ARCHITECTURAL INTEGRATION OF PHOTOVOLTAIC SYSTEMS IN HISTORIC DISTRICTS. THE CASE STUDY OF SANTIAGO DE COMPOSTELA

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ABSTRACT

Historical buildings are often energy inefficient. Renewable energy sources can be implemented in the refurbishment projects in order to cover the high-energy consumption with sustainable sources. The paper presents the results obtained in the FP7 Project EFFESUS on the architectural integration of PV systems in the historic city center of Santiago de Compostela. In this case, one of the most challenging issue was the preservation of the original form and value of the historic district, considering the rules of local legislations and policies. According to these rules, the building stock has been classified in specific levels of constraint in order to define the compatible retrofit interventions for each level. The study has been supported by historical analysis, visual tests and heritage information of the Santiago GIS Data System. From these data the roof surfaces - where the installation of PV system is deemed compatible with conservation constraints - has been estimated. This study showed few degrees of freedom for the PV installation with traditional systems. On the other hand, in a historic building there are many possibilities for integrating PV systems without altering the original aspect and considering the aesthetics, physical and mechanical compatibility. The approaches developed in others European and international projects are investigated (e.g. 3ENCULT; IEA-PVPS Task 7; IEA-SHC Task 41; SuRHiB; FP7 SolarDesign, PVACCEPT) to define correct suggestions and recommendations for preserving (and in some case enhancing) the cultural value of historic districts and buildings. Next, the solar energy irradiance and irradiation maps of a specific area have been calculated, starting from the Digital Surface Model, with the module r.sun of GRASS, an open source Geographic Information System (GIS) software. From these data, the PV potential of the district has been carried out assuming a PV efficiency of 15% and 25% of losses in electricity production. The daily production data has been calculated only on filtered roofs (heritage constraints and suitable insolation level) and summed up to compare it with the consumption profile. PV production could then cover 73% of electricity needs of the district. The GIS software GRASS has been especially useful because permits to not only manage and analyze spatial data but to interpret and understand their relationships or patterns and to combine several spatial datasets obtained in this research, i.e. PV potential and historical building data.

Key words: *energy efficiency, historic buildings, heritage constrains, renewable energy sources, PV systems, solar energy irradiance, irradiation maps, PV potential, Geographic Information System*

1 INTRODUCTION

In the near future, the decision of the European Commission to drastically cut the CO_2 emissions and increase the share of the renewable sources (Directives 2002/91/EC; 2010/31/EU; 2009/28/CE) will bring to a higher acceleration in the improvement of buildings energy performance, both contemporary as well as traditional buildings. Specific to the case of historic buildings, the integration with renewable energy sources (RES) in the refurbishment project could be considered as a challenge to cover the high-energy consumption with sustainable sources. In fact, the architectural integration of solar panels in a sensitive historic context is very critical because they have an appearance, which is not always coherent with the historical building in terms of aesthetics, colours, shapes, dimensions and surface designs. On the other hand, the market offers building integrated photovoltaic (BiPV) products suitable for the application in the historical buildings without altering the original integrity or harming the aesthetics or the cultural value. Also, several best practices [7], guidelines [1; 3; 12; 14; 15; 17; 18; 19], and solar plans (i.e. Mainbernheim, Nuremberg and Bamberg in Germany) demonstrate that PV systems could be integrated successfully in the historic context. Because of the distinctive character of the context where historical buildings are present, the installation of PV systems is only possible when the specific project has the aim to minimize physical and visual impacts. This means maintaining and enhancing the historic features and appearance, selecting reversible and compatible technologies, increasing the economic value and avoiding any kind of damage. At the same time, criteria for a successful solar design are driven by PV systems performances and economics. An accurate integration design could lead to an improved PV performance and consequently to an enhanced economics value. In fact, typical problems which affect BiPV performance such as not optimal orientation, partial shading, high PV operating temperature, could be avoided by adopting best practice design rules such as correct module wiring, use of fake modules where needed and PV module retro-ventilation.

2 METHODOLOGY

The paper presents the results obtained in the FP7 Project EFFESUS on the feasibility of the architectural integration of PV systems in the historic city center [6]. The study focuses on a specific area of Santiago de Compostela, which is representative of the typical urban morphology and construction typology. One of the most challenging issue was the preservation of the original shape and value of the district, considering the rules of local legislations and policies. For this reason, a strong multidisciplinary exchange has been developed among building physics, conservation, restoration, urban planning, solar design, and energy management. This reiterative procedure validated the process and guaranteed quality outcomes. The evaluating method consists of different phases:

- Historical analysis of urban and architectonic development of the city centre;
- Identification of constrains and restrictions for the RES integration in the urban policies;
- Assessment of architectonic, historic and aesthetics values of the area;
- Analysis of the solar energy potential;
- Calculation of PV production and load match;
- PV architectural integration criteria

