including energy generated on-site or nearby (The European Parliament, 2018; Huang et al., 2018).

In such a context, the recast Energy Performance of Buildings Directive (EPBD) requires all new buildings to reach the nZEB targets from 2021 and reach the cost-optimal level in Europe (The European Parliament and Council of the European Union, 2010; The European Commission, 2016; Pernetti et al., 2021). However, the economic feasibility of such requirements for the stakeholders is still a barrier to such transitions (Pernetti et al., 2021). Performing an economic performance analysis over a building's life cycle, called life cycle costing (LCC), is a recommended approach to verify and ensure the economic feasibility of nZEBs (Kolokotsa et al., 2009; Alsayed & Tayeh, 2019). LCC analysis can compare the

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costs of various investment options and make it feasible to find the most cost-effective, energy-efficient design options (Liu et al., 2018).

This chapter aims to review the current standards and frameworks for the life cycle costing of buildings. It discusses the different steps and requirements for performing an economic assessment of nZEBs with a life cycle approach. Therefore, several frameworks, including the relevant standards from the International Organization for Standardization (ISO) and *Comité Européen de Normalisation* (CEN), will be considered. A literature review of the published research works on the application of LCC methods will be elaborated. The chapter aims to clearly understand how an LCC study should be carried out for nZEBs and highlights the main methodological aspects. This study guides stakeholders to carry out a life cycle cost analysis of nZEBs concerning the relevant standards.

2 Life Cycle Costing in the Building Sector: Standards and Frameworks

The cost assessment of an n-ZEB over its life cycle is a crucial step for the feasibility evaluation of new buildings and the energy refurbishment of existing ones to achieve n-ZEB targets. It is usually performed along with the life cycle cost (LCC) analysis method (Bragolusi & D'Alpaos, 2022). Considering the cost-influence curve described by Griffith and Sidwell (Griffith & Sidwell, 1995) for building and construction projects, the LCC approach becomes even more critical and relevant. A cost-influence curve indicates that as the design process proceeds to the later phases, the cost of construction and intervention increases while the influence of design scenarios to reduce the overall life cycle costs declines (Fig. 1). Therefore,

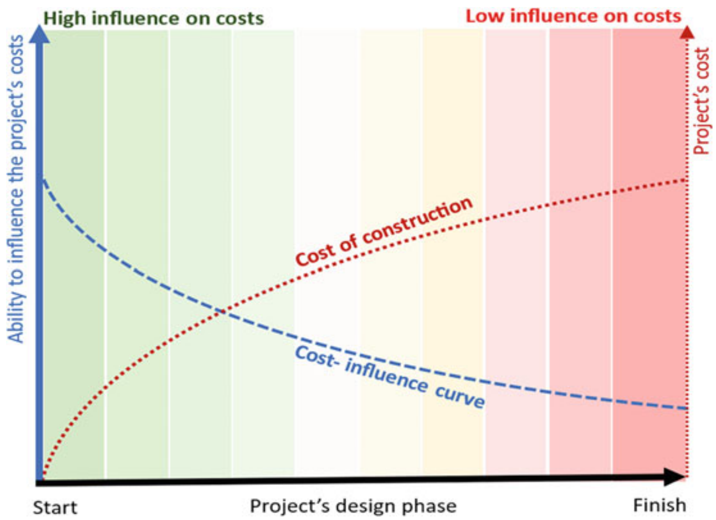

Fig. 1 The cost-influence curve in building design processes

this means the initial phases of design (i.e., conceptual design, schematic design, etc.) have the greatest influence on reducing the life cycle cost of buildings through planning and design strategies. After the completion of the design phase and the beginning of the construction phase, any change in the building's design will result in a higher cost and a lower potential for reducing them.

Such a concept as the correlation between design phases and the cost-saving potential in buildings highlights the necessity of conducting a comprehensive life cycle cost analysis during the initial stages of developing the design scenarios of buildings, although the initial phases of the design process contain a high uncertainty since the details of the design scenarios will be developed as the design steps proceed.

Furthermore, providing a commonly accepted standard for performing LCC in buildings is of paramount importance, by which the LCC methodologies and the results in different studies can be verified, replicated, and compared. Several frameworks and guidelines have been developed and published to standardize LCC in the building sector at national and international levels. Although most of the existing frameworks suggest similar procedures to carry out an LCC, there are minor variations that are worthy of investigation. This section briefly reviews the most important framework as the first step to introducing LCC methodologies in the building sector.

2.1 ISO Standards

ISO 15686-5: 2017 (2017) provides the guidelines for the life cycle cost analysis of new or existing buildings, constructed assets, and subcomponents. It also aims to standardize the relevant terminologies and elements of an LCC analysis. The main goal of the LCC, according to this standard, is for the life cycle cost of an asset (i.e., buildings, constructed assets of their subsystems) to be integrated into an evaluation and decision-making process, alongside other types of assessments, such as environmental and safety, functionality assessment, etc. According to ISO 15686-5: 2017, LCC analyses include a list of costs over a constructed asset's physical, technical, economic, or functional life within an agreed analysis period. However, a broader set of costs, including nonconstruction costs, externalities, and income, will be referred to as the whole life cost of the constructed asset (ISO 15686-5:2017, 2017).

