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Cross-Cutting Technologies for Developing Innovative BIPV Systems in the Framework of the PVadapt Project †

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† Presented at the Sustainable Places 2020, Online, 28–30 October 2020.

Published: 23 December 2020

Abstract: In the framework of the PVadapt H2020 project, a sustainable and fully adaptable building-integrated photovoltaic–thermal (BIPVT) system of substantially lower cost than conventional in-market solutions will be developed. A flexible automated process will be employed to produce PV modules as well as elements with integrated heat pipe-based heat recovery. These active energy components will be combined with passive components with structural, thermal, and other functions to produce prefabricated modules. A smart envelope System, featuring grid connectivity, load prediction/shifting, and insolation/temperature predictive algorithms, will be integrated in the BIPVT to maximize energy efficiency and cost saving. The unit cost of production, the levelized cost of energy (LCOE), and the payback period of the multifunctional BIPVT module will be below 200 €/m^2, 2 ct/kWh, and 10 years, respectively.

Keywords: modular construction; silicon photovoltaics; heat recovery; smart envelope; grid connectivity; prefabrication; sustainable by design

1. Introduction

Trends in the total population worldwide show a decline in the share of population living in rural areas of the total population, while towns and cities experience a smooth and constant increase. In Europe, the level of urbanization is expected to increase to approximately 83.7% by 2050. While being responsible for a high level of energy consumption and, therefore, generating about 70% of global GHG emissions, cities are also particularly vulnerable to the impacts of climate change [1]. Thus, it is difficult to envision a sustainable future without transforming the urban environment by applying powerful renewable energy technologies. A new and promising way is to integrate solar technologies in the constructed environment (e.g., buildings), as solar energy is the most abundant energy source in both direct and indirect forms in comparison to all the other renewable sources.

Building integration of photovoltaics replaces traditional elements (windows, cladding, roofs, or accessories) with a functional component able to generate energy. When active heat recovery is combined with building-integrated photovoltaic (BIPV) systems, either in a closed loop (like PV-T with liquid loop) or in an open loop with forced air, they are designated as "building-integrated photovoltaic–thermal" (BIPVT) systems. As a market, the BIPV sector is expected to keep growing from a 3 billion euro market in 2015 to 26 billion by 2022, bringing 20 years of R&D into fruition [2]. However, while market growth of BIPVs might inspire confidence for the future, this market share will only be 7% of the total PV market by 2020, as opposed to the current share of 3%. Combining functional building elements with solar energy technologies leads to the BIPV market comprising a wide array of products with corresponding variations in price range: integrated roof systems are priced between 200 and 600 €/m^2, whereas tiles cost between 350 and 500 €/m^2. A baseline assumption shows that the consumer will invest between 5.02 and 5.72 €/W on roof-based systems. For façade systems, the situation is similar with options available from 100 to 150 €/m^2 but featuring low efficiency thin-film PV technology to high end sophisticated BIPV systems at 750 €/m^2 [3,4].

Despite the promising outlook for the BIPV sector, there are still barriers regarding prefabrication, modularity, smartness, and recyclability, impeding widespread adoption. In Europe, the ageing building stock and low rate of new construction have led to initiatives to increase the rate of refurbishment by 1.5% to 3%. The current low rate of refurbishment adversely affects BIPV adoption, since the largest contributor to the market is rooftop systems, and roofs are usually replaced as part of deep refurbishment [4].

Taking into account the gap in the current market for modular and prefabricated BIPV, especially in the area of PV cooling and heat recovery, the main objective of the PVadapt H2020 project is to develop a BIPVT turn-key system with an exceptionally high level of modularity, applicability, sustainability, and cost efficiency. The overall concept aspires to deliver the following to the market: (i) deep refurbishment BIPVT modules designed for wall and roof replacement, (ii) shallow refurbishment BIPVT systems for replacing or adding building accessories (e.g. shaders and parapets), and (iii) new construction systems designed for residential or commercial applications as well as auxiliary buildings. Moreover, PVadapt will implement a circularity approach to the life cycle for all components and materials applied, following the principles of sustainable construction. Until now, six articles have been published in international journals and proceedings of international conferences to present the outcome of PVadapt as well as its contribution to BIPV market [5].

