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The Smart Evolution of Historical Cities: Integrated Innovative Solutions Supporting the Energy Transition while Respecting Cultural Heritage

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Abstract: Building retrofitting is seen as an efficient method for improving a building's energy performance. On the other hand, when historical buildings are considered for this procedure, retrofitting gets more complicated. As historical buildings typically consist of low-performance building and energy systems, energy retrofits can be highly beneficial. However, not every retrofit technology can be installed in a historical building. In this paper, the study carried out for the implementation of Building-Integrated Photovoltaics (BIPV) solutions in the Historic Centre of Évora is provided, within the framework of the European project POCITYF (Project H2020). The study took into consideration all the observations of the Regional Directorate of Culture of Évora and the administration of the involved schools (including the Association of Parents), the needs of the Municipality of Évora, and the capabilities of technology developers ONYX and Tegola. The proposed solutions aim at fulfilling all the guidelines for preserving the historic centre and achieving the positivity metrics agreed with the European Commission on the challenging and indispensable path to the decarbonisation of European cities.

Keywords: smart cities; energy transition; cultural heritage; Évora; POCITYF

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1. Introduction

Over the past decades, overall energy consumption demands have been increased due to global population growth and rapid economic development. Among others, buildings' energy consumption plays a crucial role in this increase. To reduce the buildings' energy consumption and greenhouse gas emissions, it is vital for cities to follow stable and long-term strategies for the transformation of their buildings and districts into Positive Energy Buildings (PEBs) and Positive Energy Districts (PEDs), respectively. A PEB is a building (or a group of buildings) that produces more on-site energy from renewable sources than it consumes [1]. The same applies to PED as well, at an urban area level. Under these energy transition strategies, building materials and energy technologies must be optimised to achieve the given goals [2].

Europe has already set its goals for becoming the first climate-neutral continent and implement integrated and innovative solutions in its buildings and districts. Under the European Green Deal [3], it aims at an economy where (i) there are no net emissions of greenhouse gases by 2050; (ii) economic growth is decoupled from resource use; (iii) natural capital is protected, sustainably managed, and restored; (iv) the health and well-being of citizens is protected from environment-related risks and impacts; and (v) no person and no place are left behind. The goal is to create many PEBs and PEDs among European countries as a step towards the 2030 set goals [4] for (i) 40% cuts in greenhouse gas emissions (compared to 1990′s levels); (ii) 32% share for renewable energy; and (iii) 32.5% improvement in energy efficiency.

On the one hand, building retrofitting is seen as a more efficient method for improving energy performance than building reconstruction [5]. Standard energy retrofits include installing walls or insulating roofs, renovating windows, upgrading heating systems, installing ventilation and air conditioning systems, and optimising system operation schedules [6]. Further energy retrofit actions include lighting improvements such as lamp replacement and the use of lighting control systems, the introduction of solar energy systems, improvements to mechanical equipment, and the use of renewable energy [7]. On the other hand, when historical buildings become the case, then retrofitting gets more complicated. As historical buildings typically consist of low-performance building and energy systems, energy retrofits can be highly beneficial. However, not every retrofit technology can be installed in a historical building, as the buildings must not be damaged, especially in the cases of cultural heritage buildings. In addition, several other barriers arise when considering the historical buildings' energy transition, mainly based on their architectonic, conservative, and cultural barriers, along with each country's existing regulations. Thus, alternative methods of retrofitting must be considered for historical buildings.

In accordance with Europe's goals and given that most European cities have buildings of historical interest, POCITYF [8] is an EU-funded smart city project that will help cities to become greener, smarter, and more liveable while respecting their cultural heritage. As cities are responsible for the majority of the global energy consumption and buildings use about 40% of global energy [9], by implementing and testing PEDs and PEBs in the involved cities, POCITYF will support Europe in the race to become the first carbon-neutral continent by 2050. In this sense, POCITYF will demonstrate innovative smart city technologies (to be called hereafter Innovative Elements–IEs) in two lighthouse cities, Alkmaar (NL) and Evora (PT), and replicate them in six fellow cities. POCITYF combines positive energy blocks with grid flexibility, e-mobility, innovative ICT technologies, and citizen engagement strategies while respecting the urban cultural heritage.

In this paper, an insight about POCITYF's general strategy is given, while the focus is on describing (some of) the proposed IEs that will be implemented in Évora's historical buildings during the project (i.e., until 2023). More specifically, this work describes the study carried out within POCITYF for the implementation of Building-Integrated Photovoltaics (BIPV) solutions in the historic centre of Évora. This study houses all the guidelines aiming at preserving the historic centre while achieving the positivity metrics agreed with the European Commission on the challenging and indispensable path to the decarbonisation of European cities. Under these guidelines, Évora and the rest of the participating cities in POCITYF, that will follow Évora's example, will make a step towards their transformation to smart cities and preserve their cultural heritage buildings at the same time. Although Évora is one of the two lighthouse cities and one of the eight cities participating in the project, it is the only city that fulfils the requirements for the paper, as it is a UNESCO World Heritage Site with many historical buildings and the testbed of many BIPV solutions.

In Section 2, the past related work is given and is followed by a short description of POCITYF's general strategy in Section 3. The participation of Évora as a lighthouse city in POCITYF is given in Section 4. The paper's main contribution is discussed in Section 5, where all proposed solutions are thoroughly described, along with their implementation in the selected areas of cultural interest. Conclusions are drawn in Section 6.

2. Past Related Work

2.1. Research Studies

There is a limited number of studies regarding the application of innovative solutions in heritage contexts to support the energy transition, mainly due to the presence of architectonic, conservative, and cultural barriers.

Borda and Bowen, in their 2017 work [10], review some of the developments regarding smart cities and their effects on the cultural heritage sector. In this work, the enabling technologies for smart cities and smart cultural heritage consist of: (i) Internet of Things (IoT), (ii) Cloud computing, (iii) Wireless Sensor Networks (WSNs), (iv) Mobile broadband, and (v) Short range wireless, such as Bluetooth Low Energy (BLE) and NearField Communication (NFC). Moreover, they mention visualisation technologies as an important component for smart cultural heritage developments. In the same sense and year, Angelidou et al., in their work in [11], investigate how the historical and cultural heritage of cities can be enhanced by smart city tools, solutions and applications. By examining the incorporation of the historical and cultural heritage in three smart city strategies, they found that, despite the technological advancements, cultural heritage is not systematically exploited and formally incorporated in smart city initiatives.

In 2018, Allam and Newmer, in their paper [12], while reviewing the literature on the nature, challenges, and opportunities of smart cities, also propose a framework that takes into account the dimensions of culture, metabolism, and governance. This framework highlights that the economic dimension underlies each of the three dimensions (i.e., smart culture, smart metabolism, and smart governance) and it does not require its own focus in the development of smart cities.

Marsella and Marzoli, in their work in [13], present the work conducted in the EU project STORM [14], a European Research and Innovation Action co-funded in the H2020 framework. Under STORM, the creation of intelligent tools for gathering data from libraries, sensors, and crowdsensing techniques took place in order to help cultural heritage stakeholders in the prevention, response, and recovery phases. The developed tools were based on a variety of sensor types (e.g., air temperature sensors, LIDAR sensors, etc.) and aimed at (i) protecting cultural heritage by climate changes; (ii) enabling the smart cities technologies for protecting the cultural heritage protection.

Siountri and Vergados, in their 2018 work "Smart Cultural heritage in Digital Cities" [15], mention that the Smart Cultural Heritage concept encompasses: (i) Heritage; (ii) Urban factors; and (iii) Digital technologies. In addition, they also remark that even if the technological advancements have already led to many achievements, there is a need for further promoting and understanding the connection of Smart Cities to Cultural Heritage and integrating them into the smart city plans.

Akram et al., in their 2016 work in [16], evaluate the possibility of making heritage buildings more sustainable and preserve their cultural values at the same time. To achieve the above goal, they compare the construction materials, the traditional and futuristic design features, as well as the environmental impact of each era and energy source. The interesting point is that the heritage buildings presenting a great possibility of becoming greener due to the high quality of their construction materials and features. These materials and features represent many "values" from different perspectives, such as energy and materials expenditure and architectural characteristics that can no longer be replaced.

Adding to the above study regarding the materials of cultural heritage buildings and their impact on smart cities applications, Tse et al., in their 2018 paper [17], propose an indoor pollution study for Biblioteca Joanina in Coimbra, Portugal, a UNESCO heritage monument. More specifically, they installed a low-cost edge-based sensing platform inside the monument and then helped the library managers to understand how to modify the paths of tourists in order to reduce the atmospheric particles pollution in the library. What is most interesting in this work is the impact of the outside pollution into the library, higher than expected, likely due to the ancient doors and window, that do not represent a bearer for the PM2.5 or PM10.

Pierucci et al., in their 2018 work [18], compare the performance of smart windows with PVCC glass with the traditional solar control glasses and building-integrated photovoltaic panels. They perform a comparative life-cycle assessment of two buildings with the same size and typology, but one equipped with PVCC and the other with the traditional solar control glasses and building-integrated photovoltaic panels. The comparison's results show that smart building-integrated adaptive technologies show benefits under comfort and operational energy points of view when compared to traditional ones. In addition, they contribute to the reduction of the carbon footprint of new and existing buildings.

