Comparative cost analysis of traditional and industrialised deep retrofit scenarios for a residential building

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Abstract

In this paper, the economic competitiveness for deep retrofit actions between the industrialised off-site and the traditional on-site approaches are discussed by using a comparative Life Cycle Costing (LCC) analysis. This assessment was based on a deep analysis of all renovation-related cost and timing processes, from design to operation and maintenance phases. The study was based on three retrofit scenarios for an existing building in Italy undergoing a deep renovation. The Life Cycle Inventory (LCI) was developed starting from real costs and a list of bills collected by the design team and the industrialised technologies developers. Afterwards, the LCC modelling was performed for all scenarios. The results show that the two deep retrofit approaches (traditional and industrialised) are comparable in terms of investment costs, even if a gap of around -7% and +16% still exists. This highlights a potential for technological optimisation. Moreover, the operation and maintenance phase has shown to be key to transforming the expected higher quality of the industrialised components into a prolonged life expectance, hence highly impacting the whole cumulated Net Present Value. Finally, the analysis of the End of Life (EoL) phase in case of possible reusing of some dismantled components in the industrialised scenario resulted in contributing in a relevant way to increase the final value of such an approach.

Keywords

deep retrofit of existing building, industrialised approach, prefabricated envelopes, multifunctional envelopes, LCC

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1 INTRODUCTION

Buildings in the EU are responsible for 40% of energy consumption and 36% of greenhouse gas emissions (International Energy Agency (IEA), 2019). Hence, the buildings sector is the largest energy consumer in the EU and one of the largest CO_2 emitters (European Commission - Energy Department., 2020).

Building stock retrofit is a crucial aspect and a primary concern in the European agenda as a reflection of the relevant role played by existing buildings in terms of energy consumption and CO_2 emissions, as demonstrated through the launching of the Energy Performance of Buildings Directive EPBD recast (2018/844) and the Renovation Wave strategy, presented in 2020 by the European Commission to boost building renovation in Europe (European Commission, 2020).75% of the existing buildings in the EU are energy inefficient, with an energy label below A (European Commission - Energy Department., 2020). European regulations regarding building retrofit in Member States, therefore, aim to improve the energy performance of the existing building stock (Annunziata et al., 2013). Three main categories of energy renovations can be identified: light, medium, and deep retrofit actions, with a building performance respectively less than 30%, between 30% and 60%, and above the 60% of final primary energy as declared in (European Commission, 2019). In terms of shallow and deep renovation solutions and related impacts, a theoretical techno-economic comparative study was conducted by (Semprini et al., 2017) for the city of Bologna. Given the ambitious target of CO_2 neutrality in Europe by 2050, set by the European Green Deal, a deep energy renovation of the building stock is a must, and the current renovation rate needs to be quickly and dramatically increased (Hélène Sibileau, 2021), (Semprini et al., 2017).

To achieve this vision, the deep retrofit of buildings has to be empowered through innovations able to trigger quicker renovation while assuring long-lasting performances. A potentially relevant game changer to trigger this transition is building industrialisation (through digitalisation and prefabrication), given the proven advantages evident from the new building sector.
The implementation of an industrialised retrofit approach was deeply studied in different research and innovation projects, as summarised in (D'Oca et al., 2018). This approach consists of the off-site production of prefabricated envelope modules (for the roof and the façades) ready to be directly installed on-site on the existing building, generally without the use of scaffolding, supported by a very detailed design grounded on the exploitation of different digital tools. The main envisaged advantages are related to construction site time reduction, cost compression, and low disturbance for the inhabitants (Andaloro et al., 2019), in parallel with improving the general building efficiency, exploiting an increased interconnection between the envelope and the energy systems (Sandberg et al., 2016). The current practices and future potential for such an industrialised approach were presented in (Konstantinou & Heesbeen, 2022). Moreover, the expected impacts of modularity and prefabrication in terms of sustainability were deeply investigated by (van Oorschot et al., 2021) for prefabricated timber façades.

In literature, a quite wide variety of solutions and a number of studies on their performances can be found. The hygro-thermal performances of multifunctional prefabricated timber frame façades integrating solar thermal panels, windows, decentralised ventilation machines, and shading systems were investigated by (Riccardo Pinotti, 2019). Another prefabricated façade system integrating a micro-heat pump and semi-centralised ventilation was studied and tested by (Ochs et al., 2015). Another study about the improvements in the indoor environmental quality and the energy consumption of an existing office building through the use of a prefabricated module was done by (Pungercar et al., 2021), showing 77% energy consumption reduction for a temperate climate.

Prefabrication and modularity could also trigger the creation of new spaces added to the existing buildings to increase energy performance, as discussed in (Fotopoulou et al., 2018). Finally, it is worth mentioning that a retrofitting intervention with an industrialised approach without relocating the inhabitants during the work was studied by (Zanni et al., 2023) and implemented in a real building, achieving structural and energy performance improvements. From a structural point of view, the retrofit solution entailed the adoption of a wooden shell made of CLT prefabricated panels.

Despite the development of several prefabricated technical solutions and the constant improvements in their technologies, the topic of the costs was hardly discussed due to many reasons: confidentiality, lack of standardised methodology, lack of reliable primary data, and sensitive calculation procedure. The costs of the actual implementations of low-tech industrialised renovation solutions (with a very low level of multifunctionality) were reported in (ECSO, 2017) based on the Energiesprong experience in the Netherlands. Energiesprong is heavily promoting such an industrialised approach through a series of real cases of implementation of low-tech retrofit solutions, aiming at activating such a market and optimising the final renovation costs through mass activation.

The off-site industrialised retrofit approach considered in this analysis aims at providing a prefabricated solution set to achieve the nearly Zero Energy Building (nZEB) energy target, minimising the on-site work by integrating the needed components directly in the new envelope. The building renovation's underlying energy concept is based on energy demand electrification, generating energy with a heat pump system to deliver hot-cold water for both Domestic Hot Water (DHW) and space heating-cooling. The DHW distribution exploits the existing building hydraulic network, while a new water distribution system runs into the new prefabricated façade to a semi-centralised mechanical ventilation system, part of the so-called Energy and Fresh air prefabricated façade kit. Such an innovative system comprises a double-flow ventilation machine with heat recovery, with an added water-air heat exchanger to control the air inlet temperature. This allows to supply each flat with both fresh air and heating/cooling power, depending on the season. Finally, a Building Integrated Photo Voltaic (BIPV) cladding with appealing innovative finishing allows to generate on-site solar energy, eventually storable in a battery, to increase self-consumption and lower the final energy building demand. FIG. 1 shows the kind of industrialised façade and roof module concepts considered in this analysis.

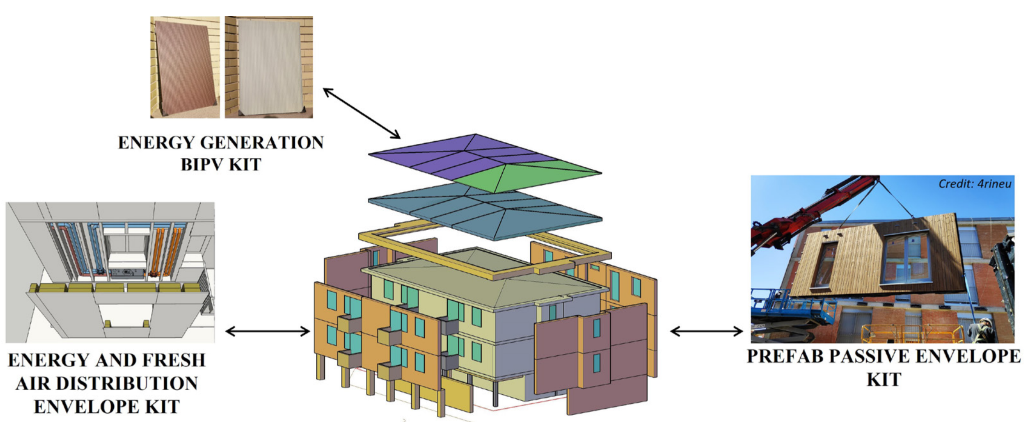


FIG. 1 Schematic representation of the prefabricated envelope (roof and façade) solutions used in the industrialised deep retrofit approach.

