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An integrated life cycle assessment and life cycle costing approach towards sustainable building renovation via a dynamic online tool

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HIGHLIGHTS

- An online platform for dynamic lifecycle analysis is presented.
- An energy-retrofitting use case in a multi-family residential building is examined.
- The primary energy needs, carbon emissions, and lifecycle costs are analyzed.
- The retrofitting use case can lead to a 95 % reduction of $CO2_{eq}$ emissions.
- For 25 years of operation, a total of 515 k€ can be saved.

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ABSTRACT

Building stock retrofitting is essential to achieve the ambitious sustainability goals of the building sector due to its high energy consumption rates. The evaluation of the various building interventions shall be holistically assessed in terms of environmental and costing impact. The aim of this paper is twofold: First, it presents the innovative characteristics of a developed online tool (Virtual intEgrated platfoRm on LIfe cycle AnalYsis - VERIFY) able to perform dynamic life cycle analysis and global warming impact assessments by capitalizing on the well-known LCA and LCC methodologies, applicable in the case of building renovation. VERIFY is able to analyse dynamic life cycle inventories that consider the temporal profiles of energy consumption, and the time-dependent temperature changes, while being also interoperable in terms of exchanging data with other available energy simulation engines, or even using real-time monitoring data from sensors, processing any data time granulation. Second, the paper evaluates, from a life cycle perspective, the impact of specific energy retrofitting measures, meeting the Passive House Standard, for the case of a multi-family residential building in Athens, Greece. The proposed energy-retrofitting scenario examines actions related to the deep retrofitting of the building envelope and the upgrade of the thermal components as well as to the incorporation of clean electricity generation based on renewable energy systems; all aiming to drastically reduce the environmental impact of the building, rendering it almost near zero energy. Through the planned infrastructure installations, the primary energy needs and CO_{2eq} emissions were reduced by 91 % and by 95 % respectively, while for a building operational lifespan of 25 years, savings up to 515 k€ compared to the baseline scenario, can be achieved.

Abbreviations: ACH, Air Changes per Hour; API, Application Programming Interface; ASOS, Automated Surface Observing Systems; BIM, Building Information Modelling; CED, Cumulative Energy Demand; COP, Coefficient of Performance; DHW, Domestic Hot Water; DLCA, Dynamic Life Cycle Assessment; EoL, End-of-Life; EPD, Environmental Product Declaration; EU, European Union; FU, Functional Unit; GHG, Greenhouse Gas; HTML, Hypertext Markup Language; HTTP, Hypertext Transfer Protocol; HVAC, Heating, Ventilation and Air Conditioning; H&C, Heating and Cooling; ISO, International Organization for Standardization; KPI, Key Performance Indicator; LCA, Life Cycle Assessment; LCC, Life Cycle Costing; LCI, Life Cycle Inventory; MCDM, Multi-Criteria Decision-Making; NER, Net Energy Ratio; NZEB, Nearly Zero Energy Building; NPV, Net Present Value; O&M, Operation and Maintenance; PEB, Positive Energy Building; PES, Primary Energy Savings; PV, Photovoltaics; PVC, Polyvinyl Chloride; RES, Renewable Energy Sources; RoR, Ruby on Rails; SDGs, Sustainable Development Goals; SCOP, Seasonal Coefficient of Performance; SEER, Seasonal Energy Efficiency Ratio.

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1. Introduction

During the last decade, the sustainability of buildings has gained increasing interest from researchers, building specialists, and policy-makers [1,2]. The building sector is considered a fundamental element towards mitigating environmental impacts and reaching climate targets in line with the Sustainable Development Goals (SDGs) [3]. On a global scale, one-third of the final energy consumption and almost 40 % of total CO_2 emissions is attributed to buildings [4]. In the European Union (EU), 42 % of non-residential buildings and 38 % of residential buildings were built before 1970 [5], while around 75 % of the building stock is energy inefficient [6], with an energy consumption per square meter of floor area higher than the established energy consumption benchmarks of reference buildings [7]. Building renovation and energy-efficiency measures present a huge potential to achieve significant energy savings, and reach the medium-term emission reduction targets of at least 55 % by 2030, contributing to sustainability and climate neutrality of Europe by 2050, as envisaged by the European Green Deal [8]. The establishment of the "Renovation Wave" [9], aims to increase sharply the renovation rates and processes, as well as accelerate buildings deep energy renovations, to foster the share of Nearly Zero Energy Buildings (NZEBs) and Positive Energy Buildings (PEBs). Achieving sustainability in buildings requires the i) manufacturing of innovative and ecological building materials, ii) market introduction of efficient building design, renovation, and construction processes, iii) further integration of smart technologies and iv) higher penetration of Renewable Energy Sources (RES) in the energy mix, towards facilitating energy transition and decarbonization of the building stock [10].

The use of life cycle assessment (LCA) in building applications began three decades ago, to evaluate the environmental impact during buildings' lifetime, and throughout their various life cycle phases, i.e. from cradle-to-grave [11]. A life cycle approach in buildings considers design and operation changes during the whole service life of the building and estimates the potential environmental impacts, resource flows, and costs [12]. More specifically, LCA is able to take into account impacts occurring at multiple stages throughout the building life cycle, considering specific properties and quantities of building materials or technologies, while also providing estimates and insights about material and energy use (e.g. lifetime primary energy savings) and associated carbon emissions. On top of that, life cycle analysis entails the economic and cost-related trade-offs analysis of products, processes or systems and interventions in buildings in terms of life cycle costing (LCC) and overall investment valuation, e.g. by calculating life cycle costs, investment costs, and economic indicators, during their manufacturing, construction and operation lifetime [13]. In this context, it can be used also as a tool to benchmark alternative design, construction, and/or retrofitting options, supporting decision-making towards an optimal state; critically improving both the environmental impact and the energy performance of the buildings (focusing on energy consumption and carbon footprint reduction) accompanied by cost-effectiveness along their entire lifecycle [14]. It can also support building designers and engineers to compare all the environmental impacts and economic features, to conclude the most sustainable solutions with a longer lifetime and high recyclability [15]. Furthermore, it is necessary towards shifting the environmental considerations from the level of lifetime characteristics of the components to the level of the whole lifespan of the building.

The sustainability performance of buildings can be evaluated capitalizing on the well-defined LCA and LCC methodologies [16]. LCA and LCC can assist in the design of highly energy efficient and net carbon buildings along with social and economic benefits for their users [17]. LCA and LCC can provide such evaluations for various climatic conditions and building typologies [18], taking into account all the different life cycle stages of the building, i.e. design and production, transportation of materials, construction, use (operation & maintenance), and end-of-life (demolition, recycling and reuse, disassembly and final disposal) [19]. The analysis may focus on either whole buildings, parts of them, or on isolated building systems/components and materials, considering either their entire life cycle or part of it [20]. Nowadays, LCA is used in building design for several objectives [21], such as enhancement of building materials in terms of thermal and structural properties, sustainable and improved indoor environment, eco-design options, building certification, optimization of construction processes, evaluation of new innovative building technologies, and comparison of construction/retrofitting projects in line with the NZEB principles. Such an analysis can also be extended to the level of a community/neighborhood/district scale [22].

Special attributes of building infrastructure strengthen the need of LCA, for measuring and evaluating building performance. These attributes include i) the long useful life of buildings - typically around 50 years, ii) the high energy and environmental burden of buildings during their use phase, and iii) several technological, material, design, and operational changes often demonstrated in buildings. [23]. The employment of LCA allows for the evaluation of operational impacts, associated to the energy use during the use phase, as well as embodied impacts, that take into account the energy and carbon content of building materials, construction products, manufacturing processes, and refurbishment actions in the building's lifecycle [24]. It facilitates the fulfillment of building life cycle environmental performance targets and policies related to energy use, comfort and operation, and the design of energy efficiency measures [25]. The type of energy efficiency measures and the building renovation expenses are not aligned among countries, owed to the diversification of geographical, climatic, social, legal, technological, and economic conditions [26], as well as the existence of various building typologies [27] and different context-specific building characteristics [28]. Given the large number of old and energy-inefficient buildings, as well as the existence of the aforementioned building specificities, retrofitting options can be benefited from an evaluation perspective using a life cycle analysis aiming to effectively design or improve building performance. According to LCA studies, the use phase is responsible for 80 %–90 % of life cycle energy consumption in buildings [23,29,30]; thus contributing the most to building greenhouse gas (GHG) emissions [31]. As a consequence, available research mostly focuses on the operational energy of the building [32]. Transportation and demolition usually account for about 1–2 % of the total life cycle energy consumption [25,33], whereas the remaining percentage is attributed to manufacturing, construction, and/or refurbishment processes. LCC deals with the estimation of all incurred costs relating to building energy retrofitting and systems, components, and materials installations [34], and supports interventions and investment decision-making, when designing a renovation project or a new building [35].

Moreover, there is a continuously increasing interest in the link of Building Information Modeling (BIM) and ingested data with the relevant LCA/LCC calculation algorithms, able to retrieve automatically, building-related materials quantities [36]. Previous thorough reviews dealing with the use of LCA in the building sector, in the last two decades, have revealed that most investigations focus on energy use and GHG emissions [37–39]. Most researched groups of LCA studies are oriented to the development of frameworks capable of facilitating the LCA workflow during the design stage and have proposed, as simplified as possible, screening approaches to choose among available materials and energy systems, for which a plethora of design data exist, during the early design stages [40]. Some also consider the cost-effectiveness and anticipated embodied impacts, during the design phase [41], while a few studies are available, that account for water management considerations [42].

The current paper advances beyond the current most commonly used LCA approaches, as it includes except for an integrated LCA/LCC approach, the consideration of dynamic consumption data along with basic inventory datasets, able to account also for i) variations in temperatures, ii) any updates in the energy grid mixture (local or even national) and consequently in the emissions, iii) building occupancy effects and own RES primary production and consumption profiles. This is a step towards the development of dynamic LCA frameworks, able to account for even real-time data, which in general have been proven more realistic in terms of results, as also denoted by [43], because they take into consideration the temporal evolution of GHG releases and any uptakes. Specifically, as noted down by Collinge et al.[44], the temporal resolution of building-level data, along with the continuous (to the extent this is possible) capturing of effects that an electrical grid (but not limited to) has on the life cycle analysis of buildings, cannot be captured by static LCA approaches (thus resulting in underestimations compared to reality). This is true, especially if someone also considers that buildings nowadays should be designed and operate as active nodes of interconnected energy systems, at least at the level of a district.

The paper aims to investigate and evaluate the life cycle impact of a deep retrofitting scenario, according to the passive house requirements, for the case of a Greek building, from an ongoing EU-funded building-oriented project entitled RINNO [45], based on a newly developed house-built online tool, conducting dynamic life cycle assessment and costing computations named as "Virtual intEgrated platfoRm on LIfe cycle AnalYsis (VERIFY)". The retrofitting actions are analyzed, in terms of life cycle primary energy savings, $CO_{2\text{-eq}}$ savings, and life cycle costs and are compared with the baseline data (representing the performance of current systems), to extract valuable outcomes regarding the environmental and cost performance of the building from a life cycle perspective. The paper started off with the role and importance of LCA and LCC methodologies in buildings and continues with a short but comprehensive presentation of the current available LCA and LCC standards as well as the concepts and methods of relevant non-commercial tools in the research academy, to support the cognitive background of the reader, and identify key research limitations and practical gaps on current LCA/LCC practice. Then, the methodological background and software architecture of VERIFY, and its available modules are described in detail, to emphasize its offered benefits and improvements in the field. Finally, the developed tool is used for the evaluation of a building renovation project in Athens, aiming to examine its real-life applicability potential, and analyze the impact achieved and results generated.

2. Materials & methods

2.1. Relevant LCA and LCC standards for buildings and construction industry

LCA is internationally standardized and recognized, under a common methodological approach by the specific ISO standards ISO 14040 [46] and ISO 14044 [47,48]. According to the ISO 14040 series, the LCA methodological framework comprises four (4) key interrelated steps, i.e. i) the Goal and scope definition, ii) the Life Cycle Inventory (LCI) analysis, iii) the Impact Assessment, and iv) the interpretation of the results. LCA certifications of building products can be developed by manufacturing companies, called Environmental Product Declarations (EPDs) [49], in compliance with ISO 21930 [50]. LCC concept requirements and guidelines were set by the ISO 15686-5 [51], which establishes a clear terminology and a common methodology for LCC; being a common basis for setting targets against which actual cost performance can be tracked and assessed over the asset lifespan.

At the European level, LCA methodology in buildings is supported by the European standards EN 15643-2 and EN 15978. EN 15643-2 is dedicated to the definition of the framework and specific requirements for the assessment of environmental impacts considering buildings' technical characteristics and functionalities. EN 15978 provides a calculation method for implementing LCA in buildings, pertaining to the life cycle environmental loads of construction products and building materials, as well as of entire buildings [52]. The standard defines four (4) main life cycle phases for LCA application in buildings, namely production and design, construction, use, and end-of-life (EoL). The concept of LCA is also incorporated in the European Standard EN 15804 for establishing EPDs [49] and in the Construction Products Regulation (CPR), while it is also applied in multi-criteria certification schemes for sustainable and green buildings such as Building Research Establishment Environmental Assessment Method (BREEAM) and Leadership in Energy and Environmental Design (LEED) [53]. In this vein, building LCA results can be exploited to prove that the building reached an appropriate level of excellence, rendering it also as a reference case for the building market. Regarding LCC, the European standard EN 16627 defines the economic principles and cost calculation methods for evaluating the economic performance of a newly constructed or existing renovated building. Moreover, the EN-15459-1 focuses on the buildings' energy systems by specifying a calculation method of the economic performance of energy savings options in buildings.

In addition, intending to adopt a unified approach for building sustainability assessment, the European Commission established in 2020 a common life cycle evaluation and reporting framework for the sustainability performance of both residential and office buildings across Europe, named Level(S) [54,55]. Level(S) introduces a life cycle perspective of analysis under three (3) thematic areas, namely i) environmental performance, ii) health & comfort and indoor air quality performance, and iii) cost and risk performance, i.e., optimization of building life cycle cost and value as well as building adaptation to future risks of climate change. The framework defines an overarching set of six (6) macro-objectives and sixteen (16) core indicators associated with EU and national policy goals in areas such as energy, material use and waste, water, indoor air quality, and climate change. Level(S) envisions introducing a whole life carbon approach into construction policies and renovation plans for a sustainable built environment.

2.2. Screening of developed life cycle analysis tools for building assessment

Several building LCA tools have been developed to support the use and application of the LCA methodology, in the built environment in Europe, and all over the world. Widely known examples of available on the market LCA and LCC-related software for analysis are SimaPro, LCAiT, GaBi, BeCost, OneClick LCA, BEES, EQUER, ATHENA™ Impact Estimator, TEAM™ etc. However, this section is dedicated to indicative examples and previous works related to developed non-commercialized tools and models identified for the topic of building LCA, such as VERIFY tool. Numerous open computational tools have emerged by researchers and technical experts for the estimation of the life cycle carbon footprint of buildings, based on national data and bills of quantities. Good examples are the tools developed by Malmqvist et al. (2011) [56], Rossi et al. (2012) [57], and Fu et al. (2014) [58]. There are also tools specifically dedicated to residential buildings and different building typologies as that of Li et al. (2016) [59] and Solís-Guzmán et al. (2018) [60]. The environmental impact of Building Integrated Photovoltaic (BIPV) systems was also examined by Jayathissa et al. (2016) [61]. Regarding LCC, an indicative example is the NZEB cost spreadsheet developed by Pernetti et al. (2019) [62], within the context of H2020 CRAVEzero project. Furthermore, tools such as those of Domjan et al. (2019) [63] and Kong et al. (2021) [64] can evaluate both the environmental impacts and costs during the entire building life cycle and display relevant LCA and LCC metrics to support comparability between projects and decision-making. In general, diversified LCA approaches are observed in Europe, North America and Australia [20]. The dynamic effect of time-dependent parameters and properties in buildings has been also introduced, for example in the frameworks and tools designed by Tiruta-Barna et al. (2016) [65] and Su et al. (2017) [66]. In addition, in the study of Negishi et al. (2018), an operational methodology supported by dynamic tools and databases for performing dynamic building LCA is developed [67].

