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A Techno-Economic Feasibility Analysis for the Production of Solar Photovoltaic Modules in Sudan

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Abstract

This paper is intended to evaluate the economic viability of producing solar photovoltaic modules in Sudan. The simple payback period and the net present value were used as economic indicators to study comparatively different annual production capacities. Initial and operating costs were developed and analyzed for the product lifecycle. The number of working shifts in the base case is doubled to achieve a production rate of 20 MW/year and double shift with double quantity of machines is executed to reach a production capacity of 40 MW/year. The total initial cost for annual production of both 10 MW and 20 MW is USD 418,400.00 and for 40 MW is USD 776,800.00. The range of production cost for solar PV modules in Sudan was found to be 434.29 USD/kW- 445.87 USD/kW. Raw materials cost dominated by solar cells has the most significant contribution to the production cost. Although of the higher initial cost for the annual production capacity of 40 MW, but it is still outperforming in the payback period and at the same selling price of 450.00 USD/kW, the payback period is 1.1 years for 40 MW, 1.48 years for 20 MW, and 5.03 years for 10 MW.

Keywords

Photovoltaic; clean production; sustainability; renewable energy; payback period

1. Introduction

Sudan is a developing country that has an urgent need to face its increasing energy demand with sustainable energy supply pathways through renewable energy that already available abundantly in the country. Solar energy is available intensively in Sudan [1], and investment in the development of systems to utilize this valuable resource would benefit the overall sustainability pillars of economic, environmental, and social aspects. Manufacturing of solar systems locally in Sudan would encourage proper use of natural resources, improve the economic feasibility through reducing overhead importing cost, and create new jobs for better social life. Exporting of locally manufactured solar systems can contribute positively to the economy of Sudan and alleviate the increased inflation rates by bringing more hard currency. Ten African countries of intensive solar energy resources are surrounding Sudan [2, 3], and the region has a high demand for solar photovoltaic modules to satisfy the deficiency in the supply of sustainable power generation.

Applications of solar photovoltaic (PV) systems are started to penetrate significantly as the cost of production reduced dramatically in the recent few years, and the technology of modules production is in continuous improvement. Solar PV modules are economically competitive enough in Sudan to power water pumping for irrigation [4, 5], lighting systems, radio, and television devices [6]. Photovoltaic systems are spread-out all over rural areas in Sudan to power vaccination refrigerators [7]. Beside economic viability of solar PV systems compared to the other conventional and renewable energy-based power generation, modules have the advantages of simple design, lightweight, and mature technology with the efficient conversion of both direct and indirect solar radiation [8]. Power generation from solar PV systems have low operating cost, require no cooling systems, and chemical storage (batteries) is a well-established technology which improved the complete system reliability drastically and addressed the intermittency of solar radiation problem. The main disadvantages of solar PV systems are the high initial cost, need a large area of land, and fluctuation of solar radiation has a direct negative impact on the performance and power output of the system [9].

Low labor cost in Sudan [10] is in favor of the economic feasibility for local manufacturing of solar photovoltaic modules. Economic indicators are developed as vital tools for evaluating an investment in a project. Payback period [11-13] and net present value (NPV) [14, 15] have been used as comprehensive economic indicators to analyze the feasibility of the investment. The payback period is the time length counted from the start-up of the investment up to the point of time when all costs are recovered. Two types of simple and discounted payback period have been used to evaluate the investment [16, 17]. The time value of money has to be considered in the two indicators discounted payback period and net present value to accompany some uncertain values such as the expected interest rate [9, 18]. Besides the uncertainty of the expected interest rate, it is also unacceptable in completing the business deals in Islamic Countries such as Sudan because it is prohibited according to this religion.

Most of the earlier solar energy studies conducted for Sudan were focused on the availability of the resources by developing theoretical correlations to estimate the solar intensity in different regions of the country [19-22]. Some earlier studies developed a techno-economic analysis of the renewable energy applications manufactured locally in Sudan and others conducted for ready systems imported from the European countries. El Dam [23] conducted comparative techno-economic analysis for wind energy systems manufactured locally in Sudan with other diesel water pumping systems imported from abroad. Sloetjes et al. [24] investigated the design and cost of a solar cold storage system manufactured in the Netherland and installed for operation in Sudan.

Locally manufactured solar energy systems in Sudan are scarce and need detailed feasibility studies to convince stakeholders to invest in this new clean production projects. Sudan can have environmental benefits through balanced international trade with the exporting industrialized countries. Huang et al. [25] studied the environmental benefits from China-Africa international trade and highlighted that China is mainly importing raw materials while exporting manufactured products to Africa. The significant contribution of this paper is to provide economic viability of locally manufactured solar PV modules in Sudan and to emphasize sustainability through environmental and social benefits to the country. The detailed and propper feasibility study would encourage investors to enter confidently into such clean production projects.

