Investigation of Sun Protection Issues via the Active and Passive Building Integration of Active Solar Energy Systems: A Case Study of the Renovation of an Existing Building in Cyprus

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Abstract. The demand for a continuous and extensive use of buildings in contemporary central business districts without proper maintenance has led to an aging building stock. The need for refurbishment and use of these buildings, based on the Energy Performance of Buildings Directive (EPBD) in Cyprus, is a challenge that all real estate asset managers need to face. This paper aims to examine whether specific building integrated active solar systems (BIPV), along with their basic operation can be used as passive shading devices as part of a double shell, as indicated in the case study for the renovation of an existing mixed-use building in Nicosia, Cyprus. The proposed research starts with an analysis of building and site geometry and an investigation into a philosophy of operation through a literature review, along with the presentation of case studies where these active solar systems are integrated on double building shells. Digital energy simulations are performed where the technologies are examined as a passive shading device, as part of the double shell of the renovated building. These simulations aim to analyse whether the system can cover the energy needs of the aforementioned building, whilst providing adequate sun protection. Consequent to the results of the digital simulation, the heating and cooling energy loads – in order to keep the interior of the simulated building within thermal comfort levels – are examined, thus affording the opportunity to compare and contrast the before and after situation. Moreover, the annual primary energy production of the integrated systems is calculated and compared with the building ’s annual energy needs. The ultimate aim of this work is to determine the environmental sustainability of these building integration solutions for the refurbishment of existing buildings.

1. Introduction

Over the last decades, building sustainability came to the forefront of discussions. Awareness has been increased on how building usage can negatively affect energy consumption, climate change and contamination [1]. Given that, 50% of the world’s population lives in cities and in 10 years from now this number will reach up to 80%, whilst cities are responsible for the 70% of global carbon dioxide emissions [2], and operational costs of buildings account for 40% of energy use in the European Union (EU) [3].

At the same time, there is a legal obligation instituted by the Energy Performance of Buildings Directive (EPBD), which gives an ever-increasing role to efficient adoption of renewable energy sources and zero energy consumption to all the new buildings by 2020 [4], whilst it forces EU countries to submit long-term renovation strategies that foster investments in the renovation of buildings, which could reduce the EU’s total energy consumption by 5-6% and CO$_2$ emissions by about 5% [5]. Thus, if society consciousness moves towards more sustainable methods of buildings design and construction, the energy consumption, climate change and contamination could be controlled. Additionally, zero energy balance in buildings, needs to be a fundamental principle in any construction of new buildings or in any total renovation of existing buildings.

Taking into account that the application of passive solar planning techniques, can lead to the reduction of heating, cooling and lighting loads by 62% compared to the total energy needs of a conventional house [2], could mean that such techniques could be applied in a variety of buildings leading to significant reduction to their energy needs. The passive solar planning considerations are essential in the design of nearly zero energy buildings. Although, in order to achieve nearly zero energy conditions for a building, new or fully renovated, two fundamental aspects must to be taken into consideration: the reduction of its energy demands, and its potential to produce energy (e.g. electricity), in order to achieve the desired energy balance between consumption and production [6].

In terms of the energy production potential, the use of a solar energy system is increasingly becoming evident wherever high values of annual solar energy are recorded [3]. Thus, buildings could exploit insolation to produce energy by integrating active solar energy systems (e.g. BIPV) in their facades and roofs [7]. Although, before the integration of the active solar energy systems, there are two important components that must be considered. Firstly, the location of the building in the urban fabric, since the orientation of the site in relation with several passive design techniques, it may result up to 20-50% energy savings. Secondly, the analysis of the site’s climatic conditions in relation to the geometry and massing of the buildings. The proper analysis of these will minimize the energy needs of the buildings and increase its energy production potential [2]. The design strategy that will be followed in the construction of a new building or in the total renovation of an existing building can play a significant role in increasing their energy production potential and create a more sustainable environment.

Based on the above, the research team focused in the total renovation and energy upgrade of an existing building in Nicosia’s city centre. It is a residential building that has several problems both in the exterior and interior spaces. Part of the renovation process was the conversion of the building into an office building with public uses for the broader urban region. The ultimate aim of the research process is to improve the building conditions through the application of several passive and active design strategies, and to determine whether the total renovation of an existing building using, a double skin façade with building integrated active solar system, could be viable in the climate conditions of Nicosia, Cyprus.