ISO 15686-5: 2017 requires the maximum possible accuracy of the cost data, particularly emphasizing the most significant cost variables. Such cost data can be achieved through (a) direct estimation from known costs, (b) historical data analysis, (c) models based on expected performance, and (d) best guesses of future trends. The definition of the estimated service life and design life is delegated to ISO 15686-1 and ISO 15686-2. For those cases with a life span longer than 100 years, the standards suggest considering 100 years for the study. However, the definition of the service life is subject to the agreement and requirements of each project (ISO 15686-5:2017, 2017).

ISO 15686-5: 2017 employs net present value (NPV) and net present cost (NPC) as the LCC indicator for the analysis. It also introduces other indicators and techniques for measuring life cycle costs and whole life cycle costs, such as payback period (PP), net saving (NS), saving-to-investment ratio (SIR), (adjusted) internal rate of return (AIRR), annual cost, and annual equivalent value. As the discount rate is an essential factor in this method, this standard requires performing a sensitivity analysis using a range of rates to check the validity of the conclusion under various input conditions unless the rate is a fixed requirement. The main factors that have the most significant effect on uncertainties to be checked are the discount rate, the analysis period, and the assumption related to service life, maintenance, repair/replacement, and cost data. This standard indicates that a discount rate between 0% and 4% is usually used, and it highlights that selecting a higher discount rate discourages long-term investments (ISO 15686-5:2017, 2017).

2.2 CEN Standards

EN 15643–4:2012 (2012) provides a framework for assessing the economic performance of buildings as an integral part of the sustainability assessment of construction work. The main objectives of an economic evaluation in this framework are: (i) to identify the economic aspects and impacts of a building and its site and (ii) to enable the user and designer to make informed decisions toward building sustainability (EN 15643-4:2012, 2012).

This standard includes two types of indicators for economic performance in terms of the cost and financial value of the building over its life cycle. The framework provides a list of potential indicators that could be proposed as a basis for future standard development, although they are neither definitive nor completed yet (EN 15643-4:2012, 2012).

The standard requires defining the system boundary in the assessment in accordance with the scope of the evaluation. It also emphasizes the requirement of defining the functional equivalent of the study for the basis of the comparability of different assessments. According to this standard, the functional equivalent of the building or the subsystems should include but not be limited to information about the building type, the pattern of use, the relevant technical and functional requirements, and the required service life (EN 15643-4:2012, 2012).

This standard provides a list of different cost types and information required in each life cycle module (illustrated in Fig. 2), including the pre-constrcution, production, and construction phases (modules A0–A5); use stage (modules B1–B5); operational use stage (modules B6 and B7); end-of-life stage (modules C1-C); and beyond the system boundary (module D) (EN 15643-4:2012, 2012). Table 1 represents the list of cost data to be included in each life cycle module (EN 15643-4:2012, 2012).

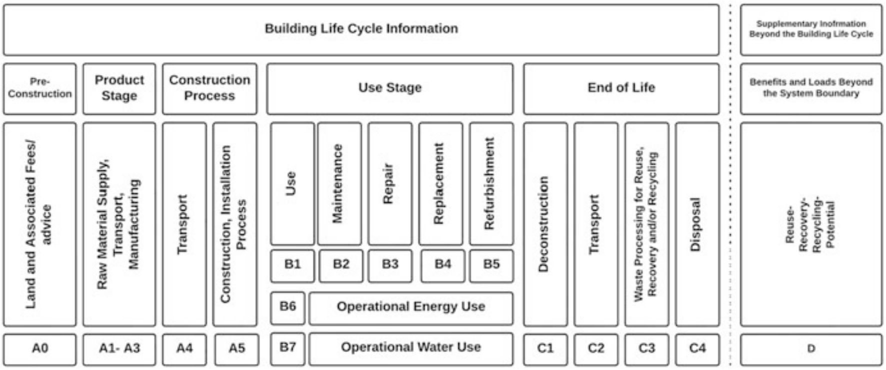

Fig. 2 Building life cycle modules and information. (Adopted from EN 16627)

This standard also demands specific data quality requirements, verification, transparency of the methods, and reporting and communication with external references.

EN 16627:2015 (2015) provides the calculation methods for assessing the economic performance of buildings with a life cycle approach. This standard describes two approaches to economic performance. The first approach is life cycle costing (LCC) for evaluating the costs over the life cycle, also considering the negative cost of energy exports, reuse, and the recycling of building components through the whole life cycle stages as a mandatory indicator. The second approach is the life cycle balance, which considers the first approach, in addition to the incomes over the whole life cycle stages, as an optional indicator (EN 16627:2015, 2015).

The standards provide guidelines for defining the system boundary of an LCC analysis for both new and existing buildings and the requirements for scenarios in which the required service life and study period of the LCC analysis do not match. It also provides a method for defining the number of necessary replacements for the building components.