The main objectives of this study are to:

- Analyze the feasibility of manufacturing solar PV modules in Sudan through simple payback period and net present value;
- Study the effect of the economies of scale through varying the annual production from the base case 10 MW/year to a double of 20MW/year, and four folds of 40 MW/year;
- Develop the profile of the payback period and net present value under variable selling price; and
- Study the impact of initial and different operating costs on the production cost.

2. Methods

Initial and operating costs were estimated based on a plant to produce solar PV modules with a total annual production capacity of 10 MW in the base case. The required machines, operation, and raw materials are set to cover the manufacturing process and to evaluate the cost of production.

The simple payback period is used in this paper as an economic indicator for the feasibility analysis of assembling solar PV modules in Sudan. The simple payback period (SPback) is calculated from the balance of the initial cost (INcst) and the net cash flow [16, 17] as:

$$\mathbf{SPback} = \frac{\mathbf{INcst}}{\mathbf{GYrev - RYcst}} \qquad \mathbf{(1)}$$

where GYrev is the accumulation of the uniform annual revenue and RYcst is the uniform annual running cost includes raw materials, workforce, and all other operating costs.

The revenue is generated from the selling of the produced modules, and the price is expressed in this study per unit power (Sprice in USD/kW):

$$\mathbf{GYrev = Sprice * PW} \qquad \mathbf{(2)}$$

where PW is the total annual production capacity of solar PV modules in kW.

Different plant sizes are studied in scenarios by increasing the annual production to two capacities of 20 MW and 40 MW. The sensitivity analysis is conducted to study the impact of variation of each of raw materials, workforce cost, initial investment, and other operating costs on the production cost. The net present value (NPV(k)) at a specific year (k) is estimated for the production lifetime from the net cash flow (NCF (k)), interest rate (i), and the salvage value (SALV) is added at the end of the period:

$$\text{NPV (k)} = \frac{\text{NCF (k)} + \text{SALV}}{(1+i)^k} \qquad (3)$$

The special effect of the raw materials, workforce, initial, and other operating costs on the production cost were also studied in the sensitivity analysis section.

3. Manufacturing Process

The solar cells are sorted out according to their appearance and delivered to the tester to check their efficiency and stacked together accordingly. The type of the produced solar PV modules depends mainly on the manufacturing process and materials used for the solar cell such as monocrystalline, polycrystalline, or thin film. After this first quality test, the solar cells are cut by passing through a laser scribing machine (to be used only with small-size modules). Solar cells are welded together by fully automatic tabber and stringer machine to form the first shape of the module. Before the lamination process, the material of Ethylene Vinyl Acetate (EVA) and Tedlar Polyester Tedlar (TPT) are prepared and cut into sizes suitable for the size of the solar PV module. The lay-up is done by putting the intended solar PV module as a sandwich between EVA in the upper and lower surfaces, covered with glass at the top surface, and TPT at the bottom surface. The busbar is connected by welding, and the solar module is transferred to the visual check and electroluminescence (EL) testing to detect microcracks and other invisible defects in the module. The solar PV module is then passed through a fully automatic machine for lamination, trimming, and EL test. The product is passed to a framing machine to put the Aluminium frames around the module. The junction box is fixed to the backside of the module, and gluing would take place. The voltage (V) and current (I) of the module are tested, passed to EL tester, fix the specifications label, and packed ready as a final product transported to the warehouse. Figure 1 shows a brief layout of the production line for solar PV modules.

