An Innovative Software Platform for Efficient Energy, Environmental and Cost Planning in Buildings Retrofitting

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Abstract. Building stock renovation is a major challenge towards a sustainable energy transition. In this context, there is a need for accurate and holistic assessment of retrofitting solutions. While Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) methods are typically used to quantify the outcomes of a retrofit solution, these methods are highly dependent on accurate data, which is often not available in the design phase. The work presented in this paper demonstrates a building renovation assessment platform that follows a holistic approach and enables rapid but accurate consideration of several renovation scenarios. The innovation lies in the integration of two specialized tools, namely VERIFY and INTEMA.building, for lifecycle and energetic calculations, respectively. The integration offers a solution for the case in which no operational data are available. After the detailed presentation of the platform, the architecture and the offered functionality, a building renovation problem is considered as a demo case. A typical low-efficiency Greek building is examined while interventions are assumed, such as insulation of external wall, replacement of glazing surfaces, as well as heat pump and photovoltaic installation. Results showcase a significant reduction in lifetime CO_2 emissions and primary energy of around 785 tons and 700 MWh, respectively. At the same time, the economic viability is ensured with estimated savings of 225 k€ during project lifecycle.

Keywords: Sustainability assessment · Life cycle · Energy modeling and simulation

1 Introduction

Globally, one third of the final energy consumption and almost 40% of total CO_2 emissions is attributed to building sector [1], while in the European Union (EU), around 75%

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of the building stock is considered energy inefficient, accounting for 40% of the EU's total energy consumption, and 36% of the total greenhouse gas (GHG) emissions [2, 3]. As depicted in the European Green Deal, building renovation and energy efficiency measures offer a huge potential for energy savings and reaching the EU emissions reduction target of at least 55% by 2030 and achieving climate neutrality by 2050 [4]. Achieving sustainability in buildings requires the application of innovative and ecological building materials, integration of smart technologies and higher penetration of Renewable Energy Sources (RES) for energy transition and decarbonization of the building stock [5].

The concept of green buildings is strongly related to building sustainability due to its contribution to environmental preservation and better quality of life [6, 7]. LCA and LCC methodologies are powerful instruments for the sustainable design and viable future of buildings. The application of these techniques through the building renovation should be integrated for achieving a highly energy efficient, cost effective and decarbonized building stock with social benefits for its users [8]. A life cycle approach considers both environmental, and economic factors and allows for the estimation of materials and energy consumption, costs, as well as GHG emissions. Decision-making towards an optimal selection of building elements through the entire life cycle [9] needs to be planned, managed and evaluated with accessible and adaptable software tools.

Malmqvist et al. (2011) proposed, within the context of ENSLIC Building project, a simplified step-by-step method and guidelines for building LCA calculations in early design phases [10]. Rossi et al. (2012) [11] created a tool in excel format to perform simplified LCA calculations for the embodied energy and carbon as well as the operational energy and carbon, at a masonry house and a steel-framed house in three European locations. Fu et al. (2014) designed an LCA calculation tool in order to estimate the carbon emissions occurring in the construction phase of LCA analysis and compare different construction plans [12]. In another work, Jayathissa et al. [13] applied an open-source LCA software to assess the environmental impact of dynamic Building Integrated Photovoltaic (BIPV) systems. The tool was developed initially by Ciroth in 2007 [14], entitled "OpenLCA". Moreover, it is useful to state that Li et al. (2016) developed an automated tool for the estimation of life cycle carbon emissions in residential buildings in China, named "Carbon Emission Estimator for Residential Buildings (CEERB)" [15], using a database with national emission factors and a carbon estimator capitalizing on the standardized LCA theory.