2. Literature Review

As it is stated above, there are crucial design techniques that can lead to an energy-efficient building, such as the building orientation and geometry, which are fundamental aspects for the beginning of the building’s design. Specifically, Ouarghi and Krati state that alongside with building orientation and geometry, the correct placement of a building in its site constitute it is a fundamental first design step [8]. According to Spiegelhalter and Tombazis & Preuss, design of buildings needs to ensure passive insulation and maximize access to natural resources required in their daily operation [9,10]. All of the above that need to be taken into consideration at the first design steps, determine solar access to the building, alongside with other major design decisions, such as the orientation and geometry of the openings which is correlated to the shading components. Additionally, the proper integration and
orientation of the active solar energy systems (photovoltaics and solar thermal systems), is crucial for the viable operation of the building [11,12].

Based on sustainable solar urban planning, several studies with different types of design tools have been carried out to determine and evaluate the early design steps of a building. In terms of massing and geometry of the building in relation to its insulation, Kanters et al. carried out a research which analysed the annual solar potential of a typical Swedish building block, and proved that the building geometry has a significant effect on its annual solar energy production potential, up to 50% [13]. Several studies focused on the optimization of the building’s geometry in order to ensure passive solar access, aiming to the minimization of the buildings energy demands for heating cooling and artificial lighting [8,14–17]. In this framework, studies have shown that buildings height and roof orientation could directly affect the utilization of the solar energy incident on the building envelope, whether by passive or active means [16,18].

All the above demonstrate that the integration of active solar systems into buildings adds various parameters to the architectural design process, thus transforming it into an interdisciplinary field. In particular, this is analysed with respect to issues related to bioclimatic design and the passive role that active solar systems play in the building, as well as with issues that have to do with their active role and their energy production potential. Thus, the research team attempted to simplify this interdisciplinary design process with the use of a roadmap for the integration of active solar systems into buildings, as it is presented in the work of Vassiliades et al. [19].

2.1 Case studies

According to several research works, integration of active solar energy systems into new or existing buildings is one of the most fundamental principles of the environmental design approach. In order for an active solar system to be considered as a building integrated, Peng states that it should be a functional part of a building’s structure or should be architecturally integrated into its design [20].

2.1.1 ALM HQ, Copenhagen, Denmark

One example of integration of active solar systems on an existing building, is a project in Copenhagen by Carsten Moller architects. An active solar system has successfully been integrated on the building façade, which functions both as an energy production system and a shading system. During the renovation of the 20-year-old building of the Danish financial services group, the ventilated double-skin façade has been replaced by a new one which integrates 84 photovoltaic solar panels from Pilkington. The 84 BIPV panels, cover 10% of the building façade and cover 5% of building’s total energy needs [21].

2.1.2 University of Technology Vienna (TU Wien)

Another example of an existing building that has been renovated with the use of building integrated active solar systems, is the high rise building of the University of Technology in Vienna. A building integrated photovoltaic system that is placed on the façade and consists of different types of insulated glass which function both as a shading system and an energy production system. According to Fischer, 54000 kg of CO₂ emissions have been saved, whilst the system’s energy production is up to 30 to 40 kWh annually [22].
3. Methodology

3.1 Methodology of Investigation

The methodology conducted in order to resolve inherent technical as well as architectural issues regarding the efficiency of the building was a multi-staged process which was aided by a cyclical feedback loop and revisions of the work done. The building was assessed through various media in order to investigate its possible pathologies, as well as design solutions via a holistic approach which would combine an energy efficient as well as an architectural and socially sustainable outcome.

3.1.1 Data Gathering

In order to obtain an insight on the building pathology, several on-site visual inspections (Figure 1) took place in order to document and verify the architectural plans and the data regarding the electrical and mechanical systems in their current state. Throughout the visits to the building, interviews were also used as a data collection tool in order to gain insight from the users, regarding matters of thermal comfort, air quality and humidity levels throughout the year. Beyond the on-site research, additional information was gathered through the local town-planning department regarding architectural and topographic data of the structure and its immediate surrounding cityscape. This data proved useful in determining the age of the building, as well as information on its uses (residential/office/retail) and possible indications on the load bearing structure.

3.1.2 Calculations

The irradiation analysis was made possible through the platform of PV-sites [23], by inserting the 3D model of the area and by using weather-files from Cyprus provided from the weather data of the EnergyPlus platform.