The existing building stock, normally, is very heterogeneous. Buildings can be categorised according to ages, architectonical styles, heritage values, architectural qualities, construction techniques, materials, components, and finishes. Only the integrated analysis among history, urban policies, and heritage constrains permits to verify the feasibility of PV systems in the historic context. As often happens, according to a preliminary analysis of urban polices and rules, the installation of traditional PV systems is deemed to have a low compatibility with the historic context. On the contrary, the application of BiPV systems seems to be partly allowed, if a specific design project is considered. Once the possible compatibility was verified, the solar energy and the PV potentials of the area were carried out. The analysis of the solar energy potential was carried by calculating the solar energy irradiance and irradiation maps of a specific area, starting from the Digital Surface Model, with the module r.sun of GRASS, an open source Geographic Information System (GIS) software. From these data, the PV potential of the district has been carried out assuming a PV efficiency of 15% (typical efficiency of silicon polycrystalline modules and future high performing CIGS modules) and 25% of losses in electricity production (performance of PV system is assessed using the parameter Performance Ratio, PR. Typical PR of BIPV systems is around 0.75 which corresponds to 25% losses). The PV potential of the whole district is then calculated by integrating the production curves from the various filtered roofs and it can be compare to the electricity load profile in order to estimate the RES share. These data are essential to define the design criteria for the integration of PV systems in the historical buildings, balancing both the needs of historic preservations and solar design.

3 HISTORICAL ANALYSIS

The historical analysis is very important to understand the original urban concept and the building consistency of the entire urban area. Particularly, the historical evolution, the urban rules, the aesthetic aspects, the heritage features and the spatial relationship among different buildings (i.e. proportion, dimensions, scale, distances, and so on) has been analysed in depth. The main features, the historic materials, the specific constrains and the presence of potential damage has been also indicated for each heritage building. The study has been supported by literature, visual tests and conservative data of the Santiago GIS Data System.

Santiago de Compostela, located in the northwest of Spain, is an ancient city, with very high historic, social and religious values. The city has become a major pilgrimage route in Europe since the discovery of St. James's tomb in 9th Century. Destroyed by the Muslims at the end of 10th Century, the old town was completely rebuilt in 11th Century with a medieval style, in order to attest the "Reconquista" of the Christianity. The old town consisted of many narrow unpaved streets with different orientations and many interconnections. The traditional wooden courthouses with arbours were lined up continuously along these streets. During the Centuries, the urban scenario changed considerably: civil and religious architectural elements of the middle Ages were also integrated into urban fabric with valuable traces of Romanesque, Renaissance, Gothic, Baroque, Industrial and Modernistic styles. The urban development in 20th Century foresaw the construction of "satellite towns" in the outskirts, without any link with the downtown. So, the historic settlement faced with the problem of depopulation and demographic change. UNESCO declared the Old Town of Santiago "*World Heritage Site*" in 1985 in order to preserve and enhance its mediaeval history and its spiritual significance. After the UNESCO's declaration, the Santiago de Compostela City Council promoted the creation of a Technical Office (Consorcio de Santiago) to be in charge of designing and developing a specific rehabilitation program for the historic city centre, both from the architectonic and social point of view [20]. In 1989 the "*Plan General de Ordenación Urbana*" was approved, a practical program with operators and resources devoted to guarantee the presence of residential houses in the historic center. This, consequentially, pointed out the need for the protection of buildings [2]. For this reason, the Municipality approved the "*Plan especial de protección e rehabilitación da cidade histórica*" (1997) that addressed the preservation, and the restructuration of the old town [3]. The plan defined a comprehensive rehabilitation program, prioritizing the following issues:

- Conservation of the environment and of the built heritage;
- Preservation of housing and improvement of the residents' living conditions;
- Consolidation of the urban activities;
- Restoration of the historical city center as a meeting place;
- Revitalization of the historical city center with compatible functions.

4 HERITAGE CONSTRAINS AND RESTRICTIONS

The "*Plan especial*" classifies the ancient buildings in two categories: listed and not. The firsts are divided in four levels of protection, related to heritage, architectonic and environmental values (Level 1, 2, 3 and 4). The seconds are divided in two categories in compliance or not with the urban image of the city center (Type 1 and 2). The definitions and the possible interventions for each category of constrain are showed below (Table 1).

Table 1: Classification of the historical buildings in the heritage regulation

Definitions	**Level of constrain of listed buildings**			
	Level 1	**Level 2**	**Level 3**	**Level 4**

	Heritage building with exceptional historic-artistic, cultural and architectonic values	Heritage building with unique features and high historic, cultural or architectonic values	Building with special architectural and environmental significance	Union of architectonic, ethnographic and cultural values that show the features of traditional architecture
Possible interventions	Restore	Restore Conservation Rehabilitation	Conservation Rehabilitation	Conservation Rehabilitation Partial o global restructuration
Definitions	**Typology of not listed buildings**			
	Type 1		**Type 2**	
	Building aesthetically compatible with other buildings located in the urban area		Buildings without orders and dissimilar from local rules	
Possible interventions	Conservation Retrofit Environmental integration		Demolition Substitution Adjustment	
Source: Elaboration of the authors from the "*Plan especial de protección e rehabilitación da cidade histórica*", 1997				

