Impact of module degradation on the viability of on-grid photovoltaic systems in Mediterranean climate: case of Shymkent Airport

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Research

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Abstract

This paper presents the techno-economic feasibility analysis of an on-grid Photovoltaic Solar System (PVSS) subject to Mediterranean climate aging effects. The PVSS under study is considered installed on the roof of Shymkent airport, located in southern Kazakhstan. A PVSS performance degradation rate of 1.48%-per-annum was considered according to the Mediterranean climate prevailing in the location. A 25-year life-cycle cost analysis comparing the rated vs de-rated on-grid PVSS led to a positive Net Present Value (NPV), a less than 9-year equity payback, and favorable internal rate of return (IRR) and Benefit to Cost Ratio (BCR) in both conditions. The analysis demonstrates that despite the expected performance degradation associated to climatic aging, a convenient feed-in tariff (FIT) and attractive financial conditions, such as those present in Kazakhstan, conform a robust setting to promote on-grid PVSS in the country.

Introduction

Air terminals are a fundamental part of the universal air transport framework, and they support and encourage the number of travellers and the travel industry all around the globe (DeVault et.al. 2012). Moreover, even if in recent years, there has been an increase in the attention directed towards the ecological effects of human activities (Allan 2002), a threat to both the aircraft industry and the air terminal industry is its low capacity to develop and work on its environmental impact in the near future (Salameh 2014).

Furthermore, there is also an increased concern on the effects that air terminals have on nature, and the air terminal industry is attempting to have more ecologically responsible air terminals (Fargione et.al. 2008; Plante et.al 2010). On the other hand, the International Civil Aviation Organization (ICAO) estimates that global greenhouse gas (GHG) emissions derived from the civil aviation industry will rise 4 to 6 times by 2050 compared to the 2010 emissions because of both the increasing number of airlines and new airports construction (Jain et.al 2010).

However, some actions could diminish the environmental impact of air terminals, like the incorporation of energy-saving light-transmitting diodes (Plante et.al 2010). In addition, the use of sun-powered photovoltaic (PV) frameworks —also known as Photovoltaic Solar system (PVSS)— at air terminals is one of the best options because it diminishes the CO₂ production while producing energy (ICAO 2014). Additionally, one of the most widely recognized energy-saving structures installed on air terminals are on-grid PV boards, which are usually installed on rooftops.

That is why installing PVSS clusters on the rooftop can give it both ecological and financial advantages to air terminals (Kellas 2012). Moreover, those PVSS clusters produce fewer CO₂, even though their generation, movement, establishment, decommissioning, and reusing produce CO₂ emanations. Besides, PV frameworks have a life expectancy of over 20 years and require low maintenance (Kellas 2012).
Because of the advantages of PVSS, an increasing number of air terminals over the world have introduced sun-based powered frameworks (Swart, Schoeman, and Pienaar 2013). Furthermore, the world's first absolutely sun-based controlled airport is the Indian Cochin International Airport. Other examples are both the Hong Kong International Airport and the London Gatwick Airport, which also use solar power plants (Zaihidee et.al 2016). Thus, airports are suitable for the application of PVSS.

On the other hand, PV modules suffer degradation over time, which reduces the generation of electricity during their lifespan and increases the power Levelized cost (Yahya, Youm, and Kader 2011). PV systems steadily degrade and lose their efficiency due to environmental stresses, including high temperature, humidity, and ultraviolet (UV) radiation. For example, Aly et al. (2019) determined that silicon-based PV panels are significantly affected by environmental factors such as ambient temperature, incident irradiance, wind speed and mounting configuration (Realini 2003).

According to observations gathered from field-aged PVSS, the degradation modes and catastrophic failures of the PVSS are caused by both the cracking and by the delamination (Aly, Ahzi, and Barth 2019; Quintana 2002). Such failure modes will reduce the PV module's performance and shorten its service life. In fact, the cracking of the backsheet on the PV panel — that is caused by a reduction in tensile strength—causes a significant volume of moisture to infiltrate, and that is the most devastating mode of backsheet failure recorded to date. Since backsheet cracking enables both water vapour and liquid to penetrate the PV panel, it can have a significant effect on PV module performance and reliability. Thus, to ensure that the PV module retains its output over its lifespan, the estimation of degradation patterns is important.