In a more recent (2020) work, in [6], Cho et al., taking into account that cultural buildings need special attention when being retrofitted in order to avoid any damage, simulate the application of six different building energy retrofit (BER) packages on a historical educational building. Each BER package consists of a different mix of a set of technologies (e.g., Photovoltaic panels, Heating- and Ventilation-Air-Conditioning systems, etc.) and is compared with each other to find which is the most energy- and thermal-efficient (heating and cooling).

2.2. Guidelines for RES Adaptation

In many countries, there were sets of guidelines for adapting the Renewable Energy Solutions (RES) integration in historical buildings and sites [19]. Each guideline is mainly focused on one integrated solution/system or a set of systems. In the sequel, some of these guidelines are indicatively given.

Back in 2009, the Scottish guidelines were set in [20] as a guide for fossil fuel reduction, mainly in historical buildings that use renewable energy solutions, mainly photovoltaic and solar thermal systems. For the same country, in 2014, Historic Environment Scotland (HES) in [21] has set the guidelines for the use of renewable energy sources, providing the readers with examples and considerations for building-integrated photovoltaics and building-integrated solar thermal systems on historical buildings and sites.

The American National Renewable Energy Laboratory (NREL), in the 2011 work by Kandt et al. [22], presented the criteria for balancing the preservation of historic sites/buildings and energy production. Their focus was on building-integrated photovoltaics and building-integrated solar thermal systems. In the same year, the Bundesdenkmalamt (BDA), in [23], set the scale of compatibility among different renewable energy source technologies. The BDA mainly refers to photovoltaic and solar thermal systems. Regarding the integration of photovoltaics and building-integrated photovoltaic systems on Italy's historical buildings, the Ministero per i Beni e le Attività Culturali (MiBACT), in [24], defines the best practices.

The Solarenergie, Dipartimento Federale dell'Interno (DFI), cantonal guideline, and Federal Office of Culture (FOC) have provided the guidelines in Switzerland. Solarenergie, in 2014 [25], describes the use of handbooks with technical solutions in order to reduce modern and historical buildings' energy consumption, mainly under building-integrated photovoltaics and building-integrated solar thermal systems. For the same systems, DFI, in [26], focuses on making clear that the installation of the systems should follow an initial clarification with the competent authorities. On the other hand, in the cantonal guideline [27], there is an approach to defining specific rules for the renewable energy sources' aesthetic and technical integration. Photovoltaics and solar thermal, building-integrated photovoltaics and building-integrated solar thermal systems are considered in the cantonal guideline. Several illustrations regarding the photovoltaic reconciling procedure and the quality of constructions are the highlight in FOC's guideline in 2019 [28].

2.3. EU Research Projects

RES integration in heritage buildings and sites has been vastly examined within international, EU, and local research projects. In the following table, Table 1, some of these projects are indicatively given, along with the funding programme, years of implementation, types of RES technologies, and the focus of each project. In the table, the projects displayed were funded by one of the following programmes: (i) Intelligent Energy Europe (IEE) [29]; (ii) Fifth RTD Framework Programme (FP5) [30]; (iii) 7th Framework Programme (FP7) [31]; and (iv) Horizon 2020 [32].

Table 1. Research projects on RES integration in historical buildings and sites (non-exhaustive list).

Project	Programme	Years	RES Type	Focus
PV Accept [33]	FP5	2001–2004	Photovoltaic, Building-Integrated Photovoltaics	Historical buildings and sites
New4Old [34]	IEE	2007–2010	Building-Integrated Photovoltaics, Building-Integrated Solar Thermal	Historical buildings
Sechurba [35]	IEE	2008–2011	Building-Integrated Photovoltaics, Building-Integrated Solar Thermal	Historical buildings and sites
3encult [36]	FP7	2010–2014	Building-Integrated Photovoltaics	Roofs
UrbanSol Plus [37]	IEE	2011–2014	Solar Thermal	Buildings, Towns
Effesus [38]	FP7	2012–2016	Building-Integrated Photovoltaics	Roofs
Pearls [39]	H2020 MCSA (RISE)	2018–2022	Building-Integrated Photovoltaics, Building-Integrated Solar Thermal	Towns, Landscapes

3. POCITYF

POCITYF's goal is to build upon intelligent, user-driven, and demand-oriented city infrastructures and services in order to foster the cities' energy efficiency. The considered city infrastructures enhanced by e-mobility solutions can lead to a substantial increase of renewable energy merit; thus leading to a wider deployment and market uptake of PEDs. Overall, POCITYF aims to transform the cities by adding layers of smartness in their key infrastructures, technologies, and services, such as buildings, energy grid, and e-mobility. It will also form an open, collaborative ecosystem towards improving citizens' quality of life, innovation, and sustainability at a district and city level. POCITYF creates new possibilities for the cities to become safer, greener, and more responsive to the needs of their citizens, businesses, and other organisations. To this end, it brings new technologies and renewed infrastructure to cut household bills, create jobs and boost growth for achieving a sustainable, low carbon and environmentally friendly economy, putting Europe at the forefront of RES production and efforts against global warming.

3.1. POCITYF's General Strategy

In order to achieve the goals set, POCITYF's strategy has been built around four multidisciplinary and complementary Energy Transition Tracks (ETTs). Each ETT aims to propose solutions on how to increase the integration of both commercialised and innovative energy systems in current city blocks, with the ultimate goal of achieving higher self-sustainability for the cities and making them more environmentally friendly for their citizens. Each ETT consists of several Integrated Solutions (Iss), while each IS further groups several Innovative Elements (Ies) dedicated to the IS's goal. The first three ETTs enable the transition towards (1) reduced energy demand, (2) increased shares of renewables, and (3) e-mobility, while the fourth focuses on Citizen Engagement. Table 2 presents POCITYF's ETTs and their respective ISs.

More specifically, in ETT#1, the included Iss are focused on achieving significant energy savings at both the building and district levels (e.g., by reducing energy bills for citizens and enabling a high share of locally produced and consumed renewable energy). The Innovative Elements (Ies) to be demonstrated and replicated in ETT#1 include both PEB-level and PED-level retrofits. In terms of the PEB level, Ies include: (a) circular insulation materials, (b) solar roofs and facades, (c) PV canopy, (d) PV skylight, I PV thermal panels, (f) thermo-acoustic heat pumps, and (g) hybrid wind/solar generation systems. In terms of the PED-level IEs, these are: (a) District Heating and Cooling (DHC) (biomass, waste and geothermal), (b) DC lighting with charging points and smart lamp posts, (c) (Peer-To-Peer) P2P energy trading platforms, (d) smart distribution management systemI(e) community solar farms, and (f) Aquifer Thermal Energy Storage (ATES) heat/cold storage. The implementation of these two levels of retrofits also consider the principles of circular economy with the (a) utilisation of available waste streams (heat/building materials after demolishing), (b) reverse collection of waste, (c) waste management tools, and (d) the Pay-As-You-Throw system.

Table 2. POCITYF ETTs and Iss.

Energy Transition Track (ETT)	Integrated Solution (IS)
ETT#1: Innovative Solutions for Positive Energy (CH) Buildings and Districts	IS 1.1: Positive Energy (stand-alone) Buildings
	IS 1.2: Positive Energy Districts Retrofitting
	IS 1.3: Feeding PEDs with Waste Streams Promoting Symbiosis and Circular Economy
ETT#2: Peer-to-Peer (P2P) Energy Management and Storage Solutions for Grid Flexibility	IS 2.1: Flexible and Sustainable Electricity Grid Networks with Innovative Storage Solutions
	IS 2.2: Flexible and Sustainable District Heating/Cooling with Innovative Heat Storage Solutions
ETT#3: e-Mobility Integration into Smart Grid and City Planning	IS 3.1: Smart V2G Evs Charging
	IS 3.2: e-Mobility Services for Citizens and Auxiliary EV Technologies
ETT#4: Citizen-Driven Innovation in Co-creating Smart City Solutions	IS 4.1: Social Innovation Mechanisms towards Citizen Engagement
	IS 4.2: Open Innovation for Policy Makers and Managers
	IS 4.3: Interoperable, Modular and Interconnected City Ecosystem

ETT#2 include ISs that mainly focus on (1) maximising self-consumption, (2) reducing grid stress, (3) avoiding renewable generation curtailment, and (4) increasing revenue through flexibility services to the grid. The Integrated Solutions of this ETT include the following IEs: (a) low temperature waste heat and geothermal sources, (b) innovative short- and long-term seasonal (in some cases storage) solutions (i.e., hydrogen fuel cells, Vehicle-To-Grid (V2G) coupled with stationary batteries, Phase Change Material (PCM)), (c) DC to work in parallel with AC grids, (d) smart Information and Communications Technology (ICT) to interconnect an Energy Management System (EMS) on a home/building/district level, € Demand-Side Management (DSM) platforms for the optimisation of energy flows, (f) thermal grid controllers, (g) market-oriented building flexibility services, and (h) storage systems connected to the LV and MV grid.

In ETT#3 the focus is on individual elements for electro-mobility on the energy system, with the goal to increase the penetration of electric vehicles (EVs) that utilise RES and enhance the potential of EVs to support grid flexibility (while reducing curtailment), promoting the decarbonisation of the mobility sector with the adoption of EVs, reducing citizens' mobility costs, and better traffic management. Innovative elements to be demonstrated and replicated in this ETT include: (a) deployment of V2G using the batteries of EVs, (b) exploitation of EVs in local car-sharing systems, (c) district-wide dissemination of smart charging stations powered mainly by RES, (d) DC public lamp posts as charging poIs, (e) bidirectional smart inverters, (f) optimal charging algorithms, and (g) EV charging management platforms.

