Energy requalification of a historical building: A case study

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Highlights

- Renovation of the building aims to reach high performance levels and sustainability criteria.
- Maximum use of daylight aims to reduce energy demand for lighting, but overheating and glare phenomena must be avoided.
- Indoor comfort is achieved by means of natural ventilation and massive walls.
- Renewable energy systems are integrated in the roof without altering the building's aesthetic.

Abstract

This paper illustrates an energy upgrading proposal of a historical building in Naples (Italy): Palazzo Fuga, better known as the Real Albergo dei Poveri which was built in the second half of the XVIII century.

The proposal consists of energy efficiency interventions on the building envelope and its plants. As energetic and thermal aspects are concerned, simulations were performed in order to size a photovoltaic system, considering lighting aspects, and to evaluate the improvement of the building energy performance. Furthermore, thermal and lighting measurements were performed with a double aim: to verify the factual state of the building and to calibrate the calculation tools to the particular situation. In this paper obtained results concerning the feasibility of interventions will be presented and discussed.

Keywords

Cultural heritage, Conservation, Energy saving, Renewable energy

1. Introduction

The Real Albergo dei Poveri of Naples, a unique monument for its architecture, dimensions and volumetric organization, was built in the second half of the XVIII century from an idea of the King Carlo of Borbone. The building had to host, educate and rehabilitate the poorest of the reign. The original project, by the architect Ferdinando Fuga, contemplated the realization of a city in the city, but the building construction was interrupted in 1819: the realized part of the building, in Fig. 1, is only one half of the original project, but it seems imposing anyway and it looks like a realm than a welfare centre.

Fig. 1. The Real Albergo dei Poveri.

In the following the building was transformed, modified, partly demolished and occupied unlawfully; the peak of these events was in 1980 when a strong earthquake caused collapses and severe damages that made the building completely unfit for habitation. In the original project the building had to be bigger than the Reggia di Caserta; it had to be 600 m long and 150 m wide and it had to include five courtyards. A four aisles church had to be disposed in the central courtyard. When the building's construction was interrupted only three courtyards had already been built, the façade length was 364 m and the central church was only sketched.

The requalification project of the Real Albergo dei Poveri was included in the question of the rebirth and re-use of abandoned historical buildings (see Table 1). In particular, energetic aspects have represented a topic of a case study of the SARA (Sustainable Architecture Applied to Replicable Public Access Buildings) project.

Table 1. The Real Albergo dei Poveri in synthesis.

Age	250 years
Surface	103,000 m^2
Volume	830,000 m^3
Levels	From 2 to 9
Main courtyards	3 (6500 m^2, each)
Minor courtyards	6 (700 m^2, each)
Total width	140 m
Total length	384 m
Maximum height	42 m
Minimum height	15 m
Spaces	440
Corridors	9 km
Renovation costs	85 M€
New use	Youth city
Promoter	Municipality of Naples

A proper compromise between energy efficiency requirements and conservation of historical buildings is necessary to avoid conflicts and to obtain good energy performances in the respect of the buildings and monuments heritage [1], [2].

The SARA project has interested only the big frontal body of the central courtyard. The body is composed of two parts, divided by a lateral corridor. “Little rooms” (6.2 m × 10 m) correspond to the old offices and to the ministers rooms are distributed on the seven levels of the body. The lateral part of the body was designed for dormitories and soup kitchen.

Experts and designers were asked to deal with:

- Renovation of the building aiming to reach high energy performance levels and fixed sustainability criteria, using traditional, natural, ecological and local materials.

- Use of high energy performance technologies aiming to reduce energy consumptions, in particular heating and lighting ones.

- Maximum use of daylight (in particular at the three top levels) aiming to reduce the energy demand for lighting, without neglecting the risk of overheating of environments during the summer.

- Collection and storage of rainwater for re-use of water aiming to reduce water needs of the buildings.

- Use of natural ventilation and low thermal transmittance of walls for indoor comfort both during winter and summer season without installing air conditioning systems, not compatible with the building structure.

- Integration of renewable energy systems, in particular in the cover at the last level.

- Monitoring of consumptions.

2. Feasibility study of interventions

All the hypotheses of intervention were compatible with the accordance that the Municipality of Naples took with the Government Department responsible for the environment and historical buildings. In particular the only elements of the building's envelope that could be modified were floors, roof and windows.