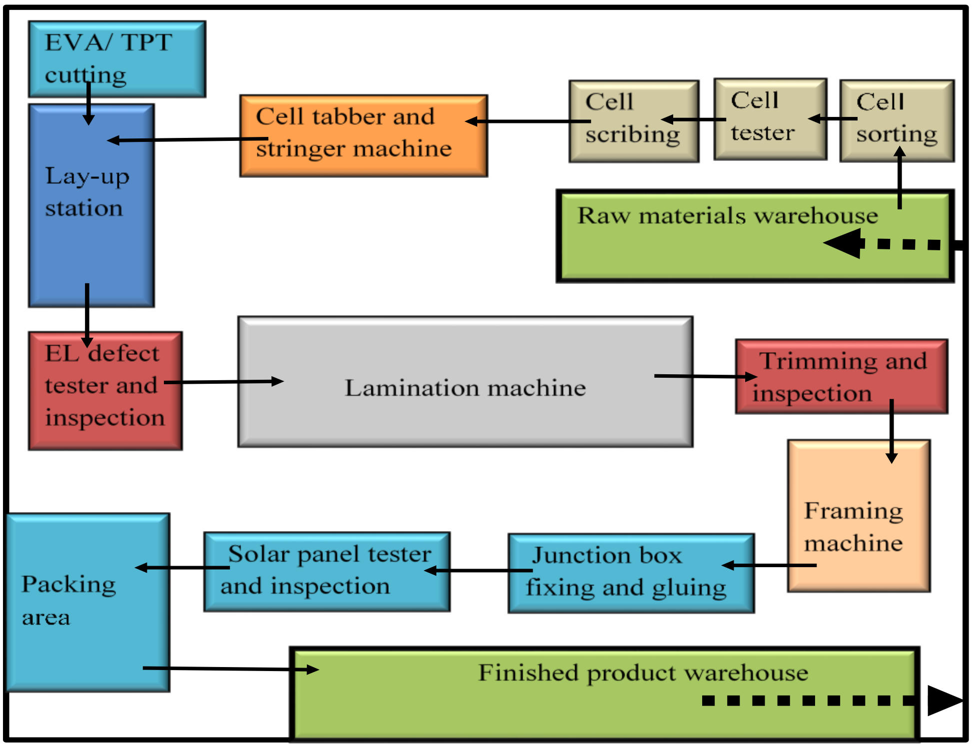

Figure 1 Layout for the production line of 10 MW/year solar PV modules.

4. Cost Development

The initial costs for annual production of 10 MW solar PV modules were set after consulting with the experts and machines suppliers [26-28]. Buildings construction and other overheads were estimated for the case of Sudan. The total initial cost is USD 418,400.00, as detailed in Table 1. For the increased annual production capacity to 20 MW, the quantity of machines is kept the same, and the production is doubled by increasing to two shifts, with one shift period of 8-hours and 300 working days per year. The annual production capacity of 40 MW is achieved by doubling the quantity of the machines and maintaining the same double-shift system. The land and buildings construction costs are assumed at USD 150,000.00 in case of 40 MW/year and the shipping, customs duty, and start-up training up to USD 40,000.00 to reach the total initial cost of USD 776,800.00.

Solar cells are assembled to produce solar PV modules, and the required raw materials are detailed in Table 2 with a total of 3,991,966.30 USD/year to produce 10 MW of modules, which is doubled and increased by four folds to produce 20 MW, and 40 MW, respectively.

Table 1 Initial cost for production of 10 MW/year solar PV modules [a].

Item	Quantity	Unit cost (2017 USD)	Total cost (2017 USD)
Full-automatic solar cell tabber and stringer machine	1	81,000.00	81,000.00
Full automatic laminator	1	54,000.00	54,000.00
Solar cell tester	1	9,000.00	9,000.00
Solar simulator (IV) tester	1	12,600.00	12,600.00
Online full automatic solar panel EL defect tester	1	20,700.00	20,700.00
Frame and angle combining	1	9,900.00	9,900.00
Auto lay-up machine	1	40,500.00	40,500.00
EVA/TPT cutting workstation	1	1,350.00	1,350.00
Mirror observation platform	1	3,150.00	3,150.00
Auto conveyor systems for glass delivery to auto lay-up station	1	13,500.00	13,500.00
Auto conveyor systems from lay-up station to laminator	1	27,000.00	27,000.00
Ribbon cutting machine	1	2,250.00	2,250.00
Module transfer carrier	3	2,250.00	6,750.00
Ready material carrier	3	3,150.00	9,450.00
String cell carrier	1	900.00	900.00
Trimming table	1	450.00	450.00
Glued junction box desk	1	900.00	900.00
Shipping, customs duty, and start-up training			25,000.00
Land and buildings construction [b]			100,000.00
Total			**418,400.00**

[a] Based on the manufactured and imported machines from China [26-28].

[b] Assumed in an industrial area, and the Sudanese Government subsidizes the land.

Table 2 Raw materials cost for annual production of 10 MW solar PV modules [a].

Item	Quantity	Unit cost (2017 USD/year)	Total cost (2017 USD/year)
Solar cell	2,343,750	1.15	2,695,312.50
EVA Film	440	215.00	94,600.00
Back sheet	660	295.00	194,700.00
Junction box	40,000	4.01	160,400.00
Soldering ribbon	5,480	16.48	90,310.40
Bus wire	1,830	16.48	30,158.40
Adhesive tape	6,000	0.36	2,160.00
Silicon gel	33,500	2.35	78,725.00
Aluminum framer	40,000	8.96	358,400.00
Tempered glass	40,000	7.18	287,200.00
Total			**3,991,966.30**

[a] Based on a Polycrystalline module of 250 W and all materials are imported from China [27].

