Cost-Benefit Analysis of Building Renovation

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ABSTRACT – The renovation of existing buildings represents a high potential for energy savings and the reduction of environmental impacts. Taking into account the direct and indirect benefits of building renovation is instrumental for the implementation of large-scale building renovation projects. Among the benefits that can be achieved, a reduction in costs is of particular interest for both investors and citizens. In order to implement cost-effective refurbishment measures, suitable procedures, tools and economic indicators should be used. This chapter investigates the cost-benefit approach to building energy refurbishment by introducing cost analysis methods, with particular focus on cost-optimisation. An example of a cost-effective analysis is then presented (for a case study). A cost-optimisation procedure is applied to identify the best packages of energy efficiency measures for building retrofitting; the main economic indicators are calculated and discussed.

Keywords – Costs-benefits; Building energy refurbishment; Cost-effective renovation; Energy efficiency; Cost-optimisation; Life Cycle Cost.

Introduction

The energy performance of existing buildings is generally so poor that the energy they consume places the sector among the most significant CO_2 emission sources in Europe; in fact, 38% of the total final energy is consumed in buildings [1,2]. A substantial percentage of this energy consumption is accredited to the residential sector, as dwellings are on average responsible for 24.8% of the total energy consumption in the EU (European Union) [3]. It has been forecasted, on the basis of their life cycle, that existing buildings will dominate the housing stock for the next 50 years; for example, in 2014, the annual rate of new buildings in the Netherlands and in Italy was 0.6% and 0.2% of the existing residential building stock, respectively [4,5]. Consequently, it has been forecasted that renovation activities will be greater than construction and demolition activities in the future.

The average age of existing buildings and the share of new buildings in the total stock represent a good basis to explore the overall efficiency at the initial stage. Figure 1 shows the European stock cohorts according to the period of construction from data of the IEE-ENTRANZE Project [6]. A high share of new dwellings – built with higher efficient standards – in a given stock indicates a higher overall energy performance of the building stock. In most EU countries, approximately half of the residential stock was built before the introduction of the first thermal regulations, i.e. before 1970. Only a few countries are exceptions to this phenomenon; the share of new dwellings in Cyprus, Spain and Ireland is significantly larger than that of other countries. At the same time, the lifetime of dwellings in the EU has been estimated to be between 70 years (Greece) and 175 years (the UK) [7]. Therefore, the potential energy savings of existing dwellings, through the application of energy renovation, may be large. Several policy measures have been in place in Europe since the last quarter of the 20th century, mainly through building decrees.

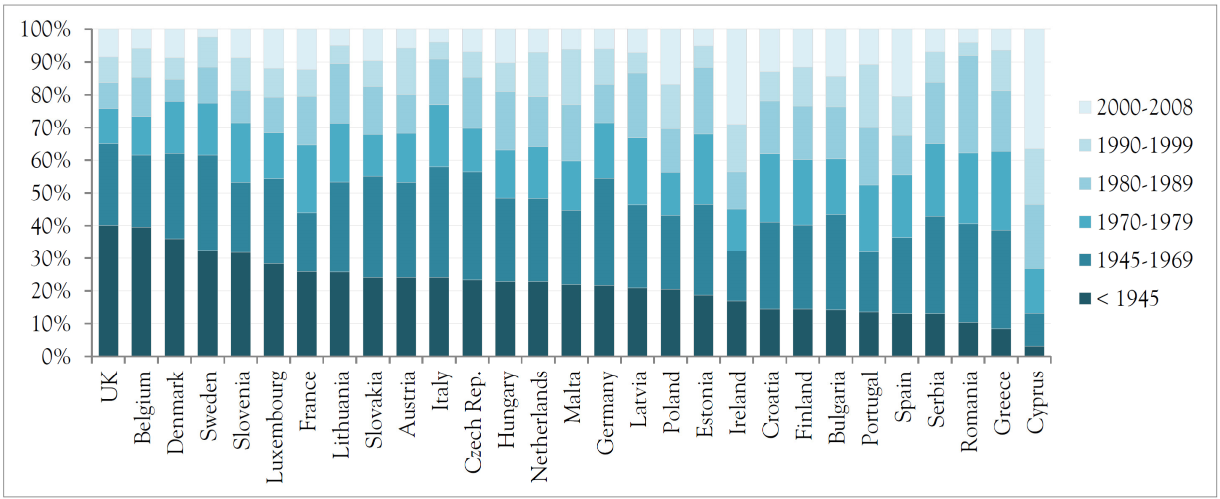

Fig. 1. Breakdown of dwellings according to the construction year.

The 2012 Energy Efficiency Directive (EED) [8] and the 2010 Energy Performance of Buildings Directive (EPBD recast) [9] are the main legislations concerning the reduction of energy consumption in buildings in the EU. The EED, on the basis of recent trends and policies in the EU, focuses on energy savings in buildings, transport, products and processes. Among other obligations, according to article 4 of the EED, Member States are required to establish long-term strategies for actuating energy renovations of their building stocks. A recent evaluation of the EED [10] has concluded that energy renovation plans or guidelines to identify the most effective measures for each climate, country (according to national energy regulations), typology of dwellings, size, age, operation and maintenance, dwelling envelope, costs, and many more, are still lacking.

The EPBD recast has been implemented in the majority of EU countries. According to the directive, all Member States have to establish and apply minimum energy performance requirements for new buildings, for major renovations of buildings and for the replacement or retrofitting of building elements (heating and cooling systems, roofs, walls, etc.). They also have to ensure the certification of the energy performance of existing buildings when they are sold or re-rented. Furthermore, the regular inspection of boilers and air-conditioning systems in buildings is also required. The EPBD recast also requires Member States to guarantee that, by the end of 2020, all new buildings will be “nearly zero-energy buildings”. New buildings and any major renovations of buildings are required to meet specific standards, e.g. overall energy performance requirements, or pre-fixed thermal transmittance values for floors, facades, roofs and windows, according to each country’s own national standards.

Despite the regulations and directives currently in force in the EU, there is still a greater focus on newly built dwellings, as they can achieve nearly zero energy standards, than on cost-effective deep renovations of the building stocks. Nonetheless, energy renovations of dwellings are considered to be more sustainable and cost-effective than demolition and rebuilding [11], and should be given priority and incentives, especially considering the low and declining construction rates in the EU [12,13].

Benefits of building renovation and cost implications

Large-scale dwelling renovation is considered difficult to put into practice. Despite the numerous studies and research results that indicate the potential of energy renovation to save energy and reduce the environmental impact of the building sector, progress is noticeably slow [12,14,15]. Furthermore, a cost-effective approach to energy renovation is instrumental in reaching the EU and national 2020/2030/2050 goals [16]. Renovating the existing stock would have implications not only on growth and jobs, energy and climate, but it could also have an impact on cohesion policies and increase the thermal comfort of the tenants, the value of the dwelling and the social standard of living. Renovating existing buildings is a 'win-win' option for the economy of EU countries [16].

However, apart from the obvious benefits that can be obtained from energy renovations, and which most of the research community has focused on [12], indirect co-benefits can also be obtained and should be taken into account. The direct benefits include energy use, greenhouse gas emission and life cycle cost reductions. The indirect co-benefits can instead be categorized as building quality, economic and user wellbeing benefits [17,18].

The building quality co-benefits refer to improvements in terms of building physics (e.g. less humidity and mould problems); easier use of the dwelling and direct control of the indoor environment by the occupant (e.g. automatic thermostats or faster hot water delivery); aesthetics and architectural integration; usefulness of otherwise non-utilized building areas (e.g. increase in the useful areas); and safety (e.g. replacing certain building elements leads to a decrease in the risks of accidents and intrusions) [17].

The economic co-benefits mainly refer to the reduced exposure to energy price fluctuations in an international context [17]. Events in recent years and stricter EU legislations have highlighted the fact that the de-carbonizing of the energy systems of nations will be a major task in the near future. Therefore, a reduced dependence on energy price fluctuations offers the user more control and increased certainty of maintaining the desired level of comfort.

Finally, the user wellbeing co-benefits refer to thermal comfort levels (e.g. decreased temperature differences and air humidity); natural lighting (e.g. better use of daylighting); indoor air quality (e.g. fewer particulates and less fine dust); internal and external noise (e.g. external noise reductions due to better insulation); pride, prestige and reputation (e.g. increased sense of environmental responsibility); and ease of installation, used as a parameter to choose the measures that lead to the most benefits [17].

So far, the above discussed direct benefits and indirect co-benefits have been considered from a private perspective. However, important co-benefits, linked to the energy renovation process that are generally referred to as macroeconomic co-benefits, can also be obtained. These are identified and intended to facilitate the development of energy policies [18]. Macroeconomic co-benefits can be divided into three main categories: environmental, economic and social. The environmental co-benefits include a reduction in air pollution and a decrease in waste due to demolition and rebuilding. From an economic perspective, lower energy prices, due to a reduced energy demand, the growth in jobs and the avoidance of rate subsidies, constitute the benefits. Moreover, renovating the building stock can lead to an improvement in social welfare and a reduction in fuel poverty. Other social co-benefits include decreases in mortality, morbidity and other psychological effects. Finally, energy security can be achieved as a result of a possible independence of imported energy. Figure 2 summarizes the direct benefits and the indirect co-benefits that can be obtained through the realization of energy renovations.