Given the technical complexity of the multifunctional prefabricated envelope solutions and the urgency to provide reliable and market-acceptable solutions for the deep renovation, the topic of the overall renovation cost was tackled. The aim of this study was to assess such an industrialised deep building retrofit approach from a cost perspective to better understand its competitiveness. The main research questions were the following: (i) How far is the industrialised retrofit approach competitive against the traditional one? (ii) What is the cost distribution of current and industrialised deep renovation?

2 METHODOLOGY

To answer these questions, a comparative economic analysis of different retrofit scenarios was developed to better understand the advantages and limits of an industrialised retrofit process over a traditional one. Specifically, a Life Cycle Costing (LCC) comparative analysis was performed for an existing building in Italy undergoing a deep industrialised retrofit process. The LCC is a lifecycle-based technique that evaluates an anthropic system from the economic point of view, from design to dismission and disposal phases. This kind of approach allows for assessing the full cost of long-life goods, in this case, buildings which imply long-term maintenance and use phase, as well as high installation costs (Ciroth et al., 2011).

2.1 THE REFERENCE BUILDING

The LCC comparison was done at the building level, based on an actual building located in Greve in Chianti (Florence, Italy), under the Italian climatic zone E. It is a social housing block of four apartments constructed in 1979. The apartments are distributed across two floors above a *pilotis* ground level, for a total net heated area of around 400 m^2. Each apartment has a gross area of 97 m^2. The façade gross area is around 415 m^2, of which 55 m^2 are windows (FIG. 2). The 8° pitched roof covers an extension of about 215 m^2, and the eight balconies cover a total surface of 21 m^2. In TABLE 2, the main building envelope and internal partition features are reported in detail. The choice of the building was made to ensure the collection of reliable primary data related to the building features and to the different retrofit strategies, given the availability of the building owners, designers, and retrofit technologies suppliers.

FIG. 2 Reference building pictures from different sides (from left to right, East, West, North).

TABLE 1 Construction details of the reference building in its state of the art.

Envelope construction typology description

Walls	Materials	Thickness	U-value
		m	W/m²K
External walls M1 - Empty box masonry (40cm)	Plaster	0,01	1,362
	Hollow brick	0,08	
	Not Ventilated Interspace	0,19	
	Solid brick	0,12	
External walls M2 - Empty box masonry - WC (40cm)	Plaster	0,01	1,362
	Hollow brick	0,08	
	Not Ventilated Interspace	0,09	
	Solid brick	0,12	
Internal walls M2 - Empty box masonry - Stairwell (30cm)	Plaster	0,01	1,227
	Hollow brick	0,08	
	Not Ventilated Interspace	0,08	
	Solid brick	0,12	

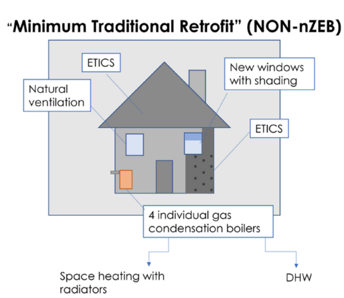
Walls	Materials	Thickness	U-value
		m	W/m²K
Ground floor P1 - Concrete masonry on Pilotis	Ceramic tiles	0,015	0,626
	Plant screed	0,055	
	Concrete load distribution screed with mesh	0,04	
	Brick slab thickness 18 cm	0,18	
	Plaster	0,005	
	EPS	0,04	
	Plaster	0,005	
Ground floor P2 - Concrete masonry on Cellars	Ceramic tiles	0,015	1,38
	Plant screed	0,055	
	Concrete load distribution screed with mesh	0,04	
	Brick slab thickness 18 cm	0,18	
	Plaster	0,01	

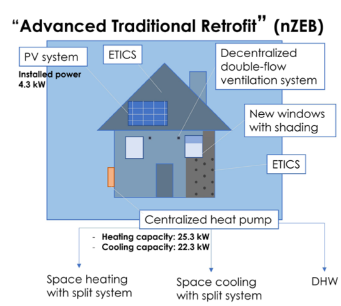
Roof	Materials	Thickness	U-value
		m	W/m²K
Flat roof S1 - Concrete masonry on unheated attic	Concrete load distributed screed with mesh	0,04	1,953
	Brick slab thickness 18 cm	0,18	
	Plaster	0,01	

Windows	Materials		U-value
			W/m²K
Whole windows	Wood		1,7

TABLE 2 Schemes of the retrofit scenarios' main features.

Scenario 1 (S1)	Scenario 2 (S2 and S2*)	Scenario 3 (S3 and S3*)





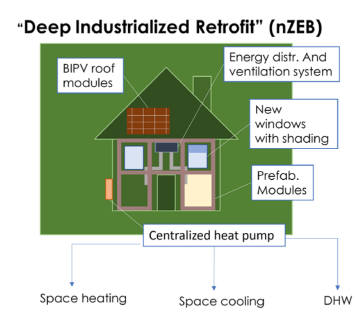


TABLE 3 Resume of the considered envelope characteristics and HVAC technologies for each of the developed retrofit scenarios

	S1: Traditional shallow retrofit	S2: Traditional deep retrofit	S2*: Traditional deep retrofit	S3 and S3*: Industrialized deep retrofit
Thermal insulation wall	ETICS (120 mm of EPS) for the whole envelope excluded the structural pillars and the roof.	ETICS (120 mm of EPS for the whole envelope, excluding the roof.	Ventilated façade composed of 120 mm of EPS for the whole envelope, excluding the roof.	Ventilated façade composed of a 160 mm mineral wool layer directly installed in the wood frame of the prefabricated façade panels.
Thermal insulation roof	Insulation of the last floor under the roof with a 100 mm layer of mineral wool (keeping the old roof)	Insulation of the last floor under the roof with a 100 mm layer of mineral wool (keeping the old roof)	Insulation of the last floor under the roof with a 100 mm layer of mineral wool (keeping the old roof)	Ventilated roof composed of a 160 mm mineral wool layer directly installed in the wood frame of the prefabricated roof panels (new roof)
Windows	New double-glazing windows with U = 1.3 W/(m^2 K).	New double-glazing windows with U = 1.3 W/(m^2 K).	New double-glazing windows with U = 1.3 W/(m^2 K).	New double-glazing windows with U = 1.3 W/(m^2 K).
Ventilation	Natural ventilation.	Decentralised mechanical ventilation machines with double fluxes (supply and exhaust).	Centralised mechanical ventilation machines with the distribution that arrive in each room (fault ceiling in the corridor).	Fresh air and energy distribution system integrated into the façade (semi-centralised mechanical ventilation with double flux).
Heating & Cooling	Condensing gas boiler for each apartment connected to existing hot water radiators in each room. Air conditioning units in each room.	Centralised heat pump connected to new split units in each room. SH and SC powers of 25.3 kW and 22.3 kW.	Centralised heat pump connected to new split units in each room. SH and SC powers of 25.3 kW and 22.3 kW.	Centralised heat pump hydraulically connected to the integrated fresh air and energy distribution system.
Renewable Energy Sources	Absent.	Traditional PV modules installed on the roof (4.3 kWp).	Traditional PV modules installed on the roof (4.3 kWp).	BIPV modules, installed on the roof as cladding elements of the prefabricated modules (4.3 kWp).

2.2 RETROFIT SCENARIOS

Three retrofit scenarios were defined as listed below and described in TABLE 2 and TABLE 3: (i) Scenario 1 (S1): Traditional shallow retrofit (non-nZEB), used as the benchmark. (ii) Scenario 2 (S2): Traditional deep retrofit (reaching the nZEB energy performance target after the retrofit). (iii) Scenario 3 (S3): Industrialised deep retrofit (reaching the same energy performances as Scenario 2).

