School Roofs: Hubs of New Renewable Energy Communities

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Abstract. Large public infrastructures, such as school buildings, have the potential to serve as vital resources for surrounding communities by incorporating photovoltaic panels on their roofs. By harnessing solar power, a school roof can become an electrical power station operating daily, with minimal environmental or architectural impact. This innovative approach can supply renewable electricity to the local community, aligning with the concept of renewable energy communities (REC). This study delves into the case of a primary school in Rome, examining strategies to distribute the generated electricity to the surrounding community. Utilizing System Advisor Model (SAM), an energy simulation was conducted to assess the performance of the photovoltaic plant. The study then analysed the energy output from the photovoltaic system in relation to streetlights and household electricity consumption. The findings underscore the effectiveness of the photovoltaic plant and the numerous benefits it offers in terms of energy efficiency, cost savings, and environmental sustainability.*

1 Introduction

Photovoltaic solar panel (PV) electricity generation is a crucial component in the transition towards a decarbonized energy system and the promotion of sustainable development [1]. Recognized as a highly promising solution for reducing greenhouse gas emissions and combatting climate change, photovoltaic solar energy presents a compelling alternative to traditional energy sources such as coal and natural gas [2]. The International Energy Agency (IEA) report outlines an ambitious yet achievable path for the energy sector to achieve Net-Zero Emissions by 2050, eliminating the need for emissions reductions in non-energy sectors [3]. Wind and photovoltaic solar energy are forecasted to collectively contribute two-thirds of the total renewable energy output, highlighting the significant role that these sources will play in the future energy landscape [4].

The emergence of the Renewable Energy Community (REC) represents a strategic initiative focused on optimizing the utilization and self-consumption of locally available

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renewable energies. These communities are introduced by the European Union Renewable Energy Directive (RED II) [5] as legally established non-commercial entities with the primary objective of collectively devising new renewable power generators and sharing both energy and benefits derived from their operation. Energy communities are now recognized as a key tool in addressing current energy transition challenges. Building on this foundation, urban spaces have the potential to become candidates for producing and sharing energy within urban communities. This shift towards community-based renewable energy initiatives not only promotes sustainability but also fosters a sense of empowerment and collaboration among community members [6].

The rooftop solar panels of a common residential buildings aren't sufficient to meet the energy needs of all the residents. The challenge lies in the lack of available space. The solution is to identify a large building nearby, such as a school building, and transform it into an electrical power station that redistributes the excess energy produced to neighbouring facilities. Any surplus energy can be made available to neighbours, especially to families in need. Thus, the school buildings become a key player in the creation of Renewable Energy Communities (REC). In this sense, it is important to consider that every city has an enormous heritage to offer: for example Rome has 1200 educational buildings and approximately 300 high schools [7]. Researchers [8,9] have primarily focused on evaluating how photovoltaic panels on school roofs meet the school energy need, while the aim of this research is to investigate the potential integration of school rooftop photovoltaic system into the broader urban landscape. This change in perspective is in line with the overarching commitment to sustainable development and environmental stewardship. By exploring ways to effectively harness photovoltaic energy on a larger scale, this paper seeks to provide valuable insights into sustainable urban development.

2 Material and method

The aim of the current study is to examine the potential of a photovoltaic system integrated on a school roof from a local community perspective. The research commences by analysing the solar radiation throughout the year at the specific site. Subsequently, estimates were made for the school's electric loads and the site's suitability for photovoltaic installation. A monthly energy performance analysis of the photovoltaic system was conducted to validate the concept. A numerical model was developed to assess the energy output from the photovoltaic system, the amount delivered to the public grid, and the energy provided to the school. Dynamic simulations of the photovoltaic system were carried out using the System Advisor Model (SAM), an open-source software tool developed by the National Renewable Energy Laboratory (NREL). SAM is a comprehensive platform for analyzing and modelling the performance of renewable energy projects, supporting various technologies such as solar, wind, and geothermal systems. The simulations were conducted hourly to match the resolution of the generation and load profiles, estimating the energy generated by the photovoltaic system and supplied to the public grid to meet local household and public lighting needs. The methodological approach is illustrated in Figure 1.