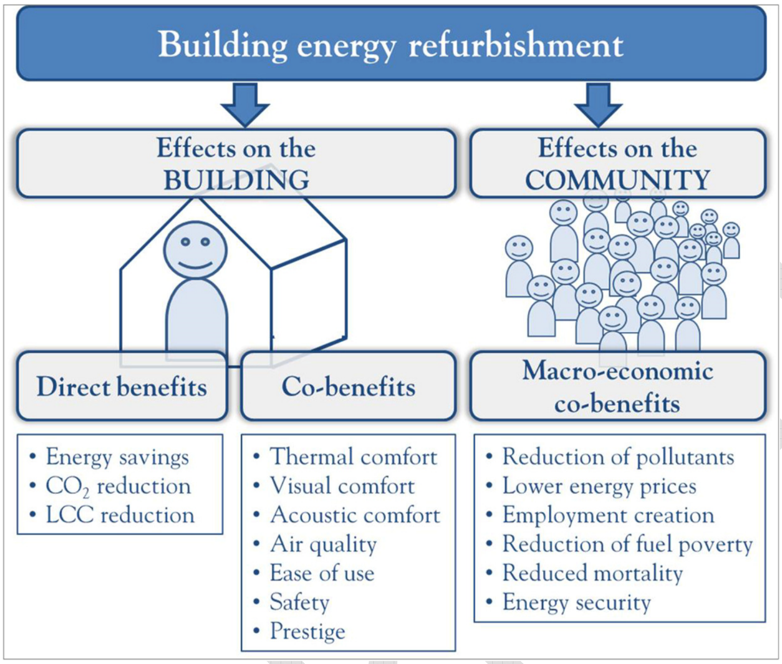

Fig. 2. Direct benefits and co-benefits obtainable from effective energy renovations of the building stock.

The integration of costs in the renovation process is one of the most significant steps towards a comprehensive understanding of the benefits of building stock refurbishment.

Cost-effectiveness in the international framework

The economic performance of buildings is also taken into account in the overall framework of building sustainability. In this context, the EN 15643 series of technical standards provides a useful system for the sustainability assessment of buildings, by which the environmental, social and economic performances can be quantified through quantitative and qualitative indicators in a life cycle approach. The overall concept of the sustainability assessment of buildings is shown in Figure 3, together with the related technical standards that provide assessment procedures and criteria.

Cost-effectiveness is the method that is used to evaluate the energy renovation process, in terms of the effective reduction of primary energy consumption and carbon emissions of the building stock, considering life cycle costs. In other words, it is an assessment method that combines lifecycle costs, energy efficiency measures and renewable energy use. In this context, Annex 56 of the International Energy Agency (IEA) – “Cost-Effective Energy and Carbon Emissions Optimization in Building Renovation” – was aimed at developing methodologies and procedures for the cost-effective renovation of existing buildings [17]. The project involved setting up a calculation basis for future standards, which was aimed at establishing the maximum effects that could be achieved by reducing carbon emissions and primary energy use. The project paid particular attention to the renovation of existing residential buildings and to cost-effective building renovations. The objective of incorporating cost-effectiveness in a building renovation process is to calculate the effect of the benefits of the renovation on the costs required to perform it.

A measure, or a package of measures, applied during the retrofitting of a building, is cost-effective when the renovation package provides more benefits than costs over the lifetime of the building or the building element. The subject of cost-effectiveness has been studied extensively, and it has been incorporated, among others, by the European Commission in 2010/31/EU Directive [9], where the concept of "cost-optimality" has also been introduced, as explained later on in the present chapter.

The scientific community has frequently dealt with the cost-effectiveness of buildings renovation. Different methods, based on the boundaries and goals of the studies, ranging from life cycle cost (LCC) and cost-benefit analyses to the addition of social costs, have been used for this purpose [12,19,20]. The LCC method seems to have been the most frequently used one in recent years to indicate the financial benefits that can be achieved over the lifetime of the measures applied during the renovation [12]. On the other hand, the research community has also used several multi-criteria methods, such as in the IEA EBC Annex 56, to calculate the cost-effectiveness of building renovations [21-24]. In the present chapter, both cost analysis and optimisation methods are presented.

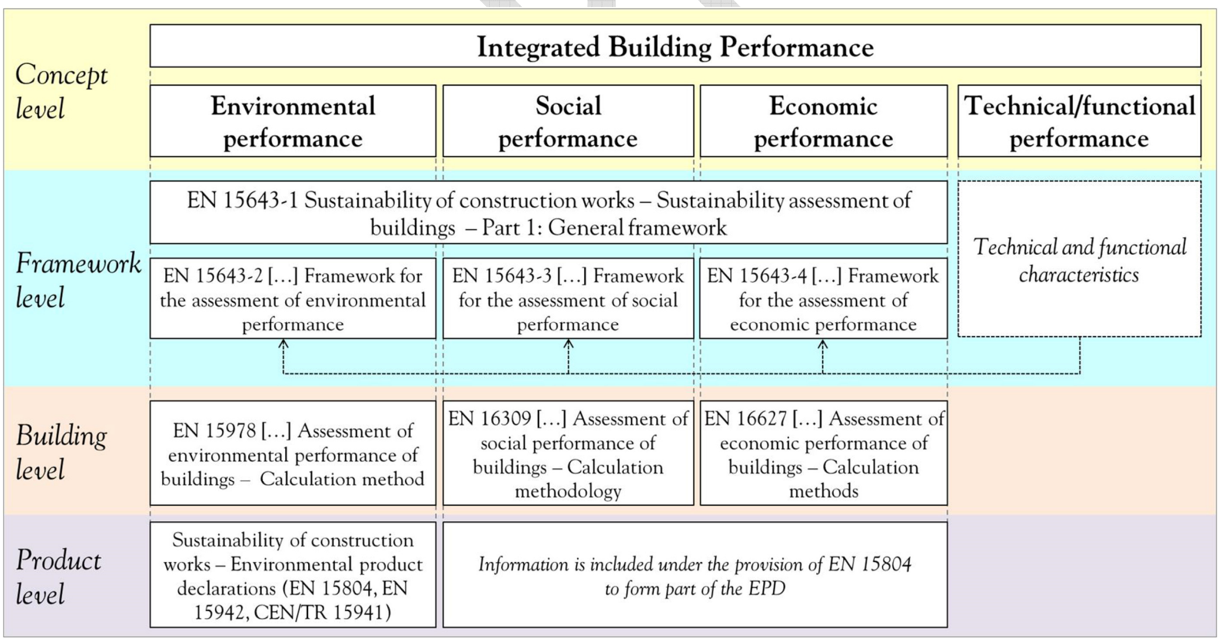

Fig. 3. Flowchart of the sustainability assessment of buildings.

Cost analysis

One of the most important benefits that can be obtained from the energy retrofitting of a building, as introduced in the previous section, is a reduction in costs in the building lifecycle through the reduction of the building energy consumption. A cost-effectiveness analysis is also named cost-benefit analysis, or even cost-revenue analysis, if the benefits are expressed in a monetary value [25]. A variety of economic analysis methods that are applied to evaluate the cost-effectiveness of renovation packages can be found in literature [12]. These methods are aimed at calculating economic indicators, such as the net present value (*NPV*), the internal rate of return (*IRR*), the discounted payback period (*DPP*), and the annual equivalent value (*AEV*). The most frequently used economic indicators and standardised economic assessment procedures are presented in the following sub-sections.

Definition of economic cost analysis indicators

An effective cost-revenue analysis should take into account the different cash flows in different periods of time, as well as the presence of the investment risks. The net present value (*NPV*) is the economic indicator that is used the most by researchers when a cash flow is taken into consideration. The *NPV* method is based on the analysis of cash flows, where the costs (*C*) and the revenues (*R*) at a given time are discounted back to their present value, as in Eq. (1),

$$(R-C)_{\mathrm{disc},t} = \frac{CF_t}{(1+r)^t} = CF_t \cdot DF(t) \qquad (1)$$

where CF_t is the net cash flow (i.e. revenues minus costs)at a given time t, r is the real discount rate and t is the time of the cash flow. The unit of time is usually a year, thus t is the number of years between the reference date (t_0, start of the period covered by the assessment) and the date of the onset of the cash flow. The term $(1+r)^{-t}$ is known as the discount factor, $DF(t)$.

NPV is the sum of all the discounted cash flows over the considered period n, as in Eq. (2).

$$NPV = \sum_{t=0}^{n} \frac{CF_t}{(1+r)^t} = \sum_{t=0}^{n} CF_t \cdot DF(t) \qquad (2)$$

The discount factor, $DF(t)$, depends on the real interest rate (r) and on the timing (t) of the considered cash flows after the starting year. The real interest rate is calculated as in Eq. (3). It depends on the market interest rate (r_m), which is the interest rate agreed on by the lender, and on the inflation rate (r_{in}), which takes into consideration the annual depreciation of the currency; both rates can vary according to the year, but are usually keep constant in this type of analysis.

$$r = \frac{r_{\mathrm{m}} - r_{\mathrm{in}}}{1 + r_{\mathrm{in}}} \qquad (3)$$

The inflation rate is obtained or estimated from available economic data over an average calculation period. The market interest rate is the average expected value of the interest rate over the calculation period. A higher discount rate –typically higher than 4%, excluding inflation – would reflect a purely commercial, short-term approach to the valuation of investments. A lower rate – typically ranging from 2% to 4%, excluding inflation – would more closely reflect the benefits that building occupants could achieve from energy efficiency investments over the entire investment's lifetime.

