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Impact of both One- and Two-axis Solar Tracking on the Techno-Economic Viability of On-Grid PV Systems: Case of the Burnoye-1 Power Plant, Kazakhstan

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ABSTRACT

Kazakhstan is committed to developing its renewable energy resources. In 2012, the government introduced a low-carbon energy strategy to reduce the production of air pollutants, including anthropogenic CO_{2e}, and to increase the share of clean energy up to 50% of total consumption by 2050. As a contribution to this strategy, the techno-economic performance of the fixed-slope on-grid Photovoltaic (PV) power plants in Kazakhstan and both the one- or two-axis solar tracking systems solar parks are compared. The aim is to determine to what extent the more effective but more expensive tracking systems might be a suitable standard in future PV power stations in the country. For this purpose, the existent fixed-slope 50 MWp Burnoye-1 commercial solar power plant located in the Jambyl region, Kazakhstan, is used as a benchmark. As expected, solar panels with tracking systems produce more electricity year-round compared to those with fixed slopes; one- and two-axis tracking systems led almost to the same amount of electricity export to the grid. Furthermore, PV power stations with one- and two-axis tracking technology could reduce CO_2 emissions by approximately 10 ktCO_{2e} per year. However, using one or two-axis tracking systems lead to an increase in the ratio of extra-cost to extra-energy production of around 26% and 33%, respectively. Moreover, that means that both tracking scenarios are not economically competitive compared to fixed panels. Nevertheless, if a tracking system has to be considered, the results of this work demonstrate that one-axis tracking should be preferred as they reduce GHG emissions while having a higher electricity generation compared to the fixed system.

Keywords:

RETScreen;
Burnoye-1;
Solar tracking systems;
Photovoltaic;
Kazakhstan 2050;
Clean Technologies;

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1. Introduction

Kazakhstan is the ninth largest country by size and the biggest in central Asia, with more than 18 million inhabitants as of 2019. In 2013, First President Nursultan Nazarbayev signed the “Concept for Transition of the Republic of Kazakhstan to Green Economy,” where special mention was made to the importance of carbon emissions reduction [1]. Moreover, one of the main reasons for the onset of the transition was that 75% of the total power generated in Kazakhstan is coming from coal-fired plants, which lead to high CO_{2e} emissions [2]. After that, many incentives have been approved in current policies. Nowadays, renewable energy has become an appealing option for investors, as they can invest in producing heat and power while reducing local air pollution and greenhouse gas emissions.

Moreover, one of the main renewable sources nowadays is solar energy. As researchers from MIT university state, solar energy usage and production have increased 300X in the last 20 years [3]. That became possible

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because the cost of solar power decreased thanks to the development of new advanced technology and more efficient panels. Furthermore, governmental regulations, together with adjusted policy standards and subsidies, played a significant role in both cost decrease and enhancement of solar energy production [3].

In addition, Kazakhstan has an immense potential to develop solar power projects due to climate conditions. Furthermore, Kazakhstan's annual irradiance reaches 1200–1700 kWh/m^2, mainly in the south region of the country, where solar irradiance is abundant all-year-round [4]. Photovoltaic (PV) systems are a very convenient and popular power source to consider in Kazakhstan, given a large number of silicon resources and local production of PV panels [5]. Additionally, current national green tariffs and subsidies favor renewable energy projects in the country [6]. In general, the Kazakhstan electricity market includes a retail and wholesale type of market. Additionally, it involves organizations that can purchase electricity from power generators. In this case, power generating organizations sell electricity at the wholesale market only if those organizations satisfy specific criteria. Moreover, power generating organizations connect to the national power grid and regional electric network; however, in both cases, contracts with the main system operator need to be made. The system operator across Kazakhstan is KEGOC JSC, which is at the Order of the Ministry of Energy. In addition, another option to buy electricity is consolidated auctions that resale power to the end-users. Consumers, in their turn, purchase electricity at the decentralized regional markets with conditions stated in the Civil code [7].

On-grid green power systems are favored with a high Feed-in-Tariff (FiT), which is supported and indexed by the government for 15 years, in accordance with international practices. Moreover, in Kazakhstan, the Feed-in-Tariff is around 34.61 KZT/kWh (0.103 USD/kWh) for solar power plants, while it is 8.65 KZT/kWh for coal-fueled power plants (0.026 USD/kWh) [5]. Furthermore, the government, with the help of the European Bank for Reconstruction and Development (EBRD), supports and provides debt financing to renewable energy projects on a competitive basis, and it launched Kazakhstan's Renewable Energy Financing Facility [5].