Listed buildings are compatible only with the following types of intervention:

- **Restore** refers to the intervention realized in monumental buildings in order to reaching general conservation, replacement or reconstruction of the original architecture typology;
- **Conservation** refers to the interventions that aim to preserve the condition of health, security and aesthetics without altering the structure, the layout and the formal characteristics of the buildings;
- **Rehabilitation** refers to an improvement of functional conditions and habitability of the building. In this case the alteration of internal layout is allowed and the conservation of the architectonic elements must be guarantee (facade, entrance, stairs, and so on);
- **Restructuration** is applicable to the buildings that are inadequate for their use, due to damage or functional problems. It permits major changes, respecting aesthetics, envelope, materials, volumes and forms.

Depending from the consistency and the conservation of the listed building, different type of interventions are permitted. Particularly, on buildings damaged or ruined, a global restructuration is permitted. Each level of protection has an individual ordinance regarding facades, interiors, roofs and staircases. Initially, the possibility of using solar systems in the historical roofs has been investigated (Table 2).

Table 2: Rules for the intervention on the historic roofs

Eaves and cornices	
Aesthetics	The vision of the front or the top of the structural elements of the roof is forbidden
	The proportion and the modular design of existing roofs must be maintained
Materials	The new frames must be conform to traditional buildings (stone and concrete)
Roofs	
Aesthetics	The volume and the shape of the roofs must be similar to the existing roofs
	The roof must be sloped, with well-defined height (similar to historical buildings)
	The inclination of the slope must be 20-28°
Materials	The roofing materials must be conform to traditional building: - Curve Arabic tile (for traditional buildings); - Copper roofing (for buildings with contemporary forms); - Other materials (only for extension or new part).
Windows in the roofs	
Aesthetics	The dormers must be realized only for new construction or building extensions

	The height must not exceed the inclined plane of the pitch of the roof
Materials	The frame must have a colour conforming to the historical ones and must be barely visible
Source: Elaboration of the authors from the "*Plan especial de protección e rehabilitación da cidade histórica*", 1997	

This situation seems to let few degrees of freedom for the intervention on original roofs or their re-construction integrating PV components. On the other hand, there are many possibilities for the application of solar system in the roof without altering or harming the original aspect and also considering aesthetics, physical and mechanical integration (e.g. solar-brick can be directly installed on the roof surface respecting the small structure of the roof bricks, solar tiles can replace traditional tiles keeping the same colour, shape and pattern, flexible PV modules can be integrated on metal laminates fully respecting the roofing system shape and surface). Several research projects [22; 24; 26; 27] have already demonstrated the expression potentiality of PV modules highlighting that many innovative BiPV products are available on the market [25]. The great availability of PV products designed for building integration, enhances the possibility to use these systems also in sensitive and heritage contexts, opening new challenges for architects, designers and also for decision makers. So, the possibility of using solar systems in other parts of the historic buildings was explored (Table 3).

Table 3: Rules for the intervention on the historic facade, doors, windows, canopies, and signs

	Facades	**PV integration**
Aesthetics	The facades must have rhythmic and harmonic proportion	🟥
	Side and rear facades shall have a design and the materic characteristics similar to the rest of the building	
	The original facade can be modify only in not listed buildings, with a design coherent with the image of the historic center	
Materials	Materials eligible are: plaster and gypsum; stone, plaster and gypsum; stone; stone veneer.	
	Doors and windows	
Aesthetics	Doors and windows must have an organic design	🟨 Only in modern glass
	The doors cannot conceal the walls	
	The galleries must have a rhythm and size in accordance with the rest of the facade	
Materials	Materials must have the same colour of that of the windows	
	The doors must be realized in painted wood	
	The materials eligible for the windows frames are wood painted, lacquered or enamelled metal	
	Canopies	
Aesthetics and materials	In general, the canopies are not allowed	🟨
	The canopies can be made with traditional shapes, colours and materials, only after official authorization	
	Advertising signs	
Aesthetics	The colours shall be in accordance with the colour scheme of the facade	🟨
Materials	Materials eligible are: glass, painted wood, plates of metal printed, acrylic and stone, aluminium, steel or brilliant materials	
🟨 = Partially allowed 🟥 = Not allowed		
Source: Elaboration of the authors from the "*Plan especial de protección e rehabilitación da cidade histórica*", 1997		

In this case, the degrees of freedom for the RES integration are few. However, it is possible to think of specific projects characterized by a high degree of integration among RES integration and the historical value of the historic city centre or the heritage building, which considers at the same time the matters related to aesthetics and material compatibility.

