Journal of Cleaner Production 381 (2022) 135202

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Holistic renovation of a multi-family building in Greece based on dynamic simulation analysis

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A R T I C L E I N F O

Handling Editor: Panos Seferlis

Keywords:
Renovation
Dynamic simulation
Primary energy savings
Solar energy
Life cycle analysis

A B S T R A C T

This paper investigates numerically the deep renovation of a multi-family building in Greece to reduce dramatically its energy demand and also to incorporate renewable energy sources, rendering it a positive one; thus in position on an annual basis to offer net electricity to the grid. The examined building has 8 apartments of 75 m^2 floor area each and is located in Moschato, a suburb of Athens in Greece. The goal of the present investigation is to determine the energy savings, but also to calculate the financial and environmental benefits through a life cycle analysis. The energy simulation of the building is conducted on annual basis by using a novel and detailed dynamic software tool (INTEMA.building), which is developed in the Dymola environment using the Modelica modeling language. This tool makes possible the detailed simulation of both passive and active systems in the building environment. Furthermore, it includes the control of the energy systems and can provide accurate enough results, encompassing detailed numerical models for the systems investigated, accounting for an adjustable time step of the dynamic analysis. According to the calculations, the proposed retrofitting scenario can achieve a reduction of the heating loads by 93% and of cooling loads by 78% respectively. The electrical demand for domestic hot water can be decreased by about 79%, while the electricity demand for appliances and lighting by about 60%. In terms of specific thermal needs, the specific heating demand can be reduced from 151.5 kWh/m^2 down to 10.7 kWh/m^2, while the cooling specific demand from 112.6 kWh/m^2 to 24.4 kWh/m^2. Moreover, it is calculated that the reduction in the primary energy demand after the renovation can be up to 88%, with the building providing around 5.3 MWh of net electricity to the grid on a yearly basis through a net-metering connection. Finally, the life cycle cost analysis indicated 622 k€ savings and specific CO_2 avoidance per renovated floor area in the range of 2.64 tons CO_2/m^2.

1. Introduction

Buildings consume high amounts of energy which is estimated at around 40% of the worldwide energy consumption (European Commission, 2020). Therefore, they play an important role in the energy transition era and in the achievement of world-level sustainable development goals. European Union is a leader in this direction by promoting a sustainable energy strategy in the European countries regarding the building sectors, with the support of suitable directives (e.g., Directive 2018/844/EU (European Commission, 2018), COM/2020/662 (European Commission, 2020)). The renovation of the buildings can play a critical role in the reduction of the buildings' energy consumption aiming to i) improve the building envelope, ii) reduce energy waste, iii) improve the energy efficiency of HVAC systems and iv) improve indoor thermal comfort conditions (Benavente-Peces and Ibadah, 2020). Moreover, proper eco-friendly materials should be selected aiming to minimize the life cycle impact of the building on the environment (Rehman et al., 2021).

The renovation of the buildings can be achieved by choosing the proper modifications of the building envelope and estimating the building energy performance before the renovation (baseline case) and after the renovation. The use of accurate and flexible numerical tools for estimating the building energy behaviour, also in a dynamic fashion, is an accelerator towards achieving the maximum possible energy savings and the market roll-out of the deep renovation process. Therefore,

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https://doi.org/10.1016/j.jclepro.2022.135202
Received 21 September 2022; Received in revised form 3 November 2022; Accepted 13 November 2022
Available online 17 November 2022

Nomenclature

A_{col}	Collecting area, m^2
A_{PV}	Photovoltaic panel area, m^2
a_0	Zero-order efficiency coefficient of the solar collector
a_1	First-order efficiency coefficient of the solar collector, W/m^2K
a_2	Second-order efficiency coefficient of the solar collector, W/m^2K^2
COP	Coefficient of performance (heating mode)
c_p	Specific heat capacity, J/kgK
E	Energy, kWh
EER	Energy efficiency ratio (cooling mode)
ES	Energy savings, %
G_T	Solar incident irradiation on the tilted surface, W/m^2
GHG	Greenhouse gas emissions, kg CO_2
h_{in}	Indoor heat convection coefficient, W/m^2K
h_{out}	Outdoor heat convection coefficient, W/m^2K
Hu	Lower heating value, kJ/kg
k	Thermal conductivity, W/mK
L	Layer thickness, m
LCC	Life cycle cost, €
PE	Primary energy demand, kWh
P_{el}	Electricity, kW
pr	Primary energy factor
SEER	Seasonal energy efficiency ratio (cooling mode)
SCOP	Seasonal coefficient of performance (heating mode)
T	Temperature, °C
U	Thermal transmittance, W/m^2K
V	Volume, m^3

Greek Symbols

η_{col}	Solar thermal collector efficiency
η_{el}	Photovoltaic electrical efficiency
η_{hex}	Heat recovery system effectiveness
ρ	Density, kg/m^3

Subscripts & Superscripts

amb	Ambient
cool	Cooling
el	Electricity
f,in	Fluid inlet
f,out	Fluid outlet
frame	Opening frame
fuel	Fuel
glass	Opening glass
heat	Heating
inlet	Inlet to the building
load	Load
st	Storage
u,b	Useful heat from boiler
u,s	Useful heat from solar
w,in	Water inlet
w,out	Water outlet
window	Window
zone	From the zone
0	Reference

Abbreviations

AECs	Architects, Engineers and Constructors
ACH	Air changes per hour
BEPS	Building energy performance simulation
BIPV	Building integrated photovoltaics
CDA	Conditioned demand analysis
CFD	Computational fluid dynamics
DHW	Domestic hot water
HVAC	Heating ventilation and air-conditioning
IFC	Industry foundation classes
LCA	Life cycle analysis
PV	Photovoltaic panel

various energy tools have been developed aiming at the suitable study of the buildings' energy behavior in order to evaluate them properly (Kahsay et al., 2020). In this direction, tools that can simulate the buildings' energy behavior, have been developed. These are usually dynamic tools that solve the energy balance equations on the building cell during the year period. Usual software tools are EnergyPlus (EnergyPlus), TRNSYS (TRNSYS: Transient System Simulation Tool) and Matlab/Simulink (Matlab/Simulink and URL).

Literature includes a variety of studies with simulations about the building(s) energy efficiency with different followed methods. Foucquier et al. (2013) reviewed building energy models and energy performance prediction models. They included in their work different physical and computational models, such as computational fluid dynamics (CFD), nodal and zonal models, in parallel with machine learning tools and provided illustrating examples. On one hand, CFD approaches, allow for a detailed 3D numerical representation of the building(s) behavior, but with a large computational cost, which makes them suitable only for exemplar occasions and research needs, such as for example ventilation systems or to accurately capture convection and/or radiation phenomena (Cuce et al., 2019; Zhai et al., 2002). On the other hand, zonal models follow 1D or even 2D approaches and divide each building zone into several cells able to capture temperature and contaminant distributions (Megri and Haghighat, 2007) of a less but acceptable level of detail. This type of model is used in large space buildings and achieves a balance between numerical efficiency and accuracy (Lu et al., 2020). Most of the commercial building energy performance simulation software (BEPS), such as for example EnergyPlus and TRNSYS, use the nodal approach which considers homogenous volumes characterized by uniform state variables. Thus, one zone is numerically approximately represented by a node and the heat transfer equations are solved for each node (Lorenzetti, 2002; Axley, 2007). The advantage of such approaches lies in their low computational cost, which provides the ability of BEPS to conduct simulations of large time scales with low actual CPU running times. By this last approach, reduced order models of buildings can be constructed providing acceptable predictions (Kim and Braun, 2015). Generally, the major drawback of all aforementioned formulations, is that they require detailed knowledge of all parameters of the building(s) construction drawings and material properties, design specifications for all the energy systems, supported as well, where possible, with corresponding actual operational profiles and environmental data (Foucquier et al., 2013). For that reason, statistical models have as well been developed that do not require any physical data, i.e., building geometry and thermal properties. They are totally based on data available from measurements. As an example, a linear multivariate regression technique applied to buildings was introduced by Parti M. and Parti C (Parti and Parti, 1980). to predict energy consumption called, conditioned demand analysis (CDA). Asadi et al. (2014) predict accurately the annual energy consumption by utilizing CDA demonstrating the significant effect of building shape. Using CDA, researchers identify promising technologies that support the reduction of electricity consumption and decarbonization (Papineau et al., 2021). Genetic algorithms are also used for simple prediction of energy consumption models and optimal design of energy systems (Siddharth et al., 2011). In another work, Ciulla and D'Amico (Giuseppina and D'Amico,

2019) developed a tool by statistical analysis, using TRNSYS and CDA, to support the user in the decision-making stage about the building requirements. Moreover, Ham et al. (Ham and Golparvar-FardEPAR, 2013) experimentally examined the actual building performance with a thermal camera and proposed a method that combines thermal image processing with CFD models to calibrate the building performance.

As concerns the renovation of buildings, there are interesting studies in the literature. Soto Francés et al. (Soto Francés et al., 2020) used EnergyPlus to examine the renovation of schools in Spain during the SHERPA project. They concluded that the retrofitting of the schools is not a cost-effective choice, but they suggested the use of photovoltaics (PV) for producing electricity as an alternative. Moreover, they used the simulation results in order to suggest future steps in order to face the proper energy poverty in the building sector. In another study with EnergyPlus, Attia et al. (2022) investigated the renovation of a building in Brussels and they concluded that the use of external insulation and high-quality windows are important renovation interventions. They also reported significant energy savings with the proper control of the thermostat temperature but they also calculated discomfort problems during the extremely cold/hot days of the year. Heinz and Rieberer (2021) examined the retrofitting of a building by combining an air-source heat pump with PV and using TRNSYS software. The analysis was performed for Zurich in Switzerland and they finally calculated a 29% reduction in the electricity consumption from the grid. Cerezo-Narváez et al. (2021) examined the renovation of a building in Andalusia (South of Spain) with TRNSYS software. They concluded that the energy savings can be around 69%, while there is the possibility of 100% energy reduction.

It is obvious that the literature includes many studies regarding energy simulations of buildings, with numerous software, of varying levels of detail. The present analysis is conducted with a new and pioneering software called INTEMA.buidling, which is developed in the Dymola environment (Dymola) and uses the Modelica language (Modelica Language). This software is suitable for conducting detailed dynamic in-time studies, by using advanced component-based models for the building envelope and for the energy systems (e.g., heat pumps, solar thermal collectors). Also, it can consider the building(s) connections with multi-energy networks (electricity, heating/cooling, gas) accounting also for storage options. Therefore, the present tool is not restricted only the building energy analysis but also it is able to simulate properly energy systems separately, inside the building environment or in a network system. Furthermore, the present tool gives the possibility for applying advanced control strategies in the operation of the active systems, for achieving significant energy savings and optimizing the building's thermal behavior. A critical advantage of the present tool is the use of adjustable time steps in order to simulate the fluctuations of the system behavior, according to each user's needs. Moreover, it follows a component-based build-up process, rendering it in a position to develop any user-preferred advanced model of any system required, with a high level of detail. Therefore, INTEMA.building is a flexible and adjustable tool that can simulate any possible scenario with a reasonable computational time. Also, it is important to state that the INTEMA. building tool is able to simulate the renovation of every building without restrictions due to the flexible environment and the component-based libraries that can easily be adjusted in every case study.

Trying to follow a holistic approach to the renovation process, the INTEMA.buidling tool is also designed to exchange information with the VERIFY tool (Seitaridis et al., 2022), which is used for the life cycle analysis. Such an approach, allows the consideration of dynamic energy consumption (and/or demand as in the present study) and production 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 ii) other parameters, which static LCA/LCC approaches cannot account for; thus resulting in underestimations compared to reality.

In the present work, using the above tool a holistic renovation of a real building in Greece located in Moschato, in the suburbs of Athens is conducted. The detailed analysis aims to reduce dramatically the energy needs of the building and also to transform that into a positive one, by incorporating renewable energy sources for electricity and heating production. It is critical to state that the selected interventions are both passive and active. Specifically, the passive interventions concern the enhancement of the building envelope (e.g., external insulation, windows replacement), while the active regard the retrofitting of the energy systems by installing efficient heat pumps, the installation of a mechanical ventilation system with heat recovery, the energy retrofitting of the equipment and lighting installation, as well as the incorporation of solar thermal collectors and photovoltaics in the building. The dynamic character of the present analysis with small- and adjustable-time steps (in the range of μs up to min) makes it possible to follow properly the abrupt variations of the indoor temperature and of the thermal loads, something that increases the accuracy of the simulation work. The results of the present work reveal to a certain degree, for at least climatic conditions similar to that of Athens, the performance enhancement margin one can achieve, with the selected deep retrofitting interventions selected, in terms of energy, cost and environmental aspects. In this direction, this analysis includes the calculation of the energy savings, the primary energy reduction, the life cycle cost analysis and the greenhouse gas emissions life cycle analysis.

2. Material and methods

The present section includes information regarding the developed tool (INTEMA.building) along with results from its verification procedure. Next, the building system under consideration is described and the two examined scenarios are fully defined. Lastly, the utilized mathematical background is briefly described.

