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Transparent photovoltaic integrated in the double skin façade for the energy requalification of the Italian typical buildings of the 60s and 70s

Fabrizio Ascione[1], Nicola Bianco[1], Teresa Iovane[1*], Giacomo Manniti[1], Gerardo Maria Mauro[2],

1 Università degli Studi di Napoli Federico II, Department of Industrial Engineering (*corresponding author: teresa.iovane@unina.it)

2 Università degli Studi del Sannio, Department of Industrial Engineering

ABSTRACT

The redevelopment of the existing building stock is essential to reach sustainability goals, worldwide. The energy retrofit measure analyzed in the study is based on the installation of a double skin facade with the integration of transparent photovoltaic on a structural exoskeleton that has the function of providing the building with a higher level of structural and seismic safety. The examined building is an Italian typical building construction of the 60s and 70s, i.e., it represents an archetype building and not a real building. After carefully collecting the input data, the graphical software DesignBuilder® is used to model the building geometry and the HVAC systems, while EnergyPlus software is used for dynamic energy simulation. The model is validated against the energy need for the type of reference buildings. Initially, the effect related to the double skin façade is assessed, and then a gradual inclusion of the transparent photovoltaic is implemented. Therefore, the energy benefit, in terms of primary energy consumption, due to the combined use of the two technologies is evaluated. When PV panels cover the entire area of the external facade, a saving of 55% in primary energy consumption is achieved.

Keywords: energy requalification of buildings, double skin façade, exoskeleton, building integrated photovoltaic

NOMENCLATURE

	Abbreviations	
BIPV	Building integrated photovoltaic	
DSF	Double skin facade	
MBE	Mean bias error	%
PEC	Primary energy consumption	kWh/m^2
PV	Photovoltaic	
U	U-value, thermal transmittance	W/m^{2}K

	Subscripts
hg	heating gas
p	primary
c	cooling
b	total building

1. INTRODUCTION

The COVID-19 pandemic is the biggest shock of last decades. The IEA's Global Energy Review [1] forecasts a global electricity demand fall by 5% and a Global CO_2 emission fall by 8% (as result of a decline in coal and oil use). Nevertheless, the past showed us that the rebound in emissions may be larger than the decline with the improvement of economic conditions. It is necessary to think more to save energy, to have a circular economy and to use energy sources with low environmental impacts. It is estimated that about 40% of the total energy consumption in Europe is linked to the building sector, which is also responsible for about a third of CO_2 equivalent emissions [2]. Economically and in the interest of sustainability, saving in this sector is essential for achieving the EU's energy and environmental objectives, that set a 40% cut in greenhouse gas emission and an increase in the use of energy renewable sources by 32% compared to the 1990 level as a target for 2030. To achieve these targets, the vast majority of buildings built in the 1900s need to be energetically redeveloped, as explicated by the EU Directives 2010/31 and 2018/844. The European building stock is not only energetically inefficient, but also inadequate to the current requirements of thermal and acoustic comfort, healthiness and accessibility. Regarding the energy retrofit measures, many researches focused on the building envelope. The performance of the building envelope has to ensure the thermal and hygrometric comfort, as well as low energy losses and thus energy demands, by satisfying environmental and technological requirements [3] and indoor comfort. In this context, a lot of studies were carried out on double skin facade system (DSF) and on building-integrated photovoltaic (BIPV) systems. Joe *et al.* [4] have analyzed the impact of a double-skin facade, by varying the type of windows' panes and depth of cavity, by obtaining a reduction in energy consumption of 5.62%. Ng *et al.* [5] evaluated the energy performance of six commercially semi-transparent PV modules, by taking into consideration several window-to-wall ratios and four main orientations in Singapore. Peng *et al.* [6] combined these two solutions, by means of the development of a type of ventilated façade (BIPV, Building-Integrated Photovoltaics) with a double envelope DSF. Wang *et al.* [7] analyzed the performance of two different kinds of dynamic facades, with double envelope, by integrating the use of photovoltaic modules (PV-DSF) and with single photovoltaic insulating glasses (PV-IGU). The results underlined that the PV-DSF perform better than the PV-IGU in reducing the solar energy gain. Furthermore, the systems allowed an average energy saving of 28.4% and 30%, respectively, compared to common insulating glass windows.