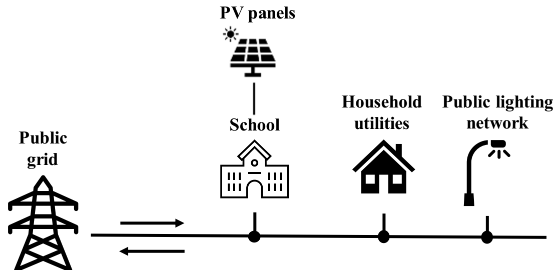

Fig. 1. Flowchart of the methodological approach.

The economic viability of the solar photovoltaic system is evaluated using economic indicators like payback period (PP), net present value (NPV) and profitability index (PI). The initial investment cost is determined based on the cost per kilowatt of the photovoltaic system. According to the 2021 market analysis by the International Renewable Energy Agency (IRENA), the rooftop photovoltaic are implemented at costs of 724.5 €/kW. The initial cost includes the expenses related to system components and installation, while the operation and maintenance costs are estimated at 9.2 €/kWh. These initial investment and operating costs are considered as the outflows of the designed system. Cash inflows are calculated based on the cost of energy that meets the load demand and the cost of energy exported to the utility grid. The cost of electricity is determined by the Regulatory Authority for Energy, Networks, and the Environment (ARERA), with prices ranging from 0.44 €/kWhe (when electricity is purchased from the national grid) to 0.11 €/kWhe (when electricity is sold to the national grid). The project's lifespan is set at 25 years, aligning with the replacement time of the photovoltaic panel [10]. Additionally, the reduction of CO_2 emissions is examined using a CO_2 emission factor of 258.3 gCO_2-eq/kWh for electricity, as reported in the 2021 ISPRA Report [11].

2.1 The case study: “Europa primary school” in Rome

The “Europa primary school”, now part of the Comprehensive Institute "Carlo Alberto Dalla Chiesa", is located in the south part of Rome. It was originally planned as a secondary urbanization service in 1972, prior to the introduction of the first Italian law concerning energy efficiency (national law n. 373/76). The building has 2 floors with a 2800 m² area on each floor. It’s characterized by a simple and compact design, made of prefabricated elements. It consists of a ground floor that continues halfway up to the first floor, served by two internal staircases and two external emergency exits. Three small courtyards provide light and air circulation to the inner parts of the building, including the lobby, bathrooms, and gym. Various types of skylights on the roof improve internal lighting, while also creating a modular space that adds variety to an otherwise monotonous environment. Figure 2 provides an aerial perspective, offering a comprehensive view of this iconic venue.

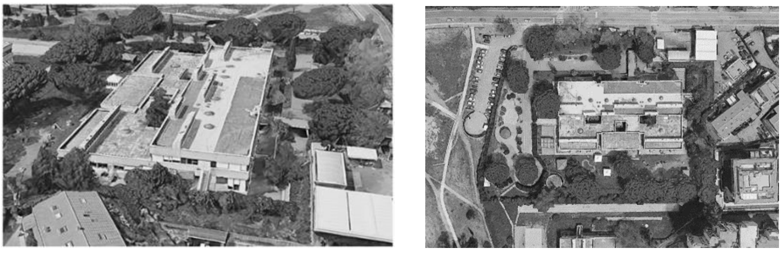

Fig. 2. Aerial views of the Europe primary school.

2.2 Boundary conditions

The initial analysis involved gathering data on solar irradiation and temperature, which are key factors that directly impact the performance of a photovoltaic system. Monthly weather information for the school was sourced from the NREL National Solar Radiation Database (NSRDB), a comprehensive dataset with high temporal and spatial resolution. This dataset includes measurements of solar radiation such as global horizontal, direct normal, and diffuse horizontal irradiance, along with other meteorological data. It was determined that the annual average solar irradiation on a horizontal surface in Rome is approximately 4.10 kWh/m²/day. This information is crucial for understanding the potential output of the photovoltaic system.