2.1. The developed tool - INTEMA.building

The present simulation study is conducted with an in-house developed building performance simulator, named INTegrated Energy MAnagement - buildings or "INTEMA.building" in short. The development was carried out in the framework of the EU HORIZON2020 project RINNO (RINNO, 2020).

The tool is based on the Modelica language (Modelica Language) in the Dymola environment (Dymola). Modelica is an ideal language for cyber-physical modeling, supporting the communication of different components. INTEMA.building takes advantage of the extensive Modelica code repository (Modelica Libraries) and builds upon well-validated open-source libraries in the field of building energy performance simulations. More specifically, the tool uses the Buildings (Wetter et al., 2014), BuildingSystems (C. Nytsch-Geusen et al., 2016), IDEAS (Jorissen et al., 2018), and AixLib (Fuchs et al., 2015) (Müller et al., 2016) libraries, which are all inheriting the main modules from the IBPSA library (Modelica IBPSA library).

An important advantage of this tool is based on the ability for performing simulations with high temporal and spatial accuracy by using adjustable time steps (compared to most of the available tools in the open literature), rendering it in a position to capture operational fluctuations of systems behavior, any temporal scale, i.e., in the range of μs up to min, if deemed as necessary. Moreover, the present tool gives the possibility for any user to mathematically formulate the representation of any system component with an adaptable level of detail, while also allowing the user to construct system-level simulations, including control management strategies.

INTEMA.building can be regarded as a proper tool for investigating the dynamic behaviour of both passive and active systems, in the buildings sector. More specifically, this tool allows the investigation of the building energy performance by calculating indoor temperature levels, heating/cooling loads, while also giving the possibility for simulation of multi-zone scenarios. Also, INTEMA.building can include in the same simulation scenario, the consideration of control strategies for optimizing the system's overall performance. Moreover, this tool can account for building(s) interactions with multi-energy networks (electricity, heating/cooling, gas) accounting also for storage options, for different energy rates and carriers.

The tool is also enabled by a web-based interface. There are two main libraries named "Building Envelope Model" and "Energy Systems" which include the repository of models that the present tool offers, which is expandable. More specifically the "Building Envelope Model" library includes different components of the building envelope (e.g., wall, window, thermal bridges), along with examples of typical buildings. The other main library named "Energy Systems" includes solutions like heat pumps, boilers, solar thermal collectors, photovoltaics, pumps, storage tanks, phase change materials, etc. Both libraries can be combined for creating a realistic model of a building study case. It is also useful to add that INTEMA.building includes its own libraries with weather data for various locations in Europe and all over the world. Moreover, there is the possibility to define the location through a map, and the weather data of the particular region are automatically retrieved from the Photovoltaic Geographical Information System (PVGIS) service provided by the European Commission (JRC Photovoltaic Geographical Information System (PVGIS)). Furthermore, the user may also upload manually his/her own typical meteorological year (TMY) files if this is required. Another option that INTEMA.building provides, concerns the extraction of data from BIM files (Building Information Modeling files) in order to conduct the respective simulations in a quicker way, accelerating the investigation process.

Fig. 1 shows the component-based environment of the tool, including different components from various libraries. This figure corresponds to the examined renovation scenario where the total building is connected with a reversible heat pump for covering both heating and cooling loads. More specifically, this figure shows that the main component of the building is connected to the heat pump through air ports, while also infiltration and ventilation are implemented through air ports. The heat recovery system is simulated by passing the proper fresh air quantity through a heat exchanger with constant effectiveness given by the user. Moreover, the building model receives the proper internal thermal loads from the heat ports in order to simulate properly the thermal loads from occupants, appliances and lighting. The materials of the building's structural elements are defined with suitable tables and all the structural elements are connected with the ambient and the building thermal zone. More specifically, the external walls, the windows, the roof and the basement are coupled with the internal thermal zone in order to simulate properly the building's thermal behavior. The heat pump device is connected to the building in order to provide hot or cold air quantities when there is a demand. The heat pump is controlled with a control system based on two PI controllers, one for heating and one for cooling. The PI controllers are properly tuned by conducting sensitivity studies regarding their parameters and more specifically by determining the gains that lead to accurate results regarding the achievement of the indoor temperature inside the desired limits. More details regarding the control system can be found in Appendix A.

2.2. Verification of the INTEMA.building

The verification of the tool is presented in two steps. The first step in subsection 2.2.1 is the verification of the "Building Envelope Model" library is given, while the verification of the "Building Envelope Model" library is given in subsection 2.2.2.

2.2.1. Verification of the "Building Envelope Model" library

The verification of the "Building Envelope Model" library was conducted by following the European Standard EN15265 (CEN EN 15265, 2007) for energy performance calculations in buildings. EN15265 defines 12 scenarios regarding the simulation of a small reference building and for each scenario, different parameters are set for its loads and its structural composition. These 12 scenarios were simulated with INTEMA.building under the same conditions, as defined in (CEN EN 15265, 2007). These scenarios are representative cases that take into account different inertia of the material, different operating schedules, different solar gains and the existence of a roof. So, the tool is tested under different cases which take into consideration typical operating conditions that are found in real buildings.

The comparative results regarding the heating thermal loads and the cooling loads are depicted in Fig. 2. According to this figure, both sources (INTEMA and standard) agree reasonably well for all 12 cases examined. The average deviation was calculated to be 3.9% for the heating thermal loads and 2.1% for the cooling thermal loads. More specifically, the deviation of the heating load ranged from 0.24% for scenario 1 up to 9.27% for scenario 11, while for the cooling from 0.14% for scenario 1 up to 8.69% for scenario 4. It is also remarkable to state that in some scenarios the INTEMA.building tool gives higher loads and in other scenarios gives lower loads, something that shows that there is no systematic error that always overestimates or underestimates the results.

2.2.2. Verification of the "Energy systems" library

The next step is the verification of the "Energy Systems" library through a typical example of a building connected to a reversible heat pump. In order to perform this verification step and owing to the lack of a specific standard, the results of the INTEMA.building model were

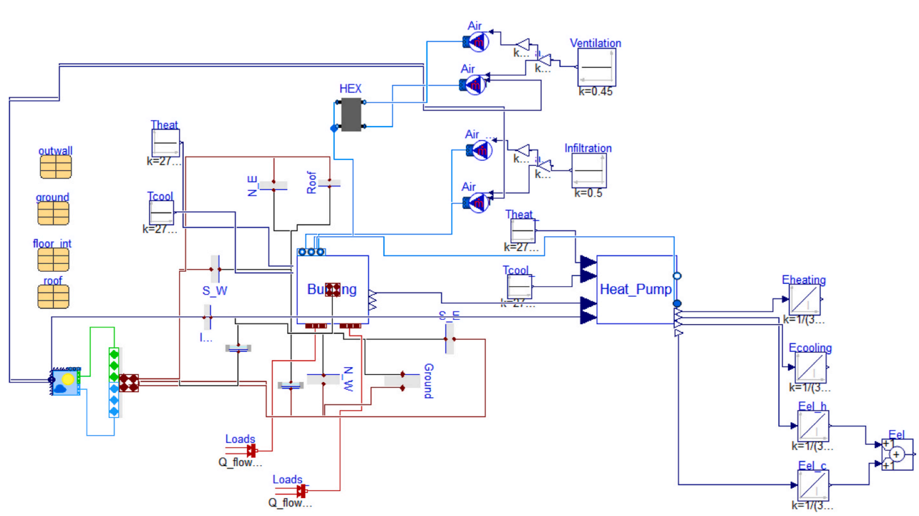

Fig. 1. Example of the simulation environment (component-based) of the tool for the renovation scenario.

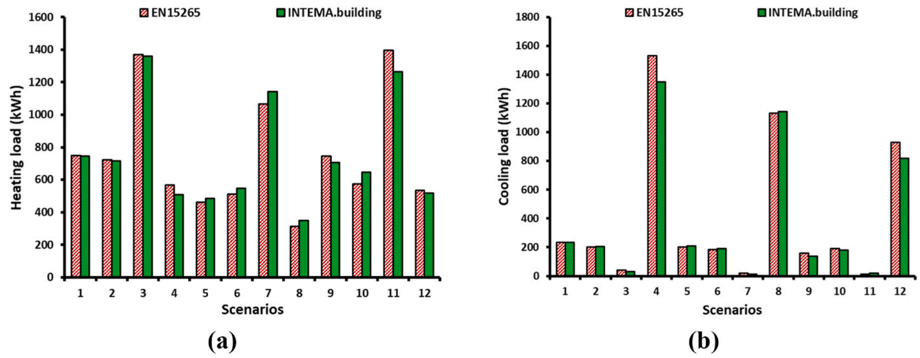

Fig. 2. Comparison of the simulation results with the EN15265 regarding (a) the heating loads, and (b) the cooling loads.

compared against a corresponding model in TRNSYS 18 software (https://sel.me.wisc.edu/trnsys/) (https://sel.me.wisc.edu/trnsys/features/trnsys18_0_updates.pdf). This numerical test case includes a single zone building located in Athens, Greece (37°59′N, 23°43′E), of four external walls of the same material composition, one roof and one floor. There is also a window located in the center of the south direction. More details regarding building geometry and the developed model in TRNSYS can be calculated in Appendix B.

Table 1 includes the energy comparison results of both tools on a yearly basis. The deviations between the results of these two models, for the examined parameters, are in the order of a maximum of 4%, which is considered within acceptable limits for such types of simulations. Specifically, the highest deviations are 0.82%, and 3.47% for the cooling and heating loads respectively, while the deviation of the total electricity demand of the heat pump is 2.82%. The efficiency indicators (SEER and SCOP) present very small deviations, i.e., 0.82% and 0.57% respectively. The highest deviations were tracked for electricity demand (4.01%), but this is lower than 5%, which can be regarded as a typical limit that indicates a high level of accuracy, as it has been reported in the previous validation analysis with the European Standard.

Additionally, Fig. 3 depicts the variation of the heating, cooling and electricity demands of the examined building with both tools. It is evident that the curves are close to each other for the whole year period.

2.3. The examined study case - baseline scenario

In the present study, a multi-family building with 8 apartments on 4 floors is studied in the location of Moschato, which is a suburb of Greece (37°58′01.8″N, 23°41′48.9″E). Fig. 4 illustrates the examined building with real photos and IFC (Industry Foundation Classes) depictions. The building was constructed in 1970s and it has an inefficient building envelope. It is considered a typical example of the building stock in the examined location since many similar buildings exist in Moschato, as well as in the wider area of Athens. Therefore, the results of the present work can be expanded to a great number of buildings, of similar typology.

Table 1
Comparison of the obtained data with INTEMA.building and TRNSYS.

Parameters	INTEMA. building	TRNSYS	Deviation
Cooling energy - E_{cool} (kWh)	2473	2453	0.82%
Heating energy - E_{heat} (kWh)	5627	5829	3.47%
Total electricity demand E_{el} (kWh_{el})	2893	2977	2.82%
Electricity demand for cooling - $E_{el,cool}$ (kWh_{el})	883	883	0.00%
Electricity demand for heating - $E_{el,heat}$ (kWh_{el})	2010	2094	4.01%
Seasonal Cooling performance indicator - SEER	2.801	2.778	0.82%
Seasonal Cooling performance indicator - SCOP	2.800	2.784	0.57%

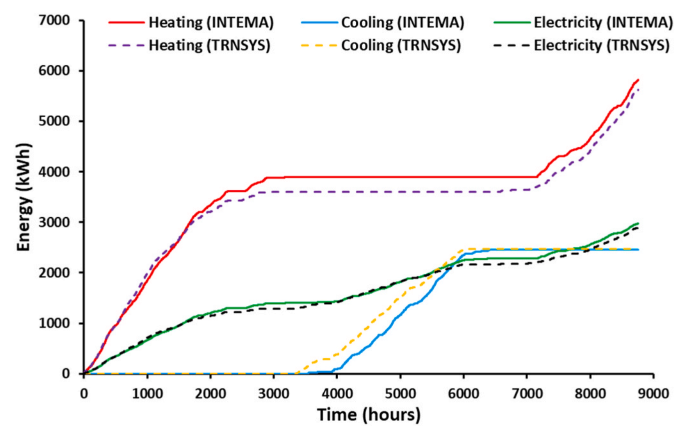

Fig. 3. Cumulative heating, cooling and electricity demands during the year with INTEMA.building and TRNSYS.

Fig. 5 depicts the four-floor plans (ground, 1st, 2nd and 3rd) giving the exact geometry of every apartment. There are 8 similar apartments of 75 m^2 net area each, while the height of every floor is 2.8 m^2. There is also a basement in the present building, but this is not taken into consideration in the energy needs of the building, because it is an unheated space. The main structural elements of the building are given briefly in Table 2. In addition, the present case study concerns an uninsulated building envelope, while most of the windows are single. There are some apartments with double windows, but they are also relatively old; hence not meet high-performance standards. The U-value of the single windows, including the frame, was 5.76 W/m^2 and for the double windows was 3.13 W/m^2K, while the g-value was 86%. The total glazing area on the west side is 105.7 m^2, while on the east 89.5 m^2.