EN 16627:2015 requires considering the building-related energy flows aligned with the Energy Performance Buildings Directive (EPBD) in the B6 module, including heating, domestic hot water supply, air conditioning, mechanical ventilation, artificial lighting, auxiliary energy used for pumps, control, and automation. This standard also demands considering the building-related energy data not covered in the EPBD (e.g., safety installation, etc.) in module B6 and reporting them separately. Also, in case non-building-related energy (i.e., computers, washing machines, etc.) are considered, their related results should be reported separately (EN 16627:2015, 2015).

To align with EPBD, EN 16627:2015 assumes that on-site energy generation should first be considered to satisfy the building-related energy demand and then non-building-related energy. The standards require not to deduct the exported energy from the required imported energy to operate the building but to report the income of

Table 1 The cost data in each life cycle module

Modules	Cost data to be included in each life cycle module
Modules A0, A1–A5	Costs directly related to the purchase or rental of the site
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	Costs incurred between factory and site
	Professional fees
	Temporary and enabling works
	Construction of asset
	Initial adaptation or fit out of asset
	Landscaping, external works on the curtilage
	Taxes and other costs related to permission to build
	Subsidies and incentives
Modules B1–B5	Building-related insurance costs
	Leases and rentals payable to third parties
	Cyclical regulatory costs
	Taxes
	Subsidies and incentives
	Revenue from the sale of assets or elements but not part of a final disposal
	Third-party income during operation
	Repairs and replacement of minor components/small areas
	Replacement or refurbishment of major systems and components
	Adaptation or subsequent fit out of asset
	Cleaning
	Ground maintenance
	Redecoration
	Disposal inspections at the end of the lease period (excluding end-of-life final disposal);
	End of lease
	Planned adaptation or planned refurbishment of assets in use
	Building-related facility management costs
Modules B6 and B7	Operational energy costs (as defined by EPBD-related standards)
	Operational water costs
	Taxes
	Subsidies and incentives
Modules C1–C4 and D	Deconstruction/dismantling, demolition
	Transport costs associated with the process of deconstruction and disposal
	Fees and taxes
	Costs and/or revenues from reuse, recycling, and energy recovery at the end of life
	Revenue from sale land

Adopted from EN 15643

the energy export and any subsidy or incentives in module B6. It also does not make a distinction between the energy generation systems that are a part of the building fabric and those that are not (EN 16627:2015, 2015).

EN 16627:2015 includes some indications for selecting the macroeconomic parameters. It requires using a real discount rate of 3% for the sake of the comparability of the net present value (cost) of studies, although it allows performing additional calculations using other values for the discount rates. This standard does not suggest a specific value for escalation rate, indicating that different rates may be used building components or services (EN 16627:2015, 2015).

The standard uses net present value (NPV), net present cost (NPC), annual cost (AC), and annual equivalent cost (AEC) to measure the economic performance of buildings. It also provides a list of other possible indicators that are not in the scope of the standard but can be used for other aspects of the economic assessment (EN 16627:2015, 2015).

EN 15459:2007 (2007) provides detailed guidelines on economic evaluation procedures for energy systems in buildings. It aims to standardize evaluation methods and practices to be fully or partially applied in the economic feasibility assessment of energy-saving options. It also permits a comparison of the different energy-saving solutions, the evaluation of the overall economic performance, and the assessment of the possible energy-saving measures on energy systems in buildings. The main structure of the relevant costs in EN 15459: 2007 is shown in Fig. 3 (EN 15459:2007, 2007).

EN 15459: 2007 takes into account two main categories of costs covering the initial investment and replacement costs, including building construction related to energy savings (e.g., construction materials, insulation, etc.) and the cost associated with the installation of energy systems. The second cost category must include all running costs related to the operation of the energy system, maintenance, and metering (EN 15459:2007, 2007).

EN 15459: 2007 uses global cost and annuity cost indicators to evaluate the life cycle cost of the energy systems in buildings. It provides guidelines for the calculation steps of the main indicators and other economic parameters, such as discount and annuity factors. It also presents a list of the standard technical life span of a variety of energy systems in buildings in terms of the years to be considered in developing replacement scenarios, alongside the value of yearly maintenance and end-of-life disposal costs in terms of the percentage of the initially required investment of each system (EN 15459:2007, 2007).

2.3 Level(S)

Level(s) is a common framework of the Joint Research Centre-European Commission for the sustainability assessment of buildings with a life cycle perspective. It includes six macroobjectives, including (1) greenhouse gas emission over the building's life cycle, (2) resource-efficient and circular material life cycle, (3) efficient use of water resources, (4) healthy and comfortable spaces, (5) adaption and