ETT#4 focuses on improving citizens' quality of life and increasing the city's efficiency by involving citizens in the early development, design, and evaluation phases. Innovative elements to be demonstrated and replicated here include (a) P2P energy transactions, (b) gamification of bidding and trading in decentralised systems, (c) infotainment apps, (d) local caIigns, (e) crowdfunding, and (f) energy ambassadors creating local energy communities with the use of platforms.

Lighthouse cities (i.e., Evora and Alkmaar) have already pointed out the innovative elements that they are going to demonstrate throughout POCITYF. Fellow cities, in their turn, have already picked the innovative elements that they are interested to replicate.

3.2. Monitoring & Evaluation

POCITYF, as a Smart City project, incorporates a multitude of solutions that will accelerate the energy transition of its lighthouse cities and help with the replication activities in its fellow cities. Positive energy buildings and districts, grid flexibility, circular economy, e-mobility, and citizen-driven innovation are all integral parts of the POCITYF ecosystem. Therefore, the project success can only be evaluated through specific, tailored Key Performance Indicators (KPIs) [40] that need to be defined according to the scope of the specific interventions and stakeholders' needs, as well to provide comparability through established evaluation frameworks and monitoring databases [41].

Each KPI in POCITYF is responsible for monitoring and evaluating one or more of the following concepts:

- Energy performance
- Environmental performance
- Economic performance
- ICT performance
- Mobility performance
- Social performance
- Governance performance
- Propagation performance

Energy performance indicates the level of achieved energy efficiency in a system and is demonstrated using a set of energy-related KPIs (e.g., energy demand and consumption, degree of energetic self-supply by RES, etc.). Calculated KPIs can be used to assess the impact of the POCITYF project in facilitating the energy transition of the lighthouse cities. The impact can be assessed in terms of, for example, increasing self-sufficiency, reducing the amount of energy consumed, increasing renewable self-consumption with energy storage, or simply increasing the amount of renewable energy generated.

Environmental performance measures the level of environmental sustainability. It entails considerations on the (efficient) use of (renewable) resources, improved energy and water efficiency, the reduction of air contaminants and greenhouse gas emissions, increased reuse and recycling, and the reduction of hazardous waste and toxic pollutants. Related KPIs include, among others, greenhouse gas emissions and energy demand and consumption KPIs.

Economic performance defines the roadmap for assessing the performance of economic viability of the lighthouse cities' interventions and common technical evaluation methodologies to guide the monitoring and the evaluation activities needed to calculate the economic KPIs (e.g., average electricity price for companies and consumers, carbon dioxide reduction cost efficiency, etc.). The objective is to provide an evaluation plan to measure and analyse the economic performance, impacts, and effectiveness of the POCITYF interventions focusing both on the integrated solutions and, in a more holistic picture, on the ETT into which the ISs are aggregated and later on the city level.

In the POCITYF project, the ICT technologies (data communication, data management platforms and analytics) aim at supporting and enhancing the innovative solutions and general efficiency measures in energy, mobility, governance, and social dimensions. These enhancements are expected in such aspects as the increased flexibility of the domain-specific systems with the support of ICT, the increased usage of open data, improved data privacy and security, as well as more effective real-time data sharing, leading indirectly to energy efficiency improvements, caused by ICT technologies improvements. The successful usage of ICT and highly efficient domain-specific technologies in the energy and mobility domains will increase the overall impact of all ISs developed in the POCITYF project. KPIs that are related to ICT solutions include, among others, the increased system flexibility for energy players and the quality of open data.

The mobility performance of district cities is measured via the respective mobility KPIs (e.g., electric vehicles and low-carbon emission vehicles deployed in the area, number of EV charging stations and solar powered V2G charging stations deployed in the area, etc.). Mobility performance will indicate the extent to which the POCITYF project was able to stimulate the transition from traditional fossil-fuel-based vehicles to low-carbon ones (i.e., EV, PHEF, and hydrogen). Apart from the usage of new types of vehicles, the implementation and usage of the new charging infrastructure should be measured as well.

Social performance is crucial to estimate the extent to which the project facilitates the involvement of citizens and social actors in the planning, decision-making, and implementation activities. Citizen groups represent groups of citizens with various activities related to POCITYF actions and objectives. They include actors such as residents, non-residential agents with a high interest, citizen associations, professional associations (e.g., engineers, taxi drivers), neighbouring cities/towns, as well as citizen ambassadors. Their perspective is of the utmost importance for the citizen-centric approach of POCITYF.

The successful governance practices contribute to the effective and progressive process of the project implementation as well as to a city with an efficient administration and a well-developed local democracy, thereby engaging the community proactively in innovative ways, which is translated into increasing citizen participation and enhancing the active involvement of various user groups, the community, and professional stakeholders in city developments. Accordingly, in POCITYF, the governance performance dimension is addressed by a set of KPIs (e.g., online visits to the municipal open data portal, legal framework compatibility, etc.), which allow for the evaluation of the effective governance of smart cities from the side of the municipality administration, planning, monitoring, and evaluation. In addition, the aspects of the legal domain (regarding the regulatory framework and its compatibility with the proposed solutions and implemented policies at the project or city level) are included as supporting monitoring measures.

The success of the implementation and, consequently, the replication of smart solutions in the context of a smart city depend on a series of external and internal indicators. The propagation aims at the improvement of the replicability and scalability of smart city solutions at a wider city scale. Propagation is about the potential for dissemination to other locations, other contexts, and other cities. Propagation depends in the first place on the inherent characteristics of the (innovative) smart city solutions both for transfers to other locations and countries, and for up-scaling from small single projects in the same city. KPIs that are related to propagations include social compatibility and the diffusion to other locations.

4. The Case of Évora

Eight cities participate in POCITYF, either as lighthouse (LH) cities or as fellow cities (FCs). The general idea behind this categorisation is the following: the LH cities are responsible for demonstrating ISs that they have already implemented in the past. FCs will use this knowledge to implement these ISs. An exchange of knowledge will also take place between the LH and FCs. The LH cities in POCITYF are: (i) Évora (Portugal) and (ii) Alkmaar (Netherlands). The FCs are: (i) Granada, (ii) Bari, (iii) Celje, (iv) Ujpest, (v) Ioannina, and (vi) Hvidovre. Each city has set its PEBs and PEDs for participating in POCITYF. In each PEB or PED, a group of ISs will be implemented, either in terms of demonstrating the IS (LH cities) or in terms of replicating an IS after the demonstrations (LH cities and FCs).

Note that all POCITYF cities have a proven record of actions aiming at achieving the Energy Union's objective of creating a resilient energy system and an ambitious climate policy for secure, sustainable, competitive, and affordable energy, setting themselves even more ambitious emission reduction goals than the EU. For example, the two leading LH cities, Évora and Alkmaar, have approved sustainable energy action plans and are active members in European networks on energy, mobility, and ICT.

4.1. Évora as a POCITYF LH City

Évora is a middle-sized city inhabited by about 53,000 citizens. It is located in the southern inner mainland of Portugal. Due to its well-preserved old town centre, partially enclosed by medieval walls, and many monuments dating from various historical periods, Évora is a UNESCO World Heritage Site and a member of the Most Ancient European Towns Network [42]. These characteristics present peculiar conditions for the integration of ISs in its buildings and districts.

Évora is participating in POCITYF with three PEDs, where the PEBs are located: (i) Évora city centre; (ii) Valverde village; and (iii) Industrial and commercial park. These PEBs are the hosts of the demonstrations that will take place in Évora. Table 3 presents the complete list of the IEs per IS that will be demonstrated in Évora.

Table 3. Évora's IEs in POCITYF.

ETT#1: Innovative Solutions for Positive Energy (CH) Buildings and Districts	IS 1.1: PV Glass, PV Canopy, PV Skylight, Tegosolar PV, Traditional PV Shingle, Bidirectional Smart Inverters, Energy Router, Building Management System (BMS), Home Energy Management System (HEMS), Positive Computing Centre. IS 1.2: Smart Lamp Posts with EV charging and 5G functionalities, Energy Routers (district level), P2P Technical Validation Tool, P2P Energy Trading Platform, Community Solar Farm IS 1.3: 2nd Life Batteries, PAYT
ETT#2: Peer-to-Peer (P2P) Energy Management and Storage Solutions for Grid Flexibility	IS 2.1: 2nd Life Batteries, Renewable Energy Communities Management Platform, Flexibility Control Algorithms, P2P Energy Trading Platform
ETT#3: e-Mobility Integration into Smart Grid and City Planning	IS 3.1: EV charging management platform, EV charger prototype with PV integration, Bidirectional smart inverters for EV smart charging and V2G applications, Smart lamp posts with EV charging and 5G functionalities, Intelligent and optimal control algorithm IS 3.2: Freezing storage in store, Market-oriented building flexibility services
ETT#4: Citizen-Driven Innovation in Co-creating Smart City Solutions	IS 4.1: Digital Transformation in Social Innovation, Gamification, Tourist Application, Cultural Experiences Market, Mobile application on energy consumption IS 4.3: City Urban Platform, Wi-Fi data acquisition systems, Data Lake, Smart cloud for Innovative Start-ups

In Figure 1, the exact location on the map of each PEB and the typology of buildings in each area are depicted. In addition, there is a list of each solution that will be deployed per PEB and at the district level as well.

