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Technical Note

Sustainable Development of Abandoned Mine Areas Using Renewable Energy Systems: A Case Study of the Photovoltaic Potential Assessment at the Tailings Dam of Abandoned Sangdong Mine, Korea

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Abstract: As mineral resources are depleted, most mines are typically abandoned and left unattended, resulting in serious social problems that impede sustainable development of these areas. The mining industry has recently introduced the use of renewable energy systems to solve the problems. This study assessed the photovoltaic (PV) potential of an abandoned mine tailings dam at the Sangdong mine in South Korea. A regional shading analysis and field investigations indicated that the usable area for installing the PV system was 44,220 m^2. The design capacity of the system was 3 MW considering the space available for the PV array. Power generation was simulated by inputting data about the hourly weather, system design, and a site assessment into System Advisor Model software. Simulation results indicated that 3509 MWh of electricity could be generated annually. Moreover, economic feasibility analysis, assuming a 20 year project period, confirmed that the net present value of the PV systems would be $1,903,000 USD. Therefore, installing a 3 MW PV system on the mine tailings dam at the Sangdong mine is feasible and could provide an efficient option for sustainable development of the abandoned mine land.

Keywords: renewable energy; abandoned mine; mine tailings dam; photovoltaic system; feasibility study

1. Introduction

Nowadays, the mining industry has used renewable energy systems at abandoned mines to support the sustainable development of mine areas [1]. For example, photovoltaic (PV) systems are operated at abandoned mines around the world, such as the Chevron Questa mine in the USA [2], the Meuro mine in Germany [3], and the Sullivan mine in Canada [4]. In the United States, large-scale wind farms have been installed at the Dave Johnston mine in Wyoming [5], the Somerset mine in Pennsylvania [6], the Zortman and Landusky gold mines in Montana [7], and the Buffalo Mountain mine in Tennessee [8]. These renewable energy projects have been successful in cultivating a substitute industry on land abandoned after mine closure [9].

Several studies were conducted to assess the feasibility of renewable energy projects at abandoned mine areas. In the United States, the National Renewable Energy Laboratory (NREL) and the Environmental Protection Agency (EPA) have operated the Re-Powering America's Land program, and performed preliminary investigations on the feasibility of siting PV, wind power, and hydroelectric systems at abandoned mines [10–12]. As a consequence, some PV power plants are operating at the Chino abandoned mine in New Mexico [13] and the VAG abandoned mine in Vermont [14]. In Australia, a 50 MW PV power plant is under construction at the Kidston abandoned mine in

Queensland [15]. In South Korea, some regional-scale studies have been conducted to analyze the PV and wind power potentials in seven abandoned mine promotion districts [16,17]. Moreover, the feasibility of PV systems that provide electricity to nearby facilities for treatment of acid mine drainage at abandoned mines was assessed at a local scale [18]. A PV system floating on a mine pit lake was analyzed at the Ssangyong open-pit limestone mine [19].

A few studies were carried out for planning and operating PV systems at abandoned mines. However, there are few studies assessing the potential of PV systems on the tailings dams in abandoned mine areas. A tailings dam is an earth-filled embankment dam used to dispose of uneconomic byproducts of mining operations after separating the valuable fraction of the ore. Since most abandoned mines have tailings dams, installation and operation of PV systems might be possible if the surface of the tailings embankment could be used. This might provide an alternative for the reuse of the abandoned land. Therefore, it is required to assess the potential of PV systems on mine tailings dams quantitatively.

Against this background, this study analyzed the potential of a 3 MW PV system on the mine tailings dam at the Sangdong mine in South Korea. A solar site assessment of the mine tailings dam was performed using a geographic information system (GIS) and a fish-eye lens camera. After designing a 3 MW PV system, the amount of electricity generated through the system and its economic potential were analyzed using the System Advisor Model (SAM) software developed by NREL.

2. Materials and Methods

2.1. Study Area

The study area is the abandoned mine tailings dam of the Sangdong tungsten mine located in Gangwon Province, South Korea (Figure 1). The Sangdong mine was one of the largest tungsten mines in Korea before ceasing production in 1992 due to low metal prices, and is considered to be the largest tungsten resource in the world [20]. This dam embankment incorporates approximately 4 million tons of mine tailings. This study focused on the wide, flat surface of the tailings embankment because many PV modules could be installed there without surface modification. Table 1 shows the meteorological site conditions of the study area.