As a first finding, various methodological disparities and discrepancies or critical framework limitations exist among several life cycle analysis tools and evaluations, eradicating the consistency and accuracy of LCA. A limited number of LCA studies have been developed using a dynamic life cycle approach in building LCA considering climate change data modelling and dynamic energy simulations or dynamic environmental analysis including energy mix changes, as in the case of [68]. In fact, most of the current LCA approaches do not consistently account for existent life cycle variations [69], in terms of a) embodied energy of building materials, ii) energy supply (including also renewable sources), iii) any architectural and environmental rules, as well as iv) dynamic parameters during the building/district lifetimes, as changes in the energy mix, the retrofitting options and occupancy patterns [69–71]. In addition, LCA tools encounter considerable challenges pertaining to site-specific considerations, uncertainty problems in the use cases, and the dynamic nature of datasets or components [72]. An important research gap in the life cycle analysis of buildings is the consideration of the temporal variation and uncertainty phenomena and their relation to the calculation of real-time impacts and dynamic characterization factors, such as dynamic life cycle inventories (LCI), considering the temporal profile of emissions. For example, when it comes to the estimation of the life cycle GHG emissions occurring during the operation of RES systems, most LCA tools capitalize on average emission factors, implying a constant factor value during the year. However, time-varying emission factors should be used due to the variable renewable energy production throughout the day and season, as well as owing to the dynamic effect of the energy efficiency measures [73]. The need for real-time performance monitoring and calculations led to the emergence of LCA tools that take into account the dynamic behavior and temporal variations in energy systems embedded in buildings. Moreover, buildings offer services that might change over time and be subject to modifications resulting in different dynamic scenarios that should be investigated by a Dynamic Life Cycle Assessment (DLCA), for example in the exemplar case of energy-positive buildings, which offer the excess of energy produced, on an annual basis, to the interconnected grids.

Given these facts, building life cycle modeling should adopt an integrated LCA and LCC approach resulting in a holistic and comprehensive analysis of benefits and costs, highlighting the optimal performance and the most sustainable building solutions. Numerous data sources originating from various building components, processes, and life cycle stages are required. Effective simulation methods for optimal energy management [74] and cost-effectiveness of building solutions, are also essential to feed the life cycle models [75]. Ideally, calculation tools need to have the ability to deal with a large amount of data and information regarding local area dynamics, building features, and system parameters, either ingested from multiple-origin databases and/or through communication with other software tools, or based upon own-built databases, consolidating and categorizing several data types and dynamic inventories. Considering also the potential changes occurring at different stages of their life cycle, due to the long service life of buildings, new methods should take into account their dynamic and time-dependent performance during this period and should provide real-time results towards proposing corrective actions and improvement measures. The EU policy-makers and researchers in the field of LCA and decarbonization acknowledge that the sustainability of buildings should be developed from a life cycle perspective towards dynamic life cycle carbon approaches [72,76]. To this end, when it comes to performing building life cycle analysis, particular attention should be given primarily to the consideration of elemental dynamic factors and real-time aspects under different timesteps and horizons, accounting for the variation of specific variables that demonstrate temporal changes and effects during building lifetime, such as the energy mix and emission inventory variations, the dynamic building occupancy profile and consumption patterns, the load and temperature changes, and the periodic installation of new components. To address the aforementioned shortcomings, a tool dedicated to dynamic life cycle analysis (VERIFY) has been developed.

2.3. Virtual intEgrated platfoRm on LIfe cycle AnalYsis (VERIFY) – A holistic LCA & LCC tool

VERIFY is designed to perform environmental and economic assessment of buildings, following a component-based life cycle approach. VERIFY tool offers real-time environmental assessment calculations, followed by corresponding economic ones, considering dynamic building operation time-series data and LCI datasets, temporal variations in temperature and any time-varying factors pertaining to the energy grid mix and the building usage, such as the occupancy profiles and effects, and any building related self-energy production and consumption patterns. Data injected through an Internet of Things (IoT) sensorial network, feeds such computations, providing hourly/daily/monthly environmental and cost results. Any data time granulation can be processed by VERIFY, according to each user needs. VERIFY supports calculation engines, with a variable (user adjustable) time step. The result is a life cycle comprehensive report involving a set of well-defined Key Performance Indicators (KPIs) summarizing the sustainability profile of the system under consideration. The following sections outline the inner workings of the tool.

2.3.1. VERIFY background & methodology

The overall methodological framework of VERIFY is based on quantitative methods and algorithms categorizing, measuring, and calculating LCA and LCC indicators for a diverse set of examined energy-related components and technologies that can be installed in buildings, while providing also real-time data monitoring and project evaluation. VERIFY calculates the life cycle performance of assets present in buildings in terms of primary energy and renewable energy generation, while it also can consider the cost-effectiveness of the solutions to identify the best renovation strategies leading to an optimal balance of environmental impacts and costs, via an effective comparison and benchmarking of alternative scenarios. The corresponding calculations are based on ISO 14044 methodology and are tailored to the environmental impact categories related to climate change and energy, i.e. Global Warming Potential (GWP) and Cumulative Energy Demand (CED). In addition, VERIFY also embeds environmental targets and policies for the sustainability performance of buildings in line with Level (S) framework. In particular, three (3) Level(S) macro-objectives are already addressed by VERIFY methodology, namely the following: 1. GHG emissions along a buildings' life cycle, 2. Resource efficient and circular material life cycles, 3. Optimized life cycle cost and value, respectively. To do so, VERIFY considers bills of quantities related to construction, transformed into inventories. It also takes into account cost elements for each material/product and specific lifetimes for each building component in comparison to the planned building lifetime. Further customization of the tool aims, soon, to include and comply with all thematic areas and macro-objectives of Level(S), to provide a quite broad uniformity level for building sustainability analysis in terms of LCA.

Concerning the life cycle phases for the target energy-related technologies/systems, which are currently supported, include a) the production and design, b) construction, and c) use phase. EoL has not been included at this stage due to the uncertainty of waste treatment methods applied in most EU countries. To illustrate this, life cycle modeling and analysis focus on the manufacturing and installation processes as well as the operation of the technologies present or installed in buildings, considering both the embodied and operational energy content for all components. So that VERIFY can carry out a life cycle analysis, its own customized database with data provided by technology providers, well-reviewed literature, and technical reports, according to each country's dynamics and existing building profiles, are included. It also includes data for multiple technical components provided internal editing and analysis costing data sourced from well-established technology databases e.g. [77], and electricity/fuel data by specific databases from Eurostat [78,79] and European Commission [80]. The database offers an inventory of global warming (provided in CO2-eq) and primary energy (provided in MJ) factors for conventional and innovative technologies/ systems. In addition, VERIFY's database contains specific local data and information about the meteorological and energy mix profile as well as the energy prices for twenty-seven (27) EU countries.

An overview of VERIFY data and methodological framework, its overall structure and modelling flow analysis, as well as key elements and steps for conducting life cycle modelling and analysis, are depicted in Fig. 1. The project options can be segmented into four main steps, namely creation of electrical and thermal plans, optional creation of an investment plan, and the final association of electrical, thermal and investment plans to a geographical location. VERIFY guides the user through the required steps in an intuitive sequential manner. More information about the required steps for project setup and creation with VERIFY is provided in Appendix A.

VERIFY supports the usage of energy consumption and production time-series data, instead of aggregate energy values (typically yearly based), to enhance accuracy and enable real-time calculations. In this manner, historical, synthetic, and/or real-time sensor data can be used for the building energy performance description. More specifically, datasets can be provided either:

- directly by the VERIFY users - dataset file upload is supported by the platform of the tool by utilizing previous captured time series data information (historical data)
- via the communication of the platform with IoT external sensorial networks. The key functionality
- of real-time data for monitoring and evaluation is provided (real-time data).
- automatically - VERIFY is able to obtain energy demand data from building energy simulation tools and specialized energy analysis software, and store it in its local database (synthetic data).

Specifically for the latter case, or in case of no or low data availability, a software integration approach can mitigate this problem, by using as input simulated "synthetic" data. VERIFY is coupled through an automated API with a specialized energy building simulation engine, own developed, named INTEMA.building [81]. INTEMA.building is a detailed energy analysis tool that performs dynamic in-time simulations for the thermal behavior of the buildings coupled with active energy systems. INTEMA.building is offered as a web-based application for conducting accurate building energy simulations, able to energy systems (production, consumption and storage). The basis of the simulation engine lies in the development and implementation of white-box models for a range of energy systems. INTEMA.building is based on open-source Modelica libraries, currently being developed to be fully customizable with a web-based user-friendly interface. More specifically, the tool is developed in the Dymola environment [82] using the Modelica modeling language [83] by exploiting the existing repository of components from the libraries Buildings [84] and BuildingSystems [85]. Moreover, there are extra house-built components created to satisfy the simulation needs and the models analysis with a high level of detail. All required passive (i.e., walls, windows) and active components (i.e., PV panels, boilers, heat pumps, batteries etc.) with the corresponding controls, are combined to form the appropriate building system representation automatically. The tool utilizes weather data from the Photovoltaic Geographical Information System (PVGIS) provided by the EU [86]. INTEMA.building also supports building geometry inclusion and consideration via BIM files (.ifc). The tool has been successfully verified according to the relative European Standard EN 15265–2007 standard [87]. Passive components and the overall building thermal behavior have been verified and achieved high accuracy in all 12 cases involved. More details for the software and its verification procedure can be found in Appendix B.

2.3.2. VERIFY architecture

The tool architecture, as depicted in Fig. 2, consists of the interaction with the end-user via the front-end application layer. The front-end layer assists users to perform the following actions: 1) set up a building energy plan, 2) connect monitoring devices responsible to gather real-time data from distributed energy infrastructure of a building, 3) upload historical sensor data using files in CSV format and 4) perform life cycle analysis (under environmental and costing terms) of a building energy plan. VERIFY supports these user actions through a user-friendly and responsive graphical interface, interactive forms that enhance user experience, and finally dynamic charts that plot useful information and the results of the life cycle analysis.

The following programming tools are orchestrated, to ensure the

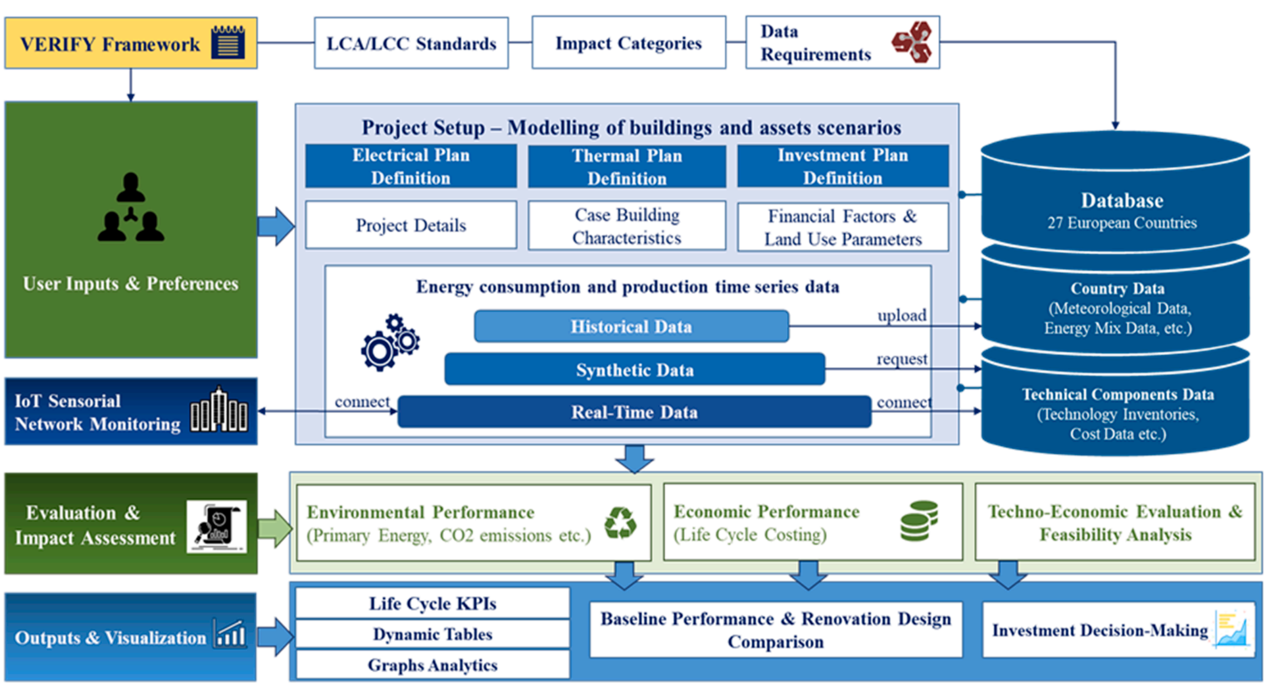

Fig. 1. Overview of VERIFY data and methodology framework, and project evaluation pathways.

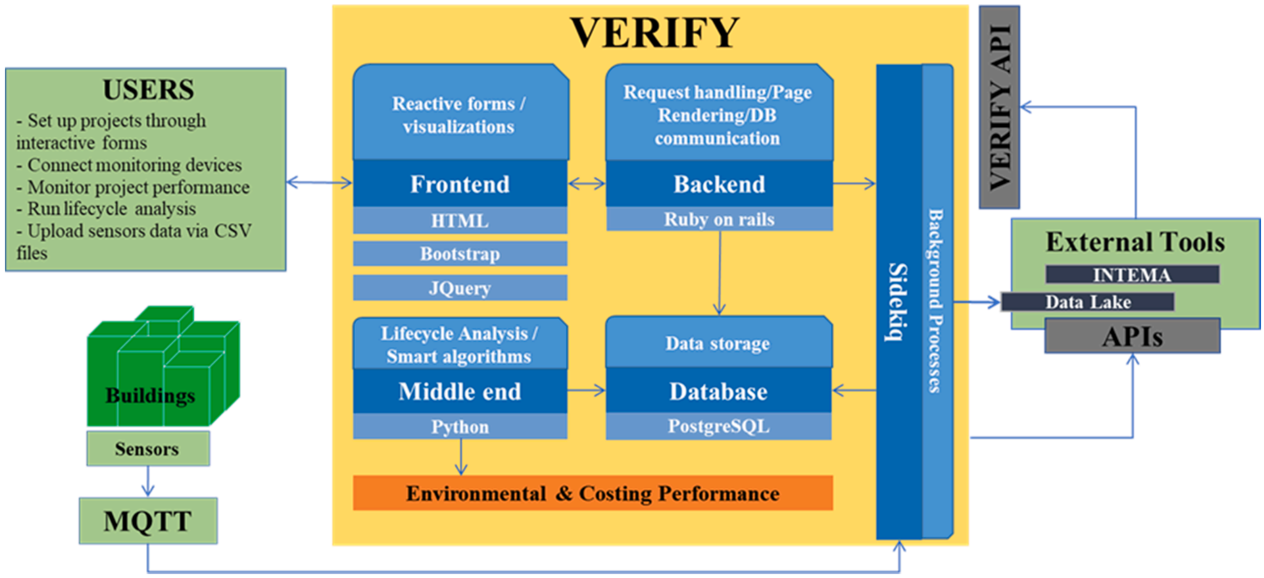

Fig. 2. System Architecture of VERIFY.