2. PVadapt BIPVT Technology

The overall BIPVT solution proposed by PVadapt includes two components, i.e., a structural/thermal component and a HeatMat/PV component, which will be produced separately, and an assembly/joining methodology will be developed for the on-site integration (Figure 1).

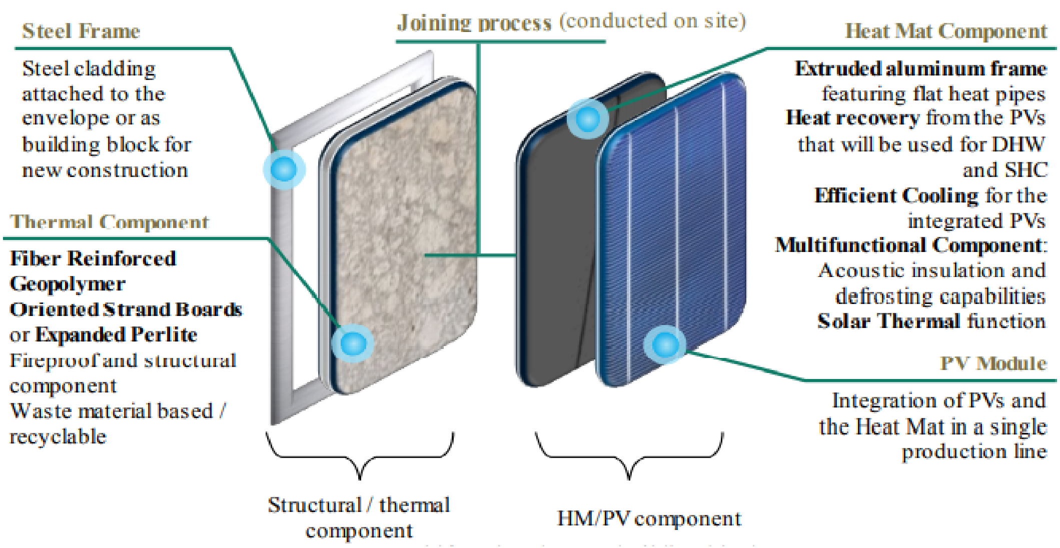


Figure 1. Multifunctional BIPVT building block, which will be developed in the framework of the PVadapt H2020 project.

The combination of these two components will produce “building blocks” of sufficient customization to allow components suitable for roof and façade installations, as well as new constructions. However, throughout the whole project, principles of sustainable design will be applied to all levels of product development, including production processes, installation, maintenance, dismantling, and reuse/recycling of the components. The developed PVadapt will be modular, adaptable, and recyclable, offering diverse services for inhabitants (Figure 2).

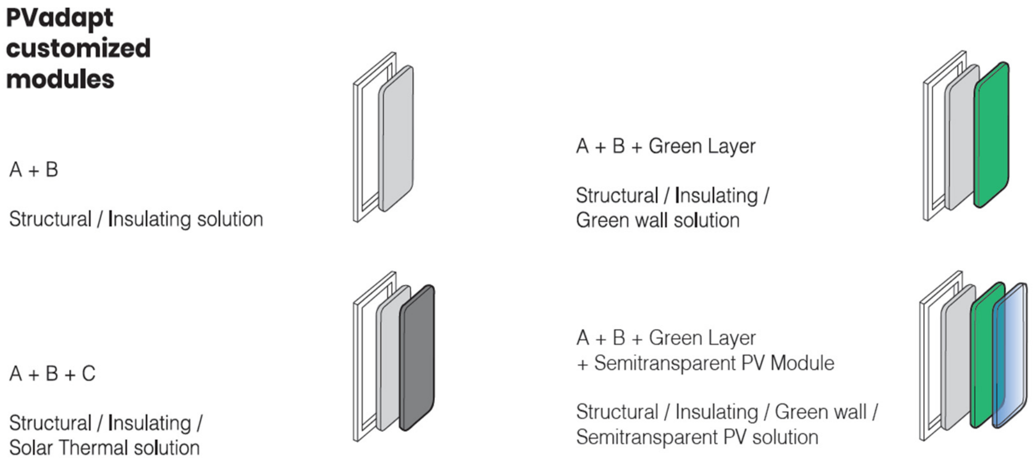


Figure 2. Concept of the four customized modules developed for the purposes of the PVadapt project.