In this context, the developed tool "VERIFY" offers a) an integrated LCA & LCC calculation methodology based on a holistic life cycle approach considering existing building performance, new building designs and building renovation projects; b) a detailed lifecycle analysis of the use phase concerning RES production and energy/fuel consumption components as well as degradation effects and replacement actions for long-term projects; c) personalized project setup and creation by capitalizing on country specificities, meteorological data, material data, building properties and specific user preferences; d) a private database for materials and energy production taking into account all energy consumption for components construction and their initial environmental footprints ('cradle-to-gate') e.g. primary energy and emissions; e) the ability to store a large amount of data in private data repositories through the use and function of a Data Lake; f) communication with external tools related to energy modelling and simulation in order to obtain synthetic energy data (i.e. energy simulation data) useful in the analysis of building components. A significant feature regards the case where there are no adequate data available for the building operation. For this case, an integration with the “Integrated Energy Management - building (INTEMA.building)” tool offers accurate synthetic data, based on which the LCA can be drawn. Coordination of the proposed tools allows the estimation of the impact of various renovation scenarios in terms of energy efficiency, environmental emissions and economic cost during the whole life cycle of the building.

The remainder of this paper is structured as follows: Sect. 2 gives a description about VERIFY and INTEMA architecture and main goals. Section 3 presents the proposed environmental and costing methodology for the building renovation sector. Section 4 describes the renovation scenario setup procedure through the proposed software tools. Section 5 presents the tool application for a typical building in Greece, gives the overall evaluation results and discusses the outcomes. Finally, conclusions are drawn in the Sect. 6.

2 Objectives and Architecture

Valid building renovation scenario requires multidisciplinary expertise and a large set of parameters in each domain. The followed approach tackles these issues by coupling two distinct specialized software applications under a single platform. After a short description for each of the tool main objectives, the integration architecture is presented.

2.1 VERIFY Goals and Objectives

VERIFY is a software developed by CERTH for conducting LCA and LCC analysis [16]. When assessing the performance of a building under renovation scenarios, VERIFY investigates the improvement in terms of renewable energy production, environmental emissions reduction, and cost optimization. The optimal renovation strategies are investigated leading to a balance of environmental impacts and costs. Depending on the climatic conditions, fuel prices and emission factors at the country of interest, VERIFY’s methodology approach is to highlight the effects of choices during the installation and the use-phase of the building for: a) electrical production systems, b) thermal power components, c) building specifications and materials. VERIFY has been implemented based on open-access tools, to provide a) holistic LCA and LCC analysis under the umbrella of a single software tool, b) easy and friendly user interface through server-based access, c) connection with external software tools and/or platforms, d) connection with internal data repositories, e) personalized and safe environment, f) compliance with data ontologies (e.g. SAREF).

LCA methodological approach, established by the specific ISO standards ISO 14040 [17] and ISO 14044 [18]. In addition, LCC concept in building practice, set by the ISO 15686–5 [19] is followed and performed. LCA and LCC modelling approach can be applied for a single energy system, building and/or multiple buildings/blocks projects subject to planned interventions. Effective comparison of alternative scenarios is supported along with comparative graphs and tables.

2.2 INTEMA.Building Goals and Objectives

The need for reliable and accurate calculations for the building's energetic behaviour is critical to calculate properly the energy savings and the CO_2 emissions reduction when planning retrofitting solutions. INTEMA.building is a dynamic Building Performance Simulation (BPS) engine developed by CERTH providing physics-based simulations of high accuracy and validity in the results [20]. INTEMA.building offers among others multi-zone dynamics calculation, HVAC systems (e.g., boiler, heat-pump, solar thermal collector, storage tank), electrical generation and storage systems, thermal comfort calculation, as well as ancillary modules for load/RES forecasting and battery scheduling. The tool leverages the Modelica language [21] capabilities to implement high order dynamic models for both passive and active elements. At the same time, a web-based interface is provided for the non-expert users which besides fully supporting the building system definition, also supports automatic data import through BIM (.ifc) file.

2.3 VERIFY and INTEMA.Building Architecture

A significant advantage of the platform lies in the integration of two specialized software applications under a single platform. The developed architecture depicted in Fig. 1 enables all required functionality and interoperability among the tools, while taking into consideration security and scalability concerns.