VERIFY's best possible function. More specifically, the basic HTML view of a VERIFY's page is visually enhanced by the Bootstrap CSS framework, an open-source toolkit that is used to quickly design responsive websites. Along with Bootstrap, JQuery was used to add extra functionality to the web pages, such as opening/closing modal forms. JQuery supports easy document manipulation, event handling, and animations is a mature project and is used vastly in the development of web applications. Finally, JavaScript libraries are used to facilitate the fast development of the tool and provide an interactive user environment. The front end of the application communicates directly with the back end through the HTTP protocol. Under the back-end layer, the core of the application and the coordination of the actions take place during the VERIFY's operation. The back-end layer is responsible for handling user requests, performing the corresponding actions, and generating the expected analysis results. The communication between the back-end system and the database of VERIFY serves the ability to add or remove records from the database, as well as perform validation on these data to ensure the system's integrity. For the implementation of the back-end, Ruby on Rails (RoR) is used. Ruby on Rails is a full-stack web framework, which is used to develop web applications and contains a set of tools to make the development quick and easy. It is shipped under the MIT Open-Source license, and it is supported by a large community of developers. RoR follows the Model-View-Controller development pattern that offers a clean code structure. It is written in Ruby, an object-oriented programming language, which has been also used for the development of VERIFY's back-end system. A strong point of RoR is the easy modeling of the database's tables. More specifically, each table can be modeled as a Ruby class and the data can be easily fetched or removed, without the need of composing complex queries. Additionally, constraints can be imposed on the various models of the database so that invalid data will never be inserted into the database.

VERIFY needs to store various data into a database to keep track of 1) user preferences, 2) energy plans created and their details, 3) time-series data and 4) the results of the life cycle analysis. To achieve that, a strong and reliable database system is required. PostgreSQL was selected, based on 1) the object-relational approach, 2) the open-source formation, and 3) the ability to manage various volumes of data as well as the support of complex data types. It conforms with the SQL prototype, however, it is easily extensible and offers a variety of additional features compared to a classic SQL database, such as custom-type columns. PostgreSQL is released under the PostgreSQL License, which is like the BSD or MIT licenses. The database of the tool is installed under the platform framework, to ensure rapid and accurate communication with the platform, effective usage by many peripheral components, and avoidance of confidential data transfer through external networks.

The middle-end environment introduces the layer, where smart algorithms considering LCA and LCC analysis are implemented. The need for fast performance and complex mathematical computations are conducted using Python programming language. Python is a versatile, easy-to-use language supporting the fast development of software. It also supports efficient, well-known and vastly supported libraries for arithmetic operations (numpy[1]) and the manipulation of large data (pandas[2]). To be successfully executed, the smart algorithms require time-series data regarding the district/city's energy consumption/production. To obtain this data the middle-end communicates directly with the PostgreSQL database. After the analysis is conducted, the middle-end layer exports the results to the front-end layer, which is responsible for the environmental and costing KPIs displayed to the user.

2.3.3. VERIFY life cycle analysis

Following the project definition, VERIFY conducts life cycle analysis towards the extraction of KPIs and graphs mapping performance and benchmarking examined scenarios. Table 1 provides a summary of the main input categories and data requirements for VERIFY core LCA & LCC methodology. Indicative features and parameters per input and data category are presented. The geographical area is a key attribute that defines the spatial size covered by the location coordinates, whereas the climate zone is a parameter indicating various climate characteristics such as degree days, irradiation, humidity, wind, etc.

The set of well-defined KPIs mapping the performance related to the most important life cycle carbon activities is exported through the life cycle report of VERIFY. An indicative list of the core indicators, which can be calculated by VERIFY tool, categorized in LCA and LCC indicators, is outlined in Table 2. KPIs include aspects related to primary energy and Primary Energy Savings (PES), CO_2 emissions and savings (expressed in kg or ton $CO_{2\text{-eq}}$), self-consumption, life cycle costs, payback time etc. KPIs are monitored and calculated at specific or

[1] https://numpy.org/.
[2] https://pandas.pydata.org/.

Table 1
VERIFY primary and secondary data and inputs. Categories pertain to specific project details, country dynamics factors, building characteristics as well as component and system technical specifications.

Category	Factors	Indicative Features/Parameters
Project	Lifecycle	Project Lifespan
		Initial Year of Analysis
	Meteorological Data	Climate Zone
		Temperature
	Geographical Data	Geographical Area
		Location Coordinates
Country Dynamics	Energy Mix	Fuel/RES Source Distribution
	Energy Conversion Factors	Primary Energy Factors
	Emission Factors	CO_2 Emission Factors
Building	Building Profile	Building Typologies
		Usage Type
	Floor Area Details	Floor Surface/Floor Height
		Number of Floors
		Wall Surface/Wall Materials
		Window/Glazing Surface
	Energy Needs	Annual Electricity Demand
	User Preferences	Target Temperature
		Winter/Summer Flexibility
		Systems Usage Priority
		Number of Occupants
	Cost Factors	Investment/Capital Costs
		Infrastructure Costs
		Operation & Maintenance Costs
Component (System or Material)	Electricity Generation (PV Systems)	Installed Power
		PV Material
		Number of PV Panels
		Conversion Efficiency
		Mounting Type/Angle Values
	Heating Cooling Ventilation	Heating/HVAC System Type
		Thermal Rating
		Usage Level
		Property Type
	Insulation Glazing	Insulation Material & Thickness
		Glazing Frame Material
		Glazing Layer Thickness
		Frame Coverage
		Number of Layers
	Energy Storage/ Domestic Hot Water (DHW)	DHW Type
		Tank Capacity
		Fuel
	Environmental Data (EPDs) Technology Inventories	Initial Embodied Carbon and Energy Content

various time intervals, e.g., once, on daily basis, on annual basis, and during the entire project lifetime, depending on the nature and impact of each indicator. The potential interconnection of VERIFY with sensorial networks at project demonstrations allows monitoring and calculation of KPIs in real-time and enables adjustment of the LCA algorithm, towards providing on the one hand continuous update and self-accuracy of results, while on the other, corrective actions towards optimal operation of the assets or buildings in the project.

2.4. Case study: Deep energy renovation of a residential building according to the passive house premium standard

To examine the applicability of VERIFY, the case of an old residential building was investigated. The building is a multi-family house located in the Moschato-Tavros municipality of Athens, Greece, and it is planned to be renovated considering the Passive House concept [88]. It has four floors with two apartments per floor 75 m^2 each, and a total floor area of 750 m^2 (see Table 3). It provides accommodation to fourteen building residents. It is constructed with conventional concrete and brick materials, aluminum frames and single glazing in windows, while it is equipped with old heat pump units for six of the apartments (two in each apartment), as well as an oil boiler and a natural gas boiler that cover the heating needs of one apartment each. Conventional solar thermal collectors coupled with a storage tank provide hot water in four apartments, while the rest of the apartments use for this purpose electrical resistances. Information about the building's energy performance is modeled on an annual level, i.e., energy consumption and production time-series are generated and retrieved by INTEMA.building, and inserted into VERIFY as.csv files for conducting the life cycle analysis [81]. In the specific study, simulation data have been calculated with an average time granularity of 1/2 min. The building life cycle analysis is based on two defined scenarios representing the current status of the operation (baseline) and a deep energy renovation package according to the Passive House Premium standard towards reducing the entire building's carbon footprint (planned renovation scenario).

The boundaries of the investigated use case include the infrastructure and operational (use) stage. The disposal is out of the scope of the current study. The comparative life cycle analysis considers i) the infrastructure impacts related to the manufacturing phase also including installation, and replacement of systems, and building materials and highlights those elements contributing significantly to the embodied energy and carbon content throughout the building lifecycle, and ii) the life cycle operational impact of their use. A functional unit (FU) according to the ISO 14040 on LCA was defined. Based on a one-year modeling period of the building energy demand and consumption data, the energy amount per year per m^2 is calculated. In this context, the 1 m^2 of floor area was taken, which is usually the FU in building LCA. Energy absolute values are all expressed, measured, and calculated in kWh/year/m^2 to be easily benchmarked, while carbon emissions are presented in kg and ton $CO_{2\text{-eq}}$/year or kg $CO_{2\text{-eq}}/m^2$/year. The primary energy conversion factors used in this study were taken in accordance with the Greek legislation [89], being the following: 2.9 for electricity, 1.1 for oil and 1.05 for natural gas. The analysis of the carbon emissions was based on specific emission factors of 0.0458 kg $CO_{2\text{-eq}}$/kWh for natural gas, 0.2662 kg $CO_{2\text{-eq}}$/kWh for oil, and 0.41 kg $CO_{2\text{-eq}}$/kWh for electricity. A lifespan of 25 years for the project is considered.

2.4.1. Baseline Scenario: Current Status of operation

As a first step, a baseline scenario is needed to evaluate the current environmental footprint of the building. The baseline scenario considers the current state of operation of the building both on the building envelope, and the currently installed electromechanical systems. The baseline scenario also considers the maintenance or replacement processes of specific infrastructure components that may take place during the targeted lifetime. The energy simulation was conducted with the INTEMA.building tool considering time-series simulation data describing the building performance for a specified one-year period from July 2020 to July 2021. The time-series data produced by INTEMA. buiilding fed VERIFY inputs. The simulation data account for the variation of load profile, temperature and power output, and have been normalized in line with the defined FU. The key characteristics of the demo building are shown in Table 3. The total energy demand for the baseline is also provided. The table refers also to key technical properties of the building components e.g., the nominal power of systems, insulation and glazing materials, thickness and U-value of openings and building elements, the useful lifetime of building systems/components e.g., the useful lifetime for boilers is 20 years, etc. The thermal loads refer to the yearly operation of the building considering the indoor temperature setpoints at 20 °C during winter and 26 °C during summer.

Table 2
Key performance indicators (KPIs) calculated by VERIFY.

Indicator	Description	Unit
Life Cycle Assessment (LCA)		
Embodied Infrastructure CO_2 Emissions	$CO_{2\text{-eq}}$ emissions produced due to the new components installations in the 1st year of the project's lifetime	kg
Embodied Infrastructure Primary Energy	Total infrastructure primary energy costs due to the new components' installations for the 1st year of the project's lifetime	kWh
Net Energy Ratio (NER)	Recovered amount of primary energy spent for the initial components' installations	–
Self-Consumption	Amount of energy consumed from the energy generated by the electricity production components (PV and/or wind turbines)	kWh/year
Self-Sustenance Ratio	Average daily ratio of the renewable energy consumed to the total energy consumed for the 1st year of analysis	–
Self-Consumption Ratio	Average daily ratio of the energy consumed from RES to the total energy generated that day for the first year of analysis	–
Lifetime CO_2 Emissions	Total $CO_{2\text{-eq}}$ emissions (infrastructural and operational) yearly and during the project's lifetime	kg, kg/year
Lifetime Primary Energy Demand (PED)	Total primary energy costs (infrastructural and operational) yearly (annual PED) and during the project's lifetime	kWh, kWh/year
Lifetime Primary Energy Savings (PES)	Efficiency of the new installation scenario compared to the existing one in terms of primary energy during the project's lifetime (as well as monitoring on annual basis) considering infrastructure and operational costs	kWh, kWh/year
Lifetime CO_2 Emissions Savings	Efficiency of the new installation scenario compared to the existing installation scenario in terms of $CO_{2\text{-eq}}$ emissions, during the project's lifetime as well as on annual basis (annual CO_2 savings), considering infrastructure and operational costs.	kg, kg/year
Energy Payback Time (EPBT)	Number of years required for the new installation scenario to recover the infrastructure and operational costs in terms of Primary Energy	years
CO_2 Payback Time (CPBT)	Number of years required for the new Installation Scenario to recover the infrastructure and operational costs in terms of $CO_{2\text{-eq}}$ emissions	years
Life Cycle Costing (LCC)		
Initial Investment	Total monetary costs for the initial installation of the components in a building.	€
Lifetime Capital Costs	Amount of money that was invested for the installation and replacement of the components in a building for each year of the project's lifetime	€, €/year
Lifetime O&M Costs	Total monetary costs emerging from the operation and maintenance of the installed components on annual basis and during the project's lifetime	€, €/year
Lifetime Fuel Costs	Total fuel costs of all installed components in the project for all the years of the analysis. Costs of components that consume electricity to provide thermal energy, like heat pump and air-condition units are not considered.	€, €/year
Lifecycle Costs (LCC)	Total monetary expenses (capital costs, O&M Costs and fuel costs) for the whole duration of the project.	€
Electricity Bills	The monetary costs for electricity bills in relation with project's electrical components. The indicator can calculate also the part of the bill for the components that their final energy form is thermal.	€/year
Electricity Revenues	Monetary gains that come solely from electricity components	€/year
Lifetime Income	Monetary gains coming from the excess energy for whole project's lifetime	€
Lifetime Cost Savings	Efficiency of the new installation scenario compared to the existing in terms of monetary costs, yearly and during the project's lifetime	€, €/year

2.4.2. Planned retrofitting scenario: Deep energy renovation towards passive house design

The passive house standard is an exemplar of well-performing standardized building design, which offers at the same time increased energy efficiency and thermal comfort, and less environmental impact. The proposed deep energy retrofitting is aligned with the criteria considered, according to the passive house requirements [90], based on five key design principles, i.e. thermal insulation of the opaque building components, passive house windows, efficient ventilation with heat recovery, assured indoor air quality and airtightness, and thermal bridge reduced design.

In this context, the planned retrofitting scenario pertains to interventions associated with radical building envelope changes, aiming to minimize thermal losses and reduce energy needs. It also entails the replacement of the old Heating and Cooling (H&C) systems with new heat pump units, able to cover the H&C loads with relatively low energy demand, as well as the integration of RES systems i.e., PV systems aiming to provide clean generation, electricity surplus, and self-consumption. Building energy consumption and production time-series data correspond to the next year after baseline i.e., the period between July 2021 and July 2022. More specifically, the following energy retrofitting measures are considered:

- installation of thermal insulation
- renovation of glazing (glass and frame materials)
- replacement of conventional fuel heating systems and old heat pumps with highly efficient air-to-air heat pumps (mini-split units)
- installation of decentralized ventilation system with heat recovery (in every apartment)
- installation of selective solar flat plate collectors to all apartments
- installation of flat roof PV panels with 30° inclination towards the southwest direction and a Façade Photovoltaic system on the southwest external walls. The useful lifetime of the PV assets typically ranges from 30 years up to 40 years depending on the component/technology.
- Installation of new highly efficient lighting equipment

The planned infrastructure installations and key characteristics are presented in Table 4.

3. Results and discussion

This section includes the results accounting for the dynamic energy modelling and simulation, environmental impact assessment, and life cycle costing estimation of the building on its current state (baseline) and according to the planned renovation actions in line with passive

Table 3
Baseline Scenario – Key characteristics of the case building.