The Burnoye, which is the location of the present case study, is situated in the southern region (Jambyl) of Kazakhstan and has an average monthly temperature of –13.7 during January and 22.9 during July [8]. In 2015, this location was chosen for the construction of the 50 MWp Burnoye Solar-1 solar PV power plant, based on fixed panels. As of today, Burnoye-1 generates around 0.1% of the total electricity production in Kazakhstan [5]. This investigation aims to determine whether the installation of one- and two-axis solar tracking systems provide higher electricity generation and reduce GHG emission compared to fixed PV panels with the same capacity, as well as determine if the not fixed panels are a more attractive long-run investment for the country. Furthermore, this work compares the financial yield between one- and two-axis tracking mechanisms to determine which one would produce more considerable benefits for shareholders of this and future projects in the region.

2. Literature Review

Decreasing the carbon footprint and using renewable energies have arisen as a modern trend due to the obvious benefits of green technologies [35]. Moreover, the United Nations (UN) has been a promoter of this trend, as one of its sustainable development goals (SDG) aims to increase the production of clean energies, as well as make them more affordable by 2030.

For example, Nigeria is collaborating toward this SDG and is improving solar power generation across the country, which currently relies over 50% on expensive and private self-generation of power based on petrol and diesel. The socio-economic growth of Nigeria drives its increasing energy demand, while facing an unstable national power grid with no immediate option but increasing self-generation [35]. Nevertheless, the popularity of PV panels has been increasing in Nigeria as a result of decreased cost, technological innovations, positive public perception, promotional strategies, and subsidies provided by global and governmental entities [35].

Solar PV arrays can be installed on the rooftop of a residential building, and it has been proved that PV panels could be installed in large areas with no additional features such as controlling and monitoring equipment, thus reducing significantly its cost of operation compared to conventional power sources [36]. Two residential buildings in Sweden with available rooftops were taken for that case study. Installed solar PV generated eight times more energy compared with the total annual consumption of both buildings. However, sometimes those large-size PV installations caused overvoltages, and although the local grid connecting these two buildings could handle it, in the case of a single house installation, it could be an issue [36].

Renewable energy sources (RES) offer many benefits, and there are many alternative power systems nowadays, which may bring uncertainty to decision-makers since their primary aim is to reach the maximum possible potential of the system [37]. Moreover, RES-based electricity generation offers several advantages, such as low operational costs and being green and renewable energy sources, which positively decrease CO_2 emissions, as well as increase cost savings and have a low marginal cost of energy production.

- Some solutions for the integration of RES with the utility grid are:
- Smart Grid Systems for RES, which show advantages in better resiliency, quality and reliability of delivered power;
- Micro-Grid, which can operate as a fully sustainable generation plant;
- Energy Storage Systems (ESS), which provide better distribution in power peak demands;
- Advanced Forecasting;
- Flexibility in power generation [37].

Furthermore, Tarabsheh and Etier [9] investigated the possibility of using solar energy at Hashemite University, located in Jordan, by determining the optimum slope and angle of the solar panels on an hourly basis for the whole year period. Their work proved the cost-effectiveness of the tracking systems and showed that energy production increases to nearly 6% for the one-axis tracking system, while in the case of the two-axis system, energy production increases about 31% when compared with fixed systems [9].

Garni et al. [10] followed a similar aim but analyzing the best tracking system in terms of technical and financial feasibility for a PV system in Makkah, Saudi Arabia. Seven different tracking systems were studied, demonstrating that two-axis tracking systems might generate up to 34% more electricity in that particular location [10]. In addition, Drury et al. [11] found that in the USA both the one-axis and two-axis tracking of photovoltaic panels may increase electricity generation by 12-25% and 30-45% compared to south-facing fixed PV systems, respectively. Moreover, Garni et al. also found that solar panels installed with tracking systems produced more electricity in arid regions such as the western and southwestern USA compared to regions with persistent snow or cloud cover [11].

Moreover, the effectiveness of tracking systems varies significantly depending on climate and location, more specifically, according to solar horizontal irradiance and distance between the sun and the PV panels [12]. For example, tracking systems promote more significant PV electricity generation in arid areas than in humid regions [12]. Furthermore, a study conducted at Mugla University campus in Turkey found that the implementation of two-axis solar tracking systems in PV plants increased the electricity production in more than 30% compared to fixed PV panels, using similar modules and inverters in both cases [13]. Likewise, Filik et al. [12] found that the average total electricity generation increase with the tracking system is around 33% compared to fixed PV panels with the same capacity for their selected region in northern Turkey. For colder places, such as Berlin (Germany), the amount of total electricity production by a PV system may increase by nearly 39% with solar trackers; however, in warmer cities such as Aswan (Egypt), the increase may reach only around 8%. Furthermore, Almarshoud [14] found that in Saudi Arabia, the difference in produced energy between the one-axis and two-axis tracking cases is only 3–4.5%, while between the fixed and one-axis cases, this value equals to 28–33%. Additionally, it is important to notice that the tracking system might consume 5–10% of the generated electricity [15]. Therefore, an accurate life-cycle cost analysis must consider the amount of electricity used by tracking motors, as well as the initial cost of the tracking system.