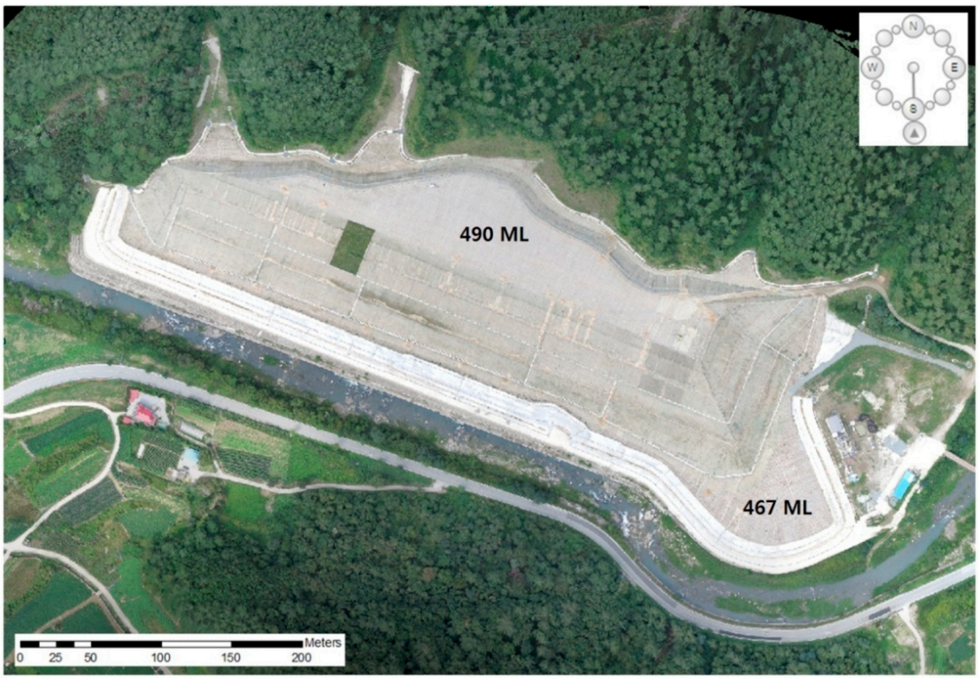

Figure 1. View of the abandoned tailings dam at the Sangdong mine in Korea.

Table 1. Meteorological site conditions of the study area.

Item	Value
Latitude (deg)	37.1
Longitude (deg)	128.8
Dry-bulb temperature (°C)	11.2
Direct normal irradiation (kWh/m^2/year)	1591.4
Global horizontal irradiation (kWh/m^2/year)	1262.9
Wind speed (m/s)	1.5

2.2. Methods

A five-step feasibility analysis was performed. In the first step, the area usable for installing a 3 MW PV system was analyzed, considering the surrounding topography. The study area was represented in 3D (Figure 2) using ArcGIS (ESRI, Redlands, CA, USA) and a digital topographic map published by the National Geographic Information Institute of Korea [21]. A digital elevation model (DEM) with 10 m grid spacing was created from the topographic contours (contour interval 5 m) of the map. In order to assess, conservatively, the shading effects on the surface of the tailings embankment, the daily hours of sunshine on the surface were analyzed at the winter solstice using the DEM and solar radiation analysis tool in ArcGIS [22]. This tool calculates the hours of sunshine at a specific location based on its latitude and altitude, while also considering the surrounding topography.

In the second step, detailed shade effects relating to trees and plants (or other light barriers) were examined through a field investigation. A skyline image at the solar site was captured using a fish-eye lens camera (SunEye 210 [23]). The image was used to analyze on-site barriers to light reception. A shading matrix was generated from the results of the shadow-effect analysis. For an explanation of the shading matrix, refer to [24].

