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Possibilities of Creating Net Zero Carbon Emissions Cultural Buildings: A Case Study of the Museum at Eleutherna, Crete, Greece

John Vourdoubas*

Mediterranean Agronomic Institute of Chania, Crete, Greece, Tel: +30-28210-35020
Email: vourdoubas@maich.gr

Abstract

Mitigation of climate change requires the reduction of carbon emissions in all human activities including in energy use in buildings. Creation of low or near zero CO_2 emissions buildings due to energy use is currently achievable since the required sustainable energy technologies are mature, reliable and cost-effective. The present work is focused on the creation of zero carbon emissions cultural buildings with reference to the museum in Eleutherna, Crete, Greece. Past research regarding the increase of energy efficiency in museum buildings as well as the use of renewable energy technologies in them has been reviewed. Use of solar photovoltaic energy for electricity generation and ground source heat pumps for air-conditioning in order to cover all the annual energy requirements in the museum has been suggested. The proposed renewable energy technologies are well known and cost-effective. The covered area of the museum is 1,800 m^2 and its annual energy requirements have been estimated at 216,000 KWh. The size of the required solar-PV system has been calculated at 144 KW_{peak}; for the ground source heat pump, it is 123.2 KW. The total cost of the sustainable energy systems has been estimated at 290.58 €/m^2 for its covered surface while the annual CO_2 emissions savings is 162 tonsCO_2. The results of the current work indicate that zeroing carbon emissions due to operational energy use in museum buildings is currently feasible with the use of mature, reliable and cost-effective renewable energy technologies.

Keywords: Carbon emissions; Crete-Greece; Eleutherna; energy efficiency; geothermal heat pumps; museums; solar photovoltaics.

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* Corresponding author.

1. Introduction

The necessity to mitigate climate change has increased the efforts to reduce energy consumption and carbon emissions in public buildings including cultural heritage buildings. Improving energy efficiency and reducing carbon emissions in museums requires a compromise among various factors including: a) Preservation of architectural characteristics of historic buildings when integrating benign energy technologies, b) Maintaining the required indoor climate conditions for the protection of the artifacts exhibited, and c) Achieving comfort for the visitors and absence of indoor pollutants. In particular, the integration of solar photovoltaic (solar-PV) systems or other solar energy technologies in museum buildings requires the preservation of the historic characteristics of the building. Various approaches have been used for improving energy efficiency in museum buildings, including: a) Altering the setpoints of indoor temperature and relative humidity without damaging the artifacts exposed, b) Using passive and active energy saving techniques and technologies combined with building retrofitting, and c) Installing renewable energy technologies in them.