The school electrical load demand, from Monday to Friday, follows a consistent pattern throughout the day [12]. The load remains relatively low and stable from 1:00 to 7:00, gradually increasing thereafter, peaking at around 13:00, and maintaining high levels until approximately 15:00. Subsequently, the load begins to decrease gradually, with a slight slowdown in the decline around 18:00. A notable drop in load occurs between 21:00 and 22:00, followed by a period of low and stable energy consumption post 22:00. The school is unused from end of May/early June until mid-September and during the weekend.

Research studies [13,14], focusing on electrical consumption of school building, estimate that the average electricity consumption for appliances and artificial lighting is about 10 kWh/m² per year.

Starting from this, being unavailable detailed utility bills specific to the case study and necessitating the estimation of electricity loads during a year, the annual electrical energy consumption was approximated at around 56,000 kWh. Leveraging this data, it becomes feasible to construct the annual curve of the school electrical loads.

2.3 Photovoltaic plant

The design of a photovoltaic plant is contingent upon the specific site characteristics. Various factors such as the location of the site, spatial limitations, grid connectivity, energy requirements, and solar energy availability are all critical considerations. The total surface area available on the school roof is 2240 m². The rated capacity of a solar energy system, measured in kilowatts-peak (kWp), indicates the maximum power output it can produce under standard test conditions. This information is essential for determining the appropriate size and efficiency of the system for optimal performance. Each photovoltaic module is South-west oriented with an azimuth angle of 225° and inclined at the optimal tilt angle of 35° [15]. No buildings or other structures shade the modules. It was entered an average efficiency of a typical photovoltaic module of 20% and the overall system loss is quantified at 14.08%. Given the presence of a grid at the site, the photovoltaic system can export surplus energy to the utility grid, thereby prompting the design of a grid-connected system.

2.4 Energy output from grid to household utilities

The electrical energy generated by a photovoltaic system and fed to the grid has been evaluated in relation to the energy demand of household utilities in Rome. Data on household energy consumption in Rome was obtained from the study referenced in [16] that includes information on both domestic and non-domestic electricity consumption in the 155 urban planning zones of Rome, regardless of the energy provider. The data, which pertains to 2021, was provided by the distribution company Areti. Average data can be found in Table 1.

Table 1. Domestic and non-domestic electrical consumption in Rome according to [16].

	Utilities Number	Average monthly consumption (kWh)	Average monthly consumption per user (kWh)	Average annual consumption per user (kWh)
Domestic electrical consumption	1,321,992	233,737,722	177	2,122
Non-domestic electrical consumption	298,920	510,686,443	1,708	20,501
Total	1,620,912	744,424,165	459	5,511

2.5 Energy output from grid to streetlights

The electrical energy generated by the photovoltaic system and fed to the grid has been calculated in terms of the number of streetlights in Rome. Data on the public lighting network in Rome, as of 2021, was sourced from the Agency for the Oversight and Quality Assurance of Local Public Services of the Capital City of Rome (ACOS). According to the ACOS 2021 report, the public lighting network spans approximately 6,370 kilometres of roads and illuminates over 650 monuments, serving 226,728 lamps. This translates to an average of one lamp per 12 inhabitants and one light point every 28 meters of road. Notably, LEDs make up around 92% of the total public lighting fixtures. Average data can be found in Table 2.