The feasibility study has focused on structures, plants and envelope of the building. In particular, concerning energy aspects, calculations were performed considering the hypothesis of a photovoltaic plant, daylight penetration, and thermal efficiency of the building.

At the factual situation, neither heating nor air conditioning systems work in the building. In agreement with the architectural project, a high performance plant was hypothesized, with floor radiant panels for heating. No air conditioning was considered during summer [3], [4]. Natural ventilation was hypothesized for air change [5], [6].

The analyses and calculation procedures will be described in the following sections. The start point was the respect of the monument with the aim to hand it down to future generations as an intact historical document [7], [8].

3. The PV intervention

One of the most significant intervention hypotheses for the energy efficiency of the Real Albergo dei Poveri in Napoli is the design of a PV roofing at the top level (VII) of the AB lot, which is constituted by a big open space. The architectural project included the interior rebuilding of this level, by eliminating the floor and partially substituting it with a suspended footbridge (Fig. 2). The aim was to lighten the structure and to make visible the level below, creating a visual link between the two levels. Since the roof could be modified, the restorer architects proposed to place a transparent or a semi transparent roof in order to allow daylight entrance, in addition to the side windows. Furthermore daylight could pass through the holes aside the footbridge and reach the VI level. From a different point of view, considering energetic and sustainability's aspects, a PV roofing seemed a very effective solution.

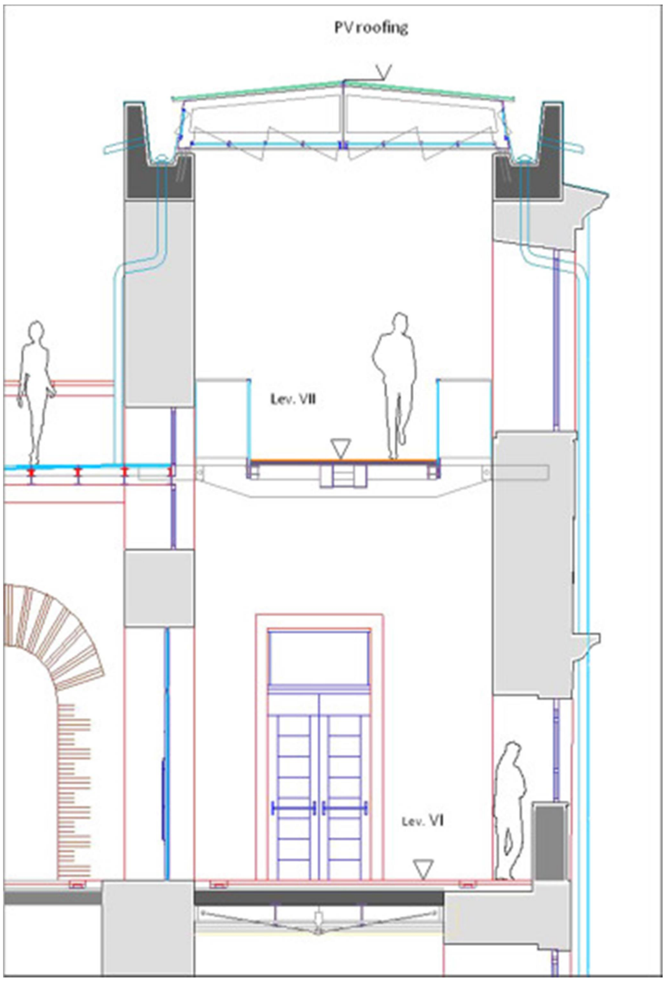

Fig. 2. Cross section of PV roof and levels VI and VII (from: Comune di Napoli).

Indeed, the realization of a PV roofing at Real Albergo dei Poveri in Naples assumes a great symbolic and demonstrative value.

The PV roofing covers the entire corridor, as shown in Fig. 2.

The orientation of the receiving surface has been strongly conditioned by a strict constraint: the non-invasively and non-visibility of the roofing by main points of view in the city, as required by the superintendence authority. The therefore obligated orientation has an azimut, γ of −41° (East) with respect to South and a tilt, β, of 4° and it is certainly not an optimal one.