The limit of acceptability of an investment is closely related to the value of the interest rate. For this purpose, the internal rate of return (*IRR*) is introduced as a further economic indicator. The *IRR* is the interest rate that determines the return on capital invested over the assessment period. In other words, the *IRR* is the real interest rate (r) for which the *NPV* is equal to zero, as in Eq. (4).

$$IRR = r \mid NPV = 0 \tag{4}$$

The discounted payback period (*DPP*) is the period of time required to recoup the funds expended on an investment. In the *NPV* method, the *DPP* is the number of years (n) for which the *NPV* is equal to zero, as in Eq. (5).

$$DPP = n \mid NPV = 0 \tag{5}$$

Considering the different building retrofitting options, the *NPV* method can be used to determine and compare the cost-effectiveness of the proposed options. In a cash flow analysis, the annual revenues are considered as avoided annual costs, determined as the differences between the annual costs of the building before and after the retrofit. The annual costs generally refer to the building operations (e.g. energy cost), but can also take into account other aspects, such as building maintenance, replacement of components, etc. Retrofitting options with positive *NPV* are cost-effective, because the sum of the actualised revenues is higher than the sum of the actualised costs (including the investment cost at t_0) over the assessment period. The best retrofit option is basically the one that has the highest *NPV*. If the *DPP* is also considered, the best option is characterised by both the highest *NPV* and the lowest *DPP*.

The annual equivalent value (*AEV*) is a uniform annual amount which, when totalled over the analysis period, equals the total net value of the project. This indicator is used to compare investment options in which the natural replacement cycle cannot easily be related directly to the period of analysis. The *AEV* is calculated as in Eq. (6), that is:

$$AEV = \frac{NPV}{f_{\mathrm{pv}}(t)} = NPV \cdot a(t) \tag{6}$$

where $f_{\mathrm{pv}}(t)$ is the present value factor and $a(t)$ is the annuity factor, as expressed in Eq. (7), that is:

$$f_{\mathrm{pv}}(t) = \frac{1}{a(t)} = \frac{(1+r)^t - 1}{r \cdot (1+r)^t} \tag{7}$$

Standardised economic evaluations

Economic sustainability assessment of buildings (EN 15643-4)

The EN 15643-4 Standard [26] is part of a series of technical standards (EN 15643) that provide a system for the sustainability assessment of buildings using a life cycle approach. The purpose is to enable comparability of the results of assessments, and not to set benchmarks or levels of performance. The fourth part of the EN 15643 series of standards concerns the economic performance of buildings. An assessment of this performance addresses the life cycle costs and other economic aspects, all of which are expressed through quantitative indicators. This standard excludes the economic risk assessment of a building and return on investment calculations.

According to EN 15643-4, the economic performance of a building is defined as the performance related to *economic impacts* and *economic aspects*. *Economic impacts* represent any changes in the economic conditions, whether adverse or beneficial, wholly or partially, that result from *economic aspects*. *Economic aspects* are aspects pertaining to construction works (i.e. building and civil engineering works, structural and non-structural elements), parts of works (i.e. construction products or sets of them) and processes or services related to their life cycle that can cause changes in the economic conditions.

Life cycle is defined by the Standard as consecutive and interlinked stages in the life of the object under consideration. Whereas the *life cycle assessment* (LCA) involves the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system (e.g. building) throughout its life cycle, *life cycle cost* (LCC) refers to the cost of a building, or a part of works, throughout its life cycle, on condition that certain technical and functional requirements are fulfilled. The technical and functional requirements can include, for instance, requirements on structural safety, fire safety, indoor air quality, security, adaptability, energy efficiency, accessibility, etc. In this context, the quantified functional requirements and/or technical requirements of a building or an assembled system (part of works) are named *functional equivalents*, if they are used as a basis for comparison. *Functional equivalents* include information on the building type and use category, the pattern of use (e.g. occupancy), relevant technical and functional requirements and the required service life. Comparisons of the results of assessments of different solutions and design options should be carried out considering the functional equivalence of options and building categories.

The Standard refers to two economic performance indicators: *cost* and *financial value*. These indicators are used in two economic assessment approaches:

1) Economic performance, expressed in *cost* terms over the life cycle. In this concept, the “lowest life cycle cost” of a building over its life cycle is the most economic one. This implies that the building variants do not differ with respect to their functionality, or with respect to any income streams produced by the building. This concept of economic performance does not include developments on the real estate market, but only the cost related to the building over its life cycle.

2) Economic performance, expressed in terms of *financial value* over the life cycle. In this concept, the best financial value of a building is the most economic one, i.e. the building with the highest (discounted) revenue minus the cost over the life cycle. This concept is close to the income approach to property evaluation, and it includes market-related revenue streams. The financial value is obtained as the aggregate of costs and revenues of economic aspects expressed in monetary units.

Revenues can include the energy generated by renewable energy sources (RES) and any avoided energy costs that arise from RES. The exported energy should not be deducted from the imported energy required to operate the building, but the income resulting from the generated (and exported) energy needs to be determined.

Table 1. Overall costs in the building life cycle.

Stage of the building life cycle	**Activity**	**Related costs**
Before use [a]	Pre-construction	Site costs, including purchase and rental.
	Product stage	Aggregated cost of products supplied at the factory gate.
	Construction process	Costs of transport between the factory and site, and of activities necessary to prepare the building site and to provide infrastructures and services. Costs of labour, products, fixtures, fitting-out, commissioning, valuation and handover, and security systems.
During use	Maintenance	Costs for regular and routine activities, such as inspections, caretaking, management of a planned service contract. Insurance costs. Leases, rents. Taxes. Subsidies and incentives. Cyclical regulatory costs. Cleaning and redecoration.
	Repairs	Costs of repairs or replacement of minor components.
	Replacements	Costs of the replacement of major systems and components. Revenue from re-use, recycling.
	Refurbishment	Costs of infrastructures, fitting out, commissioning, validation and handover.
	Operational energy use	Energy costs, including costs of fuel and electricity for heating, domestic hot water supply, air conditioning (cooling and humidification/de-humidification), ventilation, lighting , auxiliary energy for pumps, control and automation, lifts, escalators, safety and security installation and communication systems. Other non-building-related energy uses (e.g. plug-in appliances) can be included.
	Operational water use	Costs of all the used water and its treatment (e.g. drinking water, water for sanitation, domestic hot water, irrigation water, water for thermal systems, other specific water uses of building-integrated systems, such as fountains, swimming pools etc.).
After use [b]	Deconstruction	Costs of dismantling, including inspection, planning, site clean-up.
	Transport	Costs of the transport of materials from the building site to the storage or disposal site.
	Waste processing for reuse, recovery, recycling	Cost of the re-use, recycling, and energy recovery of salvaged materials, such metals, aggregates, timber, plastics, etc.

[a] Professional fees, taxes, subsidies and incentives included.
[b] Fees and taxes included.

In an assessment of the economic performance of a building, the life cycle starts from the decision whether to build, refurbish, renew, extend, retain or demolish. It proceeds through the contractual arrangements for the design and specification, procurement of products, construction work, handover for fit-out and use, commissioning, actual use and finally, at the end decommissioning, the deconstruction or demolition. The overall information about the life cycle of a building covers the different stages over the lifespan of a building, while supplementary information, beyond its life cycle, can also be considered, such as benefits and loads outwith the system boundary (e.g. reuse, recovery, recycling potential). The stages of the building lifecycle are classified as *before use*, *during use* and *after use*.

The *before use* stage includes the following phases: 1) pre-construction (land and associated fees/advice), 2) the product stage (raw material supply, transport, manufacturing) and 3) the construction process (transport, construction, installation process). The *during use* stage includes aspects that do not necessarily represent consecutive phases, such as : a) use, b) maintenance, c) repairs, d) replacements, e) refurbishment, f) operational energy use, g) operational water use. The *after use* stage includes the following activities: 1) deconstruction, 2) transport, 3) waste processing for reuse, recovery or/and recycling, 4) disposal.

An overview of the costs sustained in the different phases of the life cycle of a building is provided in Table 1.

Calculation procedure and indicators for the economic sustainability assessment of buildings (EN 16627)

Whereas the EN 15643-4 Standard provides general framework and definitions for the economic assessment of new and existing buildings, the EN 16627 Standard [27] supplies calculation rules and economic indicators based on principles developed in the ISO 15686-5 Standard [28].

The EN 16627 Standard is applicable to new and existing buildings as well as refurbishment projects. It considers the following approaches to calculate economic performance.

a) *Life cycle costing* (LCC): economic performance, expressed in cost terms over the life cycle, in which the negative costs related to energy exports and to the re-use and recycling of parts of the building during its life cycle and at the end of life are taken into account.

b) *Life cycle economic balance*: LCC as well as incomes over the life cycle and at the end of life.

The process for the calculation of the economic performance entails eight main steps, as shown in Figure 4. The first step concerns the identification of the purpose of the assessment, and this is achieved by establishing the objective and criteria. The intended use of the economic assessment may also include:

- assistance in the decision making process (comparison of the economic performance of different design options, comparison of the economic performance of refurbishment, reconstruction and/or new construction, contributing to the identification of the potential for improved performance, contributing to the setting of budgets),
- declaring the expected performance, with respect to legal, funding or other requirements,

- documenting the economic performance of a building,
- support for policy development.