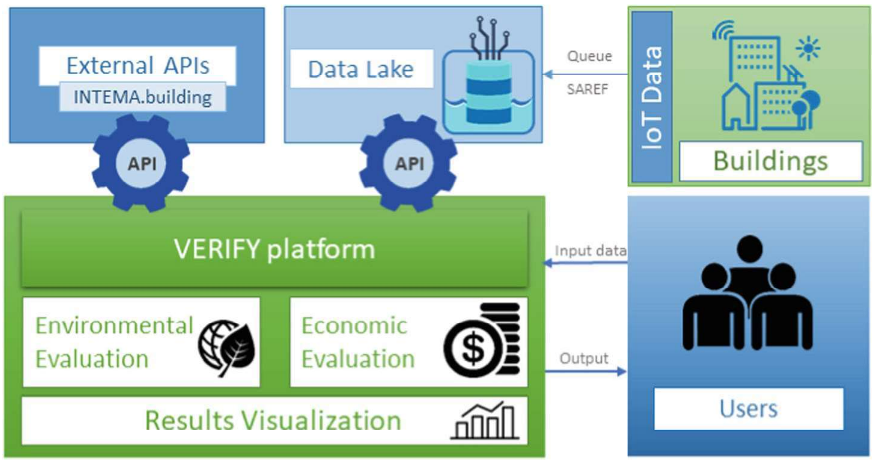

Fig. 1. VERIFY and INTEMA.building architecture

VERIFY constitutes a holistic software approach which enables the association of building modelling with energy consumption and production time series to evaluate and measure the building's performance through a graphical user interface. Time series data can originate through multiple sources as: 1) historical data manually provided by the user through.csv file upload, 2) synthetic data automatically provided by INTEMA.building tool and 3) real time data automatically gathered from the building's sensorial network. Real time data are stored in a large data repository which follows: 1) the Data Lake approach and 2) the Smart Applications REFerence (SAREF) ontology scheme [22]. VERIFY easily communicates with external software tools (e.g., Data Lake, INTEMA.building) using RESTful APIs. Environmental and economic computations are performed through smart Python algorithms in the core of the platform. Analysis results are presented through dynamic tables and graphs.

3 Environmental and Costing Methodology for Buildings

Typical LCA and LCC methodologies focus on evaluating the environmental and economic impact of a product or a service through its life cycle encompassing many stages of the value chain (raw materials extraction, manufacturing, distribution etc.) [23, 24].

A large variety of passive and active assets are included under the building structure. As a result, various direct and indirect interactions between them occur (e.g., the boiler consumption depends strongly on the quality of the wall insulation). Hence, even if the components are allocated to predefined suitable sectors (e.g., electrical production, active thermal) for easier manipulation, the analysis is performed regarding the building as an entity during its life cycle. According to the developed methodology, a building envelope consists of passive components (e.g., walls materials, insulation, glazing), thermal (e.g., heat/cool sources, thermal storage) and electrical components (e.g., appliances, PVs).

In order to simplify the project creation and provide the ability to users to create and modify different scenarios easily, VERIFY requires a relatively small set of scenario setup input information. The majority of environmental and costing initial data is provided by a private VERIFY's database. The dedicated database consists of multiple categories divided into: 1) energy production, 2) energy storage, 3) active thermal components and 4) passive thermal components capable to cover most of the building scenario needs. The analysis considers infrastructure energy of the components construction, initial environmental footprints and possible replacements; which are incorporated and automatically imported to the final computation procedure. In contrast to other methodologies where the use phase is analyzed using some average values [25] or the components maintenance [26, 27], the current methodology follows a more detailed approach regarding the use phase of the buildings. Specifically, accurate timeseries for assets consumption/production are retrieved either from the INTEMA.building tool after detailed dynamic simulations, or from installed sensors/meters in real pilot buildings (real time dispatch or stored data).

Finally, by applying the proposed methodology in the VERIFY tool, demanding in terms of time (performance time) building retrofit, is realized adequately fast and precisely.

4 Retrofitting Scenario Setup Procedure

The retrofitting scenario setup includes multiple steps, starting by: 1) importing specific scenario configurations preferences, 2) claiming synthetic/projected data from INTEMA.building tool, 3) performing the LCA and LCC analysis and 4) viewing the KPI computation results. The retrofitting procedure is depicted in Fig. 2 under the detail sequence diagram.