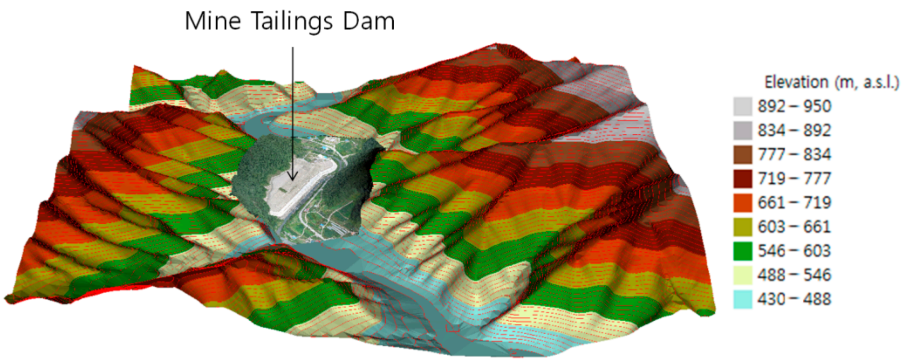

Figure 2. Representation of the 3D terrain around the study area.

In the third step, the 3 MW PV system was designed by considering the specifications of PV modules and inverters, the array spacing, and the area usable for PV installation analyzed in the first step. It was assumed that the PV modules would comprise solar arrays with a fixed tilt angle. Tables 2 and 3 list the parameters of the PV modules and inverters, respectively.

The open circuit voltage in the PV module (V_{module}) and the maximum and minimum maximum-power-point-tracking (MPPT) voltages in the inverter ($V_{mx-mppt}$ and $V_{mn-mppt}$) were used to determine the number of modules per string (M_S) using Equation (1). Equation (2) was used to calculate strings in parallel (S_p) by considering the total capacity of the PV system (C, kW), the module maximum power (P_{module}), and modules per string.

$$M_s = \left[\frac{V_{mx-mppt} + V_{mn-mppt}}{2}\right] / V_{module} \quad (1)$$

$$S_p = [(C \times 1000\ \mathrm{W/kW})/P_{module}]/M_s \tag{2}$$

Table 2. Parameters of photovoltaic modules used in this study.

Parameter	Value
Material	mono-Si
Manufacturer	Sunpower
Model	SPR-210-BLK
Length/Width (m)	1.5/0.8
Power capacity (kW/unit)	0.21
Efficiency (%)	16.9
Open circuit voltage (Voc)	47.7
Maximum power voltage (Vmp)	41.0
Nominal operating cell temperature (°C)	45.0
Temperature coefficient (%/°C)	0.4

Table 3. Parameters of inverters used in this study.

Parameter	Value
Manufacturer	Sunpower
Model	SPR-12000f
Efficiency (%)	95.5
Maximum AC power (W)	12,000.0
Nominal AC voltage (V)	240.0
Maximum DC voltage (V)	600.0
Minimum/Maximum Maximum-Power-Point-Tracking (MPPT) DC voltage (V)	230.0/500.0

The number of inverters (I_{EA}) was determined using Equation (3). R_{DC-AC} represents the DC-to-AC ratio, and was given a value of 1.0. Here, P_{inv} is the maximum AC power in the inverter:

$$I_{EA} = \left(M_s \times S_p \times P_{module}\right)/\left(R_{DC-AC} \times P_{inv}\right) \tag{3}$$

The fixed tilt angle of solar arrays was set to 35° considering the latitude of the study area. Moreover, Equation (4) was used to calculate the spacing between solar arrays [25]:

$$X1 = L \times \{cos(Tilt) + sin(Tilt) \times \tan(Lat + 23.5°)\} \tag{4}$$

where $X1$ is the spacing between solar arrays (m), $Tilt$ is the fixed tilt angle in degrees, L is the length of the module (m), and Lat is the latitude in degrees of the study area.

Next, Equation (5) was used to determine the total area of the solar site required. M_w denotes the width (m) of a module:

$$\text{Required area}\left(\mathrm{m}^2\right) = (M_s \times M_w) \times X1 \times S_p \tag{5}$$

In the fourth step, simulation of the electricity produced from the newly-designed PV system was performed using SAM software. SAM simulates PV power generation by comprehensively considering hourly weather data with module and inverter characteristics to project hourly estimates of electric power production [26]. The shading matrix generated from the onsite solar assessment and the meteorological data provided by the Korea Meteorological Administration [27] were entered into SAM. The Sandia PV array and inverter performance models [28] were selected to compute the electricity production. The simulation was conducted by considering the possible energy losses due to the electrical systems (Table 4).

Table 4. Parameters of energy losses considered in this study.