2. Literature survey

2.1 Energy consumption in museums and historical buildings

A case study on energy consumption and CO_2 emissions in two museums in Hangzhou, China has been reported [1]. The authors estimated the specific annual energy consumption during the operation of the two museums at 176.4 KWh/m^2 and 91 KWh/m^2 while their carbon emissions were at 167.58 and 86.45 kgCO$_2$/m^2 correspondingly. They have also mentioned that during their operation phase the two museums consumed 94-96.5% of their life cycle energy consumption while they emitted 90-94% of their life cycle CO_2 emissions. Energy saving strategies in air-conditioning in museums have been reported [2]. The authors have implemented a case study in a modern museum and they concluded that energy savings up to 40% could be achieved if the indoor relative humidity (RH) range changes from 50+/-2% to 50+/-10%. They also mentioned that smaller energy savings at 6-13% could be achieved if the indoor temperature varies between 21^{o}C in the winter and 23^{o}C in the summer instead of being constant at 22^{o}C. An energy study of the museum of Science and Industry located in Chicago, USA, has been presented [3]. The authors stated that the museum was using electricity and natural gas for covering its energy requirements. The share of electricity in lighting was 30%, in space cooling 22%, and the rest 48% in the operation of various equipment. The share of natural gas in space heating was 96% and in hot water production 4%. A study on energy efficiency in retrofitted and new museum buildings in Europe has been presented [4]. The authors have studied eight museums in Europe and they measured the total annual energy consumption in five of them. It was varying from 69 to 149 KWh/m^2. They estimated that with the use of various energy saving techniques the overall energy consumption in the museums could be reduced from 39 to 77%. The authors additionally found that the payback period of the energy savings investments was varying between 11.3 and 49 years. A study on the increase of energy efficiency in cultural buildings has been reported [5]. The authors have studied the improvement of energy efficiency in nine European museums. They tried to achieve total energy savings by 35-40% and to reduce CO_2 emissions by 50%. Studying the museums of Delphi and Heraklion in Greece they found that the use of passive solar techniques and various energy saving measures could improve their energy efficiency without affecting their functionality. Energy consumption in the Hermitage museum in Amsterdam has been reported [6]. The authors have investigated the impacts of energy consumption on fluctuations of indoor climate. They found that relaxing the indoor temperature and RH could reduce the overall energy consumption in the museum by 49-63%. They also estimated that by keeping the indoor climate conditions constant at 21^{o}C and 50% RH, the annual energy consumption was 1,053 KWh/m^2, where as when relaxing the indoor climate conditions, it could be reduced to 385-534 KWh/m^2. A methodology for mapping future energy needs in European museums has been presented [7]. The authors have developed a prediction method for future energy demand for different types of museum buildings and climate conditions all over Europe. They used seven performance indicators including indoor temperature, indoor RH, heating demand, cooling demand, humidification demand, dehumidification demand and total energy demand. A review on the indoor environmental conditions in museums and their impact on energy consumption has been published [8]. The authors stated that maintaining the required environmental conditions for museum artifacts might not lead to the desired reduction in energy consumption. They have also mentioned that the indoor environmental control includes the following parameters: temperature, RH, lighting and indoor pollutants. Energy conservation in museums using different setpoint strategies has been reported [9]. The authors stated that many museums employ tight indoor climate restrictions in order to protect their artifacts from degradation. They have implemented a case study in a museum in the Netherlands simulating its energy consumption at different setpoint strategies. They concluded that the optimum strategy of the indoor climate yields energy savings of 77%, improving thermal control and decreasing chemical degradation. A case study in Amsterdam museum regarding a more energy efficient Heat Ventilation Air Conditioning (HVAC) system has been presented [10]. The authors stated that maintaining a strict indoor climate reduces the risks for the objects but increases the energy demand in the museum. Performing computer simulations, they concluded that by using less strict indoor climate control, the annual energy demand of the HVAC system in the museum, which was at 84.55 KWh/m^2, could be reduced by 15%. A simulation study in four museums investigating the energy impact of different climate classes for the ASHRAE museum has been implemented [11]. The authors stated that significant energy savings are achieved when moving from class AA to class B which is considered to adequately protect most artifacts in the museums. The amount of energy saved, they mentioned, depends on the type of the building and its characteristics. An investigation on possible energy efficiency interventions in Galleria Borghese, Rome has been made [12]. The authors stated that improving energy efficiency in the air conditioning system, particularly in cooling during the summer, had the highest impact in increasing its sustainability. A report on the feasibility of energy retrofitting in historical buildings in Italy has been presented [13]. The authors mentioned that energy retrofitting in this type of building has to solve two important points: the restrictions regarding the use of renewable energy technologies in them and the high payback times of the energy investments.