Table 2. Characteristics of the public lighting network in Rome according to [17]

Total number of lamps	226,728
Average distance between lamps (m)	31.39
Total annual energy consumption for lighting (MWh)	66801
Annual average energy consumption for lamp (kWh)	294.63

3 Results and discussion

According to the previously outlined methodological approach, an hourly energy simulation was conducted to assess the performance of the photovoltaic plant. The plant yielded a total peak power of 427 kWp, with an annual AC energy output of 529,177 kWh. The annual energy output from the PV system was calculated to be 127.53 kWh/m², with the spatial layout of the school building's roof, typically unobstructed by shading, enhancing the efficiency of the photovoltaic panels. In Figure 3a, the monthly energy output from the photovoltaic system is depicted. The highest monthly energy production, totalling 66,913 kWh, is achieved in June whereas the lower one, equal to 15,316 kWh, is achieved in November. By estimating the total electrical loads, the total annual energy sent to the school energy system was calculated to be 58,573 kWh. Consequently, the annual AC energy output exported to the public grid amounted to 470,603 kWh. Figure 3b illustrates the monthly energy output fed into the utility grid.

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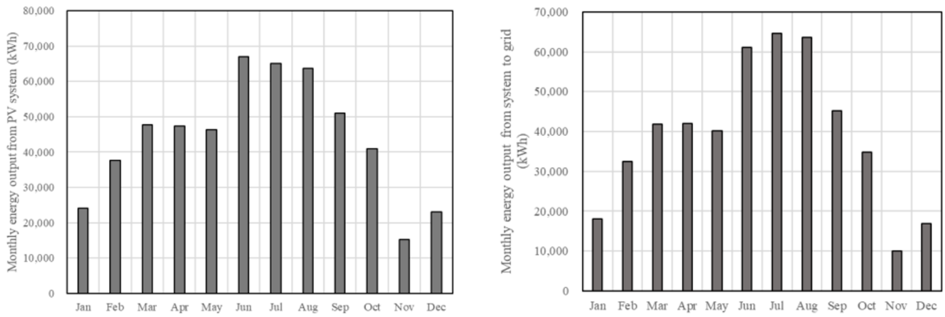

(a) (b)

Fig. 3. Monthly energy output from PV system (a) and from PV system to grid (b)

Regarding the results for energy produced by the photovoltaic system in terms of the number of household utilities energy demand, the electrical energy output could supply the energy demand of 222 household utilities, equal to 464 people. Similarly, regarding the results for the electrical energy output in terms of the number of streetlights served in the city of Rome, the electrical energy output could supply the energy demand of 1597 lamps. Additionally, it was determined that 4.8 m² of PV panels could supply the energy needs of an individual citizen. The summary results are shown in Table 3.

Table 3. Energy output from PV system to domestic utilities and streetlights

Number of supplied household utilities	222
Number of supplied lamps	1597
Total length of illuminated roads (km)	50.13

The initial cost of the system is calculated to be 309,361.5 €. The cash flow performance of the solar PV system, shown in Figure 4, considers a discount rate of 4.64%. The annual cash flow is analyzed over a 25-year period, with a simple payback period of 5 years. The net present value (NPV) is determined to be 1,177,911.93 €, resulting in a profitability index (PI) of 3.81. The PI compares the NPV to the initial investment cost, with a PI greater than zero indicating project profitability.

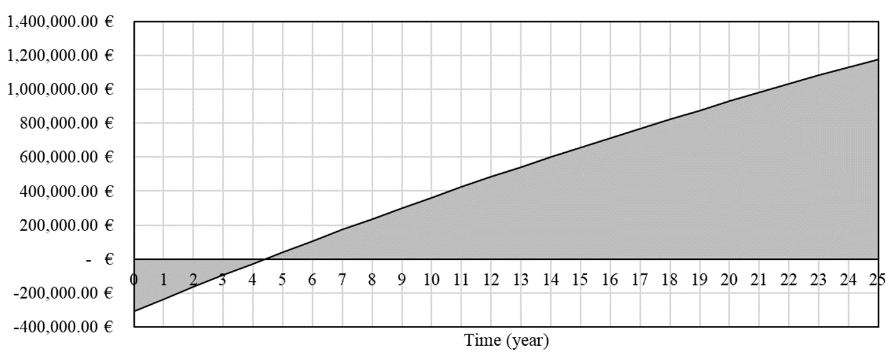

Fig. 4. Cash flow performance.