Moreover, it is necessary to understand the mechanisms of degradation to predict electricity output over the lifetime of the PV modules, as well as to find solutions to prevent and reduce degradation. For these reasons, researchers have tested PVSS reliability, and they have found that, even if PVSS last more than 25 years outdoors, they degrade (Yahya et.al 2011; Chianese et.al 2003; DeGraaff et.al 2011; Wohlgemuth et.al 2011; Vázquez and Rey-Stolle 2008; IEA-PVPS 2013; Halwachs 2017; Maish et.al 1997). Moreover, mechanical stress, moisture, elevated temperature, and ultraviolet radiation can lead to different failures in operation. Furthermore, the reduced solar cell performance due to damage appears even before its warranty finishes (Yahya et.al 2011; DeGraaff et.al 2011; Kato 2011).

On the other hand, there are cosmetic issues that do not affect the performance nor safety of the module (DeGraaff, Lacerda, and Campeau 2011). Nonetheless, cosmetic issues can trigger or enhance other problems as well as reveal other non-Visually detectable failures that affect power output. For example, "snail tracks" are discolourations on the solar cell, and even if there is no evidence yet that they cause a significant reduction in module performance, they are indicators of the presence of cell cracks (Parnham et.al 2917; IEA-PVPS 2014; Tracy 2017). That is important because glass breakage is one of the most frequent defects caused during transportation and deployment of a PVSS. Even if cell cracks do not directly affect cell performance, they still promote or even cause certain types of degradation, such as the deterioration of electrical insulation, corrosion, delamination, among others (DeGraaff, Lacerda, and Campeau 2011). For example, Liu et al. (2019) performed quantitative analysis on two PVSS combining
the equivalent-circuit model and optoelectronic characterization methods, and they found that the encapsulant discolouration in PVSS mostly contributes to its degradation (Meyer et.al. 2014).

On the other hand, one of the major causes of PV deterioration is extreme climate conditions (Liu et.al. 2019), with the degradation of short circuit current (Isc) being the largest contributor to the reduction of the maximum power point (Pmax) in most climatic areas. Isc degradation is mainly due to delamination, discolouration, and cracks present in the cells; however, a small percentage can be due to light-induced degradation (LID) and soiling (accumulation of dirt over the panels) (DeGraaff et.al. 2016; Yedidi et.al. 2014; Meyer et.al. 2014; Bogdanski et.al. 2010; Omazic et.al. 2019). In addition, Isc degradation is the largest contributor to the reduction of the maximum power point (Pmax) in desert climates (Smith, Jordan, and Kurtz 2012). A minor factor in the degradation of Isc comes from the fill factor (FF), which is associated with breakage of corrosion and solder bond (Yedidi et.al. 2014; Jordan et.al. 2013; Sakamoto 2003; Lindroos and Savin 2016; Skoczek et.al. 2009). Thus, it is necessary to consider PVSS deterioration when studying if the installation of PVSS is feasible in a given climate zone, as the climate is a major factor in its performance.

In this paper, the degradation effect due to the Mediterranean climate on the PVSS that would be installed on the roof of the International Airport of Shymkent was analyzed using a life-cycle cost analysis run in the RETScreen Expert platform. Shymkent is a city located in the southern part of Kazakhstan (Fig. 1), with Continental-Mediterranean climate according to the Köppen climate classification (Ontustyk 2019).

The PVSS would be installed on the roof of the airport, and the top view of the airport roof was obtained using the Google Earth Pro software (Fig. 2). A total roof area of 2820 m² would be covered by PV.

**Literature Review**

Financially, the degradation of a PV module or system is important because a higher degradation rate negatively affects power production, and it reduces cash flow. Furthermore, if there are inaccuracies in the determined degradation rates, these can increase the financial risk. Technically, it is also important to understand the degradation mechanisms because they may eventually lead to failure. In PVSS, a 20% decline is typically considered a failure; however, there is no consensus on the definition of failure for these systems because a high-efficiency module with 50% of degradation may still have a higher efficiency than a non-degraded module that uses a less efficient technology (Weather-Atlas 2019).

As indicated by the National Renewable Energy Laboratory (NREL), PV modules can be affected by conditions like damp heat, UV exposure, thermal cycling, and humidity freeze (Omazic et.al. 2019). Moreover, the way that PV modules are affected differ between these elements.