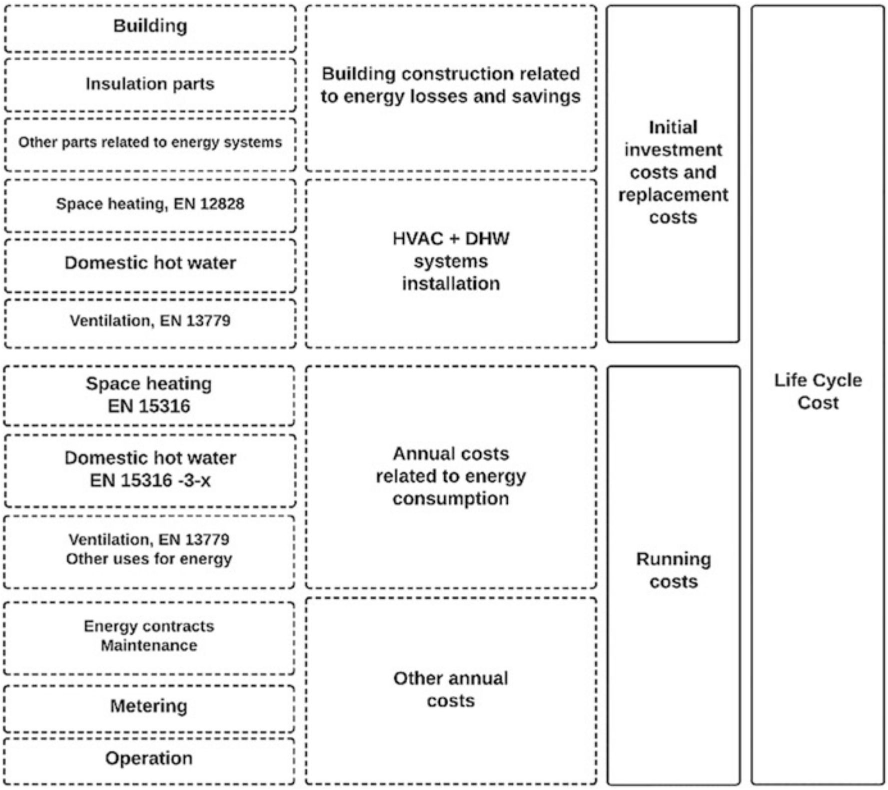

Fig. 3 The structure of the main relevant cost in building and energy systems. (Adopted from EN 15459)

resilience to climate change, and (6) optimized life cycle cost and values. Level (s) framework considers three levels of the building life cycle, including Level 1 – conceptual design, Level 2 – detailed design and construction, and Level 3 – as-built and in-use stage (Dodd & Donatello, 2021).

Regarding Life cycle costing, at the first level, it can be applied to calculate and understand the life cycle cost and long-term perspective on the cost of buildings, alongside the incorporation of main LCC concepts into conceptual and subsequent design phases. At the second level, it can be applied to calculate the life cycle costs of buildings, select tools and databases, and understand the calculation steps based on EN 15459 and ISO 15686-5, including the assumption and the parameters to be used. At the third level, it can be applied to revise the life cycle costs and projections based on monitoring data and to report the life cycle costs for the building. The life cycle cost objective in Level(s) includes construction, operation, maintenance, refurbishment, and disposal. It encourages integrating the sustainability aspects into the risk rating process and market value assessment of the buildings, emphasizing the transparency of the provided information. The LCC indicators proposed by Level(s) include the life cycle cost of euro / (m^2 * year), value creation, and risk factors (Dodd & Donatello, 2021).

2.4 Other Frameworks

Apart from the standards and framework described previously, there are several guidelines for conducting an LCC study developed by public, private, or academic entities. Most of these guidelines follow one or more of the standards in general; however, they might have specific requirements related to the goals of their guidelines.

The framework published by the US National Institute of Standards and Technologies (NIST), known as Building for Environmental and Economic Sustainability (BEES 4.0) (Lippiatt, 2007), aims to provide a guideline for measuring the environmental and economic performance of buildings. The study period proposed by these guidelines covers 50 years. The system boundary of the LCC study in this framework starts with the purchase and installation of the products and ends at the end of the study period. It does not consider the end-of-life phase as a requirement, which means all life cycle phases related to raw material acquisition, production, and end-of-life processing are omitted from the study (Lippiatt, 2007).

The limited system boundary, as described, is one of the main differences between economic and environmental performance assessments highlighted in this framework. BEES uses net present value (NPV) to measure the project's life cycle costs over the study period and requires using a real discount rate equivalent to 3.0%, as mandated by the US Office of Management and Budget for most federal projects (Lippiatt, 2007).

Stanford University provided LCC procedure guidelines to be applied to different phases of design and building ownership, including scoping, feasibility and programming, schematic design, design development, construction documents/permitting, construction, closeout, and ownership. The different goals and tasks of LCC in each phase are outlined. The overall LCC process in this guideline includes establishing the objectives of the analysis, determining the criteria for evaluating alternatives, identifying and developing design alternatives, gathering cost information, and developing the life cycle cost for each alternative. This guideline also provides reference values for each building subsystem's useful technical life span, e.g., envelope, heating, ventilation and air conditioning (HVAC) systems, electrical systems, etc.). These values can be used to define the maintenance and replacement schedules as they affect the life cycle cost of buildings (Stanford University, 2005).

This guideline also uses NPV as the method and indicator for measuring life cycle costs and provides a procedure for calculating payback time in building projects. However, residual value (the estimated value of the building components at the end of service life) is included in formulating LCC, considering it equal to 0. This guideline also provides reference values for the study period of different buildings equivalent to 30, 15, and 10 years for new construction projects, retrofitting/renovation projects, and labs/high-tech buildings, respectively (Stanford University, 2005).