Taking into consideration the low-quality building envelope, the infiltration and natural ventilation ratio were selected at 2 air changes per hour (ACH) in total. Also, the indoor temperature setpoints were selected at 20 °C during winter and 26 °C during summer. The specific lighting load of the building was selected at 5 W/m^2, the specific equipment load for appliances was selected at 4 W/m^2, the occupants of the building were selected at 14 and the usage factor was estimated to be at 60% (Greek Technical Chamber TOTEE, 20701-1, 2017), (ASHRAE Handbook, 2017). Moreover, the total specific thermal load per person was selected at 80W which is a reasonable value for a residential building (ASHRAE Handbook, 2017). All aforementioned data are included in Table 3 and are in accordance with the real operating conditions of the specific building (as of current status).

The next part of the baseline scenario description regards the equipment for covering the heating/cooling loads and the domestic hot water (DHW) needs. In the examined case, every apartment has its own system for covering its energy needs and therefore there is no centralized

Fig. 4. Multifamily building Moschato-Tavros (a) façade photo, (b) satellite photo, (c) IFC façade, (d) IFC top view.

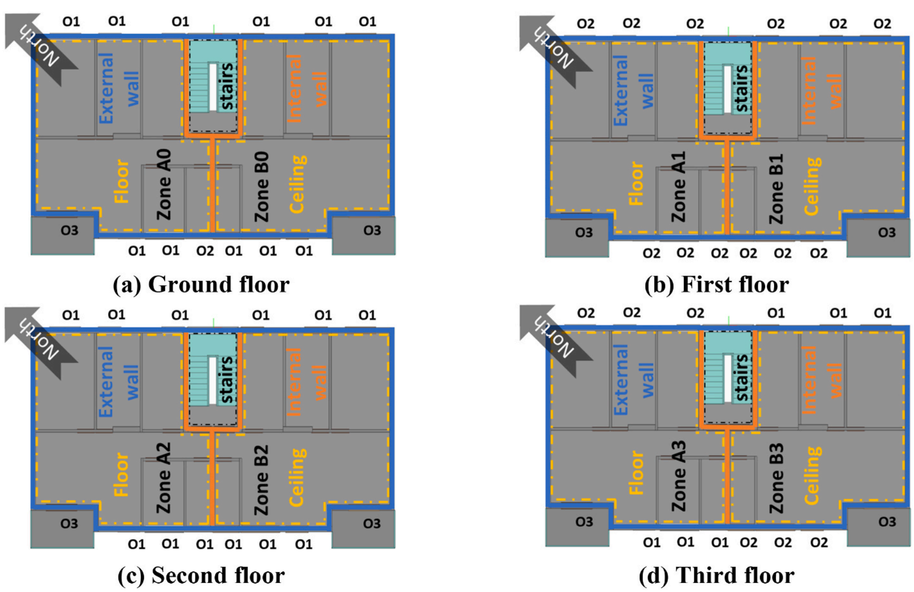

Fig. 5. Floor plans of the four floors of the examined building.

Table 2
Entities of multifamily building Moschato-Tavros.

Structural element	Description	Thickness (m)	U (W/m^{2}K)
External wall (W)	Plaster - Brick - Concrete - Plaster	0.25	3.45
Internal wall (I)	Plaster - Concrete - Plaster	0.25	3.85
Ceiling (C)	Cement mortar - Concrete - Plaster	0.23	3.85
Floor (F)	Ceramic tile - Cement mortar - Concrete - Plaster	0.23	4.20
Opening 1 (O1)	Window: Single glass - Aluminum	0.005	5.76
Opening 2 (O2)	Window: Double glass - Aluminum	0.030	3.13
Opening 3 (O3)	Door	0.051	1.80

Table 3
Input in the simulation tool for the baseline scenario.

Parameter	Value
Cooling temperature setpoint	26 °C
Heating temperature setpoint	20 °C
Specific load for the appliances	4 W/m^2
Specific load for the lighting	5 W/m^2
Usage factor	60%
Infiltration & natural ventilation rate	2 air changes per hour
Thermal load from occupants	80 W/person

system. Cooling needs are covered with heat pumps in all apartments, while heating needs are covered in different ways. One apartment has an oil boiler, one has a natural gas boiler and the remaining six apartments have heat pumps for the heating loads. The DHW is covered with electrical resistances in four apartments, while the other four apartments have a typical solar thermal system with flat plate collectors assisted by an electrical heater. Table 4 summarizes the energy systems used in the 8 apartments. The numbering of the apartments follows that of Fig. 5. For

Table 4
Technologies of the energy systems of the baseline scenarios.

Apartments	Technologies of the energy systems		
	Heating	Cooling	DHW
A0	Heat pump	Heat pump	Electrical resistance
B0	Heat pump	Heat pump	Electrical resistance
A1	Heat pump	Heat pump	Solar thermal system
B1	Natural gas boiler	Heat pump	Solar thermal system
A2	Heat pump	Heat pump	Electrical resistance
B2	Heat pump	Heat pump	Electrical resistance
A3	Heat pump	Heat pump	Solar thermal system
B3	Oil boiler	Heat pump	Solar thermal system

the scope of the current analysis and to increase the accuracy of the numerical results, requiring also acceptable processing time, every apartment has been modeled as a separate thermal. The nominal efficiency of the oil boiler was selected at 80%, of the natural gas boiler at 90%, while the SCOP and the SEER of the heat pumps were set equal to two (2) because they are old machines with low performance. The aforementioned efficiency values are in accordance with Greek legislation for the buildings by taking into consideration the age of the equipment (Greek Technical Chamber TOTEE, 20701-1, 2017).

Regarding the DHW, the demand was selected at 50 L/day per person (Greek Technical Chamber TOTEE, 20701-1, 2017) and the desired temperature of the hot water was selected at 45 °C. A typical distribution of the DHW demand during the day was used, by considering relevant data from (Ahmed et al., 2016), while the temperature of the cold grid water has been taken from (Greek Technical Chamber TOTEE, 2010); the mean yearly water temperature in Athens is around 17.8 °C, ranging from 10.9 °C in February up to 25.7 °C in August. Table 4 summarizes the data of the used systems for DHW production. For the apartments with solar thermal systems, it is considered that every apartment has a solar collector of 2 m^2 collecting area, coupled with a storage tank of 160 L volume. This collector is a simple flat plate collector, and its characteristics are presented in Table 5, in accordance with Greek regulations (Greek Technical Chamber TOTEE, 20701-1, 2017). The electrical heater efficiency was also estimated at 98%. Moreover, the electricity demand distribution for the appliances and the lighting and the appliances has been selected to follow a typical pattern according to (Paatero and Lund, 2006).

2.4. Renovation scenario description

The renovation scenario examined, as part of this study, serves two scopes, i.e.: a) to reduce significantly the energy needs of the building and b) to transform the building into an Energy Positive one by installing PV panels on it, which cover its needs but also provide net electricity to the grid, on a yearly basis. Therefore, the renovation scenarios include i) retrofitting actions for the building envelope, ii) retrofitting the existing active energy systems and iii) exploitation of the available solar energy potential, with solar thermal collectors and photovoltaic panels. Below, the applied renovation interventions are listed. All the remaining parameters have the same values as in the baseline scenario. Table 6 summarizes the input data of the renovation scenario in comparison with the baseline scenario. This table aims to give briefly the inputs of both scenarios in order to make clear their differences.

Table 5
Data for the DHW analysis in the baseline scenario.

Parameter	Value
Specific hot water demand	50 L/day per person
Hot water temperature	45 °C
Mean yearly supply water temperature in Greece	17.8 °C
Electrical heater efficiency	98%
Solar collector area per apartment	2 m^2
Storage tank per apartment	160 L
Zero-order collector coefficient - a_0	0.73
First-order collector coefficient - a_1	5.51 m^2/WK
Second-order collector coefficient - a_2	0.006 m^2/WK^2
Incident angle modifier at 50° incident angle	0.88

A) Installation of external insulation (expanded polystyrene foam)

The main goal of this intervention aims at reducing thermal losses. More specifically, expanded polystyrene foam with thermal conductivity of k = 0.034 W/mK was added to the external walls (12 cm added, U-value reduced to 0.25 W/m^{2}K), roof (20 cm added, U-value reduced to 0.16 W/m^{2}K) and basement ceiling (3 cm added, U-value reduced to 0.86 W/m^{2}K).

B) Windows replacement

The replacement of the existing low-quality windows with advanced windows leads to reduced thermal losses and enhances the building's airtightness. More specifically, triple-glazed low-e aluminium/pvc windows were selected with a glazing U-value at 0.6 W/m^{2}K, frame U-value at 1.0 W/m^{2}K and g-value equal to 37%. The airtightness of the envelope (infiltration and natural ventilation rate) is reduced from 2 ACH down to 0.4. It is useful to state that the air quality of the indoor space is kept at the proper levels by the use of a mechanical ventilation system, which is described below.

C) Decentralized mechanical ventilation with heat recovery

The use of a mechanical ventilation system with heat recovery for providing fresh is important for keeping the indoor air quality in the proper quality standards and also reduces the thermal loads due to the existence of a recovery system. For every apartment, the volumetric flow rate of the ventilation system was selected at 100 m^3/h which corresponds to 0.45 ACH approximately. The effectiveness of the heat exchanger in the heat recovery unit was set at 72%.

D) Installation of decentralized reversible air-to-air heat pumps

Use of decentralized highly efficient reversible air-to-air heat pumps in all the apartments in order to cover the heating loads during winter and the cooling loads during summer. These heat pumps present a SEER = 5 and a SCOP = 3, typical values for reversible heat pumps.

Table 6
Summary of the simulation inputs of the examined scenario.

Parameters	Renovation	Baseline
U-value of the external walls	0.25 W/m^{2}K	3.45 W/m^{2}K
U-value of the roof	0.16 W/m^{2}K	3.85 W/m^{2}K
U-value of the basement	0.86 W/m^{2}K	4.20 W/m^{2}K
U-value of the windows (glazing & frame)	0.68 W/m^{2}K	3.13/5.70 W/m^{2}K
g-value of the window	0.37	0.86
Infiltration/Mechanical ventilation rate	0.4/0.45 ACH	2 ACH
Heat recovery efficiency of the ventilation system	72%	–
Heat pump SCOP	3	2
Heat pump SEER	5	2
Natural gas boiler efficiency	–	90%
Oil boiler efficiency	–	80%
PV area on the roof	97.48 m^2	–
Nominal efficiency of the roof PV	19.9%	–
BIPV on the southeast side	12.24 m^2	–
Nominal efficiency of the BIPV	5.8%	–
Solar thermal collector area per apartment	2.5 m^2	2.0
Storage tank volume for DHW per apartment	160 L	160 L
Specific load of the lighting	1.6 W/m^2	5 W/m^2
Specific load of the appliances	2.0 W/m^2	4 W/m^2

E) Installation of PV panels installed with net-metering connection

Photovoltaic panels are installed in the building aiming to cover all the electrical demand and also provide net electricity to the grid. A net-metering connection was assumed for the present study, thus there is not any storage unit in the examined system.

- Installation of highly efficient PV panels on the roof: These panels are located horizontally in order to put as many possible panels and to avoid shadings among them. Every panel has an area of 2.21 m^2. After an initial sizing, it was calculated that 44 panels with dimensions (2.11 × 1.05) m^2 are able to be installed. The selected PV panels have nominal efficiency of 19.9% and it is the SHARP (NU-JD440) panel (Sharp). This panel has a nominal power of 440 W.

- Installation of vertical building integrated photovoltaics (BIPV) in the southeast direction: Taking into consideration the available space, 4 panels were selected to be installed on the top floor. Every panel has dimensions of 2.45 m × 1.25 m, a total area of 3.06 m^2 and maximum efficiency of 5.8% (ONYX) (Solar Onyx). It is important to state that the mean reducing shading factor is 96% was calculated according to the described methodology in (Greek Technical Chamber TOTEE, 20701-1, 2017).

F) Solar thermal collectors coupled to storage tanks

Use of an integrated solar thermal system in every apartment separately in order to reduce the electricity consumption by the electrical resistance. More specifically, selective solar thermal collectors of 2.5 m^2 coupled to a storage tank of 160 L are selected to be installed in every apartment. The system includes auxiliary electrical resistance. The used collectors are advanced systems with efficiency coefficients as below: $a_0 = 0.77$, $a_1 = 3.75$ W/m^2K and $a_2 = 0.015$ W/m^2K^2. Also, the storage tank is an insulated one with 5 cm insulation of thermal conductivity around 0.034 W/m^2K.

G) Retrofitting of the equipment and lighting installation

The existing equipment and the lighting are retrofitted/replaced with low-consuming technologies aiming to the reduction of the electricity demand. The new values for the specific nominal electrical load were set at 1.6 W/m^2 for the appliances and at 2 W/m^2 for the lighting.

