Contents list available at IJRED website

International Journal of Renewable Energy Development

Journal homepage: https://ijred.undip.ac.id

Research Article

Techno-economic analysis of fixed versus sun-tracking solar panels

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Abstract. The potential output of photovoltaic (PV) panels is influenced by several factors, including the direction of solar radiation from the sun toward the panel's surface. The maximum output of the panels is obtained when the panels are vertical to the sun's rays. In this study, a techno-economic analysis is conducted to examine whether an automatic one-axis sun tracker system is an economically feasible option for installing a large-scale PV park in the Nicosia district in the central part of Cyprus. The performance of a one-axis sun tracker with an installed capacity of 781 kWp is compared to a PV system with a fixed flat structure having the same capacity and larger capacity at 1034 kWp. Output generated by the three PV system options is simulated by three alternative simulation software (SolarGIS, PVSyst, and PVGIS). Financial analysis is performed utilizing simulated PV power output, accounting for electricity feed-in tariff and overall cost of the project. The cash-flow model is run for several scenarios defined by different leverage ratios, including no leverage. Considering the technical parameters of a PV system and solar panel characteristics, such as the degradation effect on solar panel efficiency and solar radiation, we estimate the solar tracking system produces about 20%–30% more energy compared to a fixed structure. We find both technologies are economically viable options, however, a one-axis tracker system performs better financially. LCOE in all scenarios is below the highest acceptable level for solar PV projects in Cyprus which is 103 EUR per MWh. LCOE for a solar tracker PV is 39 EUR per MWh with a 30% leverage ratio and up to 79 EUR per MWh with 85% leverage. LCOE for a sun-tracker is ~20% lower than LCOE for a PV with a fixed axis of comparable size. Despite higher investment costs, the solar tracking PV system performs with a 12% higher equity internal rate of return, and a 9% shorter loan payback period compared to the same installed power of a fixed structure. The Financial analysis is complemented by quantified benefits due to avoided carbon emissions. Accounting for carbon benefits makes a sun-tracker PV system economically a better option over the fixed tracker PV system, resulting in 228,000 EUR more benefits. Overall, the present value of net benefits of a solar-tracker PV amounts to 1.39 mil. EUR and due to high irradiation in Cyprus, the carbon footprint of PV power output represents only 6% of the footprint of generating electricity in thermal power plants. When these benefits are accounted for the sum of NPV and social benefits will turn out to be higher for a one-axis tracker compared to the total social benefits of a fixed tracker of the same size.

Keywords: financial analysis, LCOE, GHG emission, solar energy, photovoltaic, tracking system

Received: 9th Sept 2022; Revised: 15th April 2023; Accepted: 6th May 2023; Available online: 12th May 2023

1. Introduction

The adoption of renewable energy sources is strongly encouraged due to environmental and climate change challenges. Major changes in the energy sector are required to stop global warming, including a decrease in the use of fossil fuels, widespread electrification, improved energy efficiency, and the use of sustainable energy sources (Batac *et al.*, 2022). Electricity generation accounts for around 23 percent (13.3 Gt CO_{2eq}) of greenhouse gas emissions worldwide and holds the key source of global CO_2 emissions (Minx *et al.*, 2022). Finding sufficient supplies of clean energy for the future is one of society's major problems. Alternative renewable energy sources (RES), such as solar energy, are frequently used to supplement exceeding human energy requirements. Covering 0.16% of the Earth's surface with 20% efficient solar conversion systems would provide 20 TW of power, almost twice as much fossil energy is consumed globally (Moradi *et al.*, 2016). Moreover, given the growth in population and the advancement of society, renewable energies may meet the rising global need for electrical energy (Sadat-Mohammadi *et al.*, 2018). The need to decarbonise the power sector is made more critical by the fact that the world's energy needs are increasing and that pathways to decarbonisation in other sectors such as buildings, transportation, and industry will depend on zero-carbon electricity (Boehm *et al.*, 2022).

Solar energy is widely recognised to reduce climate change and environmental pollution brought on by greenhouse gas emissions (GHG) from the energy sector (Ebhota *et al.*, 2022). The energy sector has made some significant progress in recent years toward moving away from fossil fuels, particularly with the addition of renewable electricity generation. In 2021, renewable energy capacity increased by 9.1% (257 GW), bringing total installed renewable electricity capacity to 3,064 GW. Solar

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energy continued to lead capacity expansion with an increase of 19% (133 GW), followed by wind energy with 13% (93 GW). It continued to dominate renewable capacity expansion, jointly with wind energy, accounting for 88% of all net renewable additions in 2021 (IRENA, 2022). However, the deployment of solar energy should be accelerated because, by 2030, it is anticipated that its production, along with that of wind energy, would make up the majority of all electricity generated (IPCC, 2022). Utilising photovoltaic (PV) systems to capture solar energy is an effective method of producing clean electricity with limited operating costs and minor environmental effects (Khamharnphol *et al*, 2023).

The necessity for clean power has created an urgent need for research into maximising solar energy's generation in photovoltaic systems. To enhance the efficiency of solar energy systems, the development of solar energy technology is necessary (Aquino Larico and Gutierrez, 2022). The efficiency of solar systems is significantly dependent on the performance of PV solar cells. Radiation from the sun, which is made up of photons of light, is the source of solar energy. Converting sunlight directly to electricity is accomplished via PV solar cells (Berisha *et al.*, 2018). A photovoltaic panel's energy output varies during the day when it is fixed in relation to the ground and pointed south (Baouche *et al.*, 2022). Moreover, the poor radiation angle of the fixed panel lowers the efficiency of power generation at the beginning and end of the day (Nsengiyumva *et al.*, 2018).

In order to boost the performance of photovoltaic (PV) panels, numerous studies have been conducted in the literature. The result of recent research conducted by Rodríguez-Gallegos *et al.* (2020) shows a single-axis tracker in a solar system can boost electrical efficiency by 25 to 35%, and a two-axis tracker can do so by up to 45%. A techno-economic assessment has compared the different types of automatic solar trackers and manually adjustable tilt mechanisms for behind-the-meter PV applications in Turkey (Gönül *et al.*, 2022). The systems are compared financially and assessed based on internal rate of return (IRR), discounted payback period, and levelized cost of electricity (LCOE). The result showed that the fixed-tilt systems had a payback period of 10.3–13.3 years. In comparison to fixed-tilt, dual-axis solar trackers boost power generation by the most (30.4–34.6%) but have the longest payback period (16.7–24 years) of all available options. The most practical approach is monthly manual tilt adjustment, which reduces the payback period of fixed-tilt systems by about 8 months to 9.6-12.6 years while increasing electricity generation by 3.6-5%.

Another study compared the power generation of fixed and tracking structures (east-west single-axis tracking) in different cities of Iran located in the same geographical locations (Tafazoli *et al.*, 2022). When designing a sample power plant, they used a software modelling to assess several sun tracking scenarios. The findings indicated that this type of tracker can increase annual energy production at power plants by up to 20%. Compared to fixed structure, the production quantity with this technology varies from a 44% rise on a summer day to a 15% drop on a winter day.

Talavera *et al.* (2019) assessed the technical and economic parameters of the fixed and tracking photovoltaic systems for five different locations and technologies, including fixed, horizontal one-axis and two-axis tracking systems. The outcome shows that fixed and one-axis systems are cost-competitive in terms of electricity prices, however two-axis systems are discouraged.

In Cyprus, the primary energy generation in 2019 was 89% oil-based, 2% coal-based, and the remaining was based on renewable energies. The country obtained 9% of its primary energy from renewable energies, with 48% of this from solar, 42% from bioenergy, and 10% from wind in 2019 (IRENA, 2022).

Cyprus, with more than 3300 hours of sunlight per year, has the highest potential for solar energy in the European Union, but it now imports the majority of its electricity, which makes it the ideal place to develop solar energy. Although some progress has been made, there has been little innovation and funding for solar technology. Many obstacles must be overcome, such as a lack of technical knowledge of the entire energy cycle (European Commission, 2017). Increased investment in RES power generation, both at the commercial and building level, as well as a significant overhaul of road traffic are necessary to meet EU mandated reductions in carbon emissions. The country aims to increase the proportion of RES in the nation's energy mix, which is needed to boost its overall RES-derived energy consumption to 23 percent by 2030 in order to meet EU-mandated standards. Despite the excellent potential for generating electricity from PV, Cyprus is far behind the national and EU targets for implementing RES (IRENA, 2020).

Several studies have investigated the potential and feasibility of solar energy on the island of Cyprus. Poullikkas (2009) carried out a feasibility study on the installation of large photovoltaic (PV) parks in Cyprus, in the absence of a relevant feed-in tariff. A parametric cost-benefit analysis is performed by adjusting parameters such as PV park orientation, PV park capital investment, carbon dioxide emission trading system price, etc. in order to discover the least-cost feasible alternative for the building of a 1 MW PV park. The power unit cost or benefit before tax, after-tax cash flow, net present value, internal rate of return, and payback period are all calculated for the given scenarios. The findings show that, in the absence of a feed-in tariff, the capital investment in the PV park is a crucial factor in determining the project's profitability.