No shading due to interference between modules is observed since they are disposed on a slightly inclined pitched roof; furthermore there are not buildings shading modules. According to the restorer architects' request, the proposal of a half transparent roof was examined.

3.1. Half-transparent PV roof

The PV system is composed of 186 modules (square mono-crystalline silicon cells), each giving 400 W_p (total capacity: 74.4 kW_p). The conversion plant is composed of 14 inverter, each characterized by an active power of 5 kW. The transparent roof is about 20% of the total area, so that lighting of the spaces below it is assured.

PV modules are not standard ones, but custom made to fulfil architectural restrictions and waterproofing needs.

The PV modules frame is made of metallic modular elements with a useful surface of 257 cm × 140 cm. The glass-cell-glass sandwich's thickness varies from 1.0 to 1.8 cm and its weight varies from 25 to 45 kg/m^2. PV module characteristics are reported in Table 2.

Table 2. Characteristics of PV modules for half-transparent roof.

Modules number, N_{mod}	186
Modules number for each side, $N_{mod,side}$	93
Module base, b_{mod} [cm]	140
Module height, h_{mod} [cm]	257
Total surface, $S_{t,mod}$ [m^2]	3.6
Active surface, $S_{a,mod}$ [m^2]	2.8
Peak power, $P_{n,mod}$ [W$_P$]	400

The energy production of the system was calculated considering the average solar irradiation on each side of the roof (Table 3).

Table 3. Yearly energy production of the PV roof.

Side	$P_{n,side}$ **[kW$_P$]**	I **[kWh/(m^2 year)]**	h_e **[h/year]**	η_m **[%]**	E **[MWh/year]**
SE	37.2	1.68×10^3	1.68×10^3	75	46.9
NW	37.2	1.54×10^3	1.54×10^3	75	43.0
					89.9

The yearly total energy production was estimated to be about 89.9 MWh, with a peak of 12.5 MWh (in July) and a minimum of 2.61 MWh (in December).

The proposal of a half-transparent roof was made to satisfy the necessity of increasing daylight access in the two top levels of the building. The use of daylight in buildings is to be favoured, not only for indoor environmental quality, but also to reduce electric light energy consumptions.

From this point of view, the PV roof would produce energy and, at the same time, it could improve daylight entrance (top lighting technique). However, the effects of overheating of environments and dazzling cannot be neglected in presence of top lighting. Indeed, it should be considered that half-transparent PV could modify indoor microclimate, also because of modules overheating during their operation. Consequently, proper ventilation is necessary and in particular natural ventilation solutions are more suitable, because mechanical systems may need the majority of produced energy.

For the abovementioned reasons, the possibility of an opaque PV roof was considered.

3.2. Opaque PV roof

An opaque PV roof could guarantee comfort conditions to occupants, without the need to use air conditioning provided that lighting needs are satisfied. Moreover energy production could be increased

(+20% with respect to the previously described solution), avoiding dazzling and limiting environments' overheating during summer.

From the above results and considerations, the opaque PV roof seemed to be the best solution from many points of view, with the exception of daylight entrance. For this reason, the differences in daylight distribution corresponding to the proposed solution of PV roofs needed to be evaluated, in order to identify the most convenient solution.

4. Daylight analysis

By means of the lighting simulation software Dialux [9], a model of the two top levels (comprising the corridor and the suspended footbridge) was set up. It is worthy noticing that both levels are already daylit by means of side windows. A good agreement between the simulated model and the real building was assessed by comparing measured illuminance values, collected in three different days at particular times, with simulation results obtained for the same days and hours. Both clear sky and overcast sky conditions were considered. The percentage differences between measured and calculated illuminances do not exceed 15%. Daylight Factors (DF) were calculated both on the corridor and on the footbridge (see Table 4). Moreover, illuminances were evaluated in the following conditions:

- under overcast sky (CIE overcast sky model) during the morning (9:00 a.m.) of a winter day (21st December), in order to analyze illuminance levels with unfavourable daylight conditions.

- under clear sky (CIE clear sky model) in different days of the year and at different times, in order to evaluate the effects of direct solar radiation.

Table 4. Daylight Factors (DF) on the two considered levels.

