Development of an innovative compact hybrid electrical-thermal storage system for historic building integrated applications in the Mediterranean climate.

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Abstract: Currently in the EU, there are limited examples of operationally integrated solutions capable of achieving optimal interaction of energy networks, combining both electricity and heat-cooling energy supply and storage. There is thus, a need for the efficient use of renewable energy resources through hybrid systems utilising generation and storage of energy. The present study proposes a novel concept for the development of an innovative compact hybrid electrical-thermal storage system for stand-alone and district connected buildings. The proposed hybrid storages will be used to upgrade existing building configurations and will be monitored in real-life operation in a historic building in Cyprus. The building has been selected to be part of a hands-on technology exhibition area of renewable energy systems complimented with visual means to enhance the experience of visitors. The RES systems will be enhanced with enabling technologies offering the benefits of smart digitalised home solutions that can seamlessly be integrated in the neighbouring communities / districts to form energy communities. The municipality is to use the systems as a hands-on experience for informing society about the use of new technologies in their homes capable of offering a transition to the low-carbon economy achieving high levels of energy savings. Moreover, the integration of such systems in this specific application is to be used as an exploration of the sensitive issue of the architectural integration of technologically advanced systems into the listed buildings of historical centers. The concept presented herein is part of the ongoing research programme HYBUILD, which is funded by the European Union through HORIZON 2020.

Keywords: Innovative hybrid systems, electrical-thermal storage, architectural building integration, Mediterranean climate, historic buildings.

1. Introduction

One of the main concerns globally is that of how to address the phenomenon of climate change - which is mainly caused by human activities. Many countries worldwide establish and implement new policies to address climate change and its dramatic consequences. The European Commission has set the renewable energy directive which establishes a common policy for the countries in the European Union for the promotion of renewable energy sources. The plan includes the electricity, heating and cooling and transport sectors (Pantano et al. 2016, Urabe et al. 2013, Zhao et al. 2015). In this context, buildings must be more energy efficient and with lower carbon dioxide emissions. For this purpose, the required energy of buildings is targeted to be produced mainly from renewable energy sources (photovoltaic solar power systems on building's roofs or facades supported by batteries where possible) and would be more energy efficient if heat pumps are used for the heating and cooling needs of the building but in a controlled mode that will efficiently meet the needs of the building where is actually used. Architects and builders are including solar systems as a way to meet green building standards and property owners are seeking PV as a way to reduce their utility bills, as well as their carbon footprints.

The installation of renewable energy sources should be seen as part of a holistic building design to improve the energy efficiency of a building and its carbon footprint utilizing on the way solutions that offer higher efficiencies than current state of the art solutions. This objective becomes slightly more difficult when solar energy systems should be installed in historic buildings to achieve the zero energy objective. Taking a holistic building approach is a logical process which enables the best possible balance to be struck between saving energy and reducing carbon emission, sustaining heritage significance, and maintaining a healthy building area.

The aim of this paper is to examine the available technologies related to the exploitation of solar system for energy saving and determine the integration of such systems in this specific application of architectural integration into listed buildings of historical centres. Furthermore, the objective of this study is to introduce the novel concept in the development of an innovative compact hybrid electrical-thermal storage system for stand-alone and district connected buildings and its application into a demo-site that constitutes a historic building in Cyprus.

This paper is organized as follows: 'Section 2' describes and analyzes solar technologies for building integration and describes the difference between BAPVs and BIPVs, while 'Section 3' describes the background behind the solar energy integration into historic buildings. 'Section 4' shows some case studies where solar systems are integrated in historic buildings, while 'Section 5' presents the HYBUID project and the demo site of Aglantzia, Cyprus, and finally 'Section 6' draws the conclusions and future prospects.