Evaluation of the potential of solar energy utilisation in Famagusta in Cyprus was investigated by Ouria and Sevinc (2018). In-depth research was done on the Social Housing Complex (SHC) district of Famagusta's solar energy usage potential. Climate variables, radiation types, geographic parameters, orientation strategies, height to width ratios, and landscape analyses were all considered as effective solar energy parameters. The study's findings demonstrated that, despite the abundance of solar energy available, it is not being used to its full potential. It is advised that solar panels be used to produce renewable energy for lightning.

Kassem *et al.* (2019) compared the potential electricity generation from using small-scale wind turbines and solar photovoltaic systems for residential buildings in three locations in Northern Cyprus. They evaluated the effectiveness of the 6.4 kW grid-connected rooftop PV system using three different simulation programs (PVGIS, PV*SOL, and PVWatts). Their analysis revealed that the proposed PV projects at the investigated sites had significant energy generation potential. Additionally, due to the lower cost of electricity and the capacity to recoup the original investment, the suggested PV system is the most cost-effective alternative for producing electricity when compared to wind systems. Similarly, a detailed and integrated feasibility analysis of a 100 MW grid-connected solar plant project is provided by Kassem *et al.* (2020). They investigated the energy output, GHG emissions, and financial aspects using RETScreen Expert software. The findings showed that Northern Cyprus could employ the suggested solar system to generate electricity. Obtaining the result of previous studies, despite the abundance of solar radiation and proven feasibility of solar projects on the island of Cyprus, along with the increasing energy demand and necessity of using green energies, solar energies currently account for a negligible share of the country's energy production. One of the reasons is that new technologies have not been introduced and examined in large scale PV projects. Solar trackers are widely used in PV parks, but to the best of our knowledge, this technology is still unknown in Cyprus, and there is no operating PV park using them at the time of writing. Moreover, the rapid development of solar PV technology and the availability of equipment at various prices complicate the decision-making process for choosing the most efficient technology adopted by the focused market and proposing attractive cash flow for the project's lifetime. This indicates the need for an investment assessment tool to consider the flexibility and diversity of compliance options available to operators (Fan *et al.*, 2020). One of the most critical factors in PV project assessment is project cost per kWp, which is highly affected by selected technology. Currently, the cost of installing a tracking system per kilowatt peak (kWp) of installed power is higher than the cost of conventional fixed systems. Due to the price reduction in the PV industry, especially in modules, the economic advantage of the surplus yields obtained with tracking systems is now questionable (Oner *et al.*, 2009).

Therefore, due to the lack of studies that compare the energy output of fixed versus solar tracker systems, considering the challenge of balancing the higher tracker costs with increased yields, we aim to assess the possibility of using solar trackers in a utility-scale PV park by applying a cost–benefit analysis.

Hence, the main objective of this research is to identify the most cost-effective PV systems by comparing fixed structures with solar tracker systems to determine how the latter may increase output in a utility-scale PV plant. For this purpose, we presented a techno-economic assessment of a developing PV park in the Nicosia district. Three scenarios are established for different technologies using data obtained from three simulation analyst software programs: SolarGIS, PVSyst, and PVGIS.

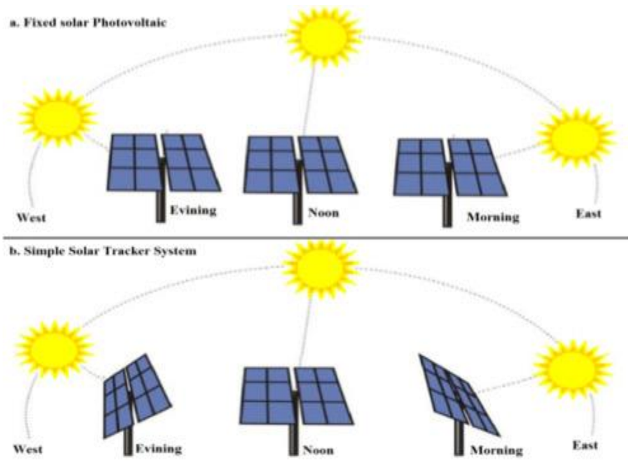
The overall goal of this paper is to determine the cost-effective and reliable solutions for PV systems to exploit solar energy's underutilised potential accelerating clean energy production and reach the EU mandated reduction in carbon emission by 2030. Moreover, we contribute to the debate on the European Green Deal, and the implementation of Fit for 55 policy package in particular.

2. Methods

In this study, two technologies are compared: fixed structures and solar tracker systems, to see how solar tracker systems may improve production in a utility-scale PV plant. To perform such a comparison, similar components in different alternatives are used to remove their possible effects on the results. Therefore, there is one alternative technology (solar tracker) used compared to the main technology (fixed structure).

2.1 Fixed Structure versus Sun-tracking technology

Solar panels can be either fixed or sun tracking with two main types: single-axis or dual-axis. In a fixed solar system, solar panels are connected in one place, and the solar panels are stationary and intended to capture any sunlight that reaches the cells; they are not intended to move. Fixed solar panels are regarded as a less effective technology since they convert only 15% of the solar energy they receive into electricity (Jose *et al.*, 2022). Although fixed PV systems are currently used the most, they are characterized by losses from shading and less-than-optimal orientation, which reduce electricity output. When a surface is moved to follow the sun, the energy yield on that surface increases. A sun tracker is a device that orients a payload towards the sun to overcome seasonal and diurnal reception angle disparities in a photovoltaic panel (Asiabanpour *et al.*, 2017).



Source: Al-Rousan *et al.* (2018).

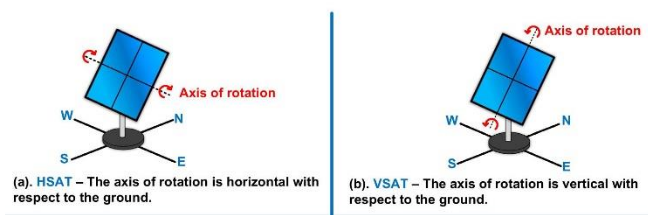
Fig. 1 Fixed vs Solar Tracker system

The sun tracker navigates the photovoltaic panel, positioning it towards the sun's radiation to conclude a perpendicular or near perpendicular condition with as many operating hours as possible to maximise energy production. The tracked array rises too quickly to full power and stays there on a clear, sunny day. The fixed array only maintains maximum power for a few hours in the middle of the day. According to the literature, tracking PV modules towards the sun offers a gain in yield of 15% to over 37.5% for the one-axis tracking system relative to fixed-mounted PV installations depending on the location and solar resource (Abdallah, 2003; Eke *et al.*, 2012; Huang *et al.*, 2013; Khadidja *et al.*, 2014). Figure 1 depicts the fixed solar PV compared to the solar tracker.

Regarding movement capability, sun-tracking systems are designed to track the sun on a single axis (according to the azimuth angle) or to track the sun on both axes (according to the azimuth and solar altitude angles) (Eke *et al.*, 2012; Shufat, 2019), which vary in terms of the degrees of freedom available for movement (Hafez *et al.*, 2018).

Single-axis trackers follow the sun accurately enough that their output can be very close to complete tracking. Sun-tracking system classifications are based on movement capability and control systems. Solar trackers can have either a horizontal or a vertical axis type. The horizontal single-axis tracker (HSAT) has one degree of freedom moving on a north to south axis of rotation, and is used in regions with lower latitude. The vertical single-axis tracker (VSAT) also has one degree of freedom moving on a one axis of rotation from east to west, and is used in high latitudes. Figure 2 shows these configurations.

This study is focused primarily on single-axis horizontal trackers. This tracker configuration is suggested for large field installations and commercial application, where a single drive motor can move as much as 200 kW of panels in multiple



Source: El Hammoumi 2022

Fig. 2 Horizontal single axis versus Vertical single axis tracker interlinked rows. The only real drawback is in the winter, when the midday sun is very low in the sky, and the panels produce less power. However, in the winter mornings and afternoons, the ability of the tracker to roll the panels over to a forty-five-degree angle produces slightly more power in the mid-morning and afternoon than at the sun's highest point (Precision Solar, 2011).

2.2 PV simulation models

This study was conducted using data from a developing PV park in central Cyprus utilising three simulation software: SolarGIS, PVSyst, and PV GIS.

SolarGIS was founded in 2010 in central Europe. A solar PV system simulator is available online with the SolarGIS-pvPlanner program. The simulator makes assessment findings available online for any chosen location. Utilising web programming technologies from Google Web Toolkit, it combines numerical simulation models from the most recent research with fresh climatic databases (Elieser Tarigan *et al.*, 2014). The basis for the SolarGIS methodology is the use of statistically compiled sunlight and temperature data that is stored in the database (Marcel and Tomáš, 2012).