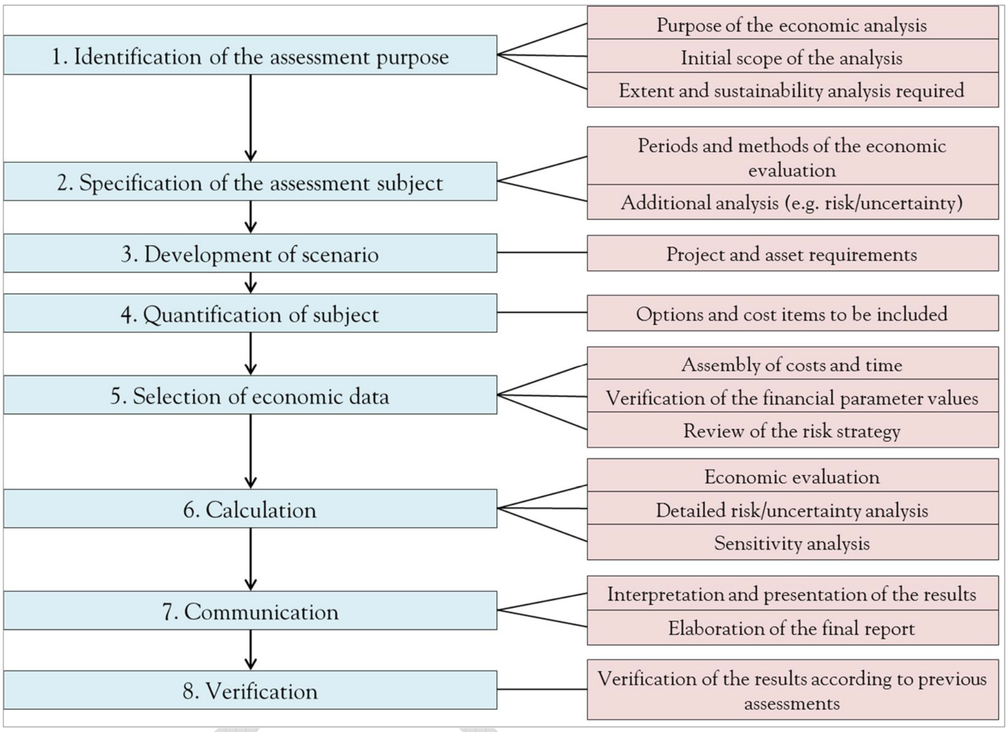

Fig. 4. Procedure for the economic performance assessment of buildings.

The second phase concerns the specification of the subject of the assessment by means of an identification of the analysis period, the economic evaluation methods and the possible need for additional analysis (risk/uncertainty and sensitivity analysis). Assessments are carried out on the basis of a chosen *reference study period* (RSP). The default value for the RSP should be the *required service life* (ReqSL) of the building, which is defined as the period of time after installation during which a building, or an assembled system (part of works), meets or exceeds the technical performance and functional requirements. When the RSP is less than the ReqSL, the end of life costs are calculated and then discounted to the end of the ReqSL. When the RSP is longer than the ReqSL, refurbishment or demolition and re-construction scenarios should be developed; the economic assessment should include the overall costs and incomes of both the actual ReqSL and its extension.

If a building undergoes a major refurbishment, in which the refurbishment changes the building type, the building use, or required service life, i.e. the *functional equivalent*, then a new assessment should be carried out. In this case, the costs of the refurbishment materials and reconstruction/installation processes are allocated to the *before use* stage.

The third step of the procedure is the scenario development, which is attained by identifying the project and asset requirements. The scenarios should be realistic, representative and in accordance with the technical and functional requirements given in the *functional equivalent* section and taken from the client's brief, the regulatory requirements and the project specifications. The information or data should be assumed, estimated or calculated, or based on actual measurements and reported in the assessment report. The sources of information and methods should be documented in the report.

The fourth action pertains to the quantification of the subject, and this is obtained by identifying the various options that have to be included and cost items that have to be considered. The cost items are those that were introduced by EN 15643-4 and which are listed in Table 1.

The fifth step of the economic assessment procedure is the selection and the collection of economic data and the times related to the verification of the financial parameter values and the period of analysis. For the assessment of the life cycle costing, in terms of net present value, it is necessary to specify the discount rate that has to be used for the calculation. For comparability purposes, the *NPV* should be conducted with a real interest rate of 3%. The higher the selected rate, the less influence the costs will have on the calculation of the net present value later on during the required service life. Higher rates tend to favour lower initial cost solutions, which in turn can lead to higher annual operating costs.

Escalation rates may be used as a type of sensitivity analysis when there are grounds to anticipate that the standard rate of inflation does not apply in the case of a specific option. Real rates should generally be used; these rates exclude the impact of future inflation. Nominal rates may be used, on agreement with the client, or when justified by the situation. Different escalation rates may be used for different components of the analysis, including energy costs, water and waste water costs, construction, services and in use costs.

Data quality requirements should be applied: the data should be as up to date as possible; the data should be checked for plausibility; the technological coverage should reflect the physical reality of the declared product or product group; the geographical coverage should be representative of the region in which the production is located.

The calculation represents the sixth step of the assessment procedure. It includes the economic evaluation, a detailed risk/uncertainty analysis and a sensitivity analysis. The costs and incomes should initially be calculated without applying any discount or escalation rate. This gives the nominal value. The level of aggregation of the costs and incomes depends upon the level of detail that is available. It is important to identify which of these costs are recurrent costs and which are non-recurrent costs, and to specify the year used for the reference cost and the year of occurrence of the cost.

The EN 16627 Standard specifies what economic indicators, such as the discount factor ($DF(t)$), the net present value (NPV) and the annual equivalent value (AEV), can be included in the calculation. The following additional economic indicators can be considered:

- *Value stability in a short-term perspective*. The investment costs at the time of completion and handover of the building are compared with the market value/current market price at the time of delivery. The market value is preferably determined on the basis of the income approach (e.g. direct capitalisation, discounted cash flow, gross income multiplier). Value stability is achieved when the market value has at least reached the same level as the investment costs.

- *Value stability and performance in a medium-to-long-term perspective*. No established or accepted methods are so far available to evaluate the stability value or performance over an extended period of time. The medium-to-long-term stability value and performance are influenced by the specific market, location and building characteristics, among others. The subject under observation in a sustainability assessment of buildings is the building itself and its site. Therefore, only the building-related contribution to the stability value and performance can be assessed. This can be done using "consequential" indicators, for instance:
  - *flexibility and adaptability* of the building to changing user needs, in order to lower the risk of changes on the market,
  - *energy performance* of the building, in order to reduce the risk of energy price changes and to lower the risk of depreciation, if a high energy performance becomes the "standard" on the real-estate market (and property rating),
  - *environmental performance*, in order to reduce several risks (e.g. reputation risk) and to lower the risk of depreciation, if an environmental performance becomes the "standard" on the real-estate market (and property rating),
  - *adaptability of the building to climate changes*,
  - *durability*.
- Economic indicators described in ISO 15686-5 [28], such as the discounted payback period (*DPP*), *net savings* or *net benefits*, *savings to investment ratio*, internal rate of return (*IRR*).

The seventh and the eighth phases concern the communication of results and the verification of results, respectively. The communication of results is carried out through a report that includes:

- general information on the assessment (e.g. the purpose of the assessment, identification of the building, the assessment method, the period of validity of the assessment, etc.),
- general information on the subject of the assessment (e.g. the assessed *functional equivalent*, the reference study period, specific data on the building),
- statement of the boundaries and scenarios considered in the assessment,
- data sources,
- expression and communication of the results.

A verification of the results may be necessary, and if so, it should concern:

- consistency between the purpose of the assessment, the boundaries and the used scenarios,
- traceability of the data,

- consistency with the environmental and social assessments of the building,
- completeness and justification of the completeness for the quantification at the building level.

Economic evaluation procedure for energy systems in buildings (EN 15459)

The EN 15459 Standard [29] provides a calculation method that can be used to assess the costs of heating systems and other technical building systems. The Standard does not address the assessment of the whole economic impact of the building, as in the EN 16627 Standard, but it concerns a specific scope of the building, that is, the economic issues of the heating systems and other systems that are involved in the energy demand and energy consumption of the building. The method can be used, as a whole or in part, for the following applications:

- to consider the economic feasibility of energy saving options in buildings,
- to compare different energy saving options in buildings (e.g. plant types, fuels),
- to evaluate the economic performance of the overall design of the building (e.g. trade-off between energy demand and energy efficiency of the heating systems),
- to assess the effect of possible energy conservation measures on existing heating systems, through an economic calculation of the cost of energy use, with and without energy conservation measures.

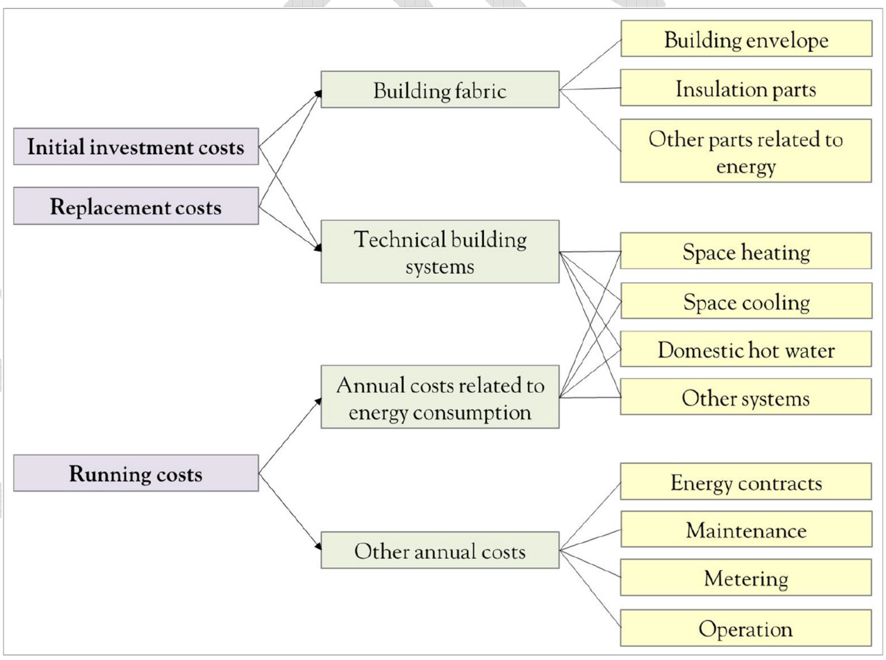

Fig. 5. Framework of the overall costs.