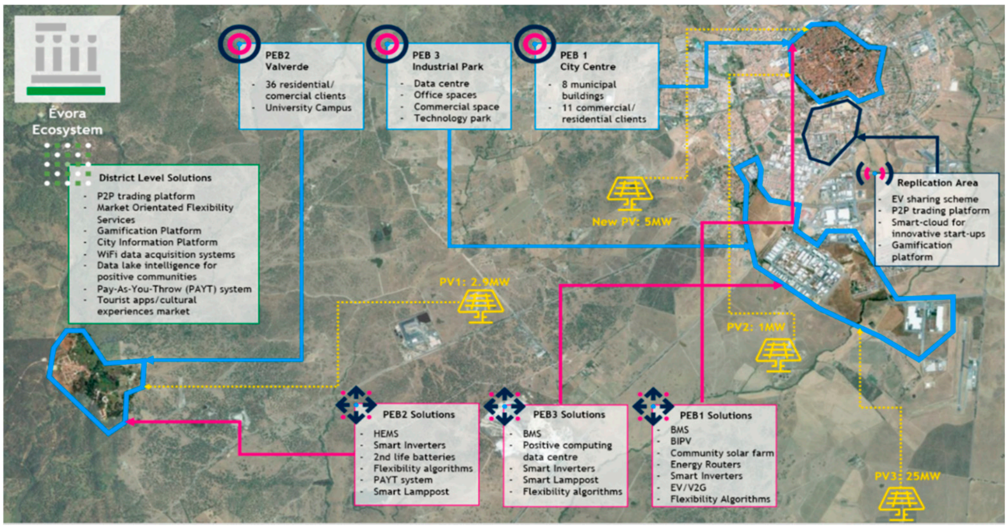


Figure 1. The 3 Positive Energy Blocks (PEBs) in Évora.

4.2. Distinguish PEBs and PEDs of Cultural Interest

Évora's well-preserved historical city centre (PEB1) is one of the richest monuments in Portugal, having earned the title of city-museum as well. In harmony with the urban fabric, the monumental complexes have led to the classification of Évora as a World Heritage Site by UNESCO since 1986. On the other hand, on this historical matrix, it is once again reemerging as a pole of regional development through the creation of products and services of excellence in tourism and the development of urban infrastructures that prioritise the well-being of its inhabitants. Furthermore, energy efficiency has become a policy priority for Évora due to its ability to address challenges such as reducing the dependence on foreign energy, reducing the GHG emissions, and improving the competitiveness of the economy.

This World Heritage City is the first urban area in Portugal to hook up to the intelligent energy grid. By promoting energy efficiency, micro generation, and electrical mobility, Évora is a shining example of sustainability for the whole country. The city has 31,000 domestic customers with installed smart meters; it also has an improved capability of RES and EV connections. Évora was selected because it complies with a set of criteria relevant to this experiment, such as: dimension, type of grid, national and international visibility, average level of consumption, inclusion in the national pilot network of electric vehicle charging stations.

Moreover, the city centre values its environmental component and the promotion of sustainable development. It holds heritage, cultural, academic, and services vocation with environmental quality. It also has a national and international recognition of its recovery policies and heritage preservation.

4.3. Distinguish ISs That Could Affect the Cultural Heritage of the PEBs–PEDs

To support the PEBs in reaching their objectives, energy flexibility solutions allow the groups of buildings to modify energy consumption and generation profiles according to various needs, while respecting users' comfort preferences. Examples of such needs refer to the reduction of electricity costs through the matching of buildings' demand and on-site generation (increasing the benefits of ETT#1-related solutions) or the decrease in electric vehicles' charging peak loads (mitigating impacts associated with the electrification of energy demand under ETT#3). For the municipal buildings in PEB1 of Évora, 10 energy routers that are equipped with battery energy storage systems are smartly operated via flexibility control algorithms to improve self-consumption and self-sufficiency ratios and reduce electricity costs.

Regarding e-mobility, a set of new solutions will also be deployed and tested in the cultural site (PEB1): smart lamp posts, vehicle-to-grid (V2G) chargers with PV integration, and an EV charging management platform. The first is a modular lamp post, developed by the Ubiwhere company, composed of efficient LED lighting, EV Charger capabilities, and telecommunication services that enable the deployment of a 5G solution (4G and Wi-Fi are also included). The second consists in EV chargers which consider local PV generation to smart-charge EV. The integration is done using voltage control algorithms, thus going beyond the state-of-the-art by combining the charging control with a high level of integration with the LV network control elements, resulting in possible improvements in the power quality and voltage deviation. These chargers will also allow the injection of energy in the demonstration areas. Finally, the EV charging management platform will allow a better integration of the V2G capabilities of the EV chargers, minimising the impact of integration EV in the power grid. This platform will also enable users to manage their charging and discharging preferences and allow for a totally remote control of charging options using web-app and mobile-app interfaces.

5. Implementing ISs while Respecting Cultural Heritage

The fact that the historic centre has been a UNESCO World Heritage Site since 1986 comprises the added challenge of the solutions being able to conserve the city's cultural heritage (respecting the legal framework in force) while contributing to the PEB's positivity. In this sense, two different solutions aim to enable the historic centre and its citizens to take an active part in the pressing energy transition:

- Community Solar Farm (CSF) on the outskirts of the city of Évora;
- Renewable energy community formed by Évora's municipal buildings.

5.1. Community Solar Farm on the Outskirts of the City of Évora

The Community Solar Farm (CSF) project aims to provide the residents of the historic centre of Évora with the opportunity to access photovoltaic generation solutions, given that they are unable to install this type of solution in their homes, due to the protection mechanisms of cultural heritage that prevent the installation of photovoltaic panels in the walled interior of the city of Évora. Thus, CSF aims to provide the inhabitants of the historic centre with the possibility of owning and/or benefiting from a part of the generation of the plant, being rewarded for the corresponding produced energy. In POCITYF, CSF is represented by the "Community Solar Farm" given in IS1.1.

A solution based on the new legislative framework for collective self-consumption and renewable energy communities could respond to the challenge that CSF proposes. Based on the new legislation, the solution is fully aligned with the innovative character of POCITYF and the same disruptive character of the Portuguese Decree-Law No. 162/2019. As an innovation project, POCITYF proposes to explore, find, and design new solutions under the aforementioned legislation and the regulation of self-consumption of electric energy. Furthermore, the consortium is available to share with the Portuguese National Authority for Energy and Geology (DGEG), during this assessment process, the lessons learned and contribute, as a pilot project, to the implementation and improvement of the provisions set out in that Decree-Law.

In practice, the intention is to take advantage of this new legislative context and implement a renewable energy community (REC) in which the role of a self-consumption production unit (SCPU) would be played by the photovoltaic plant outside the historic centre of Évora. In turn, consumption points in the historic centre would play the role of REC's user facilities (UF).

As for the land that can be used to install the photovoltaic plant, the City Council of Évora (CME) provided land that is approximately 4 km from the historic city centre (see Figure 2). The technical solution is currently being drawn up, and apart from the technical feasibility study, different business models will be presented, aiming to bring value to both citizens and operators/promoters of the central.

Figure 2. Map with the possible location of the CSF in green and relative position in relation to the centre of Évora and the substation of Caeira.

5.2. Renewable Energy Community in Évora's Municipal Buildings

The historic centre of Évora presents very restrictive laws for the protection of cultural heritage, which constitute an obstacle even concerning the implementation of business-as-usual solutions for renewable generation (e.g., photovoltaic panels). Eight municipal buildings (Municipal Market 1 de Maio, Arena, Tetro Garcia de Resende, EB1 School of S. Mamede, Évora City Hall Building (CME), Vista Alegre School, Rossio Laboratorio Vivo School for the Electric Decarbonisation–LvpDé) will be provided with renewable generation capacity. Consequently, to overcome the constraints, five different BIPV (Building-Integrated Photovoltaics) solutions were designed by two entities of the consortium, that comply with the specifications and guidelines imposed by the Regional Culture Administration of Alentejo: ONYX—A Spanish company specialised in BIPV solutions; and Tegola–an Italian company specialised in aesthetic photovoltaic roofing. In terms of the POCITYF, the above solutions are part of the provided BIPV solutions and the Renewable Energy Community Management Platform, both described in ETT#2. Examples of BIPV solutions that will be installed in Evora are given in Figure 3.

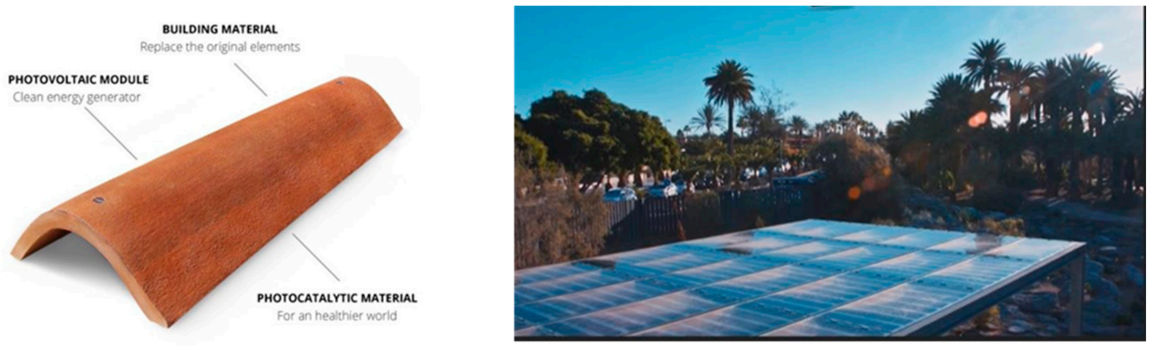


Figure 3. Examples of BIPV solutions to be installed in Évora (**left**: photovoltaic tiles; **right**: aesthetic photovoltaic pergolas).

