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SOLAR ENERGY AND GEOGRAPHIC INFORMATION SYSTEMS: APPLICATION OF ROOFTOP PV SYSTEMS IN KÜTAHYA PROVINCE

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ABSTRACT

In recent years, electricity generation from renewable sources has gained popularity. In particular, electricity generation based on solar energy is expected to be the most suitable solution to meet the energy needs of urban environments in the near future. While providing renewable-based energy to urban areas poses a major challenge, rooftop Photovoltaic (PV) systems that harness solar energy could pave the way to a more sustainable environment for cities. From an environmental perspective, every MWh of electricity generated from renewable sources reduces the introduction of large amounts of greenhouse gases into the atmosphere, thereby promoting a healthy environment and reducing global warming. Small-scale building-connected solar energy systems contribute significantly to the rapid growth of electricity generation potential from solar energy globally. This study aims to investigate the future of PV systems placed on roofs in the central housing sector of Kütahya, focusing especially on building roof areas. In this context, average solar radiation maps are provided to estimate the electricity generation potential of rooftop PV systems and evaluate the production potential. In addition, Geographic Information System (GIS) was used to evaluate the total roof area and solar potential of residential buildings in Kütahya province through spatial analysis. Finally, performance simulations were conducted, allowing solar potential prediction from annual solar irradiance, considering local building construction and PV design requirements. As a result of the analysis, it was determined that a total of 1979.7 MWh of electricity could be produced annually from a total roof area of 35121 m2 from a group of faculty buildings in the university campus located in the Kirazpınar neighborhood of Kütahya center, and a recommendation was made to form a basis for future studies on the energy efficiency of different PV solar cells.

Keywords: Geographic Information Systems (GIS), Solar energy, PV systems, Environmental Sustainability.

INTRODUCTION

In recent years, the increasing population on a global scale and the correspondingly increasing need for energy have become alarming. Therefore, the use of renewable and clean energy sources has great benefits that will reduce greenhouse gas emissions (Çömert et al., 2015). In 2015, renewable technologies attracted $286 billion in new investment and contributed to more than 23% of worldwide energy production (Khan et al., 2017). Solar energy is one of the most promising among all renewable technologies (Buker and Riffat, 2016). Creating integrated applications has been the focus of recent PV developments worldwide (Demircan and Gültekin, 2017). Germany introduced the concept of feed-in tariff policy for small-scale building integrated energy production in the early 1990s. In addition, countries such as the UK, USA, Spain and Italy have experienced rapid growth in their domestic PV markets by implementing this type of feed-in tariff policy (Özcan, 2013). Similar business models involving microcredit mechanisms have stimulated the solar energy market in developed countries (Uyan, 2017).

The great economic and infrastructure development and the transformation in lifestyle in the last decade have intensified the energy needs of the Turkish society, as we can observe the rapid growth in the construction sector (Yılmaz and Hotunluoğlu, 2015). Approximately 31% of total energy demand is related to the Turkish housing sector. It is reported that there was a 48% increase in energy consumption in the residential sector between 2001 and 2011. However, in the same period, the EU managed to experience a 9% decrease in the final energy consumption of the residential sector (Atmaca & Atmaca, 2015). Latest statistics show that natural gas accounts for 30% of total energy use in households in Turkey, followed by solid fuels at 26%, electricity at 16% and petroleum products at 5%. Natural gas consumption in the same sector increased from 8 million m3 to 14 million m3 (Eurostat, 2013). Therefore, the current situation requires a paradigm shift and new approach in energy consumption practices and trends in buildings. Turkey is trying to reduce its dependence on the fossil fuel-based energy sector (Barak, 2022). One of the justifications for this effort is that Turkey is very rich in renewable resources; It is obvious that it has a position especially in solar energy (Ak and Ergün, 2023). However, until recently, only a small part of the vast renewable potential has been used in our country (Tanrikulu and Partigöç, 2024). In addition, the focus is on large-scale projects aimed at creating small-scale and integrated applications. For this reason, the use of PV systems in the construction sector, especially in the housing sector, is of great importance (Leblebici and Uğur, 2015).

This study aims to investigate the future of PV systems placed on roofs in the Kütahya central district housing sector, focusing especially on building roof areas. For this purpose, the pilot area where the study will be carried out was determined, solar potential maps were estimated with GIS methods, the total roof areas in the residential sector were calculated and the electricity generation potential from rooftop PV application was determined.