2.5. Evaluation metrics

Lastly, the utilized evaluation metrics are defined, while for the mathematical background the reader is referred to Appendix C.

2.5.1. Primary energy

Primary energy (PE) is an important index for evaluating the overall performance of the system. It can be written as a sum of different energy demands (E_i) by multiplying them with the respective conversion coefficient to the primary energy (pr_i) (Greek Technical Chamber TOTEE, 20701-1, 2017):

$$PE = \sum_{i=1}^{k} (pr_i \cdot E_i) \tag{1}$$

where the primary energy factor for oil is taken equal to 1.1, for natural gas 1.05 and for electricity 2.9 according to the Greek legislation (Greek Technical Chamber TOTEE, 20701-1, 2017).

2.5.2. Energy savings

Energy savings (ES) is another important index. It compares the energy demand of the baseline scenario to the renovation scenario. It can be written for the heating load, the cooling load and primary energy demand for example. The general definition is given as follows:

$$ES = \left| \frac{E_{baseline} - E_{renovation}}{E_{baseline}} \right| \tag{2}$$

2.5.3. Greenhouse gas emissions life cycle

The greenhouse gas emissions life cycle ($GHG_{lifecycle}$) is a very important indicator that is calculated by conducting a detailed life cycle assessment (LCA). In the present work, the recognized LCA methodological approach is conducted according to the specific ISO standards ISO 14040 (International Organization for Standardization (ISO), 2006a) and ISO 14044 (International Organization for Standardization (ISO), 2006b), (EN ISO 14044:2006/A1:2018, 1404). Focusing on global warming impact exclusively, two main stages for the target energy-related technologies/systems are involved in this paper regarding: a) manufacturing process and b) operational use-phase in terms of global warming indicators and amount of primary energy respectively. Below, the general expression regarding the life cycle CO_2 emissions is given (International Organization for Standardization (ISO), 2006a):

$$GHG_{lifecycle} = CO_2emissions_{manufacturing} + CO_2emissions_{functional} \tag{3}$$

2.5.4. Lifecycle cost

Regarding the financial evaluation of the renovated systems, the lifecycle cost (LCC) is calculated according to ISO 15686-5 (International Organization for Standardization (ISO), 2017). More specifically, this economic assessment methodology considers all projected significant cost flows over the life cycle period, expressed in monetary value. The LCC is defined as below (International Organization for Standardization (ISO), 2017):

$$LCC = \text{Capital Cost} + \text{O\&M Cost} + \text{Fuel Cost} \tag{4}$$

Regarding the data for the calculations of the CO_2 emissions, references (Ilgin and Gupta, 2010) (https://www.dapeep.gr/viosimi-anaptixi/energeiako-meigma/) (https://www.carbonfootprint.com/) have been used. The cost of the fuels and other devices have been selected to be representative of Greece according to the Refs. (https://ec.europa.eu/eurostat/databrowser/view/ten00118/default/table?lang = en) (https://energy.ec.europa.eu/data-and-analysis/weekly-oil-bulletin_en) (https://ec.europa.eu/eurostat/databrowser/view/ten00117/default/table?lang = en). In this work, the lifespan of the investment was set to 25 years. Table 7 includes the basic data for the performed economic analysis. Regarding specific CO_2 emissions, the specific emission factors were 0.0458 kg_{CO2}/kWh for natural gas, 0.2662 kg_{CO2}/kWh for oil and 0.41 kg_{CO2}/kWh for electricity.

For the purposes of the current study, proper installation and replacements, for the various system components individually, have been selected to be applied both for the baseline and the renovation scenario. In the baseline scenario, a heat pump replacement by the 6th and 17th year, a solar collector replacement by the 16th year, a boiler-tank

Table 7
Basic data for the financial investigation.

Device/energy source	Specific cost
PV panel	1127 €/kW
BIPV	6000 €/kW
Heat Pump	258 €/kW
Solar thermal collector	100 €/m^2
K-FLEX insulation panel (30 mm)	543 €/m^3
Expanded polysterene insulation	90 €/m^3
Iron hot water tank	6 €/Lt
Microventilation	1560 €/(m^3 air change per minute)
Natural gas price	0.0483 €/kWh_{th}
Oil price	0.1054 €/kWh_{th}
Electricity price (import)	0.20 €/kWh_{el}
Electricity price (export)	0.25 €/kWh_{el}

replacement by the 11th year and an aluminum glazing replacement by the 23rd year, have been considered. In the renovation scenario, the heat pump is assumed to be replaced by the 11th and 22nd year, the solar thermal collectors by the 16th year and the hot water tank by the 21st year.

It is important to state that the calculations regarding the greenhouse gas emissions life cycle and the lifecycle cost were performed with the VERIFY software platform (Seitaridis et al., 2022), which was coupled properly with the INTEMA.building tool. More specifically, INTEMA. buildings feeds the VERIFY tool with the required time series data of the energy demands (electricity, oil, natural gas) and respective power production profiles (either from local RES and/or the main grid), as well as with other critical parameters of the building envelope (e.g., material quantities) for each of the energy system configurations examined.

3. Results and discussion

Section 3 includes the obtained results of the simulation regarding the case study of the multi-family building in Moschato. Subsection 3.1 presents the results of the baseline scenario (existing situation), while Subsection 3.2 presents the results of the renovation scenario. In the end, Subsection 3.3 gives a detailed discussion of the obtained results. It has to be added that the present simulation has been conducted with a nominal time step of 1 min, which is adjustable during the solution process (down to even 1 s, for the specific calculations) in order to follow the system performance and to satisfy the time events that occur due to sharp events (e.g., changes in the signals of the control systems).

3.1. Baseline scenario

Fig. 6a depicts the variation of the time series of the heating and cooling loads, while Fig. 6b depicts the cumulative loads for the baseline scenario. The yearly heating load demand is calculated to be around 90890 kWh, while the cooing of around 67573 kWh. These values correspond to a specific heating demand of 151.5 kWh/m^2 and to specific cooling demand of 112.6 kWh/m^2. These numbers are relatively high because the examined building is a non-insulated one, with poor-performing windows and generally without an energy-efficient design. Moreover, the maximum cooling and heating load of the building is calculated at 75 kW$_{th}$, which is a relatively high value. It is also important to refer that the cooling period for the examined building starts on the 11 of May and till the 21 of October, while the heating period starts on the 23 of October up until the end of April. Consequently, there are some small periods, during April and October, which do not require the operation of the heating/cooling systems.

The next step is to present the separate energy behavior of characteristic apartments, which use different energy systems, as aforementioned. In this direction, three different cases have been selected to be presented to cover all possible cases. More specifically, Fig. 7 concerns the B1 apartment, which uses a natural gas boiler for heating and a heat pump for cooling, Fig. 8 concerns the B2 apartment with a reversible heat pump for cooling and heating, while Fig. 9 concerns the B3 apartment with oil boiler for heating and heat pump for cooling. The rest apartments use reversible heat pumps for covering both cooling and heating needs, therefore it is considered that they have similar behavior to the B2 apartment (Fig. 8).

Fig. 7 reveals that apartment B1 consumes 9584 kWh of natural gas

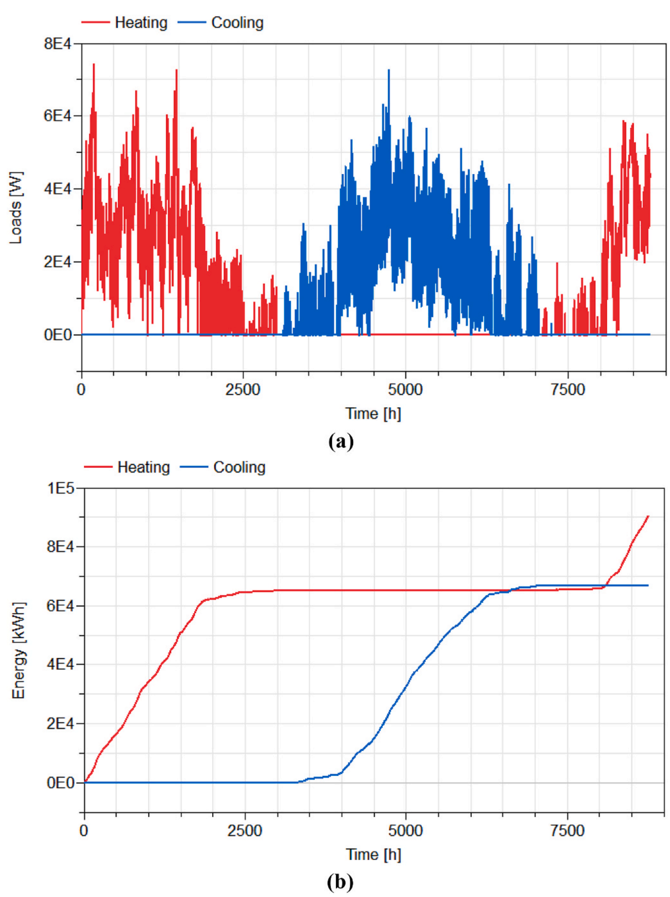

Fig. 6. Yearly heating and cooling demands of the building (8 apartments) for the baseline (a) Instantaneous loads and (b) Cumulative loads.

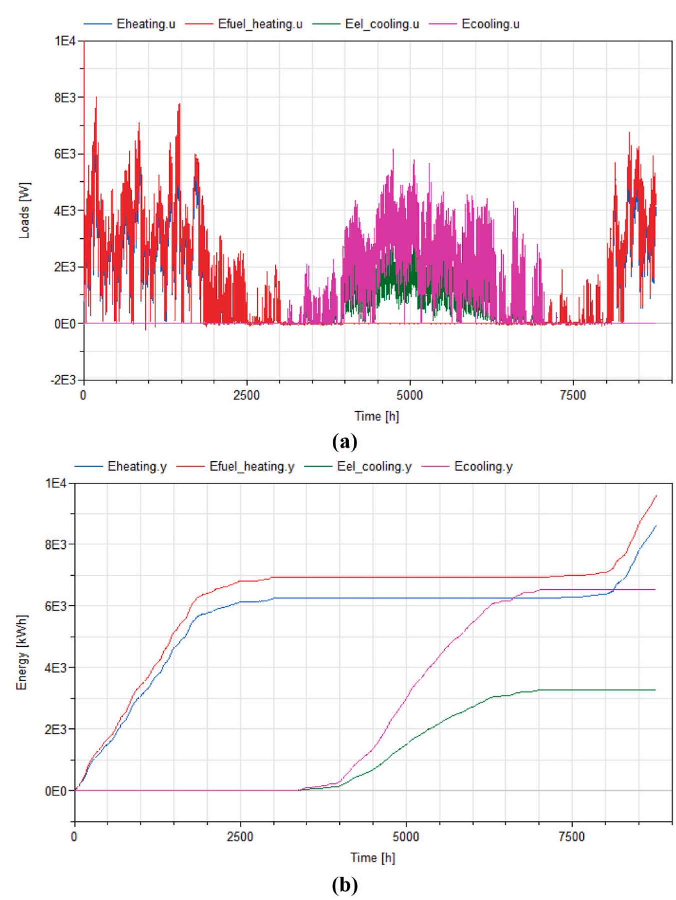

Fig. 7. Yearly heating and cooling demands of the B1 apartment (Natural gas Boiler for heating and Heat pump for cooling) for the baseline (a) Instantaneous loads and (b) Cumulative loads.

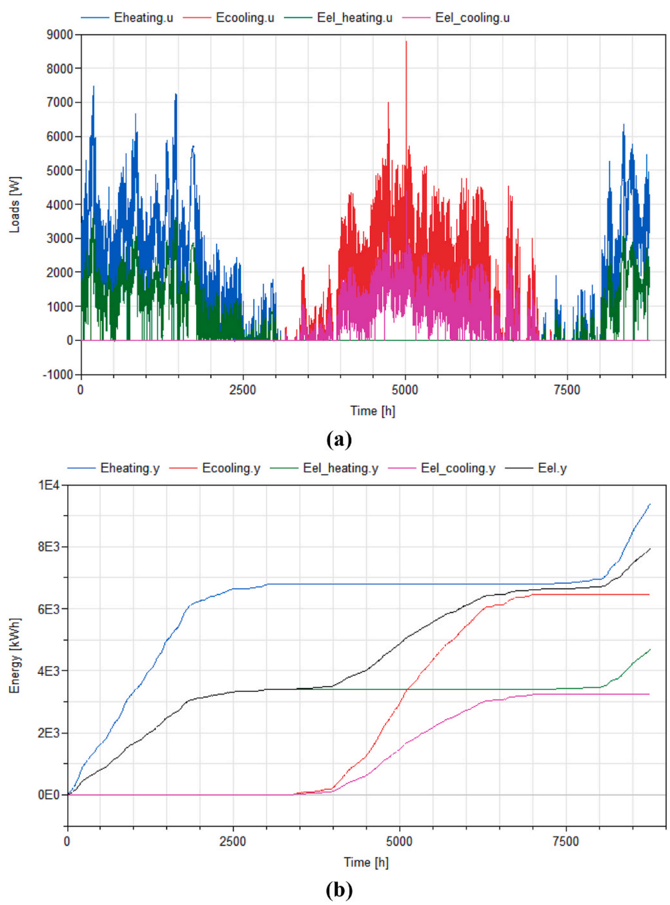

Fig. 8. Yearly heating and cooling demands of the B2 apartment (Heat pump for heating and cooling) for the baseline (a) Instantaneous loads and (b) Cumulative loads.