PVGIS was developed at the European Commission Joint Research Centre in 2001. PVGIS focuses on research on solar resource assessment, photovoltaic performance studies, and disseminating knowledge and data about solar radiation and PV performance. For the simulation of a solar PV system in the research areas, PVGIS is a simple, quick, and reliable software application (Kassem *et al.*, 2019). The PVGIS web application has undergone several changes over the years, with the current version of PVGIS 5 used in this study.

PVSyst, developed in 1992, was designed for use by architects, engineers, and researchers. For the design and modeling of grid-connected, standalone, pumping, and DC-grid PV systems, PVsyst has become a reliable and practical tool (Husain *et al.*, 2021). It offers a user-friendly approach with a project development guide. PVsyst can import meteo and personal data from many different sources and propose an array/system configuration that allows users to conduct a preliminary simulation of PV projects. Additionally, it evaluates system losses resulting from partial shadowing, wiring, and inverter losses, as well as the impact of changes in ambient temperature on its calculations of electrical output power (Khamharnphol *et al.*, 2022).

2.3 Site location data

The project's location is in the district of Nicosia, the central part of Cyprus (latitude 34.98 + N longitude 33.24 + E, altitude 527 m). Global horizontal irradiation and direct normal irradiation in the area were 1,857 and 2,027 kWh/m2, respectively. In contrast, global tilted irradiation was 2,043, and 2,445 kWh/m2 for fixed and tracker systems, respectively. The minimum daily global irradiation in December was 3.13 and 3.56 kWh/m2 for fixed and tracker systems, while the maximum in July was 7.33 and 10.57 kWh/m2, respectively. The average annual global irradiations were 5.60 and 6.80 kWh/m2 for fixed and tracker systems, respectively. July had the maximum amount of solar irradiation, while the minimum achieved irradiation was in December. The PV output in July for fixed and tracker systems was 138 and 193 MWh, respectively, and in December, 73, and 65 MWh, respectively. Figure 3 shows the monthly direct normal irradiation (DNI) in the project location and how it varies during a year. Total annual direct normal irradiation in the year when research conducted was 2027 kWh/m^2.

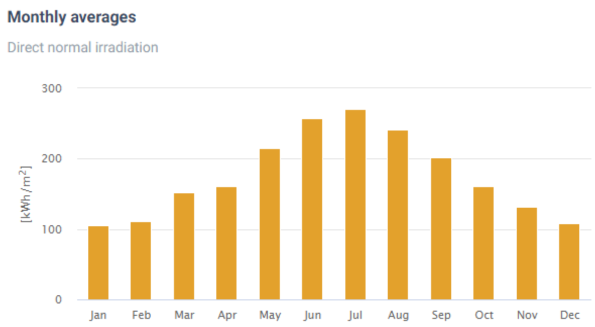


Fig. 3. direct normal irradiation (DNI) in the project location

The average slopes on the site are N-S 5.6% and W-E 12.4%, while the maximum slopes are N-S 6% and W-E 12.4%. Based on the technical datasheet presented by the manufacturer, the installation of the tracker system is feasible on a slope up to 18% (N–S) and the fixed system on a slope below 25% (N–S). Therefore, no significant physical alternations to the site will be needed, and the surface levelling of the plot will be almost the same for installing both tracker and fixed structures; the cost of land preparation is negligible in the comparisons. General topographic conditions are identified as "suitable" for constructing and operating a photovoltaic park.

2.4 Project layout

An adequately paved registered road is in the northwest part of the site, 58 meters away from the land. Therefore, there is a need to build and maintain 60 meters of road to have sufficient access to the site. However, construction/operation expenses for the access road did not affect the economic comparison between the tracker and fixed system scenarios. Key technical figures for the initial design are summarised below.

Scenario 1: Tracker Structure (781 kWp)

Using a single-axis tracker system, we tried to utilise the entire site by minimising the distance between rows (axis to axis). The result was that, considering all costs, we could achieve a power of 781.2 kWp installed DC, equivalent to 703 kW AC output power (Figure 4). The fenced area is about 1.2 ha, with a total

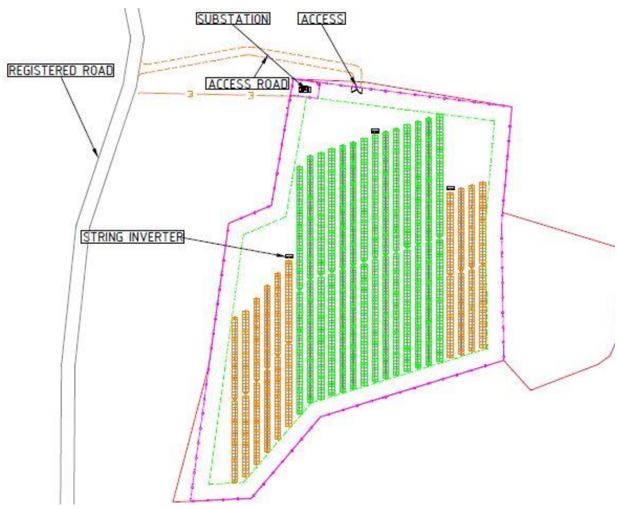


Fig. 4 Layout of tracker structure

Fig. 5 Layout of fixed structure (781 kWp)

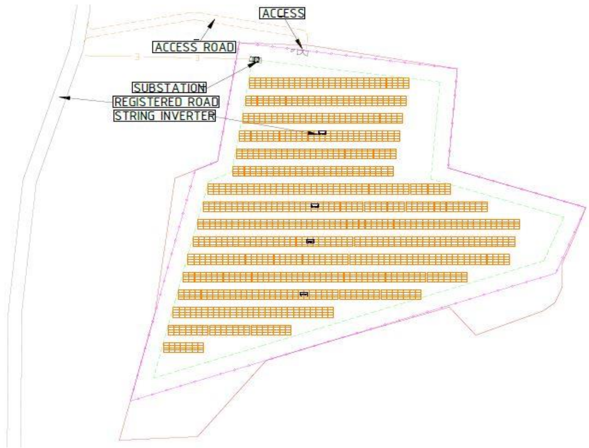


Fig. 6 Layout of fixed structure (1,034 kWp)

fence length of approximately 480 meters. The design used 14 pieces of 1-x/84 module tracker, 10 pieces of 1-x/56 module tracker, and 1,736 pieces of a high-power 450 W solar module with 20.4% efficiency equipped by half-cut and multi-busbar technology in the layout. A 20' container substation and three string inverters were used to conduct generated electricity to the grid lines.

Scenario 2: Fixed Structure (781 kWp)

For the fixed structure, two scenarios were created. First, the power plant was designed with the same installed DC PV power as the tracker (781 kWp). For this location, the optimum irradiation angle was 25 degrees, in which solar panels absorb the maximum possible sunshine. Therefore, solar modules would be installed on the ground at a 25-degree angle. By limiting total installed power, the achieved output power considering all power losses in the system would be 703 kWp. The fenced area is about 1.32 ha, with a fence length of approximately 521 meters. In the design, as shown in Figure 5, 13 pieces of 112 module structures and 10 pieces of 28 module structures were used; 1,736 high-power 450 W solar modules with 20.4% efficiency equipped with half-cut and multi-busbar technology were used in the layout. A 20' container substation and four string inverters were used to conduct generated electricity to the grid lines.

Scenario 3: Fixed Structure (1034 kWp)

In the third scenario, the entire site was utilised by minimising the distance between rows. Calculating the angle mentioned above, we derived the distance between rows of approximately 7 meters, resulting in 3.1 meters of sufficient distance between the modules for moving operating vehicles. By fixing the dimensions mentioned above, we achieved a power of 1,034 kWp installed DC, equivalent to 930 kW AC output power, considering all losses. The design used 17 pieces of 112 module structures and 14 pieces of 28 module structures, with 2,296 high-power 450-W solar modules in the same configuration. See Figure 6.

The type and technology of solar modules, inverters, and substations are similar in both tracker and fixed structure systems:

- Solar modules: monocrystal, power output 450 W, efficiency 20.4%.
- Inverters: String type, maximum PV input voltage of 1,500 V, nominal PV input voltage of 1,080 V.
- Transformer station: Oil immersed for distribution purposes.

