



Techno-economic analysis and life-cycle environmental impacts of small-scale building-integrated PV systems in Greece



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ABSTRACT

Photovoltaic (PV) power system is a technology for producing electricity from renewable resources that is rapidly expanding thanks to its capability to save conventional fossil fuels and to decrease the emissions of greenhouse gases. However, as more attention is being focused globally on the development of building-integrated PV systems, the technical, the economic as well as the environmental assessment of these systems is crucial to ascertain their viability. The purpose of this paper is to present an economic and environmental analysis of relatively small rooftop PV-grid-interconnected energy systems of 2–10 kW_p rated power, located in Athens, Greece. The techno-economic feasibility of the PV systems is conducted employing the computerized renewable energy technologies assessment tool 'RETScreen'. The energy and environmental assessment of the systems is carried out employing SimaPro 7.1 software, which is a standard Life Cycle Assessment tool. The results of the economic analysis indicate that with the current prices, investment in PV-grid-interconnected systems with power capacity higher than 5 kW_p is in general viable. However, an increase in energy sale prices and/or cost reductions in the production of PV systems are crucial for the successful development of small-scale residential size PV systems in the country. The environmental analysis reveals that the PV systems with higher rated power perform worse as far as the environmental impact is concerned. The critical phase of the life cycle of PV systems is the module manufacturing process, which is characterized by high electricity consumption, representing most of the environmental impact. Nevertheless, it is further shown that the application of PV technology presents important environmental benefits compared to conventional energy production systems.

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1. Introduction

The global warming, air pollution and natural resources degradation are matters of concern caused by fossil fuel-based electricity generation. In order to tackle emission problems and, at the same time, meet future energy demands, the development and implementation of renewable energy and related technologies is essential. Because solar energy is non-depleting, site-dependent and non-polluting, there is a growing interest in this renewable energy source. Among several available technologies, photovoltaic (PV) solar is the most promising and has attracted significant technical and financial support from both the public and the private sectors [1,2].

PV technology transforms solar radiation energy directly into electricity current, i.e. electric energy, using the photovoltaic effect, without pollutant emissions. Solar PV power systems can be installed, and possible integrated, on various building surfaces catering for its energy needs in an environmental friendly and perhaps aesthetically acceptable way [3]. It is generally accepted that the annual increase in installed power systems is almost exclusively due to relatively small residential PV-grid-interconnected systems of 1–50 kW_p in size [4]. Deployment of PV applications is expected to reduce greenhouse gas (GHG) emissions by displacing fossil fuel generated electricity from the grid with 'cleaner' solar generated one, as well as, to achieve cost savings for residential consumers. However, the environmental advantages over fossil fuel-based technologies are offset by significant additional cost over conventional generation. It is also important to consider the entire life cycle of a PV system to ascertain its viability, simply because a notable amount of energy is consumed and significant amounts of greenhouse gas (GHG) emissions are involved in the manufacturing phase, as well as, in the transport and disposal of

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these systems [5]. It is imperative, therefore, to investigate both the economic return of the investment and the actual GHG emissions from the whole life cycle of PV systems in order to quantify their above-mentioned benefits [6–9].

Several studies have been conducted about the financial potential of building-integrated PV-grid-interconnected installations. Adamamola [10] presented the economic analysis of a rooftop 2.07 kW_p PV power system located in a laboratory building at the University of Life Sciences – Ås, in Norway. The author concludes that a combination of feed-in-tariff and initial investment financial support of up to 40% can boost the utilization of PV systems in the country. Nevertheless, if the financial support is higher than 45% of the initial investment, no further premium fee is necessary to support this type of system. Another similar case was studied in Surabaya, Indonesia [11], where a 1 kW_p PV system was investigated. Similar to the case of Norway, the analyzed system can be viable, economic-wise, if feed-in tariff of 0.25 \$/kWh is applied. Bakos et al. [12] also examined the economic feasibility of a residential 2.25 kW_p PV system in the city of Kastoria, in Northern Greece. The authors imply that only high incentives up to 55%, in conjunction with feed-in-tariff of 45 €/kWh, could lead to financially viable PV projects in the country.