5 ASSESSMENT OF HERITAGE VALUES OF THE AREA

After the analysis of the local legislations and policies on cultural heritage preservation [3; 4; 19], the study focused on a specific buildings block located between Rúa do Vilar and Rúa Nova (Figure 1). The area includes 41 edifices with different architectonical style, constructive typology, materials and heritage values [4]. Generally, the buildings located in Rúa do Vilar have mediaeval origins: they are narrower and smaller (wide 4-7 m; depth 7-10 m). The houses in Rúa Nova have baroque origins: they are wider (wide 4-7 m; deep 12-15 m), with a large internal patio that in the past was used as garden. In both cases, the buildings have three or four floors [13; 20]. The highest level often was cantilever over the ground floor, creating arcades on the street [6].

Traditionally, the workshops were on the ground floor and the owners' houses were on the upper floors. Currently, there are mixed functions, with commercial uses in the ground floor and residential uses in the upper floors [13; 20]. Regarding the constructive aspects, generally the structure is in stone with different masonries: the ground floor has a masonry facade while the upper floors are constructed with wooden walls [20; 21]. A typical element of the Galician style are the galleries, the weather-protected transitional space with large windows (Figure 2).

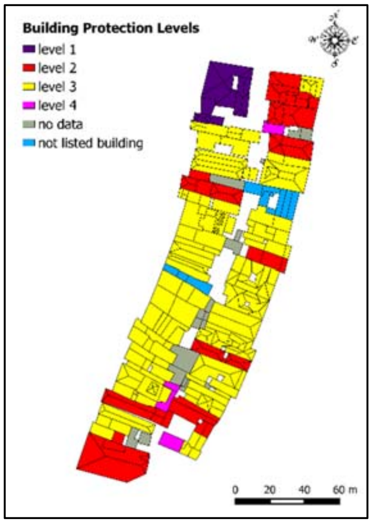
Figure 1: The analysed building block (Source: Elaboration of the Authors from Google maps photo of Santiago city center)

Figure 2: An example of the typical gallerias in the building block

In the building block, the following analyses have been carried out:

- Identification of specific levels of constrain and possible energy retrofit;
- Individualization of roofs with damage problems;
- Estimation of roof surfaces where the installation of PV systems is compatible with the historic heritage;
- Definition of suggestions and recommendations for the integration of RES in the historic city centre.

The buildings stock includes: 1 building listed as level 1 (Casa do Dean); 8 buildings listed as level 2; 32 buildings listed as Level 3 (19 in Rúa do Vilar and 13 in Rúa Nova), 6 building listed as Level 4 and 3 uncatalogued buildings (Figure 3) (Santiago GIS Data System, 2014). For each building the different possibility of intervention has been investigated (Figure 4). Next the roofs with damage problems due to the advanced state of decay, lack of safety conditions or aesthetics non-compliance compared to other buildings has been shown. The data on damages descripted in the "*Plan especial*" have been confronted with visual tests performed on site (Figure 5).



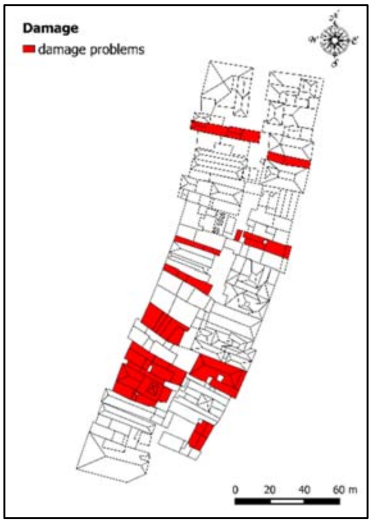


Figure 3: Building protection levels in the building block
Figure 4: Possible interventions for the heritage buildings
Figure 5: Roofs with damage problems or aesthetically non-complained

In these cases, it is necessary to improve the security level. Deteriorated historic features should be repaired rather than replaced. But, where the severity of the deterioration requires the replacement, the new features should match the old ones in colour, texture and, where possible, materials. In these cases, where the roof is damaged, unsecured or without heritage values, the installation of PV roof tiles could be particularly cost-effective as the new roof covering [5; 12; 14; 19]. A PV installation on the roof, in fact, could be timed to coincide with replacing the roof covering. As a recommendation, due to compatibility problems it is always better to replace the whole roof instead of a part [1; 5; 14; 17; 18]. From these data, the analysis of solar energy potential and PV potential has been carried out. The heritage constrains and the state of damage of the building has been considered as a "*filter*" for the entire study.

6 ANALYSIS OF THE SOLAR ENERGY POTENTIAL

In order to compute solar irradiation and irradiance mean values and to relate this information to a geo-database with buildings information the following methodology has been applied:

- Validation of buildings data-base;
- Computation of solar irradiation and irradiance values on grid cell;
- Computation of statistical values for each pitch of the roofs in the database.
- This data-base is the input for computing the photovoltaic potential.

Firstly, the geo-database of existing buildings (http://sip.consorciodesantiago.org) has been modified and integrated using google satellite information (Figure 6).