Building profile		
Building Picture	**Building Type/Typology**	**Energy Demand**
	Type: Residential Typology: Multi-family house Construction Year: 1970 Total Floor Area: 750 m^2 Useful Area: 600 m^2	Electricity Demand 100,609 kWh/y H & C Demand Total: 163,130 kWh/y Heating: 92,715 kWh/y Cooling: 70,415 kWh/y
Building envelope characteristics		
Elements	**Materials**	**Properties**
Walls	External Walls: Plaster – Brick – Concrete – Plaster	Thickness: 0.25 m U-Value: 3.45 W/(m^2K)
	Internal Walls: Plaster – Concrete – Plaster	Thickness: 0.25 m U-Value: 3.85 W/(m^2K)
Roof	Ceiling area: 170 m^2 Cement mortar – Concrete – Plaster	Thickness: 0.23 m U-Value: 3.85 W/(m^2K)
Windows	Glass Type: Normal Layers: 1 (Single glass) Frame Material: Aluminum Frame Coverage: 20%	Surface: 195 m^2 Thickness: 0.20 m U-Value: 3.13 W/(m^2K)
Doors	Not insulated wooden doors	U-Value: 1.8 W/(m^2K)
Floor	Ceramic tile – Cement mortar – Concrete – Plaster	Thickness: 0.23 m U-Value: 4.2 W/(m^2K)
Building systems parameters		
Thermal load per User: 80W/person		Target Temperature (H/C): 20°C /26°C
Domain	**Building Systems**	**Parameters**
Heating	Oil central heating system (boiler) (usage in 1 apartment)	Thermal rating: 10 kW Efficiency: 80 % Usage: 15 % Lifetime: 20 years
	Natural gas heating system (boiler) (usage in 1 apartment)	Thermal rating: 10 kW Efficiency: 90 % Usage: 15 % Lifetime: 20 years
Heating & Cooling	Old heat pumps (split units) (usage in 6 apartments for heating and all for cooling)	Thermal rating: 40 kW SCOP: 2.0 SEER: 2.0 Heating/Cooling Usage: 70% / 100% Lifetime: 10 years
Domestic Hot Water (DHW)	Conventional solar thermal flat plate collectors coupled with storage tank (usage in 4 apartments)	Tank Capacity: 800 L Collecting Surface: 8m^2 Lifetime: 20 years
Mechanical Ventilation	No ventilation system	–
Lighting	Standard incandescent lighting	Specific load for lighting: 5 W/m^2
Appliances	Refrigerator/Electric stove /Washing Machine	Specific load for appliances: 4 W/m^2

Table 4
Planned Retrofitting Scenario - Key energy retrofit measures and system installations in the demo building.

Retrofit measure	Domain	Properties
Insulation	Building Envelope	Material: Sheep Wool Surface: 629 m^2 Thickness: 0.14 m U-value: 0.15 W/(m^{2}K)
Glazing	Building Envelope	Glass Type: Thermochromic Layers: 2 / Thickness: 0.04 m Frame Material: PVC Frame Coverage: 20 % Glass U-value=0.6 W/(m^{2}K) Frame U-value=0.6 W/(m^{2}K) g-value=0.37 frame fraction: 25 %
Micro-ventilation system with heat recovery	Ventilation	Power rating: 1 kW Air Infiltration Rate: 0.5 ACH Heat recovery effectiveness: 75 %
Air-to-air heat pump	Heating & Cooling	Thermal rating: 40 kW SCOP: 3.0 SEER: 5.0 Lifetime: 10 years
Selective solar flat plate collectors (all apartments)	Domestic Hot Water (DHW)	Tank Capacity: 1200L Collecting Surface: 20 m^2 Lifetime: 20 years
Flat Roof PV System	Electricity generation	Material: Polycrystalline silicon modules No of Panels: 48 Power: 16 kW Efficiency: 19 % Lifetime: 30 years
Façade PV System	Electricity generation	Material: Polycrystalline silicon modules No of Panels: 15 Power: 5 kW Efficiency: 19 % Lifetime: 40 years
Lighting equipment	Lighting	New energy-efficient LED lighting systems Nominal lighting power: 3 W/m^2

house premium standard, in order to evaluate the impact of the building renovation procedure. The energy and environmental performance of the building are assessed, by calculating its energy demand profile, primary energy needs, carbon emissions and associated savings. The total life cycle costs and savings through the lifetime of 25 years are estimated in terms of net present value (NPV).

3.1. Energy assessment of the building renovation procedure

Table 5 presents the building's current state and planned retrofitting energy parameters. Considering the current infrastructure (baseline scenario), the total annual energy needs of the building are equal to 167.7 kWh/y/m^2 for electricity and 271.9 kWh/y/m^2 for H&C. Due to the fact, that, in the current building state, energy production is not available/supported, all of the demanded electricity is imported from the grid. After the retrofitting measures are applied, the electricity needs for the building's operation are reduced significantly; thus, accounting for 51.8 kWh/y/m^2. The PV-generated energy during the first year of the analysis is estimated at around 37.1 kWh/y/m^2, whereas the amount that is used to cover the building's own needs is 19.8 kWh/y/m^2, corresponding to 53.3 % of the total energy generation and 38.1 % of the annual electricity demand. The excess generated energy of 17.3 kWh/y/m^2 (46.7 %) is exported to the electricity grid. In addition, an amount of 32 kWh/y/m^2 needs to be imported from the grid, because the building does not have any energy storage system (i.e., battery system); therefore the generated energy can be only used instantly and might not be available at some times of the day (mainly at nighttime and cloudy days). Similar behavior is observed for the H&C needs, which are extremely lower than in the baseline scenario when the energy-retrofitting options are applied. The annual H&C demand corresponds to 39.9 kWh/y/m^2.

In order to illustrate the ability of VERIFY to take into account dynamic values and data granularity, as well as to follow a dynamic life cycle analysis approach, a specific building energy variable which incorporates time-dependent features in the context of temporal and spatial variations is presented in greater detail. Figs. 3 and 4 below show the energy demand results in terms of time-series analysis of the building's heating & cooling loads for the baseline and the planned renovation scenario, as extracted from the energy simulations. Results show a strong reduction of the thermal loads (over 80 %), when considering the interventions of the planned renovation scenario. Worth to mention that VERIFY takes also as inputs the specific temporal profiles of electricity production, electricity and fuel consumption, temperature, and emissions.

3.2. Environmental assessment of the building renovation procedure

VERIFY calculated the impacts due to the building operations and the embodied energy of materials used, following a GWP approach and taking into account the whole lifecycle and replacement of systems. Based on the list of KPIs, VERIFY provides insights into the gains achieved, in terms of primary energy and carbon emissions. The life cycle primary energy needs and carbon per building component of current and planned infrastructure are illustrated in Table 6. Since the building is renovated according to the premium passive house design, it does not need conventional heating systems, as it can make efficient use of the internal heat sources and exploit the heat recovery concept to cover a significant part of its heating needs. This is due to the installation of highly efficient building materials, such as the natural wool insulation for the envelope, as well as the thermochromic glass and the PVC frame for the openings. The removal of conventional heating systems results in a significant reduction of primary energy requirements and emitted carbon for the building. Moreover, the newly installed air-to-air heat pumps lead to outstandingly better environmental performance, throughout the building's whole lifecycle, due to the higher efficiency and less power required for H&C needs. In addition, the new glazing materials can result in almost the half amount of emissions. The GHG emissions caused by the installed component (embodied impact) are probably higher, but the new glazing will contribute to lower GHG emissions over the life cycle. The primary energy requirements imposed by the new installations (insulation, heating, and PV components) can be far outweighed by the abortion of the conventional heating systems and old heat pumps. Overall, the planned retrofit reduces the grid-related primary energy needs and carbon emissions dramatically.

The environmental impact analysis of the whole building for lifetime

Table 5
Annual energy profile parameters of the demo building.

Building Energy Parameters (kWh/y/m^2)	Current Status (Baseline)	Planned Renovation Scenario
Electricity Demand	167.7	51.8
Annual Imports	167.7	32.0
Self-Consumption	0.0	19.8
Annual Exports	0.0	17.3
Electricity Generation	0.0	37.1
Heat Demand	154.5	4.9
Cool Demand	117.4	35.0
Total H&C Demand	271.9	39.9
Heat Load (Supply)	154.1	4.9
Cool Load (Supply)	108.3	35.0
Total H&C Load	262.3	39.9

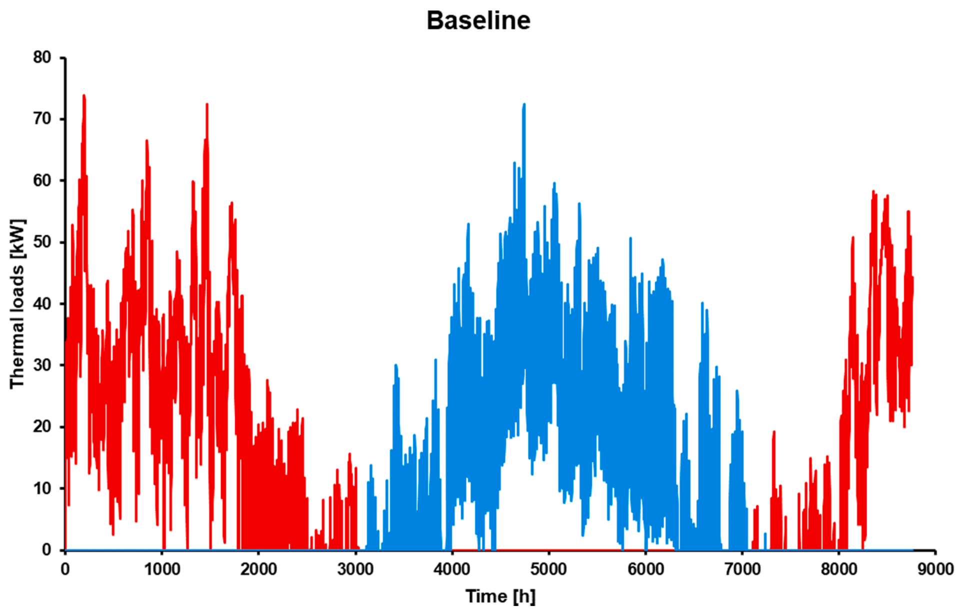

Fig. 3. Building Heating & Cooling Load TimeSeries – Current State (Baseline).

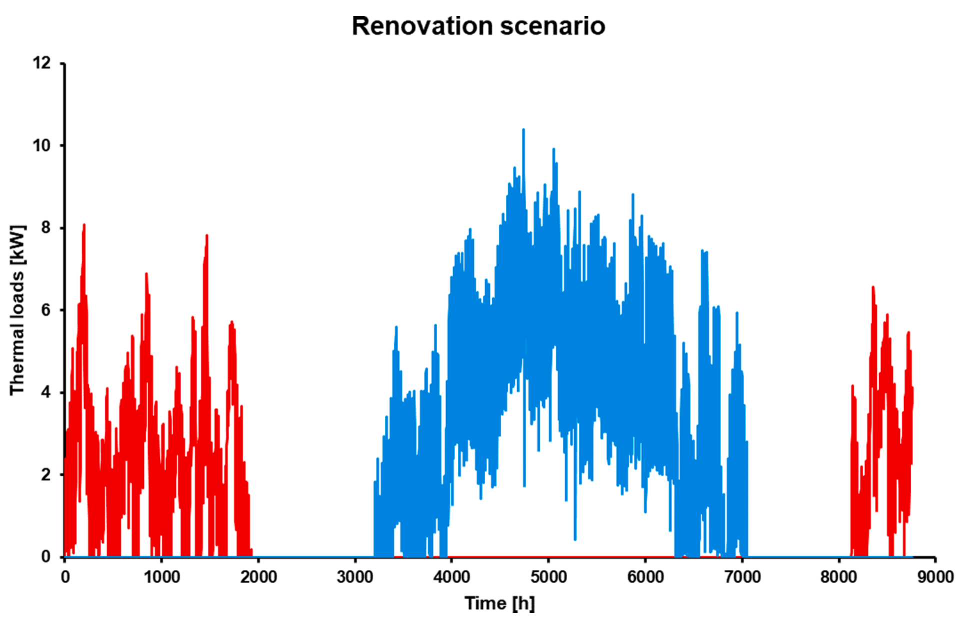

Fig. 4. Building Heating & Cooling Load TimeSeries – Planned Renovation Scenario.

period of 25-years is summarized in Table 7. The planned infrastructure interventions require an available primary energy amount for install and operation purposes equal to 34.11 MWh per year. This means significantly lower primary energy needs of more than seven times less compared to baseline scenario. The initial primary energy needs of 902.3 MWh required due to the very high embodied energy content of the new infrastructure can be easily compensated in a few years of building operation. The analysis also indicated that the polystyrene materials of the retrofitting exhibited the greatest amount of embodied energy. Renovation with high-efficiency heat pumps can be an important way to reduce the environmental impact. The operational primary energy needs of the building when considering the planned renovation scenario are reduced from 578.62 to 56.85 kWh/y/m^2.

Overall, the planned retrofitting measures can lead to significant primary energy and carbon footprint reduction throughout the entire project lifespan. According to results, the lifetime PES, when the retrofitting scenario is applied, account for approximately 8,218 MWh i.e. an amount of 11.5 MWh per m^2 of total heated area can be saved. This means a reduction to the primary energy needs of around 91 %, corresponding to lifetime carbon savings of about 1,647 ton CO_{2eq} or to a reduction of carbon emissions by almost 95 %. This is around 355.31 MWh of primary energy savings per year, while the saved amount of emissions corresponds to 68.88 ton $CO_{2\text{-eq}}$ per year, i.e., almost 115 kg $CO_{2\text{-eq}}$ per m^2 per year. The amount of 8,218 MWh includes both the avoided primary energy due to RES exports and the primary energy minimizations due to retrofitting.

Figs. 5 and 6 illustrate the temporal PES and CO2 savings (in $CO_{2\text{-eq}}$) that can be achieved considering a building lifespan of 25 years. The light blue bars represent the operational savings during the use phase, while the dark blue bars refer to the embodied energy and carbon incurring due to material and system installations taking place when the planned retrofitting initiates, as well as due to the maintenance activities

Table 6
Life cycle primary energy and CO2 impact per component.

Component/ Technology	Current Status (Baseline)		Planned Renovation Scenario	
	Primary Energy (MWh)	CO2-eq (ton)	Primary Energy (MWh)	CO2-eq (ton)
Glazing (aluminum/ PVC)	233.58	18.18	344.4	5.7
Hot water iron	389.42	76.47	92.43	18.79
Solar thermal collectors	36.89	2.15	36.89	2.15
Natural Gas Boiler	265.29	12.34	–	–
Oil Boiler	543.64	131.62	–	–
Heat pump units	5,134.90	1,006.19	496.07	102.21
Ventilation	–	–	0.06	0.004
Roof flat PV	–	–	218.7	49.3
PV Façade	–	–	36.17	2.6
Polystyrene insulation walls	–	–	245.98	10.29
Polystyrene insulation ceiling	–	–	126.14	5.28
Polystyrene insulation floor	–	–	18.92	0.792
Grid	7,490.6	1,464.5	813.5	159.0

and/or component replacements for both baseline and planned retrofitting. For the case of the mini-split units, representatively, this replacement happens every ten years.

The dark blue bars can be on the negative or positive side for some years of the analysis because they highlight the losses or gains related to the installation and maintenance/replacement of specific infrastructure components. When dark blue bars are on the negative side, they illustrate the losses and negative impact of the planned retrofitting attributed to the installation of new systems, their maintenance or replacement. In the case dark blue bars are on the positive side, the maintenance or replacement of the infrastructure components has taken place in the baseline scenario, thus the planned renovation scenario is more efficient in terms of primary energy and carbon emissions for those specific years. Figs. 7 and 8 depict the accumulated primary energy and CO_2 savings (in $CO_{2\text{-eq}}$) during lifespan. It can be easily shown that, when the retrofitting options of the proposed renovation scenario are implemented, the building begins to achieve primary energy savings and carbon savings from the 2nd and 3rd year of operation, respectively.

Another important aspect of the retrofitting process is the time required for the PV systems installed, to recover the primary energy and carbon imposed by the infrastructure manufacturing and installation processes. The achieved EPBT and CPBT are estimated for both PV system types (see Table 7). Flat roof PV achieves shorter payback times than the PV Façade, due to the higher power and level of solar irradiance leading to more energy generation.

3.3. Economic assessment of the building renovation procedure

Lastly, the life cycle costing analysis focuses on providing a cost evaluation of the entire investment, by tracking the cost-effectiveness of the installed building infrastructure for the 25 years of analysis. Table 8 presents a breakdown of the life cycle costs per individual component both for the current and planned infrastructure.

LCC results are summarized in Table 9. All cost categories are calculated in terms of NPV i.e. they encompass the time value of money, including a project-specific discount rate of 5 %. Fuel and capital costs comprise the most significant contributory components to the life cycle costs. The current infrastructure is from a life cycle costing perspective excessively more expensive than the proposed interventions, in terms of fuel costs as well as of O&M costs. In particular, the cost of oil and

Table 7
Building Environmental Analysis based on LCA indicators.