From an environmental perspective, life cycle GHG emissions and the Energy PayBack Time (EPBT) of building-integrated PV systems have been studied extensively. Kato et al. [13] estimated the CO₂ emissions in the manufacturing phase of monocrystalline cells for a 3 kW_p residential PV system installed on a rooftop using off-grade silicon supplied by semi-conductor industries. The results of the study show that for an annual electrical output of 3.47 MWh, the total indirect CO₂ emissions of the system are 315.8 ton CO_{2eq}/year. Kannan et al. [8] and Muneer et al. [14] also performed EPBT and GHG analysis of monocrystalline PV power systems. In these two latter studies, all three phases, i.e. manufacturing, operation and decommissioning, were considered. According to Kannan et al.'s work, the life cycle energy use and the EPBT for a 2.7 kW_p PV system operating in Singapore are 2.2 MJ/kW_{el} and 4.5 years, respectively. The relevant GHG emissions are approximately 165 gr-CO_{2eq}/kWh_e. On the other hand, Hondo [15] found that the GHG emissions for rooftop type polycrystalline PV systems are 53.4 gr-CO_{2eq}/kWh_e. The author implied that if solar-grade polycrystalline silicon used for PV cells is substituted by solar-grade amorphous silicon, the GHG emissions are reduced to 26.0 gr-CO_{2eq}/kWh_e. Jungbluth [16,17] also investigated the energy requirements and the emissions of 12 different small 3 kW_p grid-interconnected polycrystalline PV systems. His results show that the EPBT and the GHG emissions lie in the range of 3–6 years and 39–110 gr-CO_{2eq}/kWh_e, respectively.

Regarding both the economic and the environmental perspective, Bernal-Agustín and Dufo-López [18] investigated PV-grid-interconnected energy installations in the city of Zaragoza, in Spain. Their economic analysis shows that with the current prices, investment in PV systems is generally profitable, but the high payback time could discourage investors. The environmental analysis indicates the integrity of grid-interconnected PV systems, obtaining recuperation times for the energy that vary between 2.5 and 3.6 years. Liu et al. [19] also examined the environmental and economic performance of 8 solar PV systems (ranging from 3 kW to 1.14 MW) deployed on the Desert Research Institute's Reno and Las Vegas campuses. The authors found that the life cycle energy consumption varies between 0.586–0.898 MJ/kWh_e, while the GHG emissions range between 35 and 58 gr-CO_{2eq}/kWh_e. For the six larger systems, i.e. power capacity higher than 50 kW, the cost payback time lies in the range of 14.4–26.7 years and the 25-year return on investment varies from 0.95 to 2.0. The cost per ton CO_{2eq} avoided by displacing conventionally generated grid electricity is in

the range of \$100–180, which is 2–3 times as high as the estimated cost for carbon capture from pulverized coal power plants.

To the best of the authors' knowledge there is no systematic evaluation of the performance and effectiveness of PV systems in Greece. The present research work intends to provide information on both the economic and environmental viability of five, relatively small, residential PV-grid-interconnected power systems with power capacities ranging from 2 to 10 kW_p, located in Central Greece, and in particular in the city of Athens. An integrated techno-economic analysis is performed employing the RETScreen 'Clean Energy Project Analysis Software' through electric energy production estimations and financial feasibility considerations, in light of the Greek investment law [20]. Furthermore, results of the present research show that an appropriate increase in energy sale prices and/or potential cost reductions can boost the utilization of building-integrated PV systems in Greece. The environmental performance of the PV systems under consideration is also evaluated employing the SimaPro 7.1 software [21], which is a tool for the assessment of the impacts of the system across all life cycle stages, i.e. from the extraction of raw materials and manufacturing process to its operational life and final, end-life, disposal. In particular, two metrics of environmental performance are considered: the Global Warming Potential at 100 years (GWP100) and the Primary Energy Requirement (PER). These metrics are compared to those of conventional energy systems to illustrate the environmental benefits of solar PV systems. It is envisaged that the computational results and the proposals included in this work could serve as a technical, economic and environmental basis for the development/proposal of appropriate public policies to encourage the implementation of small-scale grid-interconnected PV systems for residential applications in Greece.

2. Case study (City of Athens, Greece)

Greece is one of Europe's sunnier regions. It is located in the SE Mediterranean area with an affluent and reliable supply of solar energy, even during winter. The entire Greek territory is characterized by high solar irradiance, thus the annual solar energy at horizontal surface varies between 1450–1800 kWh/m² [22]. The southern part of Greece, especially the Aegean Archipelago Islands, has the highest values of global solar irradiation, while less solar irradiance is to be expected in Northern Greece [22]. Interesting enough the seasonal solar potential variation and the corresponding electricity demand in the country are consistent, with higher values during the summer period and lower values during the winter months.

The electricity grid of Greece may be divided into two; (i) the mainland national grid and (ii) the so called "Non-interconnected Islands", i.e. islands which have autonomous systems that are not connected to the mainland grid. The electrical system of the mainland Greece is dominated by centralized Thermal Power Plants and relies largely on local lignite resources and imported natural gas. On the contrary, the electricity generation in the non-interconnected islands grid is carried out almost exclusively via diesel electric generators and relies heavily on oil-fuel imports.

2.1. Solar resource potential of Athens

In order to investigate the performance of a PV system, it is essential to have all the necessary meteorological data for the site under consideration. The city of Athens has been identified as the application site for the investigation and performance assessment of the PV system under consideration in this research work.

Athens is the capital and largest city of Greece. It is located on latitude 37.9° North and longitude 23.7° East, in Central Greece.

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