In this paper, the installation of a double skin facade (DSF) – through an exoskeleton and the integration, inside the added facade, of transparent photovoltaic devices that allow to obtain free and clean energy – is proposed as energy retrofit intervention, for a typical building in Southern Italy (Mediterranean climate), built between the 60s and 70s.

The proposed intervention pursues two objectives:

- the reduction of energy consumption through the application of the DSF,
- the exploitation of renewable sources also, which represents one of the main goals for addressing the energy issue in the building sector.

2. METHODOLOGY

The starting point of each energy retrofit measure is the assessment of the baseline performance. The examined building is an archetype building (modeled starting from common peculiarities of real building and validated against average energy performance). The data collected, with reference to both building envelope (opaque and transparent) and installed systems, are representative of structures of the years 1960s-1970s. The graphical software DesignBuilder® [8] is used to model the building geometry and the HVAC (heating, ventilating and air conditioning) systems. This software is a graphic interface of EnergyPlus [9] with which the dynamic energy simulation is performed. This latter allows to carry out simulations of the building performance on hourly or sub-hourly basis, by considering the accumulation and release of energy by the building's and systems' components. Once created the model, the energy results from simulations are evaluated and validated in order to have a necessary confirmation about their reliability. The validation is carried out by comparing the results of the simulation with the energy needs for the type of reference buildings. For verifying the coherency of simulation results, the Mean Bias Error (MBE) is calculated. This value must be ≤ ±5% according to both M&V guidelines [10] and ASHRAE guidelines [11]. The retrofit measure proposed consists of the creation of a "structural exoskeleton" which allows to get two benefits, giving a better structural stability to the building and ensuring an energy improvement. The solution chosen includes the realization of a glazed system to cover the exoskeleton formed by panels installed in the frame geometry of this structure. This glazed facade system, the so-called Double Skin Facade (DSF), forms a second skin (transparent) of the building, providing several advantages and also some criticalities. Furthermore, a further improvement is the integrated transparent photovoltaic system, located within the glazed modular system. The photovoltaic is integrated in the system in different percentages. This system is applied only at the building facade most exposed to the sun. The impact of the proposed energy retrofit measure on the building energy demands is analyzed, considering the characteristics of the new part of the structure and therefore the electricity production the photovoltaics.

3. CASE STUDY: MODELING AND VALIDATION

As case study, a city building located in the Metropolitan City of Naples is considered (Italy, Tyrrhenian coastline, Italic climatic Zone C [12], design winter outdoor temperature = 2°C, design summer temperature = 32°C). The building has a typical southern Italian structure of the 60s - 70s (fig. 1, where the typology is shown). It is a residential building, but two floors of the structure are used for shops (ground floor) and offices (first floor). The longest facades are oriented to north-east and south-west respectively. The total building area is 7457.1 m² and the conditioned area is 6708.9 m². The building is made up of 7 floors. For what concerns the thermophysical properties of the envelope components, the values of thermal transmittance were calculated according to the UNI EN ISO 6946 [13]. The thermal transmittance proposed by the abacus A.3. of the relevant standard UNI TS 11300-1/2008 [14] of this kind of building envelope is in the range 0.98 – 1.11 W/m²K, depending on the thicknesses. Thus, the values 1.01 W/m²K, calculated for the examined building, is perfectly in agreement. All other envelope components, opaque and transparent, are modeled in the same accurate way. About the transparent building envelope, it differs between offices, retails and residential use. On the ground floor (retail zones), windows have been developed with the intention of ensuring the safety of people and adequate protection against the risk of injury, falls, vandalism, with a U-value of 5.4 W/m²K. On the first floor (offices), there are 3 mm thick single-glazed windows, with an internal shading system, with a U-value of 6.3 W/m²K. On the following floors, (residential zones) there are single-glazed systems with wooden frames, with a U_W = 5.9 W/m²K.