Overall, in most of the discussed case studies, the locations have an analogous climate and regional similarity. Furthermore, in most of the locations, the increase in electricity generation by implementing tracking-solar systems is significant. It is worth mentioning that the current case study of Burnoye-1 has similar climate characteristics to Eskisehir (Turkey), where the summer is hot, and it also shares regional similarity with the southwest USA where most regions are arid [11,12]. Consequently, it is expected that the Burnoye-1 case study presents similar results regarding electricity generation.

The technical benefits of sun trackers in terms of increasing power production are evident. However, PV systems using tracking systems carry on additional initial costs and extra operating and maintenance (O&M) expenses needed to guarantee the reliability of the system [11,16]. Furthermore, it has been found that in some cases, when irradiance or financial parameters are not favorable, the added tracking system may make a project economically infeasible [17].

Furthermore, this work explores current solar irradiance and financial conditions in Kazakhstan to determine whether one- and two-axis tracking mechanisms are economically attractive add-ups. If proven favorable, tracking systems may turn as an opportunity to hasten the energy transition in the country through Burnoye-1 and future projects in the region.

3. Methodology

The reliable and efficient way to analyze the viability of on-grid photovoltaic systems is the usage of the RETScreen analysis software. It is an intelligent decision support tool that helps to evaluate the performance of renewable energy projects. The platform performs analysis in 5 steps [23], and that was used as a research methodology. In this particular study, the tool was used to thoroughly analyze the case in terms of sensitivity and greenhouse gas emission [18,19].

- *Energy model,* which requires information regarding base and proposed cases, project location, type of energy used in the projects, and regional resources. Based on the previous information, the following estimation was made:
    - Estimation of electricity production using the current fixed-slope PV system.
    - Selection of one- and two-axis sun-tracking technologies that can be available locally (nationally produced or imported) compatible with current PV panels on the site. After that, the estimation of the production of electricity with these two new configurations is assessed.
    - Estimation of the annual solar irradiance in Burnoye-1 and climate conditions.
- *Cost budgeting* analysis, where periodic, annual, and initial costs need to be added by the user. Also, it includes capital and running costs of solar PV technology and associated sun trackers suitable for Burnoye-1.
- *Life-Cycle Cost analysis* (LCCA) for three different scenarios exporting electricity to the grid. In this analysis, the following data need to be gathered:
    - FiT and subsidies, which are applicable to PV power plants in the country;
    - Applicable taxes (if any);
    - Inflation and FiT escalation rates;
    - Loan conditions (i.e., debt ratio, rate and payment term);
    - Minimum return rate expected by investors in this sector (discount rate).

The outcomes of the LCCA were scrutinized among the three scenarios to determine the best financial option and include the Net-Present Value (NPV), Internal Rate of Return (IRR), Equity Payback, and Benefit-Cost ratio (B-C).

- *Sensitivity Analysis*, which determines the most determinant factors in the financial outcome of the project. For this purpose, with an estimation of the uncertainty of each input parameter, a multivariable Monte Carlo analysis is performed to determine which are the most critical input parameters in determining the expected financial outcomes. Monte Carlo simulation takes into account not only input parameters but selects on a random basis 500 values. Thus, it helps to identify the effect of those financial values on key indicators.
- *Greenhouse Gas Emission analysis*, which provides an estimation of the CO_{2e} emissions avoided by each of the three considered PV scenarios (fixed case scenario, and both one- and two-axis tracking systems case scenarios). This analysis complements the financial impact of each solution with its environmental benefits.

4. Results and Discussion

4.1. Energy Model

Table 1 presents the monthly average irradiance in the sector of Burnoye-1, including air temperature, obtained from the NASA satellite information and ground station, respectively (as extracted from RETScreen).

The energy model for the base case (fixed arrays, 30-degree slope, and 0-deg azimuth) is built according to the information available on the site of the project (as extracted from RETScreen), and the Atlas of Solar Resources of Kazakhstan was used to obtain the technical specifications of current Burnoye-1 [34]. Information about the PV systems like the power capacity, model, efficiency, and its manufacturer is shown in Table 2.

