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Transformation through renovation: An energy efficient retrofit of an apartment building in Athens

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Abstract

A 7 story social housing apartment building in Athens, Greece has been renovated following a holistic energy efficient retrofit process. The retrofit plan, resulting from tenant surveys, environmental parameters monitoring and extensive energy simulations, included commercially available technologies like insulation and energy efficient windows, innovative technologies like energy efficient lighting and smart coatings, passive techniques like night ventilation as well as RES, aiming to transform this inefficient building into a near zero energy one, achieving a reduction of the energy consumption and CO_2 emissions by 80% and significant improvement of thermal comfort conditions. An experimental campaign has been executed in order to measure and validate the energy savings and indoor comfort conditions before and after the retrofit. The results of this monitoring procedure are reported and analyzed. Measurements include air leakage and thermal imaging for determining leakage rate and heat loss through the building fabric, smart meters to record energy consumption and indoor and outdoor environmental measurements. The opinion of the occupants is taken into account through pre- and post-retrofit surveys.

Keywords: "energy efficient retrofit; post retrofit monitoring, occupants evaluation"

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1. Introduction

The built environment is not only the largest industrial sector in economic terms, it is also the largest in terms of resource flow [1]. Buildings are at the centre of our social and economic activity. People spend a significant part their lives in buildings, and they also spend most of their money on buildings. The building industry is a large contributor to CO2 emissions, with buildings accounting for 40% of the total European energy consumption and 36% of CO2 emissions in the EU. In order to address climate change the European Commission has set specific targets to be achieved by 2020, known as the 20/20 targets. These targets are to reduce energy consumption by 20%, reduce CO2 emissions by 20% and provide 20% of the total energy share with renewable energy. The European Union has also committed to 80-95 % GHG reduction by 2050 as part of its roadmap for moving to a competitive low-carbon economy in 2050 [2]. While new buildings generally need less than three to five litres of heating oil per square meter per year, older buildings consume about 25 litres on average. Some buildings even require up to 60 liters. Currently, about 35% of the EU's buildings are over 50 years old [3].

Developments in sustainable energy technologies and building management systems have enabled new buildings to meet the European Directive on Energy Performance of Buildings. However, at least 75% of the building stock that will be present in the next 20 to 30 years is already in existence and of this 70-80% is residential. As residential buildings dominate building stock with respect to living space, and have an unfavorable ratio of building envelope compared to the floor area, this type of building has a high specific heating/cooling energy demand, and a significant contribution to greenhouse gas emissions [4]. Therefore, retrofitting of residential buildings represents a major challenge and a holistic solution for retrofitting has the highest potential to transform existing and occupied buildings into energy-efficient buildings, presenting major opportunities for cost-effective investments in efficiency.

In this framework, the FP7 project called “HERB: Holistic energy-efficient retrofitting of residential buildings” aims at the creation of a framework of development, demonstration and dissemination of very innovative and cost-effective energy efficiency technologies for the achievement of very low energy residential buildings through a holistic retrofit process. Technologies envisaged for envelope retrofitting include various types of insulation materials such as Aerobel/aerogel, vacuum insulated panels, smart windows, surface coatings, multi-functional lightweight materials integrated with phase change material for thermal storage and integrated heat recovery panels. Energy efficient solutions are be deployed including energy efficient lighting using LED and light pipes, energy efficient HVAC, passive heating/cooling, heat pumps integrated with heat recovery and thermal storage, and renewable energy systems based on solar thermal and photovoltaics. The holistic approach and the technologies developed within the HERB project are applied for the retrofit of different types of residential buildings at seven countries (UK, Italy, Portugal, Greece, Switzerland, Spain and Netherlands). Performance monitoring of the buildings has taken place before and after the retrofit and the impact of the retrofit in terms of energy and CO2 savings, environmental quality and socioeconomic impact are evaluated. The technologies and buildings retrofitted will be demonstrated to the public. More information on the HERB project can be found at its website: http://www.euroretrofit.com/

This paper focuses on the on the work that has been carried out for the Greek retrofit case. More specifically, a 7 story social housing apartment building located in Athens has undergone an energy efficient retrofit in accordance with the methodology that was developed within the HERB project which is briefly presented in this paper. An experimental campaign has been carried out in order to monitor the pre and post retrofit conditions in the building in terms of indoor environmental conditions and energy consumption. Building simulation techniques have been used for the estimation of global energy savings and a socioeconomic analysis was performed in order to estimate the cost effectiveness of the retrofit and to evaluate the acceptability of the retrofit by the building users. The main results are described in the following sections.

2. The building

The Greek demonstration building is located in Athens at the Municipality of Peristeri, a densely built urban area, approximately 5 km from the centre of Athens. It is the 4th largest municipality in Greece with medium low income population and high rates of unemployment. The strong urbanization and the lack of free/green spaces have caused strong UHI effect.