Calculation surface: footbridge

Roof	**DF_m**	**DF_{min}**	**DF_{max}**
Opaque	1.22	0.35	9.50
Semi-transparent	3.99	2.75	12.0

Calculation surface: corridor

Roof	**DF_m**	**DF_{min}**	**DF_{max}**
Opaque	0.65	0.28	2.58
Semi-transparent	0.88	1.39	2.97

From the analysis carried out, it can be stressed that the presence of the half-transparent roof has a low effect on illuminance values due to daylight in the corridor, while it has a significant impact on the footbridge (more than 500%). Consequently, in order to make a choice, a more accurate evaluation of indoor environmental comfort conditions and summer heating loads should be considered.

5. Intervention on the building envelope and potential energy saving

An analysis of factual situation and interventions was carried out in order to evaluate the potential energy saving.

5.1. Factual situation

Aiming to evaluate benefits in terms of energy saving due to the designed interventions, a thermal performance model of the building was necessary. The thermal transmittance U of sample external walls was measured by means of a heat flux meter and temperature probes, a cheap and reliable methodology.

The external walls are made of tuff stones of variable thickness (from 1.1–1.3 m to 2 m), which makes them rather non homogeneous also for the presence of different wall types and vacant spaces. Both available data and specific tables were not sufficient for the characterization of the walls by applying the EN ISO 6946 standard [10], so in situ measurements of thermal transmittance were performed.

Measurements were carried out on a wall facing Carlo III Square (see Fig. 3, Fig. 4), in a sample room.

Fig. 3. The building facade.

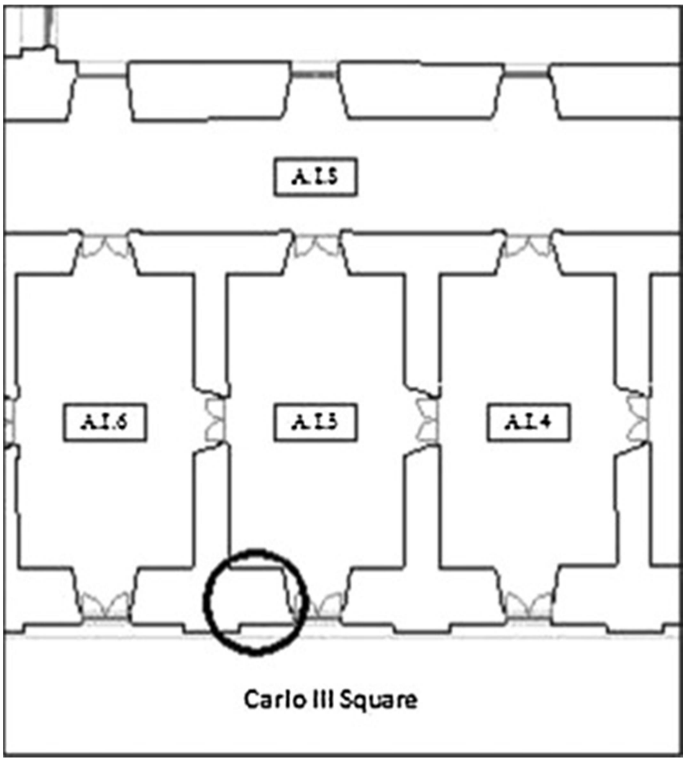

Fig. 4. Sample room and position of instruments for the measurement of thermal transmittance.

The instruments used for measurements are:

- 1 heat flux meter, see Fig. 5;