The existing and proposed heat loads, as well as the estimate for the dimensions of the proposed HVAC systems of the proposal were manually calculated using spreadsheets of the heat transfer equations derived from the “CYS CEN/TR 12831-2:2017 European Standard for Heat Load Calculation” [24]. The internal heat gains caused by human activity were calculated as 100 W/person, for lighting 10 W/m² and for equipment 200 W for 1 x PC + 1 x Printer/employee.
3.2 Building Pathology

The existing building (Figure 1) located in Diagorou and Evagorou street in Nicosia, Cyprus and is a typical 1960’s multi-storey building. The structure is uninsulated both in its horizontal as well as its vertical surfaces and is consisted of a single brick construction and concrete slabs. Furthermore, it was originally fitted with the single glazing which has still not been updated since its construction. The building also lacks a central HVAC system thus each floor is heated and cooled by dated (20yr+) local split-units. The building also suffers from extreme lack of maintenance in multiple areas, such as: The external staircase which is blocked with debris resulting health and safety hazards, the broken glazing in various windows which increase uncontrolled infiltration of air into the interior while also posing risks from the natural elements. Blocked ventilation ducts and exposed rust and humidity along the ceiling and various internal and external walls particularly on the north orientation. Additionally, the water tanks for the domestic hot water (DHW) are placed on the Ground Level which could also imply a lack of static strength or at least an inability for the building to carry further loads.

These parameters imply that the structure will perform poorly from an energy efficiency standpoint as no bioclimatic design elements or advanced mechanical systems are currently employed. Thus, immediate and extreme measures had to be taken in order to upgrade the energy consumption and general energy efficiency.

3.3 Climatic Analysis

3.3.1 Precipitation

The analysis regarding the average Yearly Rainy Days and Precipitation, with mean values of 8 days and 23mm respectively, did not support the implementation of a sustainable rain collection system. The subsequent investigations on the matter where also deemed fruitless.

3.3.2 Solar Energy

In contrast, the mean temperatures as well as the monthly sun-hours with values of 10°C-25°C and 300 hrs respectively proved very promising for a solar powered energy production system. Solar energy was also deemed as a viable choice in the selected site, due to the minimal shadowing obstructions from the East South and West which are the viable orientations for any solar system.

The Irradiance Analysis conducted, showed that the insolation is greatly different for any individual facade. In particular, the following median values were observed:

- South Facade: 1200 kWh/m²/yr or 62,3% of the maximum irradiance*
- West Facade: 1000 kWh/m²/yr or 51,9% of the maximum irradiance*
- East Facade: 750 kWh/m²/yr or 38,9% of the maximum irradiance*
- North Facade: 500 kWh/m²/yr or 25,9% of the maximum irradiance*

*The maximum irradiance is the irradiance that would occur on a flat 0° surface placed on ground level unobstructed by any shading throughout the year. This value (which is approx. 1950 kWh/m²/yr) was used as a reference point in order to classify the efficiency that could be achieved by each facade.

3.3.3 Wind Power

An average wind speed of 2.7 m/s was deemed low especially when accounting for further turbulences in the flow-field created by local barriers of the city-scape (e.g. surrounding buildings).
3.3.4 Geothermal

A geothermal solution was also deemed unviable due to the lack available area in the ground level for excavations. No further experimentation was thus undertaken towards this technology.

3.4 Proposal

From the Climatic Analysis and the data gathered, it was concluded that solar energy was a viable renewable energy resource that could be implemented through the use of Building Integrated Photovoltaic Systems (BIPV).

The design solution revolved around the proposition of a double skin façade (Figure 2) which would be at an offset from the existing building and could integrate a variety of sustainable features.

3.4.1 Double Skin Façade

The proposal started out with the introduction of an area of approx. 40 m² which could produce a high efficiency plane for a non-transparent BIPV system 8.8 kWp (Figure 3), this meant that this plane had to be facing true south at a 30° inclination [25], in order to maximize the output of the PV modules. To this end a rhombus plane was designed with offset from the southern corner of the rooftop. This idea of creating a skin that doesn't follow the perpendicularity of the structure, has been thereafter continued throughout the south-east and south-west facades with semi-transparent BIPV 70 kWp (Figure 3) panels wrapping around the building at a close, but varying distance in order to create a second skin which could utilize the stacking effect of air pressure differences in its top and bottom openings (Figure 4.1), thus facilitating the upwards airflow for cooling purposes. Furthermore, this second facade is consisted by multiple layers in order to fully exploit its sustainable dynamics.
In addition, to prevent the stacking of hot air on top floors, a preventive design measure was made, to create pass-through ducts (Figure 4.2) from the interior of the building which could bring cool exterior air directly from the West (which is the predominant wind orientation in the region). Besides the semi-transparent BIPV modules which were the first layer of the skin, a series of moveable shading louvers were designed to prevent direct light on the existing building as well as its interior spaces. This steel construction which held the double skin façade PV systems, shading louvers as well as walkable corridors was in turn bearing its own loads in order to avoid exerting excess strains on the existing building. Finally, the double skin façade incorporated a Wind Cowl (Figure 4.3) system on the top of the construction which blocked incoming western winds from infiltrating into the double skin from the top, thus preserving the stacking effect even during erratic wind conditions.