With this group of solutions, the buildings will obtain the desired and necessary positivity, as they will have an annual renewable generation superior to consumption.

In Figure 4, the eight municipal buildings and the parking lot are identified, delimiting the historic centre area that is the target of the collective self-consumption proposal. It should be noted that the different IUs' geographical distances do not exceed 2 km, in most cases being less than 1 km.

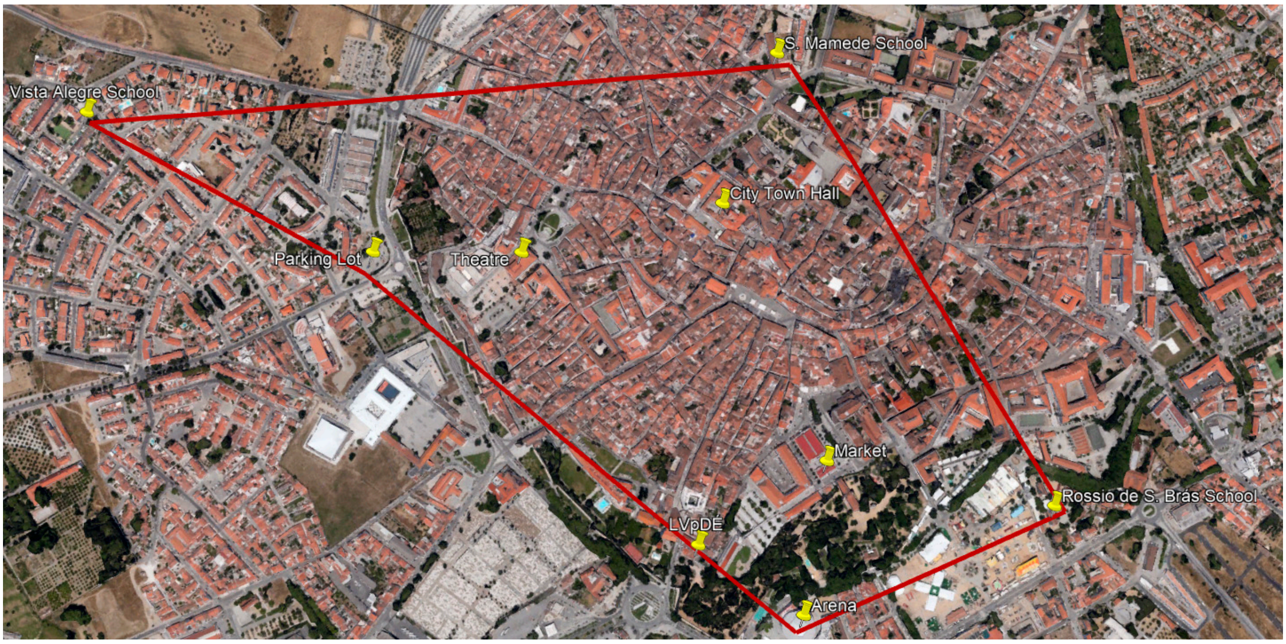


Figure 4. Spatial representation of the location of municipal buildings in the historic centre.

Thus, within the scope of the POCITYF project, and regulated by Decree-Law No. 162/2019 and the respective regulations for self-consumption of electric energy, the intention is to channel and take advantage of this surplus energy for other CME buildings located in the historic centre, constituting a collective self-consumption community with several buildings and not just those that will be endowed with BIPV solutions. Below is the list of buildings in the historic centre that are eligible for the community:

- Rossio de S. Brás School—Generator and consumer;
- S. Mamede School—Generator and consumer;
- Municipal Market 1° de Maio (fruit market)—Generator and consumer;
- Paços do Concelho (Town Hall)—Generator and consumer;
- Garcia de Resende Theatre—Consumer;
- LVpDÉ—Generator and consumer;
- Arena—Generator and consumer;
- Old Bus Station Building—Consumer;
- Vista Alegre School—Generator and consumer;
- Convent of Remedies—Consumer;
- Public garden—Consumer;
- Pátio do Salema—Consumer;
- Municipal Market 1° de Maio (fish market)—Consumer;
- Underground parking at Praça Joaquim António de Aguiar—Consumer;
- Rua Diogo Cão 19 (photographic archive)—Consumer;
- EPAC granaries, Rua Eborim—Consumer;
- Museum of Handicrafts—Consumer;
- Playground—Consumer;
- Giraldo Square—Consumer;

- Tour Desk—Consumer;
- S. Vicente Church—Consumer;
- Social centre, Rua das Fontes 41—Consumer;
- Gardens Services, Portas de Aviz—Consumer;
- D. Manuel Palace—Consumer;
- Cemetery—Consumer;
- House of scales—Consumer;
- Conviviality Centre, Rua de Machede—Consumer;
- Playroom—Consumer;
- Social services, Rua do Fragoso—Consumer;
- Conviviality Centre, Rua do Fragoso—Consumer;
- Monte Alentejano, Rossio—Consumer;
- Water Museum—Consumer;
- Central Hall—Consumer;
- Hygiene services, Rua de Machede—Consumer;
- Former EDPC building—Consumer;
- JI Penedo de Ouro—Consumer.

This high number of consumers belonging to the community could use surplus production to respond not only to the surplus of energy but also to the lag of "generation vs. consumption" (e.g., in the summer and weekend periods, schools will have very low consumption).

Considering that all the buildings in question are the property of CME, a collective self-consumption project is the best solution, to the detriment of the constitution of a renewable energy community.

5.3. Paços do Concelho (Town Hall Building)

In the Building of Paços do Concelho, the Town Hall Building, located in Praça do Sertório, two types of solutions will be implemented: ONYX's aesthetic photovoltaic skylights and photovoltaic tiles provided by Tegola. ONYX's aesthetic photovoltaic skylight solutions will be implemented to replace the existing skylight in the main building and the roof in fibre cement tile existing in the praefurnium area of the Roman Baths. Regarding the skylight of the main building, the solution proposed by ONYX is illustrated in Figure 5.

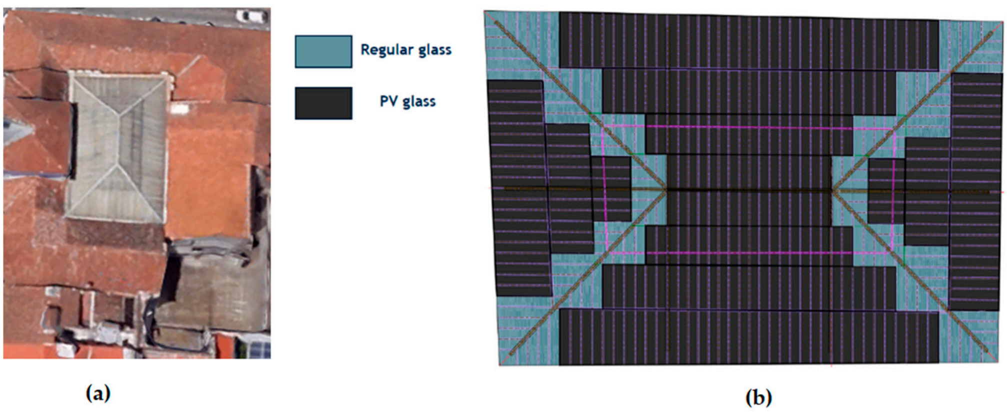


Figure 5. Skylight of the main building in Paços do Concelho where ONYX solutions will be implemented (**a**); ONYX solution designed for said skylight (**b**).

Moreover, Figure 6 provides the aerial view of the Town Hall building, indicating the geographical orientation, a parameter of the utmost importance to maximise the BIPV design.

Figure 6. Town Hall building view from the top (with North orientation depicted).

Figure 5 shows that the ONYX solution will consist of the photovoltaic solution (represented as "PV glass") and a glass solution ("regular glass"). It is important to note that the aesthetic appearance of the glass solution will be similar to the photovoltaic solution. The need to include these two solutions in the skylight design lies in the impossibility of producing "incomplete" photovoltaic solutions, since they would imply cutting the crystalline solution.

This skylight from ONYX will guarantee the ideal working conditions of the building, both from the point of view of light and from the point of view of air conditioning. Figure 7 shows an ONYX aesthetic skylight implemented in a building of the Regional Government of Andalusia, whose aesthetic profile is similar to that designed for the main building in Paços do Concelho.