The calculation method provided by EN 15459 is based on a global point of view (overall costs). The costs are separated into investment costs (including periodic replacement of the components) and running costs.

The overall framework of the costs is shown in Figure 5.

The assessment procedure provided by EN 15459 uses the global cost (GC) as an economic indicator. The global cost takes into account the following cost items:

- Initial investment costs (C_i), which are the costs that have to be considered when the building (or the specific equipment) is delivered to the customer, ready to use. These costs include the design, the purchase of systems and components, connection to suppliers, installation and the commissioning process.
- Replacement or periodic costs (C_p), which comprise the periodic costs for the components at time t_p, $2t_p$, $3t_p$, etc. where t_p is the lifespan of the component.
- Running costs (C_r), which comprise:
    - maintenance costs, which are the annual costs for any measures necessary to preserve and restore the desired quality of the installation, and include inspections, cleaning, adjustments, preventive maintenance repairs and consumable items;
    - operational costs, which are the annual costs for operators;
    - energy costs, which are the annual costs for energy and the standing charges for energy, and other consumables, including contracts for the delivered energy;
    - added costs, which are the annual costs for insurance, other standing charges and for taxes. Subsidies for renewable energy, whether delivered or produced locally, are considered as benefits and are taken into account as negative annual costs.

The global cost (GC), as calculated in Eq. (8), represents the sum of the present value of the overall costs (referred to the starting year); at the end of the calculation period, the deconstruction costs, or the residual value of the components, should be taken into account to determine the final costs. The global cost may be calculated through a component or system approach, considering the initial investment cost (C_i) and – for each component or system j – the annual costs (C_a, which is the sum of the running costs, C_r, and the periodic costs, C_p) for every year t (referred to the starting year, t_0) and the final value ($V_{f,n}$). The global cost is directly linked to the duration of the calculation period n.

$$GC(n) = C_i + \sum_j \left[\sum_{t=0}^{n} \left(C_{a,t}(j) \cdot DF(t) \right) - V_{f,n}(j) \right] \tag{8}$$

The final, or residual, value ($V_{f,n}$) is the value of a component at the end of the calculation period n, considering its lifespan and referred to the starting year. It is determined by means of a straight-line depreciation of the initial investment until the end of the calculation period and referred to the beginning of the calculation period. The concept of the final value is illustrated in Figure 6 for a generic component that is replaced every 8 years, and considering a calculation period of 30 years.

Reference values of the lifespan, the annual maintenance costs and disposal costs of some technical system components are listed in Table 2.

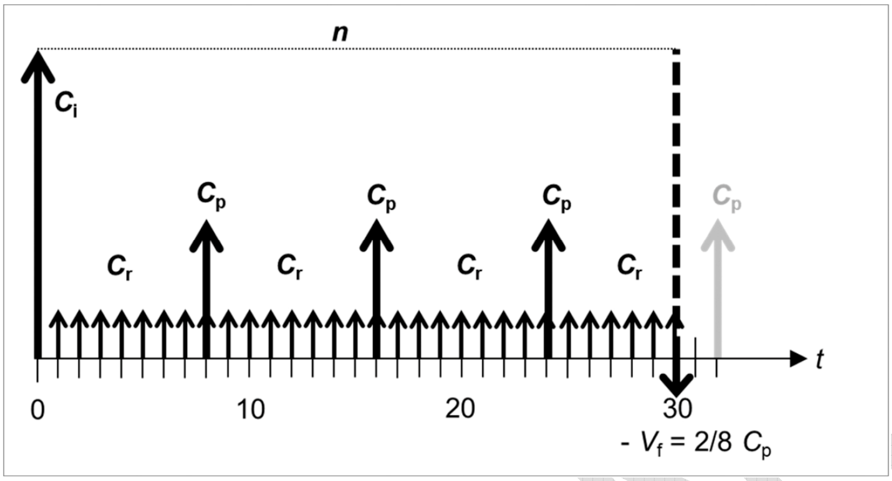

Fig. 6. Final value concept.

Table 2. Economic data for some technical system components.

Component	**Lifespan (min – max) [years]**	**Annual maintenance costs (including operation, repairs and servicing costs) [% of the initial investment]**	**Disposal costs [% of the initial investment]**
Air conditioning units	15	4	-
Boiler - condensing	20	1 – 2	-
Burners, oil and gas	10	4 – 6	-
Control system - central	15 – 25	4	-
Control system - room	15 – 25	4	-
Control valves - automatic	15	6	-
Control valves - manual	30	4	-
Convectors	20	1	-
Cooling panels and ceilings	30	2	-
Diffusers	20	4	-
Fan coil units	15	4	-
Fans	15 – 20	4	-
Fuel tank	30	0.5	5 – 10
Heat pumps	15 – 20	2 – 4	-
Heat recovery units - cyclic	15	4	-
Heat recovery units - static	20	4	-
Meters	10	1	-
Pumps - circulation	10 – 20	2	-
Radiators, water	30 – 40	1 – 2	-
Solar collector (vacuum, plate)	15 – 25	0.5	-
Tank storage for domestic water	20	1	-
Valve - thermostatic	20	1.5	5
Water floor heating	50	2	20

An alternative approach to economic evaluation presented in EN 15459 is to determine the annual equivalent costs (*AEC*) of the building. While the global cost calculation method provides a value of the total costs throughout the considered calculation period *n*, the annuity calculation method transforms, through the use of the annuity factor $a(t)$, all the costs to annual costs, i.e. the average annualised cost (see Eq. (7)). The calculations for the considered calculation period *n*, are separated into three parts, as follows:

1) investment costs that are related to the parts of the building structure that have to be taken into account, and any components and systems with a lifespan that is longer than or equal to the design payback period of the building, are distributed evenly over the design payback period of the building;

2) periodic or replacement costs are distributed evenly over the number of years between the occurrence of the costs;

3) running costs, which are calculated on an annual basis, are by definition annual costs.

Cost-optimal analysis of a building refurbishment

The previously analysed economic indicators and procedures are commonly applied in cost-effectiveness analyses of building renovations. The cost-optimal analysis is a special case of a cost-effectiveness analysis. Both are based on comparisons of the costs and priced savings (revenues) of potential refurbishment actions, but the cost-optimal analysis also allows the cost-effective action that has the highest net present value, or the lowest global cost over the estimated building life cycle, to be identified [30].

The 2010/31/EU Directive defines the cost-optimal level, when designing building renovation, as the energy performance level that leads to the lowest cost during the estimated economic lifecycle of the building [9]. A representation of cost-effectiveness and cost-optimisation is shown in Figure 7, which was partially derived from IEA [17] and BPIE [31]; a qualitative example of the global cost curve of building renovation is provided. Each point is a different option of renovation, represented in function of the global cost value (GC) and the amount of annual primary energy use of the building (*EP*). Point A is the reference situation, with reference to an ordinary renovation either for aesthetics or simple maintenance purposes; all the renovation options allow a reduced primary energy use (*EP*) to be obtained, in comparison to point A. Point B refers to the cost-optimal renovation option; it determines the lowest GC, and the *EP* value is lower than the *EP* value of point A. Point C is a cost neutral renovation option; it has the same global cost as A, but causes a higher reduction of primary energy compared to the cost-optimal solution ($|\Delta EP_{A\text{-}C}| > |\Delta EP_{A\text{-}B}|$). All points below the C to A dashed line (i.e. points in the green area) represent cost-effective solutions, because the primary consumption is reduced at lower costs compared to point A. Conversely, the points above the C to A dashed line (i.e. pink points) represent cost-ineffective solutions.

Another qualitative representation of the cost-optimisation concept is provided in Figure 8. The costs over the estimated building lifecycle (both positive and negative values, the latter in terms of revenues) are plotted against the degree of energy efficiency. The green area represents the range of cost-effective solutions and the dashed black line highlights the cost-optimal point of a building renovation [32].

In order to derive the cost-optimal level of renovations, a cost-optimal analysis procedure is presented in the following sub-sections together with optimisation methods and tools.

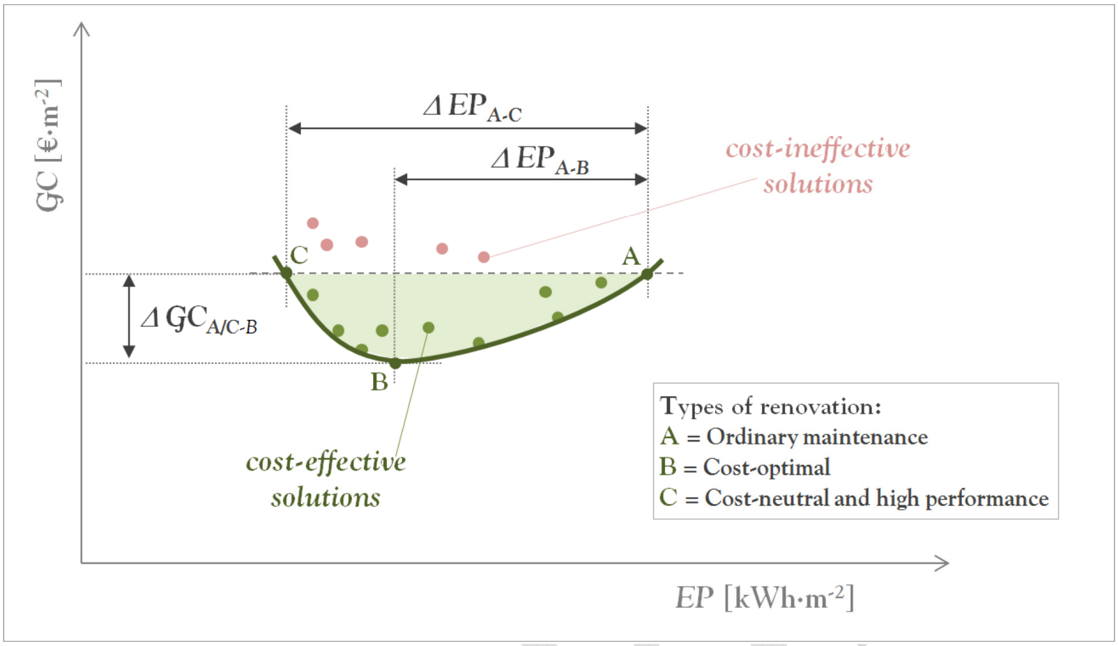

Fig. 7. Global cost curve of building renovation.