For example, thermal cycling can cause weld bond degradations and splits in sun-powered panels; damp heat has been related to the corrosion of cells; humidity freezing can cause failures in the Junction box; UV exposure contributes to staining and back sheet debasement (Peng et.al. 2012). When these problems appear, it is difficult to estimate the impact that they have.
DeGraff studied degradations that happened in the midlife of PV modules and estimated that 2% of the PV modules would not meet the producer's guarantee following 11–12 years of activity (Chianese et al. 2003). That study found a very high pace of deformity in the interconnections in the module as well as degradations caused by PV module glass breakage.

One of the climates that lead to PVSS degradation is a hot and dry climate because PV modules are exposed to severe stress factors like intensive solar and UV irradiation, extreme temperature cycles, and sand. The most frequent failure processes in a desert climate are discoloration of the EVA encapsulant, followed by delamination above the cell, and a high degree of corrosion (Liu et al. 2019).

Downtime or lifetime reduction of PVSS is due to the extreme weather conditions in regions such as in South Africa, where the downtime can last up to four hours a day in the most severe months (Kellas 2012).

In arid regions, dust is the main problem for PVSS. Gathered dust of 20 g/m² on the PVSS reduces short circuit current, open-circuit voltage, and efficiency by 15–21%, 2–6%, and 15–35%, respectively (Swart, Schoeman, and Pienaar 2013).

To summarize, the degradation rate adversely impacts the viability of the photovoltaic panels, and it is affected by the climate zone where the PVSS is installed. Thus, the influence of the Mediterranean climate of Shymkent city on the deterioration of PV panels was studied on this research, as well as the impact of dust.

**Methodology**

First, the hypothetical case where there is no degradation was considered, and an energy model was structured, calculating the power capacity of the PVSS based on the available installation area and given technology. Then, the cost analysis was completed introducing the costs of engineering services required, PVSS, transportation, operations, maintenance, and periodic costs in the life-cycle cost platform. Afterwards, the GHG emission reduction due to the possible application of the proposed system was analyzed. Next, the Internal Rate of Return (IRR), Net present value (NPV), Benefit to cost ratio (BCR), and Equity payback period were calculated after introducing the inflation, discount rate, and feed-in-tariff (FIT) in the model.

After this, the model that includes degradation was studied, introducing the average deterioration rate of PV panels for Mediterranean climates, evaluating the reduced annual power per year. Moreover, after including the electricity escalation rate, feed-in-tariff, and overall expenses on the project, the new values for the NPV, IRR, MIRR, and BCR were recalculated. Finally, both the sensitivity and risk analyses were performed.

**Energy model.**
The first step to create the energy model in Shymkent, is to make a comparison between the daily average solar radiation with other cities of Kazakhstan, and it can be seen in Table 1 that Shymkent is the city that receives the largest irradiance in the country.

### Table 1

COMPARISON OF AVERAGE DAILY SOLAR RADIATION IN DIFFERENT KAZAKHSTAN REGIONS (Kaplani 2012).

| City      | Region  | Daily Solar Radiation – horizontal (kWh/m²/d) |
|-----------|---------|---------------------------------------------|
| Astana    | North   | 3.55                                        |
| Almaty    | Southeast | 3.59                                    |
| **Shymkent** | **South** | **4.45**                                    |
| Taraz     | South   | 4                                           |
| Kyzylorda | South   | 4.21                                        |
| Uralsk    | Northwest | 3.55                                    |
| Pavlodar  | Northeast | 3.51                                    |
| Karaganda | Central  | 3.71                                        |
| Aktau     | Southwest | 3.92                                    |
| Kokcetav  | North   | 3.36                                        |
| Semipalatinsk | East    | 3.81                                        |

The average daily radiation that the tilted PV panels receive per year is 5.06 kWh/m²/d (Table 2), and as it is higher than the average daily radiation of the horizontal panels, those 30° tilted PV modules were chosen for this study. Furthermore, that arrangement allows rain to clean the solar panels, which reduces miscellaneous losses to 2–3% (Table 3).
Table 2
DAILY SOLAR RADIATION FOR HORIZONTAL AND TILTED PV MODULES. DATA OBTAINED FROM THE RETSCREEN EXPERT PLATFORM.