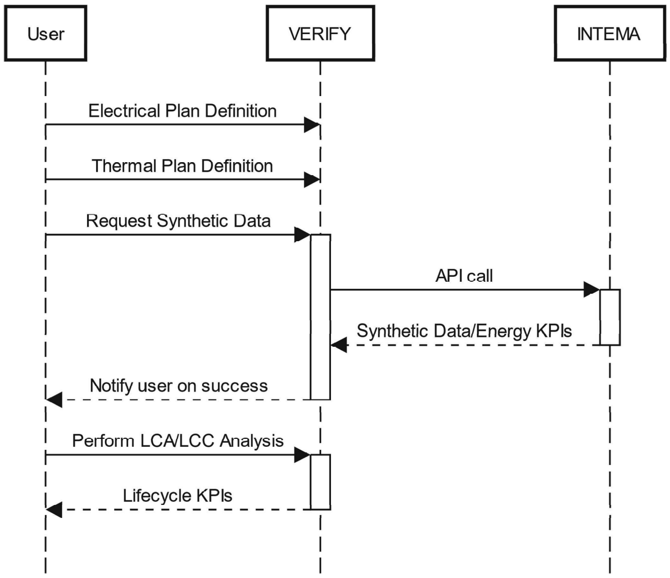

Fig. 2. Sequence diagram describing the building retrofitting planning steps

The modeling of a building and its infrastructure for both the current state and the planned renovations is achieved through the front-end layer of VERIFY and requires details regarding: 1) the building's envelope, 2) the electrical systems and energy storage devices and 3) the thermal systems. To do so, the user develops i) an electrical plan and ii) a thermal plan. The electrical plan setup consists of the energy generation (e.g. photovoltaics) and the storage systems (i.e. batteries) preferences definition. Furthermore, the location of the building and the analysis lifespan is also considered at this stage. Indicative annual consumptions (lighting and appliances) need also to be provided by the platform user. Following the configuration of the electrical plan, the thermal plan configuration includes the building envelope information and the comfort boundaries in terms of building's temperature during summer and winter periods. Moreover, details regarding the already installed or planned renovation thermal components are specified. Thermal components might be of two types: 1) active components, which contribute to electrical or fuel consumptions, and 2) passive components, which prevent energy losses.

After building set-up configuration is finalized (as represented by the electrical and thermal passive and active components) the operation data during the building use-phase is imported. These data can be either actual monitored data retrieved from the building sensorial network or synthetic data obtained through dynamic simulation. In the case of no available monitored data, synthetic data can be requested from INTEMA.building through restful API. Upon request, VERIFY forwards the relevant subset of the defined building's retrofitting scenario information to INTEMA.building. INTEMA's engine generates the Modelica system model of the particular building system. In the next step, the Modelica code is simulated in the Dymola environment based on the provided simulation date range (typically one year). While the simulation time may vary depending on the generation and storage systems present in the model, typical times do not exceed the two minutes mark. Timeseries synthetic data are generated and forwarded back to VERIFY in order to be stored and utilized in the LCA and LCC methodology. The last step involves the LCA or LCC analysis and the performance evaluation of the building. The analysis results are presented through interactive charts and table in the user interface of the platform.

5 Evaluation Scenario Results and Discussion

To highlight the main functionalities of the platform, Sect. 5 briefly presents an evaluation demo case scenario by analyzing a typical household building renovation in Greece, through the proposed software tools.

5.1 Scenario Description

A single-storey building has been chosen for the demonstration of the tool's functionality. The building is located in Athens, Greece, has a gross area of 170 m^2 and represents a typical low energy efficiency case. Heating is provided by a 24kW heating oil boiler and cooling is provided by 3 air-to-air heat pumps (mini split units). Table 1 includes the main geometric and thermal parameters of the studied building. It is useful to state that the envelope has no insulation and the windows are single-glazed with aluminum frame (without thermal break).

Table 1. Main envelope parameters

Type	Direction	Area (m^2)	Thermal transmittance – U value (W/m^2K)	Thickness (m)
External Wall	N-W	27.16	3.45	0.25
	N-E	13.94	3.45	0.25
	S-W	13.26	3.45	0.25
Window	N-E	8.8	5.74	–
	S-W	13.5	5.40	–
Internal Wall	–	16	3.85	0.25
Ceiling	–	70	4.00	0.23
Floor	–	70	4.20	0.23

The considered interventions are presented in Table 2. More specific, the interventions under evaluation include the replacement of the heating oil boiler with a natural gas one, insulation of the envelope and replacement of windows, as well the installation of a 10kW rooftop photovoltaic plant.