The building consists of two identical semi-detached, 7 story apartment buildings, one of which has been selected for retrofit in the framework of the HERB project. The building has a rectangular shape and the main façade is on north-east exposition. The total building area is around 1’160 m2 with 15 apartments, each of which belongs to a different owner. Each apartment has an area of about 69 m2 and consists of four main rooms. The bedrooms have windows on the south-west façade, while the kitchen and living room have a window and a glass-door respectively, facing north-east.

The apartment building is made of reinforced concrete and brick walls, without any insulating material and a concrete roof and ceiling. Table 1 describes the representative characteristics of the construction elements and the openings in the majority of the apartments. The maximum U-values according to the Greek Regulation of Energy Performance of Buildings [5], is 0.50 [W/m2 K] for walls, 0.45 [W/m2 K] for roof an floor and 3.00 [W/m2 K] for windows. Considering these limits, it is clear that all the elements have poor performance and great heat losses due to transmission are expected. The apartments initially had old type windows with wooden frames and single glazing. Some owners have replaced some or all of the windows with aluminum frame with single glazing and one of them with double glazing.

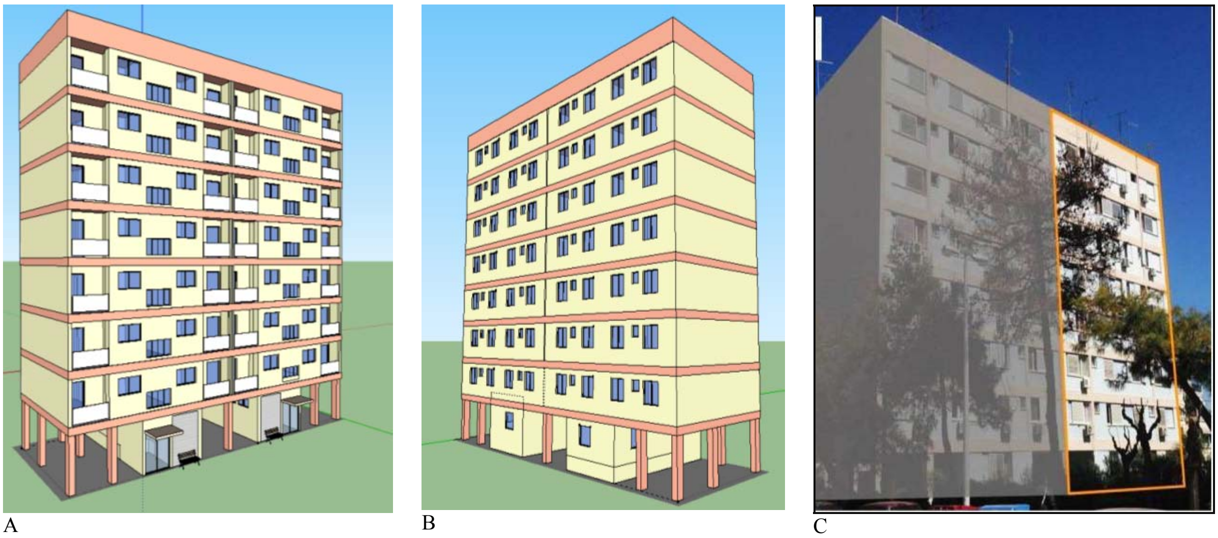


Fig. 1. Three dimensional model for architectural front (A) and rear (B) views on SketchUp and rear part of the building SW elevation (C).

Table 1: Thermal characteristics of the building envelope and openings

	External wall	Internal wall	Roof	Floor	Glazing	Frame
Type	reinforced concrete and brick	reinforced concrete and brick	concrete	concrete	Single	Wood/Aluminium
Thickness (mm)	200	150	250	150	6	-
U – value (W/m^2 K)	1.90	2.36	2.45	3.41	5.8	3.633

The apartments are heated by a central oil boiler, without having the opportunity to adjust the interior temperature to the desired levels by an individual control. Since 2013, the central heating has not been used due to the lack of financial resources of the residents. The interventions that some of the owners or tenants have implemented include the installation of air-conditioning units or other heating devices (e.g. portable electric radiators), solar water heaters. Most apartments are lit by domestic type luminaires, housing incandescent or compact fluorescent lamps with a mean power between 4-13 W/m2.

3. Determination of the retrofit plan

A holistic analysis has been developed within the HERB project and was carried out in order to determine the optimum retrofit scenario for the Greek building. The HERB design methodology consists of an iterative process that takes into account the Greek & HERB project's specific requirements. The Existing Case (current building situation) was analysed and compared to several other retrofit scenarios including innovative technologies developed within the HERB project and other state of the art commercially available energy efficient and sustainable energy technologies. For each retrofit scenario examined, the results were checked to see if the fulfill specific energy, environmental and cost targets. If the target/s were not met the process was repeated with a new set of technologies and solutions until the optimum retrofit scenario in terms of energy, environmental and cost performance was determined.