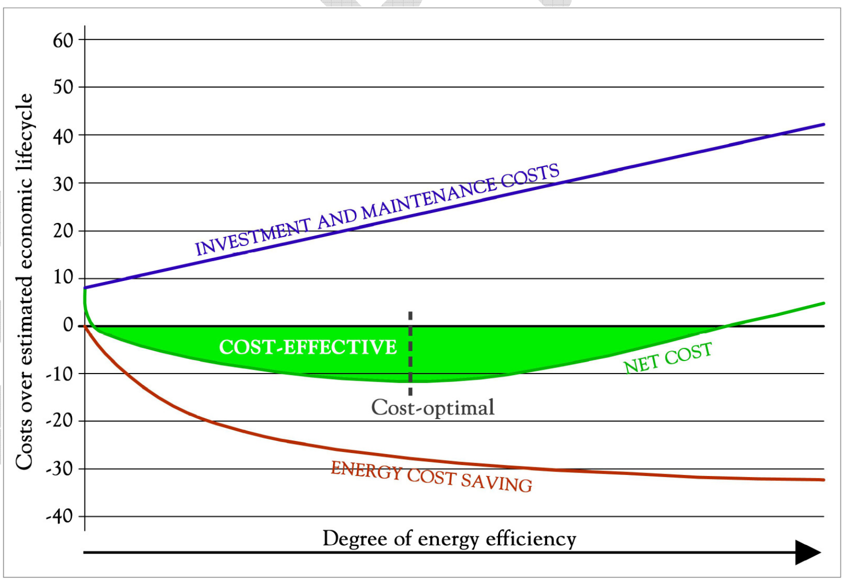

Fig. 8. The cost-optimal point over the cost-effective range.

Cost-optimisation procedure

Cost-optimality was introduced by Directive 2010/31/EU, which requires the Member States to set minimum requirements for the energy performance of buildings and building elements "*with a view to achieving the cost-optimal balance between the investments involved and the energy costs saved throughout the lifecycle of the building*" [9]. To this aim, a comparative methodology framework was set up by the EU Commission in Delegated Regulation No. 244/2012 [33], to calculate the cost-optimal levels of the minimum energy requirements.

According to Delegated Regulation [33] and its following Guidelines [34], EU Member States had to define "reference buildings" that represented the typical and average buildings of each country, in order to acquire results that were general and could be applied to the analysed building stock. In this view, cost-optimality is not perceived as a process that should be performed individually for a specific energy renovation case. However, this procedure can also be followed for a real single building to identify appropriate cost-effective and cost-optimal energy efficiency measures for its refurbishment.

The cost-optimal analysis procedure involves some distinct steps:

- definition of the reference buildings,
- definition of the packages of energy renovation measures,
- energy performance calculations to assess the building energy performance with and without the renovation measures,
- calculation of the LCC using the *NPV* method (global cost approach), and
- identification of the cost optimal (and cost-effective) set of measures.

It should be noted that a similar procedure has been followed in IEA EBC Annex 56 [17].

The first step focuses on the creation of reference buildings, a procedure that can be carried out in two different ways. The reference cases can be created through the selection of a real example that represents the most typical building of a specific category. These categories can be the type of use and reference occupancy pattern, or the floor area, compactness of the building, expressed as the envelope area/volume ratio, or building envelope constructions with corresponding *U*-values, technical systems and energy carriers, together with the share of energy use [33]. The reference cases can be defined through a "virtual building" which, for each relevant parameter, includes the most commonly used materials and systems [32,33]. Moreover, projects already carried out through the Intelligent Energy Europe (IEE) programme can be used as references e.g. TABULA [35] and ASIEPI [36]. When the analysis has to be addressed to a real single building, and the results do not need to be generalised, the step concerning the definition of reference buildings is omitted.

Energy renovation measure packages can be categorized as improvements of the building envelope measures, improvements of the energy systems (e.g. space heating and cooling, domestic hot water and ventilation) and the use of renewable sources for energy production (both thermal energy and electricity). The research community usually deals with packages of measures that include at least the first two categories and, when deep renovations are involved, the third category is also included [32,37-42]. The energy renovation measure packages can be based on practice and scenario trends for future fuel mixes or based on scenarios to achieve EU and national goals.

According to EN ISO 13790 [43], three different energy calculation models can be used to assess the building energy performance (*EP*): a monthly quasi-steady-state calculation method, a simple hourly dynamic calculation method and a detailed (hourly) dynamic simulation method. Each Member State usually has its own national method and tools to calculate the energy performance of buildings [37]. The *EP* indicators, requirements and ratings are provided in ISO 52003-1 [44].

As far as the economic evaluation (LCC) is concerned, the *NPV* method is the one that is currently used the most in order to find the optimal energy design for building renovation. The European Commission requires a global cost approach, considering both a financial scenario and a macroeconomic scenario. As far as the financial level is concerned, the global cost (GC) includes the cost items that were presented previously in the "Cost analysis" section, while the macroeconomic scenario also considers the costs that correspond to CO_2 emissions (i.e. monetary value of the environmental damage) [33].

The last step of the cost-optimal analysis regards the application of a cost-optimisation procedure to identify the cost-optimal package of energy efficiency measures. Many optimisation methods and tools have been applied in literature, and are presented in detail in the following sub-section.

Optimization methods and tools

When performing a cost-optimal analysis for a building refurbishment, the goal is to choose the optimal solution, which is often based on several criteria. The most common criteria is a level of energy performance, usually expressed in kWh·m^{-2}, at the lowest possible cost, e.g. expressed in €·m^{-2}. Optimization is a process that is necessary for a cost-optimal refurbishment analysis. Various optimization methods are used by researchers and practitioners. They can be categorized into three main groups: enumerative, calculus-based and random methods.

The enumerative methods are based on the principle of a finite search space, where the algorithm assesses the fitness function at each point in space, one at a time. The strong point of enumerative methods is their simplicity and easy implementation. However, a lack of efficiency and an inability to be applied to large datasets has been reported [45].

The calculus-based methods – also called systematic or exact methods – are based on the rigorous mathematical expression of the objective function or of its gradient [46]. These methods can be direct or indirect. The difference between the two is that indirect methods search for the local optima by solving the equation and setting the gradient of the objective function to 0, whereas direct methods search for local extrema by hooping on the function and moving in a direction related to the local gradient [45]. Calculus-based methods are used to optimise Heating Ventilation and Air Conditioning (HVAC) systems. However, calculus-based methods suffer from two disadvantages. First, the convergence of these methods is dependent on the regularity of the objective function hypotheses. Second, the methods search for local optima. They only converge to the global optimum if the starting point of the algorithm is in the neighbourhood of this optimum [45]. If several local optima exist, then the implementation requires long hours of work.

Random or stochastic methods are based on the random evolution of solutions. These methods include simulated annealing, the taboo search method, genetic algorithms and more. Genetic Algorithms (GAs) are particularly interesting and are in fact used widely, in numerous scientific fields. They are evolutionary algorithms that use an analogy of natural selection mechanisms through genetic concepts [47]. GAs use a population of solutions. Each iteration involves a competitive selection in which the non-feasible or less optimal solutions are removed. After several iterations, the final population consists of the improved solution. GAs have been used in several optimization analyses in the built environment, but mostly for HVAC systems [48-50].

The optimisation method in cost-optimal building refurbishment analyses is of a multicriteria type. The minimum criteria are an improved energy performance level and the lowest cost possible to achieve the pre-established energy performance during the lifecycle of the building. In many cases, a Pareto curve is used in order to work with multiple criteria. When the problem considers two or more objectives – such as the cost-optimal energy refurbishment of buildings – the Pareto curve is of a non-dominated solution type [45,50]. When the Pareto curve is used, the objectives are treated independently during the optimization process. Several tools are available for the multi-objective optimization of the energy refurbishments of buildings, and many more are currently being developed. These various optimization tools have different features. Palonen et al. [51] drew up a general categorisation of these tools on the basis of their customization. The customized tools for building energy performance optimization include Opt-E-Plus, GENE_ARCH, BEopt™, TRNOPT, MultiOpt2 and jEPlus+EA. These customized tools are combinations of optimization algorithms and building performance simulation engines. Opt-E-Plus, which was developed by Ellis et al. [52], is coupled with EnergyPlus. GENE_ARCH, which was developed by Caldas et al. [53], is coupled with the DOE2.1E, using GAs to find energy efficient architectural solutions. BEopt™ [54] can be coupled with DOE2.1E or TRNSYS, and it includes a graphic user interface (GUI). TRNOPT is defined as an interface that combines TRNSYS with the generic GenOpt optimization tool [55], with the goal of optimizing a single cost function. MultiOpt2 is a multi-objective optimization tool that was developed to be coupled with TRNSYS 17 [56]. Finally, jEPlus+EA couples with jEPlus, but one of its drawbacks is that all the variables are considered discrete during the optimization.