2.5. Cash-flow analysis

In financial analysis, cash flow is typically analysed through several financial measures like the net present value, internal

Table 1
Assumptions of performed cash flow analysis

Parameter	Value	Unit	Note
Development costs	150,000	€/MW	permitting + project preparation expenses
Land lease cost per hectare	5,000	€/year	€7000/year for the entire site (the entire size of project's land is 1.2 hectare).
Cost of the grid connection	150,000	€/MW	with a negligible difference when the installed DC is increased*.
Feed-in tariff	80	€/MW	The current tariff in the market is in the range of €80-105/MWh, €80-105/MWh, €70-80/MWh are assumed by Rečka *et al.*, (2023)
Discount rate	8.5	%	
Annual price increase	2	%	
Corporate income tax rate	12.5	%	
EPC cost for one-axis tracker system	900,000	€/MW	Including engineering, procurement, and construction costs
EPC cost for fixed system	820,000	€/MW	based on the most recent EPC contracts in the destination market and similar cases.
Economic life of solar panels	27	year	
Operational costs	15,000 10,000	€/MW	- for one-axis tracker system - for fixed system
Installed capacity	781 781 &1034	kWp	- for one-axis tracker system - for fixed system

rate of return, payback period, and return on investments measures (Guno *et al.*, 2021).

Net Present Value (NPV) of a project is the difference between all revenues (R) and costs (C) over the project lifetime t that are all discounted by a discount rate, r, to get their present value:

$$NPV = \sum_{t=0}^{T} \frac{R_t}{(1+r)^t} - \sum_{t=0}^{T} \frac{C_t}{(1+r)^t}$$

When NPV > 0, the project is considered as being viable, and projects with higher NPV are more profitable (Lu *et al.*, 2022).

The internal rate of return (IRR) is used to estimate the profitability of potential investments. IRR equals to the discount rate that results in NPV=0. The higher the IRR, the more net revenues a company makes from a project (Prol and Steininge, 2020).

The payback period refers to time it takes to recover the cost of an investment by undiscounted revenues from selling electricity generated by a plant that was invested. Simply put, it is the length of time an investment reaches a breakeven point and it is expressed in years.

The levelized cost of energy (LCOE) is a critical metric in determining whether to move forward with a project. The LCOE will determine whether a project will break even or be profitable. If not, the firm will not proceed with building the power-generating asset and will look for an alternative. Using the LCOE to assess a project is one of the first fundamental steps in analysing projects of this nature.

$$LCOE = \frac{I_0 + \sum_{t=1}^{n} \frac{A_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{Q_t}{(1+r)^t}}$$

where I_0 is capital expenditure (CAPEX), At is annual operating costs (OPEX) in year t, Qt is the estimated produced electricity in the corresponding year in kWh, r is the discount rate (%), n is the estimated lifetime of the system (in years), and t denotes years till project's lifetime (Ebenhoch *et al*, 2015).

Financial analysis is carried out based on factors like solar radiation, (simulated) PV power output, electricity feed-in tariffs, and solar panel characteristics like the impact of degradation on efficiency. The cash-flow model is run for each scenario while varying the leverage ratio. The equity IRR, payback duration, and NPV are calculated for each scenario. Table 1 reports the assumptions of the cash flow analysis, which are the same for all three analysed technologies unless described explicitly.

2.6 Cost-benefit analysis

To analyse social desirability of various projects and programs, cost-benefit analysis (CBA) is frequently utilised. Additionally, to all (financial) costs and revenues, the economic impacts on other agents are also accounted for (Dehnhardt *et al.*, 2022). In our case, we quantify social benefits as follows:

$$Social\ Benefits = \sum_{t=0}^{T} \frac{(R_t - C_t + B_t)}{(1+r)^t}$$

where B denotes net benefit from avoiding carbon emissions otherwise released from thermal power plants operated in Cyprus and carbon footprint of PV electricity generation, and the rest is the same as to compute NPV.

To derive benefits, we apply the emission factor for combined margin intermittent electricity generation, which should be used to calculate the baseline emissions for intermittent electricity generation such as solar, wind and tidal electricity generation, as recommended in the Guideline by European Investment bank (EIB 2023). In the case of Cyprus, the carbon footprint of electricity generation is 633 gCO_{2e}/kWh. Carbon footprint of PV electricity generation is assumed to be 38 gCO_{2e}/kWh, as recommended for Cyprus by De Wild Scholten *et al.* (2014).

Climate change impacts are valued by avoidance costs at € 100 per t CO_{2eq} (up to 2030) and at € 269 per t CO_{2eq} (from 2031), with low and high values at € 60 and € 189, and € 156 and € 498, respectively, as recommended in the Handbook on the external cost of transport (European Commission, Directorate-General for Mobility and Transport *et al.*, (2020); all values in $€_{2016}$). As an alternative, we assume the price of EU EUA for ETS, as projected for WEO Net Zero Emission scenario by Harmonised Cost Trajectories (EC 2022): the EUA price is 79 EUR till 2027, 114 EUR in 2028-2032, 145 EUR in 2033-2037, 180 EUR in 2038-2042, 202 EUR in 2043-2048, and 220 EUR up to 2050.

3. Result and discussion

3.1. Solar radiation: Power output by month and hour

In this study, we performed simulations using three softwares (SolarGIS, PVGIS-5, and PVSyst) endowed with a sun-tracking (1-X tracker) and fixed axis, respectively, all with installed capacity 781 kW a year. For a comparison, the sun-tracker technology is also compared to the technology with fixed axis that has about a third larger installed capacity (1034 kW).

Solar radiation is the most important project-specific meteorological factor that influences the amount of solar electricity produced. To accurately calculate the potential electricity output of photovoltaic (PV) panels, the global horizontal irradiance (GHI) and its components; direct normal irradiance (DNI) and diffuse horizontal irradiation (DHI), must be known (Ameur *et al.*, 2020). Power production is also influenced by air temperature and other meteorological parameters such as wind speed (WS) which affect the performance, availability and ageing of a PV system. Table 2 shows the monthly meteorological data reported by SolarGIS software. As expected, annual variations are characterised by high availabilities (both for GHI and DNI) in the summer period (from May to August), having maximum values that reach 244 kWh/m^2 for GHI, and between 258 kWh/m2 for DNI in July. On the other hand, in the cold season (from November to February), low availabilities occur with minimum values of 72 kWh/m^2 for GHI in December, and 100 kWh/m2 in the case of DNI in January. The project site location experiences minimum average monthly temperature of 8.0°C in January and maximum of 28.7°C in July.

The hourly PV power outputs are calculated as an average of all hourly data for each month for both technologies; is displayed in Figure 7 and Figure 8 for fixed structures and solar trackers, respectively. The profiles give an indication of changing power production due to weather and the selected configuration of a PV system in the course of a day.

As depicted in Figure 7 and 8, the sun tracker technology yields higher average hourly PV output than the fixed structure. Obviously, the average hourly PV output of both technologies is lower in the winter than in the summer; however, it is significantly different across the warm and cold seasons.

Table 2
Solar radiation and meteorological parameters

Month	GHI kWh/m^2	DNI kWh/m^2	DIF kWh/m^2	TEMP °C	WS m/s
Jan	76	100	33	8.0	3.8
Feb	93	106	39	8.8	4.0
Mar	144	147	55	11.8	3.7
Apr	172	156	66	15.8	3.6
May	212	204	68	20.8	3.2
Jun	235	249	58	25.7	3.3
Jul	244	258	58	28.7	3.3
Aug	218	231	58	28.3	3.1
Sep	171	192	49	24.5	3.1
Oct	128	154	44	19.6	2.8
Nov	92	127	33	13.9	3.3
Dec	72	103	31	9.7	3.6
Yearly	**1857**	**2027**	**593**	**18.0**	**3.4**

During the summer months (June, July, and August), the average hourly PV output of sun trackers is nearly 45% higher than that of fixed type. On the other hand, during the winter, the difference between the two systems in power generation is negligible. This result is similar to the findings of Tseng *et al.*, (2019) who report the single-axis-tracking PV system generation in the summer is about 15% higher than a fixed system, but in the spring, autumn, and winter there is little

Hour	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	SUM
0 . 1	-	-	-	-	-	-	-	-	-	-	-	-	-
1 . 2	-	-	-	-	-	-	-	-	-	-	-	-	-
2 . 3	-	-	-	-	-	-	-	-	-	-	-	-	-
3 . 4	-	-	-	-	-	-	-	-	-	-	-	-	-
4 . 5	-	-	-	-	0	2	0	-	-	-	-	-	2
5 . 6	-	-	-	5	29	35	24	12	1	-	-	-	106
6 . 7	-	2	38	104	156	161	139	122	104	51	10	-	887
7 . 8	58	123	217	291	343	352	330	320	321	277	183	79	2894
8 . 9	261	315	402	459	507	523	506	504	514	465	376	281	5113
9 . 10	399	462	543	583	622	642	637	639	648	592	511	411	6689
10 . 11	478	541	618	641	675	698	709	713	707	645	572	482	7479
11 . 12	492	554	632	643	667	693	721	719	692	620	570	484	7487
12 . 13	451	525	589	604	606	637	683	666	618	546	528	452	6905
13 . 14	397	456	525	545	541	586	624	600	535	464	438	386	6097
14 . 15	310	381	461	464	467	518	546	518	441	362	318	287	5073
15 . 16	194	258	319	343	363	405	429	402	324	226	155	135	3553
16 . 17	11	85	165	194	218	251	265	238	161	42	4	2	1636
17 . 18	-	1	12	40	65	86	93	62	8	-	-	-	367
18 . 19	-	-	-	0	3	9	10	2	-	-	-	-	24
19 . 20	-	-	-	-	-	-	-	-	-	-	-	-	-
20 . 21	-	-	-	-	-	-	-	-	-	-	-	-	-
21 . 22	-	-	-	-	-	-	-	-	-	-	-	-	-
22 . 23	-	-	-	-	-	-	-	-	-	-	-	-	-
23 . 24	-	-	-	-	-	-	-	-	-	-	-	-	-
SUM	**3051**	**3703**	**4521**	**4916**	**5262**	**5598**	**5716**	**5517**	**5074**	**4290**	**3665**	**2999**	**54312**