S1 considers a state-of-the-art retrofit energy target of "two energy classes improvements", as required by the 110% incentive available in Italy from 2020 to 2023 (DECRETO LEGGE, 2020), (Governo Italiano Presidenza del Consiglio dei Ministri, 2023). Such technical targets were achieved by changing windows and the boiler and by applying a 120 mm External Thermal Insulation Composite System (ETICS). S2 and S3 were dimensioned, aiming at achieving the Italian nZEB minimum requirements of at least 50% of the energy demand (heating, cooling, and DHW) covered by RES (with at least 50% for DHW energy demand). The PV sizing method followed is defined in the nZEB Italian norm (Verdi, 2015). Space Heating (SH); Space Cooling (SC) thermal powers for the heat pump were calculated based on the thermal peak loads derived from a building and energy system dynamic thermal model developed in TRNSYS, with the PV system localisation through a dedicated tool. Such a modelling procedure is described in (Gazzin et al., 2022).

To obtain a clear comparison between the traditional deep retrofit and the industrialised deep retrofit approaches, two additional cases were studied, resulting in the five scenarios summarised in TABLE 3. Scenario 2* (S2*) was defined to be directly comparable with S3. A centralised double-flux ventilation system with an indoor ducting network (instead of a fully decentralised machine, as in S2) was considered. This assumption is highly impacting in a traditional retrofit intervention because of the kind of indoor construction work to be done to host ducting and ventilation systems. Moreover, instead of an ETICS, an on-site mounted ventilated façade was included. Hence, the expected façade finishing and façade cladding lifetime are directly comparable with S3. Still, S2 allows us to benchmark the ETICS as the most widely used insulation system with painted finishing. Scenario 3* (S3*) was introduced to take into consideration that the features and costs of the S3 were reflecting a set of products still under development (Technology Readiness Level[1] TRL= 7). Hence, a 20% reduction of the final price of each prefabricated module installed on the existing building was applied to take into account ongoing processes and technology optimisations as well as the potential of market critical mass activation on the demand side. This reduction rate was discussed with the industrialised solutions technologies providers. Finally, a reduced yearly maintenance rate for the building envelope elements from 1.5% to 1% of the construction costs was considered in the S3* scenario to give value to the higher quality of the prefabrication process against the on-site one. This reduction was chosen based on the study of the industrialised mock-up maintenance procedures defined with the product developers.

2.3 LCC METHODOLOGY

2.3.1 Introduction

The LCC methodology followed in this study is based on the LCA and LCC reference norms (ISO 14040:2006; ISO 15686-5:2017). Given the study goal reported in the previous chapter, the functional unit (FU) of the study – crucial to compare different systems in a fair way – was defined as a building providing a living environment to the inhabitants over a reference study period of 50 years with the characteristics reported in the following TABLE 4.

TABLE 4 Characteristics of the living environment considered in the three systems under study.

Parameter	Value
Indoor air temperature (winter)	19°C -21°C
Indoor air temperature (summer)	25°C-27°C
Indoor humidity (winter)	30%
Indoor humidity (summer)	50%
Max CO_2 concentration	1000 ppm
Final energy consumption	12'000 kWh/y

1 https://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf

Fifty years was considered as a reference study period because the life span of a building envelope is linked to the service life of the building (Hildebrand, 2014). This means that the industrialised renovation components related to the renovation will end their service life. The rest of the building is kept without generating either costs or revenue. Even though the reference service life of a component can be longer than the remaining reference study period (after maintenance), if the component is not reused, it will end its service, keeping a residual value which was accounted for.

2.3.2 System boundaries

As the study is a comparative one, manufacturing and installation of all building components in the current status were excluded from the study boundaries, as they would be the same for all systems. The following life cycle steps were included in the study: (A0) Building renovation design, (A1-A3) Product manufacturing and packaging, (A4-A5) Transport and on-site installation, (B1-B7) Operation and maintenance of the building renovated with industrialised technologies, and (C1-C4 and D) EoL phase. And eventual circular practices such as materials and components EoL were considered in a simplified and preliminary way, given the uncertainties in the market readiness for the definition of alternative circular scenarios.

2.3.3 LCC analysis workflow

The whole LCC analysis workflow is depicted in FIG. 3. After the definition of the goal and scope, the subsequent step was the data gathering phase (Life Cycle Inventory – LCI), based on 2021-2022 costs data available from other renovation projects occurring in the same region (Tuscany, Italy) and from the same design team. A list of bills was created for the application of all retrofit scenarios for the reference building: all processes were listed, detailing, where meaningful, both labour and materials costs. For the industrialised retrofit technologies, primary data gathered from the envelope, PV, and ventilation system manufacturers were used. For the traditional scenarios, the primary data of the design team were used, given the availability of a set of offers for traditional retrofit actions. Such dataset was finally cross-checked against the regional prices tables generally used for public procurements (Il Prezzario 2023 dei lavori della Toscana, 2023). A freely downloadable Excel-based tool developed by the H2020 CRAVE zero (Pernetti et al., 2019) was used to perform the LCC analysis. The core of the LCC calculation is the Net Present Value, calculated each year as the sum C_n of the discounted costs, revenue streams, and value during the phases of the selected period of the life cycle (ISO 15686-5, 2017). The NPV used formula at year p is

$$\mathrm{NPV\_p} = \sum_{n=1}^{p} \mathrm{C\_n}/[(1+\mathrm{d})^{\mathrm{n}}]$$

Besides the NPV, the Total Cost of Ownership (TCO) was calculated as cumulated life cycle expenses and revenues after EoL. Primary data were used as pure costs, on which a fixed 25% increase was applied to take into account profit and general expenses. VAT was not considered.

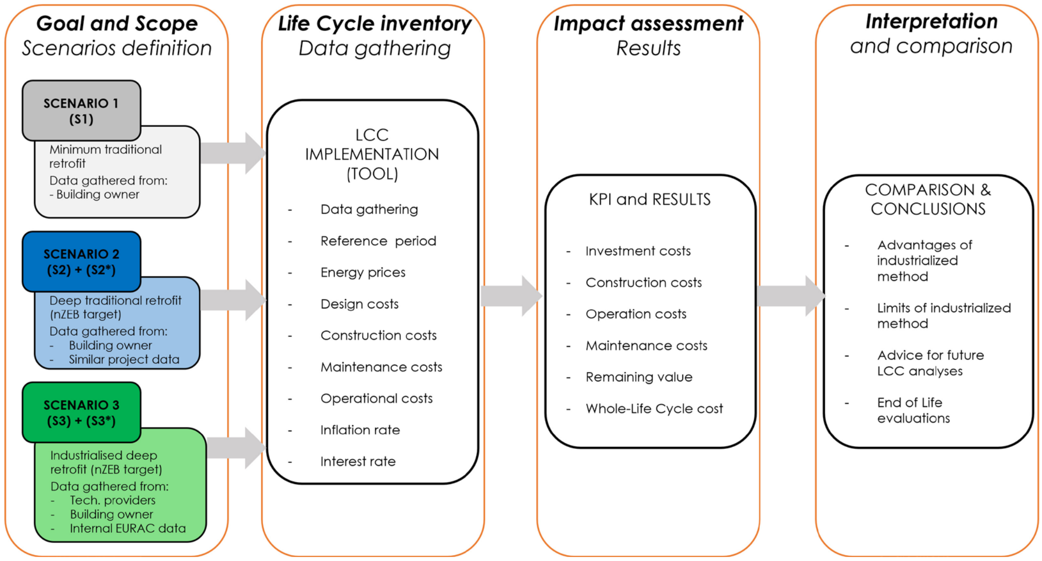


FIG. 3 Scheme of the LCC workflow used for the analysis..