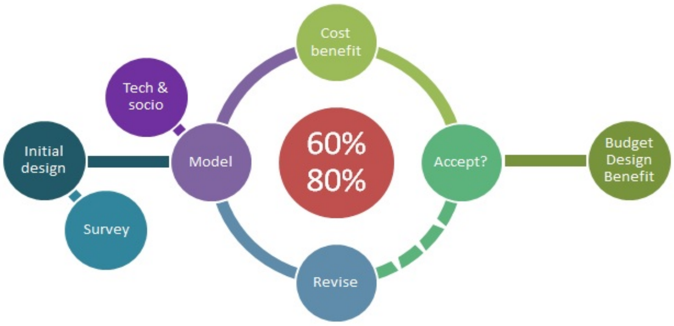


Fig. 2. The HERB design methodology.

In order to perform the above analysis several tools have been employed including: Dynamic energy modelling (TRNSYS), comfort modeling (PMV-PPD) (TRNSYS), Carbon emissions savings calculations, application of economic calculation theory to analyze the financial feasibility of the solutions, other analyses for assesing HERB innovative technologies (e.g. PV modeling (PVGIS), custom model for energy efficient lighting).

The optimum retrofit plan determined consisted of the following interventions:

- envelope insulation: exterior insulation of walls (with 8cm thick rockwool panels) and roof (with a flat Inverted roof material, comprised extruded polyethylene of 5cm and topped with coated ceramic tiles with cool properties),
- efficient windows with double glazing and thermal stops,
- ceiling fans,
- night ventilation,
- smart (Photocatalytic) coating (self-cleaning photo-catalytic nanotechnology plaster, with a thickness of about 1.5mm, appropriate for use on top of the exterior thermal insulation system),
- exterior shading of the SW windows (awnings),
- photovoltaic panels (10kWp of polycrystalline cells),
- LED lighting (replacement of all conventional – incandescent and CFL lamps)
- Innovative energy efficient lighting system developed within the HERB project installed

According to the simulations, the building before the retrofit was estimated to consume 154.5 kWh/m2/y while the total primary energy for the retrofit case was 30.5 kWh/m2/y, with the energy savings being 80.3%. The CO2 emissions savings between the existing and the retrofit case was estimated to be 80.3%, which fulfils and exceeds the 60% saving target which was set by the project.

The proposed interventions as described above have been implemented July 2015 – March 2016.

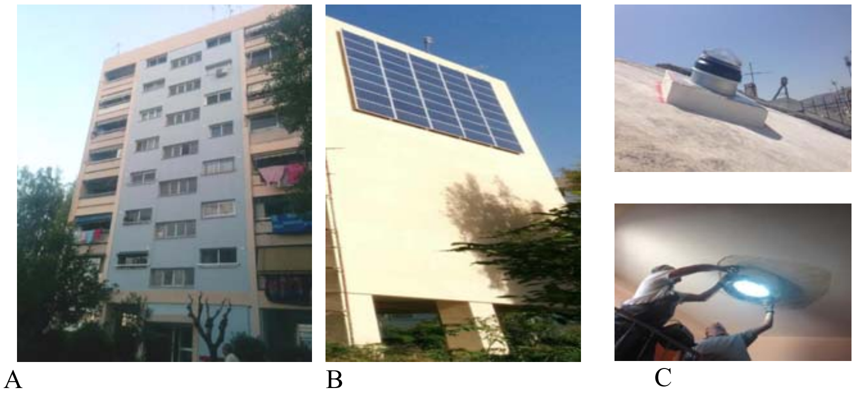


Fig. 3. Images of the retrofitted building: Building envelope interventions (A), PV panels (B) and energy efficient lighting system (C).

4. Experimental campaign

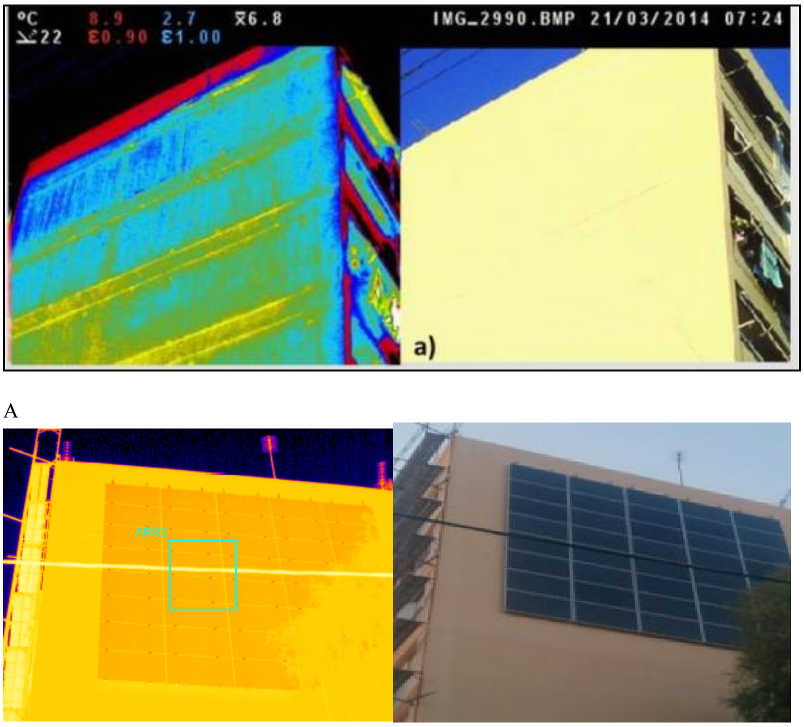
An extensive experimental campaign has been carried out pre and post retrofit. The pre retrofit monitoring was conducted for 12 months including both heating and cooling seasons and the post retrofit monitoring was conducted for 5 months including the winter and springtime. Different types of sensors have been installed in most apartments of the 7 story social housing building in order to monitor different rooms and parameters. The following measurements have been conducted during pre and post retrofit monitoring periods:

- Building Energy use with the use of smart meters that record the energy consumption (electricity) and gather the data in a portal for remote access
- Infrared thermography in order to in order to detect potential problems on the building envelope
- Air tightness measurements through blower door tests (according to ISO13829[6])
- Air leakage rate measurements through novel pulse leakage tester
- Ventilation rated using tracer gas techniques
- Building environmental parameters
    - Temperature
    - Relative Humidity
    - Lighting measurements to evaluate the lighting environment (artificial and natural lighting).
    - Thermal comfort (T, RH, T_{bg}, V)
    - Indoor air quality (PMx, VOCs., CO2)
- Outdoor environmental parameters
    - Temperature
    - Relative Humidity
    - Solar radiation
    - wind speed and direction

In addition, post retrofit, several additional monitoring activities took place in order to evaluate the performance of the installed technologies and solutions (e.g. specific lighting measurements to evaluate the performance of the installed energy efficient lighting system, solar reflectance measurements and photocatalytic activity measurements to evaluate the performance of cool and photocatalytic materials).

The results of the pre retrofit monitoring indicated that it is a building with significant heat losses/ gains and air leakage problems during both summer and winter due to the lack of envelope insulation, old single glazing wooden frame windows & insufficient shading. Significant thermal discomfort problems have been recorded and poor indoor environmental conditions. The energy consumption, although it is not very high due to the lack of central heating and cooling systems, when the outside temperature drops in winter to e.g. 10°C it doubles and the same applies for summer conditions indicating the low efficiency of the building. The results of the pre retrofit monitoring have verified that the retrofit measures that have been adopted for the Greek building are appropriate and will greatly improve the energy and environmental performance of the building as well as the indoor environmental conditions of the occupants.

The comparison of the infrared images before and after the retrofit reveals the significant improvement of the building envelope. The figures below show the impact of envelope insulation that was installed during the retrofit. Pre retrofit, the building had great problems of thermal bridges that significantly increased heat loss (Figure 4A). Figure 4B show that after the implementation of the external insulation on the building envelope, the problems of thermal bridges have been significantly limited and the building envelope presents uniformity in terms of thermal performance. As a result, thermal comfort conditions inside the apartments have significantly improved and the temperatures fluctuations throughout the day



A

B

Fig. 4. Thermal and visible images of the building envelope: pre (A) and post (B) retrofit

Pre retrofit, the roof of the building was not insulated and covered by dark bituminous membrane, reaching, as a result, high surface temperatures under hot summer conditions. Post retrofit, the insulated cool roof has a better thermal performance with observed surface temperatures significantly lower compared to the initial condition (Figure 5)