Geographic Information Systems (GIS) and Solar energy

GIS is a technology that collects, stores and updates spatial data and provides convenience to decision makers with the help of maps and is used in many different disciplines (Sun et al., 2013). GIS, which performs suitable spatial analysis for electrical energy production from renewable sources such as solar energy, is used in many developed countries today (Yushchenko et al., 2013). Solar energy production potential can be divided into three categories: geographical, technical and economic (Sun et al., 2013). Geographically, multi-criteria analyzes to determine potential solar energy-based electricity production areas in marginal lands of cities have gained momentum thanks to GIS technology. PV materials selected are also important technically and economically.

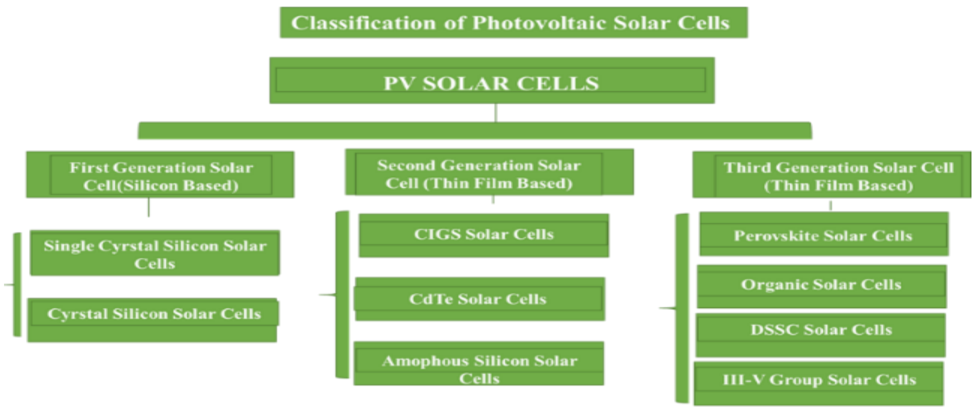
Photovoltaic (PV) Solar Cells

Solar photovoltaic (PV) technology is based on PV cells that allow direct conversion of solar radiation into electricity (Tyagi et al.,2013). PV can now be considered a mature technology both technically and economically. Researchers have developed a variety of solar cells, from first-generation to third-generation solar cells, as shown in Table 1. The first commercialized generation of solar PV was produced by using crystalline silicon as an active material. This has successfully achieved high efficiency (η) of solar PV photoelectric conversion with approximately 25%. Unfortunately, obtaining these first-generation solar cells is costly as extremely expensive processes are required to obtain high-purity silicon single crystals, thus limiting their availability. (Green et al., 2015). Later, researchers discovered gallium arsenide, cadmium telluride, actively amorphous silicon, or copper indium gallium selenide PV thin film solar cell materials with thin film technology, called second-generation solar energy, instead of crystalline silicon. However, efficiency values were obtained at values ranging between 10 and 20, lower than those of the first generation (Hardin et al., 2012; Yu, 2012).

The production of thin-film solar cells is hindered by the toxicity and scarcity of materials used in these cells. As a result, researchers have shifted their focus to third generation solar cells, such as quantum dot solar cells (with an efficiency of approximately 10%), organic solar cells (with an efficiency of approximately 11%), dye-sensitized solar cells (with an efficiency of approximately 13%), and perovskite-sensitized solar cells (with an efficiency of approximately 22%). These third generation solar cells have lower production costs and can optimize efficiency (Zhao et al., 1999; Mathew et al., 2014).

The comparison between first, second and third generation technologies in terms of efficiency, cost and stability is shown in Table 1.

Table 1. Classification of photovoltaic (PV) solar cells



Since there are many studies, publications and patents in the literature on silicon-based photovoltaic solar cells, theoretical and practical knowledge on this subject has reached a certain level. On the other hand, although the work on dye-sensitized solar cells has increased exponentially since the first publication by O'Regan and Gratzel in 1991, the number of electrodes, electrolytes, dyes, etc. The impact of these parameters on battery efficiency and cost is not sufficiently understood. More data is needed to reach a certain level of theoretical and practical knowledge on this subject.

So far, commercially available photovoltaic technologies are based on inorganic materials, which require high costs and high energy-consuming preparation methods. Additionally, many of these materials, such as cadmium telluride (CdTe), are toxic and rare in nature. Organic photovoltaics can avoid these problems. However, the efficiency of organic-based photovoltaic cells is currently far behind that achieved with purely inorganic-based photovoltaic technologies.