The main pillars comprising the overall research activity of the PVadapt project are summarized below:

2.1. Production of Energy Active Photovoltaic (PV)/Heat Mat (HM) Modules

2.1.1. Modification and Production of HM Components for Integration in PV Modules

A combined system heat mat (HM)/PV system will increase PV output and longevity through maintaining operating temperature at 25 °C. This will be accomplished due to the efficient energy transfer capacities of HM technology. The HM component will be modified for roof and façade integration as a thin (5–10 mm thickness), lightweight (20 kg/m^2), and cost-efficient element (<80 €/m^2).

2.1.2. Modular Production of PV Modules for BIPV Integration with Integrated HM Cooling Components and Customizable Interlocking Plug&Play Elements

The utilization of modular production equipment to create highly adaptable production lines to enable efficient production of small series of PV modules will result in tailored-made solutions based on the customer demands. The concept of modular production equipment will contribute to at least 15% reduction of the time required to reconfigure the production line, 10% higher resource efficiency due to more suitable processing equipment for customized products, and a reduction of at least 15% of the overall cost of production. The cost for the PV-element (solar cells excluded) is expected to be lower than 20 €/m^2. Furthermore, diodes will also be integrated to replace bulky junction boxes, allowing for seamless (Plug&Play) interconnection of BIPV.

2.2. Modular Integration of Functional Layers to BIPV Products

The PVadapt BIPV module will feature several interchangeable layers with the purpose of customizing functions utilizing the same architecture. The components will be applicable in roof and external façade configurations, and through the “layered” structure each functional component will connect to the next one, either through integration in the production stage or attachment during the installation stage.

2.3. Production of Passive Multifunctional Components for Integrated BIPV Products

2.3.1. Fiber Reinforced Geopolymers (FRG)

Production of a geopolymer structural component will incorporate more than 80% of waste of industrial origin (slag), byproducts (ash), or CDW (ceramic waste), which have been demonstrated as raw materials conferring excellent mechanical properties.

2.3.2. Bio-Waste-Based Oriented Strand Boards (Bio-OSBs)

This structural component will be designed with 100% bio-based material, which can be separated from other materials after usage and be reused or composted as an end-of-life solution. Mechanical properties of the prototypes will be optimized to develop panels, which will be tested at the demonstration sites. An essential objective for the structural component is the utilization of residual biomass like whey (or whey protein isolate) as binder and fire resistance improver and corn cob particles or cellulose and fiber fine fraction from paper recycling as filler with insulation properties (thermal conductivity $\lambda < 0.065$ W/m·K).

2.3.3. Expanded Perlite (ExP)

Expanded perlite will be produced, encapsulated, and used as granular insulation material to maximize the thermal insulation of the panel system. Expanded perlite is an inorganic, incombustible, non-corrosive, and low cost (50–80 €/m^3) insulation material, with density ranging between 50 and 150 kg/m^3 and λ values between 0.038 and 0.060 W/m·K.

2.4. Deploying the Smart Envelope System

In PVadapt, a smart envelope System featuring an ICT enabled decision support system (DSS) using wired and wireless sensors and any existing sensory infrastructure will be developed that will accurately select the most cost- and energy-efficient course of action for each installation using prediction-based deep learning algorithms, which will achieve reduction of maintenance costs of over 20%, as well as energy consumption reduction of over 10%.

2.5. Optimizing the Life Cycle of Produced Components

The supply chain for decommissioning, dismantling, separating, and recovering the PVadapt products will be designed to achieve 100% recyclability. The processes will cover removing the components, dismantling, and separation into layers and individual recycling/reuse plans.