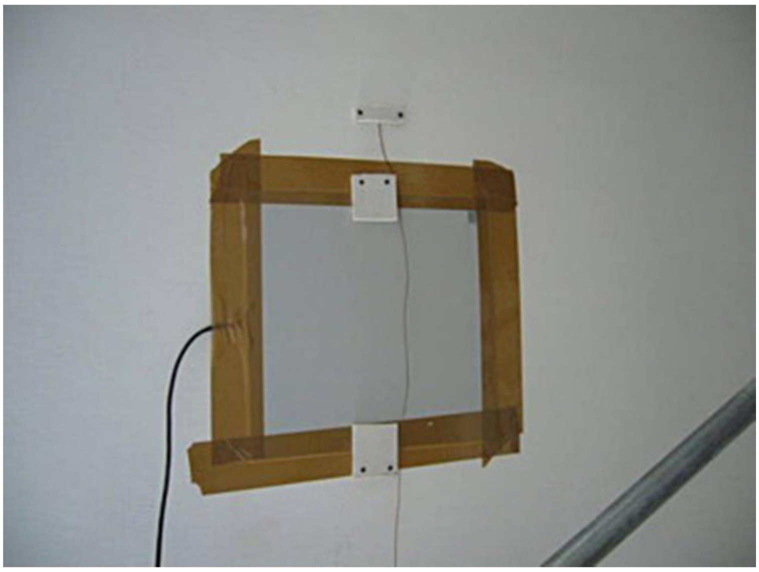

Fig. 5. The heat flux meter and one of the temperature probes installed indoor on the south wall for the measurement of thermal transmittance.

- 4 surface temperature probes, see Fig. 6;

Fig. 6. Picture of the outdoor temperature probes during measurements on the South wall.

- 1 data logger ALMEMO 2690-8.

5.2. Data collection

Several data were recorded for the measurement of thermal transmittance: a set of 1589 measurements, recorded with an interval of 20 min was used to obtain the value of thermal conductance C. Then, the value of transmittance U was calculated following EN ISO 6946 [6]. Values obtained by means of the two available methodologies are very different (see Table 5).

Table 5. Comparison between values of conductance and transmittance obtained by progressive average values method and black-box method.

Empty Cell	**Progressive average values method**	**Black-box method**	**Difference, *Δ* [%]**
Conductance [W/(m^2 K)]	0.29	0.48	39.6
Transmittance [W/(m^2 K)]	0.28	0.45	37.7

The thermal conductance *C* and transmittance *U* values obtained processing data by means of the black box method result greater than those obtained with the progressive average values method of 39.6% and 37.7%, respectively. Given the strong variations of external temperature during the day, values obtained by means of the black box method result more reliable, taking also into account that the South wall is considerably heavy. Consequently the transmittance value is assumed equal to 0.45 W/m^2 K. Since input data for the calculation with the rigorous procedure were not completely available, a detailed calculation was not applicable. So, simplified procedures were applied: partial results were obtained, but certainly more coherent to the kind of information available concerning the building. For example, instead of the energy performance indicator for heating, during the initial phase of design or during construction, it is possible to refer to other indicators, such as the specific energy need of the building envelope, or the simple heat loss for transmission.

In this case, the aim of energy assessment was to compare the two different configurations: before and after interventions, so that the application of a simplified procedure was enough. In particular the “simplified calculation of the annual primary energy saving due to an energy efficiency intervention” developed by ENEA [11] was used.

Calculation is referred to a sample vertical part of the building and in particular the one containing the sample room where the measurements of thermal transmittance were performed. The factual situation of the building envelope is the following:

- Only seven of the eight levels involved in the renovation project are heated.

- The south facade, from level I to the top has wooden window frames with a 3 mm thick glass. At the 0 level iron gates are installed in place of windows.

- The central side, the one that separates rooms from corridors, is provided with wooden doors at all the levels.

- The north side is not equipped with windows and so corridors are opened to outdoors.

After the interventions, the configuration should appear as follows:

- The south facade has wooden window frames and 9 mm stratified glass; only at the level 0 iron windows frames with insulating glass (3-4-3 mm) are installed.

- The north facade has iron window frames and insulating glasses (3-4-3 mm) at all levels, except level I and level 0. At level I wooden window frames with a 9 mm stratified glass will be installed and at level 0 will have no windows and it will remained opened to outdoors.

- The floor at level VII is replaced with reinforced wood and *Predalle*, gaining a better thermal performance compared to the factual situation.

The values of thermal conductivities of the building envelope opaque elements have been deduced by measurements of thermal transmittance. Values of thermal conductivities of other materials have been deduced by standards UNI 10351 [12] and EN ISO 10077-1 [13].

6. Results

The evaluation of the primary energy saving during the heating season was performed using the *ENEA modified* procedure [11]. Firstly the heat power saving in terms of thermal power loss for transmission, ΔQ_h, was calculated. The reliability of this procedure was evaluated comparing the values of calculated heat loss for transmission of some sample rooms with the values obtained applying the UNI 13789 procedure. The differences in results did not exceed 1.8%.

Calculations were performed for each room, considering a continuous work schedule and referring to the city of Naples (GG = 1034, GR = 137).