The area of each pitch starting from an estimation of the pitch slope has been evaluated. This slope is computed as the median of the slope calculated from the Digital Surface Model DSM ($1m^2$/px) with the Grass module r.aspetc. These data can be a first source of error because of the resolution and the quality of the DSM but measured data were not available. In order to compute the solar potential, solar irradiation and irradiance data are necessary. These data can be obtained through equations describing Sun-Earth position and the interaction of the solar radiation with the atmosphere. A very suitable model, r.sun, has been used [9] and [23]. This module manages and analyses geospatial data through GRASS, an open source Geographic Information System (Figure 7).

Figure 6: Sketch of the pitch slope in the area
Figure 7: Solar irradiance values [W m^{-2}], 20th July at 10 a.m.

The reliability of the results depends on the input data quality. In this case, only general information regarding atmospheric and geographical conditions has been obtained, in particular the input data were:

- Digital Surface Model 1m^2/px derived from LIDAR survey (2013);
- Digital Terrain Model resolution 65 m^2/px STRM 2001 [10] to consider the shadowing effect of the surrounding area;
- Linke turbity factor for each month (Table 4).

Table 4: Linke turbity during the year

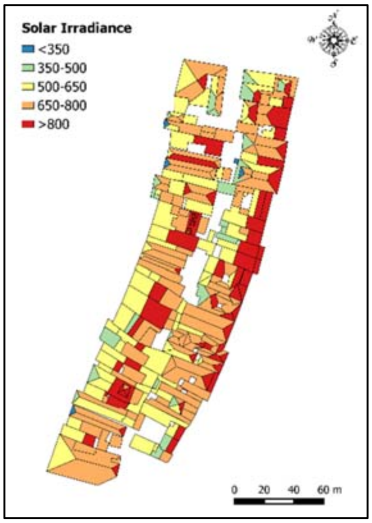
Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
3.5	4.1	3.6	4.2	5.0	5.0	4.6	4.7	4.9	4.2	3.9	2.9

Resources: http://www.soda-is.com/eng/services/service_invoke/gui.php?xml_descript=soda_tl.xml#parameters

The direct (beam) and global solar irradiation raster maps for given days, latitude and surface were computed by using the module r.sun. The model does not consider the spatial and time variation of the clouds. In fact, no spatial distributed coefficients that reduce the clear-sky radiation are available. The shadowing effect of the topography is incorporated by using rasters of the horizon height constructed with the module r.horizon.

Firstly, the solar irradiance values [W m^{-2}] for a set of local times (from 6 am to 22 pm, every hour) and for the following days have been calculated: 19th-26th January, 19th-26th March, 19th-26th July, 19th-26th September. Solar maps provide solar resource information on grid cells. Due to the resolution of the DSM, the mean value was computed for each pitch. The average of solar irradiance values is shown for the case 20th July at 10 a.m (local time) (Figure 8).

Secondly, daily sums of solar radiation [Wh m^{-2} day^{-1}] were computed. The solar radiation maps for a given day were obtained by integrating the relevant irradiance between sunrise and sunset times for that day. From this data, the monthly [kWh m^{-2} month^{-1}] and annual [kWh m^{-2} year^{-1}] sums of solar irradiation were obtained by computing the average values for each roof. The annual sums of solar irradiation has been reported (Figure 9).



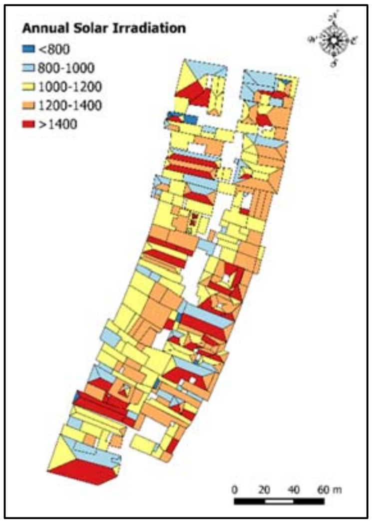


Figure 8: Average values of global solar irradiance [W/m^2] for the roofs, 20th July at 10 a.m. (local time)
Figure 9: Annual sums of solar irradiation [Wh/m^2/year].

Finally, in Figure 10 three different months, January, July and October, are shown.