3 Life Cycle Costing Methodology: Indicator Selection and Calculation

As elaborated in the previous sections, multiple institutes and organizations have published several standards and guidelines for conducting the life cycle cost analysis of the building sector energy systems. Many similarities are found among the reviewed guidelines; however, this section aims to discuss the main steps in performing an LCC study in energy-efficient buildings and to review the state-of-the-art for the assumption and application of these guidelines. Through such a discussion, the required main consideration of life cycle costing in nZEBs will be clarified, and different techniques implemented in the literature will be highlighted.

The main steps are described as follows: the definition of the goals, the definition of the scope, i.e., defining the system boundary and the life cycle modules to be included, the assumption regarding the macroeconomic parameters, selection of the economic performance indicator, etc., and finally reporting the results and discussion.

3.1 Definition of the Goals

The main goals of a life cycle cost analysis at the building level are as follows: (i) providing support for the decision-making process by comparing the economic performance of design options, (ii) identifying the potential of improving building performance (refurbishment scenarios), (iii) determining the required budgets, documenting the economic performance of buildings, and (iv) providing support for the development of policies (EN 16627:2015, 2015).

According to EN 16627:2015, the scope of life cycle costing should include all building components and connections to the utilities between the building and the site boundary that affect the relevant costs of the building; however, construction works beyond the boundary of the building site shall not be included (EN 16627: 2015, 2015).

Since the functional unit of the assessment has a significant impact on the comparability of the results, the functional unit should be the same if the life cycle costing and the evaluation of other sustainability dimensions (i.e., environmental and social) are considered to be combined. In any case, the standard requires taking into account the building type, the relevant technical and functional requirements, the pattern of use, and the required service life. EN 16627 also provides the indications for considering the difference between the required service life and the reference study period. The decision to define the reference study period might be indicated by national regulations or the purpose of the assessment. Therefore, several different assumptions regarding the reference study period are observed among published studies (EN 16627:2015, 2015).

3.2 Definition of the Scope and the System Boundary

The system boundary of the life cycle cost analysis of new buildings includes the life-cycled modules illustrated in Fig. 3. While assessing the existing building works (e.g., retrofitting), the evaluation will consist of all the related costs of the interventions, along with the expenses within the later stages of the building life cycle.

All the costs related to the operational energy use of the building should be calculated in compliance with the Energy Performance of Buildings Directive (EPBD). The building-related energy services that should be included in the assessment, according to EPBD, are space heating, domestic hot water supply, space cooling, ventilation, artificial lighting, and auxiliary energy consumption (i.e., pumps, control, and automation). The building-related energy consumption that EPBD does not cover should be included in the assessment and reported separately. Likewise, if non-building-related energy is included in the energy consumption calculation, it should be reported separately. Moreover, supposing the building is equipped with on-site energy generation systems (i.e., photovoltaics, etc.), in that case, the generated energy should be assumed first to satisfy the building-related energy demand and then supply non-building-related energy. The exported energy from on-site energy generation systems cannot be considered as compensation for the required imported energy, but the economic profits (revenue), subsidies, and incentives should be included in the operational energy use (module B6). Likewise, all operational energy costs described above must be included in module B6 (EN 16627:2015, 2015; EN 15459:2007, 2007).

3.3 Macro- and Microeconomic Parameters

Life cycle costing highly depends on the choice of macro- and microeconomic parameters applied in calculating economic costs and values (Baldoni et al., 2019). Determining such parameters, however, depends on many factors, including the following:

- internal factors of the building projects for which the assessment should be carried out;
- external factors related to the project's economic context, such as the market, alongside fluctuations over the time horizon of the assessment (Amini Toosi et al., 2020).

Those complexities indeed can affect the results highly and therefore are among the main parameters that should be defined reasonably with respect to the economic context and the study period of the assessment (Amini Toosi et al., 2021). Some guidelines designed for a specific type of construction activities in certain economic contexts may propose values for macroeconomic parameters, such as inflation rate,