Item	Value
Average annual soiling loss	5.0%
Module mismatch loss	2.0%
Diodes and connections loss	0.5%
DC wiring loss	2.0%
AC wiring loss	1.0%

Finally, in the fifth step, the economic feasibility of the newly-designed PV system was evaluated, taking into consideration the costs, income, and policies relating to renewable energy in Korea. To approximately calculate the initial costs of the proposed PV system, the initial investment cost standard suggested by the International Energy Agency (IEA) was used. From this, $1.73 USD/W was used for the PV system, following the IEA trend in 2015 [29]. The annual operating cost ($24 USD/kW/year) was also taken from reports by the IEA [29].

This study used the Renewable Portfolio Standard (RPS) system in South Korea implemented in 2012 to estimate the income obtained from electrical power generation. It is a compulsory system for renewable energy supply and, under this system, electric power transactions are carried out using renewable energy certificates (REC) [30] issued by the Korea Energy Management Corporation. The system marginal price (SMP) [31] and the REC price were considered in determining the amount obtained as income through the selling of electric power. Since REC prices fluctuate monthly in the market, the annual average REC values from 2012 to 2015 were applied, in addition to the SMP price. A REC price of $123 USD/MWh and an SMP price of $119 USD/MWh were used. In addition, REC was weighted according to weight factors for each renewable energy source, which are to be implemented from March 2015. The equations used to apply REC weight factors vary according to installation capacities (C, kW). Equation (6) was applied to calculate REC weights, and is used when the installation capacity (C) is between 100 kW and 3000 kW [32]:

$$\frac{99.999 \times 1.2}{C} + \frac{2900.001 \times 1.0}{C} + \frac{(C - 3000) \times 0.7}{C} \tag{6}$$

Equation (7) was used to calculate the net present value (NPV) of the designed PV system:

$$\text{NPV} = \sum_{t=1}^{N} \frac{E_t - C_t}{(1+r)^t} - C_0 \tag{7}$$

Here, NPV is the net present value (USD), N is the system operating period (year), C_t is the annual operating cost (USD), E_t is the annual income from the sale of electric power (USD), r is the discount rate, and C_0 is the initial cost (USD). This study applied the social discount rate of 5.5%, as proposed by the Korea Development Institute [33], and assumed the project period to be 20 years, in line with the typical lifetime of PV systems [34,35].

3. Results and Discussion

3.1. Results

Sun hours on the mine tailings dam at the winter solstice were analyzed using the DEM and the solar radiation analysis tool in ArcGIS (Figure 3). The maximum number of sunshine hours was 7.9 h/day, and the minimum was 6.1 h/day. Analysis results indicated that PV energy production could occur during a minimum of 6.1 h, to a maximum of 7.9 h per day, without interference from shadows cast by the surrounding topography on the mine tailings dam. As the average daily sunshine hours in Korea is 5.8 h/day [27], the entire surface of the tailings embankment, an area of 46,335 m^2, was usable for the PV installation.

The skyline image of the center part of the tailings embankment surface was captured using a fish-eye lens camera (SunEye 210) and the images used to itemize small obstructions (Figure 4). The result showed that on-site barriers to light reception were distributed to the east and west of the center point. On-site barriers were mainly related to the surrounding topography rather than to trees and other plants. Table 5 presents the shading matrix generated by checking the distribution of light obstructions from on-site barriers.