The organization and management system for the plant is studied to estimate the workforce cost. The plant manager is technically responsible for the daily operation and follow-up of the production plan. Research and development (R&D) is an independent section to establish clear plans for the product and staff arrangement to achieve the highest possible performance with the most cost-effective and efficient ways. The unit operations are detailed in Figure 2, and the annual salaries for the workforce are given in Table 3. The total salaries for the workforce of 91 persons to produce 10 MW/year are 364,900.00 USD/year, and the corresponding total is rearranged for the other annual production capacities to reach 150 persons with a total cost of 613,300.00 USD/year for 20 MW and 263 persons with 1,095,800.00 USD/year for 40 MW. Table 4 shows the other operating costs.

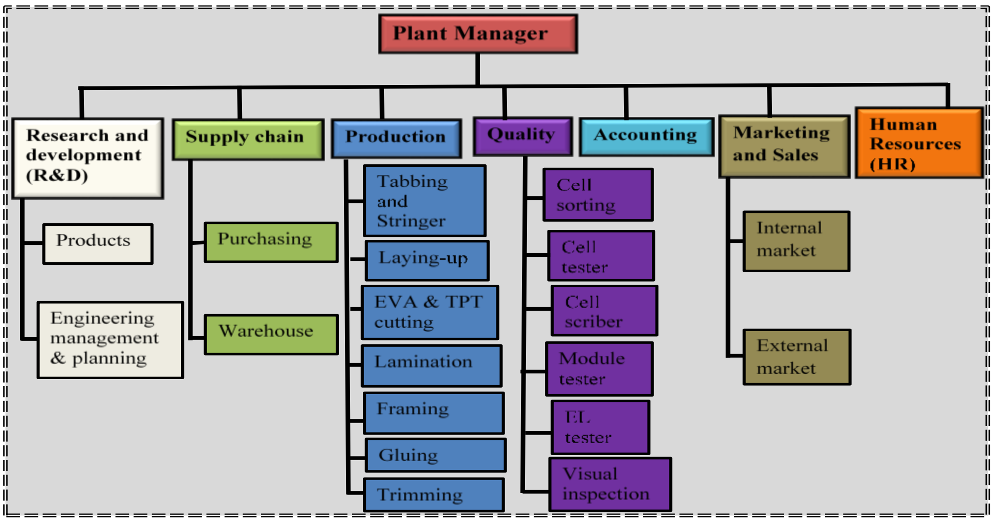

Figure 2 The unit operations for the annual production of 10 MW solar PV modules.

Table 3 The workforce cost for annual production of 10 MW solar PV modules.

Item	Number (person)	Salary (2017 USD/year)	Total cost (2017 USD/year)
Plant manager	1	6,000.00	6,000.00
Maintenance manager	1	5,400.00	5,400.00
Research and development staff	3	5,500.00	16,500.00
Purchasing staff	3	4,000.00	12,000.00
Warehouse staff	5	3,500.00	17,500.00
Tabber and stringer machine operator	4	5,000.00	20,000.00
EVA/TPT cutting operator	4	3,500.00	14,000.00
Glass/solar module carrier	5	3,500.00	17,500.00
Lay-up station operator	2	3,500.00	7,000.00
Lamination machine operator	4	5,000.00	20,000.00
Framing machine operator	3	4,000.00	12,000.00
Junction box and gluing fixer	6	4,000.00	24,000.00
Finished product carrier and packing staff	4	3,500.00	14,000.00
Cell sorter	4	4,500.00	18,000.00
Cell tester	4	5,000.00	20,000.00
Module tester	4	5,000.00	20,000.00
EL tester	4	4,500.00	18,000.00
Visual tester	2	4,500.00	9,000.00
Accounting staff	3	4,000.00	12,000.00
Marketing and sales staff	7	4,500.00	31,500.00
Human resources staff	3	4,000.00	12,000.00
Total	**91**		**364,900.00**

Table 4 Other operating costs for the annual production of solar PV modules.

Item	10 MW (2017 USD/year)	20 MW (2017 USD/year)	40 MW (2017 USD/year)
Spare parts and maintenance	40,000.00	80,000.00	160,000.00
Production tax	5,000.00	10,000.00	20,000.00
Electricity consumption	5,000.00	10,000.00	20,000.00
Phone, Internet, and IT services	5,000.00	10,000.00	10,000.00
Safety accessories for the workers	5,000.00	10,000.00	20,000.00
Total	**60,000.00**	**120,000.00**	**230,000.00**

5. Results and Discussion

5.1 Base Case

The production cost for the solar PV modules in the base case is 445.87 USD/kW over an assumed lifetime of 10-years. Figure 3 shows the disaggregated production cost for the base case. The contribution of raw materials is dominant in the production cost of solar PV modules due to the share of solar cells cost. Raw materials have about 90% of the total production cost, and solar cells required 68% of the total raw materials cost (see Table 2). This case could be specific to Sudan due to the low workforce and other operating costs.