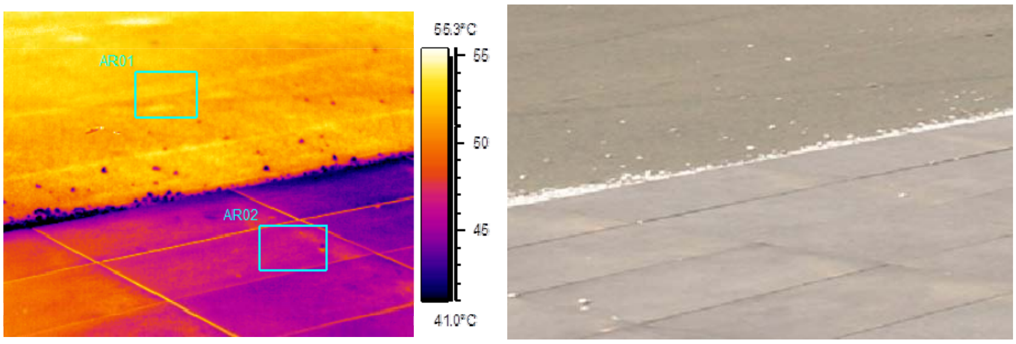
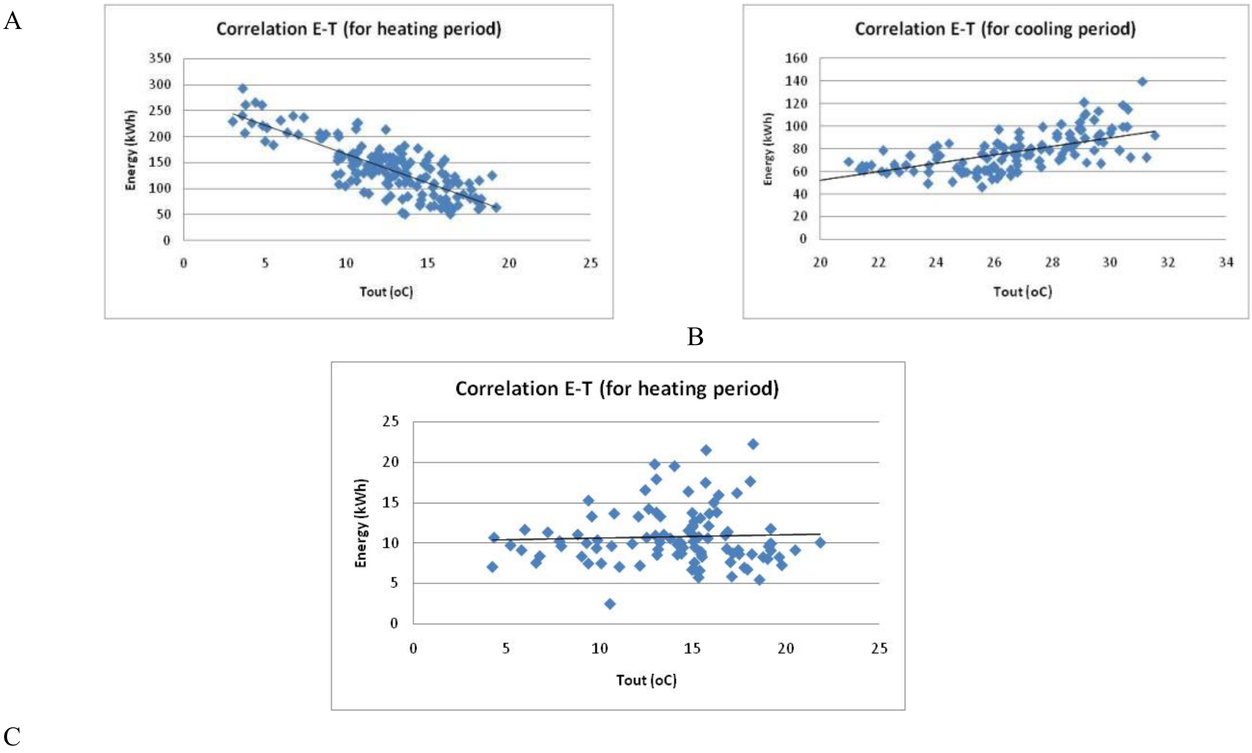


Fig. 5. Thermal and visible images of the roof pre (left part) and post (right part) retrofit

The air tightness of the building has significantly improved (for a representative apartment the ACH@4Pa measured in the pre retrofit stage (2.02 h-1) is almost 3.4 times higher than the post-retrofit (0.6 h-1).

The analysis of the post retrofit monitoring data has demonstrated that the technologies and solutions installed in the retrofitted building have contributed to a significant decrease in the energy consumption of the building. The energy signature of the building as the total energy consumption and the average outdoor temperature for each day of the year is calculated, and then plotted in the same graph. For the pre retrofit condition two graphs have been created, one for the heating and one for the cooling period. For the post retrofit condition only the graph for the heating season is presented as there are no measured data yet for the cooling season.


Correlation E-T (for heating period)

Correlation E-T (for cooling period)

Correlation E-T (for heating period)

Fig. 6. Energy signature for the Greek building for the heating (A) and cooling season (B) before the retrofit and for the heating season after the retrofit (C)

The energy signature graphs before the retrofit indicate a strong correlation between energy consumption and the outdoor temperature both for the heating and the cooling season indicating that the indoor environment of the building is vulnerable to outdoor conditions mainly due to the lack of insulation, low levels of air tightness etc. More specifically, when the outdoor temperature decreases during winter the energy consumption is significantly increased. During the cooling season when the temperature increases so does the energy consumption to meet cooling demands, although the slope is lower compared to the heating season. The energy signature for the heating period after the retrofit, presents a different situation. The relation between the outdoor temperature and the energy consumption is not as evident indicating that the interventions implemented during the retrofit were successful in thermal proofing the building and improving the thermal comfort conditions indoors.

Furthermore, the thermal comfort conditions inside the apartments have been improved after the retrofit. A statistical analysis of indoor outdoor temperatures has been performed. The following box plots represent a statistical distribution of the measured indoor temperatures of each one of the selected apartments and also the outdoor temperature. In these figures the median, lower and upper quartile values are represented as well as the extent of the rest of the data. Outliers are data with values beyond the ends of the tails. Figures 7A & 7B below demonstrate the indoor temperature distributions for all the apartments and for the month of February before and after the retrofit. During the pre-retrofit period the temperature in all apartments, except one apartment on the 3rd floor (F3_A1), presents very low values for February with median values ranging between 15-17°C. This is well below the national standard that sets the comfort limit for winter to 20°C. Most of the tenants could not afford regular heating so these values are expected. After the retrofit the conditions are found to be significantly improved. Median indoor temperature values are about 20°C meeting the national standard. In addition temperature fluctuations seem to have decreased adding to better thermal comfort conditions in the apartments after the retrofit.