KPI	Current Status (Baseline)		Planned Renovation Scenario	
	Primary Energy	$CO_{2\text{-eq}}$	Primary Energy	$CO_{2\text{-eq}}$
Initial Embodied Primary Energy (MWh)	0.00		902.30	
Operational Primary Energy (MWh/y)	347.17		34.11	
Annual Operational Primary Energy (kWh/y/m^2)	578.62		56.85	
Lifetime Primary Energy (MWh)	9,009		1,893	
			Primary Energy Savings (PES)	
Annual Primary Energy Savings (MWh/y)			355.31	
Lifetime Primary Energy Savings (MWh)			8,218	
Lifetime Primary Energy Savings (MWh/m^2)			11.5	
Initial Embodied CO_2 (ton $CO_{2\text{-eq}}$)		0.00		90.90
Operational CO_2 Emissions (ton/y)		67.29		6.67
Lifetime CO_2 Emissions (ton $CO_{2\text{-eq}}$)		1,717		286.04
			$CO_{2\text{-eq}}$ savings	
Annual CO_2 Savings (ton $CO_{2\text{-eq}}$/y)			68.88	
Lifetime CO_2 Savings (ton $CO_{2\text{-eq}}$)			1,647	
Annual CO_2 Savings (ton $CO_{2\text{-eq}}$/y/m^2)			0.115	
			Flat Roof PV	**BIPV**
EPBT (years)			3 years, 3 months	Not achieved in project lifespan
CPBT (years)			3 years, 9 months	13 years

natural gas is the highest contributor to the overall LCC, corresponding to 585,085 €. O&M costs account for 15,875 € during the 25 years project lifespan. Fuel costs are reduced significantly when the retrofitting actions are applied, plummeting to an amount of 60,901 € while O&M costs are also a little bit higher than in baseline, corresponding to 16,938 €. The capital costs of the planned retrofitting measures have a relative contribution to the LCC that is very high in the beginning of the project due to the initial installations and becomes extremely low as the project lifespan increases. This corresponds to an initial investment cost of 106,167 € and a total amount of capital costs equal to 125,857 €. Overall, total life cycle costs of current building performance are estimated at around 644,238 €, while planned retrofitting options can lead to extremely lower life cycle costs equal to 203,696 €.

Overall, the planned retrofitting actions can provide significant cost savings and also generate revenues from the energy exports to the grid owing to PV generation. The lifetime cost savings that can be achieved are equal to approximately 515,263 €. Fig. 9 presents the monetary losses and savings per year resulting from the proposed building retrofitting measures during the 25 years of analysis. The light blue bars represent the costs incurred during the infrastructure use and operation, i.e. the operational costs, while the dark blue bars illustrate the cost of the infrastructure initial installations or any replacements costs during the entire project lifespan. Fig. 10 illustrates the cumulative cost savings

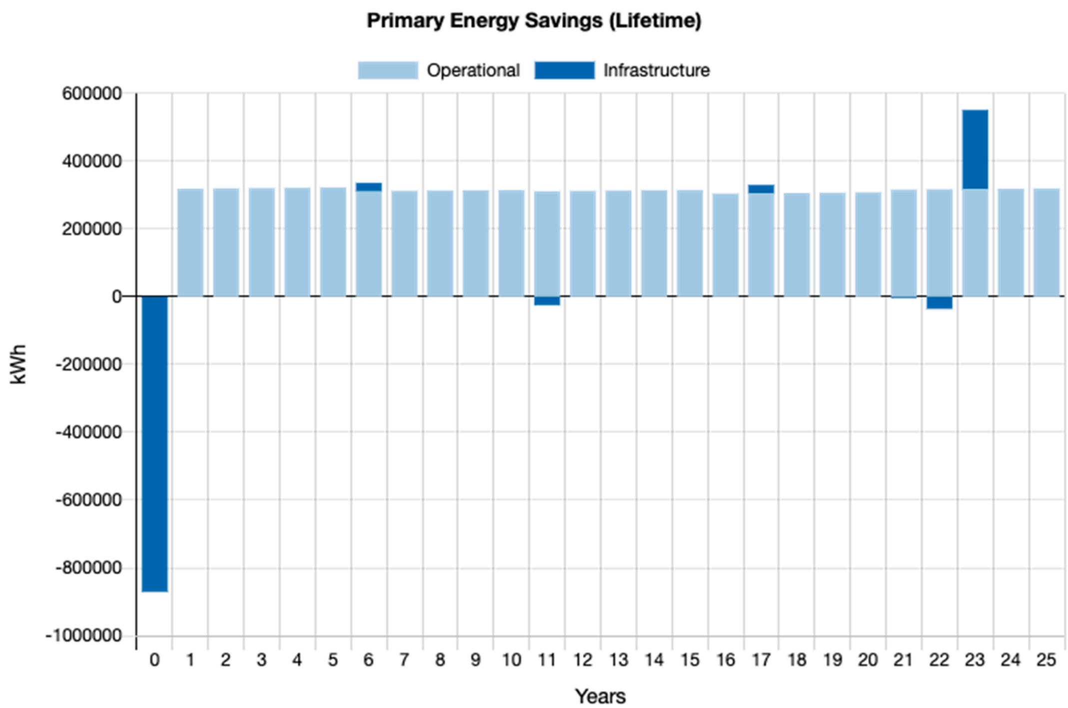

Fig. 5. Planned Renovation Scenario – Primary Energy Savings (PES) throughout the building's lifespan.

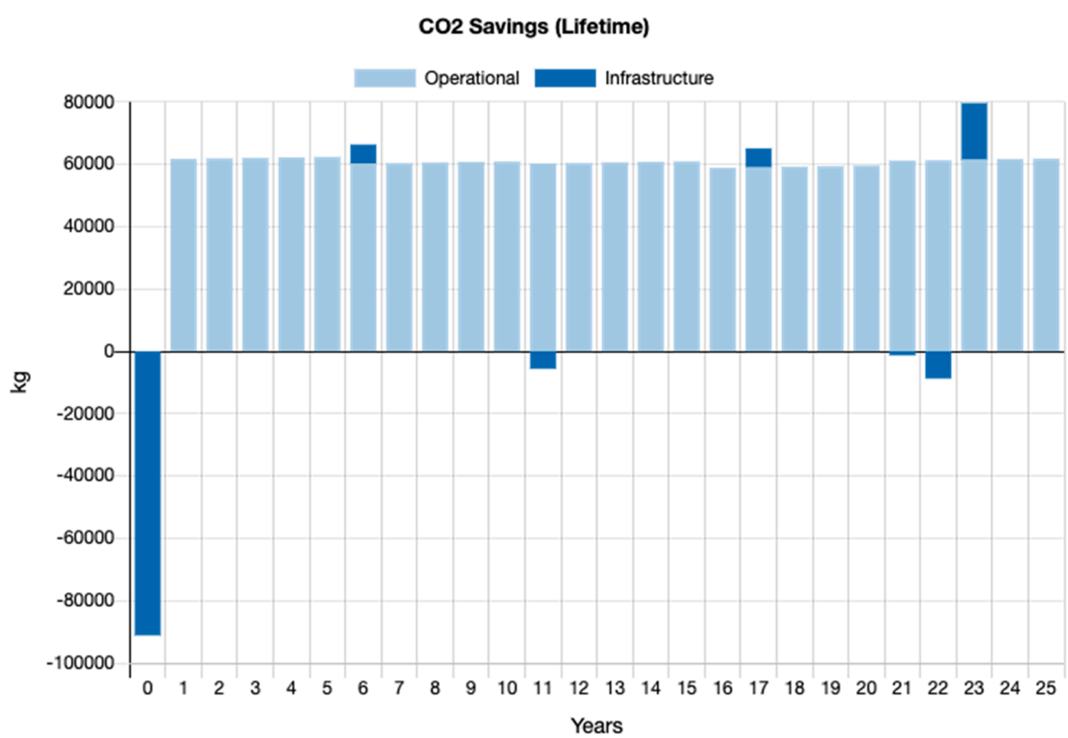

Fig. 6. Planned Renovation Scenario - CO2 savings (in $CO_{2\text{-eq}}$) throughout building's lifespan.

achieved due to the proposed interventions of the planned renovation scenario. The proposed retrofitting options are proved cost-effective, since the investment can be beneficial and gives a positive return in terms of monetary savings from the 3rd year of the project and beyond. More specifically, an attractive payback time of 3 years and 6 months is estimated for the planned passive building retrofitting.

3.4. Discussion

An elaboration on the results with VERIFY follows, to illustrate on the one hand how the inclusion of specific building renovation options can improve LCA performance and serve the building sustainability objectives, and on the other, how novel aspects and dynamic factors in life cycle analysis and evaluation of buildings can improve the quality and accuracy of the results.

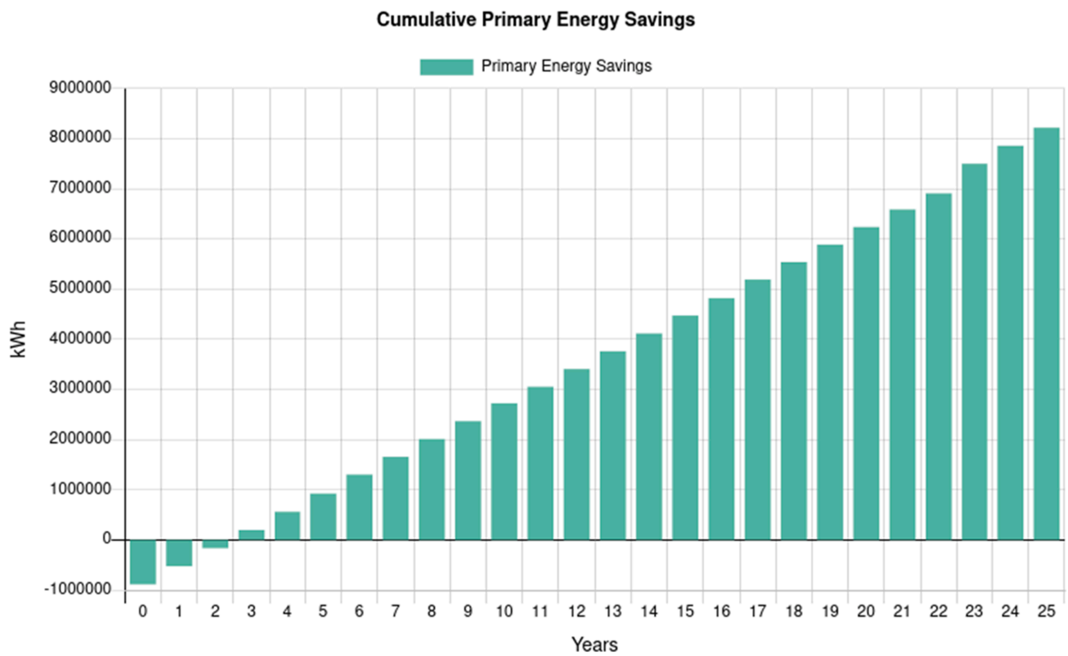

Fig. 7. Planned Renovation Scenario – Cumulative Primary Energy Savings (PES) throughout the building's lifespan.

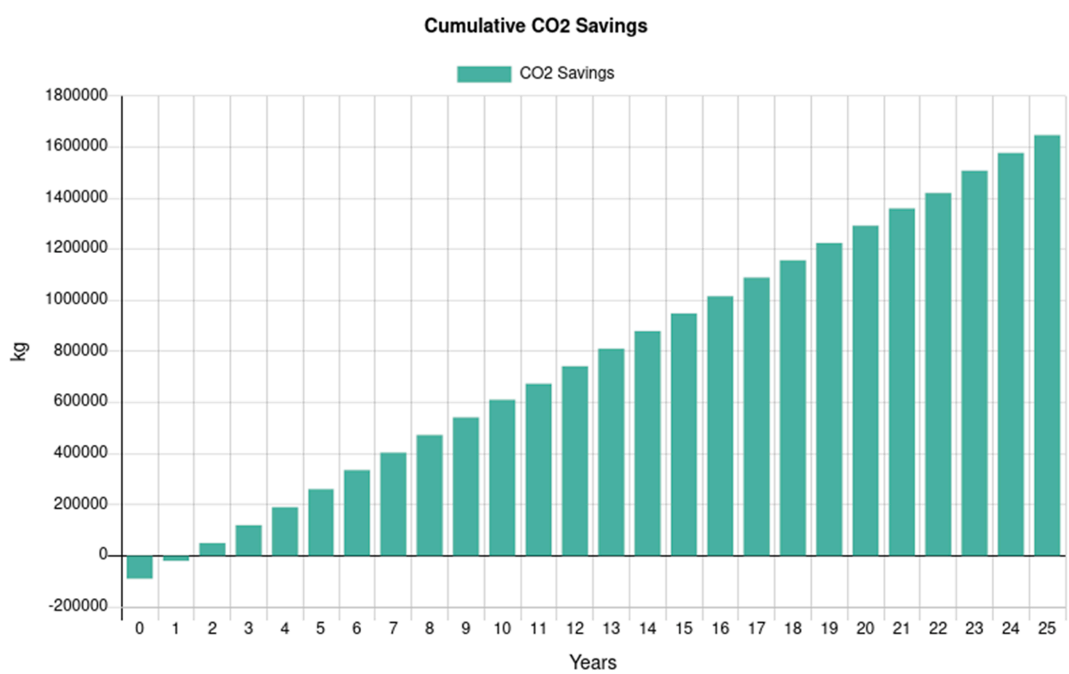

Fig. 8. Planned Renovation Scenario - Cumulative carbon savings (in $CO_{2\text{-eq}}$) throughout building's lifespan.

First of all, results indicated that key selection of building envelope characteristics (e.g., primary wall interior insulation materials and glazing elements) but also inclusion of energy production components (e.g. photovoltaics) can play a key role in improving significantly the performance of the building, implying from an energy perspective, the efficiency of the passive house standards in retrofitting. Regarding the environmental impact of the building, the analysis highlighted the strongly beneficial effect of the planned renovation scenario on the operational phase in terms of primary energy and carbon footprint reduction primarily owed to the replacement and modernisation of the heating systems. The operational primary energy needs of the building were reduced to 56.85 kWh/y/m^2 when considering the planned renovation scenario measures. Results are totally comparable with similar building renovation projects across the EU, such as the Inspire project that achieved to reduce the primary energy consumption of the renovated residential buildings in the range of 50 kWh/y/m^2 [91]. The high embodied energy content of the retrofitting PVC and polystyrene materials contributed negatively to the amount of primary energy, it is quickly outweighed though due to the very low operational primary energy needs. In addition, results showed the cost effectiveness of the proposed renovation scenario in terms of LCC, generating essential cost savings.

The results presented by the tool, incorporate dynamic-related criteria, and are calculated following the core dynamic life cycle analysis principles, including data time granularity analysis, time-dependent evaluation. VERIFY supports any required data time granularity level

Table 8
Life Cycle Costs per component - Current and Planned Infrastructure.

Component Name	Current Status (Baseline) Costs (€)	Planned Renovation Scenario Costs (€)
EPS insulation	–	13,311
Glazing (aluminum/ PVC)	19,436	22,357
Hot water iron	28,524	10,067
Panel solar thermal	3,426	3.863
Natural gas boiler	22,670	–
Oil boiler	44,484	–
Heat pump units	361,520	57,806
Ventilation	–	908
Roof flat PV	–	29,846
PV Façade	–	7,100

Table 9
Building Costing Analysis based on LCC indicators.