2. Solar technologies for building integration

There are several different types of solar energy systems available for building integration. One type is commercially exploited Solar Thermal Systems (STSs). These technologies absorb solar radiation and convert it into thermal energy used for heating water. The main types of these systems are:

- Glazed Flat Plate Hydraulic Collectors (Glazed Flat Plate Hydraulic Collectors)
- Unglazed Flat Plate Hydraulic Collectors
- Flat Plate Air Collectors
- Vacuum Tube Hydraulic Collectors
- Concentrating Hydraulic Collectors
- Unglazed Plastic Collectors

Another type of solar energy technology system that can be integrated in buildings is photovoltaic, which receives solar radiation and converts it into electricity. In particular, when solar radiation falls into materials known as "semiconductors," the energy of the incident radiation (also known as photons) releases some electrons to these materials. The potential difference developed within the material translates into direct electricity generation. These photoelectric cells are, in the state of the art solutions, made of monocrystalline or, polycrystalline or amorphous silicon (Thomas, 2006).

Photovoltaic technology is used largely on buildings due to its versatility and low cost production of electricity at the point where is needed. However, installed systems prioritize energy generation while ignoring aesthetic considerations and thus often creating a negative visual impact. These concepts have been developed in numerous publications popularizing the terms "Building Integrated Photovoltaics" (BIPV) and "Building Applied Photovoltaics" (BAPV). Currently, most PV modules are secured to a roof or onto a facade using a metal structure. The PV system is an additional or applied structural element with the sole function of generating energy hence the definition Building Applied PV (BAPV). In contrast, Building Integrated PV (BIPV), refers to the application of PV in which the system, as well as having the

function of producing electricity, also takes on the role of a building element. A Building Integrated Photovoltaics (BIPV) system is a PV system integrated into the building envelope (e.g. roof, façade, window, etc.). Thus, it replaces a building element i.e. a conventional construction material.
Technologies that are available for building integration (BIPV) are among others the following:

BIPV modules
Photovoltaic panels used for building integration are almost similar to conventional photovoltaics. The difference, however, lies in the fact that the BIPV panels are made to function as a shell resistant to weather and that some are manufactured to replace different types of construction materials, while some are prefabricated units with thermal insulation.

Flexible (Foil) BIPV
Flexible BIPV is a relatively new product that allows for attractive integration options in a building as it is lightweight and flexible, which is beneficial to its ease of installation (Jelle et al 2012). Photovoltaic cells are often made of thin-film cells to maintain flexibility and to be effective in high temperatures (e.g. in non-ventilated roofs). Flexibility is achieved mainly due to its very thin structure, combined with its ability to be installed on flexible substrates (stainless steel sheets or polymer film), giving it a handy and compact form (Chopra et al. 2004). It has also been observed that it can yield as much as 20% better than other types of photovoltaic at high temperatures (Carr and Pryor 2004). However, it should be noted that Flexible BIPVs have reduced performance due to the non-uniformity of the intensity of sunlight on their surface as well as due to the large resistances of thin-film solar cells.

BIPV tiles
The sloping surfaces of the buildings (roofs) are still considered to be the ideal place for PV application. Roof integration is done with the BIPV approach, with photovoltaic modules (without a metal frame) replacing and installing on the same level as tiles, covering the entire roof or selected parts of it. They are usually integrated with the same logic and properties of conventional roof tiles in which some of the conventional tiles are installed and replaced, thus allowing easy roofing to be reconstructed (Heinstein et al. 2013). BIPV tile products may cover the entire roof or selected parts of the roof. They are normally arranged in modules with the appearance and properties of standard roof tiles and substitute a certain number of traditional roof tiles, thus also enabling easy retrofitting of roofs. The cell type and tile shape varies. Some tile products may resemble curved ceramic tiles and will not be as area effective due to the curved surface area, but may be more aesthetically pleasing (Jelle and Breivik, 2012).

Solar Cell Glazing
The solar cell glass panels consist essentially of glass-enclosed photovoltaic cells and provide several options for windows, glazing or sloping facades and ceilings.
Photovoltaic windows have (semi) transparent modules that can be used to replace a number of architectural elements commonly made with glass or similar materials such as windows and skylights. In addition to producing electric energy, these can create additional energy savings due to superior thermal insulation properties and solar radiation control.