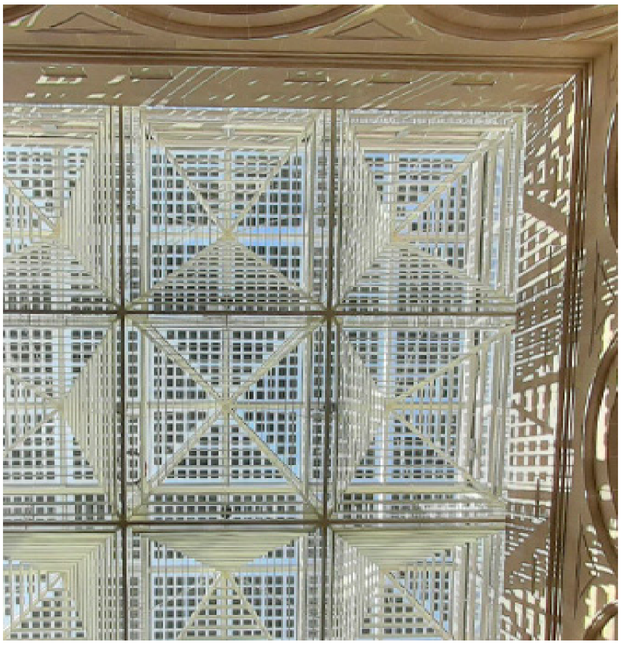


Figure 7. ONYX aesthetic skylight implemented in the Regional Government of Andalusia building.

Figure 8 presents the aesthetic photovoltaic skylight solution proposed by ONYX regarding the coverage of the Roman Thermal Baths. Similarly to the skylight of the main building of Paços do Concelho, the solution will be composed of a mixture of "PV glass" and "regular glass".

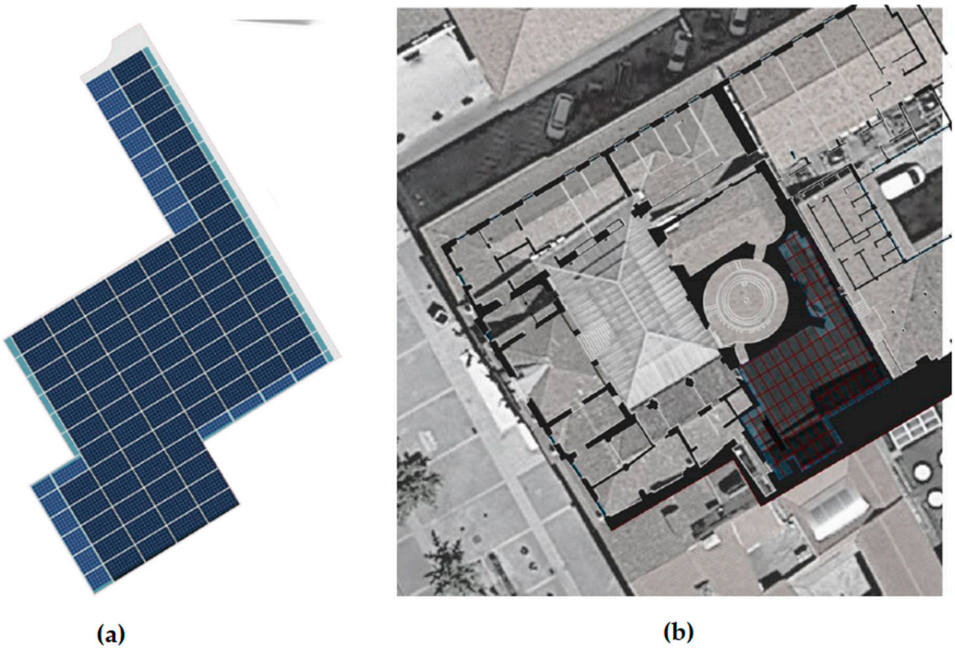


Figure 8. Aesthetic photovoltaic skylight solution proposed by ONYX for the Roman Thermal Baths (**a**); projection of the skylight over the thermal baths (**b**).

Figure 9 illustrates the interior aesthetic profile of an ONYX solution similar to that designed for the Baths.

Figure 9. ONYX aesthetic skylight solution similar to that designed for the thermal baths at the Town Hall.

Figures 10 and 11 show the new solution of photovoltaic tiles supplied by Tegola.

Figure 10. New Tegola photovoltaic tile.

Figure 11. Installation of new Tegola photovoltaic tiles.

The new solution presented by Tegola accommodates the requirements indicated by the Regional Culture Administration of Alentejo in the first interaction in 2020. Thus, the tile has an aesthetic aspect very similar to the traditional tile of the historic centre of Évora, highlighting the curved shape and clay colour. Additionally, the colour of the tile will be adapted to the colour of the tiles of the Building of Paços de Concelho, in order to ensure an aesthetic harmony. Figure 12 shows the proposal for the location of Tegola tiles in the Building of Paços de Concelho. This location considers the budget limitation of the project while intending to ensure the compliance between the different sections of the coverage.

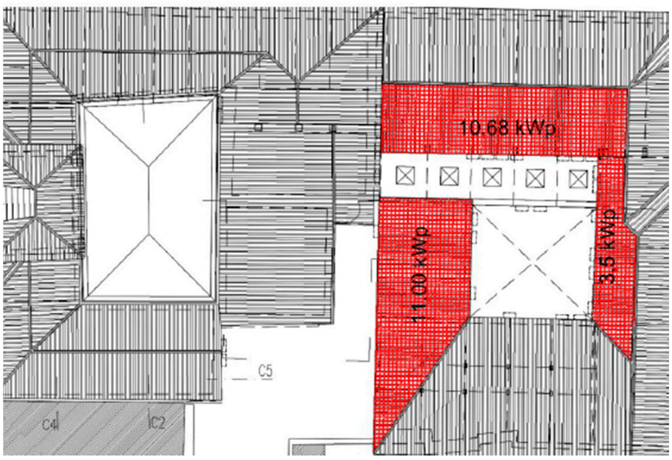


Figure 12. Location of Tegola tiles (in red) in the Municipality Palace Building.

5.4. *Arena d'Évora*

In Arena d'Évora, located on Av. Gen. Humberto Delgado, the solution that will be implemented will be Tegosolar PV, Tegola. This solution consists of a light coverage of amorphous silicon photovoltaic cells, conferring coverage and insulation capabilities, in addition to the aforementioned photovoltaic generation capabilities. Figure 13 illustrates Tegosolar PV's proposal to be installed in the Arena. The small coverage area is related to the very sensitive weight requirements of the existing cover and the maximisation of the use of irradiance in the south slope of the building. In Figure 14, an example of a building with Tegosolar PV technology is presented.

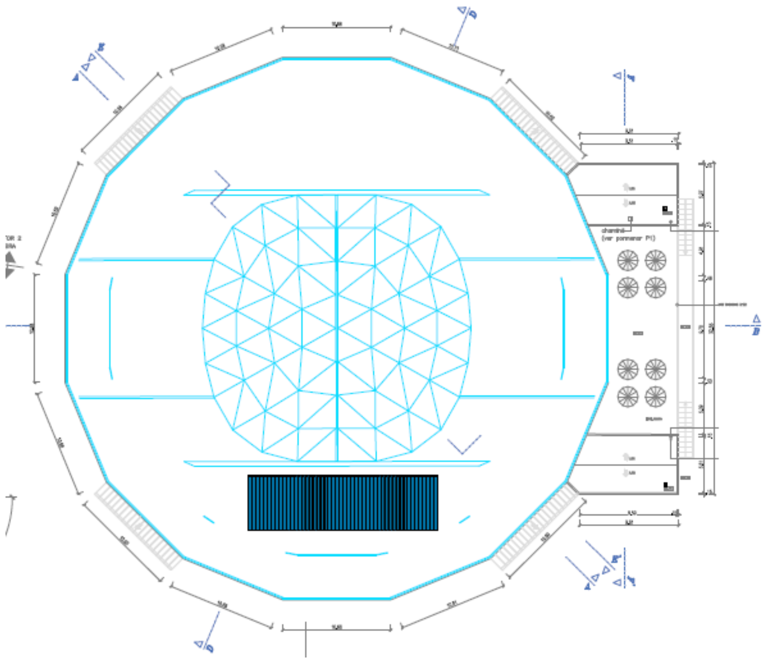


Figure 13. Tegosolar PV solution to be installed on the roof of the Arena d'Évora.

Figure 14. Example of an installation with Tegosolar PV technology.

Furthermore, Figure 15 provides the aerial view of Évora's Arena, indicating the geographical orientation.

Figure 15. Arena's aerial view, with geographic representation (North).

5.5. *São Mamede School*

In the Basic School of São Mamede, located in Largo Dr. Evaristo Cutileiro, two types of solutions will be implemented: aesthetic photovoltaic pergolas and photovoltaic windows provided by ONYX. The ONYX photovoltaic pergola will be installed as set out in Figure 16. Figure 17 shows an example of an ONYX photovoltaic pergola installed in Tony Gallardo Park in the Canary Islands. This will be the aesthetic aspect granted by the solution proposed by ONYX for the S. Mamede School. Regarding the ONYX photovoltaic windows, a study was made for their installation on the school's ground floor. The target windows of this installation are identified in Figure 18 in the blue bound zone.

Figure 16. Aesthetic photovoltaic pergola solution proposed by ONYX for S. Mamede School.