Conventional organic photovoltaic devices use a donor and receiver type of organic materials that form a heterojunction that promotes excitation splitting into two carriers. These created carriers are then transported to the electrodes by the same organic materials used to create an excitation. A material for classical organic photovoltaic devices, it must have both good light harvesting properties and good carriers with transport properties, which is a difficult task to achieve. On the other hand, DSSC battery technology separates the two requirements as charge generation is done at the semiconductor-dye interface and charge transfer is done by the semiconductor and electrolyte. That is, while optimization of spectral properties can be done by changing the dye alone, the transport properties of carriers can also be improved by optimizing the semiconductor and electrolyte composition (Nazeeruddin et al., 2011).

Third-generation solar cells, dye-sensitized solar cells (DSSCs), have attracted potential attention due to their exceptionally low cost, mechanical flexibility, ease of fabrication and assembly, and environmental friendliness. (Grätzel, 2004).

DSSC batteries developed by O'Regan and Grätzel have attracted great attention since 1991 as among the most interesting alternatives to other solar cells, being cheap in principle and environmentally friendly (Selopal et al., 2016).

Table 2. Comparison chart of first-second and third generation PV Solar cells.

PV Solar Cells	Efficiency	Cost	Stability
First generation	High	High	High
Second generation	Medium	Medium	Medium
Third generation	Medium	Low	Low

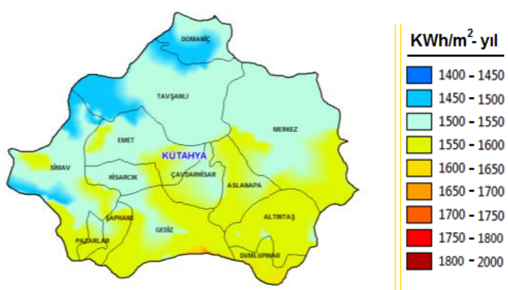
These differences will provide advantages in electricity efficiency. It is our hope that providing this information in this study will serve as a basis for future studies. Correct selection of the panel is as important in electrical energy efficiency as regional selection.

METHODOLOGY

The number of panels to be used was determined by calculating the roof areas of the buildings in the pilot region. The type of panels used, features of the inverters, tilt and azimuth angles and location information are entered into the RET Screen software. Thus, the energy analysis of the system was made; Then, relevant tables and graphs were obtained. By interpreting these tables and graphs, it was determined whether the project could be implemented or not.

Study area and Solar Potential

The Kütahya region, located in the inner part of the Aegean Region of Turkey, has a large slope area with agricultural lands culminating in high mountain ridges in the north and west (URL1). The land distribution of the region's total area of 1,201,400 (ha) has been determined by the Ministry of Agriculture and Forestry as 74% meadow-pasture and 26% irrigated agricultural lands (URL2). The city is among the regions with the required size of land for the installation potential of existing solar energy-based electrical energy production facilities. The average solar radiation in the region is around 1600 Kwh/m2-year, the recorded daily sunshine duration value is 6.1 hours and the annual value is 2559 hours. The solar map of Kütahya city shows the solar potential in Figure 1. The city's monthly global horizontal radiation varies between 1.51 and 6.48 kWh/m2/day. The annual average daily radiation amount is estimated to be 4.43 kWh/m2/day (URL3) and the annual average temperature is determined to be 10°C (URL4). Table 3 and Table 4 show the monthly average solar radiation and sunshine duration for the city of Kütahya, respectively. Irradiation values tend to increase from January to July, reaching their peak in June and July and then starting to decrease towards the end of the year. However, average sunshine hour values show the same trend as expected.



total solar radiation

Figure 1. Solar map of Kütahya city (EİE, 2018) (URL3).

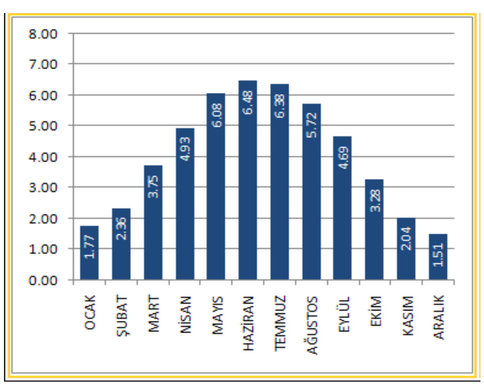


Figure 3. Kütahya Global Radiation Values

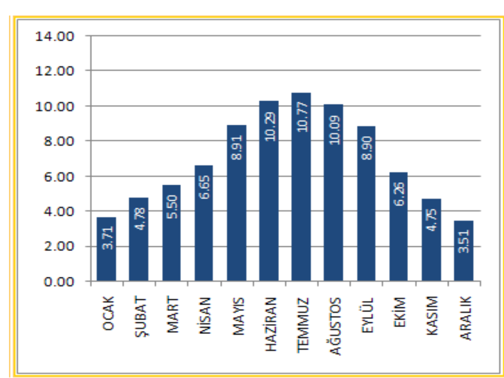


Figure 4. Kütahya Sunshine Periods (hours)