Fig 1 The building typology (multistory, reinforced concrete frames and hollow blocks for walls and ceilings)

An accurate modeling involved also the definition of typical technical systems installed, first of all the heating systems and the cooling equipment. In residential and office spaces, the microclimatic control is guaranteed by a centralized gas boiler coupled with hot water radiators, during the heating period, and by DX (*i.e.,* direct expansion) split systems in summertime. The boiler has nominal efficiency equal to 0.81 and a thermal capacity of about 300 kW. The DX systems have an EER (Energy Efficiency Ratio) of 3 Wh_t/Wh_e, and the fan total efficiency is 0.7. The distribution system (hot water loop) has vertical uninsulated main pipes with horizontal branches, and the heat emission terminals are hot water radiators. For the retail zones, the microclimatic control is allowed by DX split systems during the whole year. The heating setpoint, established by the Italian D.P.R. 16 April 2013, n. 74 [15], is 20°C, and the heating setback is 16°C. According to D.P.R. 26/93 [12], the Italian territory is divided into six climatic zones. The city of Naples belongs to Zone C, for which [12] the heating period starts on November 15 and finishes on March 31 with a maximum activation time of 10 hours per day. In cooling mode, it was considered a maximum activation time of 12 hours per day, from 16 May to 15 September, set-point 26°C. The model validation and the evaluation of energy needs are carried out by comparing the results of the simulation to the energy requests of reference buildings. The gas demand obtained from the simulation is 68 kWh/m² per year, equivalent to an annual cost of 609 € per family (for a 100 m²/flat, by considering a cost of 0.09 € per kWh of natural gas) in line with the real gas consumption considered equal to an average expenditure slightly exceeding 600 € per year, calculated on the basis of an average value for this type of building in this city. With reference to the electricity demand, the data of the Italian Regulatory Authority for Energy, Networks and Environment (ARERA) are considered. The reference annual electricity demand for an Italian family of 3 people is around 1950 kWh/year, average value referred to 2019 [16]. The electric energy consumption obtained from the simulation per 100 m² of the residential area is 1921 kWh_e. Thus, the calculated Mean Bias Error (MBE) [eq.1] is equal to 1.27%, *i.e.,* is within the limit established by M&V and ASHRAE Guidelines: MBE (%) ≤ ±5% for validated building models.

$$MBE[\%] = \frac{(M-S)_{year}}{M_{year}} \cdot 100 \qquad \text{[eq.1]}$$

Concerning the whole energy performance, the baseline primary energy consumption is equal to:

- 336 016 kWh_p/year for electricity demand;
- 423 369 kWh_p/year for gas demand.

4. ENERGY RETROFIT MEASURE AND RESULTS

The proposed retrofit consists of the creation of a "structural exoskeleton", the existing structure is flanked by a self-supporting structure (usually made of steel, highly performing in terms of rigidity and dissipative capacity) that allows an anti-seismic improvement of the building. A glazed system, formed by panels installed in the frame geometry of the structure, covers the exoskeleton. This system is applied to the south-west building facade. This results in a system large-cavity DSF, by forming a second skin (transparent) for the building. The double skin façade system (fig. 2) is formed by an external skin of double layer of glasses, 6 mm thick, with an inner layer of 13 mm filled with Argon gas, used to improve the thermal transmittance value of the double-glazed windows. Between the double glazing and the previous external wall of the building, the created walkable space is 2.50 m deep.

Fig 2 Design concept of the double-glazed external facade

With the installation of DSF, a reduction of primary energy consumption in wintertime around 25% is achieved. On the other hand, around 83% increase in space cooling consumption is noted. Indeed, the greenhouse effect that improves the winter thermal behavior affects negatively the summer performance. Globally, with the single use of the DSF system integrated in the exoskeleton, an overall primary energy reduction of 60691.97 kWh_p per year, equivalent to an annual saving of 12%, is obtained. Subsequently, transparent solar panels are incorporated in the double-glazed system. The connection of the transparent photovoltaic modules on the facade, in the modeling of the retrofit intervention with DesignBuilder software, has been made in the "Generation" section. The modules have an efficiency of 9%. Of course, here, the definition of "module" refers to the whole transparent area included in one modular frame of the exoskeleton (around 20 m^2). The specific peak power is about 50 W/m^2 and thus a lower value compared to a traditional PV technology but a frontier concerning the transparent tech. The inverter used for the electrical conversion from DC to AC has a conversion efficiency of 0.95. Different percentages of PV panels integrated in the façade are considered, in particular 10%, 20%, 30%, 40% and 100% of PV glazing (with respect to the overall glazed area). The first results, due to the introduction of the PV, are an increase in the annual electricity demand, due to the a slightly higher use of cooling systems, and a reduction of annual gas demand (even if globally, thanks to the PV production, there is a reduction of the total building primary energy demand). These results have a growing impact with the increase of the percentage of PV introduced, as shown in Table 1. However, the increment in electricity is covered by the electricity converted by the photovoltaic system, that increases with the percentage of photovoltaics, as shown in Table 2. When the PV panels cover the entire area of the external facade (100% PV), there are two months of the year in which the PV electricity exceeds the demand, as shown in Figure 3. The combined technology (*i.e.,* DSF and transparent PV panels), chosen for achieving energy saving in the winter period, maintain the desired expectations also with reference to the whole year, even if a focus to the summer cooling demand is necessary. Indeed, from the analysis of the retrofit solution, a side effect is the increased summer consumption.