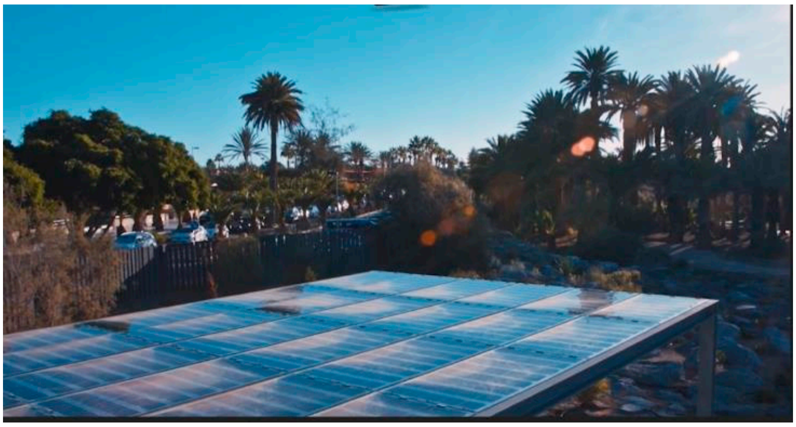


Figure 17. Photovoltaic pergola solution installed in Tony Gallardo Park, in the Canary Islands.

Figure 18. Floor windows 0 that will be replaced by ONYX photovoltaic windows, marked in blue.

Figure 19 illustrates the solution presented by ONYX for the windows mentioned above. The photovoltaic window consists of a triple laminated glass of amorphous silicon and a semi-transparency degree of 20%.

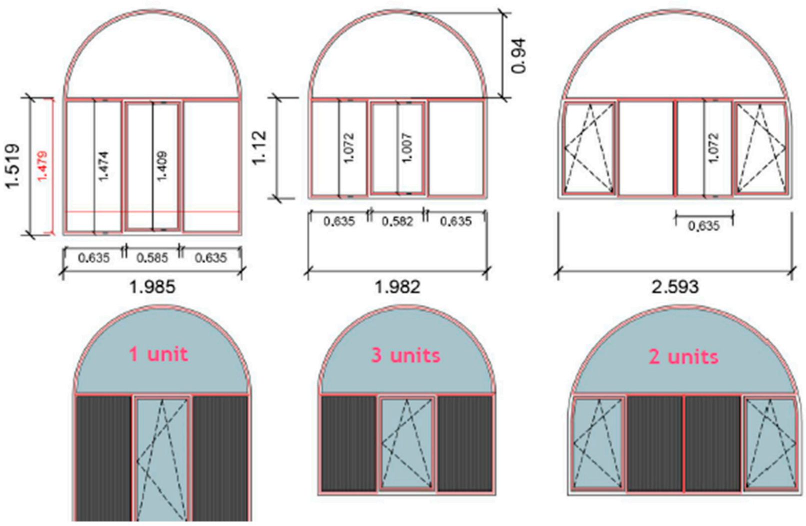


Figure 19. Illustration of the ONYX study for the installation of photovoltaic windows.

The semi-transparency of 20% will give a better air conditioning to the corridor of the ground floor, residually reducing the interior light, an option that meets the requirements of the school administration. From the aesthetic point of view, Figure 20 shows an installation similar to the one that will be installed in São Mamede School.

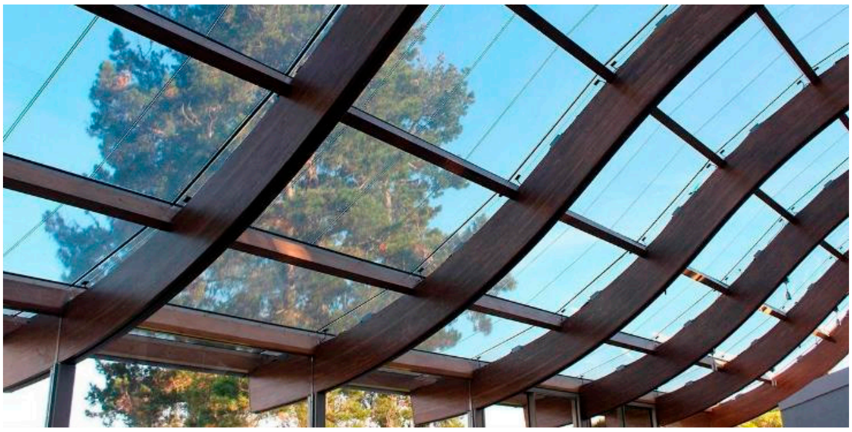
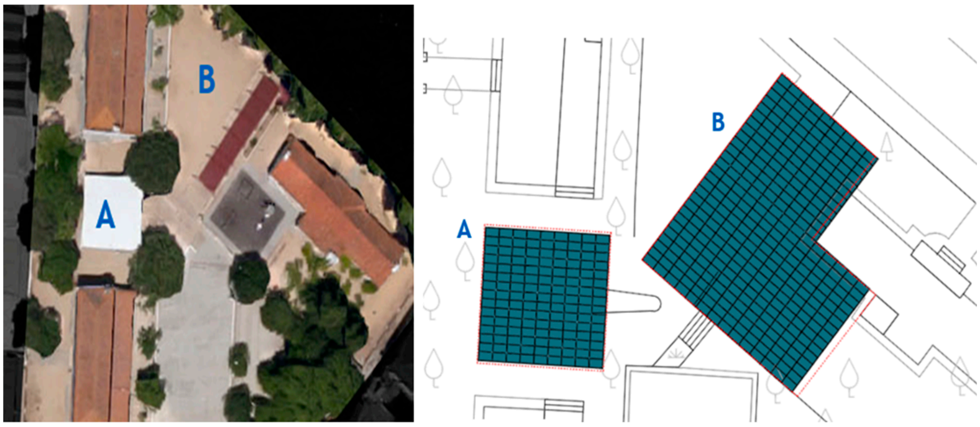


Figure 20. ONYX photovoltaic window in San Francisco, USA.

5.6. Rossio de São Brás School

In the Basic School of the 1st Cycle of Rossio de São Brás (Figure 21), located on Av. Fighters of The Great War 2, two aesthetic photovoltaic pergolas by ONYX will be implemented. The pergolas, represented in Figure 22 in areas A and B, aim at providing a covered play area for children, thus offering protection against sun exposure and weather. The proposal meets the requirements of the school administration: in area A, an existing cover will be replaced, and in area B, a small pergola will be replaced, adding, however, a larger coverage area. The aesthetic aspect granted by the solutions proposed by ONYX for the Rossio School of São Brás is shown in Figures 23 and 24.

Figure 21. Rossio de São Brás School aerial view.



(a) (b)

Figure 22. Location of pergolas to be installed by ONYX identified by A and B (**a**); Representation of ONYX photovoltaic pergolas (**b**).

Figure 23. Illustration of ONYX roofs to be installed at the Rossio School of São Brás (A).

Figure 24. Illustration of ONYX roofs to be installed at the Rossio School of São Brás (B).

5.7. Parking Lot

Regarding the parking lot located on Avenida Engenheiro Arantes e Oliveira, in the vicinity of the Garcia de Resende Theatre (see Figure 25), Tegosolar PV photovoltaic roofs will be installed in order to provide a shading area for parked cars. The installation details are illustrated in Figures 26 and 27. The aesthetic aspect of the cover will be the same as the Tegosolar PV technology presented in Figure 14.

Figure 25. Location of the car park targeted by BIPV solutions on Avenida Engenheiro Arantes e Oliveira, in the vicinity of the Garcia de Resende Theatre.

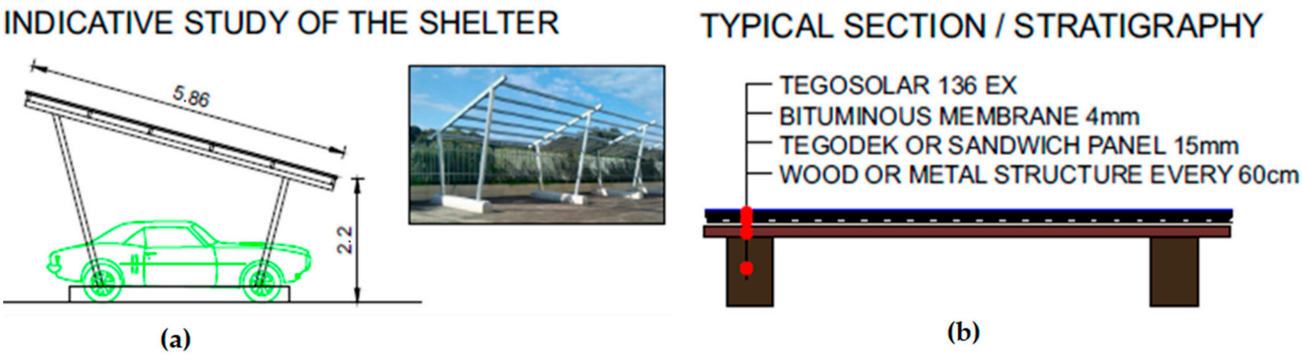


Figure 26. Identification of the type of roof to be installed (**a**) and the respective stratigraphy (**b**).