| Month     | Daily solar radiation -horizontal kWh/m²/d | Daily solar radiation -tilted kWh/m²/d |
|-----------|-------------------------------------------|----------------------------------------|
| January   | 1.77                                      | 2.86                                   |
| February  | 2.58                                      | 3.6                                    |
| March     | 3.95                                      | 4.81                                   |
| April     | 5.31                                      | 5.72                                   |
| May       | 6.5                                       | 6.39                                   |
| June      | 7.24                                      | 6.84                                   |
| July      | 7.25                                      | 6.97                                   |
| August    | 6.35                                      | 6.61                                   |
| September | 5.11                                      | 6.04                                   |
| October   | 3.52                                      | 4.84                                   |
| November  | 2.14                                      | 3.42                                   |
| December  | 1.52                                      | 2.47                                   |
| Annual    | 4.45                                      | 5.06                                   |

In order to fit the area of 2820 m², the PVSS with a power capacity of 300kWp was selected, and one of the assumptions was that there should be space available for movement between the solar panels. Therefore, the estimation is that 59 mono-Si PV panels would be needed to cover the rooftop area and as the average solar radiation is 5.06 kWh/m²/d per year, those panels would have up to 300 kWp of power capacity (Table 3).

Table 3
POWER PARAMETERS OF PVSS.

| Photovoltaic type | Mono-Si |
|-------------------|---------|
| Power capacity (kWp) | 300     |
| Efficiency (%)     | 11      |
| Solar collector area (m²) | 2727    |
| Miscellaneous losses (%) | 3       |

Malvoni et al. estimated the performance of a PVSS that was exposed to the Mediterranean climate outdoors using the Classical Seasonal Decomposition (CSD) method (Assamidanov, Nogerbek, and
Rojas-Solorzano 2018). The results of their experiment showed that the degradation rate of the PVSS was about 1.48%/year. The CSD is a common technique used to calculate the degradation rate and does not have significant uncertainties.

The reduction of the PV output power due to the annual degradation rate was introduced into the energy model with the lifespan of the project being of 25 years. Moreover, 25 different sub-models were introduced in the RETScreen platform to estimate the energy production by year after considering degradation processes, and after that, every calculated year’s production was used to build up the lifetime cash flow. Moreover, miscellaneous losses each year were increased to reflect the deterioration of the PV module performance, such that the electricity exported to the grid was reduced by 1.48% in each subsequent year. The final calculation of the output power for each year is shown in Table 4.
| Year | Electricity exported to grid (MWh) |
|------|----------------------------------|
| 1    | 436.00                           |
| 2    | 429.55                           |
| 3    | 423.19                           |
| 4    | 416.93                           |
| 5    | 410.76                           |
| 6    | 404.68                           |
| 7    | 398.69                           |
| 8    | 392.79                           |
| 9    | 386.97                           |
| 10   | 381.25                           |
| 11   | 375.60                           |
| 12   | 370.05                           |
| 13   | 364.57                           |
| 14   | 359.17                           |
| 15   | 353.86                           |
| 16   | 348.62                           |
| 17   | 343.46                           |
| 18   | 338.38                           |
| 19   | 333.37                           |
| 20   | 328.44                           |
| 21   | 323.57                           |
| 22   | 318.79                           |
| 23   | 314.07                           |
| 24   | 309.42                           |
| 25   | 304.84                           |
Cost Analysis.

The cost of obtaining PV modules is roughly 1–3$\/W \text{ (Malvoni et.al. } 2017\text{). For this project, PV panels would be obtained for 1\$/W (388.29 KZT). Thus, the cost of one photovoltaic module is 1000\$ \text{ (388,290 KZT) per one kW.}}

Table 5
INITIAL COSTS for the installation of the PVSS modules in the rooftop of the Shymkent airport.

| Initial costs          | Quantity | Unit cost (KZT) |
|------------------------|----------|-----------------|
| Engineering cost       | 1        | 1,242,892       |
| Photovoltaic           | 300 kWp  | 388,290         |
| Transportation         | 1        | 700,000         |
| **Subtotal**           |          | **118,429,892** |
| Contingencies          | 5%       | 5,921,495       |
| **Total initial costs**|          | **124,351,387** |

Transportation of all the PV modules was assumed to cost 700,000 KZT, and 5\% of contingencies were assumed. Engineering cost is assumed to be 1\% of the total initial cost (1,242,892 KZT). Therefore, including all of these expenses, the total amount of initial costs is 124,351,387 KZT, and the costs are shown in Table 5.