Other technologies
Over the last 30 years, a large amount of research on PV-Thermal (PVT) collectors has been carried out. Hybrid PV / T Systems are units that combine the characteristics of PVs and STSs, converting solar energy into electricity and heat simultaneously. To maximize electrical power

then the photovoltaic unit must be at low operating temperature upon arrival of incoming solar radiation. This can be achieved by using this heat to heat the fluid, which upon leaving the system can be used for space heating or water preheating. Additionally, a new and promising photovoltaic technology is the Perovskites. Perovskite solar cells have stunned the PV community the last few years. Since the 9.7% first efficiency of a solid-state perovskite cell was reported in 2012, rapid progress by several groups has improved this efficiency above 20% (M. Saliba et al. 2016). Furthermore, multi – junction solar cells is a new technology that attracts more and more attention the recent years. A multi - junction photovoltaic cell is a solar cell with multiple p-n connections of different semiconductor materials. Each p-n junction of each material generates electrical current in response to a different wavelength of light. A single cell produces electric current at a single wavelength in the sunlight spectrum. A multi - junction solar cell will generate an electric current at multiple light wavelengths, which increases the energy conversion efficiency of sunlight into usable electricity.

3. Historic preservation designations

The architectural and visual integration of solar panels on historic buildings are treated in different way compared to contemporary buildings as are characterized by cultural value (Moschella et al. 2013). Several researches study the architectural restoration to establish a balance between the need of conservation versus innovation and energy saving. High-quality design can play a key role in minimising any adverse effects of projects. Fundamental to achieving high-quality design is a sound understanding of the character and importance of the historic asset involved, whether at the scale of individual buildings and sites or more extensive historic areas and landscapes (Historic England, 2018).

The construction standards of historic buildings were built differ from the contemporary and often do not meet current energy and comfort needs (Lopez and Frontini 2014). The construction elements rarely can differ from the protected elements in order to provide good level of thermal insulation since the aesthetic appearance would be affected. Renewable energy sources can be used to cover the high-energy consumption with sustainable sources. The challenge is to maintain the preservation of the original form and value of the historic district considering the rules of local legislations and policies and on the other hand, to recognize the importance of accommodating renewable energy technologies where they are appropriate (NREL, 2011). Solar panels in a sensitive historic context is very critical as they have an appearance which is not always coherent with the historical building in terms of aesthetics, colours, shapes, dimensions and surfaces (Lucchi et al. 2014). The objective is to select reversible and compatible technologies that will increase the economic value and avoid any kind of damage.

Based on ICOMOS Charter for the Conservation of Historic Towns and Urban Areas , article 8, “new functions and activities should be compatible with the character of historic town or urban area”. Furthermore, “adaptation of these areas to contemporary life requires the careful installation or improvement of public service facilities”. Active solar systems are considered as contemporary elements. Thus, according to Article 10 of the same charter, these “should be in harmony with the surroundings” and should not be discouraged since (they) can contribute to the enrichment of an area” (ICOMOS, 1987, Bougiatioti and Michael 2015).

4. Case studies in historic buildings

The introduction of systems for the exploitation of renewable energy sources in built heritage is well-established in some existing buildings. The following examples trying to make the impact of the systems on the building historic fabric and surroundings as minimal as possible.

4.1. Case 1

The Building of the Tourist Office in Alès (France) is a listed sixteenth-century building that uses integrated PV in three façades. Specifically, the surface of integrated PV is 100 m^2 and the energy output is 9,5 kWp (Heinstein et al., 2013). This project focuses on certain characteristics of the cells or modules. It uses these as a tool to maintain continuity in the built environment and to match the context and overall design, while at the same time presenting the characteristics of the material. For example, the colour was chosen to suit other materials used on the building skin and the form and framing of the module was used as a new façade cladding (Farkas et al., 2009) (Fig.1).

Figure 1. Integrated photovoltaics in the façade of historic building of Tourist Office in Alès (France) https://www.france-voyage.com/cities-towns/ales-9535/tourist-office-ales-5799.htm