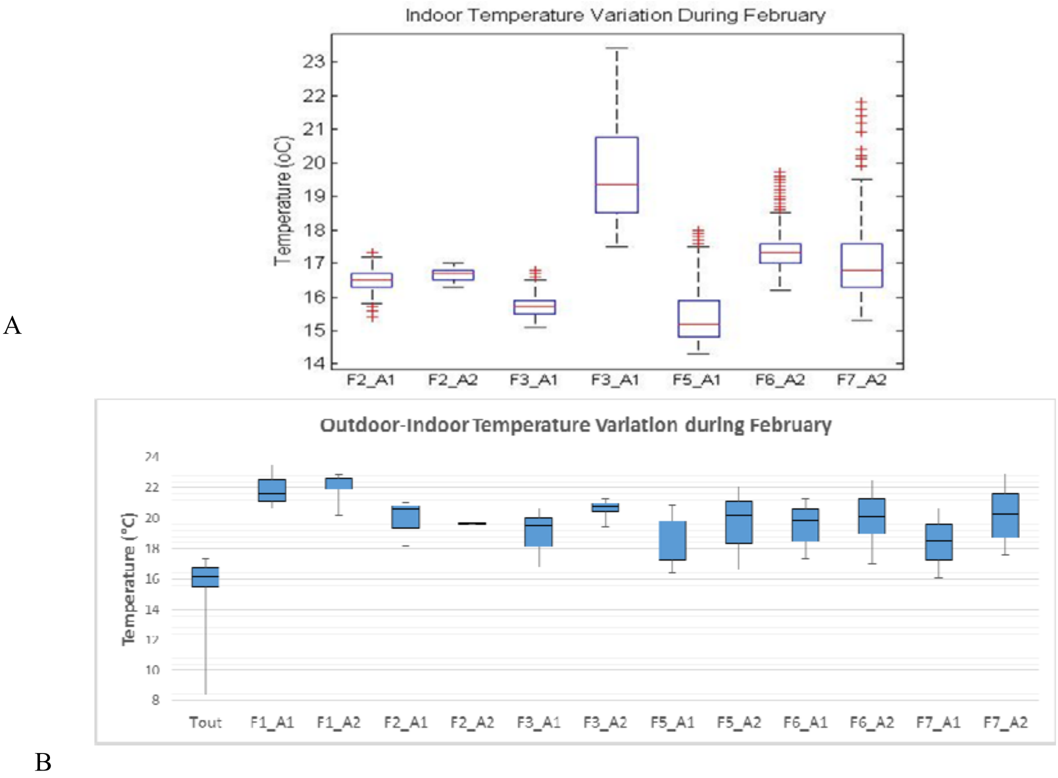


Fig.7. Box plot of the indoor and outdoor temperature for February for the apartments pre retrofit (A) and post retrofit (B)

In addition the % of hours with indoor temperatures outside the thermal comfort range has been calculated. The comfort range according to the national standards is defined between 20°C and 26°C [7]. The figures show significant reduction (>50%) in the hours of discomfort after the retrofit indicating the effectiveness of the retrofit solution in improving thermal comfort conditions inside the apartments. This is very important if we consider that due to financial restrictions the use of HVAC systems is limited.

Regarding indoor air quality measurements, CO_2 and VOCs concentrations appear to be lower during the post retrofit case and this is probably due to better ventilation conditions and the information and training that the residents received by the University of Athens on indoor air quality and ventilation. The illuminance measurements in the apartments during the post-retrofit period show that the lighting levels at the points where the pre-retrofit measurements had been made, have not changed considerably and are lit to adequate levels for residential buildings. This is expected as replacing the existing incandescent lamps with LED lamps, mainly contributes to energy savings.

Finally, the energy efficient lighting technology that was developed by UOA in the framework of the HERB project was found to improve the lighting conditions in the installed space and to contribute to the energy savings for lighting of the building.

5. Energy, environmental and socioeconomic performance of the retrofitted building

This section reports the calculation of the global energy savings for the Greek retrofitted building with the main objective to estimate certain performance indicators to demonstrate the success of the retrofit in terms of energy and environmental performance, user acceptability and cost effectiveness.