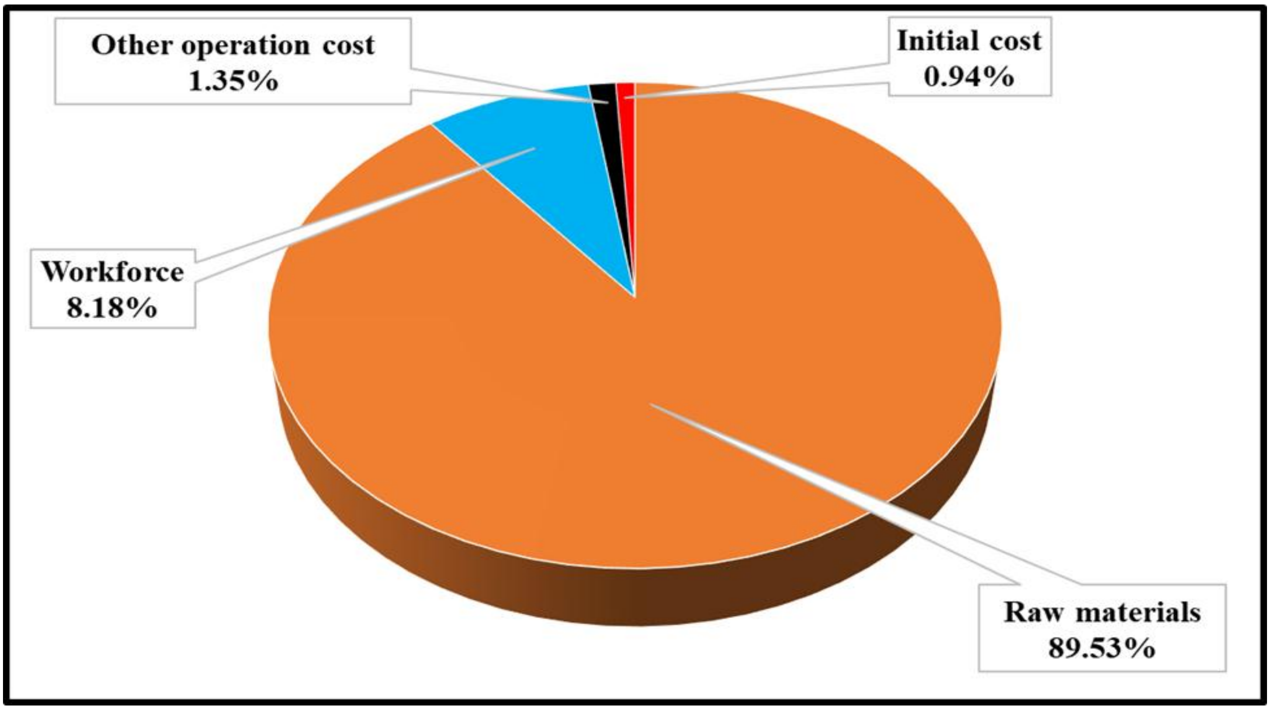

Figure 3 The disaggregated production cost for the base case. [Note: The initial cost is distributed equally over the lifetime of ten years (41,840.00 USD/year).]

The simple payback period profile with the selling price for the base case is shown in Figure 4. The selling price should be adjusted at a higher than 484.00 USD/kW to achieve a payback period of less than one year, and at a payback period of nine years, the selling price should be set at 446.34 USD/kW. The narrow range of the selling price to achieve a reasonable payback period of fewer than ten years is due to the little contribution of the initial cost on the total cost of production (see Equation.1). Applying a selling price higher than the production cost by only 4% would achieve a payback period of two years, which indicates that this project is of low financial risk. A selling price of slightly higher than 1000 USD/kW is considered for imported solar photovoltaic modules to study the feasibility of water pumping systems in Sudan [9].