4.2. Case 2

The Reichstag parliamentary building in Berlin is a major tourist attraction. It symbolises the transparency of governance and a commitment to environmental sustainability. It is one of the more spectacular examples of the drive for energy efficiency and sustainability in public buildings appearing around the world, as part of the global effort to meet rising energy costs and adopt alternative energy sources. Completed in 1894 and surmounted by a glass and steel dome, the original Reichstag housed the German government until severely damaged by fire in 1933. It was only after the reunification of Germany in 1990 that restoration was completed in 1999 and the Reichstag once again became the seat of government and one of Berlin's major landmarks. A biofuel powered, Combined Heat and Power (CHP) provides approximately 80% of the annual electricity and 90% of the heat load of the building. A large Ground Source Heat Pump (GSHP) acts as a seasonal store of both heat and cools. Photovoltaics on the roof power the solar shade within the light sculpture. Specifically, on the flat area of the Reichstag roof, 300m^2 of photovoltaic panels are placed. Moreover, a total of roughly 3,600 m^2 of photovoltaic elements with different collector designs (some of which are heliotropic) are installed on the roofs of the Reichstag Building, the Paul Löbe Building and the Jakob Kaiser Building supplying electricity in these complexes (KBP Ingenieure GmbH 2018, Foster +Partner 2018) (Fig. 2).

Figure 2. Photovoltaics elements on the roof of the historic Reichstag parliamentary building in Berlin https://www.webpages.uidaho.edu/arch464/Hall%20of%20Fame/Arch464/Spring2014/CS3/Reichstag%20Germany%201.pdf

4.3. Case 3

The Paul VI Audience Hall (Italian: Aula Paolo VI) also known as the Hall of the Pontifical Audiences is a building in Rome named for Pope Paul VI with a seating capacity of 6,300, designed in reinforced concrete by the Italian architect Pier Luigi Nervi and completed in 1971. On 25 May 2007, it was revealed that the roof of the building was to be covered with 2,400 photovoltaic panels, generating sufficient electricity to supply all the heating, cooling and lighting needs of the building throughout the year (Fig. 3). It was officially placed into service on 26 November 2008, and was awarded the 2008 European Solar Prize in the category for "Solar architecture and urban development".

The 2,400 installed photovoltaic modules face exactly south and have been installed in replacement of the deteriorated concrete panels, reproducing the dimension according to the original project of Pier Luigi Nervi. Thus, they fulfill the dual "passive" function of protecting the building from radiation and the "active" conversion of solar energy into electricity, giving the aesthetic value an exemplary environmental surplus value.

The average power of the modules is equal to 90 watts each and the producibility is increased by about 5 percent from the 2,400 panels facing north, partially reflecting aluminum, which are the only ones visible from the dome of St. Peter, whose panoramic view does not has been minimally affected.

The electric energy is produced by the generator in direct current and is sent to the inverter apparatuses that convert it into alternating and from there it is transferred to the transformer cabin, located in the base part of the same room.

The 300 megawatt-hours (MWh) annual "clean" electricity, produced by the solar generator, will be fed into the Vatican power grid to partially cover the consumption of the Hall and the neighboring buildings and each year will allow to avoid emissions in the environment of 225,000 kilograms of carbon dioxide, saving about 80 tons of oil equivalent (toe) (Archilovers, 2018) .

The Government of the Vatican City State and the competent Directorate of Technical Services see in this first installation, together with a "solar cooling" plant currently being completed in the "industrial" area of the State, an exemplary expression of the effort made to implement renewable energy generation systems in the Vatican. In the near future, more substantial programs are planned, so that a significant percentage of their energy needs are met by highly innovative renewable energy conversion systems.

Figure 3. Photovoltaics panel on the roof of the historic Paul VI Audience Hall in Italy
https://www.archilovers.com/projects/14001/copertura-solare-dell-aula-paolo-vi-in-vaticano.html#images

5. HYBUILD project

The HYBUILD project is funded by the European Union through HORIZON 2020, and focuses on the development of two innovative compact hybrid electrical/thermal storage systems for stand-alone and district connected buildings. HYBUILD will develop an innovative hybrid storage concept for cooling and heating energy provision, as well as for domestic hot water production, suitable for both the Mediterranean and the Continental climate. These configurations will allow for energy savings ranging from 20 to 40% on an annual basis in both Mediterranean and Continental climates.

The HYBUILD systems combine thermal (sorption, latent and sensible) and electric storages in one system. Solar energy can be stored in the sorption storage (Mediterranean concept) as well as in an electric storage. The electric power within the systems is provided by a DC-bus system, which is more efficient than a state-of-the-art AC based system. The DC architecture is expected to reduce the volume of conversion and distribution by 1/3 as compared to an AC architecture while, a long term reduction of the costs by about 20% is realistic.