5.1. Global energy savings

Building simulation techniques have been used for the estimation of global energy savings in order to avoid differences in the boundary conditions (climatic conditions, user behavior) between the pre and post retrofit case. The building simulation models developed were properly calibrated and validated using the measured data collected during the pre and post retrofit monitoring periods and were found to meet the specific requirements of the methodology that was defined within the HERB project based on relevant ASHRAE and ISO standards [8, 9]. In order to calculate the energy savings a whole building calibrated simulation method has been developed which is based in a multi-zone energy model, dynamic simulation with a 8760 hours weather file, using Design Builder software. Two independent building simulation models have been developed and carried out representing the baseline scenario (pre retrofit building) and the post-retrofit respectively. The comparison between measured data and the outputs of the model simulation correspond to hourly data. The acceptable tolerances are measured by the statistical indexes MBE and CV (MSE). After calibration, fine tuning and validation both pre and post retrofit models were found to meet the acceptable tolerances and have been used for the estimation of global energy savings using the same climatic data and user behavior for the pre and post retrofit case. The cumulative annual energy saving in the building reaches 81%. The energy saving for lighting reaches the value of 88.6% of reduction. The global energy consumption excluding appliances while reducing peak loads against the values measured before retrofitting reaches 45.4 kWh/m^2 y in primary energy. The renewable electricity produced in the building from the PV system which has been installed in the SE façade reaches 9860kWh per year (efficiency=0.15) or 6570 kWh per year if we consider a reduced efficiency of 0.13 due to the heat losses of the inverter.

Regarding the impact of the retrofit on thermal comfort conditions, it was found that there are strong differences on air temperature during the heating season between the baseline (pre retrofit) condition and the post-retrofit one. Especially, the temperature increase of the post-retrofit condition, reaches 3.74°C on January, while the average temperature increase for the heating period is estimated at 3.10°C. Furthermore, minimum T values during the heating period have increased by even 5 °C. During the cooling period, the temperature displays a reduction ranging between 0.5 °C -1.5 °C. Calculations of the PMV according to ISO7730 [10] indicate a significant improvement of indoor thermal comfort inside the apartments during both winter and summer after the retrofit.

Finally, the reduction of CO_2 emissions after the retrofit has been calculated. According to Greek standards, CO2 emissions are calculated by multiplying the energy consumption (kWh) with a constant, depending on the power source. For this case, the only power source that is taken into account is electricity. The corresponding constant for electricity is: 0.989 (kgCO2/kWh). The annual savings of CO2 emissions for the post-retrofit condition reach reaches 81.64%.

Comparing the global energy savings results calculated with this methodology and the results obtained in the design phase from the holistic analysis, it can be seen that there is a very good agreement indicating that the holistic methodology and assumptions made were appropriate.

5.2. Cost effectiveness of the retrofit

The cost effectiveness of the Greek retrofit has been estimated using a specific socioeconomic tool that was developed within the HERB project. The tool estimates the payback result of the retrofit solution implemented in the framework of the HERB project compared with the payback of the investment on state-of-the-art energy efficient technologies that could be adopted rather than HERB technologies. In addition, the tool estimates the cost effectiveness of the retrofit in terms of cost saved energy (defined as the average net costs incurred to reduce one kWh which are compared with the average end-user energy cost (estimated as a weighted average based on energy consumption perfil and energy prices)). The retrofit is considered cost effective if the saved energy costs are lower than the average end-user energy cost in the baseline (i.e., without retrofit). The results for the Greek retrofit are presented in the following table.

Table 2: Cost effectiveness performance indicators

CE Performance Indicators	(Units)	Results
Payback	Years	2.9
Cost-saved energy	EUR/kWh avoided	0.14

It should be noted here that in order to perform the calculations with the socioeconomic tool UOA has used the real costs of the retrofit as they are recorded in the invoices and receipts. Comparing the socioeconomic analysis results acquired after the retrofit with the results of the pre retrofit analysis small deviations are observed. The payback period of the HERB retrofit compared to the state of the art retrofit was initially estimated to be about 9years and with the current calculation this value is 2.9. The main reason for this apart from small adjustments in the energy and retrofit cost data is the input value for the cost of electricity. In the current analysis the value of 0.179Eur/kWh is used. This value is obtained by Eurostat for 2014 and includes taxes, levies and value added tax (VAT) for household consumers, which is more appropriate for the calculations. Initially a much lower value was considered not taking into account taxes etc.

5.3. Occupants evaluation

This section reports the methodology and findings regarding the tenants' perception and satisfaction regarding the retrofitting works carried out at the Greek building. The main objective of this work is to record the occupants' perception regarding the quality of their indoor environment after the retrofit and their satisfaction on the retrofit and the technologies and solutions installed in the apartments. In order to achieve this objective two questionnaires one for the situation before and one for the situation after the retrofit and has distributed them to the occupants of the building have been developed. Both questionnaires include some general questions, questions related to perception of the occupants about their indoor environmental quality (i.e. air quality, thermal comfort, lighting, acoustic etc.) and the post retrofit questionnaire also includes on the occupants satisfaction regarding the retrofit.