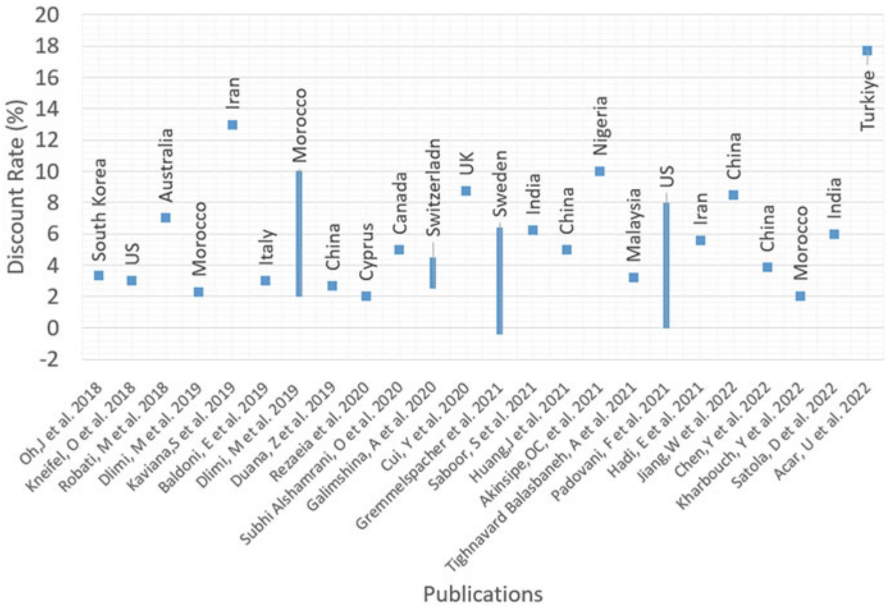

Fig. 4 Discount rate implemented in the reviewed research studies

interest rate, and discount rate, to be included in the life cycle cost analysis. However, the review of the published studies highlights that different researchers might consider a wide range of values for such parameters (Figs. 4 and 5 and Table A1).

EN 16627 proposes using the real discount rate of 3% for comparability among different assessments. However, the assessor can also adopt other values for additional analyses based on consultations with the client and justified by commercial, political, regulatory, and sustainability-related objectives or requirements. The selection of a lower discount rate encourages higher initial investment, which can yield a lower operating cost for the buildings in the future since the future cost and benefits of the building will get a lower discount factor, and therefore, it will result in higher values in terms of net present value at the time of life cycle costing.

A research study (Copiello et al., 2017) demonstrated that the impact of the discount rate on life cycle cost analysis is approximately four times greater than the impact of the price of electricity. This result reaffirms the importance of choosing macroeconomic parameters in an LCC analysis. It is advised to select the macroeconomic parameters in accordance with each project's economic context to have a robust LCC analysis; nonetheless, theoretical studies and sensitivity analysis to assess the cost-effectiveness of different design options under various economic outlooks are deserving of investigation (Amini Toosi et al., 2020).

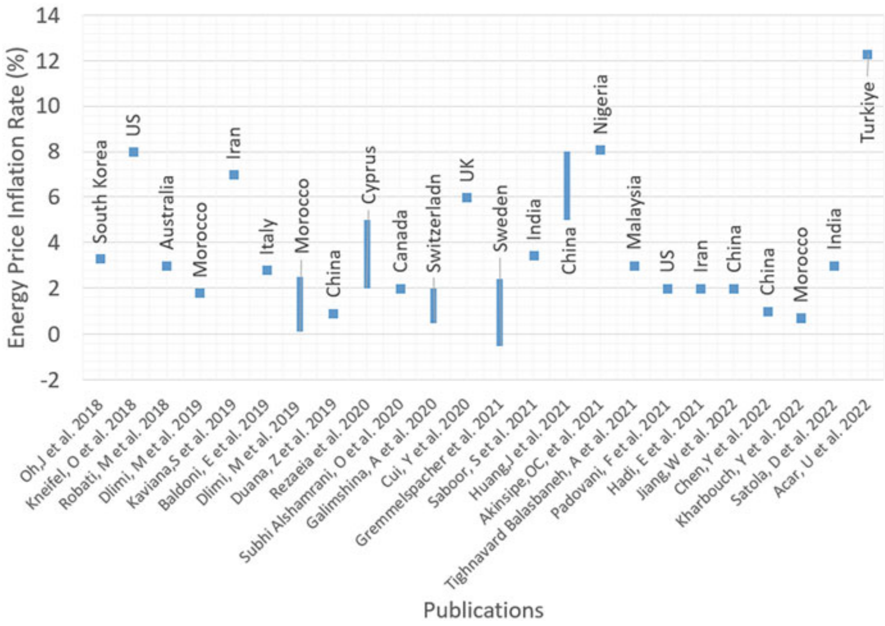

Fig. 5 Energy price inflation rate (EnPIR) implemented in the reviewed research studies

3.4 Indicator Selection and Calculation

Several indicators to assess the economic performance of buildings, including nZEBs design options and building refurbishment projects, have been proposed by standards and guidelines and implemented in different studies. However, the choice of the LCC indicator may depend on how the design scenarios should be compared, and the results need to be reported.

According to EN 16627, net present value (NPV) is a standard indicator for life cycle costing, which takes into account all the discounted future cash flows, including the cost and revenues across the building life cycle and study period. It can be used to determine and compare the economic performance of different design options and show the design scenarios' overall life cycle cost and benefit (EN 16627:2015, 2015).

The standards also suggest other LCC indicators and can be found in the literature, such as net saving or net benefit, saving-to-investment ratio (SIR), payback period, and adjusted internal rate of return (AIRR), as described in ISO 15686-5 (2017).