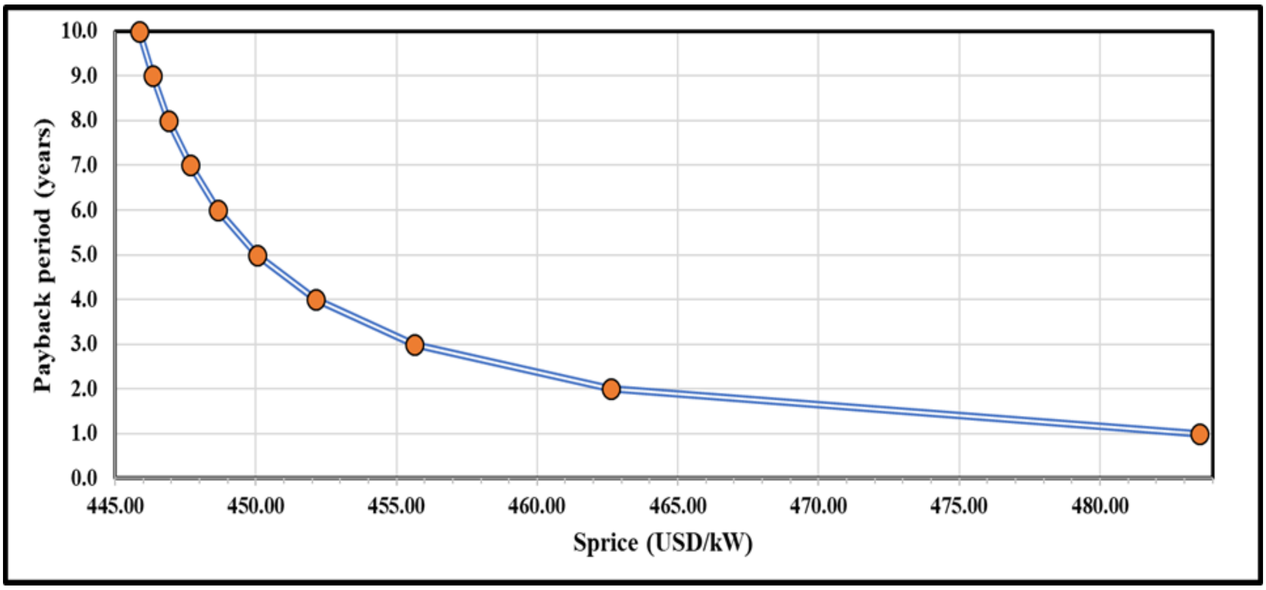

Figure 4 Payback period profile for the base case.

5.2 Sensitivity Analysis

The studied annual production capacity of 10 MW in the base case is increased to 20 MW and 40 MW to analyze the impact of economies of scale on the payback period, net present value, and production cost.

Figure 5 shows the payback period profiles with the selling price for the three studied annual production capacities. The profile of 40 MW/year is always outperforming at the left part of Figure 5 and at a selling price of 450.00 USD/kW, the payback period for 40 MW is 1.1 years, 1.48 years for 20 MW, and 5.03 years for 10 MW.

The production cost in the base case 445.87 USD/kW is reduced by 7.91 USD/kW and 11.58 USD/kW for 20 MW and 40 MW, respectively.

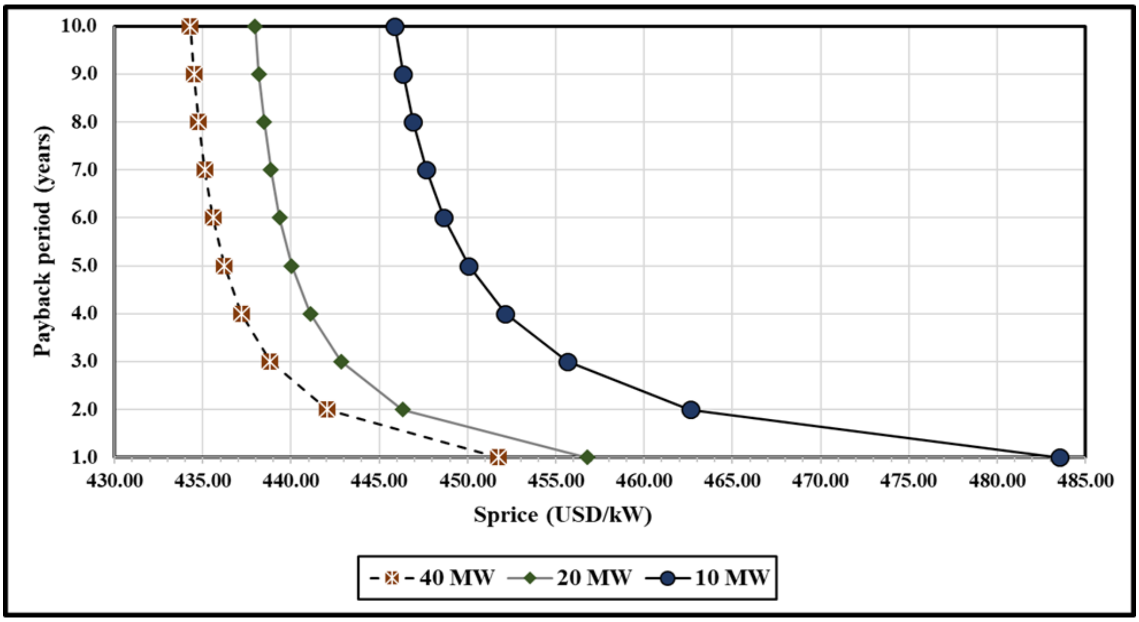

Figure 5 Payback period profile for the three studied cases.