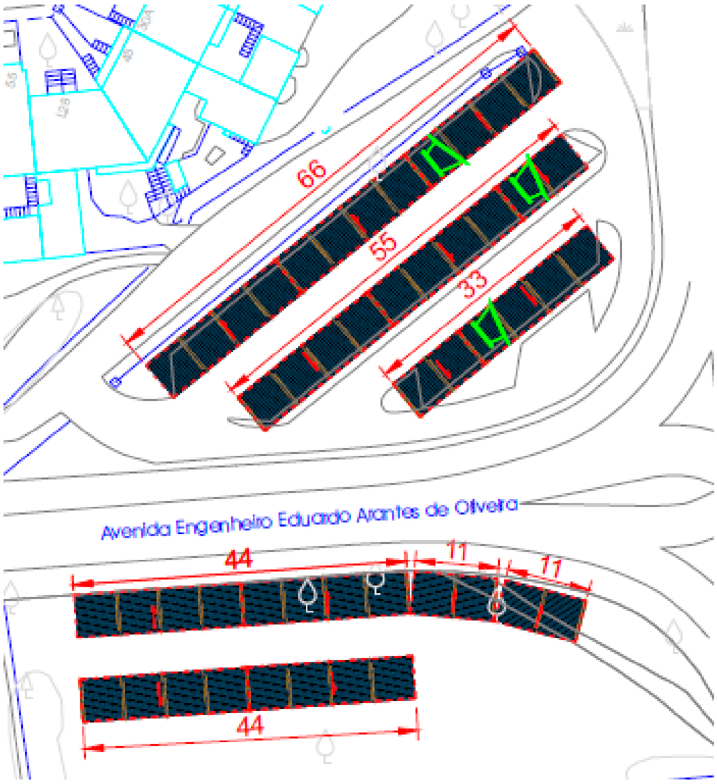


Figure 27. Layout of the photovoltaic roofs with Tegosolar PV to be installed in the parking lot.

5.8. LVpDÉ

The Living Laboratory for the Decarbonisation of Évora, alias LVpDÉ, located in Rua do Raimundo (see Figure 28), will house two types of BIPV solutions: ONYX's aesthetic photovoltaic pergolas and roof covers with Tegosolar PV technology.

Figure 28. Living Laboratory for the Decarbonisation of Évora (LVpDÉ), located in Rua do Raimundo.

As mentioned, the ONYX photovoltaic pergola will be installed in three distinct locations. The three solutions will consist of a double laminated glass of crystalline silicon and its aesthetics will be similar to that presented in Figure 16. Note that, in the case of LVpDÉ (see Figure 29), no pillars/support beams are required, and the ONYX solution is supported by the existing facades.

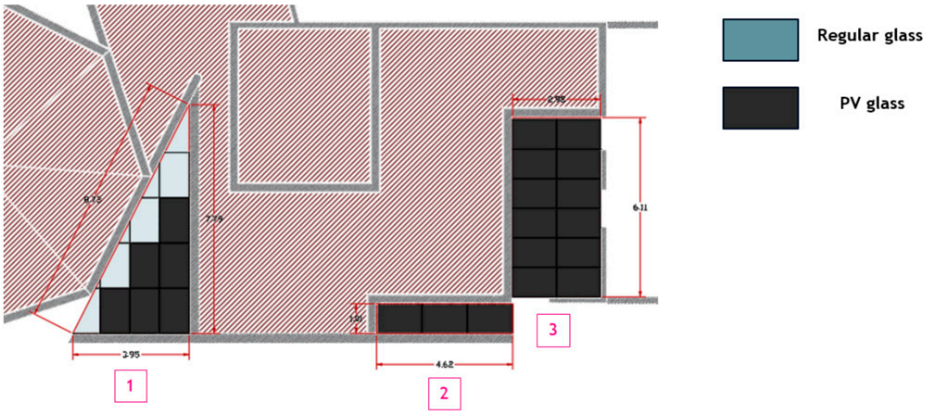


Figure 29. ONYX solutions to be installed on LVpDÉ.

Regarding Tegosolar PV technology, Figure 30 shows the proposal made for the coverage of LVpDÉ. Note that Tegosolar PV technology is indicated in din blue color, while the dark grey areas refer to a material with the same aesthetic appearance as Tegosolar PV. The reason for the application of the two distinct layers lies in the impossibility of "cutting" and adapting photovoltaic material to the corners of the surfaces. As an illustrative example, Figure 31 shows the installation of the Tegosolar PV product on a residential roof.

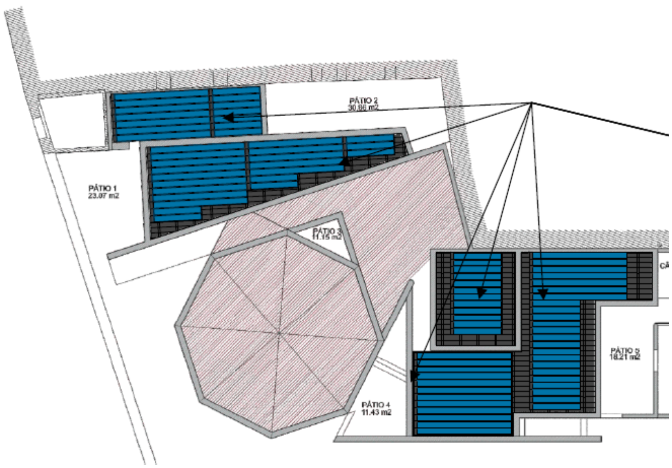


Figure 30. Application of Tegosolar PV technology in the coverage of LVpDÉ.

Figure 31. Tegosolar PV technology in a residential penthouse.

5.9. Municipal Market 1° de Maio (Fruit Market)

Concerning the Municipal Market 1° de Maio, located in 1° de Maio Square, an ONYX aesthetic photovoltaic skylight will be installed in the blue-outlined area of Figure 32. The proposed solution for the market consists of a double laminated glass of crystalline silicon, whose aesthetic design is similar to that of the Edmonton Congress Centre, represented in Figure 33.

Figure 32. Municipal Market May 1, with the location of the onyx photovoltaic skylight.

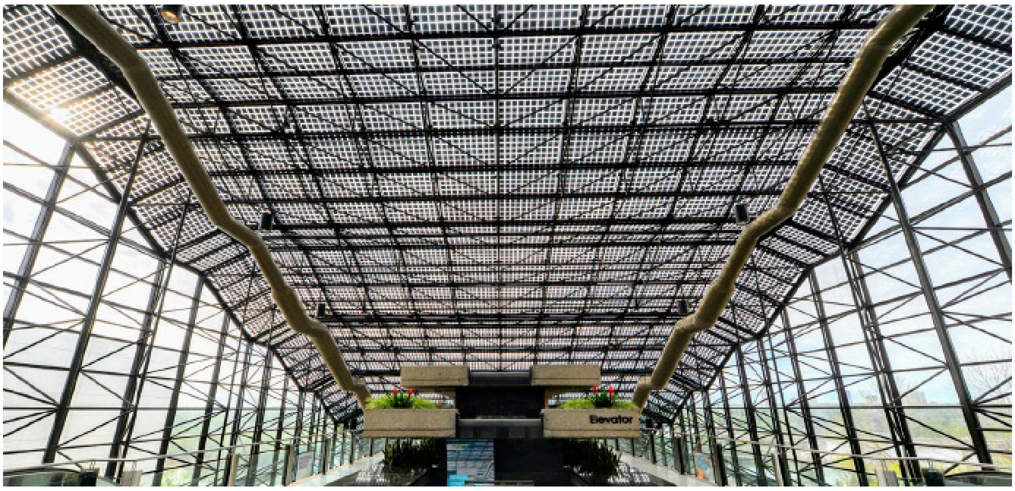


Figure 33. ONYX photovoltaic skylight installed at the Edmonton Congress Centre.

5.10. Summary of Solutions with Renewable Generation Capacity

In this section, a summary of the renewable generation capacity that the BIPV solutions will introduce in the historic centre is given. Analysing Table 4. Annual productions associated with BIPV solutions of municipal buildings, which details the generation foreseen for each of the installations, it is verified that, with the sized powers, an annual renewable production of about 845 MWh will be achieved.

Table 4. Annual productions associated with BIPV solutions of municipal buildings.

	Market	Arena	Theatre	EB1 S. Mamede	Town Hall	Rossio School	LVpDÉ	Parking	Total
Predicted generation (kWh/year)	20,008	1456	0	51,346	463,304	156,278	18,823	133,847	845,062

Additionally, the surplus generation that will arise at certain times of the year (e.g., during weekends schools will continue to have production but their consumption will be residual) will not be sold to the national electricity grid as usual, but rather shared with other municipal buildings of the historic centre, in light of the recent Portuguese Decree-Law No. 162/2019. Thus, BIPV solutions will not be the only disruptive solution to be implemented in the historic centre, being also the driver of an innovative renewable energy community involving the buildings of the historic centre of the Municipality of Évora.

6. Conclusions

This paper presents the study carried out for the implementation of BIPV solutions in the historic centre of Évora within the framework of the European project POCITYF (Project H2020). The study carried out throughout the demanding year 2020 considered all observations of the Regional Directorate of Culture of Évora and the administration of the involved schools (including the Association of Parents), the needs of the Municipality of Évora, and the capabilities of technology developers ONYX and Tegola. Thus, this study aims to house all the guidelines aimed at preserving the historic centre, while proposing to achieve the positivity metrics agreed with the European Commission on the challenging and indispensable path to the decarbonisation of European cities.

At POCITYF, in addition to the creation of the three PEBs, we are committed to empowering the citizens of the historic centre of Évora, so that they can have the same opportunities to engage in the energy transition as any other citizen. Moreover, the solutions presented here have a high replication potential not only in Portugal but also in Europe. It is a distinctive feature of POCITYF to contribute new and disruptive solutions that can provide Europe, especially its historic cities, with tools to lead electrical decarbonisation. As POCITYF continues to bring its cities to the new "smart cities" era, more results will arise and will be presented in future works, along with other useful information, such as 3D images showing the level and performance of the integration of the new technologies in the cities.

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