Generic optimization tools can ideally be coupled with any simulation engine, such as EnergyPlus, TRNSYS etc. GenOpt, DAKOTA and MATLAB Optimization and Direct Search Toolboxes are some examples of generic optimization tools. The advantage of generic optimization tools is that they can be coupled with any simulation engine the user requires. However, these generic tools are expected to be less user-friendly for inexperienced users [51]. This is often caused by the adoption of different configurations of the model files in different simulation programmes and in the input-output files structure [51]. GenOpt was developed to tackle the issues that generic optimization tools face. Similarly, new generic optimization tools have been developed to allow users that are inexperienced with GUI to use them and to make them easy to couple with simulation programmes, such as the MOBO (Multi-Objective Building Optimization) tool and others.

In short, many methods and tools that can be used to optimize the available cost-efficient energy refurbishment solutions are accessible and more are being developed. Ultimately, this decision is user-dependent, and the fundamental criterion is the optimization that best fits a given problem.

Example of cost analysis

An example of cost analysis, in which the procedures and indicators presented in the chapter are applied, is reported in the present section. The objective is to identify the cost-optimal solution among the different possible energy retrofitting options that can be applied to an existing building.

The considered building is an uninsulated single-family house built in the 1946-60 period in Palermo (Italy). It is characterised by a very poor energy performance; the annual primary energy use for space heating, space cooling and domestic hot water (DHW) amounts to 219 $kWh{\cdot}m^{-2}$. The main geometric data of the conditioned space, and the thermo-physic features of the envelope components, are reported in Table 3. The building is equipped with a standard gas boiler (73% mean seasonal efficiency) to cover the space heating and DHW needs, and a split air conditioning system for space cooling (*EER*=2.35 at full load). The heating emitters are radiators, and an external probe is used as the heat control system.

Table 3. Main geometric and construction data of the case study.

Picture of the building	**Geometric data**		**Thermo-physical features of the building envelope**	
	V	583 m^3	U_{wall}	1.18 $W{\cdot}m^{-2}K^{-1}$
	A_f	162 m^2	U_{roof}	2.20 $W{\cdot}m^{-2}K^{-1}$
	A_{env}/V	0.75 m^{-1}	$U_{f,bottom}$	2.00 $W{\cdot}m^{-2}K^{-1}$
	A_w	20.3 m^2	U_w	4.90 $W{\cdot}m^{-2}K^{-1}$
	A_w/A_{env}	0.046	$g_{gl,n}$	0.85

A global building refurbishment has been carried out adopting the energy efficiency measures (EEMs) listed in Table 4. Each measure is described through a parameter; for instance, thermal insulation is described by the thermal transmittance parameter. Up to 5 energy efficiency options (EEOs) have been proposed for each measure. Each option represents a different value of the associated parameter that leads to an increasing level of energy efficiency. The first level usually represents an inefficient solution and is used as a test value. The second and third levels are close to the requirements fixed by the current national legislation [57]. The fourth and fifth levels (if applicable) are more efficient solutions. Each option corresponds to a technically feasible solution, which can be set in function of different scenarios of refurbishments, in accordance with the third step of the EN 16627 procedure (see Figure 4).

The initial investment cost associated to each EEO has been obtained either from extensive market surveys or from official databases. The investment costs are indicated in Table 4 for each EEO. The energy carrier costs are provided by the Italian National Authority for Electricity, Natural Gas and Water (AEEGSI) [58]. The estimated energy carrier price development trends are those suggested by the European Commission on a biannually updated basis (PRIMES model), according to Annex 2 of Commission Delegated Regulation No. 244/2012 [33].

Table 4. Energy efficiency measures (EEMs), options (EEOs) and the related initial investment costs for a global refurbishment of the case study.

EEM		Param.	Unit	EEO 1	EEO 2	EEO 3	EEO 4	EEO 5
1	Thermal insulation of the walls *Investment cost*	U_{wall} C_i	[$W \cdot m^{-2}K^{-1}$] [k€]	0.65 *8.51*	0.48 *8.96*	0.42 *9.64*	0.36 *10.59*	0.30 *11.93*
2	Thermal insulation of the roof *Investment cost*	U_{roof} C_i	[$W \cdot m^{-2}K^{-1}$] [k€]	0.50 *3.49*	0.38 *4.04*	0.35 *4.24*	0.33 *4.39*	0.30 *4.65*
3	Replacement of the windows *Investment cost* *Associated technology*	U_w C_i -	[$W \cdot m^{-2}K^{-1}$] [k€] -	5.80 *4.80* *single glass*	3.00 *5.58* *double glass*	2.60 *6.81* *double glass*	2.20 *8.13* *low-e double glass*	1.80 *8.51* *low-e double glass*
4	Solar shading devices *Investment cost* *Associated technology*	τ_{sh} C_i -	[-] [k€] -	0.20 0.89 *fixed louvres*	0.20 *2.34* *movable louvres*			
5	Replacement of the thermal system: - space heating and DHW generator *Investment cost* *Associated technology*	η_{gn} C_i -	[-] [k€] -	0.88 *2.53* *standard boiler* [a]	0.93 *2.75* *standard boiler* [b]	1.00 *3.96* *condensing boiler* [c]		
	- space cooling chiller *Investment cost*	*EER* C_i	[-] [k€]	2.90 *4.20*	3.50 *4.72*	4.00 5.25		
	Or, alternatively: - heat pump for heating, cooling and DHW [c] *Investment cost*	*COP* *EER* C_i	[-] [-] [k€]	2.50 2.30 *12.1*	3.10 2.90 *13.2*	4.10 3.50 *18.7*		
6	Thermal solar system *Investment cost*	A_{coll} C_i	[m^2] [k€]	2 *2.00*	4 *4.00*	5 *5.00*		
7	Photovoltaic system *Investment cost*	W_{PV} C_i	[kW_p] [k€]	1 *3.00*	3 *9.00*	4 *12.0*	5 *15.0*	

[a] Heating emitters: radiators; heat control system type: central.
[b] Heating emitters: radiators; heat control system type: zone.
[c] Heating emitters: fan-coils; heat control system type: room.

Among all the EEOs, the cost-optimal solution is the package of energy efficiency measures, each characterised by a parameter value among those proposed, that leads to the lowest global cost (GC) for the chosen building lifespan (calculation period). The global cost calculation has been performed according to EN 15459 [29], considering 30 years as the building lifespan and 4% as the real interest rate. No financial incentives have been taken into account. The technical lifespan of the building elements and the annual maintenance costs have been set according to EN 15459 (see Table 2). Sensitivity and uncertainty analyses (sixth step of EN 16627 shown in Figure 4) have here been omitted.

In the present calculation example, the cost optimisation procedure is based on a sequential search-optimisation technique, considering discrete options (or levels) of energy efficiency measures. The procedure refers to the model developed by Christensen et al. [54]. A reference set or package of energy efficiency options (EEOs) is assumed as the starting point of the optimization calculation. The procedure allows a sequence of "partial optimum" points to be identified. Each "partial optimum", which is a package of EEOs, is obtained from the previous one by modifying all the parameters that characterize the levels of each energy efficiency measure one at a time. The next "partial optimum" is the one which, compared to the previous one, allows the highest reduction, in terms of global costs, and which, from time to time, becomes the reference set. The last "partial optimum" is the cost-optimal solution. The optimisation procedure is presented in detail in Corrado et al. [59] and it has been demonstrated to be effective and robust.

The energy performance of the case study, in both its current condition and when the refurbishment measures are applied, is calculated according to the Italian technical specification UNI/TS 11300 series [60], which specifies a quasi-steady state calculation method based on EN ISO 13790 [43] and EN 15316 series [61].

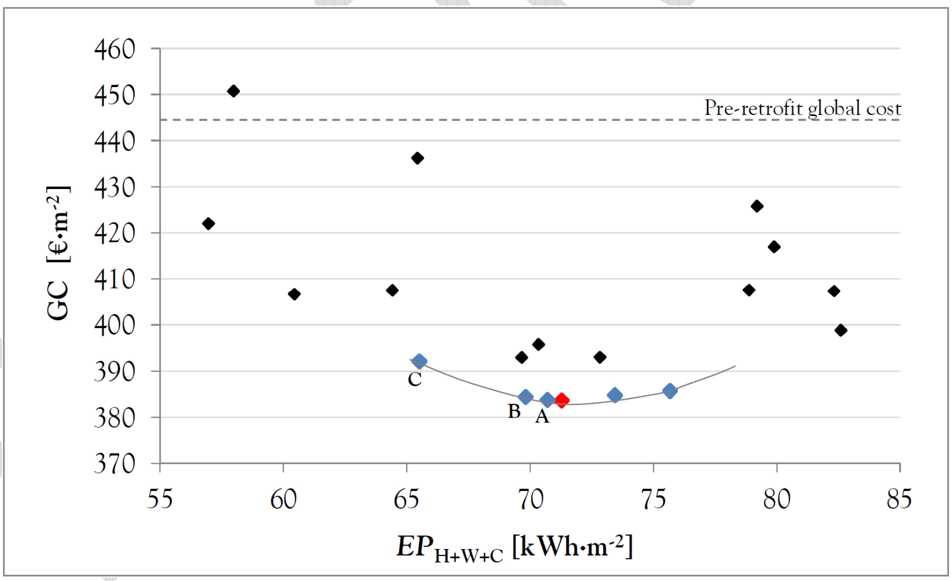

Fig. 9. "Partial optimum" points and cost-optimal range.