According to Plante (Wattsap.kz 2020), there is no need to include expenses for the periodic costs because the PVSS only needs the inverter replacement after 15–16 years, which means that during the life span of the system, there would be only one inverter replacement. Inverters usually cost 10\% of the total cost (Plante 2014), so it would cost 12,435,139 KZT in this case. Moreover, there are also labour maintenance costs of approximately 480,000 KZT per year to have one technician checking and maintaining the PVSS that would clean the PVSS after snow and dust storms, among other tasks. All annual costs (O&M) are shown in Table 6.

Table 6
OPERATING AND MAINTENANCE AND PERIODIC COSTS.

| Annual costs (O&M)       | Quantity | Unit cost (KZT) |
|--------------------------|----------|-----------------|
| Labor                    | 2        | 480,000         |
| **Subtotal**             |          | **960,000**     |
| Periodic costs           | Year     | Unit cost (KZT) |
| Replacement of inverters | 15       | 12,435,139      |
GHG Emission analysis.

The GHG emission factor in Kazakhstan's grid is 0.582 tCO2e/MWh (The World Bank 2018). However, the World Bank suggests that the electric power transmission and distribution losses (T&D) in Kazakhstan in 2014 was 7% per year. (Solar Reviews n.d.), and when the T&D is included, the GHG emission factor increases to 0.626 tCO2e/MWh. Moreover, the GHG emission for the base case without and with PVSS (not considering degradation) are 273.1 tCO2e/MWh and 19.1 tCO2e/MWh, respectively. Therefore, for the base case system, the gross annual GHG emission reduction is equal to 253.9 tCO2e per year. Furthermore, even if we include the degradation rate in the system, the emissions would be reduced by the same amount in the first year. However, by the 25th year, the PVSS with degradation would have an emission reduction of only 174.9 tCO2e.

Financial Analysis. Input parameters.

For the financial analysis, an assumption of zero GHG income during the whole project was made. The average inflation rate in Kazakhstan in the last ten years has been 7.31% per year, and this value was used for this study (Asian Development Bank 2017).

On the other hand, the Feed-in tariff in Kazakhstan is equal to 34 KZT/KWh (Plecher 2019). The electricity escalation rate was considered to be of 7.31%, which is the same percentage as the average inflation rate calculated. No loans or grants are considered. Based on the last five years, the discount rate is about 11.1%, according to the National Bank of Kazakhstan (Kursiv 2019). These values shown in Table 7 are the input parameters for the financial analysis. The airport is owned by the governmental “Airport Management Group” company, so there are no taxes to be considered (National bank of Kazakhstan 2019).

| Table 7 | INPUT PARAMETERS IN THE FINANCIAL ANALYSIS. |
|---------|------------------------------------------|
| Inflation rate (%) | 7.31 |
| Discount rate (%) | 11 |
| Project life (years) | 25 |
| Incentives and grants ($) | 0 |
| Electricity export escalation rate (%) | 7.31 |
| Feed-in Tariff (KZT/kW) | 34 |
| Electricity exported to the grid (MWh) | 436 |

Results And Discussion

Life-cycle cost analysis for rated PVSS.
Results of the life-cycle cost analysis demonstrate that the base case is feasible. As can be seen in Table 8, it was determined that the equity payback period is 6.7 years. In addition, the IRR equity is 17.9%. Moreover, the NPV is positive and reached a total of 96,158,481 KZT, and the BCR is more than zero, equal to 1.8.

Table 8
RESULTS OF FINANCIAL ANALYSIS FOR RATED PVSS.

|                        |         |
|------------------------|---------|
| IRR                    | 17.9%   |
| Equity payback period  | 6.7 years |
| Net present value (NPV)| 96,158,481 KZT |
| Benefit to cost ratio (BCR) | 1.8     |