Fig. 7 Fixed-structure photovoltaic power output – hourly averages [Wh/kWp]

Hours	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	SUM	% change
0 . 1	-	-	-	-	-	-	-	-	-	-	-	-	-	
1 . 2	-	-	-	-	-	-	-	-	-	-	-	-	-	
2 . 3	-	-	-	-	-	-	-	-	-	-	-	-	-	
3 . 4	-	-	-	-	-	-	-	-	-	-	-	-	-	
4 . 5	-	-	-	-	-	1	-	-	-	-	-	-	**1**	**50%**
5 . 6	-	-	-	5	139	231	129	44	0	-	-	-	**548**	**517%**
6 . 7	-	-1	57	204	343	411	392	339	224	59	3		**2031**	**229%**
7 . 8	29	106	225	241	286	333	336	320	289	211	115	34	**2525**	**87%**
8 . 9	93	122	143	148	182	219	226	206	167	105	73	69	**1753**	**34%**
9 . 10	-6	17	38	54	84	113	117	90	39	-18	-45	-34	**449**	**7%**
10 . 11	-93	-69	-43	-13	16	38	36	4	-49	-99	-127	-116	**-515**	**-7%**
11 . 12	-129	-108	-81	-42	-11	6	-2	-35	-79	-115	-149	-143	**-888**	**-12%**
12 . 13	-116	-104	-72	-33	-1	13	3	-26	-57	-83	-119	-123	**-718**	**-10%**
13 . 14	-72	-61	-32	6	37	54	45	19	-4	-22	-46	-65	**-141**	**-2%**
14 . 15	-2	3	37	70	101	127	121	97	75	59	45	17	**750**	**15%**
15 . 16	69	82	118	149	189	225	223	203	180	146	84	55	**1723**	**48%**
16 . 17	-2	56	173	223	279	337	333	307	243	38	0	0	**1988**	**121%**
17 . 18	-	0	-1	58	158	379	286	159	0	-	-	-	**1039**	**283%**
18 . 19	-	-	-	-	0	-1	-1	0	-	-	-	-	**-2**	**-8%**
19 . 20	-	-	-	-	-	-	-	-	-	-	-	-	-	
20 . 21	-	-	-	-	-	-	-	-	-	-	-	-	-	
21 . 22	-	-	-	-	-	-	-	-	-	-	-	-	-	
22 . 23	-	-	-	-	-	-	-	-	-	-	-	-	-	
23 . 24	-	-	-	-	-	-	-	-	-	-	-	-	-	
SUM	**-229**	**43**	**562**	**1070**	**1802**	**2486**	**2244**	**1727**	**1028**	**281**	**-166**	**-306**	**10543**	**19%**
change, %	**-8%**	**1%**	**12%**	**22%**	**34%**	**44%**	**39%**	**31%**	**20%**	**7%**	**-5%**	**-10%**	**19%**	

Fig. 8 Solar tracker photovoltaic power output – hourly averages [Wh/kWp] and changes compared to Fixed-structure

difference in power output at the selected location in Taiwan. This is because in summer, the solar tracking system's solar radiation angle is smaller than that of the fixed system, and thus, power generation is higher than that of the fixed system. At midday, the main power generation period, occurs. Whereas the PV panel elevation of the solar tracking system is around 0 degrees at noon, the fixed system maintains a south tilt of 25 degrees all year long. When compared to the fixed type, at midday in the summer, the sun tracker is better, however, as the days began to shorten due to the angle, the disparity widened and power generation began to decline.

This result for the cold months is also aligned with similar research conducted by Muhammad Hamdi *et al.* (2019) in Indonesia to compare the performance of fixed and sun-tracking PV technology. Their results show that during the rainy season and at low ambient temperatures with high precipitation or cloudy weather like December 2017, fixed structures have 0.4% greater hourly PV output than one-axis trackers.

3.2. Power generation by technology and software simulation

All applications estimated yearly in-plane irradiation based on the technology (fixed/tracker) regardless of other parameters; the results are slightly different in each scenario as reposted in Table 3. A fixed system analysed using PVSyst and SolarGIS gets almost similar outputs for yearly in-plane irradiation while PVGIS generates the lowest amount of electricity. However, it is not the case with the tracker system, as PVGIS generates more electricity for yearly in-plane irradiation compared to SolarGIS, and PVSyst. All three simulation applications showed higher yearly in-plane output for the one-axis tracker in comparison to the fixed type.

Depending on the technology, annual electricity generation of the 1-X tracker is in a range of 1,481–1,644 MWh compared to 1,177–1,377 MWh for the PV with fixed axis, which is 20 to 30 per cent more. This is similar to the previous analysis conducted by Lewandoski *et al.* (2022), in which, to assess the difference in PV generation between PV plants in Brazil, a power plant consisting of two 300 kW on-grid power plants, one with a solar tracking system and the other with a fixed system, was used. They found that the plant that uses the solar tracker, achieved 30% greater generation compared to the fixed plant. In a similar vein, Tafazoli *et al.* (2023) concluded that the yearly production of a PV system equipped with a single-axis solar tracker is 16% higher than the fixed-base technology model. Another study that resulted in a similar conclusion found that the system with a horizontal axis tracker generates more electricity than the fixed-structure system by 18.32% (Andino García *et al.*, 2021).

The PV with fixed axis with 32% larger installed capacity generates between 1,558 and 1,789 Mwh a year which is only 3–10 per cent more than what PV with 1-X tracker generates. The slope angle is optimised by 14 and 28 degrees using SolarGIS for the tracker and the fixed structure, and 32 and 30 using PVGIS. Azimuth angle is also optimised using SolarGIS at 116 and 180 degrees for the tracker, and the fixed structures, respectively Specific photovoltaic power output, a critical factor for the cash-flow calculations, is estimated using SolarGIS for 1976 and 1,653 kWh/kWp for the tracker and the fixed structures.

3.3. Cash-flow results

The electricity production of a PV system depends on the available solar potential and the type (or efficiency) of the solar

Table 3
Power generation by technology and software simulation

Technology (installed power)	Simulation application	Yearly in-plane irradiation (kWh/m2)	Optimum slope angel (degree)	Optimum Azimuth angel (degree)	Specific photovoltaic power output (kWh/kWp)	Yearly energy production (MWh)	Yearly PV energy injected to grid (MWh)	System loss (%)	Total loss (%)	Performance ratio (%)
1-X tracker (781 kWp)	SolarGIS	2409	14	116	1976	1481	N/A	-13.8	N/A	80.8
	PVGIS-5	2505	32	N/A	N/A	1514	N/A	-14	-22.61	N/A
	PVSyst	2330	0	0	N/A	1644	1624	-13.3	N/A	89.2
Fixed axis (781 kWp)	SolarGIS	2022	28	180	1653	1235	N/A	-13.8	N/A	80.9
	PVGIS-5	1959	30	-17	N/A	1177	N/A	-14	-23.05	N/A
	PVSyst	2057	25	0	N/A	1377	1301	-16.3	N/A	80.9
Fixed axis (1034 kWp)	SolarGIS	2022	28	180	1653	1634	N/A	-13.8	N/A	80.9
	PVGIS-5	1959	30	-17	N/A	1558	N/A	-14	-23.05	N/A
	PVSyst	2057	25	0	N/A	1789	1722	-16.2	N/A	82.3

Table 4
Cash-flow model result

Technology (installed power)	Photovoltaic power output (kWh/kWp)	Opex cost (EUR)/year	Total Capex cost (EUR)	Leverage Ratio	Equity IRR (%)	Payback period (year)	NPV (EUR)	LCOE (EURc/kWh)
1-X tracker (781)	1976	11,715	898,150	Unlevered	9.5	10.1	124,520	3.9
				30%	11.1	9.2	128,896	4.0
				50%	12.9	8.6	175,107	5.4
				70%	15.9	7.3	220,816	6.9
				85%	21.2	5.9	254,885	7.9
Fixed axis (781)	1653	7,800	835,670	Unlevered	8.1	11.0	-28,497	N/A
				30%	9.4	9.9	134,570	5.0
				50%	10.7	8.9	182,674	6.8
				70%	12.8	7.6	225,673	8.4
				85%	16.2	6.4	272,980	10.1
Fixed axis (1034)	1653	10,340	1,106,380	Unlevered	8.4	10.8	-14,323	N/A
				30%	9.7	9.8	146,924	4.1
				50%	11.1	9.2	224,640	6.3
				70%	13.5	7.8	247,935	7.0
				85%	17.1	6.3	287,960	8.1

PV modules. A cash flow calculation was conducted using the given assumptions from Table 1 and simulated data on the three possible projects reported in Table 3 to find the most cost-effective scenario.