Table 1: Percentage variations of primary energy requests [%]

	$PECh_g$	PEC_c	PEC_b
10% PV	-6%	81%	-12%
20% PV	-36%	82%	-18%
30% PV	-36%	83%	-21%
40% PV	-37%	84%	-27%

Table 2: Photovoltaic electricity and global electricity saved

	PV electricity produced [kWh_e]	Total electricity saved [%]
10% PV	10729.45	6%
20% PV	24774.29	13%
30% PV	33565.73	17%
40% PV	49511.52	25%
100% PV	128968.4	65%

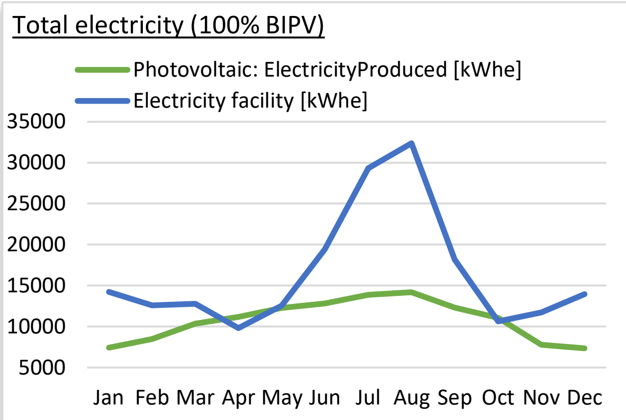

Fig 3 Differences in monthly electricity consumption and production with 100% of BIPV

This increase of cooling need, by properly managing the ventilation inside the air cavity between the inner and outer facades, can be reduced. Thus, the ventilation rate was increased, in summer, from the basic value of 1 vol/h to 10 vol/h, then 20 vol/h, 30 vol/h and 40 vol/h.

Table 3: Energy consumption for cooling and percentage energy saving with the increase of ventilation value

	Energy consumption for cooling [kWh_e]	Energy saving [%]
DSF baseline	57510.2	
DSF 10 vol/h	48702	-15.32%
DSF 20 vol/h	46523.6	-19.10%
DSF 30 vol/h	45539.7	-20.81%
DSF 40 vol/h	44959.6	-21.82%

Table 3 shows the energy demands for cooling, for the base DSF and by varying the ventilation in the air cavity. It is clear that, referring to the base case without any intervention, the increase in energy consumption in summer drops from the initial value of 83% to values between 55%-43%. This entails a further reduction on the total building energy demand.

5. CONCLUSIONS

For the improvement of RC buildings, structural exoskeletons are increasingly applied as a new iron frame. Such systems offer the opportunity also of a new skin for buildings. In this investigation, the retrofit project has enabled to achieve the driving goal of reducing winter demand in combination with a higher level of seismic safety and a non-negligible percentage of on-site energy production from renewables (65.3%, in case of 100% BIPV for the DSF). The gradual inclusion of the various percentages of PV inside the facade has been operated to better understand the effects due to the combined use of the two technologies (DSF and BIPV). The use of the double skin facade improves the thermal insulation towards the outside, in winter provides a useful greenhouse effect, and thus decreases the energy demands for heating. This is obtained because the solar gains enter, while the thermal infrared emission can be managed, by ventilation (in summer) or recovered (in winter). Solar energy conversion is one of the technologies of generation from renewable sources with the greatest potential. Yet, the technology that exploits the operation of photovoltaic cells present in opaque panels has a limit, and thus the integrability in transparent technologies. On the other hand, the transparent photovoltaic has a still limited diffusion, due to the low yields guaranteed by this technology (about 1/3 compared to panels with opaque cells), but thanks to research and development, in a few years, it will be more widely applied. Here we have expressed a possible application in common buildings for retrofit purposes.

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