Table 9 shows the overall cash flow of the project, and it can be seen that the equity payback period of the project would be of seven years, and this means that the total investment would be paid completely in the seventh year of the project. Moreover, in the last year, 80,955,664 KZT would be obtained from the project. In total, 824,550,467 KZT would be earned, which is almost seven times the investment cost.
| Year | Annual Cash Flow (KZT) | Cumulative Cash flow (KZT) |
|------|------------------------|---------------------------|
| 0    | -124,351,387           | -124,351,386              |
| 1    | 14,889,584             | -109,461,803              |
| 2    | 15,978,013             | -93,483,790               |
| 3    | 17,146,005             | -76,337,784               |
| 4    | 18,399,378             | -57,938,407               |
| 5    | 19,744,373             | -38,194,034               |
| 6    | 21,187,686             | -17,006,347               |
| 7    | **22,736,506**         | **5,730,159**             |
| 8    | 24,398,545             | 30,128,704                |
| 9    | 26,182,079             | 56,310,782                |
| 10   | 28,095,989             | 84,406,771                |
| 11   | 30,149,805             | 114,556,576               |
| 12   | 32,353,756             | 146,910,333               |
| 13   | 34,718,816             | 181,629,148               |
| 14   | 37,256,761             | 218,885,909               |
| 15   | 4,149,674              | 223,035,582               |
| 16   | 42,902,785             | 265,938,367               |
| 17   | 46,038,979             | 311,977,346               |
| 18   | 49,404,428             | 361,381,774               |
| 19   | 53,015,892             | 414,397,666               |
| 20   | 56,891,353             | 471,289,019               |
| 21   | 61,050,111             | 532,339,130               |
| 22   | 65,512,875             | 597,852,005               |
| 23   | 70,301,866             | 668,153,870               |
| 24   | 75,440,932             | 743,594,802               |
| 25   | 80,955,664             | 824,550,467               |
Life-cycle cost analysis for de-rated PVSS.

The overall cash flow, considering the 1.48% degradation rate of PV panels, is shown in Table 10, and it can be seen how the Electricity exported to the grid decreases 1.48% each year compared to the previous year. Nevertheless, it can also be seen that, just like in the base case, the cash flow is positive, with the difference that it is positive in the 8th year of the project instead of the 7th year. However, if we compare the cash flow in the 25th year, it can be observed that the cash flow in the base case is 244,375,066 KZT higher than in the degradation case (Table 9 and Table 10), which indicates how the cash flow reduces when the degradation is included.
Table 10
CASH FLOW FOR DE-RATED PVSS

| Year | Electricity exported to grid (MWh) | FIT ($/MWh) | O&M (KZT) | Periodic costs | Annual Cash flow (KZT) | Cumulative Cash flow (KZT) |
|------|-----------------------------------|-------------|-----------|----------------|----------------------|---------------------------|
| 0    |                                   |             |           |                | -124,351,387         | -124,351,387               |
| 1    | 436.00                            | 34,000.00   | 960,000.00 |                | 13,864,000           | -110,487,387              |
| 2    | 429.55                            | 36,485.40   | 1,030,176  |                | 14,642,025           | -95,845,362               |
| 3    | 423.19                            | 39,152.48   | 1,105,481  |                | 15,463,453           | -80,381,908               |
| 4    | 416.93                            | 42,014.53   | 1,186,292  |                | 16,330,686           | -64,051,222               |
| 5    | 410.76                            | 45,085.79   | 1,273,010  |                | 17,246,256           | -46,804,965               |
| 6    | 404.68                            | 48,381.56   | 1,366,067  |                | 18,212,837           | -28,592,128               |
| 7    | 398.69                            | 51,918.25   | 1,465,927  |                | 19,233,245           | -9,358,882                |
| 8    | 392.79                            | 55,713.48   | 1,573,086  |                | 20,310,454           | 10,951,572                |
| 9    | 386.97                            | 59,786.13   | 1,688,079  |                | 21,447,596           | 32,399,169                |
| 10   | 381.25                            | 64,156.50   | 1,811,477  |                | 22,647,978           | 55,047,147                |
| 11   | 375.60                            | 68,846.34   | 1,943,896  |                | 23,915,083           | 78,962,230                |
| 12   | 370.05                            | 73,879.01   | 2,085,995  |                | 25,252,586           | 104,214,816               |
| 13   | 364.57                            | 79,279.56   | 2,238,481  |                | 26,664,362           | 130,879,179               |
| 14   | 359.17                            | 85,074.90   | 2,402,114  |                | 28,154,495           | 159,033,674               |
| 15   | 353.86                            | 91,293.88   | 2,577,709  | 12,435,139     | 17,292,154           | 176,325,829               |
| 16   | 348.62                            | 97,967.46   | 2,766,139  |                | 31,387,294           | 207,013,807               |
| 17   | 343.46                            | 105,128.88  | 2,968,344  |                | 33,139,284           | 240,153,090               |
| 18   | 338.38                            | 112,813.80  | 3,185,330  |                | 34,988,309           | 275,141,400               |
| 19   | 333.37                            | 121,060.49  | 3,418,178  |                | 36,939,685           | 312,081,085               |
| 20   | 328.44                            | 129,910.01  | 3,668,047  |                | 38,999,017           | 351,080,103               |
| 21   | 323.57                            | 139,406.43  | 3,936,181  |                | 41,172,212           | 392,252,315               |
| 22   | 318.79                            | 149,597.04  | 4,223,916  |                | 43,465,495           | 435,717,810               |
| 23   | 314.07                            | 160,532.59  | 4,532,685  |                | 45,885,425           | 481,603,236               |
| 24   | 309.42                            | 172,267.52  | 4,864,024  |                | 48,438,915           | 530,042,151               |
| 25   | 304.84                            | 184,860.27  | 5,219,584  |                | 51,133,249           | 581,175,401               |
In addition, both FIT and O&M costs increase each year because both escalation and inflation rates are considered (Table 10). As a result, in the case that includes degradation, the IRR is 15%, NPV is equal to 54,298,008 KZT, and the BCR is 1.44 (Table 11). Nevertheless, as the NPV is positive, BCR is higher than one, and the IRR is adequate, the project is feasible even when the degradation rate is considered. Moreover, as this study is one the first in considering the financial projections of implementing PVSS in the Mediterranean climate zone of Kazakhstan, it can be used as a reference in future projects.