In total 16 people have participated in the pre retrofit survey and the same 14 in the after the retrofit one (2 people were unavailable to participate again during the post retrofit survey). This means that the pre and post retrofit results can be compared. In addition, the building has 7 floors and 15 apartments. Occupants from every one of the 7 floors (apart from the 4th who were not there during the survey period) have participated in the survey, so the whole building is well represented. Furthermore, 82% of the occupants are either unemployed or pensioners, meaning that they stay at home for many hours daily (64% stay at home more than 16 hours per day) and thus they have a good perception of the indoor environment during all hours of the day/week.

In general, after the retrofit all the tenants declared that they are satisfied with the overall quality of their indoor environment in terms of thermal comfort, air quality, lighting and acoustics, while before the retrofit 69% of the tenants characterized the quality of their indoor environment as "bad". More specifically, regarding thermal comfort, before the retrofit, the occupants characterized their thermal environment as cold (69%) during winter and as warm/hot (88%) during summer, indicating that the thermal comfort conditions are not satisfactory. Furthermore, 69% have commented that they face significant drought problems in their apartments during winter. After the retrofit, 85% of the occupants characterized the indoor thermal comfort conditions as satisfactory and the rest as acceptable for both seasons. More in detail, during winter and summer the thermal sensation is characterised as neutral by most of the occupants (14% found that during summer the thermal sensation is slightly warm). No drought problems have been reported after the retrofit. Furthermore, a significant reduction in the number of hours that they use heating equipment after the retrofit has been declared by the occupants and was also verified by the energy consumption reduction measured and estimated.

Regarding indoor air quality, before the retrofit 31% of the occupants characterised the air quality in the apartment as "bad". This is due mainly due to internal sources of pollution (e.g. smoking inside the apartments, cleaning with chemical products etc.) and the lack of regular ventilation. After the retrofit, several occupants found their indoor air quality to be improved basically because of the natural ventilation strategies they were advised to follow by the University of Athens team.

Natural lighting before the retrofit was characterized as 'bad" by 56% of the occupants. This is mainly due to glare problems faced in the rooms located in the unshaded facade of the building and due to the lack of natural light in the place where the energy efficient lighting system was installed. After the retrofit, the 86% of the occupants characterize the natural lighting conditions as neutral/satisfactory. Artificial lighting was found to be satisfactory by most of the occupants even before the retrofit and continue to do so after the replacement of the incandescent lamps by LED lamps. 14% of the occupants found the lighting levels to be more bright after the retrofit but not in a negative sense. A specific question was asked to the tenants aiming to evaluate the performance of the energy efficient light pipe and all the tenants (100%) have confirmed that the technology has improved the lighting conditions in the installed space.

Furthermore, the mold/ condensation problems reported before the retrofit by 38% of the occupants were eliminated after the retrofit due to the envelope interventions.

Regarding the retrofit satisfaction, it should be highlighted that all the occupants have declared their satisfaction. Moreover, they pointed out that they have been approached by the tenants of the adjacent and nearby buildings, asking them how they can also participate in this project. All the installed technologies and solutions have been positively rated by the occupants in terms of improving the indoor environmental quality and contributing to energy savings. Finally, the occupants have reported that after the retrofit they feel that their behavior has changed in terms of energy and environmental issues. 71% are interested in knowing their energy consumption (by looking in the installed smart meters monitors) and they know how to reserve energy at home. Most of them declared that they have used heating and cooling devices for fewer hours after the retrofit. All the residents now use energy efficient lights and 71% declared that they prefer to use the ceiling fans over the AC.

It should be noted, that the occupants' perception about their indoor environmental quality is verified also by the measurements conducted in the building. All the above indicate the significant success of the holistic retrofit of the Greek building and the acceptability and satisfaction of the occupants of their indoor environmental quality and the installed technologies and solutions.

6. Conclusions

An energy efficient retrofit of a seven story social housing apartment building has been carried out. The retrofit plan includes innovative as well as state of the art technologies and solutions. An extensive experimental campaign has been carried out before and after the retrofit with the aim to evaluate the effectiveness of the retrofit. The experimental results show significant improvement of the indoor environmental conditions and reductions in the energy consumption. Furthermore, via calibrated building simulation techniques, using experimental data, the global energy savings from the retrofit have been estimated. The cumulative annual energy saving in the building reaches 81%. The energy saving for lighting reaches the value of 88.6% of reduction. The global energy consumption excluding appliances reaches 45.4 kWh/m^2 y in primary energy. Finally, 81% reduction of CO2 emissions was achieved. The socioeconomic analysis of the retrofit showed a significant user acceptability of the retrofit as it has been recorded through questionnaires and interviews by the occupants. The estimated the payback period of the HERB retrofit solution was found to be 2.9 years compared with the payback of the investment on state-of-the-art energy efficient technologies that could be adopted rather than HERB technologies. Furthermore, the analysis showed that the implemented retrofit solution is cost effective as saved energy costs (0.14EUR/kWh avoided) are lower than the average end-user energy cost in the baseline (pre retrofit).

As a conclusion from this analysis, it is evident that the retrofit of the building and innovative technologies and solutions implemented are very effective in reducing energy consumption and improving indoor environmental conditions.

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