2.4 LCC HYPOTHESES

2.4.1 Design costs

The design phase-related costs were taken into account as percentual values of the total construction costs, as defined by the Italian regulation (DECRETO 20 luglio 2012, 2012) and (LEGGE 2 marzo 1949, 1949) for the minimum design fees for architects-engineers association. Such values were then validated by the designers involved in the renovation. All these costs were defined for each phase of the project (preliminary, definitive, executive), including also energy certification fees and all the building site management and safety. This turned out to be, in total, 17 % for the traditional retrofit. Further assumed were a design cost increase of +1% for the deep traditional and +3% for the industrialised scenarios (resulting in total design costs of 18 % and 20 %), based on the current renovation experiences of the design team.

2.4.2 Construction costs

The construction costs were analysed in detail, as they represent a key factor both for the investors and for the purchasers. These specific costs were subdivided into the two following macro-categories. The first one is the "Building envelope costs", where the total costs for the manufacturing and installation of the building envelope components were included. These costs comprehend all that is related to insulation materials, prefabricated substructures, anchoring and fixing systems, windows, shading systems, passive cladding (or finishing), BIPV modules, and so on. A second cost category was labelled "Additional items cost". This category considers all the costs for all the other interventions and phases, as listed in the following: supply and installation of the building services, working site operations, preparation and rent of the working vehicles and systems, and on-site transportation costs.

2.4.3 Maintenance costs

The maintenance costs include both a yearly rate (as a percentual of the total construction cost) for ordinary maintenance and the dismantling plus reinstallation costs occurring once the items reach their service lifetime. With this approach, the yearly rate is the same among all the scenarios in relative terms. Conversely, the replacement costs are different because the technologies to be replaced are different. Hence, it is to be expected that S2 and S3 have higher maintenance costs due to the higher amount of technologies and related costs.

Building envelope systems and building services were grouped separately. The first group is the "Maintenance of the building envelope", including ETICS for S2 and the prefabricated envelope kits for S3, as well as the new windows and shadings. For all the envelope elements part of the industrialised retrofit approach, the yearly maintenance costs forecast was set as 1.5% of their construction costs, according to the Standard (ISO 15686-5, 2017). For S1 and S2, the ETICS lifespan was set equal to 25 years (Marques et al., 2018) (Tavares et al., 2020), while the industrialised envelope kits (ventilated façade) were set to 50 years.

The second category is the "Maintenance of the building services and RES", with the building HVAC system (including thermal storage, boiler or heat pump and accessories). The yearly maintenance costs, as a percentage of their construction costs, were taken from (EN 15459, 2018), as well as the lifespan of each component. In addition, the main electrical system components were considered together with the PV panels' maintenance and substitution. More precisely, the PV panels were assumed to have a typical 25-year expected life (Paiano, 2015) with a yearly 0.5% decrease in their power output (Jordan et al., 2016) and, therefore, to be entirely substituted in the 26th year of the life cycle.

2.4.4 Operation costs

Energy consumption

The yearly energy consumption of the implemented scenarios was calculated through dynamic energy simulations using the software TRNSYS (for the deep energy retrofit scenario) and national standards (for the traditional shallow retrofit), considering the different technologies involved in each case. Because of their high technological similarity and to have the same functional unit, S2, S2*, S3 and S3* were assumed to have the same energy consumption, as summarised in TABLE 5. This assumption might be challenged, considering that the insulation level is different between S2-S2* and S3-S3* because of the integration of the ducts into the façade. However, as a first assumption, given that a detailed thermal performance calculation of the S3 façade integrating ducts and piping is still missing, the final energy consumption was set identically as a "safe side" hypothesis. Finally, the use of electrical storage was taken into account in terms of investment costs for S2, S2*, S3 and S3*, with 100% self-consumption.

TABLE 5 Calculated energy consumption for each developed scenario.

Specific yearly energy demands						RES	Final energy consumption	
	Heating	DHW	Cooling	Ventilation	Appliances	PV prod.	Natural gas	Electricity
	kWh/(m² year)					kWh/year	kWh/year	kWh/year
S1	24.1	19.6	22.4	Not Implemented	18	0	16'180	14'260
S2, S2* S3, S3*	6.7	5.8	9.3	7	18	4'650	0	16'650

Energy costs

The applied energy prices for the LCC analysis and their relative yearly increases were calculated from official data furnished by ARERA[2] (2nd trimester 2023) and are reported in TABLE 6. These data refer to the typical trend in the price of electricity and natural gas for the domestic consumer.

TABLE 6 Price of the investigated energy vector and respective yearly increase, equal for all the scenarios.

	Average price	Yearly energy price increase
Energy carrier	€/kWh	%
Natural Gas	0.085	0.62
Electricity from the grid	0.23	1.47

By defining the costs of the different energy vectors involved and their respective yearly percentage increase, the energy consumption costs for the building residents over the 50-year cycle were calculated. A yearly percentage increase in natural gas and electricity costs was considered as an average of the last ten yearly increases, excluding from the calculation 2020 and 2021, which were supposed to be influenced by the global world crises.

2.4.5 End of Life costs

An EoL preliminary analysis was performed as a simplified evaluation of the industrialised retrofit competitiveness potential related to its potential capability of easy dismantling and disassembling. The underlying idea is that, once the renovation lifetime is over (50 years), some of the renovation envelope systems components could be sold for reuse. This is, of course, a hypothetical scenario given the market-related administrative and technical difficulties in adopting such circular practices in the construction sector.

Such a theoretical EoL scenario of reuse was approached as follows. All envelope and technical systems costs related to dismantling, disassembling, transportation, and landfill were calculated for all scenarios. For S3, a "reuse" forecast option was assessed only for the industrialised envelope components. Dismantling, disassembling, and transportation costs were summed to a negative value

2 "Autorità di Regolazione per Energia Reti e Ambiente". www.arera.it/it/inglese/index.htm

of revenues derived from the selling of a number of reusable components. Given the difficulties in finding reliable primary data on the topic, such revenues have been parametrically calculated as a portion of the components' initial construction costs, using reduction rates of 50% and 25%. Additionally, three hypotheses of component quantities to be really reusable were defined as 100%, 50% or 25% of the S3 list of bills, resulting in six theoretical options to be compared with "traditional EoL costs with no reuse". The cost source was the (Il Prezzario 2023 dei lavori della Toscana, 2023).

2.4.6 Inflation and discount rates

The LCC analysis proposed handles costs along a relevant time span (50 years). All costs were hence actualised via the inflation and discount rates using the coefficients included and described in (Life Cycle Cost Tool, 2023).

3 RESULTS

This chapter reports the results obtained from the comparative LCC analysis. Besides a first summary in terms of €, all detailed costs are reported as percentages (benchmarked against the S1 scenario investment costs) due to the confidentiality of the primary data sources.

3.1 OVERALL LC COSTS

The cost comparisons among the different scenarios, detailed for each LC phase, are reported in TABLE 7. It emerges that the most relevant phase is Manufacturing & Installation (M&I), followed by Maintenance, Operation, Design, and EoL. However, the use phase (as the sum of O&M) is the most expensive for all scenarios over 50 years of service life. The cheapest scenario is S1, followed by S2. Conversely, S2* is quite well in line with S3 (slightly more expensive), while S3* results cheaper than S2*. These comparisons among the scenarios are clearly shown in FIG. 4, where the relative percentages are reported against the S1 investment cost (equal to 235,423.00 €). The graph shows that: materials shares have the most impact in all scenarios, with a percentage increase from 57% (S1), 101% (S2), 121% (S2*), 131% (S3), and 118% (S3*). The design costs, of course, increase from S1 to S3* as a percentage of the total. Focusing on maintenance costs shows a comparable cost share. However, S2* has less maintenance costs because of the presence of the ventilated façade with a 50-year life span against the 25 years of the painted ETICS (S2). S3 follows the S2* trend because of the ventilated façade, while S3* maintenance results in a reduced share under the hypothesis of highly integrated components with optimised maintenance procedures.