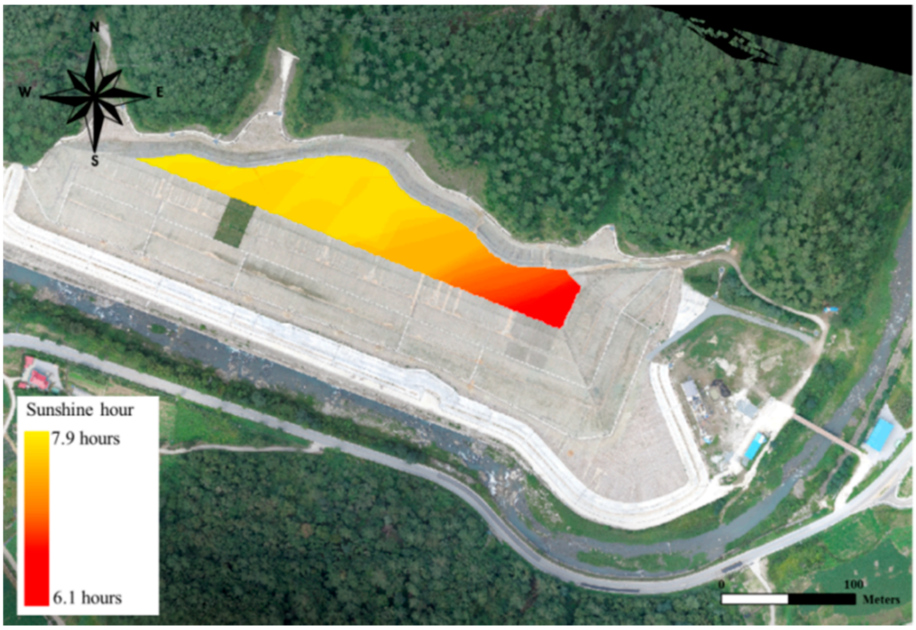

Figure 3. Daily sunshine hours on the surface of the tailings embankment at the winter solstice.

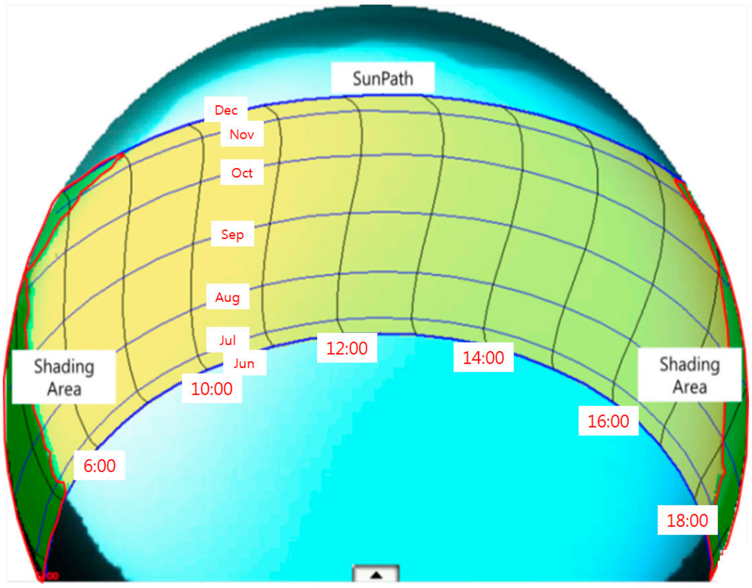

Figure 4. Result of shading analysis using a fish-eye lens camera (SunEye 210).

Table 5. Shading matrix generated from the onsite solar assessment.

Month	Time														
	5	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**
January	0	0	0	0.02	0.63	1	1	1	1	1	0.96	0.72	0.02	0	0
February	0	0	0.04	0.64	0.99	1	1	1	1	1	1	0.99	0.44	0.06	0
March	0	0.10	0.56	1	1	1	1	1	1	1	1	1	0.84	0	0
April	0	0.09	0.83	1	1	1	1	1	1	1	1	1	0.92	0.03	0
May	0	0.24	0.92	1	1	1	1	1	1	1	1	1	1	0.33	0
June	0	0.25	0.92	1	1	1	1	1	1	1	1	1	1	0.65	0
July	0	0.15	0.89	1	1	1	1	1	1	1	1	1	1	0.69	0
August	0	0.10	0.84	1	1	1	1	1	1	1	1	1	0.99	0.21	0
September	0	0.17	0.84	1	1	1	1	1	1	1	1	1	0.73	0	0
October	0	0.04	0.64	1	1	1	1	1	1	1	1	1	0.26	0	0
November	0	0	0.02	0.54	0.98	1	1	1	1	1	0.97	0.60	0	0	0
December	0	0	0	0.01	0.61	1	1	1	1	1	0.89	0.42	0	0	0

After considering the specifications of the PV modules and inverters (Tables 2 and 3) and the usable area on the surface of the tailings embankment, the 3 MW PV system was designed as presented in Table 6 and Figure 5. Since the area required for the PV installation was 32,551 m^2, the study area was of sufficient size. The PV arrays are quite rugged and resistant to electrical and mechanical damage, therefore, they should be attached to a mechanical support structure. In this study, the PV arrays were designed to be mounted on fixed steel poles set in concrete, and stood off several meters above the ground to allow air ventilation that will keep them as cool as practical.