2.2 Use of renewable energies in museums

A report on energy efficient museum buildings has been made [14]. The author stated that museum buildings can be highly energy efficient although their performance requirements are ambitious. He indicated that their energy consumption can be reduced to less than one tenth compared to traditional museum buildings. The author mentioned that the Emil-Schumacher museum in Hagen has an annual energy consumption of 117 KWh/m^2 which could be covered with the use of solar-PVs, geothermal heat pumps (GHPs) and earth to air heat exchangers. An investigation on the use of energy efficiency approaches and the integration of renewable energies in historical buildings including the use of solar energy and GHPs has been presented [15]. The authors stated that, although the integration of solar energy in historical buildings is difficult due to the lack of space and the need to preserve the exterior architecture, there are many successful examples worldwide. Additionally ground source heat pumps (GSHPs) are popular systems to improve energy efficiency in historical buildings. A report on the integration of solar energy technologies in historic buildings with reference to a case study in Katania, Italy has been published [16]. The authors stated that the application of solar energy technologies in the external building envelope should comply with preservation requirements in historical buildings. They indicated that the application of solar energy technologies in historic buildings should take into account their architectural, construction, energy and cultural aspects. An investigation on the performance of GSHPs in two historical buildings located in Venice and Florence, Italy has been made [17]. The authors compared with computer simulation the performance of a GSHP with a) an air source heat pump and b) a conventional system with a gas boiler and air-to-water chiller. Their results indicated that the GSHP system is the best solution in terms of primary energy savings. A feasibility study concerning the use of a GSHP for heating and cooling in a historic building has been implemented [18]. The authors concluded that the GSHP had the lowest annual energy requirements from non-renewable energy sources compared with other systems. A simplified method for assessing environmental and energy quality in museum buildings has been published [19]. The proposed evaluation method is based on three phases including: a) Environmental performance evaluation, b) Energy performance evaluation, and c) Assessment of environmental and energy quality. The author stated that the aspects impacting environmental and energy quality include heritage conservation, human comfort and energy efficiency. A case study on energy refurbishment of a historic building located in Perugia, Italy has been realized [20]. The building had a total covered area of 7,000 m^2 and it was using natural gas for heating and a condensing external unit for cooling. The authors studied the replacement of the old heating and cooling system with a GSHP, concluding that its annual heating and cooling requirements have been significantly reduced from 69 KWh/m^2 to 30 KWh/m^2. A report on improving energy efficiency and renewable solar energy integration in historic buildings has been published [21]. The authors stated that in building retrofitting projects, improving energy efficiency and using renewable energy technologies is not always possible without compromises. They also mentioned that the use of solar energy technologies in historic buildings can be hindered due to preservation problems and aesthetic requirements. A study on improving energy efficiency in museums with reference to Musei Senesi in Torino, Italy has been implemented [22]. The authors stated that there are few cases where energy retrofit in museums has been carried out and few data are available regarding their energy performance after retrofitting. They have performed a study on 43 museums, producing a self-assessment check-list and a handbook. In the handbook, the authors have proposed the use of the following renewable energy technologies in museum buildings: Solar-PV panels, Solar thermal panels, biomass and heat pumps.

2.3 Zero carbon emissions buildings

A report on a zero emissions science museum in Minnesota, USA has been reported [23] The museum has been designed to operate as a zero emissions building that produces all its energy needs on an annual basis from renewable energies. The museum uses solar-PV panels for electricity generation and a GHP for air conditioning. The heat pump used electricity generated by the solar-PV system. A report on energy consumption and carbon emissions in an Academic Institution located in Crete, Greece has been published [24].

Its specific annual energy consumption has been estimated at 164.96 KWh/m^2 while its carbon emissions were110.64 $kgCO_2/m^2$. The author indicated that the combined use of solar thermal energy, solar-PV energy and GSHPs could cover all its annual energy requirements, zeroing its carbon emissions. He also estimated that the investment cost of all the sustainable energy systems required was 184.32 € per m^2 of its covered surface. A study on the energy consumption and the carbon emissions in Venizelio hospital in Crete, Greece has been realized [25]. The author estimated its annual energy consumption at 280.4 KWh/m^2 and its annual carbon emissions due to operational energy use at 168 KWh/m^2. He also indicated that the combined use of solar thermal energy, solar-PV energy, solid biomass and GSHPs could cover all the annual energy requirements in the hospital, zeroing its carbon emissions. Energy consumption in various museums according to the literature reviewed is presented in Table 1.

Table 1: Energy consumption in museum buildings

Author	Location of the museum	Total annual energy consumption (KWh/m^2)	Annual energy consumption for HVAC (KWh/m^2)
Ge and his colleagues 2015	Hangzhou, China (two museums)	176,4 and 91	--
Zannis and his colleagues 2006	Europe (five museums)	69-149	--
Kompatscher and his colleagues 2017	Europe, Netherlands	--	84.55
Mueller, 2013	Europe, Germany	117	--
Pisello and his colleagues 2014	Europe, Italy	--	69

Source: Literature surveyed

The aims of the current work are:

a) Indication of reliable and cost effective renewable energy technologies which could cover all the annual energy requirements in the museum of Eleutherna, Crete, Greece,
b) Estimation of the required renewable energy systems which could cover all the annual energy requirements in the museum of Eleutherna, Crete, Greece, and
c) Estimation of its CO_2 emissions savings and the cost of the sustainable energy systems required.

Due to the absence of accurate data on energy consumption in Eleutherna's museum, published data from other museum buildings in Europe and worldwide have been used in order to estimate the energy consumption in the museum and the sizing of the proposed renewable energy systems. For more accurate calculations reliable data on energy consumption in Eleutherna's museum must be used.