2.6. Enabling Accelerated Decision Making and Installation Operatons through Implementation of Integrated Project Delivery (IPD)

The IPD methodology will address the definition of the processes and the communication mechanisms to be adopted by the stakeholders to ensure the project meets its intended goals. The IPD will put special focus on ensuring a smooth collaboration among the architect firm, engineering, and BIPV installers, making the gap between the as-designed and the as-built model negligible and meeting the project’s energy efficiency goals. While quantitative data on the benefits of adopting an IPD approach are scarce, studies point to higher reliability in terms of overall cost performance and a significant reduction in the cost of change order for errors, omissions, and design modifications. Benefits in project quality, decreased chance of claims, and reduced project duration are equally confirmed by diverse case studies [6].

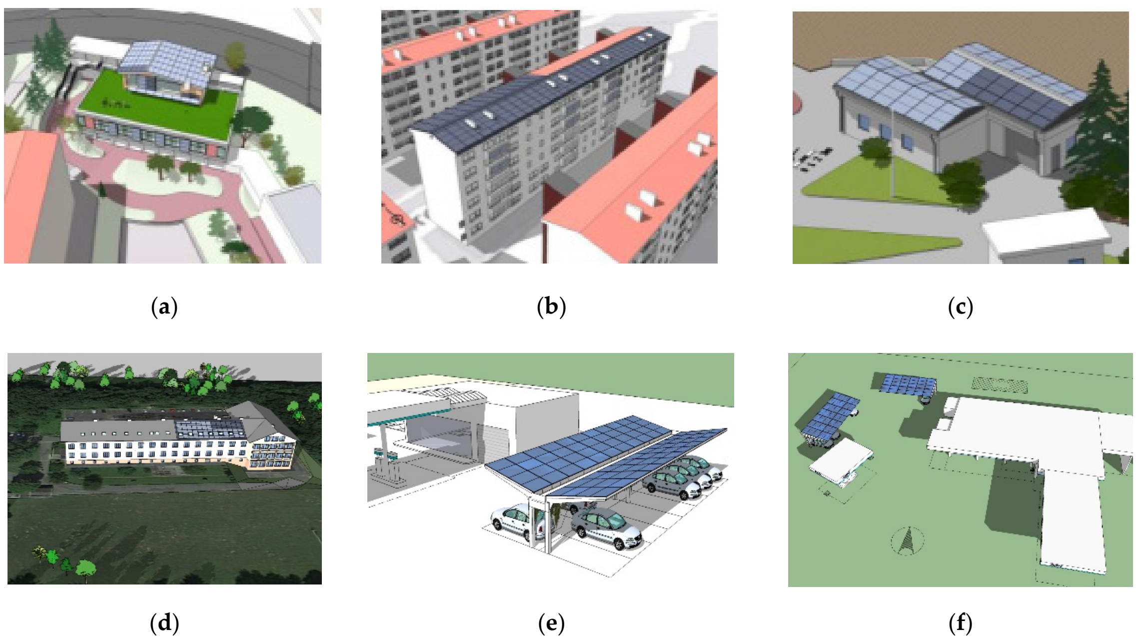
2.7. Ensuring that the Activities and Results of the Project Adhere to EU and National Member State Legislations and Regulations and Identifying Energy Efficiency and Refurbishment Incentives

The Consortium is dedicated to delivering exploitable results that will follow EU and national regulations and directives and adhere to relevant standards. Part of this process will also be to conduct corresponding standardization workshops to be in accordance with CEN-CENELEC. Furthermore, the Consortium will communicate with running or completed projects with relevant interests to share insights and results, combine resources, maximize exposure, and participate in regulatory and standardization activities.

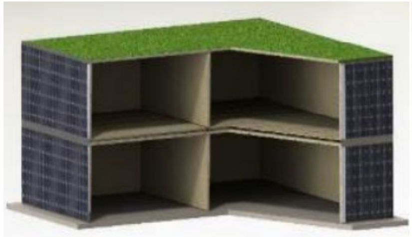
3. Demonstration Activities as Case Studies

According to the Grant Agreement, "the PVadapt technologies will be installed in flat and pitched roofs, as wall replacements and façades and shaders, demonstrating the holistic approach to BIPVs, improving their entire life cycle." The applicability and efficiency of the BIPVT solution will be evaluated under a wide range of demanding scenarios, which will be applied in demonstration sites at Fehring (Austria), Athens, Arta, Kalamata (Greece), Bilbao (Spain), and Coimbra (Portugal), representing variable climate zones in order to support the later stages of market readiness.