Figure 6 shows the changes in monthly electric power generation estimated after entering meteorological site data, the shading matrix, and system design parameters into the SAM software. The PV system on the mine tailings dam could produce 3509 MWh of electric power annually. Power production would fluctuate between seasons (generally high in the spring and fall but lower in winter due to reduced solar radiation). It should be noted that in the summer, power generation would drop in comparison with spring and fall, due to the rainy season in Korea and to the intermittent occurrence of typhoons.

Table 6. Design specifications of PV modules, inverters, and capacity.

Parameter	Value
Array spacing (m)	1.97
Modules per string	8
Array area (m^2)	18.69
Strings in parallel	1742
Total number of modules	13,936
Total number of inverters	652
Total capacity of PV system (kW)	3000
Area required (m^2)	32,551
Area usable for installing a PV system (m^2)	44,220

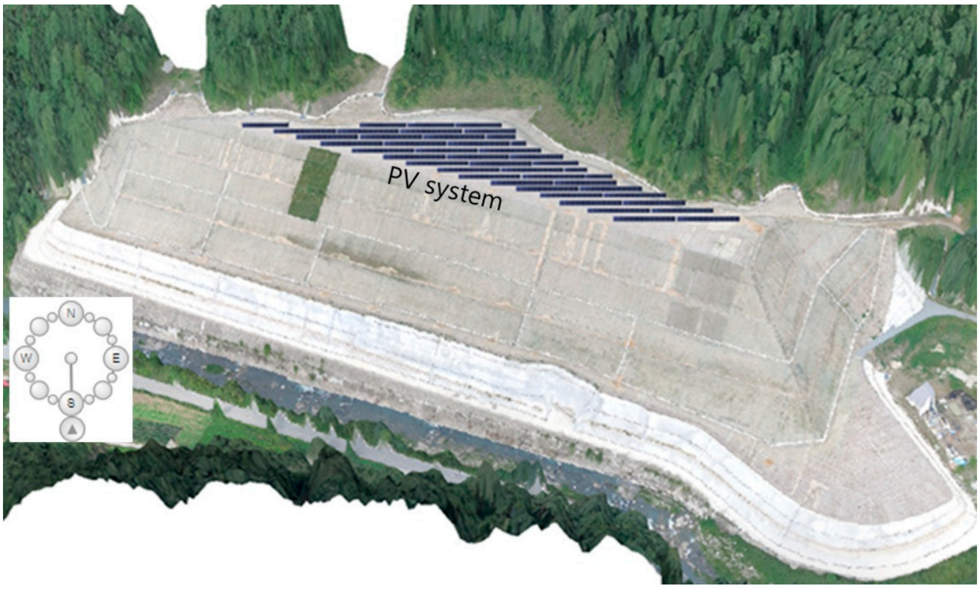

Figure 5. 3D view of the PV system designed at the study area.

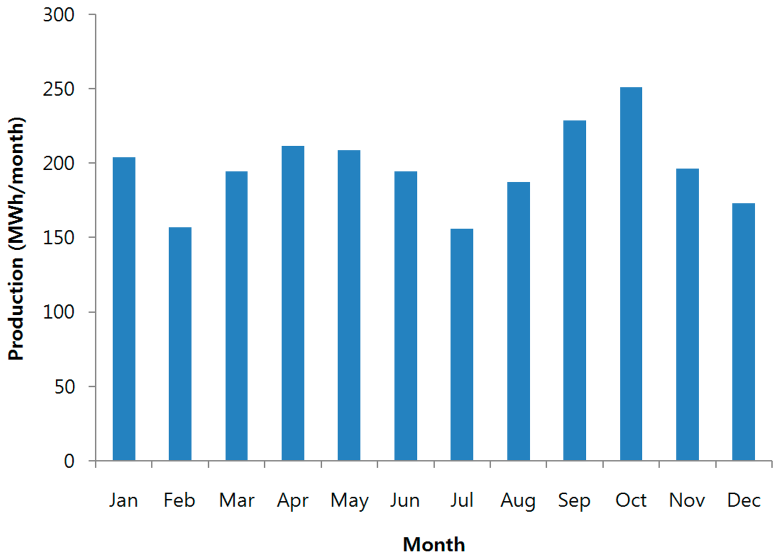

Figure 6. Variation in monthly electricity production estimated for the 3 MW PV system in the study area.