KPI	Current Status (Baseline)	Planned Renovation Scenario
Initial Investment (€)	0.00	106,167
Annual Fuel Costs (€/y)	29,771	2,952
Annual O&M Costs (€/y)	808	870
Annual Cost Savings (€/y)	n/a	20,611
Lifetime Fuel Costs (€)	585,085	60,901
Lifetime O&M Costs (€)	15,875	16,938
Lifetime Capital Costs (€)	43,277	125,857
Lifecycle Costs (€)	644,238	203,696
Lifetime Cost Savings (€)	n/a	515,263

(from ms to days, if necessary). Data inputs are based, on average, of a timestep granularity of 1/2 min, while for highly-varying conditions timestep can decrease down to 1 *sec*. VERIFY is capable of performing LCA and LCC analysis on an hourly or sub-hourly basis, using as input: i) building energy performance data (synthetic or real-time), ii) variation of temperatures iii) occupancy and ambient conditions profiles, iv) dynamic changes of energy mix and inventories. Moreover, results have been based on the interaction with the INTEMA.building simulation tool, which provides a dynamic process modelling analysis, under a variable user-adjustable timestep, in the context of energy consumption and thermal behavior of the building; and on performing computations by the two core modules of VERIFY each one accounting for the environmental and costing evaluation; thus introducing a holistic building performance assessment and life cycle analysis that paves the way towards the interoperability of energy simulation engines, and integrated energy, environmental and economic approaches. Consequently, VERIFY serves the scope of recent DLCA tools and can be considered as a supporting fully interoperable tool, with the aim to facilitate building(s) behaviour assessment and retrofitting activities. On the contrary, as with the majority of LCA software and tools, the design of the current tool is subject to potential limitations. Two limitations of VERIFY regarding LCA that can be mentioned at this point, are related with the i) environmental impact categories and the ii) technology inventories' part of the database considered in the environmental analysis. Regarding the impact categories, the tool does not include all of them, since it is tailored to global warming impact assessments and aims to be fully aligned with Level(S). The other shortcoming concerns the incorporated technologies in the database, which is currently dedicated only to the involved technology providers' data for the specific investigated demos of ongoing EU projects. Hence, technology providers of recently developed and innovative technologies should provide their data in order to expand the technologies' database.

4. Conclusions

The present study illustrated the innovative characteristics and potential applicability of a dedicated life cycle analysis tool (VERIFY) towards an including assessment framework supporting building(s) retrofitting purposes. As a first advantage, the combination of LCA and LCC methodologies, as well as the interconnection and communication of the tool with energy simulation engines has the asset of providing integrated energy, environmental and techno-economic assessments. In addition, the use of a dynamic LCA approach achieves the goal of considering temporal information to the analysis, which can be beneficial in terms of interaction in multiple steps of the analysis and real-time decision-making, improving accuracy of the results, and examining various time-varying effects, compared to static LCA approaches. Moreover, the data granularity options that VERIFY offers can improve the quality of the LCA results.

The tool was utilized to evaluate, from an environmental and economic point of view, a set of energy-efficient retrofit measures according to the passive house requirements, in a residential multi-story apartment building in Greece. Tangible results have been extracted that can support sustainable decision-making on building(s) retrofitting. The foreseen interventions resulted in lifetime primary energy savings of around

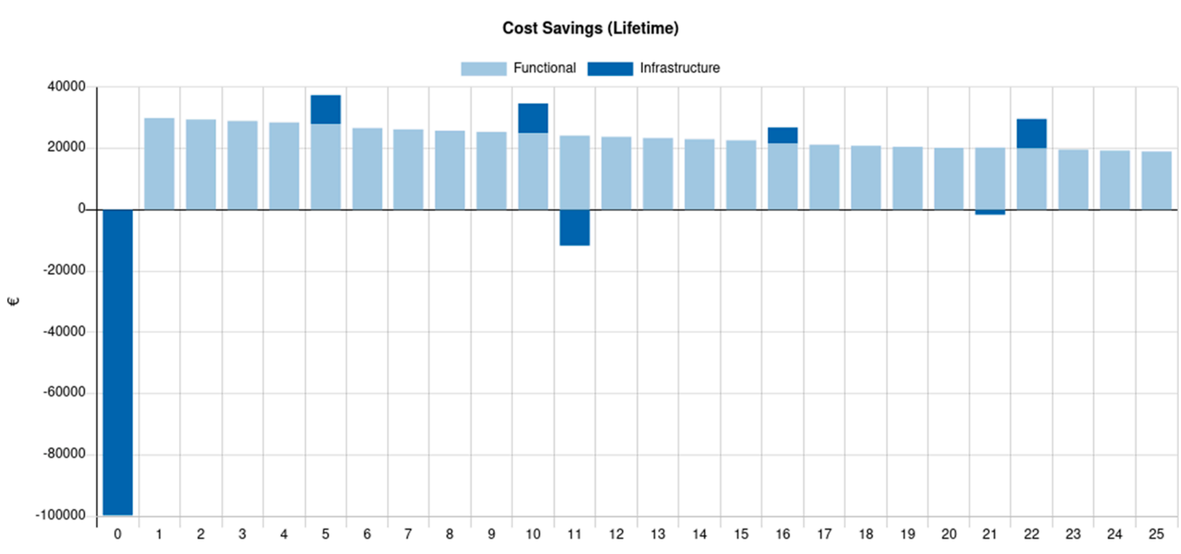

Fig. 9. Cost savings throughout building's lifespan due to planned retrofit measures.

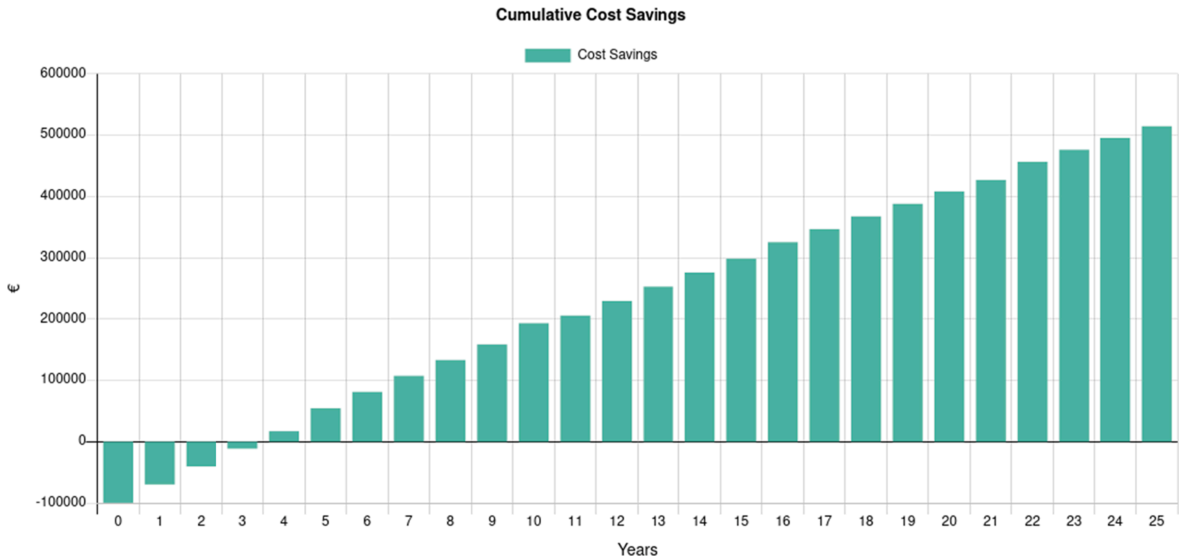

Fig. 10. Cumulative monetary savings throughout building's lifespan due to planned retrofit measures.

11.5MWh/m^2, which in turn lead to a significant reduction in the carbon footprint of the building corresponding to about 1,647 tons of CO_{2eq} in total, for the 25 years of analysis. The proposed measures were also cost-effective, in terms of life cycle costs, resulting in a saved cost amount of almost 515 k€ when considering a 25-years lifetime. The main cost components contributing to the LCC were fuel and capital costs. A significant reduction in fuel costs is observed when the planned retrofitting measures are applied. A high initial amount of capital costs is required to install the new components; however, the relative contribution of the capital costs becomes lower as the building's foreseen lifespan becomes longer.

Overall, the proposed combined LCA and LCC approach and analysis offered by VERIFY can provide useful guidelines for policymakers in the sustainable design of buildings, as well as for building engineers in retrofitting works, in line with EU climate and energy goals. VERIFY tool is committed to helping key stakeholders and communities towards effective environmental impact analysis and techno-economic decision-making in the field of smart and sustainable buildings as well as districts towards smart cities, based on advanced and multi-scale LCA computations and research, and considering various types of systems, several data formats, and different evaluation scales. VERIFY offers direct outputs targeting to motivate users towards environmentally-friendly actions and increase economic profits within projects, e.g., propose energy efficiency measures that minimize emissions, identify critical cost savings, as in the case of efficient design, planning, and pre-evaluation of planned construction and renovation activities. Besides, policy-making outputs based on potential stakeholder engagement can also be delivered, via assessing energy-oriented investments in terms of benefits from energy trading, examining economic viability and sustainability of energy import minimizations due to on-site renewable energy production and storage, and also evaluating further up-scaling, replication and expanding of energy investments towards RES penetration maximization.

It is a widely accepted fact that the building sector requires to a great extent sustainability and carbon-neutrality policy action. Several issues surrounding building renovation projects are still being debated. The sustainable transformation of the building stock can also be significantly benefited by measures being applicable on a district scale. For this purpose, a proper scaling-up approach from building to community level addressing all life cycle aspects and physical entities and assessing the various district objects is needed. VERIFY could be used also to assess the impact of technologies to other areas of interest, e.g., power grids, as well as to analyze the long-term temporal evolution of key district features both from geographical and stakeholder perspectives. The authors aim to apply VERIFY at district scale and test potential replication scenarios and applications of the configuration of the integrated system to district and community scales. In this context, the main technical, economic, regulatory and social factors affecting the replication potential and the systems scaling-up approach will be examined.

CRediT authorship contribution statement

Vasilis Apostolopoulos: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization. **Ioannis Mamounakis:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft. **Andreas Seitaridis:** Software, Validation, Formal analysis, Investigation, Data curation. **Nikolas Tagkoulis:** Software, Validation, Formal analysis, Investigation, Data curation. **Dimitrios-Sotirios Kourkoumpas:** Conceptualization, Methodology, Validation, Writing – review & editing. **Petros Iliadis:** Software, Validation, Formal analysis, Investigation, Data curation, Writing – review & editing. **Komninos Angelakoglou:** Methodology, Validation, Writing – review & editing. **Nikolaos Nikolopoulos:** Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. VERIFY Interface - Key steps for project setup and creation

The first step of developing a customized project with VERIFY tool is the creation of an electrical plan. The user can create an electrical plan of a specific VERIFY project use-case based on the electrical data form, which, is depicted in Fig. A.1. The user can insert: i) initial information about the project (basic project characteristics such as the project lifespan, the first year of analysis and the project location) ii) as well as specific data for electricity generation, consumption, and storage. The user can provide detailed information for the electricity production sources (i.e., PV, wind turbines etc.), to select among different storage technologies (e.g., flywheels and several types of batteries), while also energy consumption values (annual or monthly) for the systems can be imported. The building profile can also be defined here via selecting from a list of basic building types. In addition, VERIFY provides the option of choosing an owner profile between standalone and prosumer, based on an important functionality offered by the tool algorithms that gives the ability to perform also LCA at the community level considering community energy production from several systems and related pricing schemes [92].

The next step is the creation of the thermal plan. This step requires the definition of the building specifications, including floor area characteristics, internal climate preferences and new or existing thermal components, if any (Fig. A.2). After the building specifications are imported, detailed technical features of the thermal components need to be filled, as Fig. A.2 depicts. Thermal components are divided into two general categories: i) active thermal and ii) passive thermal components. The categorization distinguishes building equipment based on energy consumption and management in contrast to passive components, which do not need energy sources and are not able to be automatically controlled. The thermal components that can be considered in the analysis are: a) for active components: heating (e.g. boilers, heat pumps), cooling and ventilation components and b) for passive components: insulation, glazing and storage. Thermal plan is performed for current building state, planned building state and leads to comparison between current and planned building state by filling the appropriate forms. Detailed information regarding the current and planned scenario must be inserted in case of retrofitting process. For instance, active components e.g. boilers, require technical information like thermal rating (kW), usage (%) etc., while passive components need specific input data regarding the construction materials, with focus on materials, surfaces and dimensions, such as the type of material, thickness etc., as for example the frame material of glazing which can be selected among wood, PVC and aluminum.

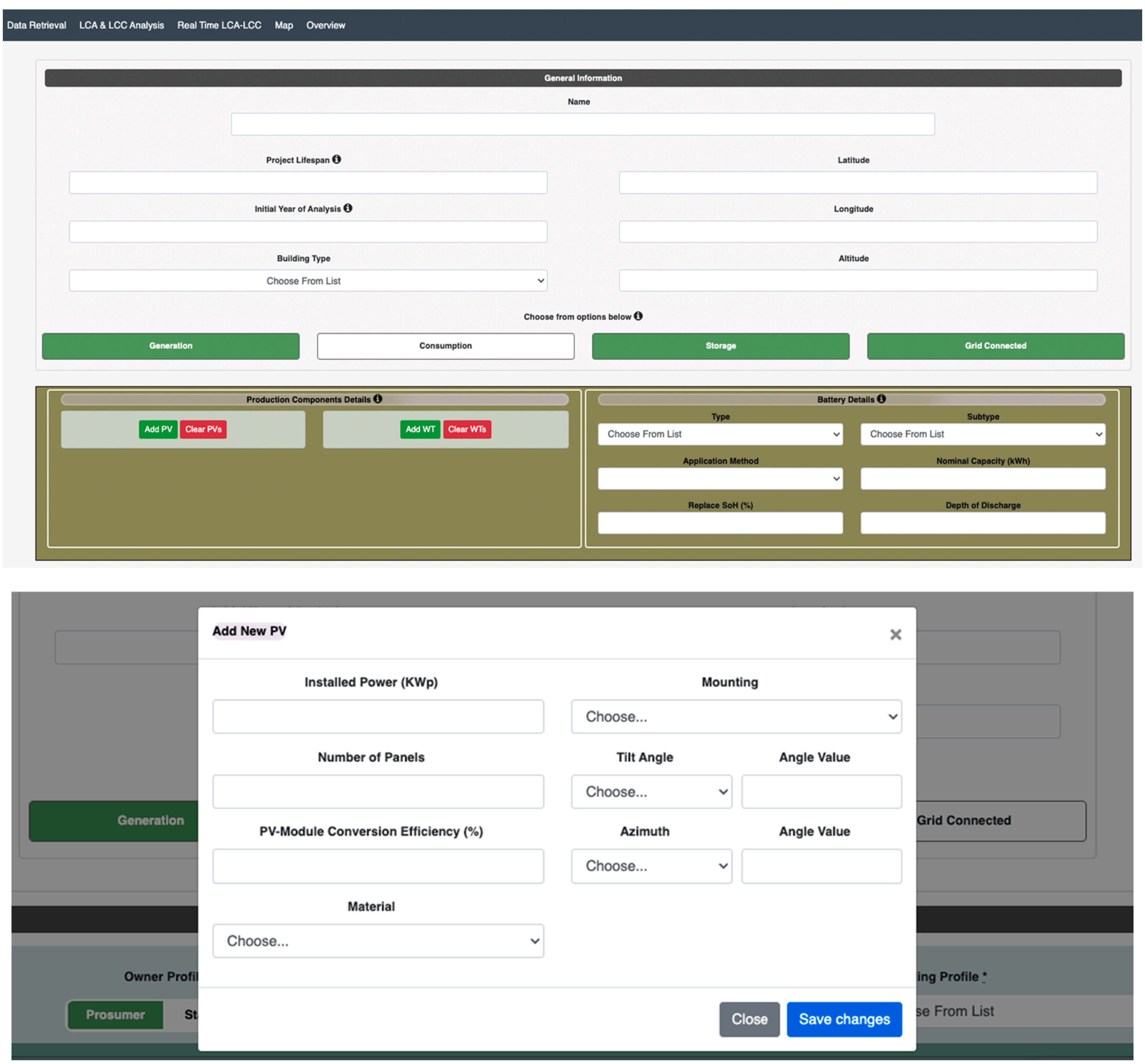

Fig. A1. Electrical Plan Creation with VERIFY – Project Details and Electrical Systems Characteristics.