The 1/1000 scale area in the map section, Dumlupınar University central campus located in Kirazpınar neighborhood of Kütahya province, was analyzed as a pilot area. Numerical data regarding the area were obtained from the official websites of Kütahya Municipality and General Directorate of Land Registry and Cadastre. Figure 2 below shows the boundaries of Kirazpınar neighborhood in Kütahya Province and the pilot area.

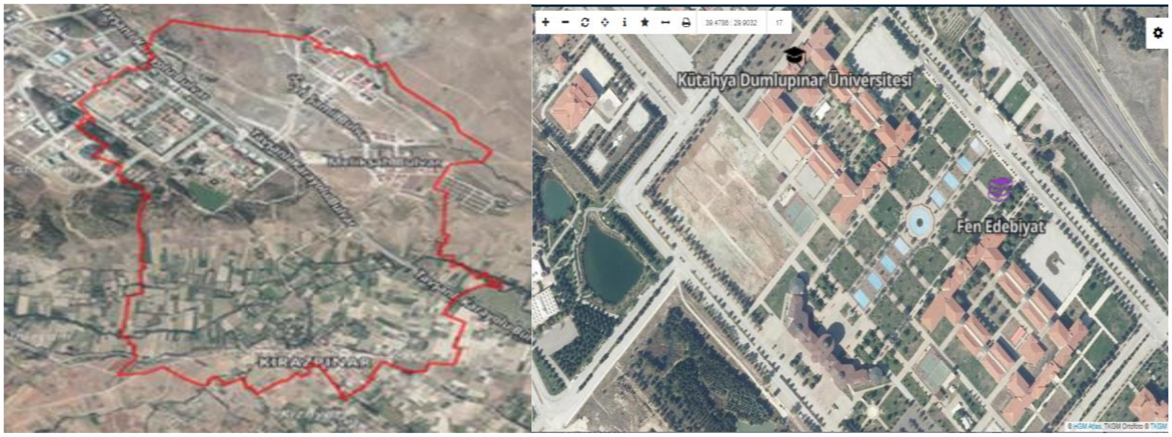


Figure 2. Kütahya Province Kirazpınar neighborhood boundaries and pilot area

Roof areas of buildings

There are several factors to consider that affect solar energy integration in an urban context with high building density, including available roof surface area, appearance of solar panels, and energy production potential (Öztürk, 2023).

In this study, photogrammetric images were first crossed with digital orthophotography. For this purpose, cadastral data digitized with orthophoto maps of the area under investigation, zoning data and Google Earth data were used. The image obtained by combining all this data in layers is shown in Figure 3 below. Once the total roof area is obtained, it is very important to evaluate the solar radiation effect and the theoretical energy production of the buildings through the special tool of the RET Screen. The selected area is the roof areas of the Rectorate, Faculty of Engineering and Faculty of Arts and Sciences buildings located within the Central Campus of Dumlupınar University in Kirazpınar neighborhood.