3. Requirements for zeroing net carbon emissions due to energy use in museums

Museums consume energy during their operation for lighting, air-conditioning and the operation of various equipment. Usually they consume grid electricity and/or natural gas. In order to zero net carbon emissions due to operational energy use in their buildings, the following two criteria should be fulfilled:

1. They should replace all the fossil fuels used with renewable energy sources, and
2. Grid electricity used annually should be compensated with solar–PV electricity generated, preferably in situ and injected into the grid. This is allowed with the net-metering initiative.

Since fossil fuels are not used in the museum and the grid electricity used, generated mainly from fossil fuels, is offset with green electricity generated by solar energy, its net carbon emissions are zeroed. It is assumed though that all the grid electricity is generated by fossil fuels, which is not true since part of it usually is generated by renewable energies, mainly solar and wind energy. It should be noted that the share of operational energy use to the life cycle energy use in museums is higher than 90% while the share of embodied energy use is less than 10% [1].

4. The Archaeological Museum ofEleutherna, Crete, Greece

The museum of ancient Eleutherna [26] was inaugurated in 2016 and it is located in the Prefecture of Rethymno, Crete, Greece. It is an on-site museum displaying artifacts from the nearby archaeological site dating from 3,000 BC until 1,300 AD. It is the only museum in Crete exhibiting objects from the Homer era including the famous Tomb of Warriors dated at 830-730 BC. The museum is housed in a modern building with a covered area of 1,800 m^2. Using the data reported in the literature surveyed, it is assumed that its specific annual energy consumption for HVAC is 75 KWh/m^2 while its specific total annual energy consumption is 120 KWh/m^2. Therefore the total annual energy consumption in the Eleutherna museum has been assumed at 216,000 KWh/m^2 while its annual energy consumption for HVAC is 135,000 KWh/m^2.

5. Use of renewable energy technologies in the museum

Renewable energy technologies can be used in the Eleutherna museum for covering all its annual energy needs and zeroing its net carbon emissions. Solar-PV electricity could be used for electricity generation and a high efficiency GHP for covering all its heating and cooling needs. Solar-PV systems could generate all the electricity required annually for lighting, operation of various machinery and the operation of the heat pump. Solar electricity generated would offset annually all the grid electricity consumed in the museum. Alternatively, solid biomass, locally produced in Crete, could be used for space heating, although this fuel is not suggested for use in the museum. Solar thermal panels could be used for hot water production, although its requirements in hot water are low. Space cooling could be provided with a solar thermal cooling system. Currently though, solar thermal cooling technology is not mature, reliable and broadly used in Crete. Since renewable energy technologies can provide all the annual energy requirements in the museum of Eleutherna, its net carbon emissions due to energy use will be zero. Renewable energy technologies which could be used in the building of the museum of Eleutherna is presented in Table 2.

Table 2: Renewable energy technologies which can be used in the building of the Eleutherna museum

Renewable energy technology	Energy generated
Solar-PV panels	Electricity
Solar thermal panels	Hot water
Solar thermal cooling	Space cooling
Solid biomass burning	Space heating
Geothermal heat pump	Space heating and cooling

Source: own estimations

5.1 Use of solar-PV energy for electricity generation

Solar-PV systems including crystalline or amorphous silicon modulus are broadly used today in Crete, Greece. They are used either in buildings offsetting the grid electricity consumed with the net-metering initiative, or in individual systems generating electricity and injected into the grid with feed-in tariffs. For the climate conditions of Crete, the average annual electricity generation is estimated at 1,500 KWh per KW_{peak}. Generation of 216,000 KWh/m^2 required annually in the museum of Eleutherna needs a solar-PV system with a nominal capacity at 144 KW_{peak}. The required surface for the installation of this solar-PV system is approximately 1,440 m^2. The system can be installed outside of the museum building, probably on the roof of a car park.

5.2 Use of high efficiency heat pumps for air-conditioning

A high efficiency heat pump like a GSHP can be used for air-conditioning of the building of the museum at Eleutherna. Assuming that it will operate for 6 hours daily, its electric power will be 61.6 KW. In order to cover the peak loads, its electric power will be doubled at 123.2 KW.