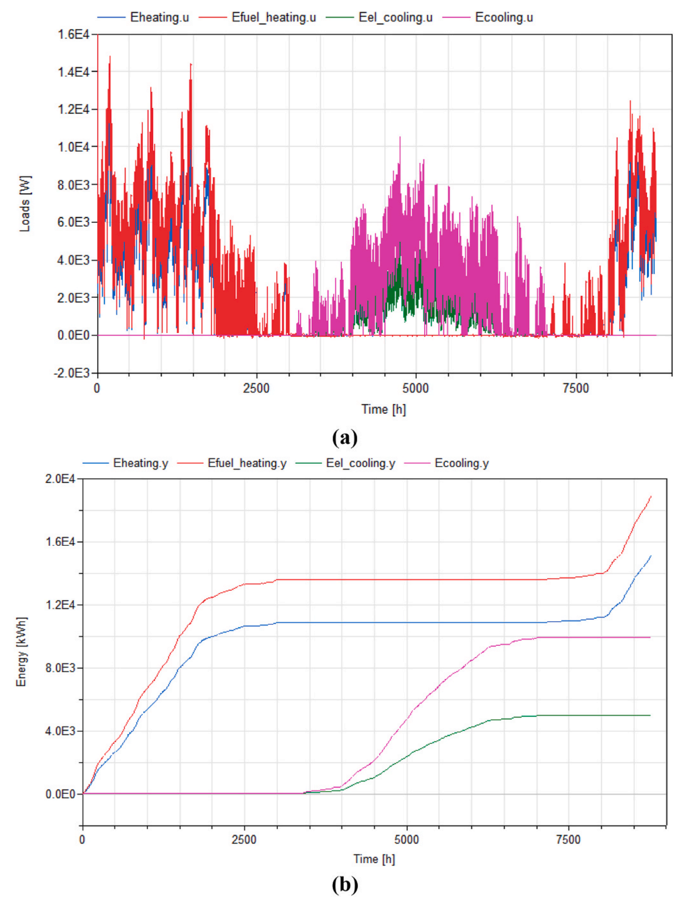

Fig. 9. Yearly heating and cooling demands of the B3 apartment (Oil Boiler for heating and Heat pump for cooling) for the baseline (a) Instantaneous loads and (b) Cumulative loads.

for covering its heating and 3269 kWh for covering its cooling needs. The maximum heating load is up to 8 kW_{th}, while the maximum cooling load is up to 6 kW_{th} approximately. Fig. 8 shows that the total electricity demand of the heat pump for covering both the heating and cooling loads of apartment B2 is 7931 kWh. The maximum heating load is calculated at 7.5 kW_{th} and the maximum cooling load is at 8.8 kW. Fig. 9 indicates that the oil demand is 18879 kWh for covering the heating needs and the electricity demand is 4951 kWh for covering the cooling needs of apartment B3. The maximum heating load is approximately 15 kW_{th}, while the maximum cooling load is around 10.5 kW_{th}. The aforementioned results show that every apartment has very different energy demands expressed in terms of oil, natural gas and electricity, according to the used equipment as well as its relative location in the building. Moreover, the different thermal behavior of every apartment makes the investigation of every apartment separately, and therefore treated as a separate thermal zone, necessary.

Table 8 summarizes the results for all the apartments and for the entire building in terms of thermal loads, energy demands and primary energy demand. More specifically, the total heating load is 90890 kWh, ranging from 8625 kWh up to 15011 kWh for the separate apartments. Moreover, the cooling load is 67573 kWh ranging from 5161 kWh up to 13571 kWh for the separate apartments. The variation among the thermal loads of the apartments is explained by various factors, such as the direction of the external walls, the type of windows, as well as the floor. More specifically, the first and the second floors have reduced thermal loads, because they have lower external surfaces and thus fewer thermal losses during winter and thermal inputs during summer. Moreover, the ground floor has increased loads, because the basement is not insulated, and this is a reason for selecting the addition of insulation under the ground floor in the renovation scenario. Thus, it can be said that the external area of every apartment plays a significant role in the thermal load demand.

The oil boiler is used only by apartment B3 and so the oil demand is calculated at 18879 kWh. Moreover, the natural gas demand is very small at 9584 kWh because only the B1 apartment currently uses natural gas, while this apartment has relatively low heating needs. The rest of the apartments use heat pumps for covering the heat demand and thus they consume electricity. At this point, it is interesting to state that the used bills for the natural gas consumption of the B1 apartment indicate that the yearly consumption is 9175 kWh, which is close to the calculated value of 9584 kWh, presenting a deviation of 4.46% which is an acceptable value. This result indicates that the estimation of natural gas consumption is performed with an error lower than 5%. Conversely, there was not sufficient data regarding the electricity bills and thus a respective comparison with the simulation results is not included in this study.

The cooling of all the apartment needs is covered by the heat pumps; thus, there is electricity demand in order to keep the indoor temperature level at the desired levels. The existing heat pumps have relatively low efficiency, because they are old and inefficient, with the total electrical demand being calculated at 67411 kWh.

The primary energy demand of the total building is calculated at 226322 kWh, while the respective primary energy of the apartments varies between 19543 kWh for the B1 and 35786 kWh for the A3 apartment. The apartments on the ground and 3rd floor are the most energy-intensive among all, according to the results. The primary energy demand for electricity is 195492 kWh and it is 86.4% of the total primary energy demand. On the other hand, the primary energy demand

Table 8
Energy demands for heating/cooling of the baseline scenario in [kWh].

	Thermal Loads		Energy demand			Primary energy demand
Apartments	Heating	Cooling	Oil	Natural Gas	Electricity	
A0	11618	12123	0	0	11870	34423
B0	10771	13571	0	0	12170	35293
A1	8770	5195	0	0	6983	20251
B1	8625	6537	0	9584	3269	19543
A2	10633	5161	0	0	7897	22901
B2	9391	6471	0	0	7931	23000
A3	16071	8608	0	0	12340	35786
B3	15011	9907	18879	0	4951	35125
Total	90890	67573	18879	9584	67411	226322

for oil is 20767 kWh and for natural gas 10063 kWh corresponding to 9.2% and to 4.4% respectively. These results are reasonable because only one apartment uses an oil boiler and only one uses a natural gas boiler, while the other apartment consumes electricity through heat pumps and also the cooling loads are covered by heat pumps.

The next step is the presentation of the simulation results of the baseline scenario regarding the coverage of the demand for DHW. Four apartments (A0, B0, B2, A2) use electrical heaters for covering the needs of DHW, while the rest (A1, B1, A3, B3) use solar thermal systems. It is notable that the apartments with solar collectors use electricity as an auxiliary energy source.

The DHW demand was assumed to be the same for all the apartments and its variation is depicted in Fig. 10a. Also, Fig. 10b shows the solar contribution and the boiler operation for one apartment with solar thermal collectors. The yearly solar coverage is calculated at around 77% and the remaining part is covered with an electrical demand of 238 kWh. These results indicate a significant reduction in electricity demand due to the exploitation of the incident solar energy on the roof collectors. It is also important to highlight that during the summer, the backup electrical resistance in the boiler has no contribution to hot water production because the solar collectors can successfully cover the thermal demand. During the winter, the solar collectors present a solar coverage of around 50%, which is also a satisfying result for the particular climate conditions.

During the year, the DHW demand of the building (8 apartments) reaches 256 m^3, in total, while the electrical demand is 5072 kWh. The respective primary energy demand for covering the electricity needs is calculated at 14709 kWh. The average solar coverage of the building is calculated at 37.1%, for all the apartments. Table 9 summarizes the main results regarding the DHW production analysis for the baseline scenario.

Moreover, the present building has a significant electricity demand for covering the needs for lighting and appliances. This electricity demand was estimated at 33302 kWh on a yearly basis. The respective primary energy demand was calculated at 96576 kWh. This is a rather high demand value, revealing that there is a potential for reducing it and/or covering a part of it, with the use of renewable electricity, from photovoltaics.

Table 9
Summary of the DHW results for the baseline scenario.

Parameters of DHW	Baseline case
Yearly volumetric demand for domestic hot water (m^3)	256
Yearly energy demand for domestic hot water (kWh)	8064
Electricity demand (kWh)	5072
Useful heat from solar energy (kWh)	2992
Total solar coverage	37.1%
Primary energy demand (kWh)	14709

Table 10
Summary of the energy demand for the baseline scenario.

Parameter	Value (kWh)
Electricity demand	105785
Natural gas demand	9584
Oil demand	18879
Primary energy demand for heating	132406
Primary energy demand for cooling	93917
Primary energy demand for appliances/lighting	96576
Primary energy demand for hot water	14709
Total primary energy demand	337607

Table 10 includes the data regarding the electricity, natural gas and oil demand, as well as the primary energy demand for heating, cooling, DHW and appliances/lighting. The total primary energy demand is 337607 kWh and the main contributor to this demand is heating with a percentage of 39.2% (132406 kWh). The appliances/lighting demand follows with 28.6% (96576 kWh), the cooling with 27.6% (93917 kWh), while the DHW demand is responsible only for 4.4% (14709 kWh) of the total primary energy demand.

3.2. Renovation scenario

The renovation scenario aims to reduce significantly the heating and cooling needs of the examined building by a great percentage. Also, the incorporation of photovoltaics aims at covering all electrical demand and providing net electricity to the grid through a net-metering

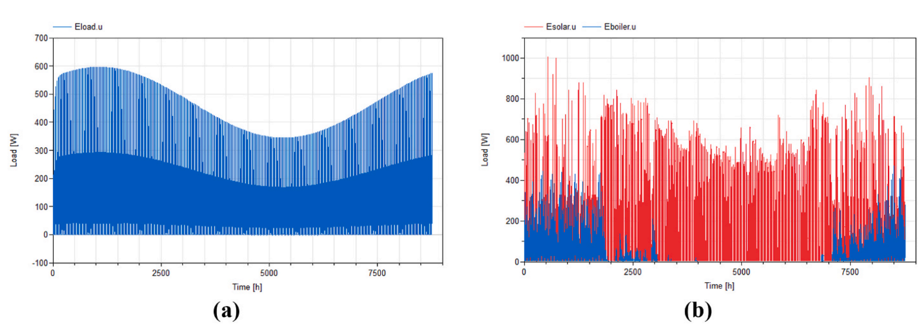

Fig. 10. (a) Yearly load variation for DHW of one apartment, (b) Boiler demand and solar useful production for the apartments (A1, B1, B3, A3).

Table 11
Summary of the results of the renovation scenario.

Parameter	Value (kWh)
Heating load	6441
Cooling load	14624
Electricity demand for heating	2147
Electricity demand for cooling	2925
Electricity demand for DHW	1080
Electricity demand for appliances and lighting (other needs)	13321
Total electricity demand	19473
Electricity production from PV on the roof	24388
Electricity production from BIPV on the south-east side	367
Total Electricity production from PV	24755
Net electricity production after covering heating/cooling demand	19683
Net electricity production after covering heating/cooling & DHW demand	18603
Net electricity production to the grid after all demands	5282

connection.

The annual energy quantities of the renovated case are presented in Table 11. The heating load was calculated at 6441 kWh, which is significantly reduced by 93% compared to the baseline scenario, for which the heating load is calculated at 90890 kWh. Regarding the cooling, the load is calculated at 14624 kWh reduced by 78% compared to the baseline scenario of 67573 kWh. The reported reductions are significant and they are a result of retrofitting the building envelope with insulation of high thickness, substituting conventional windows with triple-glazed windows, as well as controlling the ventilation with a system with heat recovery. The renovated building presents significantly low thermal demands.

The electricity demand for cooling is calculated at 2147 kWh and for heating at 2925 kWh, while the electricity demand for the DHW was calculated at 1080 kWh. It should be noted that the electricity demand for the DHW is relatively low because new solar systems were installed for all the apartments by using advanced highly efficient flat plate collectors. The solar coverage is calculated at 86.6%; a high value that indicates the important contribution of solar energy to the coverage of the DHW demand. Regarding the electricity demand for the appliances/lighting, it was calculated at 13321 kWh, significantly reduced due to the use of new and highly efficient equipment, especially for lighting purposes.

The use of photovoltaic panels on the roof leads to 24388 kWh of electricity production, while the use of BIPV on the southeast side leads to 367 kWh of electricity production. Thus, the total electricity production was calculated at 24755 kWh, which is a significant amount of produced electricity. The net electricity production, after the coverage of heating/cooling needs, is calculated at 19683 kWh, while after the coverage of heating/cooling and DHW was calculated at 18603 kWh. Considering all the electricity needs, including the demand for appliances/lighting, it can be seen that the produced electricity by the PV is able to cover 100% of the total electrical demand with an excess of 5282 kWh of electricity sold to the grid. Therefore, it is important to highlight that the suggested renovation scenario results in a positive energy building with significantly reduced demands for covering its needs.