TABLE 7 Costs distribution per LC phase and comparative scenario. Manufacturing & Installation is M&I, Operation & Maintenance is O&M.

	Investment		50 years O&M		
Scenario's	Design	M&I	Operation	Maintenance	EoL costs (w/o remaining value)
S1	€ 33'430	€ 201'993	€268'39	€ 185'373	€ 38'371
S2	€ 59'269	€ 328'362	Same energy level, € 161'000	€ 293'425	€ 59'855
S2*	€ 68'986	€ 382'192		€ 258'269	€ 61'176
S3	€ 97'518	€ 389'294		€ 265'833	€ 59'722
S3*	€ 90'031	€ 359'405		€ 216'697	€ 59'722

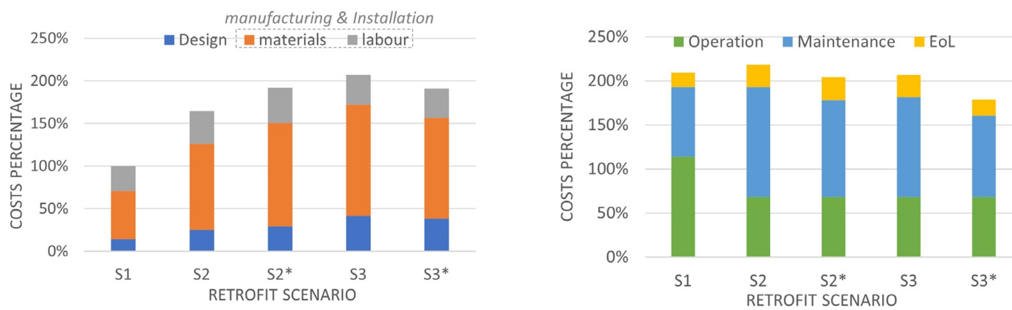


FIG. 4 Summary graphs of investment, operational and maintenance, and End of Life costs as percentages of the S1 investment costs (design, manufacturing, and installation), equal to € 235,423.00.

3.2 INDUSTRIALISED KIT COSTS ANALYSIS

As an exemplary result at the kit level, the BIPV and prefabricated Energy & Fresh Air façade modules are reported in FIG 5. and FIG 6. The costs expressed in percentage refer to the whole kit, including materials, manufacturing and assembling processes, packaging and all the installation activities, while the transportation costs are excluded.

It can be observed that the timber-based façade costs are the most relevant ones in the Fair kit while, in the BIPV kit, the majority of the costs refer to the coloured glass-glass PV panels. Ventilation components, which include the ventilation units and all the distribution systems, impact 23% of the total. It can also be observed that the installation costs differ substantially between the two kits (18% for the Energy & Fresh Air kit and 5% for the BIPV kit) because of two main reasons: (i) the overall costs of the BIPV kit is higher (around + 40%), so consequently the percentage impact of the installation is lower; (ii) the installation processes and effort is higher in the Energy & Fresh Air kit due to the presence of the distribution system to be "connected" to the existing building (inlet-outlet preparation, ducts and pipes connections, etc.). Regarding the prefabricated timber-based façade, the differences between kits mostly refer to assembly processes due to the integration of the Energy & Fresh Air kit distribution into the façade, while the materials still have a major impact due to the large number of components needed.

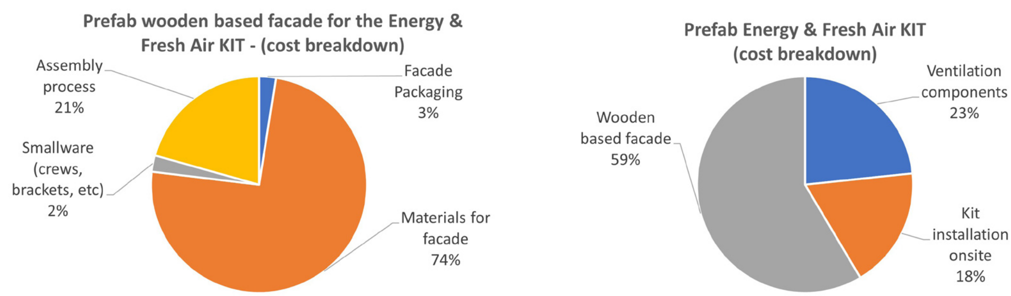


FIG. 5 Energy and Fresh air kit costs breakdown based on €/sqm and reported in %.

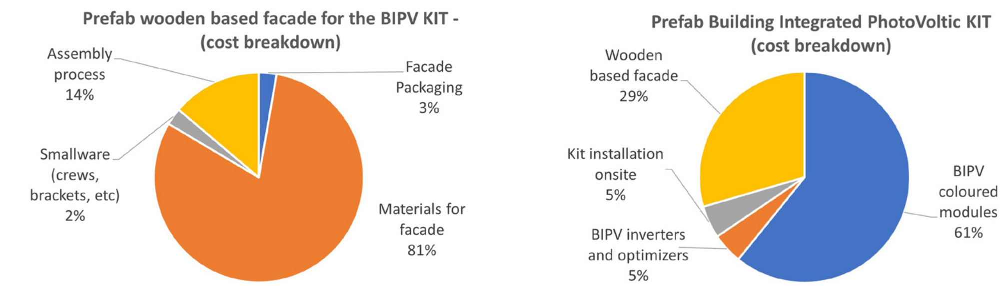


FIG. 6 Building Integrated PhotoVoltaic kit costs breakdown based on €/sqm and reported in %.

3.3 LC COSTS TRENDLINES

The work done resulted in 50-year cost analyses, allowing to generate trendlines for all assessed scenarios as depicted in FIG 7.

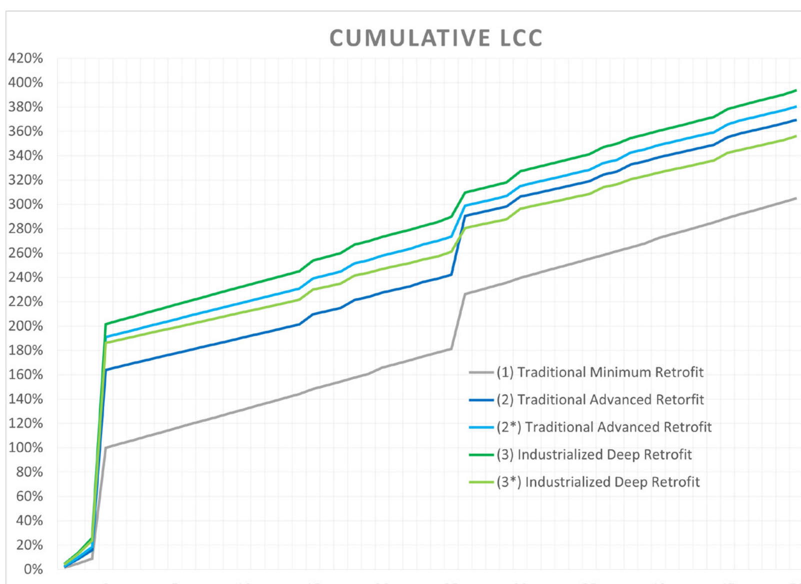


FIG. 7 Cumulative LCC Net Present Value trend along the lifetime (up to 50 years). Percentage values are defined against the S1 investment costs, corresponding to 100%.

Cumulative cost lines for scenarios 2, 2*, and 3 present the same inclination through the considered life cycle. This is due to the assumption that these scenarios have the same yearly energy consumption and maintenance costs. By looking at the line for scenario 3*, a decreased line gradient can be observed, which is related to the assumption of considering yearly maintenance costs for the building elements decreasing from 1.5% to 1%. The line gradient for S1, instead, is higher than the others because of the lower energy performance, mainly due to the absence of PV panels and mechanical ventilation.