Table 2. Installed components

	Current	Planned
Thermal Active	Boiler Oil 24 kW	Boiler Natural Gas 24 kW
	Heat Pump (Cooling) 3x3.5 kW	Heat Pump (Cooling) 3x3.5 kW
Thermal Passive	No insulation	Insulation 75 mm, Expanded polysterene
	Glazing 1 layer, 10 mm, Aluminum frame	Glazing 2 layers, 10 mm, Aluminum frame
RES	–	Photovoltaic 10 kW, Monocrystalline

5.2 Results and Discussion

In this section the analysis results of the two scenarios (prior to and after the renovation) is described and presented.

In Table 3 the energy results regarding the electrical and thermal consumption/production for the two scenarios are depicted Table 4 presents a set of indicative environmental Key Performance Indicators (KPIs) from the LCA analysis for the current and the planned scenario. Considering the Lifetime CO2 emissions and Primary Energy (PE), reduction is achieved as a result of the interventions. The exact values of the emerging savings, which besides the energy reduction, also, include the environmental/energy profits that originate from the PV's operation, are also presented. The total savings through retrofitting lifetime are calculated based on Eq. 1. Lastly, the Energy Payback Time (EPBT) and the CO2 Payback Time (CPBT) for the photovoltaic (PV) installation are calculated to happen early in the building's lifespan.

$$\begin{aligned}\text{Savings} = &(\text{Infrastructure Costs} + \text{Functional Costs})_{\text{current}} - \\ &(\text{Infrastructure Costs} + \text{Functional Costs} - \text{Profits})_{\text{planned}}\end{aligned} \tag{1}$$

The electricity import and export price were set to 0.167 and 0.5 €/kWh respectively. In addition, oil and natural gas price were set to 0.105 and 0.048 €/kWh respectively. Lifetime costs (infrastructure and functional), lifetime revenues (PV investment), electricity bills and fuel costs are significantly diminished due to the retrofitting of the building envelope and the boiler upgrade. Furthermore, considering the profit from the PV investment and the reduction of the functional costs, the savings achieved, which are calculated by Eq. 1, are considerably high. Similarly, Table 5 shows the costing KPIs extracted from the analysis. Finally, Table 6 contains three economic metrics regarding only the energy investment of the PV.

VERIFY also performs yearly environmental and cost savings comparison between the planned and the current scenario and presents the result into charts. Figure 3 presents the functional and infrastructure environmental emissions. Positive values indicate that the planned scenario achieves higher emissions reductions (e.g., lower fuel consumption). On the other hand, negative values, indicate worse performance. This can be noticed even during the first year of analysis, at which the components of the planned scenario have to be purchased and installed (heavy emissions and monetary costs), while in the case of the current scenario, the components are already installed (i.e. there are no extra costs and no additional embodied energy of new materials). Figure 4 presents the amount of avoided costs achieved, during the project lifetime. During the project initial

Table 3. Annual energy load and generation amounts

Value	Scenario	
	Current (kWh)	Planned (kWh)
Electrical consumption	11.574	11.199
Imported energy	11.574	6.916
Exported energy	0	5.119
PV generation	0	9.402
Heat consumption	96.036	91.982
Cool consumption	7.996	8.030

Table 4. Environmental KPIs

Scenario	KPIs			
	Lifetime CO2 Emissions (kg)	Lifetime PE (kWh)	Photovoltaic EPBT (years)	Photovol-taic CPBT (years)
Current	982.557	3.848.939	–	–
Planned	265.843	3.341.085	4,6	3,3
Savings	785.083	699.577	–	–

Table 5. Costing KPIs

Scenario	KPIs			
	Lifetime costs (€)	Lifetime revenues (€)	Annual El. Bills (€)	Annual fuel costs (€)
Current	391.170	0	1.948	12.896
Planned	225.690	60.290	1.158	4.419
Savings	225.770			

Table 6. RES Investment

Scenario	KPIs		
	IRR (%)	ROI (%)	LCOE (€/kWh)
Planned	20,5	494,25	0,0686

year negative cost reduction values appear due to the capital and installation expenditures. The remaining years of analysis accomplish economic gains ranging from 5 to 20 k€ per year.