According to emission factors of greenhouse gases from the electricity sector for the generation of electrical power reported by ISPRA Report 2021 [11], the estimated annual CO_2 emissions reduction is equal to 136.6 tonCO_2.

4 Conclusions

The energy simulation conducted on the photovoltaic system that can be installed on the roof of the school building showcases its potential as a significant energy resource for the local community. The sizing analysis performed has revealed how this system could operate as a substantial energy station within an urban setting, making a notable contribution to the community's energy needs and promoting sustainability and resilience. The designed system has the capability to meet a portion of the school's energy demand (58,573 kWh) and can also export excess energy (470,603 kWh) to the utility grid. The results indicate that this system could potentially fulfil the energy requirements of 222 households or illuminate 1597 lamps within a renewable energy community framework, emphasizing the crucial role that large structures like schools play in advancing sustainability and resilience in urban areas. The electricity generated by the PV panels ensures higher earnings, confirming the financial feasibility of such installations. The payback period, the net present value and the profitability index reveal that the designed solar PV system is economically viable with an excellent return within a short period (5 years). The comprehensive analysis of energy, economic, and environmental factors provide valuable insights into how the generated energy can be strategically reinvested in the local community. This model serves as a blueprint for achieving a sustainable and economically viable future. Future work will involve implementing the proposed energy system in a school building and analyzing real-world energy and economic data to compare with the projected outcomes. This iterative process ensures a practical understanding of the system's performance and its actual impact on the community, in line with the overarching objectives of sustainable urban development and renewable energy integration.

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References

1. D. Gielen, F. Boshell, D. Saygin, M. D. Bazilian, N. Wagner, and R. Gorini, Energy Strategy Reviews **24**, 38 (2019)
2. C. Şirin, J. Goggins, and M. Hajdukiewicz, Appl Therm Eng **229**, 120607 (2023)
3. S. Bouckaert, A. F. Pales, C. McGlade, U. Remme, B. Wanner, L. Varro, D. D'Ambrosio, and T. Spencer, (2021)
4. M. A. Dupré la Tour, Renewable and Sustainable Energy Reviews **179**, 113189 (2023)
5. E. U. Directive, EU: Brussels, Belgium (2018)
6. M. Musolino, G. Maggio, E. D'Aleo, and A. Nicita, Renew Energy **210**, 540 (2023)
7. L. de Santoli, F. Fraticelli, F. Fornari, and C. Calice, Energy Build **68**, 196 (2014)
8. G. M. Tina and P. F. Scandura, Energy Convers Manag **64**, 569 (2012)
9. A. Ahmed, T. Bin Nadeem, A. A. Naqvi, M. A. Siddiqui, M. H. Khan, M. S. Bin Zahid, and S. M. Ammar, Renew Energy **195**, 238 (2022)
10. T. Georgitsioti, N. Pearsall, I. Forbes, and G. Pillai, Solar Energy 183, 738 (2019)
11. A. Caputo and C. Sarti, (2015)

12. T. Qian, K. Wang, Y. Li, X. Guo, and J. Liu, IOP Conf Ser Mater Sci Eng **394**, 042105 (2018)
13. M. Zinzi, S. Agnoli, G. Battistini, and G. Bernabini, Energy Procedia **48**, 1529 (2014)
14. L. Dias Pereira, D. Raimondo, S. P. Corgnati, and M. Gameiro da Silva, Renewable and Sustainable Energy Reviews **40**, 911 (2014)
15. S. Memme and M. Fossa, Renew Energy **200**, 845 (2022)
16. F. Asdrubali, R. De Lieto Vollaro, K. Lelo, S. Monni, M. Roncone, and F. Tomassi, ECONOMIA E POLITICA 1 (2023)
17. ACOS - Agenzia per il controllo e la qualità dei servizi pubblici locali di Roma Capitale, Relazione Annuale 2021/2022 (2021)