Table 1: Solar Irradiance and Air Temperature at Buroye (Jambyl region) (as extracted from RETScreen Expert)

Month	Air Temperature [°C] Source: ground station	Daily Solar radiation-horizontal [kWh/m²/d] Source: NASA
January	–3.0	1.66
February	–1.6	2.33
March	4.1	3.23
April	11.6	4.34
May	17.3	5.51
June	23.0	6.52
July	25.3	6.64
August	23.7	6.19
September	17.8	4.96
October	10.5	3.21
November	3.7	1.94
December	–1.4	1.40

Table 2: PV system information for Burnoye-1 [24]

Type	Poly-Si
Power capacity	50 MWp
Manufacturer	Astana Solar
Model	KZ PV 230 M60
Panel dimensions	1.649 × 0.99 m
Number of units	192 192
Efficiency	16%
Nominal operating cell temperature	45 °C
Temperature coefficient	0.4%/°C
Solar collector area	312 312 m_2
Miscellaneous losses	3%

Three solar power projects in Kazakhstan were considered, which are Kulan, Gulshat, and Burnoye-1. The Clean Technology Fund (CTF) is one of the main investors of all three projects, which using PV panels provided by the local Astana Solar Company [20]. The PV system specifications used in the Burnoye-1 plant can be seen in Table 2. Additionally, the RETScreen Expert (RE) platform was used, and since RETScreen does not include Astana Solar manufacturer in its existing database, an equivalent PV model is used (Suntech, Poly-Si - STP260 - 20/Wem) which has similar characteristics as Astana Solar KZ PV 230 M60 Burno.

Burnoye-1 solar plant uses XC 680 inverters that were produced in Thailand by Schneider Electric, with an alternating current (AC) power output of 680 kW and maximum efficiency of 99% [22]. It was assumed that the same inverter could be used for scenarios with one- and two-axis solar tracking. Technical specifications of ST40M2V3P one-axis and STM3V15P two-axis solar tracking systems are listed in Table 3. According to Table 2 and Table 3, the solar panel dimension used in Burnoye-1 exactly matches the dimensional accuracy of tracking systems.

The RE platform allows us setting the model to calculate the tilted-tracking beam and diffuse (i.e., total) solar irradiance on an hourly basis by implementing the following algorithm: (a) firstly, it calculates the hourly total irradiance on an horizontal surface per each hour on an average-day having same irradiance as corresponding monthly average; (b) then, the model calculates the hourly total irradiance in the plane of the PV array; and (c) the model sums all hourly tilted values of irradiance to complete the average daily irradiance in the plane of the PV array for a given day. The daily angular position (in degrees) of sun at solar noon, with respect to the plane of the equator, is given by:

$$\delta = 23.45 \sin\left(2\pi \frac{284+n}{365}\right)$$

Table 3: Technical specifications of solar tracking systems [27]

Specifications	ST40M2V3P	STM3V15P
Number of turning axis	1	2
Holding Panels	3	15
Panel dimension	1.67 × 0.99 m	1.67 × 0.99 m
Motors	1	2
Motor Power Supply	24 VDC	24 VDC
Type of hour-angle motor	Linear Motor SM4S510M2	Linear Motor SM4S900M3
Estimated Motor Operation	800–1000 hrs	800–1000 hrs
DC motor replacement	8 yrs	8 yrs
Backup battery	CR 2512 coin	CR 2512 coin
Backup battery replacement	3–5 yrs	3–5 yrs
Turning time interval	1–15 min	1–15 min
Operating Temp	–25 °C to +70°C	–25 °C to +70 °C
Standby consumption	20 mA ± 25% @ 24 VDC	60 mA ± 25% @ 24 VDC

Table 4: Electricity exported to the grid for different tracking configurations

Tracking Mode	Electricity exported to grid (MWh/year)	Electricity revenue (USD/year)* (*) year-0 value
Fixed mode (Base case)	75 828	252 735 183
One-axis mode (Proposed case)	97 751	325 805 460
Two-axis mode (Proposed case)	100 933	336 409 416

where n is the day of the year. The one- and two-axis trackers change their parameters so that the incidence angle is the same as the angular position of the sun, and in this case, the angular position for Burnoye is used. Moreover, the electricity exported to the grid can be calculated using the data from Table 1, together with the incidence angles. This algorithm is explained in depth in the article published by the National Resources Canada organization [23]. The estimated production of electricity exported to the grid for the fixed-array, one- and two-axis solar tracking systems is listed in Table 4. As it can be noticed, electricity generated by one- and two-axis solar systems are significantly higher compared to the fixed system, with the two-axis solar tracking system increasing by 33% the electricity exported to the grid. Another perceptible outcome is the similarity in energy production by one- and two-axis tracking systems, which opens the discussion on whether two-axis tracking implementation is feasible, as it has higher capital and O&M costs compared to the one-axis configuration.

4.2. Cost Budgeting

The construction of the solar power plant Burnoye-1 cost was around USD 123 000 000, including the feasibility analysis, development of the project, and engineering works [24]. Currently, 25 technicians are running the operation and maintenance of the plant [7]. In detail, five dispatchers, four monitoring engineers, and 16 security guards are permanently assigned to the project. Salary is estimated considering a standard of living in Jambyl region [26]. Periodic cost is established based on the replacement of inverters. The cost of XC 680 inverters is not listed in the public report, but it was estimated by its characteristics, using a suitable unit cost (including its transportation cost from Japan). The replacement period of the inverter is ten years [22]. The periodic cost of the project base case includes only inverter refurbishment, assumed as 25% of its initial cost. Table 5 lists cost numbers for fixed panel mode (base case).