Net present value (NPV) is the most used LCC indicator within the literature, which helps investors compare the present value of the economic performance of the design options in terms of total cost or values (Table A1). Also, the payback period provides a clear vision of the time horizon when the initial cost and anticipated

Table A1 Summary of the reviewed articles

References	Year	Country	Study period	Indicator/notes	DR	En-PIR
Ouyang et al. (2011)	2011	China	40	NPV and IRR Different internal rate of return (IRR) is considered.	6.6	Ns
Koo et al. (2014)	2014	South Korea	40	Initial investment cost, NPV, saving-to-investment ratio, compound annual growth rate (CAGR), and improved CAGR	Ns	NS
Jafari and Valentin (2015)	2015	United States	50	NPV, initial investment and energy consumption costs	2.6	5
Brás et al. (2015)	2015	Portugal	5, 10, 15	NPV, payback time	6	4
Koo et al. (2015)	2015	South Korea	40	NPV and SIR	N.S	NS
Jafari et al. (2016)	2016	United States	5–25	NPV, optimization and sensitivity analysis on service life span, available budget and discount rate	0–6	NS
Lohse et al. (2016)	2016	Austria, Germany	33	Net present value (NPV)	2.5	0–4
Zhivov et al. (2016)	2016	EU, US, CN	25	NPV	0–7	0–3
Jafari and Valentin (2016)	2016	United States	30	Investment costs	NS	NS
Liu et al. (2016)	2016	Sweden	N.S.	Present value	0–10	NS
Copiello et al. (2017)	2017	Italy	30	NPV, initial cost (purchasing material, the energy cost of the operation phase, excluding the repair and maintenance phase)	0–15	0–4.5
Jafari and Valentin (2017)	2017	United States	15	NPV, initial investments costs, energy consumption costs, maintenance and replacement costs, resale benefits and property tax, rebound effect	2.6	5
Lucchi et al. (2017)	2017	Italy	50	NPV, global costs, payback period time, initial investment and energy consumption costs	0–3	NS
Krarti and Dubey (2017)	2017	Oman	20	Energy productivity (EP)	3	NS
Fregonara et al. (2017)	2017	Italy	30	Net present costs (NPCs), net saving (NS), saving-to-investment ratio (SIR), adjusted internal rate of return (AIRR), simply payback period (SPB), initial costs, construction and nonconstruction costs, operation costs, excluding the residual value of components	2.5	NS

Ruparathna et al. (2017)	2017	Canada	15–100	NPV	3.5–8	NS
D'Orazio et al. (2018)	2018	Italy	NS	NPV, inflation rates, discount rates, price escalation rates, and different tax deduction scenarios	1.9–6	NS
Yılmaz and Koçlar Oral (2018)	2018	Turkiye	30	NPV	NS	NS
Mili et al. (2018)	2018	Sweden	50	NPV	5	NS
Oh et al. (2018)	2018	South Korea	25	NPV, SIR, and break-even point	3.3	3.3
Kneifel et al. (2018)	2018	United States	30	NPV	3	8
Robati et al. (2018)	2018	Australia	50	NPV	7	3
Zheng et al. (2019)	2019	China	NS	NPV and value at risk (VaR)	8	NS
Song et al. (2019)	2019	South Korea	40	NPV	2.54	NS
Bleyl et al. (2019)	2019	Austria	25	NPV	4.5	NS
Yuan et al. (2019)	2019	Singapore	NS	NPV for different electricity price and discount rate scenarios Results are provided and ranked both according to energy-saving and cost-effectiveness potential,	4–12	NS
Seghezzi Re-Cecconi (2019)	2019	Italy	NS	NPV	NS	NS
Nägeli et al. (2019)	2019	Sweden	35	NPV	4	2
La et al. (2019)	2019	Sweden	40	Present value	0–10	0.5–2
La Fleur et al. (2019)	2019	Sweden	40	Present value	5	NS
Van De Moortel et al. (2019)	2019	Belgium	60	Sum of the present value (SPV), sensitivity analyses on building service life span, energy price, discount rate, insulation level of the baseline building	2	3
Dlimi et al. (2019a)	2019	Morocco	20	NPV	2.25	1.8
Kavian et al. (2019)	2019	Iran	20	NPV	13	7
Baldoni et al. (2019)	2019	Italy	30	NPV, PP	3	2.8
(Dlimi et al., 2019b)	2019	Morocco	20	NPV	2–10	0.1–2.5
Duan et al. (2019)	2019	China	40	NPV	2.7	0.9

(continued)

Table A1 (continued)

References	Year	Country	Study period	Indicator/notes	DR	En-PIR
Rezaei et al. (2020)	2020	Cyprus	20	NPV, NPS, NPI, and SIR	2	2–5
Alshamrani and Alshibani (2020)	2020	Canada	20	NPV	5	2
Galimshina et al. (2020)	2020	Switzerland	60	NPV	2.5	0.5–2
Cui et al. (2020)	2020	UK	25	NPV	8.75	6
Gremmelspacher et al. (2021)	2021	Sweden	25	NPV	−0.4 to 6.4	−0.5 to 2.4
Saboor et al. (2021)	2021	India	20	LCS, PP	6.25	3.4
Huang et al. (2021)	2021	China	20	NPV, PP	5	5–8
Akinsipe et al. (2021)	2021	Nigeria	20	Levelized cost (LLC), annualized levelized cost (ALLC), and the cost of energy (COE)	10	8.1
Balasbaneh and Sher (2021)	2021	Malaysia	50	NPV	3.2	3
Padovani et al. (2021)	2021	US	20	Total life cycle cost, NPV	0–8	2
Hadi and Heidari (2021)	2021	Iran	30	NPV, IRR	5.6	2
Jiang et al. (2022)	2022	China	50	NPC	8.5	2
Chen et al. (2022)	2022	China	20	Life cycle cost saving rate	3.85	1
Kharbouch et al. (2022)	2022	Morocco	30	NPV, PP	2	0.7
Satola et al. (2022)	2022	India	50	NPV	6	3
Acar and Kaska (2022)	2022	Turkiye	30	NPV, NS, PP	17.75	12.28
Amini Toosi et al. (2022)	2022	Italy	30	NPV	3.68	2.1
Amini Toosi et al. (2023)	2023	Italy	30	NPV	3.68	2.1

En-PIR energy price inflation rate

benefit will be equal, showing the year when the investment is compensated and returned through the economic benefits of a design option. The payback period and SIR indicator can also provide clear indices for the comparability of economic benefits in energy retrofitting design options.