Table 12 gives the demand values for both scenarios, as well as the percentage reduction. It is important to highlight that these results do not take into account the exploitation of the PV, which can cover all the needs and leads to a zero-energy building with 5282 kWh net electrical production to the grid. Thus, these results emphasize the impact of the other renovation actions except that of PV inclusion. Regarding heating, the total primary energy demand is reduced from 132406 kWh to 6226 kWh presenting a reduction of 95%, while for cooling the primary energy demand was reduced from 93917 kWh to 8483 kWh, presenting a 91% reduction. The primary energy demand for the DHW was 14709 kWh for the baseline scenario and it was reduced to 3132 kWh, presenting a reduction of 79%. The electricity reduction for the appliances lead to a reduction in the primary energy demand of 60% and more specifically from 96576 kWh for the baseline scenario to 38630 kWh for the renovation scenario. The total primary energy demand for the renovated case was calculated at 41762 kWh reduced by 88% compared to the baseline scenario with 337607 kWh. The aforementioned values indicate a significant reduction in terms of primary energy which is a very important indicator of sustainability. In other words, the primary energy reduction proves that there are important energy savings in the building which can be 88% of the initial energy demand.

Table 12
Final assessment of the renovation scenario compared to the baseline scenario in terms of primary energy without the exploitation of the PV electricity.

Parameter	Baseline (kWh)	Renovation (kWh)	Reduction
Energy demand	337607	41762	88%
Heating demand	132406	6226	95%
Cooling demand	93917	8483	91%
DHW demand	14709	3132	79%
Appliances/lighting demand	96576	38630	60%

The distribution of the primary energy demand for covering the energy needs for both scenarios is given in Fig. 11. It is clear that the main primary energy demand for the baseline scenario is the heating need at 39.2%, while the respective need is only 11% for the renovation scenario. This fact indicates that the renovation actions lead to a significant improvement in the heating primary energy demand. Also, it is useful to state that the primary energy demand for cooling was reduced from 27.8% for the baseline scenario to 15% for the renovation scenario, following a similar reduction trend with the heating need. The DHW demand presents low values in both scenarios around 5%. On the other hand, the primary energy demand percentage over the total energy demands, increases significantly as concerns the appliances/lighting for the conditions representing the renovation scenario (68.4%), compared to the baseline case (28.6%). This is logical since the renovation actions do not lead to an important reduction in the electrical load from appliances and lighting. However, it should be noted that the aforementioned analysis does not include PV electricity production, which can be used as a renewable power source for them.

At the end of this subsection, it is essential to present results about the dynamic behavior of the systems according to the simulations with the INTEMA.building tool. Fig. 12 shows the yearly variation of the total electricity demand (appliances, lighting, DHW, heating and cooling), as well as the PV production from all the assumed PVs. It is obvious that the production peak is significantly higher than the demand peak. Moreover, the energy demand is higher during the winter period, than in the summer, indicating the potential to store the excess electricity produced during summer, during which the PV production peak is tracked, for potentially covering winter demands. This fact indicates that the use of a storage system (e.g., batteries) would be beneficial in the case that there was not a net-metering connection as in the present study case. Moreover, the capacity of this storage system and its design characteristics have to be optimized by taking into account the demand and the production profiles. Another option is to investigate a demand response strategy aiming to reduce the electricity demand during peak periods and to shift it in the period with available solar irradiation potential.

Fig. 13 depicts the net difference between production and demand. This figure shows that in the first period of the year (up to 20 March approximately), the building needs electricity from the grid in order to cover the demand. After this period, the building becomes a positive energy one and it starts to cover all its needs and produce also net electricity for the grid. On the 5 of May, the system produced enough net electricity in order to cover all the grid demand up to this period. The next part of the year is the most productive and the PV system produces significant amounts of electricity up to 15 September. In the period from mid-September up to 25 October, the system produces approximately the same amount of electricity to cover its demands, while for the rest of the year the building imports electricity from the grid. Over the whole

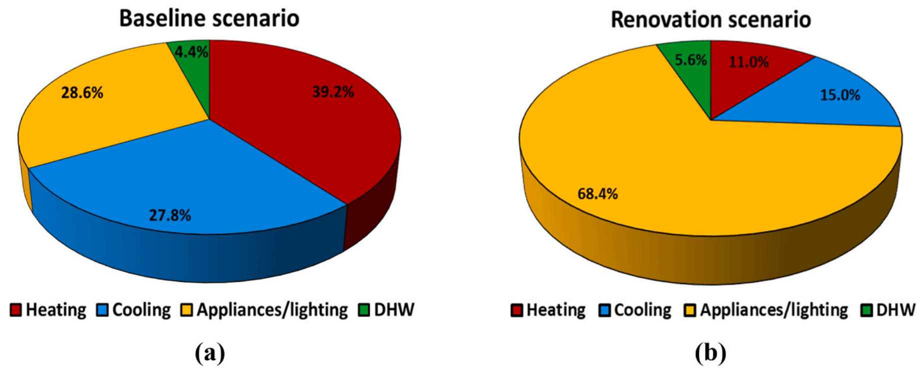

Fig. 11. Primary energy distribution for (a) the baseline scenario, and (b) the renovation scenario (without the exploitation of the PV electricity).

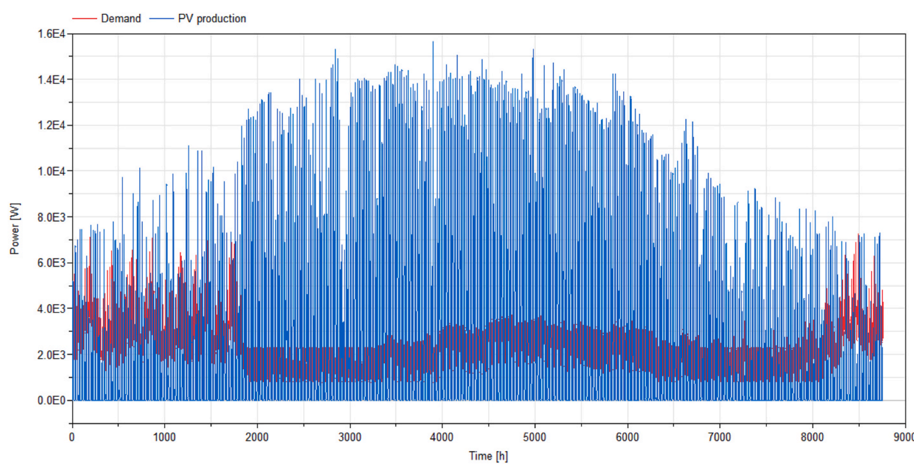

Fig. 12. Total electricity demand and PV production during the year for the renovation scenario.

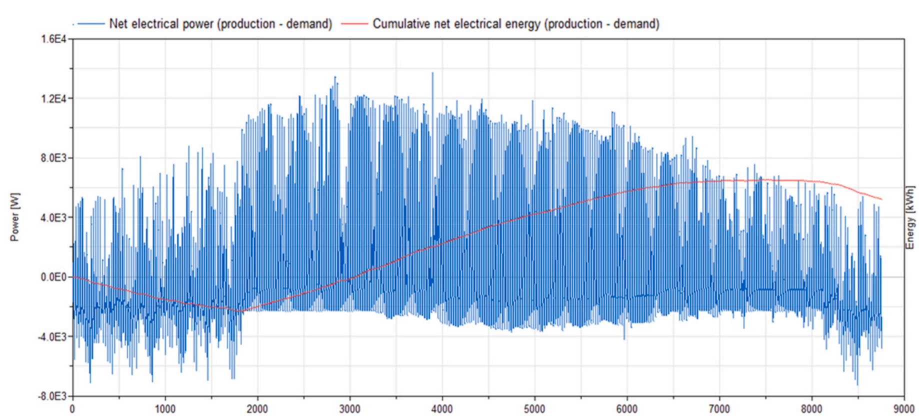

Fig. 13. Net electricity (production minus demand) of the examined building for the renovation scenario.

year, the building produces net electricity for the grid and thus the renovated building has the potential to act as an energy-positive one if the renovations are applied. More details about this conclusion are given in Fig. 14, which depicts the cumulative energy production from the PV, the total demand and the net result to the grid. It is important to state that the building produces 23.9% higher electricity than the electricity demand.

3.3. Life cycle analysis

The next step includes the calculation of the economic and environmental benefits of the renovation scenario by using a life cycle analysis. Using the VERIFY platform with the presented methodology in subsection 2.5, the lifetime CO_2 savings, the lifetime cost savings and the investment payback period were calculated.

Fig. 15 depicts the yearly and cumulative cost savings that were calculated with the LCC analysis. It is obvious that at the end of the lifetime (25 years), the total cost savings reaches 622 k€. Also, it is obvious that every year, there is a positive cost-benefit, indicating that the renovation is economically a very attractive solution. The fluctuations in the yearly cost benefits are justified by the equipment replacements during the project's lifetime. According to Fig. 15, the

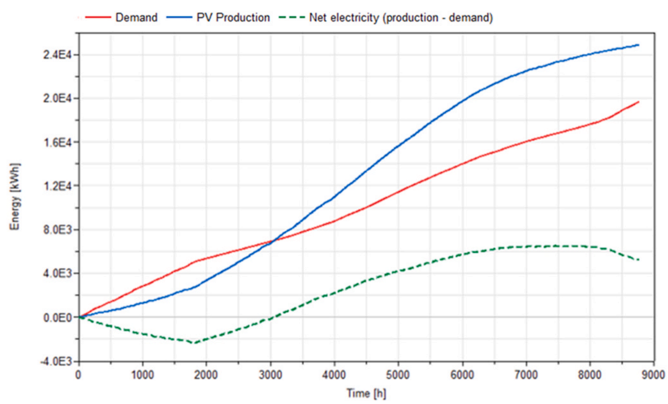

Fig. 14. Yearly variation of the cumulative electricity demand and PV production, as well as of their difference (Production minus demand) for the renovation scenario.

payback period of the initial investment cost was calculated close to 3.8 years, which implies the economic viability of the present renovation scenario.

Fig. 16 illustrates the CO_2 savings over the years, as a result of the renovation examined. The final CO_2 savings after the 25-year period were calculated at 1585 CO_2 tones; a relatively large quantity of environmental emissions gains. Generally, the yearly CO_2 avoidance has no great fluctuations and there is a significant environmental benefit all the years of the present investment.

3.4. Discussion of the results

The renovation scenario of the building in Moschato concludes that the highest reduction in the heating and cooling loads results from the use of high insulation, energy efficient triple glazed windows and heat recovery units for the ventilation system, among the multiple retrofitting interventions examined. More specifically, the specific heating demand was reduced from 151.5 kWh/m^2 down to 10.7 kWh/m^2, while

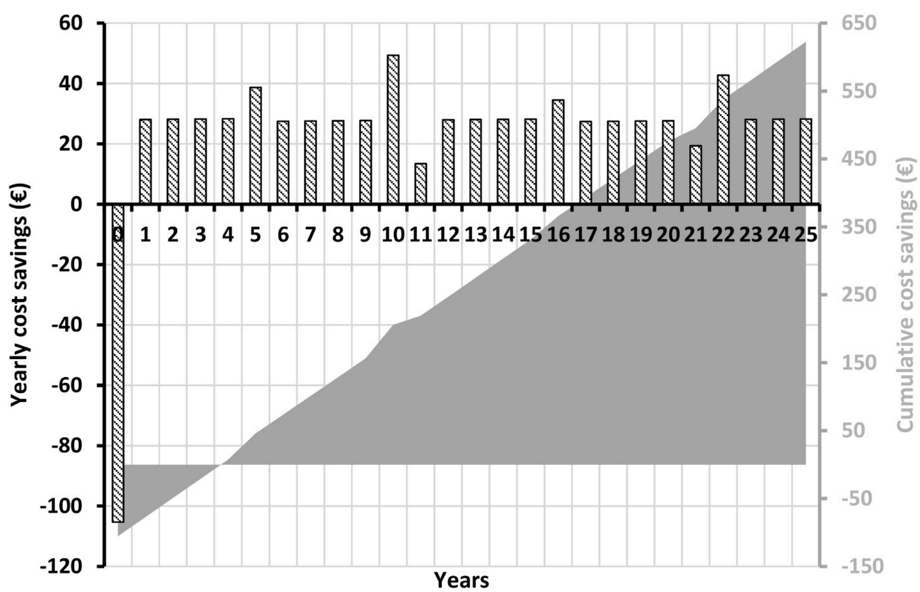

Fig. 15. Yearly and cumulative cost savings for the renovation.