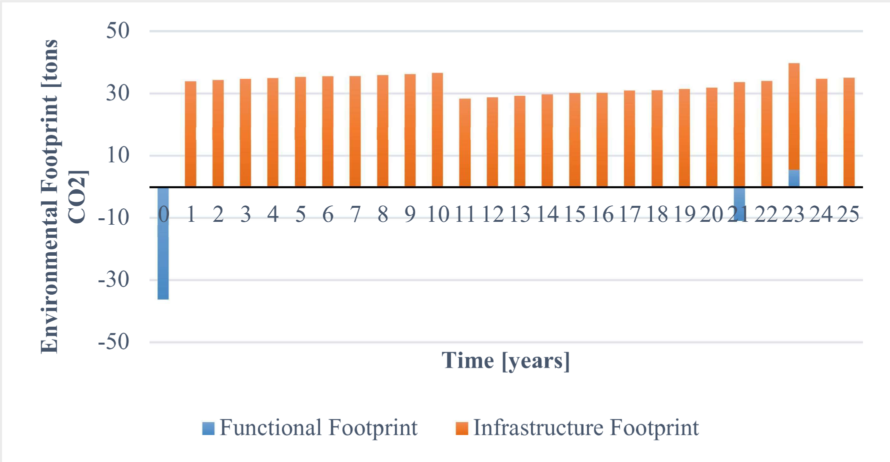

Fig. 3. CO_2 emissions reduced during project lifetime

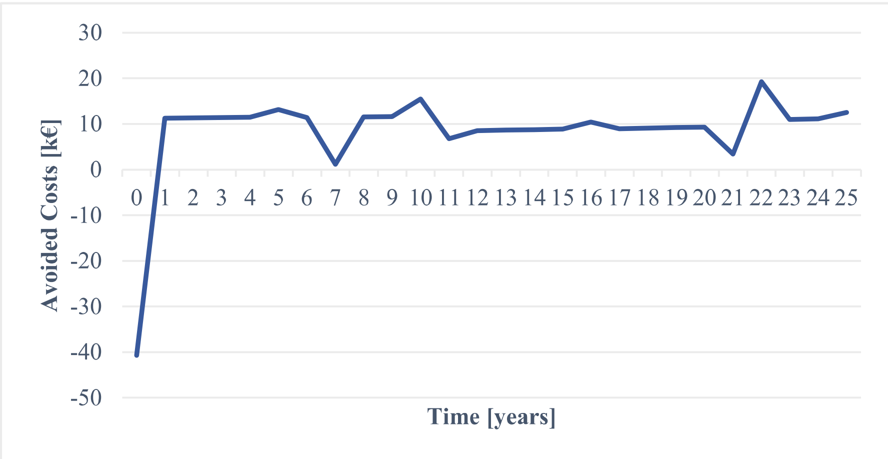

Fig. 4. Avoided costs during project lifetime

6 Conclusions

The current work presented a holistic environmental and economic evaluation tool for building retrofitting projects. The platform involves a set of innovative elements including the detailed LCA and LCC calculations based on the total building renovation. Furthermore, the tool goes beyond the classical life cycle methodologies that follow ISO 14040 and are based on aggregated yearly values and takes also into account real time data. Lastly, an integration scheme has been implemented with the INTEMA.building tool for the case of inadequate historical data.

A demo case has been presented to highlight the main functionalities of the platform, referring to the renovation of typical Greek building. Main interventions included replacement of the oil boiler with a natural gas one, insulation of the external surfaces, replacement of windows and installation of photovoltaic generation. Results indicated that a drastic environmental improvement can be achieved with 785 tons of CO2 reduction and 700 MWh of primary energy savings during the project lifetime. In terms of economic benefits, the savings were estimated at 255 k€, the IRR at 20.5% and the ROI at 494.25%. Through the demonstrated renovation assessment, the platform capabilities became evident.

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