All scenario trendlines show some "steeper steps" related to the substitution of the components for each retrofit action. For example, the steep increase after 25 years for S1 and S2 (traditional ones) is related to the dismission and reconstruction of the ETICS (façade and roof) and windows after 25 years.

S2* is characterised at year 25 by the replacement of several items (roof insulation, balconies finishings, ducts of centralised ventilation system). This does not occur for the industrialised S3 and S3*, for which all façade-embedded components remain unvaried for 50 years, apart from the windows. For S2*, the investment costs at year 0 become 20% higher than for S2 and, hence, closer to the costs of the industrialised deep retrofit (S3). Moreover, the optimised industrial deep retrofit approach (S3*) with a 20% price reduction results in being competitive with S2* already in terms of investment cost.

FIG 8. shows a set of parametric variations, starting from S3, based on reducing the scenario investment and maintenance costs. It emerges that S3 and S2* are very similar, with a 10% of S3 investment. When acting on operation and maintenance costs, the industrialised scenario can even be economically more viable compared to a traditional advanced retrofit with a ventilated façade (S2*).

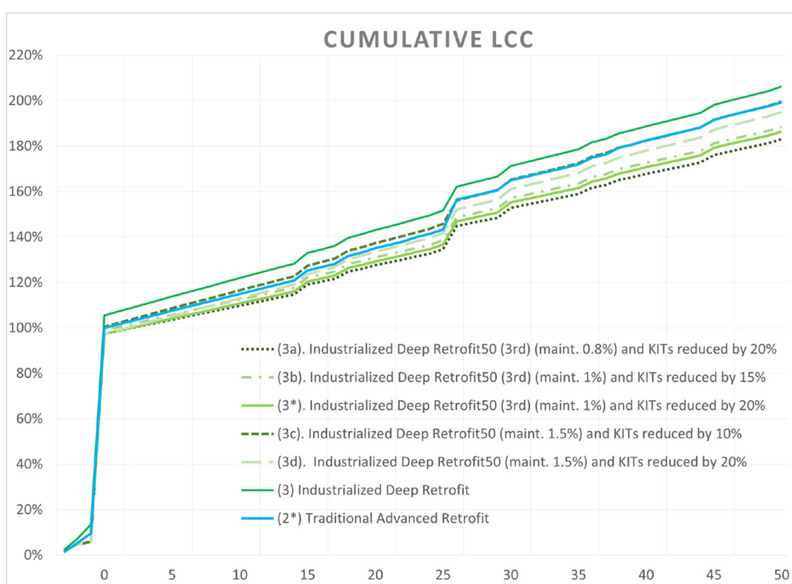


FIG. 8 Focus graph on parametric variations of investment and maintenance costs applied to S3. Reference quantity (100%) is S2*.

3.4 CONSTRUCTION COSTS

The bar chart shown in FIG 9. focuses on the investment costs only related to the building envelope systems for each scenario. As expected, the industrialised approach is more expensive in terms of investment costs, mainly because of the use of additional materials and upstream processes. The most interesting comparison is between S2* and S3, as they both have the same finishing (ventilated cladding), with a 31% discrepancy. A direct comparison between S3/S3* against S2 is misleading because of the difference in the finishing solution (painted plaster against ventilated façade). S3*, optimised with a 20% reduction of the investment cost related to the prefabrication processes and related materials only, is about 16% more than S2*.

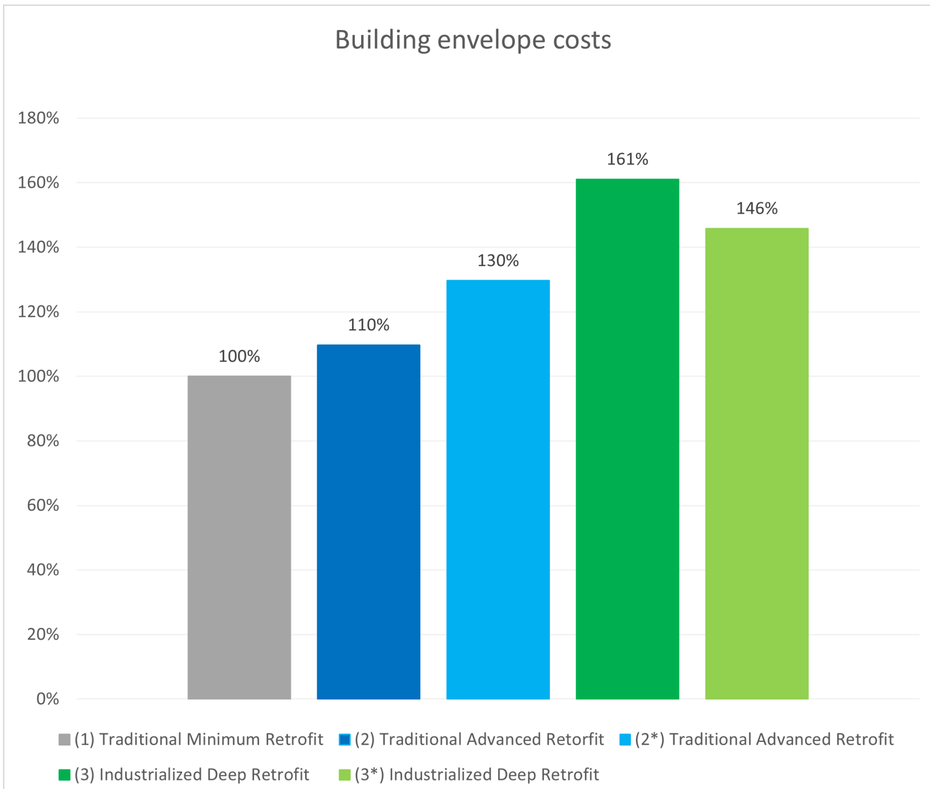


FIG. 9 Investment costs for the renovation of the building envelope for each of the analysed scenarios and their respective variations. Percentage values are defined against the 1st scenario costs (100 %).

However, FIG 10. highlights that for all the other item costs (i.e., building services installation, working site operations, preparation, and rent of the working vehicles and systems), the S3 approach provides reduced costs, thanks to time and effort savings during manufacturing and installation. For the industrialised scenario, the development of a semi-centralised double-flux ventilation system installed inside the prefabricated modules, and capable of working also as an energy distribution system, allowed to reduce the interventions inside the apartments and therefore decrease the costs related to the building services. This result is even more evident when compared to S2* (with a traditional centralised ventilation system), where the installation costs have a 27% difference on the overall "additional items" cost. 7% reduction between S3 and S3* is part of the cost optimisation process defined for the S3* integrated ducts and ventilation units. As expected, the installation costs comparison S2 and S3 shows a 74% difference thanks to the fully off-site approach.

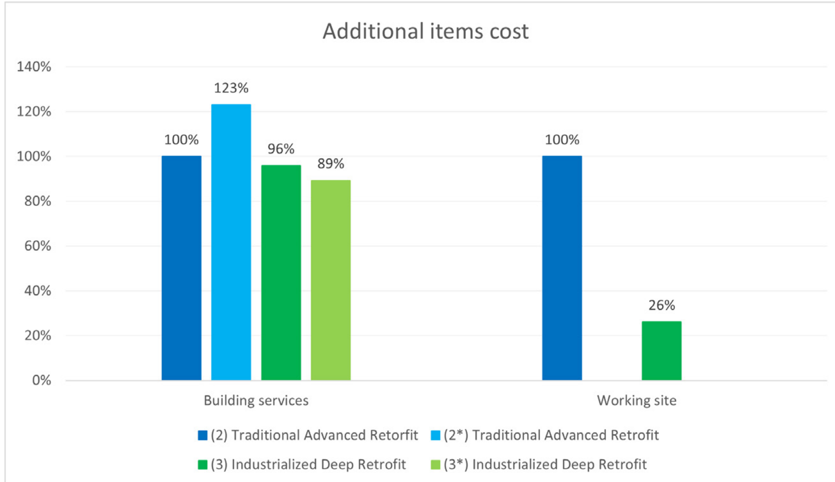


FIG. 10 Additional item costs comparison among developed scenarios and their proposed variations. Percentage values are defined about the 2nd Scenario additional item costs: correspondent to 100%.