Table 5: Costs for fixed PV system configuration (base case)

Costs	Cost	TOTAL
Initial cost (USD)		
Feasibility study	3 900 000	
Development	7 800 000	
Engineering	9 450 000	
Power Systems	92 810 892	**124 679 722**
Inverters (74 XC680)	4 781 700	
System Balance	5 937 130	
O&M costs (USD)		
Dispatchers	25 200	
Engineers	28 800	**111 600**
Security guards	57 600	
Periodic Cost (USD)		
Inverters (per 10 years)	119 5425	**1 195 425**

The effect of adding one- and two-axis sun trackers ST40M2V3P and ST44M3V15P, respectively, are considered in subsequent scenarios.

Each ST40M2V3P tracker can hold three panels (each panel with 1.6335 m*2*), while each ST44M3V15P can hold 15 panels (each panel: 1.6533 m*2*). It is worth mentioning that solar trackers used in this project have 1.626m*2* (each), which makes the chosen solar trackers compliant with current space limitations [27]. The prices for ST40M2V3P and ST44M3V15P sets were taken from SAT Control, 2018 with the following total prices (for complete PV power plant): USD 36 270 820 and USD 55 675 526, respectively.

Moreover, based on our experience and perception, it was assumed that one worker could install a single solar panel in 0.5 hours, a single one-axis solar tracker in 2.5 hours, and a single two-axis solar tracker in 7 hours, while his/her salary is around USD 5.85 per hour (2 199 KZT/hour). The salary was calculated based on salary surveys recorded from employers and anonymous employees in Kazakhstan. This value might increase by 10% each year [28].

On the other hand, solar tracker systems that required control motors have extra operational costs and associated emissions due to grid-electricity consumption. The grid-electricity used for the operation of these control motors was rated as USD 0.028 per kWh [16]. Moreover, it is assumed that the solar tracker will work 10 hours per day on average in Jambyl [28]. As a result, the yearly operational cost would increase compared with initial cost of the base case scenario to USD 93 772 and USD 37 507 for the one-axis and two-axis solar tracking systems, respectively. The number of solar panels that are held by the single solar tracker can explain such a difference. Moreover, the calculations include the fact that the two-axis tracking system operates with two linear motors: hour angle and elevation-angle motors [30]. An additional periodic cost is included in the analysis of the two scenarios with sun tracking, which correspond to the replacement of DC motors every 8 years. It also predicted that two workers could replace motors in 40 minutes for the single one-axis solar tracker and one hour for the single two-axis solar tracker. Estimated operating and maintenance (O&M) costs for both tracking systems are presented in Table 6.

Table 6: Estimated extra capital and O&M costs for tracking systems

Tracking Mode	One-axis	Two-axis
Initial Cost (USD)	163 033 074	183 090 088
O&M Costs (USD)	205 372	149 107
Periodic Cost (USD)		
Inverters (every 10 years)	1 195 425	1 195 425
Motors (every 8 years)	14 516 689	17 921 800

In summary, the installation of one-axis and two-axis tracking systems adds a high extra cost to the base case project with an estimated increase of 25% and 40%, respectively. In addition, the periodic cost is higher in the case of the two-axis tracking system since it operates with two linear motors. Nevertheless, the O&M cost is slightly higher in the case of the one-axis tracking system compared to the two-axis tracking system because the first one has more panels that need maintenance.

4.3. Life Cycle Cost Analysis (LCCA)

This section presents the life-cycle cost analysis (LCCA) of all three options (fixed case scenario and both one- and two-axis tracking systems case scenarios) considering the impact of the Feed-in-Tariff. The LCCA for the base case is determined according to the techno-economic reports publicly available.

Two companies provided financial support for the existing Bornoye-1 PV plant: the European Bank for Reconstruction and Development (EBRD) and Clean Technology Fund (CTF), a subsidiary of the World Bank Group. Table 7 illustrates debt ratios from both entities and their financial details. The debts are shown in USD equivalent values, and the debt was consolidated in the model as major debt from EBRD to simplify the analysis. As a result, a debt of 62.02% is included in the project analysis.

Table 7: Debt Details

Bank	EBRD	CTF (World Bank)
Debt Ratio	62.02%	12.3%
Debt (USD)	~77 300 000	~15 000 000
Debt Interest Rate	11.5%	1.25%
Debt Term (yrs)	15	20

Furthermore, Table 8 presents data for the financial parameters needed in the analysis that were gathered from the National Bank of Kazakhstan [31].