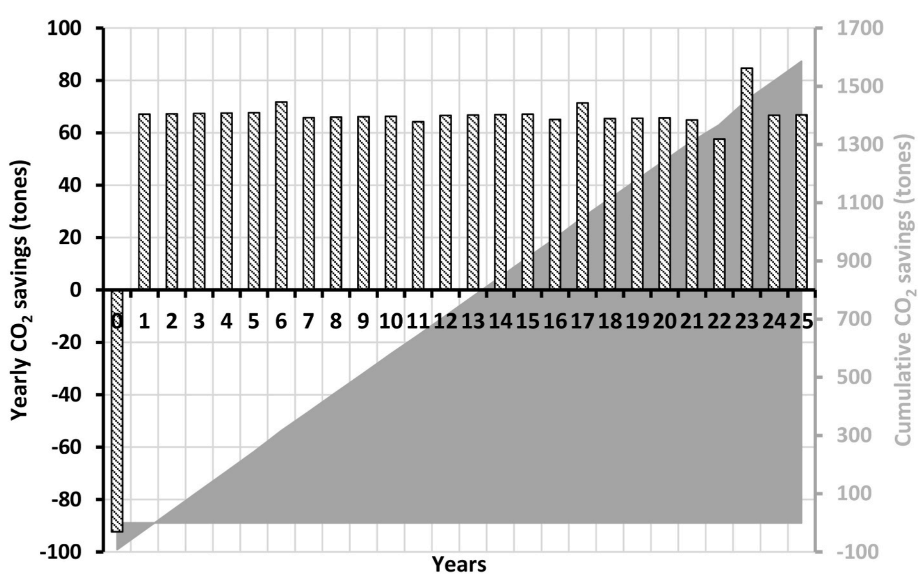

Fig. 16. Yearly and cumulative CO_2 savings for the renovation.

the cooling specific demand was reduced from 112.6 kWh/m^2 to 24.4 kWh/m^2. The specific primary energy demand was calculated at 562.7 kWh/m^2 for the baseline scenario and 69.6 kWh/m^2 for the renovation scenario. Therefore, the reduction of the heating load was calculated at 93%, for the cooling at 78% and for the primary energy at 88%. It is clear that the present renovation, which combines multiple retrofitting options, toward achieving a deep retrofit can be regarded as an effective one with a significant reduction in the heating and cooling load.

It is important to state that among the retrofits examined, for at least the level of electricity demand reduction, the installation of advanced heat pumps (combined with the vast reduction of the heating loads), and the installation of advanced selection flat plate collectors for all the apartments, are very important factors. Moreover, the appliances/ lighting needs are reduced with the installation of new and efficient equipment, by almost 60% on top of the previous one. The use of photovoltaics, both on the rooftop and BIPV at the side walls of the building, made possible the coverage of all the electricity needs of the buildings, as well as the production of a significant net amount for the grid; fostering buildings to act as an active energy node of the energy market.

Lastly, the life cycle assessment indicated significant enhancements in terms of cost savings and CO_2 emissions avoidance. Specifically, the total cost savings is around 622 k€ which is an important amount, while the payback period of 3.8 years indicates an acceptable renovation scenario that can be an attractive choice. The CO_2 emissions avoidance of 1586 tons of CO_2 for a period of 25 years shows that the environmental gain is high and it adds an extra benefit that has to be included in the overall evaluation of the studied renovation scenario.

Another useful point that has to be highlighted regards the applicability of the results in other buildings in the same area. The examined case study can be considered strongly replicable since all of the examined retrofits include off-the-self systems, mature enough to be used in real-life conditions. More specifically, according to the Hellenic Statistical Authority (https://www.statistics.gr/el/census-buildings-2011, 2011), there are 17659 buildings with 3–5 floors in the Attica, which have been built in the same decade as the current building. So, the potential for applying the present results in other neighboring buildings is great and increases the value of the extracted conclusions. Also, it is possible to generalize the present results and conclusions for residential buildings in the EU and especially Southern Climate conditions, in which solar irradiation potential and ambient temperature variations do not deviate much from those of Athens. It is also useful to state that the results of this work present high accuracy with an average error of up to 4% as it has been calculated through the verification processes in section 2.2. So, the results are reliable and they can lead to robust conclusions that can be used for the renovation of existing buildings.

Concerning the replication of the results, in other buildings, some critical key parameters can be provided, aiming to describe briefly the main outcomes of the examined case study. The examined building has a ratio of the external surface to the volume of 0.506 m^2/m^3 and the mean thermal transmittance of the total envelope is 3.91 W/m^2K for the baseline scenario. The renovation scenario reduced dramatically the mean thermal transmittance of the total envelope down to 0.602 W/m^2K, which is an acceptable value for the renovation study presented, according to Greek legislation. More specifically, for the climate conditions of Athens (Greek climate zone B), the maximum allowable limit for the mean thermal transmittance of the total envelope is 0.93 W/m^2K (Greek Technical Chamber TOTEE, 20701-1, 2017) for an external area/volume ratio of 0.506 m^2/m^3.

Regarding the heat pump installation in the renovation building, the ratio of the nominal power to the load yearly demand was calculated at 1.242 W/kWh for heating and 0.684 W/kWh for cooling. The incorporation of the PV led to the production of 23.9% higher than the total electricity demand of the renovated budling including appliances lighting, heat pump and DHW electrical resistances. Such dimensionless, as presented, renovation interventions, can be of help and support to Architects, Engineers and Constructors (AECs) to have an idea of the expected benefits, for at least climatic conditions similar to that of Athens.

Regarding the limitations of the present work, it has to be commented that typical profiles for the occupancy and the operation of the appliances and lighting have been used according to the literature in order to conduct a reasonable simulation. Also, the selected values for the specific loads have been selected according to Greek legislation. However, these profiles cannot be the same as in real operation due to unexpected phenomena in the daily behavior of the users. However, the deviations of the selected operation profiles compared to the real ones cannot lead to significant deviations in the energy results because the results of this work have been compared with existing data for the natural gas consumption and the electricity consumption in some apartments and it was found that there are no deviations over 5%. Thus, it is clear that the use of typical operation profiles can lead to reasonable and acceptable results and the limitation that was described has not an important influence on the conclusion of the present study.

In the future steps, the present tool will be improved by introducing grey-box models in its libraries which exploit existing data from the literature or from measurements. This fact will lead to data-driven approaches that aim to convert the white-box models into grey-box models with higher accuracy. More specifically, the grey box models will exploit data regarding the occupancy in residential and commercial buildings, as well as the performance of energy systems like heat pumps and boilers. The goal is to extend the existing INTEMA.building libraries by developing components that are able to describe with high accuracy the behavior of the examined buildings by using the physical models coupled with real data that describes every case separately.

4. Conclusions

Retrofitting the existing energy-intensive buildings is a key factor for achieving Sustainable Development Goals and also reducing significantly the environmental impact of the building sector. The present study introduces a series of critical renovation techniques for a typical old Greek building with 8 apartments which lead to significant energy savings. The investigation is conducted with a newly developed tool, INTEMA.building, which provides the opportunity for a detailed dynamic analysis of the building energy behavior, followed as well by the calculation of key environmental indices. The present tool is developed in the Dymola environment using the Modelica modeling language. It includes two basic libraries named "Building Envelope Model" and "Energy Systems", which include the possible repository of passive and active systems that INTEMA.building offers, whilst at next steps are linked and feeding with data, the VERIFY tool; both designed to be interoperable, aiming at supporting more holistic planning of building renovation processes. The most useful conclusions of this work can be summarized in the next bullets:

- Numerous renovation techniques were examined, including the inclusion of external insulation of the building, the installation of triple windows, the use of a heat recovery ventilation system, the use of advanced selective solar thermal systems for DHW, the installation of roof-mounted PV and BIPV, as well as the reduction of the electrical demand of the appliances/lighting with the proper replacement of the existing devices with more efficient ones. Based on the calculations, the heating load was reduced by 93% and the cooling load by 78%.

- In terms of primary energy demand, the reduction of the heating demand is calculated at 95%, the cooling at 91%, the DHW at 79% and the appliances/lighting demand at 60%. The primary energy reduction is higher than the reduction of the loads due to the synergetic enhancement of both envelope improvement and energy systems retrofitting. Overall, the primary energy demand was reduced by about 88% in the renovation case compared to the baseline case.

- Regarding the utilization of renewable energy systems, the installation of the photovoltaic panels allowed possible the coverage of all the building(s) needs (heating, cooling, DHW, electricity) and produced

24% higher electricity compared to the total energy demand of the renovated building. Also, the installation of advanced solar thermal collectors led to a 79% reduction in the electricity demand for DHW, while the solar coverage reached up to 87% in the renovated building.

- During the lifetime of the renovation case, the life cycle CO_2 savings are calculated at 1586 tons of CO_2, while the life cycle cost analysis indicated 562 k€ savings due to the renovation techniques for the lifespan of 25 years. Also, the payback period of the renovation was estimated close to 3.8 years. Practically, it was calculated that the specific CO_2 avoidance per renovated floor area was 2.64 tons CO_2/m^2, the specific lifecycle gains 1037 €/m^2 and the specific primary energy savings equal to around 12.3 MWh/m^2.

In the future, the INTEMA.building libraries will be improved by incorporating data-driven approaches and developing grey models for simulating properly the occupancy profiles in the buildings and also for estimating with higher accuracy the energy performance of the used systems.

CRediT authorship contribution statement

Evangelos Bellos: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Petros Iliadis:** Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Christos Papalexis:** Methodology, Software, Writing – original draft. **Renos Rotas:** Methodology, Software, Writing – original draft. **Ioannis Mamounakis:** Conceptualization, Methodology, Software, Writing – original draft. **Vasileios Sougkakis:** Resources, Project administration, Writing – original draft. **Nikos Nikolopoulos:** Conceptualization, Resources, Supervision, Writing – original draft, Writing – review & editing. **Elias Kosmatopoulos:** 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.

Acknowledgments

This work has been carried out in the framework of the European Union's Horizon 2020 research and innovation program under grant agreement No. 892071 (An augmented intelligence-enabled stimulating framework for deep energy renovation delivering occupant-centered innovations (RINNO)).

Appendix A. Analysis of the control system

The present work uses deterministic control systems which are based on PI controllers and aim to provide adequate heating/cooling in order to achieve the indoor air temperature within the desired limits. More specifically, the control system aims to keep the indoor temperature during the winter at 20 °C, while the goal in the summer is to achieve a maximum temperature of 26 °C. In the system with the reversible heat pumps, there are two PI controllers, one for the heating and one for the cooling season. In the cases with a boiler, there is one PI controller.

It is important to state that every PI controller is properly tuned in order to achieve suitable indoor air temperature distribution during the year. More specifically, different values for the gains and time constants of each PI controller were examined and the indoor air temperature profiles were checked. Figure A1 shows the indoor air temperature profile for the initial case without tuning and for the optimized case after proper sensitivity analysis. It is clear that in the optimized case, the indoor temperature is always between 20 °C and 26 °C, something that verifies the selection of the present control strategy. On the other hand, in the initial design without tunning, there are errors of around 0.2 K both in the heating and cooling periods.

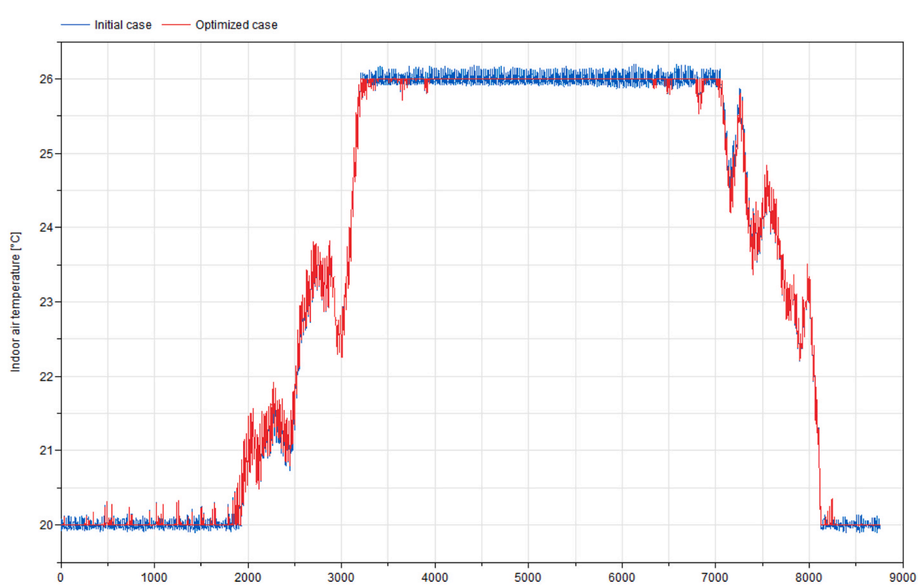

Fig. A1. Indoor air temperature distribution for the initial case without control tunning and for the optimized control tuning (PI control for the renovation case with reversible heat pump)

Moreover, the selected PI control system was compared with another usual configuration which includes hysteresis components with a deadband equal to 1 K. Figure A2 shows the comparison of the indoor air temperature for both cases. It is obvious that the use of the hysteresis components leads to a deviation of around 0.5 K between the indoor temperature and the target temperature, something that indicates that this control system is inferior. Thus, it is proved that the PI control is a suitable choice for achieving the desired indoor temperature and it is a better one compared to other usual solution.