The reduced time required for the installation of prefabricated modules was fundamental to decreasing the working site costs. Thanks to the use of the prefabricated modules, the use of a traditional scaffolding system was substituted with the utilisation of two aerial working platforms, achieving a relevant reduction in rental cost as well as time required during the on-site operation works. Transportation costs also impact the final investment cost for S3 and S3*. The need for five lowered trucks (each one capable of transporting 120 m^2 of prefabricated modules) was estimated, and this cost item represents 3% of the total investment cost for S3.

3.5 OPERATION COSTS

A comparison between the total costs related to the energy consumed over the 50 years is shown in FIG 11. S2 and S2* were not considered in this analysis because their energy performance is the same as S3 and S3*.

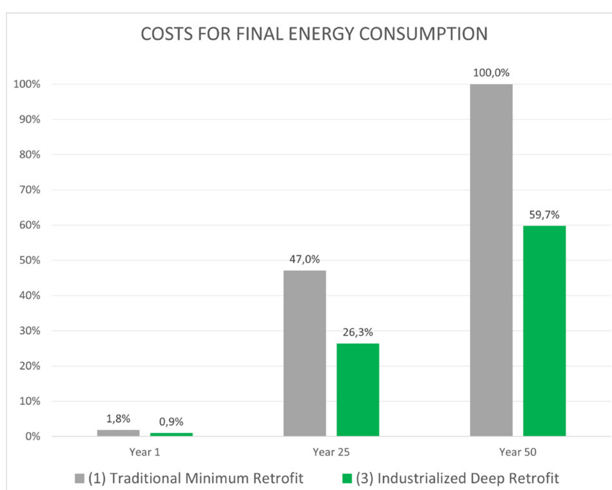


FIG. 11 Cumulative costs for final energy consumption comparison between S1 and S3. Percentage values are defined against S1 cumulated costs at year 50 (corresponding to 100%).

3.6 MAINTENANCE COSTS

The cumulative maintenance cost distribution for each developed scenario is depicted in FIG 12. These maintenance costs were subdivided into "building elements" and "building services."

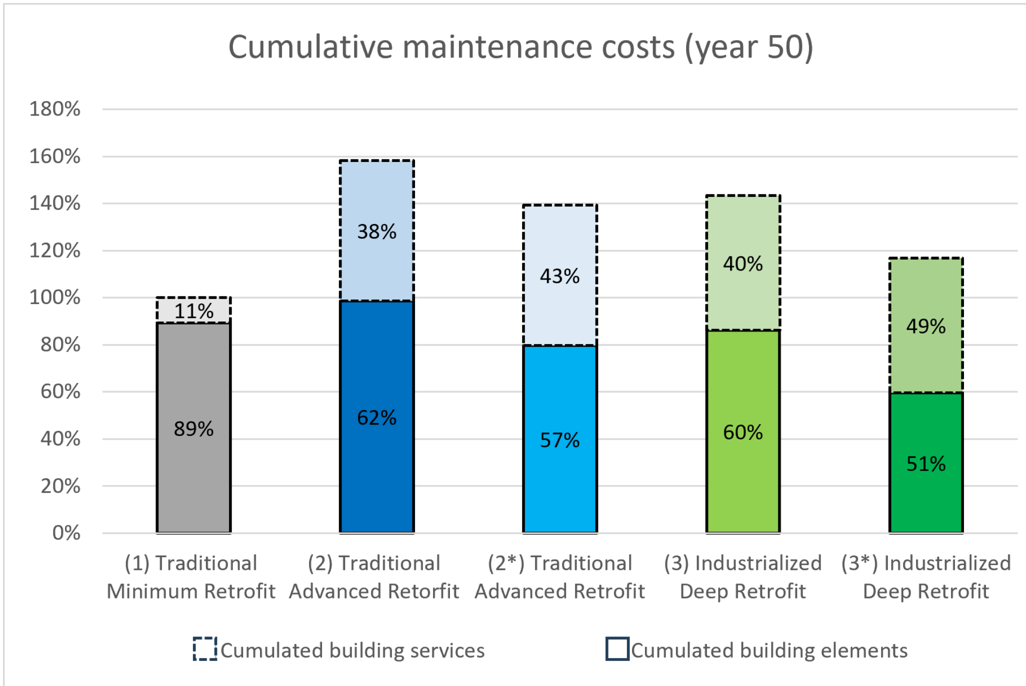


FIG. 12 Cumulative maintenance costs distribution (building elements vs building services) at the end of the life cycle. Percentage values are defined against S1 cumulative maintenance costs at year 50.

By looking at the cumulative costs for the building elements, S2 resulted in 60% more expensive than S1 because of the presence of more technologies to be maintained (and substituted). The difference between S2 and S2* is mainly due to the substitution of ETICS in S2, while the ventilated façade is considered to last 50 years (as per S3 and S3*). The additional S3* has the lowest maintenance costs compared to S3 because of the lowest investment cost. Analysing the cumulative maintenance costs for the building services, instead, the S1, as expected, presents extremely limited maintenance costs for its services due to the absence of HVAC and RES systems. Conversely, in S2-S2* and S3-S3*, because of the similar technologies involved, the cumulative maintenance and building services costs were comparable.

3.7 END OF LIFE

The parametric cost-revenue EoL results are reported in FIG 13. The simplified analysis was done only on the envelope elements, aiming at assessing the theoretical potential of reusing (at least part of) the industrialised systems at year 50. It emerges how, in the case of reusing components and materials, even just for 50% of the quantities and at 50% of the price of the construction, an economic benefit for the EoL phase can be expected. To be cost-effective, the reuse quantity of the envelope components should be at least 50%, with a revenue of 25% of construction cost, and higher than 25% if the revenue is 50%.

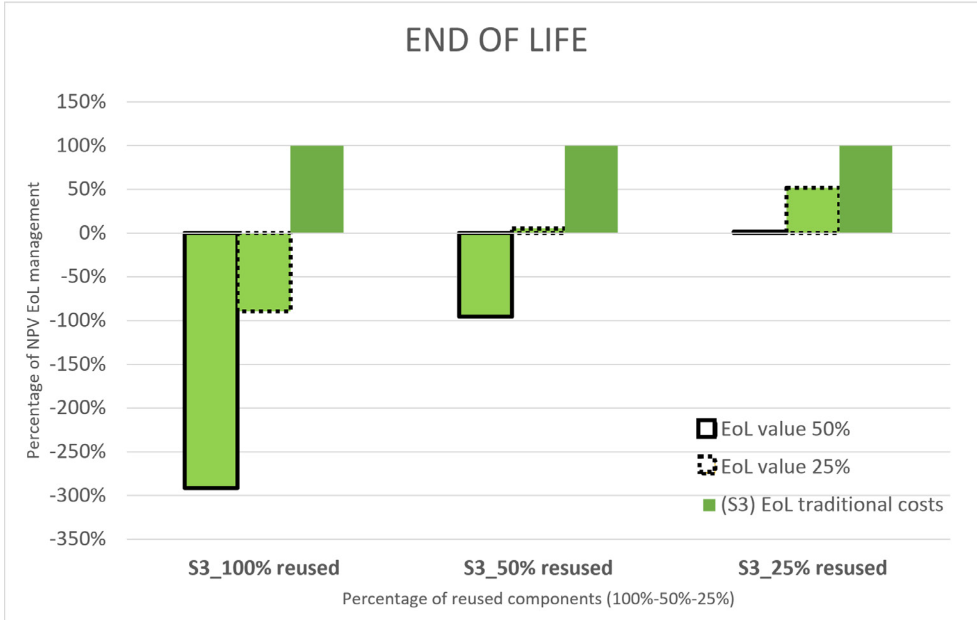


FIG. 13 End of Life scenarios for S3 considering 50% and 25% of construction costs as revenue for 100%-50%-25% of the envelope components reuse compared with the S3 costs for dismantling with no revenues.