Table 8: Financial Parameters [31]

Lifetime of Project (yrs)	25
Inflation Rate	5.3%
Discount Rate	9.25%
Reinvestment Rate	1.2%
Effective Income Tax Rate	20%

A fundamental element in the analysis is the electricity export escalation rate, which is the rate that has to be applied to escalate the Feed-in-Tariff. On May 10, 2018, the Government of the Republic of Kazakhstan adopted a resolution on amendments concerning the determination of FiT [32]. After that, the FiT must be indexed with the Consumer Price Index (CPI) and exchange rates of KZT to USD of the previous 12 months to the indexed year following the formula:

$$T_{t+1} = T_t\left(1 + 0,3\frac{CPI_t - 100\%}{100\%} + 0,7\frac{USD_{t+1} - USD_t}{100\%}\right)$$

Where,

T_{t+1} – Indexed flat tariff.

T_t – Current flat tariff.

CPI_t – Consumer price index, cumulative for 12 months before October 1 of the indexation year.

USD_{t+1} – Current exchange rate of tenge to USD (the standard monetary unit of Kazakhstan).

USD_t – Average exchange rate of the tenge to USD, calculated 12 months before the indexation date.

By applying the formula, the FiT escalation rate was estimated at 8.3% per year.

The results of the LCCA are summarized in Table 9 for a 25-year lifetime. The analysis shows that one- and two-axis solar tracker projects have very similar NPV despite the initial larger cost of the latter, more than USD 162 thousand and USD 150 thousand respectively.

Table 9: Life-Cycle Cost Analysis (LCCA) Outcome

Mode	Fixed	One-axis	Two-axis
After-tax IRR equity (%)	23.3	21.7	19.6
NPV (USD)	145 119 759	162 429 145	150 307 742
Equity Payback (yrs)	5.9	6.1	6.9
Simple Payback (yrs)	8.7	8.9	9.6
Benefit-Cost Ratio	4.1	3.6	3.2

However, the fixed system has a larger B-C ratio, 4.1 to be exact, more significant IRR on equity 23.3%, and a shorter payback period within all 3 cases with 5.9 years, which makes it the best option.

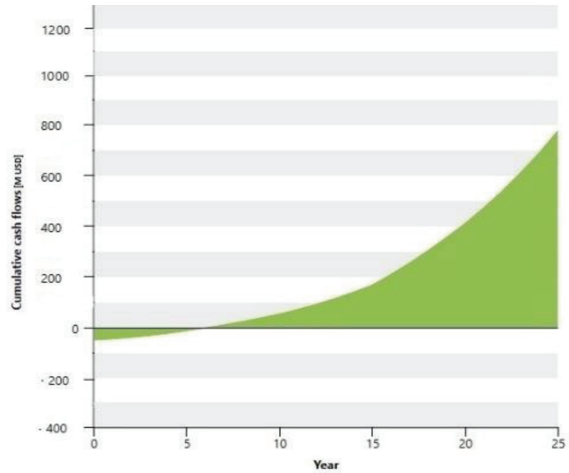
Cumulative cash flows for each scenario are presented in Figure 1.

4.4. Sensitivity and Risk (S&R) Analysis

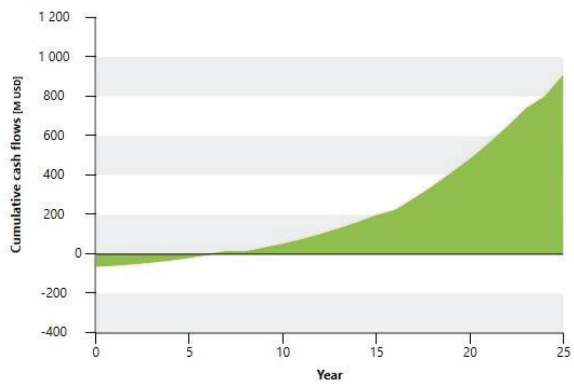
A risk analysis, based on Monte Carlo (MC) simulation, was performed to determine the sensitivity of financial indicators concerning the uncertainty of key input parameters. Monte Carlo simulation is a method to develop a S&R analysis which considers input parameters and randomly selected values within the uncertainty range indicated by the user (see Table 10 for the three scenarios and seven input parameters considered in this study). The S&R also identifies the weights of each input parameter on the output indicators of interest. The Monte Carlo simulation consists of 2 steps:

a) First, for each input parameter selected by the analyst, 500 random samples are generated using a Gaussian distribution with a mean value 0 and a standard deviation of 0.33. Once these values are generated, they remain fixed.