Table 5 indicates that most of the production cost is occupied by the cost of the raw materials followed by the workforce cost. Other operating and initial costs are the least sensitive factors to the production cost with minor contributions.

Table 5 Disaggregated production cost for the three studied cases.

Item	10 MW (2017 USD/kW)	20 MW (2017 USD/kW)	40 MW (2017 USD/kW)
Raw materials	399.20	399.20	399.20
Workforce	36.49	30.67	27.40
Other operating costs	6.00	6.00	5.75
Initial cost	4.18	2.09	1.94
Total	**445.87**	**437.96**	**434.29**

Table 6 shows the cash flow for the base case, and Figure 6 shows the net present value profile of the tenth year (k=10) under different selling price conditions with the interest rate of 5%. The net present value at ten years with a selling price 500.00 USD/kW is found to be USD 400,967.00 for the base case, increased by 2.07 folds for 20 MW, and by 4.3 folds for 40 MW. To achieve NPV (10) equals to two million USD, the corresponding selling price has to be 760.00 USD/kW for the base case, decreased by 22% for 20 MW, and decreased further by 33% for 40 MW.

Table 6 Depreciation, cash flow, and net present value for annual production of 10 MW solar PV modules.

Year	Salvage Value[a] ($)	Workforce[b] ($)	Raw materials [c] ($)	Other operating cost[d] ($)	Revenue[e] ($)	Cash flow [f] ($)	Net present Value [g] ($)
1	418,400	364,900	3,991,966	60,000	5,000,000	164,734	156,889
2	379,689	364,900	3,991,966	60,000	5,000,000	583,134	528,919
3	340,978	364,900	3,991,966	60,000	5,000,000	583,134	503,733
4	302,267	364,900	3,991,966	60,000	5,000,000	583,134	479,746
5	263,556	364,900	3,991,966	60,000	5,000,000	583,134	456,901
6	224,844	364,900	3,991,966	60,000	5,000,000	583,134	435,143
7	186,133	364,900	3,991,966	60,000	5,000,000	583,134	414,422
8	147,422	364,900	3,991,966	60,000	5,000,000	583,134	394,688
9	108,711	364,900	3,991,966	60,000	5,000,000	583,134	375,893
10	70,000	364,900	3,991,966	60,000	5,000,000	653,134	400,967

[a] Depreciated with straight line and assumption that the salvage value after 10 years would equal to 70% of land and buildings value; [b] Detailed in Table 3; [c] Detailed in Table 2; [d] Detailed in Table 4; [e] Calculated according to Equation.2, at a selling price Sprice = 500 USD/kW and an annual production capacity PW=10,000 kW; [f] Calculated as a net of revenue minus the costs. The capital cost is deducted from revenue in the first year, and the salvage value is added in the last year; [g] Calculated according to Equation.3, at an interest rate i =5%.