3.5 Reporting and Communication of Results

The results of life cycle costing shall be reported in a document, which can be supported visually. The report should be transparent and contain traceable information used in the assessment process. The reporting must provide information such as: (i) the purpose of the assessment, including the intended use and scope; (ii) identification of the building, (iii) the life cycle phase, where evaluation is carried out; (iv) the date and temporal validity of the assessment, alongside the verification and identification of the clients, assessor, and verifier (EN 16627:2015, 2015).

Moreover, any assumptions, such as the reasons for including and excluding building services or life cycle stages, along with data source and quality, shall be reported clearly. EN 16627 provided the minimum level of disaggregation of information required to be reported in an LCC documentation (EN 16627: 2015, 2015).

4 LCC Implementation: Barriers and Uncertainties

Several barriers and uncertainties may exist in the performance of an LCC study, mainly attributing to data accessibility, data quality, and uncertainty levels associated with input data (Amini Toosi et al., 2020). Predicting macroeconomic parameters, such as the inflation rate of the prices and discount rate required for life cycle costing over the study period, is a critical challenge that can affect the reliability of the results. Furthermore, a reasonable choice for the cost of construction activities, building systems, energy prices, etc. requires a deep and updated understanding of the construction market and its fluctuations. Such data can be challenging to estimate due to their dependency on the socioeconomic and political realities of the construction market. Moreover, the cost prediction of future maintenance work over the building's lifespan is challenging. Such data, however, are crucial for the performance of the life cycle cost analysis of buildings and should be gathered from reliable sources, justified, and reported reasonably and clearly to guarantee the traceability, replicability, and verification of the assessment (Amini Toosi et al., 2020).

Future studies should examine additional factors, including the performance degradation of building components, the residual value of building components at the end of their useful lives, and economic policies, like tax incentives. These factors have not received as much attention as they should. Another factor that is rarely discussed is the salvage value of building components. Koo et al. (2014) removed this component by assuming that salvage value and disposal costs would balance one another out. Other characteristics, such as the rebound impact and resale advantages, are taken into account in a few articles (Amini Toosi et al., 2021).

5 Conclusion

The development of the built environment due to escalating population growth and urbanization makes the building sector a significant driver of economies worldwide. In this context, a comprehensive economic assessment of the building sector is crucial to designing buildings and policies. This chapter aims to review and discuss the existing frameworks and methodologies for the life cycle cost analysis of buildings and clarify the advances and barriers to implementing life cycle cost in designing nZEBs.

The chapter highlighted the main methodological steps and requirements for conducting the life cycle costing of the buildings and energy systems. Different aspects, such as the definition of the goals and scope of the study, the macroeconomic parameters, and life cycle cost indicators, alongside the requirement of reporting, were elaborated and discussed. The chapter also detailed the several life cycle cost indicators proposed and implemented in different frameworks and studies, including net present value, payback period, saving-to-investment ratio, etc. Still, the net present value was found to be the most popular and recommended indicator in the current standards and the reviewed studies to evaluate the economic performance of nZEBs. It supports the decision-making process by comparing the economic performance of design options and by identifying the potential of improving building performance (refurbishment scenarios).

Moreover, a wide range of macroeconomic parameters, such as the discount rate and energy price inflation rate, were found in the literature to analyze the impact of the uncertainty level of macroeconomic parameters on the final life cycle cost results, as recommended by standards. The main standards require opting for a similar discount rate for the comparability of the results. Nonetheless, the different macroeconomic variables employed in the literature offer insights into the diversity of Life cycle costing (LCC) results across various economic settings, while rendering the comparison of results a challenging endeavor.

Therefore, for the comparability of life cycle cost results, different studies should follow relevant standards in: (i) defining the scope and (ii) selecting macroeconomic parameters, as well as provide a comprehensive and transparent report that includes all assumptions applied in the calculation process.

This chapter highlighted the main requirements for conducting a life cycle cost study of buildings aiming at clarifying the life-cycle-based economic performance analysis steps for the stakeholders. It also encourages the assessment of the life cycle cost performance of buildings according to existing standards and innovative approaches for the sake of comparability and reliability of results, alongside the possibility of improving the methods established by the current frameworks within future scientific research studies.

Appendix

Table A1 summarizes the methodological aspects of the reviewed papers, including the selected study period, the macroeconomic parameters, and the LCC indicators used for the economic assessment of the performance of buildings and energy systems.

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