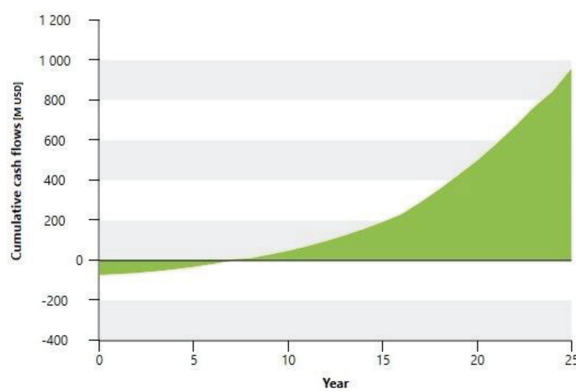
b) Second, for each input parameter, the corresponding random values from (a) are multiplied by the uncertainty indicated by the user (as a percentage) of variability around the nominal value of the given input parameter. As a result, a matrix of 500* number of input parameters will be created; therefore, 500 results will be produced and used for the outcomes of financial indicators.



(a) Fixed-Array PV System



(b) One-axis Tracking PV System



(c) Two-axis Tracking PV System

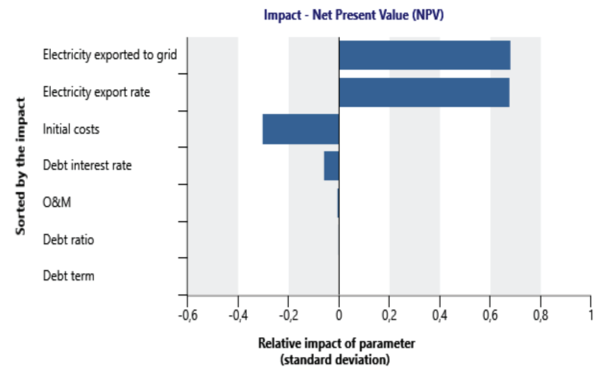
Figure 1: Cumulative cash flows (as extracted from RETScreen Expert). (a) Fixed-array; (b) One-axis tracking system; (c) Two-axis tracking system

Table 10: Uncertainty of input parameters for three scenarios

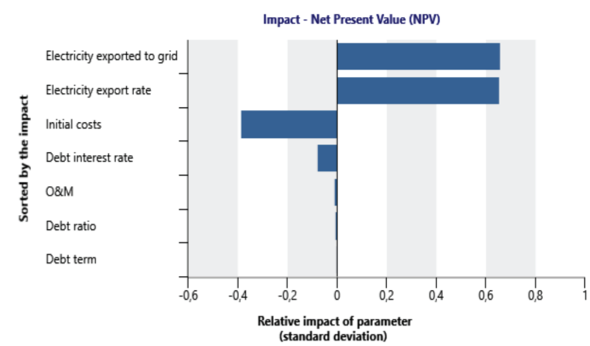
	Fixed array	One-axis	Two-axis
Initial costs range +/– (%)	10	20	20
O&M range +/– (%)	15	20	20
Electricity exported to grid range +/– (%)	10	10	10
Electricity exported rate +/– (%)	10	10	10
Debt ratio rate +/– (%)	5	5	5
Debt interest rate +/– (%)	5	5	5
Debt term range +/– (%)	5	5	5

Uncertainties were estimated based on the perception in the local market. For example, variations of the debt ratio, debt interest, and debt term were very small (5%) because there is a low risk that these values change in the short-term in the country. Both the electricity exported to the grid and electricity export rate are almost invariable, as the former is associated with proper O&M (considered as a fundamental part in the cost budgeting), while the latter is linked to the existing policy. Thus, an energy purchase agreement is regularly expected to be signed before the approval of the project. Therefore, 10% of uncertainty was set for both parameters in the MC analysis. However, the O&M cost of the project may change significantly due to unexpected labor costs increase and for the extra effort in maintaining tracking systems that can be expected due to harsh winters in the country. There is little uncertainty on PV panel costs (all materials are from local markets); nevertheless, cost varies significantly between different tracking systems purchased from foreign countries.

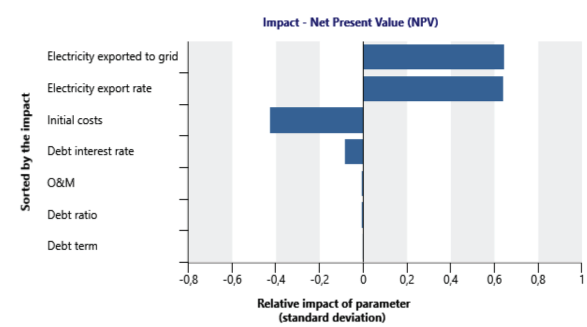
Consequently, the uncertainty of the initial cost for proposed scenarios with tracking systems was set to 20%, while for fixed-arrays (base case), it was only 10%. Given that 100% of possible scenarios resulting from MC sampling conform an entire histogram of frequency, a risk level of 5% (or equivalently, a confidence of 95%; i.e., the output range is the resulting range in histogram of frequency that encloses 95% of probable scenarios around the median) leads to the expected range of output financial indicators (e.g., NPV, IRR, etc.). Figure 2 presents the risk analysis using a Tornado chart that predicts the relative impact of each selected individual parameter onto a selected output indicator, depicting which parameters are significant and may require special attention. The direction of the horizontal bar (positive or negative) provides an indication of the relationship between the input parameter and the financial indicator. There is a positive relationship between an input parameter and the financial indicator when an increase in the value of that parameter results in an increase in the value of the financial output indicator. The chart (Fig. 2) includes the influence of varying parameters such as the amount of electricity exported to the grid, electricity export rate (i.e., FiT), initial cost, and debt interest rate on the project's Net Present Value.