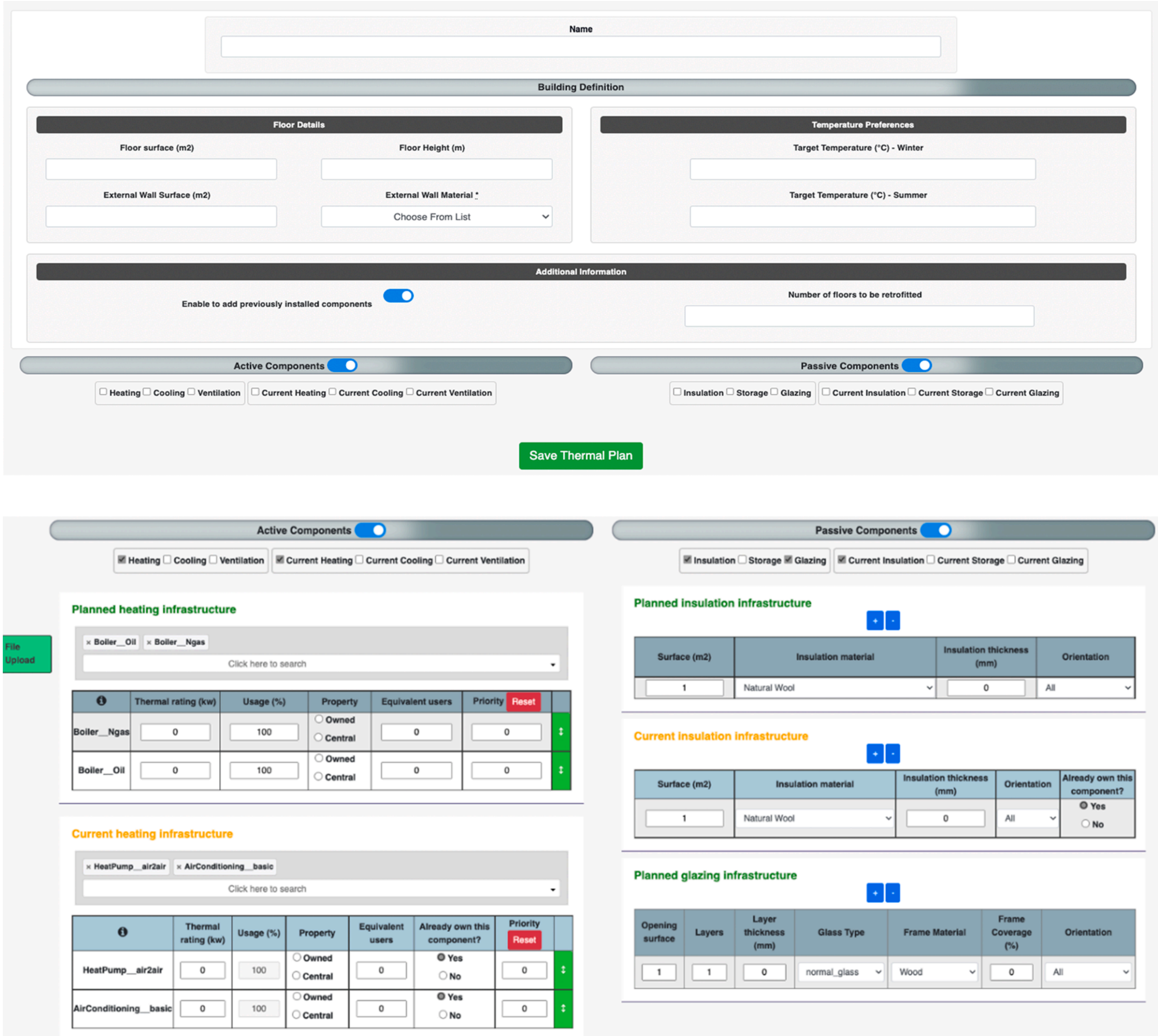

Fig. A2. Thermal Plan Creation with VERIFY – Building Details & Thermal Component Properties.

The third step which refers to the creation and evaluation of an investment plan is optional and depends on user inputs pertaining to financial factors (e.g. tax rates, WACC), loan details, land use, and acquisition parameters etc. The analysis aims to illustrate the case with optimal budget allocation via comparisons and decision-making for the roll-out of investments primarily towards increased renewable energy penetration.

The last step of the project definition is the association of the several plans, i.e. electrical, thermal, and optionally investment to a specific geographical location. Location-depended information such as weather data or primary energy factors are retrieved automatically from the database. This aspect enables the reuse of plans definitions in other projects, which maybe is located in different areas.

Appendix B. INTEMA.building tool - brief description and verification

INTEMA.building is a detailed energy analysis tool that performs dynamic in-time simulations for the thermal behavior of the buildings coupled with active energy systems (heat pump, boiler, PV, solar thermal, storage tanks, etc.). This tool is developed in the Dymola environment using the Modelica modeling language and specific building-related component libraries, namely Buildings and BuildingSystems. In addition, the tool includes two main developed component libraries named “Building Envelope Model” and “Energy Systems”; the first one includes mainly the structural components of the building (e.g. wall, window, etc.), while the other includes mainly the active energy systems (e.g. heat pump, oil-boiler, etc.). An important innovation of the present tool is the ability to simulate complex phenomena with an adjustable timestep, which can be up to 1 sec, while the nominal simulation step is set to 1 min, for the specific study. High quality meteorological data are sourced from the PVGIS tool. INTEMA.building also offers the capability to upload a BIM file (.ifc) from which it extracts building geometry. INTEMA.building is able to communicate with VERIFY in an interactive way by exchanging data (time series/profiles of power, energy and temperature parameters) about the heating/cooling, electricity, fuel demands profiles.

The INTEMA.building tool was verified with data provided by the European Standard EN15265 [87]. Twelve different scenarios (Case 1–Case 12), the boundary and operating conditions are described in detail in the Standard, were used to determine the model accuracy in every case regarding the estimation of the heating and cooling thermal loads. Table B1 summarizes the results of the comparison and the verification of the developed tool.

Table B1
Summary of the verification procedure for INTEMA.building.

Cases	Heating				Cooling			
	Reference (kWh)	Model (kWh)	rQ_H	Level of accuracy	Reference (kWh)	Model (kWh)	rQ_C	Level of accuracy
1	748.0	745.7	0.24 %	A	233.8	235.2	0.14 %	A
2	722.7	715.8	0.75 %	A	200.5	204.4	0.42 %	A
3	1368.5	1358.2	0.73 %	A	43.0	32.0	0.78 %	A
4	567.4	507.7	2.84 %	A	1530.9	1348.5	8.69 %	B
5	463.1	486.3	3.49 %	A	201.7	208.3	0.99 %	A
6	509.8	548.0	5.50 %	B	185.1	191.9	0.98 %	A
7	1067.4	1142.8	6.93 %	B	19.5	12.4	0.66 %	A
8	313.2	349.1	2.48 %	A	1133.2	1141.3	0.56 %	A
9	747.1	704.8	4.67 %	A	158.3	139.2	2.11 %	A
10	574.2	645.2	9.26 %	B	192.4	179.9	1.63 %	A
11	1395.1	1264.5	9.27 %	B	14.1	21.0	0.49 %	A
12	533.5	519.4	0.96 %	A	928.3	817.3	7.59 %	B

Below, the definitions of the relative errors, according to the standard, are given (subscript "ref" represents the corresponding values from the Standard):

$$rQ_H = \left|\frac{Q_H - Q_{H,ref}}{Q_{tot,ref}}\right| \quad \text{(A1)}$$

$$rQ_C = \left|\frac{Q_C - Q_{C,ref}}{Q_{tot,ref}}\right| \quad \text{(A2)}$$

The heating (Q_H), the cooling (Q_C), and the total load ($Q_{tot} = Q_H + Q_C$) are used for quantifying and estimating the level of INTEMA.building accuracy against the standard. The acceptable levels of accuracy, for every similar tool purpose, according to the EN15265, are provided below:

Level A: Relative errors (rQ_H and rQ_C) lower than 5 %.
Level B: Relative errors (rQ_H and rQ_C) lower than 10 %.
Level C: Relative errors (rQ_H and rQ_C) lower than 15 %.

According to the results of Table B1, it is obvious that all the cases present a level of accuracy equal to (A) or (B), something that indicates the validity of the developed model. Specifically, the mean deviation for the cooling was calculated at 2.09 %, while for the heating at 3.93 %. Therefore, the aforementioned results indicate that the INTEMA.building tool can estimate with high accuracy the heating and cooling thermal loads and it is a reliable tool according to the provided data by EN15265.

References

[1] Chau CK, Xu JM, Leung TM, Ng WY. Evaluation of the impacts of end-of-life management strategies for deconstruction of a high-rise concrete framed office building. Appl Energy 2017;185:1595–603. https://doi.org/10.1016/j.apenergy.2016.01.019.
[2] Khan JS, Zakaria R, Shamsudin SM, Abidin NIA, Sahamir SR, Abbas DN, et al. Evolution to emergence of green buildings: a review. Admin Sci 2019;9:6. https://doi.org/10.3390/admsci9010006.
[3] Röck M, Baldereschi E, Verellen E, Passer A, Sala S, Allacker K. Environmental modelling of building stocks – an integrated review of life cycle-based assessment models to support EU Policy Making. Renew Sustain Energy Rev 2021;151:111550. https://doi.org/10.1016/j.rser.2021.111550.
[4] IEA. Topics – buildings. A source of enormous untapped efficiency potential; 2020. Available online: https://www.iea.org/topics/buildings (accessed on 12 October 2021).
[5] Royal Institution of Chartered Surveyors - RICS. Building stock in the EU: energy efficient retrofits in renovations; 2020. Available online: https://www.rics.org/eu/news-insight/latest-news/news-opinion/building-stock-in-the-eu-energy-efficient-retrofits-in-renovations/(accessed on 26 May 2022).
[6] European Commission. Energy performance of buildings directive. Available online: https://ec.europa.eu/energy/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en (accessed on 12 October 2021).
[7] World Economic Forum. Here's how to decarbonize the EU's Building Stock; 2021. Available online: https://www.weforum.org/agenda/2021/01/here-s-how-to-decarbonize-the-eu-s-building-stock/(accessed on 26 May 2022).
[8] European Commission. The European green deal. COM. 640 Final. Brussels, Belgium, 11 December 2019; 2019.
[9] European Commission. A renovation wave for Europe - greening our buildings, creating jobs, improving lives. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of Regions; 2020. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0662 (accessed on 14 October 2021).
[10] Kong M, Hong T, Ji C, Kang H, Lee M. Development of building driven-energy payback time for energy transition of building with renewable energy systems. Appl Energy 2020;271:115162. https://doi.org/10.1016/j.apenergy.2020.115162.
[11] Cabeza LF, Rincón L, Vilariño V, Pérez G, Castell A. Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: a review. Renew Sustain Energy Rev 2014;29:394–416. https://doi.org/10.1016/j.rser.2013.08.037.
[12] Pal SK, Takano A, Alanne K, Siren K. A life cycle approach to optimizing carbon footprint and costs of a residential building. Build Environ 2017;123:146–62. https://doi.org/10.1016/j.buildenv.2017.06.051.
[13] Nwodo MN, Anumba CJ. A review of life cycle assessment of buildings using a systematic approach. Build Environ 2019;162:106290. https://doi.org/10.1016/j.buildenv.2019.106290.
[14] Di Maria A, Eyckmans J, Van Acker K. 26 - Use of LCA and LCC to help decision-making between downcycling versus recycling of construction and demolition waste. In: Pacheco-Torgal F, Ding Y, Colangelo F, Tuladhar R, Koutamanis A, editors, Advances in construction and demolition waste recycling. Woodhead Publishing Series in Civil and Structural Engineering; Woodhead Publishing, 2020; p. 537–58. ISBN 978-0-12-819055-5.
[15] Petrovic B, Myhren JA, Zhang X, Wallhagen M, Eriksson O. Life cycle assessment of a wooden single-family house in Sweden. Appl Energy 2019;251:113253. https://doi.org/10.1016/j.apenergy.2019.05.056.
[16] Hoogmartens R, Van Passel S, Van Acker K, Dubois M. Bridging the gap between LCA, LCC and CBA as sustainability assessment tools. Environ Impact Assess Rev 2014;48:27–33. https://doi.org/10.1016/j.eiar.2014.05.001.
[17] Lu K, Jiang X, Yu J, Tam VWY, Skitmore M. Integration of life cycle assessment and life cycle cost using building information modeling: a critical review. J Clean Prod 2021;285:125438. https://doi.org/10.1016/j.jclepro.2020.125438.
[18] Ramesh T, Prakash R, Shukla KK. Life cycle energy analysis of a residential building with different envelopes and climates in Indian context. Appl Energy 2012;89:193–202. https://doi.org/10.1016/j.apenergy.2011.05.054.
[19] Rossi B, Marique A-F, Reiter S. Life-cycle assessment of residential buildings in three different European locations, case study. Build. Environ. 2012;51:402–7. https://doi.org/10.1016/j.buildenv.2011.11.002.
[20] Islam H, Jollands M, Setunge S, Haque N, Bhuiyan MA. Life cycle assessment and life cycle cost implications for roofing and floor designs in residential buildings. Energ Build 2015;104:250–63. https://doi.org/10.1016/j.enbuild.2015.07.017.