The electrical storage will be properly selected among the most efficient technologies already in the market, and will be adapted to the operation of the domestic building environment. Particularly, the building management system (BMS) will be designed and adapted to the expected operating conditions, with a view to maximize the lifetime of the electrical storage itself.

The two concepts are presented below as described in the research proposal of the 'Innovative compact HYbrid electrical/thermal storage systems for low energy BUILDings' project (HYBUILD 2017, grant agreement N° 768824):

• Mediterranean Concept

The primary function of a heating / cooling system in the Mediterranean climate is the provision of cooling energy during the summer period, which is usually achieved in installed systems by means of electrically driven steam compression cooling systems. However, to cover space heating and demand for hot water, gas boilers and solar collectors are usually installed, as common distribution systems are based on high temperature radiators, which limit the applicability of the heat pump by compression. This leads to a high primary energy consumption during both cooling and heating periods due to the lack of system integration and the limited performance of the components. The proposed hybrid storage philosophy for the Mediterranean climate aims to incorporate an electric heat pump by compression with a heat-guided sorption storage unit for DHW to increase overall system efficiency by effectively saving the surplus electric power to heat when needed. This makes the idea attractive for both existing and new buildings as it harmonises the function of the already installed elements. In addition, an electrical storage package and a low temperature storage unit are also incorporated in order for the system to be able to store and reuse as much as possible electrical and thermal energy produced from renewable sources.

• Continental Concept

The hybrid storage concept for Continental Climate is based on a thermal PCM latent storage for DHW and an electrical storage. Contrary to the Mediterranean solution, the prioritized operation here is heating during winter and the production of domestic hot water (DHW), whereas cooling during summer plays a minor role compared to the other two. Nevertheless, due to global warming and an increased desire for comfort, cooling during summer becomes more and more important even for northern Europe and therefore, moderate cooling operation is also possible with the proposed system. The Continental concept can increase system efficiency and renewable sources exploitation through the integration of a high density, high temperature latent storage employed to store the sensible energy of the hot gas exiting the compressor which is powered by a DC driven inverter and fed by renewable electricity. The system can also implement an electrical storage, which allows a further increase of the share of renewable energy both for buildings connected and non-connected to district heating networks. The operation mode can be reversed, to provide cooling energy and DHW during the summer season. Therefore, the latent storage for DHW is used throughout the year.

HYBUILD's hybrid storage systems will be used to upgrade facilities in existing buildings in three different demo sites. One of the project applications will be implemented by the Municipality of Aglantzia in cooperation with FOSS Research Centre for Sustainable Energy of the University of Cyprus and other partners. The proposed system will be installed on a vernacular dwelling located in the historic core of Aglantzia, which will be used as a Renewable Energy and Smart Solution Center by the municipality with the support of the University of Cyprus. The proposal aims at redefining the traditional core with the aim of developing a destination that will be a cornerstone of social interaction and creative employment (Fig.4).

Figure 4. External view of the square and the building under study

The building has been selected to become a hands-on technology exhibition area of renewable energy systems complimented with visual means to enhance the experience of visitors. The RES systems will be enhanced with enabling technologies offering the benefits of smart digitalised home solutions that can seamlessly be integrated in the neighbouring community / district to form energy communities. The effort is to increase environmental awareness of the community for sustainable energy supply and sustainable growth (Phocas et al 2011, Philokyprou et al 2013). Environmental awareness has an effect on the willingness to pay about electricity that is generated from renewable energy sources and according to a study carried out by Karaoglan and Durukan (2016), when the environmental conscious consumer is between the economic situation and the environmental impact, he will consider environmental impact.

In this context, the proposal aims at creating a multifunctional space where besides the promotion of modern technologies, it will have the possibility to host events, seminars, artistic performances etc. and at the same time it will function as a reading room - a digital library for young citizens and students (Fig.5).

Figure 5. Internal view of the building under study

Particular emphasis will be placed on the preservation of the building's cultural heritage values and on the assessment of innovative technologies' contribution to the rehabilitation of historic buildings and settlements (Savvides et al 2016).