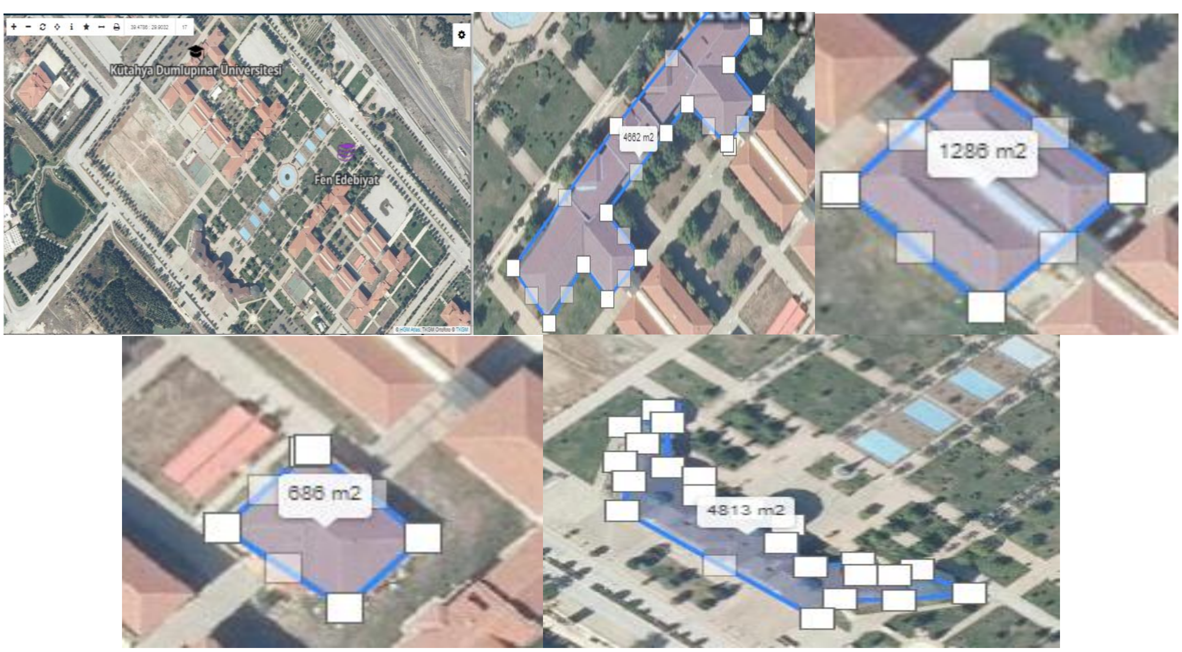


Figure 3. Study area roof areas

The roof area of the Rectorate building is calculated as 4813m2, the roof area of the main buildings of the faculties of Engineering and Science and Letters is 18648m2, the roof area of the administrative buildings of the faculties of Engineering and Arts and Sciences is 10288m2, the roof area of the social facility buildings of the faculties of Engineering and Letters is calculated as 1372m2. The total building roof area subject to the study is 35121m2. Since the subject of the research is PV roof systems, Kirazpınar neighborhood, Dumlupınar University central campus campus was determined by taking into account criteria such as solar potential, shading status, and the location of the buildings relative to each other. There are a total of 12 buildings with 2 or 5 floors in the study area. The total calculated roof area is 35121 square meters. Among these, there are 5 east-west (WW), 6 north-south (NW) and 1 north-south-east-west (NEW) facades of the buildings in the study area.

RESULTS

Suitable surface arrangements

Calculating the roof area suitable for PV system installation is an important goal of this communication. First of all, the entire area in the pilot region was examined. Elimination criteria then eliminate the ineffective area in terms of power generation and aspect ratio. The GIS technique distinguishes all roof areas except those facing south. Finally, the most suitable part of the roof for PV panel installation is selected depending on the amount of solar radiation that the PV panel can receive when mounted on a south-facing surface. The location of the buildings, whose area was calculated and their façade conditions were examined, and the total useful area for PV installation was calculated and thus reduced to 8780.25 m2 with the south-facing roof area.

Forecasting production

The capacity allocated to the total area is approximately 2 MW. This value is based on the total south-facing roof area examined in the previous section. Accordingly, 5321 panels were used in the system, each with a frame area of 1.65 m2 and an efficiency of 15.75%. Additionally, each panel in the system has a power capacity of 260 W. This offers the advantage of high-power production in a relatively smaller area compared to its counterparts on the market. Data for panels and analyzes from the RET Screen are shown in Table 5.

Table 5. PV Panels Analyze

Panasonic solar	Poly-Si	Miscellaneous losses	15 %
Maximum power	260 W_p	Inverter efficiency	95%
Efficiency	15.75 %	Miscellaneous losses	1%
Total capacity	2 MW	Total capacity factor of the system	16,4%
Total installed panel area	8780 m^2	Energy saved	1991,4 MWh

CONCLUSION AND RECOMMENDATIONS

- Although incentives are offered for the rooftop use of renewable systems in Turkey, appropriate policies and incentive programs are still needed for the adoption of PV electricity generation in residences. Similar initiatives in developed countries can create a road map.
- Rooftop potentials for PV energy production are shown in the study area. It has been determined that the net roof area for PV use in terms of aspect is equivalent to 8780.27 m2 and corresponds to 25% of the total roof area. It has been determined that if rooftop PV systems are implemented in the selected region, they can produce a certain annual capacity (MWh) and meet a good proportion of the total residential electricity demand. Contributing to environmental sustainability will be achieved by the rapid implementation of PV roof system technology. It is hoped that it will serve as a basis for more comprehensive studies.

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