The cash-flow model is run for each scenario to get the equity IRR, the payback period, NPV, and LCOE, see Table 4 for these results. We assume four leverage ratios (30%, 50%, 70%, and 85%) plus a scenario with no leverage for SolarGIS with 1-X tracker and PV with fixed axis with the same and 32% larger installed capacity, see Table 4 for the results.

The analysis shows that a one-axis tracker PV system is economically feasible, with or without a loan. It generates the highest equity IRR in all leverage levels and the shortest payback period, even though this is not the cheapest project in terms of capital expenditure (CAPEX) and operating costs (OPEX). In contrast, a PV system with a fixed axis system with a total installed capacity of 781 kWp is the cheapest project to build and operate but it also generates the lowest equity IRR and requires the longest loan payback period. Recent projects are not economically feasible when this project is funded from own resources (i.e. loan = 0). However, all leveraged options above 30% make this option economically feasible.

Using a fixed axis system with a total installed capacity of 1,034 kWp utilises the entire site and is the most expensive project to build. The unleveraged scenario is not feasible. Leveraged options exceeding 30% of the total cost, generate less revenue than the tracker system, and are superior to the fixed system, with an installed capacity of 781 kWp.

LCOE in all scenarios is profitable and financially feasible in this market. We also found that the sun tracker results in the lowest LCOE, regardless of the leverage ratio. LCOE for the sun-tracker PV for unleveraged case and with 85% leverage rate is 3.9, and 7.9 €cents/kWh, respectively. LCOE for a PV with fixed axis are up to 10.1€cents/kWh (781 kWp) and 8.1 €cents/kWh (1034 kWp) that corresponds to 85% leverage rate, see Table 3. LCOE in all scenarios are still below the highest acceptable level for a solar PV project in Cyprus that is 10.3 €cents/kWh (Al-Ghussain *et al*., 2018). Our result is similar to the findings of Hassan and Garni (2017) who concluded the photovoltaic systems with vertical or dual-axis solar trackers provide a lower LCOE than fixed-structure systems. Comparing fixed structures in terms of LCOE, projects with 1,034 kWp deliver better results, and the reason is a higher amount of production, despite the higher project cost.

Equity IRR, LCOE, and NPV are increased in all scenarios by increasing the leverage ratio. This means that even though the increased share of the loan will result in a higher equity IRR and is preferred by investors, they should, at the same time, consider their project will get a higher LCOE. The effect of increasing the leverage ratio on LCOE is more prevalent in the case of Fixed 781 kWp, Fixed 1,034 kWp (and also 1-X tracker 1,034 kWp, the model results not shown in this paper). This means that by utilising more loan, LCOE will be higher for the fixed structure system than for the tracker system of comparable size. Furthermore, it will be even more affected when the project is smaller. This is more noticeable when comparing PV power plants with other power generators using different technology or energy sources, which is not the case in this study.

According to the literature, utility-scale PV projects using bifacial panels and single-axis trackers have the lowest LCOE in the majority of the world. They also found that combining bifacial products with dual-axis trackers is still too expensive despite the higher yield. The second lowest LCOE is offered by monofacial single-axis tracker plants (Awasthi *et al*., 2020; Parrado *et al*., 2016; Rodriguez *et al*., 2020).

3.3. Social benefits

Assuming the emission factors and carbon footprint and damage factors as described in Section 2.6, central value of carbon damage, and assuming 8.5% discount rate, we get the present value of net benefits at 1.39 mil. EUR for a sun-tracker, 1.17 mil. EUR for a fixed tracker of the same capacity and 1.54 mil. EUR for a fixed tracker with larger capacity. Due to a high irradiation carbon footprint of PV power output represents only 6% of footprint of generating electricity in thermal power plants in Cyprus. Benefits associated with abatement of carbon emissions are high enough to justify social desirability all of these options.

Comparing the two tracking options with the same size (781 kW), a sun-tracker's benefits exceed a fixed tracker's benefits by 228,000 EUR (assuming central value of carbon damage, all in EUR present values, over the whole lifetime). Since the largest difference in NPVs for the two options is about 18,000 EUR pro the fixed tracker (with 85% leverage), accounting for carbon benefits makes the sun-tracker economically better option over the fixed tracker.

Benefits delivered by the fixed tracker with larger capacity exceed benefits of a sun-tracker with smaller size by about 150,000 EUR. Naturally, the larger PV system, the more carbon emission released by alternative thermal power plants are avoided and hence the larger benefits.

Table 5
Benefits due to avoided carbon emissions for 27-years lifetime, present value, in thousands EUR

	Avoided emission from thermal power plants			Carbon footprint of PV		
	1-X tracker (781 kW)	Fixed axis, (781 kW)	Fixed axis (1034 kW)	1-X tracker (781 kW)	Fixed axis, (781 kW)	Fixed axis (1034 kW)
EC et al. (2020)						
low value	873	730	967	-52	-44	-58
central value	1,483	1,240	1,642	-89	-74	-99
high value	2,770	2,317	3,068	-166	-139	-184
WEO NZE (EC 2022)	976	817	1,081	-59	-49	-65

Note: Central value of climate change impacts is assumed to be € 100 per t $CO_{2eq.}$ and € 269 per t CO_{2eq} from 2031, with low and high values at € 60 and € 189 (till 2030), and € 156 and € 498 (from 2031), respectively, all in $€_{2016}$. WEO NZE corresponds to the projected EUA price in a range of 79–220 EUR, see Section 3.

4. Conclusion

This study conducted a financial analysis of a photovoltaic power plant utilising a single-axis sun-tracking and fixed-axis mechanism in central Cyprus, Nicosia. We show that using a one-axis solar tracking system in a PV power project in Cyprus is technically and financially feasible. The outcomes revealed that the solar tracking system produces 20% to 30% more energy compared to a fixed structure. Despite higher investment costs, it offers better financial performance, such as equity IRR, payback period, and LCOE. Moreover, in the case of a total equity investment, a one-axis PV system results in the lowest LCOE, that is in this study 3.9 €cents/kWh. Solar tracker yields 12% more equity IRR compared to the same installed power of fixed structure and a 9% shorter loan payback period.

For future research, we recommend calculating and comparing Value Adjusted LCOE (VLCOE) when LCOE is a priority in choosing the preferred power generator. Cost of Valued Energy (COVE) considers time-dependent electricity prices that is recommended to design and value next-generation renewable energy systems, including storage integration trade-offs (Loth *et al.*, 2022) is another valuation metric that can be applied in the future.

Furthermore, even though most of the data was collected from a real case, due to the limitations of accessing data from operational power plants, simulated data (i.e., irradiation) are extracted from globally known applications, and because the majority of them are the same in both alternatives, they cannot affect the results of the targeted comparison. We suggest this research be repeated using all real data collected from operating projects (not simulated) to figure out how it may change the results of the comparison.

In Cyprus, there is no operational PV park that uses solar tracker technology. Solar tracker systems are widely available on the market and can be easily purchased and used in such projects. However, technology-wise, the most important limitation is facing more difficulties during the operation phase. Compared to a fixed structure, as there are moving parts in the solar tracker, it might be necessary to hire a more skilled operation team and implement more precise maintenance activities. To reflect the necessity of higher quality operation and maintenance, using other market experiences, we assumed an overall annual operation cost of €10K/MW in the case of a fixed structure and €15K/MW for a tracker system. Therefore, we believe this is a simple and easy mitigation scenario to lift the effects of this limitation.

Regarding the case country, Cyprus has been selected as an EU country with clear targets in green energy production and attractive investment plans in this field on the one hand, and on the other hand, the solar tracker technology is unknown and has never been used in this country. Results could be broadened to other similar markets.

The main result of this work is to advise developers and investors in the photovoltaic energy sector to modernise their project plans by using solar tracker systems in Cyprus as a case study and other comparable areas. Such technology should be introduced to developers, investors, and relevant authorities to be implemented. By publishing this article, we hope that investors and developers in the field of renewable energy production will begin to consider using solar tracker systems in their upcoming projects.