(a) Fixed-Array case.



(b) One-axis Tracking case.



(c) Two-axis Tracking case.

Figure 2: Normalized influence of input parameters on the NPV of the PV power system (as extracted from RETScreen Expert): (a) Fixed-array; (b) One-axis tracking; (c) Two-axis tracking

It can be clearly seen that the most significant impact on the project's NPV comes from varying electricity exported to the grid and, secondly, for the electricity export rate. The other strong effect on the viability of the project was caused by the initial cost with a negative correlation.

The primary role of both FiT and the amount of exported electricity is that both are the positive financial indicators of the project. Capital cost is the third largest and significant parameter in the financial fate of all scenarios.

4.5. GHG Emission Analysis

The fixed-array systems are the current systems in use in the Burnoye-1 plant, and it reduces greenhouse gas (GHG) emissions by around 34 996 tCO_2 per compared to fossil fuel systems (according to calculations in RETScreen Expert). However, even if when adding the one- and two-axis tracking the solar collection increases, the control motors of trackers also consume electricity from the grid, and this reduces the GHG emission reduction effect.

Nevertheless, assuming a 10-hour operation per day and tracking time-stepping interval of 15 minutes, where one- and two-axis tracking system motors consume a maximum of 6 W and 36 W of power, respectively. Solar-motors calculations demonstrate that it is expected that the one-axis tracking system will use 1.40 MWh, while the two-axis will use 1.68 MWh annually [33]. Then, these values multiplied by Kazakhstan's GHG emission factor (0.495 tCO_{2e}/kWh), provided by the

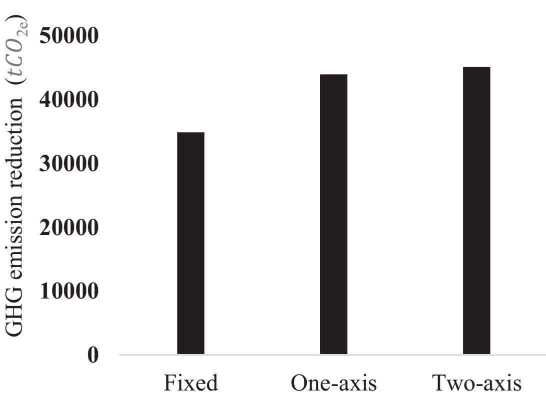


Figure 3: Net annual GHG emission reduction by fixed array and tracking systems

RETScreen Expert platform database, 2019, and subtracted from gross annual GHG reduction by panels, the net GHG emission reduction is found to be 44 137 tCO_{2e} and 45 464 tCO_{2e} for one- and two-axis cases, respectively. Figure 3 shows the net annual GHG emission reduction in fixed, one- and two-axis technologies. Nevertheless, it is evident that the difference in emission reduction for one- and two-axis technologies is comparatively small (only 1 327 tCO_{2e}).

A techno-economic assessment of the impact of adding one- or two-axis solar tracking systems on the existing 50 MWp Burnoye Solar-1 on-grid power plant, located in southern Kazakhstan, is presented in the current paper. As expected, the PV system with a sun-tracking mechanism provides higher electricity generation compared to the same capacity of fixed PV panels. The installation of one- and two-axis solar trackers would increase the electricity export to the grid from 76 GWh (for the fixed case) to 98 and 101 GWh per year, respectively. However, the initial costs would increase by 25% and 33%, respectively. On the other hand, the limited holding capacity of one-axis trackers makes their total O&M cost larger than two-axis trackers.

The Life-Cycle Cost Analysis of the three scenarios proved that all three are very feasible, but fixed arrays render better financial outcomes compared to the same system with added sun-tracking capability. A marginal difference in electricity generation and financial indicators were found among the two sun-tracking scenarios, with just a limited increased production and GHG emission reduction for the two-axis system compared to the less expensive and simpler one-axis sun-tracking configuration (GHG emissions, however, could be reduced in near 10 $ktCO_{2e}$ compared to the fixed-slope system in Burnoye-1). In conclusion, a fixed-slope array is well justified in Burnoye-1, and only if an extra production of electricity or GHG emission reduction is considered with the same installed capacity, one-axis tracking configuration should be the new configuration.

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