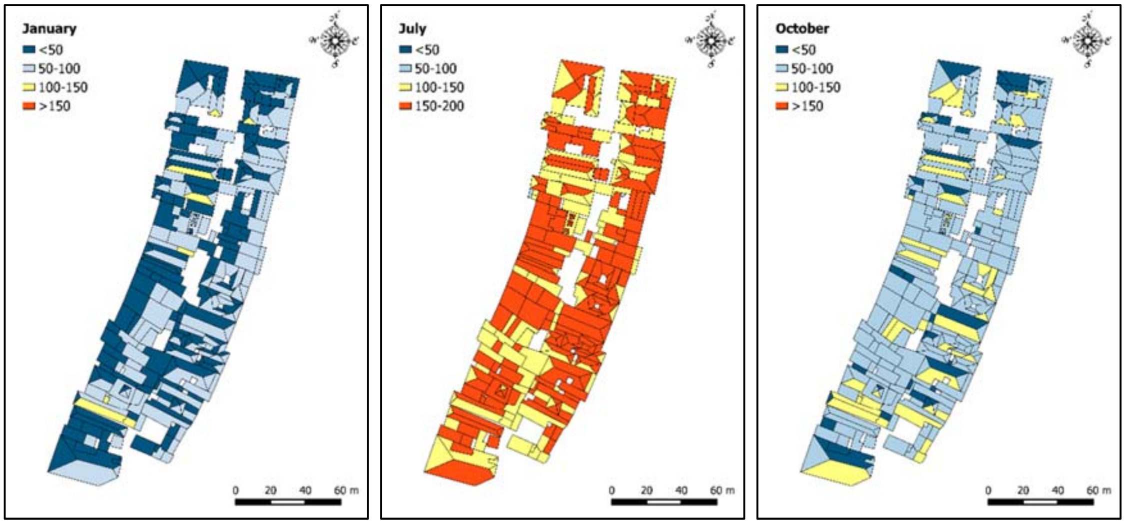


Figure 10: Monthly sums of solar irradiation [Wh/m^{-2}/month]

7 PV PRODUCTION AND LOAD MATCH

The PV system should always be sized to match at least the individual needs of a property, but it is also important to consider needs in future energy context at neighbourhood level. The calculation of the PV potential of the district was carried out assuming a typical silicon crystalline PV module efficiency of 15% (future PV modules specific for BiPV applications based on thin film technologies such as CIGS will also show similar efficiencies). The nominal power (P_n) (defined as the power at Standard Test Conditions (STC), 25^{o}C, 1000 W/m^2) per roof was calculated as:

$$P_n = A \cdot \eta \cdot G_{STC} \, [kWp]$$

where A is the area of the roof, η is the efficiency of the modules at STC, G_{STC} is the reference irradiance at STC (1 kW/m^2).

The yearly insolation values (defined as the incoming energy from the sun on the tilted surface over one year), were used as filters for roofs suitability for PV installations. The yearly final yield is defined as the electricity production per installed kWp over one year:

$$Y_f = \frac{E}{P_n} = PR \cdot Y_r = PR \cdot \frac{H}{G_{STC}} \left[\frac{kWh}{kWp}\right]$$

where PR is the Performance Ratio and includes all losses (for this work we have considered a typical PR for building integrated systems of PR=0.75 corresponding to 25% losses), H is the insolation and Y_r is the relative yield defined as H/G_{STC}. The electricity production will be:

$$E = Y_f \cdot P_n [kWh]$$

The threshold for PV suitability was selected as 1000 kWh/kWp (calculated from the insolation values using a performance ratio PR of 0.75). In fact, only roofs with an energy yield above this value make sense from an economic point of view. This aspect is subject to changes depending on installation prices and the presence of incentives. A second filter was applied: only level 3, level 4, and not listed buildings were selected for the calculations.

The daily production data was then calculated only on filtered roofs and summed up to compare it with the consumption profile. The consumption was calculated assuming a total dwelling area of around 41700 m^2 (The horizontal area of all buildings in the district is around 13900 m^2; each building was considered as three stories building) and a commercial area of 4800 m^2 (calculated considering 26 commercial units). The total P_n for the district considering only filtered roofs is of around 470 kW_p for a yearly electricity production of around 510 MWh. PV production could then cover 73% of electricity needs of the district (assuming a consumption from residential + shops of 695 MWh) (Figure 14a/b) [6]. It is also possible to analyse daily/weekly production/consumption profiles. This type of simulation has the main drawback in the fact that cloudiness is only considered as a factor during the calculation of the irradiance; this means that the higher the time resolution, the lower becomes the reliability of the data. The results are then only an average and do not represent cloudy days with no production: this aspect is of extreme importance when storage systems are designed. Figure 11a considers an entire week in January. This represents the worst scenario with higher consumption and lower production. The overall daily production is around 40% of the consumption. The calculation included also a virtual storage system which could shave the peak of production towards the consumption overnight. Figure 11b shows the same simulation for a week in July; in this case the overproduction from PV covers the consumption and charge the virtual storage. The overall daily production is 115% of the consumption. It is clear from this behaviour that a long term storage solution could also represent an interesting solution (in this case, the overall efficiency would have to be considered).