### Table 11
**COMPARISON OF THE FINANCIAL INDICATORS FOR BOTH RATED and DE-RATED PVSS**

| Financial indicators | Case without degradation | Case with degradation | Reduction |
|----------------------|--------------------------|-----------------------|-----------|
| IRR (%)              | 17.9                     | 15                    | 19.3%     |
| NPV (KZT)            | 96,158,481               | 54,298,008            | 77.1%     |
| BCR                  | 1.8                      | 1.44                  | 25%       |

### Risk And Sensitivity Analysis For De-rated Ppvss

A Montecarlo analysis was performed with 500 different scenarios within a range of +/-10% of uncertainty variation in the input parameters. Hence with a risk of 5%, the equity payback period would be between 6.19 and 7.4 years. Thus, even with a low level of risk, the equity payback period would be shorter than ten years (Table 12).

### Table 12
**RISK ESTIMATION OF THE EQUITY PAYBACK PERIOD FOR DE-RATED PVSS.**

| Median                  | yr  | 6.7 |
|-------------------------|-----|-----|
| Level of risk           | %   | 5   |
| Minimum within level of confidence | yr | 6.19 |
| Maximum within level of confidence | yr | 7.4  |

On the other hand, according to the tornado chart (Fig. 3), the initial cost, FIT, and electricity exported to the grid have the higher impact on the equity payback period. Furthermore, higher initial costs would lead to longer equity payback. In contrast, higher values of FIT and electricity exported to the grid will decrease the equity payback period. Finally, as renewable energies are becoming more efficient and inexpensive over time, the equity payback period is likely reduced in the future which would increase the feasibility of the project (Otyrar).
Conclusion

On this study, the impact on the performance of on-grid PVSS affected by module degradation in Shymkent, a southern city in Kazakhstan was evaluated. Shymkent has a Mediterranean climate, and the analysis considered the feasibility of installing a PVSS at the roof of the International Airport of this city.

The degradation in PVSS performance due to local climate was estimated to be 1.48% per year, and its consideration leads to a significant deterioration of the feasibility of the system.

Moreover, if the PVSS degradation is included, the IRR, NPV, and the BCR of the investment would be reduced by 19.3%, 77.1%, and 25%, respectively. Thus, the degradation rate of PVSS in Mediterranean climate zones has major influence on the technical and financial performance of the system. Nevertheless, even after considering the degradation, our estimations suggest that the PVSS is feasible, and this study can be used as a reference for future PVSS, not only in the Mediterranean climate regions of Kazakhstan but also in any other area of the world that are subject to a similar climate.

Declarations

Consent for publication.

Not applicable.

Availability of data and materials.

All data generated or analysed during this study are included in this published article.

Competing interests.

The authors declare that they have no competing interests.

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Authors’ contribution.

Zhalgas Ismagulov and Adil Anapiya: reviewed previous works, existing models, and their formulation, as well as their applications and limitations. They also collected input technical-economic data, set up the initial model and participated in paper drafting.

Dinara Dikhanbayeva: revised and classified the data before introduced into the model. She also revised the literature review and energy model until completion. and participated in paper drafting and revision.
Luis Rojas-Solórzano: reviewed the model formulation and input data, as well as participated in the analysis of results and paper drafting and revision as a supervisor.

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