The integration of active solar systems into the building sector is an innovative experimental process of the program. The regulatory framework for the protection of the traditional character of buildings prohibits in most cases the installation of technical systems that are visible and consequently the installation of active solar systems in the listed building envelopes. Despite this fact, solar collector for domestic hot water are eligible to be installed in order to cover the users' need. It is noted that, due to a number of aesthetical and regulatory issues, it has been decided to place the hybrid systems in an independent metallic shelter which will be placed in the square (as part of a comprehensive landscape design), while on the roof of the building it is proposed to install photovoltaic panels which offer increased integration possibilities (Fig. 4 and Fig. 6) (Savvides et al. 2014, Michael et al. 2010,).

Figure 6. Plan of the square and the building under study

Within the framework of the operation of the "Renewable Energy Sources Center" the continuous renewal of these technologies with newer production systems is expected, aiming at the projection of the architectural integrated active solar systems. Replacing systems, apart from technological development, will aim at exploring the sensitive issue of architectural integration of technology systems into listed buildings of historic centers.

6. Conclusions

The objective of this paper was to review the available active solar systems that can be integrated to buildings and examine the integration of those systems in historic buildings through case studies. Moreover, it introduces an innovative concept that utilises the solar resource with storage to generate and manage the energy of buildings extending its application into a historic building in Cyprus. A key sustainable design strategy to preserve, reuse and maintain historic structures but at the same time recognize the importance of accommodating renewable energy technologies where they are appropriate. The integration of active solar systems on built heritage, needs a multidisciplinary design that takes into account the requirements of minimum intervention and reversibility.

Energy consumed in a residential building for heating, cooling and hot water accounts for a large part of the world's energy consumption. Therefore, the integration of renewable energy into buildings is a must for the purposes of reducing carbon dioxide emissions and reducing the devastating effects of climate change. Until the previous years, the integration of photovoltaic systems was mainly done on the roofs of buildings with the addition of conventional photovoltaic panels for the sole purpose of producing energy. In recent years, several BIPV technologies have been developed which, in addition to generating electricity, have additional properties, such as thermal, and can replace different construction materials of a building's envelope. The main technologies used in the BIPVs category as presented in this paper are BIPV modules, Flexible (Foil) BIPV, BIPV tiles, and Solar Cell Glazing. The most common integrated photovoltaic technology is Flexible (Foil) BIPV and thin film technology, which are mainly used in building facades as well as BIPV tiles technology. Novel technologies such as Perovskite solar cells and PV/Ts are also gaining interest nowadays.

Despite a large portion of the potential of PV integration in existing buildings, several factors make their application into historic buildings more difficult such as economic reasons, lack of knowledge among decision makers and architects, general unwillingness for ‘new’ technologies and architectural/aesthetic aspects. To ease the use of technology in historic buildings, several steps should be reinforced. Firstly, local authorities, professional, agencies and historic organization should work together to identify the heritage features and values and write guidelines that will help designers for historic evaluation and solar design integration. Secondly, for the installation of solar active systems in sensitive context is good to develop a formation of designers and decision makers that will provide technical and formal possibilities of PV systems.

The overall objective of the present project is the development of an interdisciplinary and holistic approach that incorporates energy generation, energy storage and energy distribution for cooling-heating energy provision and domestic hot water production, suitable for both the Mediterranean and the Continental climate. Both hybrid electrical-thermal storage systems will be able to efficiently cover both heating and cooling demand respectively. The potential to install and monitor the developed systems in real demo-sites in three countries with different climatic conditions allows the exploitation of the results from countries with similar climatic characteristics.

The real demo-sites will be able to increase the energy consumption awareness of consumers and of the social community based on interaction. The development of the novel concept will help in writing guidelines and standardization for the reduction of energy consumption and CO_2 emissions. Apart from the implementation of the system as mentioned above, the full concept can be used both in new and retrofitted residential buildings in order to minimize the total EU energy consumption and keep up with the European directives. Moreover, the integration of such systems in a demo-site that is characterized as historic building is utilized to explore the sensitive issue of the architectural integration of technologically advanced systems into listed buildings of historical centers.

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