The overall architectural design was performed following EN 50583-1:2016 "Photovoltaics in buildings-Part 1", which reports that photovoltaic modules are considered to be building-integrated if the PV modules form a construction product providing a function as defined in the European Construction Product Regulation CPR 305/2011. Based on EN 50583, BIPV functions should be electricity generation and, depending on the application, one or more of the following: mechanical rigidity or structural integrity, primary weather impact protection (rain snow, wind, hail), energy economy (e.g., shading, daylighting, thermal insulation), fire protection, noise protection, separation between indoor and outdoor environments, security, shelter, or safety. As reported by IEC 63092 "Photovoltaics in buildings", which applies to photovoltaic modules used as construction products (Part 1) and to their corresponding systems to integrate them into the building (Part 2), five mounting categories distinguish between vertical and sloping, i.e., Category A: sloping, roof-integrated, not accessible from within the building; Category B: sloping, roof-integrated, accessible from within the building; Category C: non-sloping (vertically) envelope-integrated, not accessible from within the building; Category D: non-sloping (vertically), envelope-integrated, accessible from within the building; and Category E: externally-integrated, accessible or not accessible from within the building. Following the above-mentioned strict norms, a comprehensive and multi-disciplinary architectural design was adopted for each demonstration site (Figure 3).



(**g**)

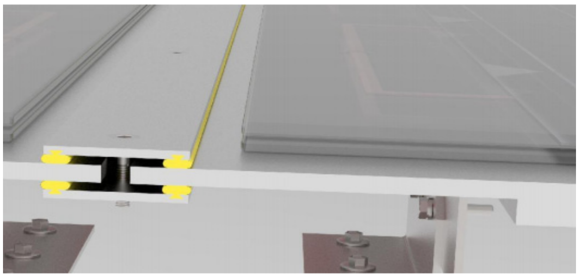


(**h**)

Figure 3. Indicative architectural designs of demonstration sites: (**a**) Bilbao, Oxtar Urban Gela (Spain); (**b**) Bilbao, Otxar residual building (Spain); (**c**) EYDAP building, Athens (Greece); (**d**) Cambium Fehring (Austria); (**e**) Arta service station (Greece); (**f**) Kalamata service station (Greece); (**g**) Athens administrative building (Greece); (**h**) Coimbra (Portugal).

The architectural approach is supported by the modular and sustainable construction and assembly processes to deliver robust and reliable refurbishment of BIPVs in façades and roofs as well as new constructions, which is based on light steel framing (LSF) technology. This innovative modular construction method will be the foundation of the PVadapt process, providing a robust component architecture that is ideal for the addition of multiple building-transforming functionalities. Furthermore, ready-to-market solutions will be developed to ensure BIPVT functions, e.g., watertightness (Figure 4).

(**a**)



(**b**)

Figure 4. (**a**) Standard panel assembly; (**b**) cross-section of the vertical watertight functionality (primary weather protection) for roofs.

4. Conclusions

As indicated, the PVadapt H2020 project is focused on the development of cross-cutting technologies attributed to building elements producing both electrical and thermal energy and new construction components able to be adapted to BIPV elements. The project also aims to establish management prediction algorithms to better match energy supply/demand as well as proper advanced tools for balancing thermal and electrical networks followed by a user-friendly interface to support alternative business cases and confronting the existing standards. Finally, based on the overall outcome, viable business models will be established, and proper synergies will be performed in order to propose the creation of new standards regarding the BIPV industry.

Author Contributions: All authors contributed equally to this article. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the European Commission for project PVadapt under Grant Agreement number 818342.

Conflicts of Interest: The authors declare no conflict of interest.

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