6. Environmental and Economic considerations

Installation of renewable energy systems in Eleutherna’s museum covering all its annual energy needs will result in a reduction of carbon emissions. Assuming that the use of 1 KWh of grid electricity in Crete is equivalent with emissions of 0.75 $KgCO_2$, the total annual decrease in carbon emissions, due to the use of green electricity in the museum, will be 162 tons. The cost of the required solar-PV system can be estimated, assuming that the installation of 1 KW_{peak} in Crete, Greece costs 1,750 €. The total cost of installing 144 KW_{peak} is 252,000 €. The cost of the GSHP can be estimated assuming that its unit cost is 2,200 € per KW. The cost of a 123.2 KW heat pump will be 271,040 €. The size, the cost and the carbon emissions savings due to the use of renewable energy systems in the museum of Eleutherna are presented in Table 3.

Table 3: Size, cost and carbon emissions savings due to the use of renewable energy systems in thye museum of Eleutherna

Renewable energy system	Size	Cost	Cost per m^2 of covered surface	Annual Carbon emissions savings (ton CO_2)	Annual carbon emissions savings per m^2 of covered surface ($kgCO_2$)
Solar-PV	144 KW_{peak}	252,000 €	140 €	162	90
GSHP	123.2 KW	271,040 €	150.58 €	--	--
Total	--	523.040 €	290.58 €	162	90

Source: own estimations

7. Discussion

Reports on museums which cover all their energy needs with renewable energy sources are rather limited. Most of the existing studies are focused in the reduction of their energy consumption with various interventions and the use of various renewable energy technologies for power generation and air-conditioning. Annual energy consumption in various museum buildings is lower than in other types of buildings according to the existing studies. Financing the use of renewable energy technologies in museum buildings could be a problem particularly when public funding is limited due to various reasons. Alternatively the involvement of the private sector could be an option offering financial support from Energy Saving Companies (ESCOs) since the energy investments are cost-effective and profitable. Estimations of the required renewable energy systems covering all the energy needs in the museum of Eleutherna have been made without considering any reduction in energy consumption which probably could be achieved with alteration of the setpoints of temperature and RH control of the indoor environment. In this case, the size and the cost of the sustainable energy systems required will be smaller. The proposed systems are mature, reliable and cost-effective, used in many applications so far. Promotion of the above-mentioned sustainable energy systems in the museum presupposes: a) Their technical maturity, reliability and cost-effectiveness, b) The possibility of financing these energy investments, c) The existence of the appropriate legal framework allowing for the use of these energy systems, and d) The existence of public policies promoting the creation of nearly zero/zero carbon emissions public buildings complying with the European directives and the national legislation.

8. Conclusions

Museums utilize energy in order to maintain favorable indoor conditions for preserving the exposed artifacts, to offer comfort to the visitors and to minimize indoor pollution. Use of sustainable energy technologies for reducing their carbon emissions should balance with the needs of preserving the architectural characteristics of the museum buildings. The museum of Eleutherna in Crete, Greece is a recently established modern museum which could zero its carbon emissions using renewable energy technologies, generating all its annual energy requirements. Use of GHP for covering all its needs in air-conditioning has been proposed, combined with a solar-PV system generating all the annual electricity required. Annual energy consumption for air-conditioning in the museum of Eleutherna, with a covered surface of 1,800 m^2, has been estimated at 135,000 KWh, while its total annual energy consumption is 216,000 KWh. For covering all its air-conditioning requirements, a geothermal heat pump at 123.2 KW is needed while a solar-PV system with nominal capacity at 144 KW_{peak} could generate all the electricity needed annually. The cost of the required GHP has been estimated at 271,000€ while the cost of the solar-PV system is 252,000€. The total cost is 523,040€ or 290.58€ per m^2 of covered surface. Total annual CO_2 emissions savings due to the use of renewable energy systems in the museum have been estimated at 162 tons CO_2 or 90 $kgCO_2$ per m^2 of covered surface.

9. Recommendations

Future work should be focused in monitoring the real annual energy consumption for lighting, air-conditioning and other uses in Eleutherna’s museum, and in the investigation of the possibilities of reducing its overall energy consumption without damaging the exposed artifacts, as well as the visitor’s comfort. Additional studies for other cultural buildings in Greece should be implemented in order to assist the extensive use of renewable energy technologies in them and to reduce their carbon footprint due to energy use. Promotion of sustainable energy investments in museum buildings requires awareness raising and sensitization of the local and public authorities engaged with museum’s operation as well as the staff of the museums regarding the benefits due to the use of benign energy sources in them.

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