Table 7 indicates the results of an analysis of the economic potential by setting the initial investment cost of the PV system at $5,189,000 USD and considering the SMP and weighted REC. Income from the sale of electricity was expected to be $737,000 USD in the first year. The payback period was estimated to be about 11.5 years. The NPV calculated over 20 years stood at $1,903,000 USD, with an internal rate of return (IRR) of 9.8%.

Table 7. Results of economic analysis for the 3 MW PV system in the study area.

Item	Value
REC weight factor	1.0
Investment cost ($\times 10^3$ USD)	5189
Income in first year ($\times 10^3$ USD)	737
Net present value ($\times 10^3$ USD)	1903
Payback (year)	11.5
Internal rate of return (%)	9.8

3.2. Discussion

Mining is widely accepted to be potentially hazardous to public health and safety, as well as to the surrounding environment [36,37]. Areas adjacent to mines are exposed to many safety and health problems due to ground subsidence and toxic minerals dissolved into water and soil [38–40]. Therefore, mine areas are usually neglected and not utilized for other purposes once they are closed due to depletion.

In areas with abandoned mines, a local economic slump aggravated by the "doughnut effect" phenomenon (inhabitants moving away from contaminated areas) have occurred, resulting in serious social problems that impede sustainable development of such areas. In many countries, a variety of promotion policies and projects were launched to solve these problems. Moreover, many studies have been conducted worldwide to provide better promotion policies for sustainable development of abandoned mine areas, and to assess the social impacts on their communities [41,42].

For instance, 90% of all mines in Korea are abandoned, most left unattended [43]. Therefore, the Korean government selected seven abandoned mine promotion districts in 1995 according to the "special act on development of abandoned mine areas". It carried out several projects to cultivate a tourism industry on abandoned land by installing large-scale entertainment resorts including casinos, museums, and golf courses [44]. However, the effect of projects on abandoned mine areas was temporary because tourism based on large-scale entertainment resorts was not sustainable in areas near abandoned mines due to the adverse local conditions. These included factors such as the human social environment, geographical accessibility, and business environment [45,46]. Therefore, new promotion policies and projects are required to promote the reuse of abandoned mine land in Korea. From the results, we determined that installing a 3 MW PV system on the mine tailings dam at the abandoned Sangdong mine is feasible and could provide an efficient option for sustainable development of the abandoned mine land.

4. Conclusions

In this study, the feasibility of a 3 MW PV system to be installed on the abandoned mine tailings dam at Sangdong mine in Korea was assessed. The PV system was designed in consideration of the voltage relationship between the PV modules and inverters, and spacing of the PV array, after a solar site-assessment using GIS and a fish-eye lens camera. The annual amount of electricity that could be generated by the PV system was estimated at 3509 MWh/year. In addition, results of an economic feasibility analysis indicated that the net present value would be $1,903,000 USD by establishing a project period of 20 years. The payback period (capital recovery) was calculated to be 11.5 years, with an IRR of 9.8%. Therefore, installing a 3 MW PV system on the abandoned tailings dam at the Sangdong mine is recommended as an efficient option for sustainable development of this abandoned mine land. In future work, further technical elements should be considered to design the 3 MW PV power plant in details.

Installation of a large-scale PV system on the surface of the tailings embankment has not been considered as an option for reuse of abandoned mine land. According to this analysis, however, using the abandoned mine tailings dams for large-scale PV systems is feasible and economically beneficial. In terms of the environment, environmental restoration projects could be promoted at abandoned mine areas through redevelopment of sites polluted by mine tailings. Moreover, the creation of new business models and jobs related to the design, construction, and operation of systems utilizing renewable energy should stimulate growth in local economies. For these reasons, the use of renewable energy technology, including PV systems, in the mining industry is expected to continue to provide incentives for sustainable development of abandoned mine areas.

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Author Contributions: Yosoon Choi conceived and designed the experiments; Jinyoung Song performed the experiments; Yosoon Choi analyzed the data and contributed reagents/materials/analysis tools; Yosoon Choi and Jinyoung Song wrote the paper.

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