Author Contributions: AEG: Conceptualization, methodology, formal analysis, project administration, writing—original draft, MŠ: supervision, conceptualisation, formal analysis (CBA), resources, review and editing, validation. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by The Prague University of Economics and Business, grant number F1/62/2020".

Conflicts of Interest: The authors declare no conflict of interest.

References

Abdallah, S. (2004). The effect of using sun tracking systems on the voltage–current characteristics and power generation of flat plate photovoltaics. *Journal of Energy Conversion and Management*, 45 (11-12),1671–1679. https://doi.org/10.1016/j.enconman.2003.10.006

AL-Rousan, N., Ashidi Mat N., Mat Desa, Kh. (2018) Advances in solar photovoltaic tracking systems: A review, *Renewable and Sustainable Energy Reviews,* 82(3), 2548-2569. https://doi.org/10.1016/j.rser.2017.09.077

Al-Ghussain, L., Abujubbeh, M., & Fahrioglu, M. (2018). Assessment of PV investment in Northern Cyprus. *16th International Conference on Clean Energy (ICCE-2018),* 9-11 May 2018, Famagusta, N. Cyprus. https://doi.org/10.1109/gpecom.2019.8778550

Ameur, A., Berrada, A., Loudiyi, K., Aggour, M., (2020) Forecast modeling and performance assessment of solar PV systems. *J. Clean. Prod.* 267, 122167. https://doi.org/10.1016/j.jclepro.2020.122167

Aquino Larico, E. R., & Gutierrez, A. C. (2022). Solar Tracking System with Photovoltaic Cells: Experimental Analysis at High Altitudes. *International Journal of Renewable Energy Development*, 11(3), 630-639. https://doi.org/10.14710/ijred.2022.43572

Asiabanpour, B., Almusaied, Z., Aslan, S., Mitchell, M., Leake, E., Lee, H., Fuentes, J., Rainosek, K., Hawkes, N., Bland, A. (2017). Fixed versus sun tracking solar panels: An economic analysis. *Clean Technol. Environ. Policy.* 19, 1195–1203. https://doi.org/10.1007/s10098-016-1292-y

Awasthi, A., Kumar, A., Manohar, M., Dondaria, C., Shukla, K. N., Porwar, D., & Richhariya, P. (2020). Review on sun tracking technology in solar PV system. *Journal of Energy Reports*, 6, 392-405. https://doi.org/10.1016/j.egyr.2020.02.004

Bahrami, A., Okoye, CO., & Atikol, U. (2017). Technical and economic assessment of fixed, single and dual-axis tracking PV panels in low latitude countries. *Renewable Energy,* 113, 563-576. https://doi.org/10.1016/j.renene.2017.05.095

Baouche, F.Z., Abderezzak, B., Ladmi, A., Arbaoui, K., Suciu, G., Mihaltan, T.C., Raboaca, M.S., Hudisteanu, S.V., Turcanu, F.E. (2022). Design and Simulation of a Solar Tracking System for PV. *Applied Science*, 12, 9682. https://doi.org/10.3390/app12199682

Batac, K. I. T., Collera, A. A., Villanueva, R. O., & Agaton, C. B. (2022). Decision Support for Investments in Sustainable Energy Sources Under Uncertainties. *International Journal of Renewable Energy Development,* 11(3), 801-814. https://doi.org/10.14710/ijred.2022.45913

Berisha, X., Zeqiri, A., & Meha, D. (2018). Determining the Optimum Tilt Angles to Maximise the Incident Solar Radiation - Case of Study Pristina. *International Journal of Renewable Energy Development*, 7(2), 123-130. https://doi.org/10.14710/ijred.7.2.123-130

Boehm, S., L. Jeffery, K. Levin, J. Hecke, C. Schumer, C. Fyson, A. Majid, J. Jaeger, A. Nilsson, S. Naimoli, J. Thwaites, E. Cassidy, K. Lebling, M. Sims, R. Waite, R. Wilson, S. Castellanos, N. Singh, A. Lee, and A. Geiges. 2022. State of Climate Action (2022). Berlin and Cologne, Germany, San Francisco, CA, and Washington, DC: Bezos Earth Fund, Climate Action Tracker, Climate Analytics, ClimateWorks Foundation, NewClimate Institute, the United Nations Climate Change High-Level Champions, and World Resources Institute. https://doi.org/10.46830/wrirpt.22.00028 .

De Wild Scholten M., Cassagne V., Huld T. (2014), Solar Resources and Carbon Footprint of Photovoltaic Power in Different Regions in Europe. In Conference Proceedings: Proceedings of the 29th EUPVSEC. Munich (Germany): WIP, 3421-3430. JRC89270. https://doi.org/10.1016/j.solmat.2013.08.037

Dehnhardt, A., Grothmann, T., Wagner, J. (2022), Cost-benefit analysis: What limits its use in policy making and how to make it more usable? A case study on climate change adaptation in Germany, *Environmental Science and Policy* 137, 53–60. https://doi.org/10.1016/j.envsci.2022.08.005

Ebenhoch, R., Matha, D., Marathe, S., Muñoz, P.C., Molins, C. (2015), Comparative Levelized Cost of Energy Analysis, *Energy Procedia,* 80, 108 – 122. https://doi.org/10.1016/j.egypro.2015.11.413

Ebhota, W. S., and Tabakov, P. Y. (2022). Impact of Photovoltaic Panel Orientation and Elevation Operating Temperature on Solar Photovoltaic System Performance. *International Journal of Renewable Energy Development,* 11(2), 591-599. https://doi.org/10.14710/ijred.2022.43676

El Hammoumi, A., Chtita, S., Motahhir, S., El. Ghzizal, A. (2022) Solar PV energy: From material to use, and the most commonly used techniques to maximise the power output of PV systems: A focus on solar trackers and floating solar panels, *Energy Reports* 8,11992–12010. https://doi.org/10.1016/j.egyr.2022.09.054

Eke, R., & Senturk, A. (2012). Performance comparison of a double-axis sun tracking versus fixed PV system. *J. of Solar Energy*, 86, 2665-2672. https://doi.org/10.1016/j.solener.2012.06.006

European Commission, Directorate-General for Mobility and Transport, Essen, H., Fiorello, D., El Beyrouty, K. (2020). Handbook on the external costs of transport : version 2019 – 1.1, Publications Office. https://data.europa.eu/doi/10.2832/51388

Fan, L., Gu, B., & Luo, M. (2020). A cost-benefit analysis of fuel-switching vs hybrid scrubber installation: A container route through the Chinese SECA case. *J. of Transport Policy*, 99, 336-344. https://doi.org/10.1016/j.tranpol.2020.09.008

García, H. A. , Duke, A. R., and Flores, H.Y. (2020) Techno-economic comparison between photovoltaic systems with solar trackers and fixed structure in “El Valle de Sula” , Honduras, 6th International Conference on Advances in Environment Research, *IOP Conf. Ser.: Earth Environ. Sci.* 776 012011. https://doi.org/10.1088/1755-1315/776/1/012011

Gönül, Ö., Yazar, F., Duman, A.C., Güler, Ö. (2022) A comparative techno-economic assessment of manually adjustable tilt mechanisms and automatic solar trackers for behind-the-meter PV applications. *Renew. Sustain. Energy Rev.* 168, 112770. https://doi.org/10.1016/j.rser.2022.112770

Guno, C. S., Agaton, C. B., Villanueva, R. O., & Villanueva, R. O. (2021). Optimal Investment Strategy for Solar PV Integration in Residential Buildings: A Case Study in The Philippines. *International Journal of Renewable Energy Development,* 10(1), 79-89. https://doi.org/10.14710/ijred.2021.32657

Hafez, A.Z., Yousef, A.M., Harag, N.M. (2018), Solar tracking systems: Technologies and trackers drive types – A review, *Renewable and Sustainable Energy Reviews,* 91, 754-782,. https://doi.org/10.1016/j.rser.2018.03.094

Hassan, M.U., Saha, S., Haque, M. E. (2021). PVAnalytX: A MATLAB toolkit for techno-economic analysis and performance, evaluation of rooftop PV systems. *Energy,* 223, 120074. https://doi.org/10.1016/j.energy.2021.120074 .