3.4.2 Interior Layout Redesign and Insulation

Beyond the addition of a double skin façade, changes have also been made to the existing structure. As a basic strategy it was imperative to create an “adiabatic” shell from the constant heat fluctuations of the climate. Thus, external insulation of polystyrene 80 mm U=0.295 W/m²K was proposed on the outer shell of the building in order to maintain also a constant interior temperature due to the thermal capacity of the brick walls and concrete slabs. In addition, all existing openings would be replaced with PVC frame double-glazing of U=1.9 W/m²K which achieves greater performance compared to aluminium frames. Furthermore, in order to both alleviate strains from the existing structure, non-load bearing elements were deleted in order to create cut-outs (Figure 5) through the building, which would aid both ventilation as well as the creation of social sustainability areas. This design approach gave the opportunity for a change in the layout of the existing floor plans which was arranged to have secondary or auxiliary spaces to the north as a buffer zone, whilst the main workspaces and living spaces where allocated towards the south. Finally, minor proposals were made for the adoption of smart devices that
could further the efficiency [e.g. smart thermostats, smart meters, smart plugs and A rated electrical appliances].

Figure 5. Ventilation Cut-outs, Interior Layout of typical Plan.

3.4.3 Mechanical Systems

On an effort to further the efficiency of the building towards nZEB category a Ventilation/Cooling system was proposed according to the area m² of each floor. This meant that each floor was calculated individually to produce the needs of the overall system. The calculations resulted in 6 external VRV type units. Each would regulate the interior temperature of each floor with the assistance of ceiling-concealed type interior units fed by ducts and airflow blinds. The ventilation system also utilizes heat-recovery units in order to further minimize the heat losses when extracting fresh air from the exterior. DHW needs would be met by solar thermal panels mounted on the double skin while the electrical systems and appliances would be powered by the PV façade entirely. In any case, a back-up pellet boiler is recommended when extreme temperatures render the heat-pump inoperable.

Figure 6. Electrical and Mechanical System Diagram

4. Results

The refurbishment of the building using active and passive practices, reduced significantly its energy needs. Particularly, the interior layout redesign, combined with the insulation of the building shell and the sun protection provided by the double façade, and supported with a more efficient ventilation/cooling/heating system, resulted the reduction of the building’s thermal needs by 85% and its cooling needs by 50% (Figure 7). It should also be noted that these results do not account the additional reduction of cooling needs due to the added ventilation and shading provided by the double skin façade, as they required a specialized CFD (computational fluid dynamics) model to produce. This formulates a further research goal for the research team.
Regarding the energy production potential of the refurbished building, it is based on the BIPV system, which is integrated on the double façade, and has a peak output that reaches nearly 80kWp (semi-transparent BIPV system: 70 kWp and non-transparent BIPV system: 8.8 kWp). This could cover the cooling needs of the building in total (Figure 7). As for the heating loads which are significantly lower at 15 kW, it is safe to assume that the BIPV system could completely cover them, even with a reduced production for example because of limited insolation of the system due to winter conditions (Figure 7).

![Figure 7. Load calculations before and after proposal and BIPV output.](image)

5. Conclusions

In conclusion and having in mind the specific climatic conditions of Cyprus as well as the south-eastern Mediterranean, the presented results show that buildings located in these or similar latitudes can be renovated successfully to nZEB type buildings, regardless to their initial conditions. This could help prove that the existing building stock of Southern Europe, which mainly consists of older constructions can be rescued and refurbished rather than demolished. These holistic concepts of solar energy utilization through double skin facades in the Mediterranean Countries can be duplicated in bigger or smaller scale to a large portion of existing buildings which would ultimately be a step towards furthering the sustainability goals of EU 2050 which would are hindered by almost 40% [3], due to the state of the built environment.

At the same time, the research presents a complete case study of an existing building refurbishment with the utilisation of BIPV, implementing a multi-criteria methodology for the integration of active solar energy systems in existing buildings. The study presents in a quantitative manner the active and passive role of integrated photovoltaic systems and validates the importance of their building integration in buildings of southern Europe. It also highlights the necessary contribution and parallel use of active and passive means for the refurbishment of a building towards the nZEB requirements.

5.1 Further Research

Further research goal would be to explore further the interior conditions such as humidity, light and air quality of the proposed design, through a simulation database such as the platform of EnergyPlus in order to create model of these parameters which could be there after tweaked, in order to produce an optimally fine-tuned proposal. Moreover, the further reduction of cooling needs due to the added ventilation and shading, would be calculated with the use of CFD (computational fluid dynamics) model to produce. In addition, a techno-economic analysis would also be suggested in order to investigate the monetary gains and break-even horizons on large scale sustainable renovations.
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