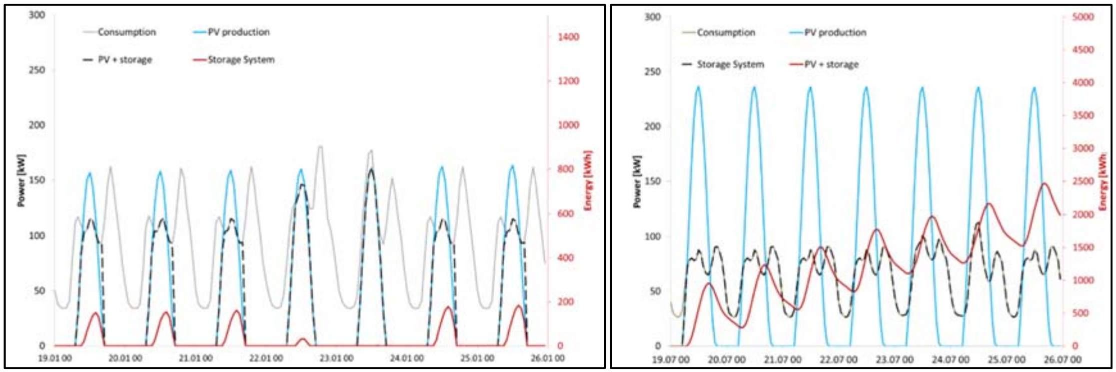


Figure 11: Production is from filtered roofs, consumption for the whole district. The efficiency of the virtual storage system was considered of 100%. Left: a week in January. Right: A week in July.

The unlimited virtual storage solution was proposed as an alternative to the typical strategy of "fit and forget" where the plants are installed without considering the energy system as a whole and that can cause problems on the grid level.

8 PV ARCHITECTURAL INTEGRATION CRITERIA

The terms "building integrated photovoltaic" (BiPV) refers to the concept of integrating PV elements into the building envelope, establishing a symbiotic relationship between the architectural design, functional properties and economic regenerative energy conversion. BiPVs have some advantages compared to non-integrated systems, primarily because there is no need for allocation of additional land and furthermore they allow distributed energy generation, close to the energy consumption site. Moreover, the on-site electricity production can reduce the total building material costs and achieve significant savings in terms of the mounting costs.

Some BiPV products allow a deep integration into the building envelope, also replacing traditional parts, such as roof or facade elements. Thus, they serve as "building" material and power generator simultaneously. In the framework of International Energy Agency project IEA-PVPS Task 7 "*Photovoltaic power systems in the built environment*" [22] several architectural criteria have been defined for BiPV formal integration quality:

- **Naturally integrated**: the PV system is a natural part of the building and without PV, the building would be lacking something - the PV system completes the building;
- **Architecturally** pleasing: based on a good design, the PV system adds eye-catching features to the architecture;
- **Good composition**: the colour and texture of the PV system is in harmony with the other materials;
- **Grid, harmony and composition**: the sizing of the PV system matches the sizing and grid of the building;
- **Contextuality**: the total image of a building is in harmony with the PV system (e.g. for historic buildings);
- **Well-engineered**: the elegance of design details is taken into account. All details are well conceived, the amount of materials is minimized;
- **Innovative new design**: the PV system adds a value to building because is an innovative technology in the field of architecture, asking for innovative, creative, thinking of architects.

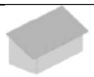
Another more recent International Energy Agency project, named IEA-SHC Task 41 "*Solar Energy and Architecture*" [24], focused on the architectural quality of building integrated solar energy systems. It defined the "architectural integration quality" as the result of a controlled and coherent integration of the solar collectors simultaneously from all points of view, functional, constructive, and formal (aesthetic) [15].

These criteria play an important role also in a historic context. From these principles, the research "*Sustainable Renovation of Historical Buildings*" (SuRHiB) developed a specific architectural guideline for the integration of solar technologies in historical roofs [17; 18; 19]. The research proposed the following criteria for the integration of PV panels (Table 6):

- **Planarity** and **respect of the lines**: to consider orientation and inclination of the roof;
- **Shape**: to put the PV panels in a uniform shape;
- **Grouping**: to install the panels in groups of many components, reducing the spaces among the panels;
- **Accuracy**: to avoid the installation of PV panels out of the borders of the roof;
- **Visibility**: to integrate the PV modules in order to improve the total appearance of the building.

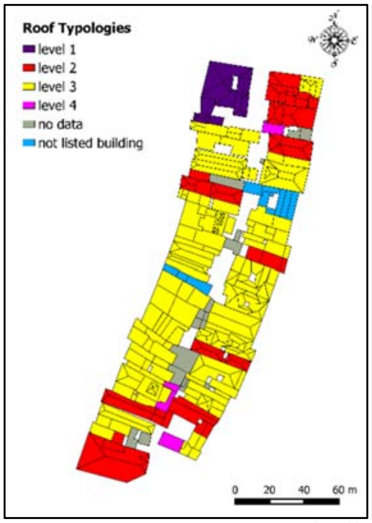
Also, several recommendations for the retrofit are presented (Table 5).