It is remarkable to state that the present work uses typical meteorological year (TMY) weather data. In this manner, the control systems have been tested under representative conditions and thus they were found to be reliable choices. In other words, the present control system is a suitable one to follow the realistic variations of the ambient conditions in terms of temperature, solar irradiation, etc.

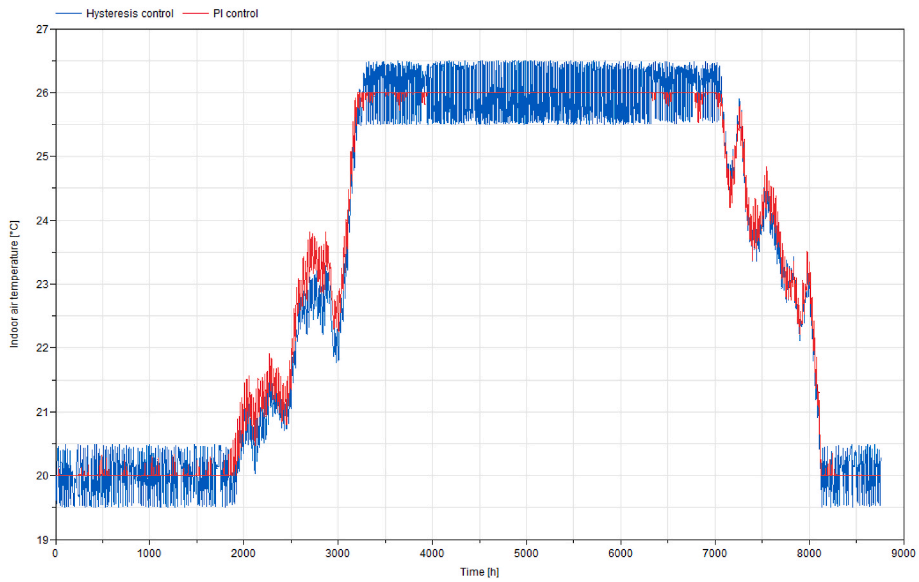

Fig. A2. Indoor air temperature distribution for the case with PI control and Hysteresis control (renovation case with reversible heat pump)

Appendix B. Details of the verification procedure with the TRNSYS tool

The present Appendix includes information regarding the developed model in TRNSYS for the verification procedure. The developed building has a floor area of 100 m^2 (10 m × 10 m) and a height of 3 m. Table B1 includes the details of the envelope's structural elements and the thermal properties of the selected materials.

Table B1
Data of the envelope structural materials of the simulation with TRNSYS

	Thickness	Thermal conductivity	Density	Specific heat capacity
	(cm)	(W/mK)	(kg/m^3)	(J/kgK)
External wall				
Plaster	0.5	0.87	1800	1000
Brick	9.0	0.68	1700	1000
Insulation	8.0	0.035	60	840
Brick	9.0	0.68	1700	1000
Plaster	0.8	0.87	1800	1000
Roof				
Concrete	15.0	1.15	1800	1000
Insulation	8.0	0.035	60	840
Ground				
Concrete	15.0	1.15	1800	1000
Insulation	8.0	0.035	60	840

The infiltration rate was selected at 0.5 ACH, the internal convection coefficient between air and walls at 7.7 W/m^2K and the external convection coefficient between air and walls at 25 W/m^2K. Moreover, the window in the south wall has an area of 4 m^2 including a 20% frame, of thermal transmittance (U) equal to 1.1 W/m^2K and total solar energy transmittance (g) is set to 62%. The floor is assumed to be over the ground and air exist below it (the examined building is located on the first floor. Moreover, no internal gains were used in this scenario. The heating and cooling loads are covered by using a proper reversible heat pump which can be used for all the year period. The setpoints were selected at 21 °C for winter and 26 °C for summer. The reversible heat pump in TRNSYS was designed properly and it has a flow rate of 300 l/s. Table B2 summarizes the main data of the simulation analysis.

The developed system model in TRNSYS utilizes a set of library components. The building was modeled with the Type56 component, the heat pump with the Type119, the heating thermostat with the Type106, the cooling thermostat with the Type113 and the weather data with Type16. Moreover, extra simple components for printing the results (Type65), integrating the results (Type24) and making calculations (equator) were used.

Table B2
Summary of the basic data of the simulation with TRNSYS

Parameter	Value/Description
Height of the building	3 m
Length of the building	10 m
Width of the building	10 m
Location	Athens, Greece (37°58′N, 23°42′E)
Wall directions	Four walls in four directions
Windows	South double window
Window area	4 m^2
Window U-value	1.1 W/m^2K
Window g-value	62%
Infiltration rate	1 air change per hour
Internal gains	No gains
Inside heat convection coefficient	7.7 W/m^2K
Outside heat convection coefficient	25 W/m^2K
Flow rate of the cooled/heated air	300 L/s
Heating temperature setpoint	21 °C
Cooling temperature setpoint	26 °C
Simulation period	All the year - 8760 h

Appendix C. Basic mathematical background of the developed models

Basic equations regarding the developed models and their performance are included in the present appendix.

C.1 Basic equations regarding the building envelope

The thermal transmittance of the structural elements (U-value) of the building (walls, roof, floors) can be estimated according to the next expression (Greek Technical Chamber TOTEE, 20701-1, 2017):

$$U = \frac{1}{\frac{1}{h_{in}} + \sum_{i=1}^{n}\left(\frac{L_i}{k_i}\right) + \frac{1}{h_{out}}} \tag{C.1}$$

where the (L_i) is the thickness of every layer, while the (k_i) is the thermal conductivity of every layer. Totally, there are (n) layers in the examined structural element, while this number is different from element to element. The heat convection coefficients were calculated according to ISO 6946:2017 (ISO 6946:2017, 2017). For example, for the roof, they take the values $h_{in} = 7.7\ W/m^2K$ and $h_{out} = 25\ W/m^2K$ which are also in accordance with Greek Legislation (Greek Technical Chamber TOTEE, 2070).

The thermal transmittance of the window (U_{window}) can be calculated by using the U-value of the glass (U_{glass}), the thermal transmittance of the frame (U_{frame}), the area of the glass (A_{glass}) and the area of the frame (A_{frame}), as below (Greek Technical Chamber TOTEE, 20701-1, 2017):

$$U_{window} = \frac{A_{glass} \cdot U_{glass} + A_{frame} \cdot U_{frame}}{A_{glass} + A_{frame}} \tag{C.2}$$

C.2 Basic equations regarding the energy systems

The next part of the mathematical part regards energy systems. These equations give a suitable description of them in order to explain the followed methodology in a clear way.

Heat recovery system

The heat exchange in the heat recovery system can be described by using the effectiveness of the heat exchanger (η_{hex}) which is defined as below (Zhao and Liu, 2022):

$$\eta_{hex} = \frac{T_{inlet} - T_{amb}}{T_{zone} - T_{amb}} \tag{C.3}$$

where (T_{inlet}) is the inlet temperature in the room from the heat recovery system, (T_{amb}) is the ambient temperature and (T_{zone}) is the temperature of the examined thermal zone.

Solar thermal system

The thermal efficiency of the solar collector (η_{col}) is described by the next formula (ISO, 1994):

$$\eta_{col} = a_0 - a_1 \cdot \frac{T_{f,in} - T_{amb}}{G_T} - a_2 \cdot \frac{\left(T_{f,in} - T_{amb}\right)^2}{G_T} \tag{C.4}$$

where ($T_{f,in}$) is the fluid inlet temperature in the collector and (G_T) is the incident solar irradiation on the collector aperture. The parameters (a_0), (a_1)

and (a_2) are the efficiency characteristic parameters which are depended on the collector type.

The useful heat gain from the solar system ($\dot{Q}_{u,s}$) can be written as below (Duffie et al., 2020):

$$\dot{Q}_{u,s} = \eta_{col} \cdot A_{col} \cdot G_T \tag{C.5}$$

where (A_{col}) is the collecting area of the solar thermal collector.

The energy balance in the working fluid can also be written in order to express the useful gain in temperature terms as below (Duffie et al., 2020):

$$T_{f,out} = T_{f,in} + \frac{\dot{Q}_{u,s}}{\dot{m} \cdot c_p} \tag{C.6}$$

where ($T_{f,out}$) is the fluid outlet temperature from the solar thermal collector and (c_p) is the fluid's specific heat capacity.

Storage tank

The storage tank which is connected to the solar thermal system receives the heat inputs from the solar field, stores a part of its quantity and feeds the building with DHW, while there is also a small thermal loss percentage to the ambient. Therefore, it can be written as below (Lykas et al., 2022):

$$\dot{Q}_{st} = \dot{Q}_{u,s} - \dot{Q}_{load} - \dot{Q}_{loss} \tag{C.7}$$

Where ($\dot{Q}_{load}$) is the load heat demand, ($\dot{Q}_{loss}$) is0307 the tank thermal losses and ($\dot{Q}_{st}$) is the stored energy in the tank which can be written as below (Lykas et al., 2022):

$$\dot{Q}_{st} = \rho \cdot V \cdot c_p \cdot \frac{dT_{st}}{dt} \tag{C.8}$$

where (ρ) the fluid density, (V) the thermal storage tank volume and (T_{st}) the average storage tank temperature.

Boiler

The boiler is used for heat production for space-heating purposes for the baseline scenario. The following mathematical formulation can be used for oil-boiler and for natural gas boiler by using in every case the proper efficiency and fuel values. The useful heat production of the boiler ($\dot{Q}_{u,b}$) is calculated by using the following expression (Wetter et al., 2014):

$$\dot{Q}_{u,b} = \eta_b \cdot \dot{Q}_{fuel} \tag{C.9}$$

Where ($\dot{Q}_{fuel}$) is the fuel energy demand and (η_b) is the boiler efficiency at the current operating point.

Also, the useful heat production of the boiler ($\dot{Q}_{u,b}$) can be expressed according to the energy balance in the operating medium (e.g., water) as below (Wetter et al., 2014):

$$\dot{Q}_{u,b} = \dot{m}_w \cdot c_p \cdot \left(T_{w,out} - T_{w,in}\right) \tag{C.10}$$

Where ($\dot{m}_w$) is the mass flow rate of the heated water in the boiler, c_p is the specific heat capacity of the water, while ($T_{w,in}$) and ($T_{w,out}$) are the inlet and outlet water temperatures respectively.

In order to take into consideration the capacity factor of the boiler, the efficiency can be expressed by using a third-degree polynomial with the parameter the ratio of the ($\dot{Q}_{fuel}$) is the fuel energy demand to the respective nominal value ($\dot{Q}_{fuel,0}$) (Wetter et al., 2014):

$$\eta_b = b_0 + b_1 \cdot \left(\frac{\dot{Q}_{fuel}}{\dot{Q}_{fuel,0}}\right) + b_2 \cdot \left(\frac{\dot{Q}_{fuel}}{\dot{Q}_{fuel,0}}\right)^2 + b_3 \cdot \left(\frac{\dot{Q}_{fuel}}{\dot{Q}_{fuel,0}}\right)^3 \tag{C.11}$$

Furthermore, the fuel demand can be calculated as (Wetter et al., 2014):

$$\dot{m}_{fuel} = \frac{\dot{Q}_{fuel}}{H_u} \tag{C.12}$$

Where ($\dot{m}_{fuel}$) is the mass demand rate of the fuel and (H_u) is the lower heating value of the fuel.

Heat pump

The heat pump is a device that produces heating or cooling and consumes electricity. The proper description of the heat pump can be conducted by defining the respective efficiency indicators.

The coefficient of performance in a heat pump for heating purposes (COP) is defined as the ratio of the heating production ($\dot{Q}_{heat}$) to the electricity demand (P_{el}) (Yang et al., 2022):

$$COP = \frac{\dot{Q}_{heat}}{P_{el}} \tag{C.13}$$

The coefficient of performance in a heat pump for heating purposes (EER) is defined as the ratio of the cooling production ($\dot{Q}_{cool}$) to the electricity demand (P_{el}) (Yang et al., 2022):

$$EER = \frac{\dot{Q}_{cool}}{P_{el}} \tag{C.14}$$

The respective seasonal values (SCOP) and (SEER) are calculated by taking into consideration the total energy demand in the year period.

Photovoltaic panels

The simulation of the photovoltaic follows the two-diode model which is described in Ref (Duffie et al., 2020). in detail. Moreover, the detailed PV modeling in the INTEMA tool has been also described in Ref. (Rotas et al., 2022). It is useful to define below the photovoltaic electrical efficiency (η_{el}) (Duffie et al., 2020):

$$\eta_{el} = \frac{P_{el}}{A_{PV} \cdot G_T} \tag{C.15}$$

where (A_{PV}) is the total area of the installed PV.

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