Hassan Al Garni, A. A. (2017). Techno-Economic Feasibility Analysis of a Solar PV GridConnected System with Different Tracking Using HOMER Software. August 2017, *Engineering2017 IEEE International Conference on Smart Energy Grid Engineering (SEGE).* https://doi.org/10.1109/sege.2017.8052801

Heysela, C. S., Filion, Y. R., (2014), Estimating the payback period of in-line micro turbines with analytical probabilistic models, *Procedia Engineering,* 70, 815 – 822. https://doi.org/10.1016/j.proeng.2014.02.089

Huang, B., Huang, Y., Chen, G., Hsu, P., & Li, K. (2013). Improving solar PV system efficiency using one-axis 3-position sun tracking. *Energy Procedia,* 33, 280–287. https://doi.org/10.1016/j.egypro.2013.05.069

EIB (2023), EIB Project Carbon Footprint Methodologies. Methodologies for the assessment of project greenhouse gas emissions and emission variations - Version 11.3 (January 2023), European Investment Bank, Luxembourg, 2023. https://doi.org/10.11129/detail.9783955531713.17

IPCC. 2022. Climate Change 2022: Mitigation of Climate Change—Contribution of Working Group III to the Sixth Assess ment Report of the Intergovernmental Panel on Climate Change. Edited by P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. vanDiemen, D. McCollum, . Cambridge: Cambridge University Press. https://doi.org/10.1017/cbo9781107415416

IRENA. 2022. Renewable Capacity Statistics 2022. Abu Dhabi: The International Renewable Energy Agency. https://doi.org/10.47556/j.ijikmmena.2.2.2013.2

Jose, P.J., Akbari, P., Dhokiya, J., Ajmera, Z., Pandya, V., Jani, Y.N., Ravalia, A., Keshvani, MJ. (2022), Solar tracking: The best alternative to obtain more solar power output, *Materials Today: Proceedings,* 67(6), 921-926. https://doi.org/10.1016/j.matpr.2022.08.065

Kassem, Y., Al-Zoubi, R., Gökçekuş, H. (2019) The Possibility of Generating Electricity Using Small-Scale Wind Turbines and Solar Photovoltaic Systems for Households in Northern Cyprus: A Comparative Study. *Environ.* 6(4), 47. https://doi.org/10.3390/environments6040047

Kassem,Y., Çamur, H. and Awadh Alhuoti, S.M. (2020), Solar Energy Technology for Northern Cyprus: Assessment, Statistical Analysis, and Feasibility Study, *Energies*, 13, 940; https://doi.org/10.3390/en13040940

Khadidjaa, B., Drisa, K., Boubekerb, A., & Noureddinec, S. (2014). Optimisation of a solar tracker system for photovoltaic power plants in Saharian region, example of Ouargla. *J. of Energy Procedia*, 50, 610 – 618. https://doi.org/10.1016/j.egypro.2014.06.075

Khamharnphol, R., Kamdar, I., Waewsak, J., Chiwamongkhonkarn, S., Khunpetcha, S., Kongruang, C., & Gagnon, Y. (2023). Techno-Economic Assessment of a 100 kWp Solar Rooftop PV System for Five Hospitals in Central Southern Thailand. *International Journal of Renewable Energy Development,* 12(1), 77-86. https://doi.org/10.14710/ijred.2023.46864

Lewandoski, C., F., Santos, R., F., Sio, J., P., M., K., da Costa Canfild, D., do Carmo, M., B., da Silva, F., M., Siqueira, J., de Oliveira, W., Ikpehai, A., Romeu, R. (2022). Study of the Efficiency of the Solar Tracker System compared to the Fixed Solar Generation System. *Research, Society and Development*. 11. e6711628671. https://doi.org/10.33448/rsd-v11i6.28671

Loth, E., Qin, C., Simpson, J., G., Dykes, K. (2022), Why we must move beyond LCOE for renewable energy design, *Advances in Applied Energy*, 8, 100112. https://doi.org/10.1016/j.adapen.2022.100112

Lopez-Prol, J. and Steininger, K.W. (2020) Photovoltaic self-consumption is now profitable in Spain: Effects of the new regulation on prosumers’ internal rate of return, *Energy Policy*, 146. https://doi.org/10.1016/j.enpol.2020.111793

Lu, Z., Hasselström, L., Finnveden, G., Johansson, N. (2022), Cost-benefit analysis of two possible deposit-refund systems for reuse and recycling of plastic packaging in Sweden, *Cleaner Waste Systems,* 3, 100048. https://doi.org/10.1016/j.clwas.2022.100048

Hamdi, B.R.D.M., Dewi, T., Rusdianasari, R. (2019), Performance Comparison of 3 Kwp Solar Panels Between Fixed and Sun Tracking in Palembang – Indonesia, *6th International Conference on Sustainable Agriculture, Food and Energy*. 347, 012131. https://doi.org/10.1088/1755-1315/347/1/012131

Ouria, M. and Sevinc, H. (2018), Evaluation of the potential of solar energy utilisation in Famagusta, Cyprus, *Sustainable Cities and Society,* 37, 189-202. https://doi.org/10.1016/j.scs.2017.10.036

Marcel, S. and Tomáš, C. (2012) SolarGIS: New web-based service offering solar radiation data and PV simulation tools for Europe, North Africa and Middle East. *Eurosun2012*. https://doi.org/10.18086/eurosun.2010.13.21

Moradi, H., Abtahi, A., & Messenger, R. (2016). Annual performance comparison between tracking and fixed photovoltaic arrays. *2016 IEEE Conference on Photovoltaic Specialists, Portland,* US. https://doi.org/10.1109/pvsc.2016.7750252

Nsengiyumva, W., Chen, S.G., Hu, L., Chen, X. (2018). Recent advancements and challenges in Solar Tracking Systems (S.T.S.): A review. *Renew. Sustain. Energy Rev.* 81, 250–279. https://doi.org/10.1016/j.rser.2017.06.085

Parrado, C., Girard, A., Simon, F., Fuentealba, E. (2016) 2050 LCOE (levelized cost of energy) projection for a hybrid PV (photovoltaic)-CSP (concentrated solar power) plant in the Atacama Desert, Chile. *J. of Energy*, 94, 422-430. https://doi.org/10.1016/j.energy.2015.11.015

Poullikkas, A. (2009). Parametric cost-benefit analysis for the installation of photovoltaic parks in the island of Cyprus. *J. of Energy Policy*, 37(9), 3673-3680. https://doi.org/10.1016/j.enpol.2009.04.037

Rečka, L., Máca, V., Ščasný, M. (2023). Green Deal and Carbon Neutrality Assessment of Czechia. *Energies* 16, (5), 2152. https://doi.org/10.3390/en16052152

Rodrıguez-Gallegos, C., Liu, H., Gandhi, O., Prakash, Singh J., Krishnamurthy, V., Kumar, A., S. Stein, J., Wang, S., Li, L., Reindl, T., & Marius Peters, J. (2020). Global techno-economic performance of bifacial and tracking photovoltaic systems. *Joule*, 4(7), 1514–1541. https://doi.org/10.1016/j.joule.2020.05.005

Sadat-Mohammadi, M., Nazari-Heris, M., Nafisi, H., Abedi, M., (2018), A Comprehensive Financial Analysis for Dual-Axis Sun Tracking System in Iran Photovoltaic Panels, *2018 Smart Grid Conference (SGC)*. https://doi.org/10.1109/sgc.2018.8777900

Salas, I.V., Grases, M., Débor, P., Espadas,C., Grases, C., E. Olías, (2010).Comparison between two 1 kW PV Grid-Connected Systems (One with a new tracker and one fixed). *IEEE Photovoltaic Specialists Conference* Spain. https://doi.org/10.1109/pvsc.2010.5744148

Solar Power World (2016), Advantages and disadvantages of a solar tracker system. *SPW.* Accessed on May 9, 2016. https://doi.org/10.1016/b978-0-323-88499-0.00001-x

Shufat, S. A. A., Kurt, E., & Hancerlioğulları, A. (2019). Modeling and Design of Azimuth-Altitude Dual Axis Solar Tracker for Maximum Solar Energy Generation. *International Journal of Renewable Energy Development*, 8(1), 7-13. https://doi.org/10.14710/ijred.8.1.7-13

Tafazoli, M., Salimi, M., Zeinalidanaloo, S., Mashayekh, J., Amidpour, M. (2023). Techno-Economic Analysis of Electricity Generation by Photovoltaic Power Plants Equipped with Trackers in Iran. *Energies*, 16, 235. https://doi.org/10.3390/en16010235

Talavera, D.L., Muñoz-Cerón, E., Ferrer-Rodríguez, J.P., Pérez-Higueras, P.J. (2019). Assessment of cost-competitiveness and profitability of fixed and tracking photovoltaic systems: The case of five specific sites. *Renew. Energy*, 134, 902–913. https://doi.org/10.1016/j.renene.2018.11.091

Tarigana, E., Djuwaria, Purbab, L. (2014) Assessment of PV Power Generation for Household in Surabaya Using SolarGIS–pvPlanner Simulation, *Energy Procedia* 47, 85 – 93. https://doi.org/10.1016/j.egypro.2014.01.200

Tseng, K. H., Wang, Ch. Y., Lin, G-H., (2019), Effect of the Sun Elevation for Fixed PV System and Single-Axis-Tracking PV System. *IEEE 6th International Conference on Industrial Engineering and Applications (ICIEA),* Tokyo, Japan, 2019, pp. 805-809, doi: 10.1109/IEA.2019.8714782.https://doi.org/10.1109/iea.2019.8714782