Table 5: Criteria and recommendations for the insertion of PV systems in historical roofs

Type of roof				
				
Criteria	**Shed**	**Gable**	**Hip**	**Pyramidal**
Planarity	🟩	🟩	🟨	🟨
Respect of the lines	🟩	🟩	🟨	🟥
Shape	🟩	🟩	🟨	🟥
Grouping	🟩	🟩	🟨	🟥
Accuracy	🟨	🟨	🟨	🟨
Visibility	🟨	🟨	🟨	🟨
Recommendations				
Cover the surface	🟩	🟩	🟥	🟥
Multi-functionality	🟩	🟩	🟨	🟨
Applications	🟩	🟩	🟩	🟩
Aesthetics	🟨	🟨	🟥	🟥
Sixing	🟨	🟨	🟥	🟥
🟩 = Allowed 🟨 = Partially allowed 🟥 = Not allowed				
Source: Elaboration of the authors from the "*Research SuRHiB – Sustainable Renovation of Historical Buildings*" [17]				

Local Heritage Offices in Europe, usually, accepted this method [1; 5; 6; 13] and, for this reason, it has been adopted also in Santiago de Compostela. The shape of the roofs in the building block has been identified as follows (Figures 12 and 13):

- 8 shed roofs, with a total area of 478 m^2;
- 92 gable roofs (with double slope), with a total area of 6.324 m^2;
- 69 hip roofs (with four pitches), with a total area of 3.645 m^2;
- 31 pyramidal roofs, with a total area of 531 m^2.



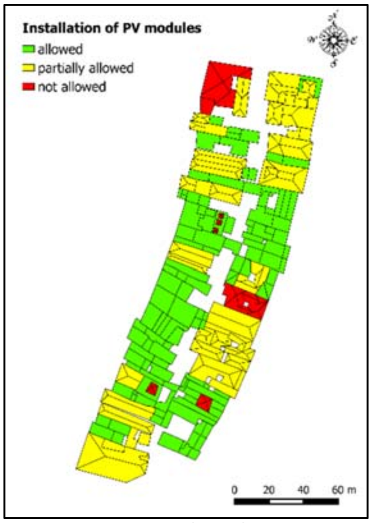


Figure 12: Distribution of different typologies of roofs
Figure 13: Roofs where the installation of PV modules is allowed

The total area with the intervention is allowed or partially allowed is 10.487 m^2 (Level 3 and 4 and not listed buildings with shed, gable and hip roofs). The cost effective roofs area is 2.909 m^2. The daily production data was then calculated only on these filtered roofs. The total P_n is of around 436 kW_p for a yearly electricity production of around 470 MWh. PV production could then cover 68% of electricity needs of the district. The results of this analysis are showed below (Figure 14c).

Figure 14: On the left hand side: roofs with annual final yield > 1000 kWh/kWp. Central part: roofs filtered by constrain levels. On the right hand side: roofs filtered by constrain levels and typology

It is also possible to localize the PV in alternative spaces, less visible than roof from public place, as gardens, internal facades or auxiliary buildings (i.e. sheds, garages and canopies). This decentralized solution permit to avoid the negative impact on the appearance not only from the public space of the city, but also the long-range effect of the surrounding hills and mountains. Specific guidelines on the compatibility of solar systems in historical buildings [1; 12], also in these case, suggest the optical integration that can be obtained by the use of same colours, shapes, dimensions and planarity with the level of the facade.

Several BIPV applications show how it is possible to play with PV technology to obtain desired patterns and design, such as the converted Electricité de France building [15] and the demonstration projects of PVACCEPT project [25]. In the first example, the architects (Emmanuel Saadi Architecture) used PV crystalline technology placing the cells with a certain gap between them in semi-transparent modules obtaining a pixelling effect, fitting very well with the existent bricks envelope pattern. In PVACCEPT project, several BiPV demonstrators were integrated in sensitive places in Italy and Germany using thin-film PV technology, which offers a more homogeneous appearance compared to crystalline.

9 CONCLUSIONS

The work shows that the integration of PV systems in the historic center is feasible, guarantying the preservation and maintaining the values and the aesthetical characteristics of the buildings. Obviously, this requires a multi-disciplinary project, careful to ensure the compatibility, the reversibility and the integration of the intervention. In the historic area considered, is particularly significant that, even putting a number of constraints always very restrictive, the PV production could then cover 68% of the electric consumption. Despite this, a large portion of the potential for PV integration in existing buildings remains unused. The reason for scarce application of BIPV components could be ascribed to several factors, such as economic reasons, lack of knowledge among decision makers and architects, general reluctance to “new” technologies and architectural/aesthetic aspects. An international survey conducted in the framework of Task 41 project [26] highlights that one of the main barriers is the lack of knowledge among decision makers, developers and clients, due to a lack of awareness of the existing possibilities offered by the PV technology in terms of formal flexibility.

To facilitate the use of this technology in historic buildings, several elements should be strengthened. First of all, working with preservation professionals (local authorities, professionals, agencies and historical organizations) is an important step in the design phase because they have an important role in identifying the heritage features and values. Another important point is the involvement of local government and authorities that can realize specific guidelines for helping the designer in the historic evaluation and also in solar design. The formation of the designers and decision makers on the technical and formal possibilities of PV systems is another important element to boost the penetration of solar design in sensitive contexts.

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