The results of the cost-optimisation procedure applied to the case study are presented in Figure 9, which shows the "partial optimum" points that result from different reference sets of EEOs assumed as starting points of the optimization procedure. Each point refers to a package of EEOs, and is represented in function of the global cost over a 30 year building lifespan and the annual primary energy for space heating, space cooling and DHW, both of which are normalised to the conditioned net floor area of the building. The red point in Figure 9 corresponds to the cost-optimal solution, which offers the lowest global cost. The "partial optimum" points on the global cost curve (blue points in Figure 9) could also be considered acceptable solutions; they present a very slight cost variation (2%) from the cost-optimal solution [21,62]. The points below the dashed line in Figure 9 are cost-effective renovation options, i.e. they determine a lower global cost with respect to the building in the current condition subject to ordinary maintenance and occasional replacements of components.

The packages of EEOs related to the cost-optimal solution and to the "A", "B" and "C" "partial optimum" points in Figure 9 are listed and compared in Table 5. It can be noted that the solutions do not differ as a result of changes in the technical systems and the RES technology, but do differ for increasingly higher levels of thermal insulation of the envelope.

Table 5. Cost-optimal package of energy efficiency options and other acceptable solutions.

EEM		**Param.**	**Unit**	**EEOs package**			
				Cost-optimal	**A**	**B**	**C**
1	Thermal insulation of the walls	U_{wall}	$[W \cdot m^{-2}K^{-1}]$	0.42	0.42	0.42	0.30
2	Thermal insulation of the roof	U_{roof}	$[W \cdot m^{-2}K^{-1}]$	0.38	0.35	0.30	0.30
3	Replacement of the windows	U_w	$[W \cdot m^{-2}K^{-1}]$	3.00	3.00	3.00	3.00
4	Solar shading devices	τ_{sh}	[-]	0.2 *fixed louvres*	0.2 *fixed louvres*	0.2 *fixed louvres*	0.2 *movable louvres*
5	Replacement of the thermal system: - generator for heating and DHW (condensing)	η_{gn}	[-]	1.00	1.00	1.00	1.00
	- chiller for space cooling	*EER*	[-]	2.90	2.90	2.90	2.90
6	Thermal solar system	A_{coll}	$[m^2]$	2	2	2	2
7	Photovoltaic system	W_{PV}	$[kW_p]$	1	1	1	1

Other packages of EEOs are analysed hereafter; they have been obtained from the cost-optimal (CO) package by increasing the level of each EEM parameter (see Table 4) one at a time. The analysed packages of EEOs are reported in Table 6 and can be identified as follows:

- S1 = CO with higher thermal insulation of the walls,
- S2 = CO with higher thermal insulation of the roof,
- S3 = CO with higher thermal insulation of the windows,
- S4 = CO with a heat pump instead of a condensing boiler,
- S5 = CO with a higher solar collector area.

Table 6. Analysed packages of energy efficiency options. The EEOs marked with an asterisk differ from

the cost-optimal solution.

EEM		Param.	Unit	EEO package				
				S1	S2	S3	S4	S5
1	Thermal insulation of the walls	U_{wall}	[W·m^{-2}K^{-1}]	0.30*	0.42	0.42	0.42	0.42
2	Thermal insulation of the roof	U_{roof}	[W·m^{-2}K^{-1}]	0.38	0.30*	0.38	0.38	0.38
3	Replacement of the windows	U_w	[W·m^{-2}K^{-1}]	3.00	3.00	1.80*	3.00	3.00
4	Solar shading devices	τ_{sh}	[-]	0.2 *fixed louvres*	0.2 *fixed louvres*	0.2 *fixed louvres*	0.2 *fixed louvres*	0.2 *fixed louvres*
5	Replacement of the thermal system: - generator for heating and DHW (condensing)	η_{gn}	[-]	1.00	1.00	1.00		1.00
	- chiller for space cooling	*EER*	[-]	2.90	2.90	2.90		2.90
	- heat pump for heating, cooling and DHW	*COP* *EER*	[-] [-]				2.50* 2.30*	
6	Thermal solar system	A_{coll}	[m^2]	2	2	2	2	5*
7	Photovoltaic system	W_{PV}	[kW$_p$]	1	1	1	1	1

The main economic and energy indicators calculated for each package are reported and compared with the cost-optimal and the base case (i.e. building in the current condition) in Table 7. The cost-optimal solution, as expected, presents the lowest global cost (384 €·m^{-2}) and the highest *NPV* (60 €·m^{-2}), and determines 67% of energy savings – in terms of annual primary energy use for space heating, space cooling and DHW – compared with the base case.

Table 7. Economic and energy indicators of the base case and the packages of energy efficiency options.

Indicator	Symbol	Unit	Base case	EEO package					
				Cost-optimal	S1	S2	S3	S4	S5
Global cost (30 years)	GC	[€·m^{-2}]	444	384	388	384	396	561	412
Net present value (30 years)	*NPV*	[€·m^{-2}]		60.5	56.7	59.8	47.9	–117	31.8
Discounted payback period	*DPP*	[a]		23	23	23	24	>30	27
Annual primary energy for heating, DHW and cooling	EP_{H+W+C}	[kWh·m^{-2}]	219	71.3	66.8	69.8	67.4	42.5	72.3
Energy savings	ΔEP_{H+W+C}	[%]		–67%	–69%	–68%	–69%	–81%	–67%

All the other analysed packages are cost-effective, except S4 (heat pump instead of condensing boiler), which presents a discounted payback period that exceeds 30 years, even though it determines the highest energy savings (81%) of all the analysed solutions. The increase in the solar collector area (S5) does not lead to any higher energy savings than the cost-optimal solution; in addition, it presents a lower net present value and higher discounted payback period. The EEO packages with increased levels of thermal insulation of the opaque envelope components (S1 and S2) present similar energy saving and economic indicator values to the cost-optimal solution, as can be also seen in Table 5. The same amount of energy savings (69%) can be achieved by applying more performing windows (S3) to the cost-optimal solution, even if a lower *NPV* is found (48 €·m^{-2}).

Conclusions

The energy performance of existing buildings is generally inadequate, and the energy consumed in these buildings place the sector among the most significant CO_2 emission sources in Europe – in fact, 38% of the total final energy is consumed in buildings. According to several research studies and statistical information, the number of renovation activities will be greater than the number of new constructions and demolitions in the future. However, large scale renovation of buildings is hard to mobilize. Despite the numerous studies and research results that have indicated the energy renovation potential for saving energy and reducing the environmental impact of the building sector, progress is noticeably slow. In this chapter, we have attempted to show that taking into account the direct and indirect benefits of building renovation is essential for the implementation of large-scale building renovation projects. Moreover, the cost of the renovations, in relation to the efficiency that can be achieved at the end of the renovation process, is of equally great importance in order to mobilize the sector.

The integration of costs in the renovation process is one of the most significant steps towards a comprehensive understanding of the benefits of building stock refurbishment. Cost-effectiveness is the assessment method of the energy renovation process aiming at the effective reduction of primary energy consumption and carbon emissions of the building stock, in terms of life cycle costs. The goal of incorporating cost-effectiveness in a building renovation process is to calculate the effect of the benefits of the renovation on the costs required to perform this process.

In order to carry out an effective cost analysis, the correct procedure and the most convenient indicators should be used. A detailed analysis of cost assessment methods, as provided by technical standards, is presented in this chapter. In a life cycle cost approach, the net present value and the global cost of a building retrofit action have been shown to be the main indicators that can be used for cost-effectiveness.

When a building renovation is designed, the cost-optimal package of energy efficiency measures in a cost-effectiveness analysis is the solution that leads to the lowest global cost (or the highest net present value) during the estimated economic lifecycle of the building. The cost-optimisation is usually carried out by means of a suitable procedure that encompasses optimisation tools, energy performance calculation methods, and a choice of feasible energy efficiency solutions. The example of cost-optimal analysis presented in this chapter has demonstrated that more than one cost-optimal solution might be found for the same building. High energy savings can be achieved, by taking into account several feasible measures with different levels of energy performance, and a cost-effective renovation can be even guaranteed.

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Nomenclature

A	area [m^2]	g	total solar energy transmittance [-]
a	annuity factor [-]	GC	global cost [€]
AEC	annual equivalent cost [€]	IRR	internal rate of return [%]
AEV	annual equivalent value [€]	NPV	net present value [€]
C	cost [€]	R	revenue [€]
CF	cash flow [€]	r	real interest rate [%]

COP	coefficient of performance [-]
DF	discount factor [%]
DPP	discounted payback period [a]
EER	energy efficiency ratio [-]
EP	energy performance [kWh·m^{-2}]
f_{pv}	present value factor [-]
U	thermal transmittance [W·m^{-2}K^{-1}]
V	volume [m^{3}]
V_f	final value [€]
W	power [W]
η	efficiency [-]
τ	transmission factor [-]

Subscripts

a	annual
C	space cooling
c	collectors
disc	discount
env	envelope
f	floor
gl	glazing
gn	generation (heat)
H	space heating
i	investment
in	inflation
m	market
n	normal incidence
p	periodic
PV	photovoltaic
r	running
sh	shading
W	domestic hot water
w	windows

Acronyms and abbreviations

BPIE	Buildings Performance Institute Europe
CO	cost-optimal
DHW	domestic hot water
EBC	Energy in Buildings and Communities
EED	Energy Efficiency Directive
EEM	energy efficiency measure
EEO	energy efficiency option
EPBD	Energy Performance of Buildings Directive
EU	European Union
GA	genetic algorithm
GUI	graphic user interface
HVAC	Heating Ventilation and Air Conditioning
IEA	International Energy Agency
IEE	Intelligent Energy Europe
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
ReqSL	required service life
RES	renewable energy source
RSP	reference study period