[21] Roux C, Schalbart P, Assoumou E, Peuportier B. Integrating climate change and energy mix scenarios in LCA of buildings and districts. Appl Energy 2016;184:619–29. https://doi.org/10.1016/j.apenergy.2016.10.043.
[22] Lotteau M, Loubet P, Pousse M, Dufrasnes E, Sonnemann G. Critical review of life cycle assessment (LCA) for the built environment at the neighborhood scale. Build Environ 2015;93:165–78. https://doi.org/10.1016/j.buildenv.2015.06.029.
[23] Sharma A, Saxena A, Sethi M, Shree V. Varun life cycle assessment of buildings: a review. Renew Sustain Energy Rev 2011;15:871–5. https://doi.org/10.1016/j.rser.2010.09.008.
[24] Macias J, Iturburu L, Rodriguez C, Agdas D, Boero A, Soriano G. Embodied and operational energy assessment of different construction methods employed on social interest dwellings in Ecuador. Energ Build 2017;151:107–20. https://doi.org/10.1016/j.enbuild.2017.06.016.
[25] Hu M. Life-cycle environmental assessment of energy-retrofit strategies on a campus scale. Build Res Inf 2020;48:659–80. https://doi.org/10.1080/09613218.2019.1691486.
[26] Zinzi M, Mattoni B. Assessment of construction cost reduction of nearly zero energy dwellings in a life cycle perspective. Appl Energy 2019;251:113326. https://doi.org/10.1016/j.apenergy.2019.113326.
[27] Martínez-Rocamora A, Rivera-Gómez C, Galán-Marín C, Marrero M. Environmental benchmarking of building typologies through BIM-based combinatorial case studies. Autom Constr 2021;132:103980. https://doi.org/10.1016/j.autcon.2021.103980.
[28] Roberts M, Allen S, Coley D. Life cycle assessment in the building design process – a systematic literature review. Build Environ 2020;185:107274. https://doi.org/10.1016/j.buildenv.2020.107274.
[29] Ramesh T, Prakash R, Shukla KK. Life cycle energy analysis of buildings: an overview. Energ Build 2010;42:1592–600. https://doi.org/10.1016/j.enbuild.2010.05.007.
[30] Ingrao C, Messineo A, Beltramo R, Yigitcanlar T, Ioppolo G. How can life cycle thinking support sustainability of buildings? Investigating life cycle assessment applications for energy efficiency and environmental performance. J Clean Prod 2018;201:556–69. https://doi.org/10.1016/j.jclepro.2018.08.080.
[31] Echarri-Iribarren V, Echarri-Iribarren F, Rizo-Maestre C. Ceramic panels versus aluminium in buildings: energy consumption and environmental impact assessment with a new methodology. Appl Energy 2019;233–234:959–74. https://doi.org/10.1016/j.apenergy.2018.08.091.
[32] Mastrucci A, Marvuglia A, Leopold U, Benetto E. Life cycle assessment of building stocks from urban to transnational scales: a review. Renew Sustain Energy Rev 2017;74:316–32. https://doi.org/10.1016/j.rser.2017.02.060.
[33] Vilches A, Garcia-Martinez A, Sanchez-Montañes B. Life cycle assessment (LCA) of building refurbishment: a literature review. Energ Build 2017;135:286–301. https://doi.org/10.1016/j.enbuild.2016.11.042.
[34] Del Rosario P, Palumbo E, Traverso M. Environmental product declarations as data source for the environmental assessment of buildings in the context of level(s) and DGNB: how feasible is their adoption? Sustainability 2021;13:6143. https://doi.org/10.3390/su13116143.
[35] Araújo C, Almeida M, Bragança L, Barbosa JA. Cost-benefit analysis method for building solutions. Appl Energy 2016;173:124–33. https://doi.org/10.1016/j.apenergy.2016.04.005.
[36] Soust-Verdaguer B, Llatas C, García-Martínez A. Critical review of BIM-based LCA method to buildings. Energ Build 2017;136:110–20. https://doi.org/10.1016/j.enbuild.2016.12.009.
[37] Asif M. An empirical study on life cycle assessment of double-glazed aluminium-clad timber windows. Int J Build Pathol Adapt 2019;37:547–64. https://doi.org/10.1108/IJBPA-01-2019-0001.
[38] Elkhayat YO, Ibrahim MG, Tokimatsu K, Ali AAM. A comparative life cycle assessment of three high-performance glazing systems for office buildings in a hot desert climate zone. Clean Techn Environ Policy 2020;22:1499–515. https://doi.org/10.1007/s10098-020-01891-2.
[39] Lyu Y, Chow T. Economic, energy and environmental life cycle assessment of a liquid flow window in different climates. Build Simul 2020;13:837–48. https://doi.org/10.1007/s12273-020-0636-z.
[40] Budig M, Heckmann O, Hudert M, Ng AQB, Xuereb Conti Z, Lork CJH. Computational screening-LCA tools for early design stages. Int J Archit Comput 2021;19:6–22. https://doi.org/10.1177/1478077120947996.
[41] Zeng R, Chini A, Ries R. Innovative design for sustainability: integrating embodied impacts and costs during the early design phase. Eng Constr Archit Manag 2020;28:747–64. https://doi.org/10.1108/ECAM-09-2019-0491.
[42] Hasik V, Ororbia M, Warn GP, Bilec MM. Whole building life cycle environmental impacts and costs: a sensitivity study of design and service decisions. Build Environ 2019;163:106316. https://doi.org/10.1016/j.buildenv.2019.106316.
[43] Zieger V, Lecompte T, Hellouin de Menibus A. Impact of GHGs temporal dynamics on the GWP assessment of building materials: a case study on bio-based and non-bio-based walls. Build Environ 2020;185:107210. https://doi.org/10.1016/j.buildenv.2020.107210.
[44] Collinge WO, Rickenbacker HJ, Landis AE, Thiel CL, Bilec MM. Dynamic life cycle assessments of a conventional green building and a net zero energy building: exploration of static, dynamic, attributional, and consequential electricity grid models. Environ Sci Technol 2018;52:11429–38. https://doi.org/10.1021/acs.est.7b06535.
[45] RINNO H2020 - An augmented intelligence-enabled stimulating framework for deep energy renovation delivering occupant-centered innovations. Available online: https://rinno-h2020.eu/(accessed on 26 May 2022).
[46] International Organization for Standardization (ISO). ISO 14040:2006 - Environmental management — life cycle assessment — principles and framework. Geneva, Switzerland; 2006. Available online: https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/03/74/37456.html (accessed on 20 October 2021).
[47] International Organization for Standardization (ISO). ISO 14044:2006 - Environmental management — life cycle assessment — requirements and guidelines. Geneva, Switzerland; 2006. Available online: https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/03/84/38498.html (accessed on 20 October 2021).
[48] EN ISO 14044:2006/A1:2018 - Environmental management - life cycle assessment - requirements and guidelines - amendment 1 (ISO 14044:2006/Amd 1:2017) Available online: https://standards.iteh.ai/catalog/standards/cen/f074a39a-8dc7-4be4-8b1c-bf5953993800/en-iso-14044-2006-a1-2018 (accessed on 20 October 2021).
[49] Röck M, Saade MRM, Balouktsi M, Rasmussen FN, Birgisdottir H, Frischknecht R, et al. Embodied GHG emissions of buildings – the hidden challenge for effective climate change mitigation. Appl Energy 2020;258:114107. https://doi.org/10.1016/j.apenergy.2019.114107.
[50] International Organization for Standardization (ISO). ISO 21930:2017 - Sustainability in buildings and civil engineering works — core rules for environmental product declarations of construction products and services. Geneva, Switzerland; 2006. Available online: https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/06/16/61694.html (accessed on 20 October 2021).
[51] International Organization for Standardization (ISO). ISO 15686-5:2017 - Buildings and constructed assets — service life planning — Part 5: life-cycle costing. Geneva, Switzerland; 2017. Available online: https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/06/11/61148.html (accessed on 20 October 2021).
[52] BSI Standards Publication. BS EN 15978:2011 Sustainability of construction works. Assessment of environmental performance of buildings. Calculation method. Available online: https://www.en-standard.eu/bs-en-15978-2011-sustainability-of-construction-works-assessment-of-environmental-performance-of-buildings-calculation-method/(accessed on 20 October 2021).
[53] Michalak J, Michałowski B. Understanding of construction product assessment issues and sustainability among investors, architects, contractors, and sellers of construction products in Poland. Energies 1941;2021:14. https://doi.org/10.3390/en14071941.
[54] Joint Research Centre (European Commission); Dodd N, Donatello S, Cordella M. Level(s): a common EU framework of core sustainability indicators for office and residential buildings - user manual 1: introduction to the level(s) common framework (Publication Version 1.0). Publications Office of the European Union: LU; 2020.
[55] Joint Research Centre (European Commission), Dodd, N, Cordella M, Traverso M, Donatello S. Level(s): a common EU framework of core sustainability indicators for office and residential buildings: Part 3, how to make performance assessments using level(s) (Beta v1.0). Publications Office of the European Union: LU; 2017. ISBN 978-92-79-76907-8.
[56] Malmqvist T, Glaumann M, Scarpellini S, Zabalza I, Aranda A, Llera E, et al. Life cycle assessment in buildings: the ENSLIC simplified method and guidelines. Energy 2011;36:1900–7. https://doi.org/10.1016/j.energy.2010.03.026.
[57] Rossi B, Marique A-F, Glaumann M, Reiter S. Life-cycle assessment of residential buildings in three different European locations, basic tool. Build Environ 2012;51:395–401. https://doi.org/10.1016/j.buildenv.2011.11.017.
[58] Fu F, Luo H, Zhong H, Hill A. Development of a carbon emission calculations system for optimizing building plan based on the LCA framework. Math Probl Eng 2014;2014:e653849.
[59] Li D, Cui P, Lu Y. Development of an automated estimator of life-cycle carbon emissions for residential buildings: a case study in Nanjing, China. Habitat Int 2016;57:154–63. https://doi.org/10.1016/j.habitatint.2016.07.003.
[60] Solís-Guzmán J, Rivero-Camacho C, Alba-Rodríguez D, Martínez-Rocamora A. Carbon footprint estimation tool for residential buildings for non-specialized users: OERCO2 project. Sustainability 2018;10:1359. https://doi.org/10.3390/su10051359.
[61] Jayathissa P, Jansen M, Heeren N, Nagy Z, Schlueter A. Life cycle assessment of dynamic building integrated photovoltaics. Sol Energy Mater Sol Cells 2016;156:75–82. https://doi.org/10.1016/j.solmat.2016.04.017.
[62] Pernetti R, Garzia F, Paoletti G, Weiss T. Towards the definition of a NZEB cost spreadsheet as a support tool for the design. IOP Conf Ser: Earth Environ Sci 2019;323:012004. https://doi.org/10.1088/1755-1315/323/1/012004.
[63] Domjan S, Arkar C, Medved S. Computer-aided supporting tool for LCA evaluation of energy efficiency of the buildings – assessment method and case studies. IOP Conf Ser: Earth Environ Sci 2019;323:012109. https://doi.org/10.1088/1755-1315/323/1/012109.
[64] Kong M, Lee M, Kang H, Hong T. Development of a framework for evaluating the contents and usability of the building life cycle assessment tool. Renew Sustain Energy Rev 2021;150:111475. https://doi.org/10.1016/j.rser.2021.111475.
[65] Tiruta-Barna L, Pigné Y, Navarrete Gutiérrez T, Benetto E. Framework and computational tool for the consideration of time dependency in life cycle inventory: proof of concept. J Clean Prod 2016;116:198–206. https://doi.org/10.1016/j.jclepro.2015.12.049.
[66] Su S, Li X, Zhu Y, Lin B. Dynamic LCA framework for environmental impact assessment of buildings. Energ Build 2017;149:310–20. https://doi.org/10.1016/j.enbuild.2017.05.042.
[67] Negishi K, Tiruta-Barna L, Schiopu N, Lebert A, Chevalier J. An operational methodology for applying dynamic life cycle assessment to buildings. Build Environ 2018;144:611–21. https://doi.org/10.1016/j.buildenv.2018.09.005.

[68] Ramon D, Allacker K, Trigaux D, Wouters H, van Lipzig NPM. Dynamic modelling of operational energy use in a building LCA: a case study of a Belgian office building. Energ Build 2023;278:112634. https://doi.org/10.1016/j.enbuild.2022.112634.

[69] Anand CK, Amor B. Recent developments, future challenges and new research directions in LCA of buildings: a critical review. Renew Sustain Energy Rev 2017;67:408–16. https://doi.org/10.1016/j.rser.2016.09.058.

[70] Bueno C, Hauschild MZ, Rossignolo JA, Ometto AR, Mendes NC. Sensitivity analysis of the use of life cycle impact assessment methods: a case study on building materials. J Clean Prod 2016;112:2208–20. https://doi.org/10.1016/j.jclepro.2015.10.006.

[71] Skaar C, Jørgensen RB. Integrating human health impact from indoor emissions into an LCA: a case study evaluating the significance of the use stage. Int J Life Cycle Assess 2013;18:636–46. https://doi.org/10.1007/s11367-012-0506-8.

[72] Fnais A, Rezgui Y, Petri I, Beach T, Yeung J, Ghoroghi A, et al. The application of life cycle assessment in buildings: challenges, and directions for future research. Int J Life Cycle Assess 2022;27:627–54. https://doi.org/10.1007/s11367-022-02058-5.

[73] Schram W, Louwen A, Lampropoulos I, van Sark W. Comparison of the greenhouse gas emission reduction potential of energy communities. Energies 2019;12:4440. https://doi.org/10.3390/en12234440.

[74] Fotopoulou MC, Drosatos P, Petridis S, Rakopoulos D, Stergiopoulos F, Nikolopoulos N. Model predictive control for the energy management in a district of buildings equipped with building integrated photovoltaic systems and batteries. Energies 2021;14:3369. https://doi.org/10.3390/en14123369.

[75] Hadi E, Heidari A. Development of an integrated tool based on life cycle assessment, levelized energy, and life cycle cost analysis to choose sustainable facade integrated photovoltaic systems. J Clean Prod 2021;293:126117. https://doi.org/10.1016/j.jclepro.2021.126117.

[76] Francis A, Thomas A. A framework for dynamic life cycle sustainability assessment and policy analysis of built environment through a system dynamics approach. Sustain Cities Soc 2022;76:103521. https://doi.org/10.1016/j.scs.2021.103521.

[77] Aarhus University, Department of Engineering: Photovoltaic Solar Energy Group and Technical University of Berlin, Department of Digital Transformation in Energy Systems. Technology-data base — technology-data documentation, release 0.3.0; 2021. Available online: https://technology-data.readthedocs.io/en/latest/index.html (accessed on 30 January 2022).

[78] Eurostat. Electricity prices by type of user. Available online: https://ec.europa.eu/eurostat/databrowser/view/ten00117/default/table?lang=en (accessed on 30 January 2022).

[79] Eurostat. Gas prices by type of user. Available online: https://ec.europa.eu/eurostat/databrowser/view/ten00118/default/table?lang=en (accessed on 30 January 2022).

[80] European Commission. Weekly oil bulletin. Available online: https://energy.ec.europa.eu/data-and-analysis/weekly-oil-bulletin_en (accessed on 30 January 2022).

[81] Seitaridis A, Mamounakis I, Tagkoulis N, Iliadis P, Bellos E, Papalexis C et al. An Innovative software platform for efficient energy, environmental and cost planning in buildings retrofitting. In: Maglogiannis I, Iliadis L, Macintyre J, Cortez P, editors. Proceedings of the artificial intelligence applications and innovations. AIAI 2022 IFIP WG 12.5 International Workshops. Cham: Springer International Publishing; 2022. p. 217–28.

[82] Dymola - Dassault Systèmes®. Available online: https://www.3ds.com/products-services/catia/products/dymola/(accessed on 7 October 2022).

[83] Modelica Language — Modelica Association. Available online: https://modelica.org/modelicalanguage.html (accessed on 7 October 2022).

[84] Wetter M, Zuo W, Nouidui TS, Pang X. Modelica buildings library. J Build Perform Simul 2014;7:253–70. https://doi.org/10.1080/19401493.2013.765506.

[85] Nytsch-Geusen C, Banhardt C, Inderfurth A, Mucha K, Möckel J, Rädler J et al. Buildingsystems - Eine Modular Hierarchische Modell-Bibliothek Zur Energetischen Gebäude Und Anlagensimulation; 2016.

[86] JRC photovoltaic geographical information system (PVGIS) - European Commission. Available online: https://re.jrc.ec.europa.eu/pvg_tools/en/#TMY (accessed on 7 October 2022).

[87] EN 15265:2007 - Energy performance of buildings - calculation of energy needs for space heating and cooling using dynamic methods - general criteria and validation procedures. Available online: https://standards.iteh.ai/catalog/standards/cen/3b7d56e1-21c8-4f7f-8fe0-eb9a39c80893/en-15265-2007 (accessed on 7 October 2022).

[88] Passivistas. The Tavros Project. Available online: https://tavros.passivistas.com (accessed on 22 December 2022).

[89] Greek technical chamber. TOTEE 20701-1. Technical guidelines on buildings' energy performance; 2017.

[90] Passivhaus Institut. Passive house requirements. Available online: https://passiv.de/en/02_informations/02_passive-house-requirements/02_passive-house-requirements.htm (accessed on 5 July 2022).

[91] Final report summary - INSPIRE (Development of Systemic Packages for Deep Energy Renovation of Residential and Tertiary Buildings Including Envelope and Systems) | FP7 | CORDIS | European Commission. Available online: https://cordis.europa.eu/project/id/314461/reporting (accessed on 22 December 2022).

[92] Mamounakis I, Efthymiopoulos N, Tsaousoglou G, Vergados DJ, Makris P, Varvarigos E. A novel pricing scheme for virtual communities towards energy efficiency. In: Proceedings of the 2018 IEEE international energy conference (ENERGYCON), June 2018. p. 1–6.