The economic potential of a different EoL management, through the dismantling, disassembling, and reuse of sold components, is even clearer from FIG 14. in terms of TCO. In fact, the best EoL with reuse hypothesis applied to S3 shows a TCO lower the S2* and S3, highlighting the theoretical potential of circular reuse of envelope components in terms of economic benefit on the whole life cycle. EoL revenues might play a role in reducing the TCO by around 27%.

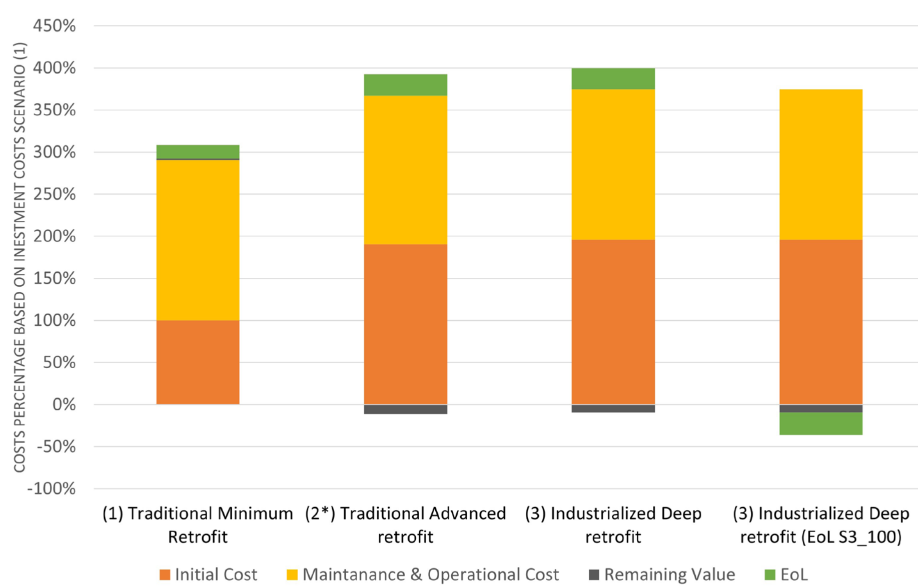


FIG. 14 *Total Cost of Ownership value breakdown for the different phases. 100% reference is the investment cost of S1.*

4 DISCUSSION

The benchmarking of traditional and industrialised scenarios, especially looking at S2* versus S3 and S3*, shows a substantial equivalence in terms of investment, operation, and maintenance trends. However, the industrialised approach carries some advantages that might be potentially turned into a value proposition able to impact the S3-S3* LCC performances, lowering the investment and/or the operation & maintenance costs. Such advantages are: (i) High manufacturing and installation quality, with potentially longer components service life and lower overall retrofit intervention performance loss. (ii) The roof insulation included in the S3 family based on industrialised kits offers the value of having a brand-new roof, compared to the S2 family, with only a layer of insulation applied under the roof. (iii) The S3 and S3* insulation thickness are actually higher than S2 and S2* because of the ducts passing into the façade, even if an energy consumption reduction was not taken into account. S3 and S3* are expected to perform better than S2 and S2*. (iv) There could be a relevant economic benefit in terms of more profitable interest rates based on the use of a more robust renovation approach grounded on more durable and performing prefabricated technologies. (v) In S3 solutions family, there is the possibility to differently handle the EoL phase thanks to the increasing easiness of reuse and recycle of components and materials (Juaristi et al., 2022). Such topics will need dedicated techno-economic studies to provide robust quantitative evaluations to be used in an LCC analysis.

The comparative LCC analysis performed was a relevant step for the deepening of the market uptake potential of the industrialised deep retrofit approach compared to the traditional ones. However, the adopted LCC methodology has shown to be a tricky method because of the high cost variabilities and need for strong hypotheses. The main affecting parameters are the service lifetime of the components, the evolution of energy and material prices in time, the geographic variability of prices which hinder the generalisation of the findings, the difficulties in monetising the co-benefits and in the assessment of performance changes during time. The very low number of actual industrialised deep retrofit buildings still does not allow the creation of a robust benchmark for the industrialised solutions features characterisation over time.

Finally, the overall analysis has shown different terms of comparison. Of these, S1 and S2 should not be considered directly comparable, given the strong differences in the typologies of intervention and of the functional unit. In other words, the industrialised retrofit approach allows to obtain renovated building performance that is hardly achievable with a traditional deep retrofit. In this sense, the technical benefits of the industrialised retrofit in terms of energy efficiency should also be proven and could lead to a relevant saving in the operational phase compared to the traditional deep retrofit solutions.

5 CONCLUSIONS

The presented work aimed at evaluating the potential competitiveness of the industrialised against the traditional deep retrofit approaches by applying a bottom-up comparative LCC methodology. The use of innovative timber-based façade and roof kits integrating windows, highly appealing BIPV modules, and a semi-centralised mechanical ventilation machine (with the related needed aeraulic network) were considered and assessed in terms of costs and revenue trends along the life cycle.

It can be firstly concluded that the LCC methodology at the building level shows high potential to benchmark coherently the industrialised against the traditional retrofit approaches. Nevertheless, many technical hypotheses and assumptions were made, heavily impacting the results, for which the model could be defined “sensitive”. In this perspective, a sensitivity analysis will be crucial to deepen and strengthen those very influencing modelling choices. For example, materials pricing variability, industrialised retrofit co-benefits, maintenance costs, and product development optimisation can be considered crucial aspects to be further investigated.

However, a reliable cost comparison between the two renovation processes was set up, allowing a fair definition of the competitiveness of the industrialised against the traditional deep retrofit approaches. At the building´s 50th-year life, a fork of plus 7% and minus 16% was calculated as the difference between the industrialised and the traditional scenarios.

The prefabricated kits LCC results highlight the need to work on reducing the materials used, which represent the highest cost share of the industrialised solutions.

In terms of cost distribution at the building level, the best industrialised and traditional scenarios (S3*-S2*) showed an investment cost difference of +11%. The construction cost (materials more than labour) appeared to be the main issue regarding the competitiveness of the final industrialised solution. However, given the prefabricated multifunctional envelope technologies optimisation potentials in terms of system design and materials selection, a supplementary reduction of the initial investment should be further evaluated. The investment cost for building services and the integration of renewables, besides the working site management and processes, were lower for the prefabricated scenario, more precisely 7% and 74%, respectively. Moreover, thanks to the direct installation of the major parts of the HVAC system inside the prefabricated modules, the interventions inside the building become simpler and faster, permitting the building occupants to remain in their apartments. Such co-benefits were not evaluated in this study, but their quantification should be further investigated. The operation and maintenance phase has shown to be crucial to increase the competitiveness of the industrialised retrofit. The topic of “better final quality” of this approach, however, needs to be better investigated and quantified for future integration in such LCC analyses. Moreover, the studied End of Life scenario with the possibility of reusing part of the industrialised retrofit components has shown to be a theoretically interesting option to lower the TCO by about 27%.

As a general next step, further LCC analyses should be carried out on real industrialised renovations, collecting primary data able to catch the variabilities of costs in time for different technologies and countries.

This leads to the conclusion that the industrialised approach's “co-benefits” could be the actual trigger to increase the adoption of such prefabricated solutions, contributing to a practical increase of the European building stock renovation rate. Among the most promising “co-benefits”, the following need to be mentioned: improved performances in operation (final energy and maintenance), the possibility to attract better investment leveraging the reduction of the risk, reusing of disassembly-capable components as a more valuable EoL strategy, building users do not need to leave their apartments during renovation, less construction time which means less disturbance.

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