As anticipated, the ENEA simplified procedure provides results in terms of differences between the two configurations, when an intervention on the building's envelope is considered. So it says nothing about absolute performances of the building before and after interventions, because heat losses due to ventilation, Q_v, and heat gains both due to sun, Q_s, and to internal ones, Q_i, are considered having the same value in the two configurations, but they are not quantified. The only quantified values before and after interventions are the Q_h ones, so, all results are presented in terms of absolute differences except for ΔQ_h which is presented both in absolute and percentage terms.

Table 6 shows, for each room: ΔQ_h, the annual energy saving referred to the heating period ΔQ_a and the saved primary energy, ΔQ_{pr}. N_{room} is the number of rooms for each level. The total saving of primary energy was calculated for each level as well as for the whole AB lot. A 80% global average seasonal efficiency η_g was considered, to take into account the high performance of emission, in accordance to Italian Technical Specification UNI/TS 11300-2 [14] due to the use of floor radiant panels and to the fact that other subsystems are characterized by high efficiencies to meet law requirements. Since no plant is working at the factual state of the building, the same plant situation has been considered before and after interventions.

Table 6. Primary energy saving during the heating season.

AB lot

Room	ΔQ_h [W]	ΔQ_a [kWh]	$\Delta Q_{pr,room}$ [kWh]	N_{room}	$\Delta Q_{pr,level}$ [kWh]	Percentage reduction of Q_h [%]
A.0.5	177	581	726	8	5808	22.1
A.I.5	116	381	476	12	5710	23.0
A.II.5	97	318	397	4	4769	26.2
A.III.5	96	315	394	15	5911	23.2
A.IV.5	101	333	416	15	6235	26.8
A.V.5	106	346	436	15	6534	22.3
A.VI.5	414	1361	1701	15	25,520	42.5
Total					60,485	27.1

In conclusion, a saving of 27.1% was estimated for the entire heating season. The primary energy saving was calculated also considering the thermal conductivity of tuff indicated in UNI 10351 [8], which is equal to 1.7 W/(m K): in this case the obtained value is 18.1% and therefore bigger than the previous one.

The estimated annual reduction of CO_2 emissions ($R_{CO_2,a}$) was calculated considering that each 1 kWh produced by the National energy system corresponds to a production of 0.531 kg of CO_2. So:

$$R_{CO_2,a} = Q_{pr,tot} . F_{mix}$$

where $R_{CO_2,a}$, annual reduction of carbon dioxide emissions, kg CO_2/year; $Q_{pr,tot}$, primary energy annual saving due to energy efficiency interventions on the building envelope, kWh/year; F_{mix}, emission factor of the Italian electrical mix at the distribution equal to 0.531 kg CO_2/kWh.

If we consider the evaluation of the energy saving previously reported, it follows:

$$R_{CO_2,a} = 6.05 \times 10^4 * 0.531 = 3.21 \times 10^4$$

with $R_{CO_2,a}$ in kg CO_2/year.

So, the estimated annual reduction of carbon dioxide emissions is 32.1 t.

7. Conclusions

In this paper the complex topic of energy requalification of historical buildings is approached through a case study which shows how the choice of compatible solutions to improve the energy efficiency requires accurate analyses from different points of view such as preservation and aesthetic aspects. Indeed, this is a widely interdisciplinary field in which each individual solution needs to be carefully evaluated, considering advantages and disadvantages.

From the results obtained by applying the photovoltaic, lighting and thermal models to the Real Albergo dei Poveri, it can be inferred that:

- an opaque PV roof results to be more convenient than a semi transparent PV roof, for aesthetic, energy production and thermal comfort aims. This is true also for daylight entrance: the half transparent roof causes a very low increase of daylight in the corridor at the VI level, while it has a very significant impact only on the footbridge at the top level. There, however, it could cause dazzling and overheating during the summer season;

- given the windows' geometry and location, no significant variation in daylight access can be obtained without modifying the envelope's aesthetic;

- the presence of thick and heavy external walls requires no intervention of thermal insulation;

- the estimated PV energy production with the opaque solution is about 107.9 MWh/year;

- interventions on windows and on the floor at the VII level determine estimated energy savings of about 27.1% for the entire heating season;

- the estimated annual reduction of carbon dioxide emissions is 32.1 t.

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