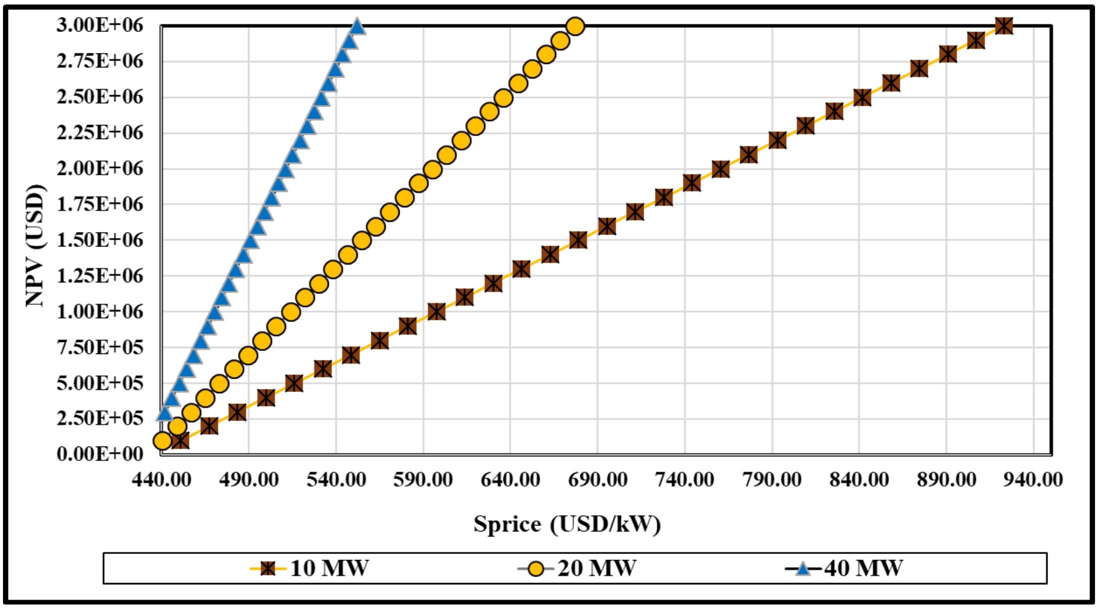

Figure 6 Net present value profile for the three studied cases. [Note: NPV (k) is estimated from Equation.3 at variable Sprice, k=10 years, i = 5%, and SALV (10) = 70% of land and buildings value.]

The profile of NPV distributed on the lifetime is shown in Figure 7 with a selling price fixed at 500.00 USD/kW; interest rate variated to 2%, 5%, and 10%. Under these conditions, the peak net present value achieved in the second year of production after the revenues recovering the initial and operating costs. At the tenth year of production (k=10), NPV (10) of the base case at an interest rate 2% (535,737.00 USD) is closer to the NPV (10) of 20 MW at an interest rate 10% (521,550.00 USD), while NPV (10) of 20 MW at an interest rate 2% (1,109,740.00 USD) is closer to the corresponding NPV (10) of 40 MW at an interest rate of 10% (1,083,891.00 USD).

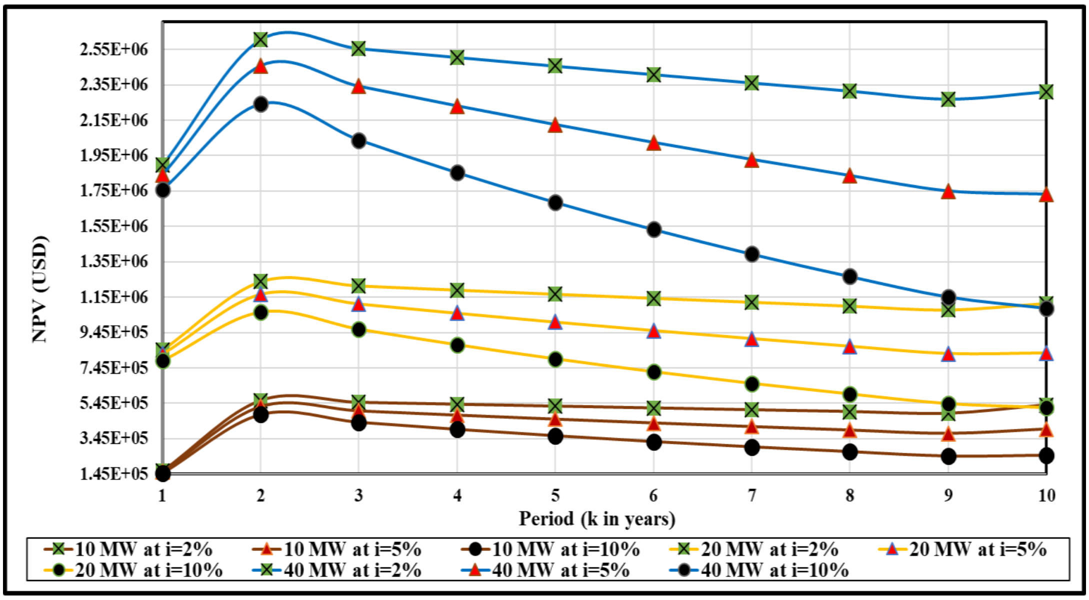

Figure 7 Distributed net present value on time for the three studied cases. NPV (k) is estimated from Equation.3 at variable k=1 to k=10 years, Sprice=500.00 USD/kW, variable i = 2%, 5%, and 10%, and SALV (10) = 70% of land and buildings value.

The relationships between production cost (Cpro) and independent variated raw materials (Rm), workforce(Wf), initial cost (INcst), and other operating (Oper) are shown in Figure 8, Figure 9, Figure 10, and Figure 11, respectively. These linear relationships are useful for estimating the production cost at different circumstances of the initial and operating costs.

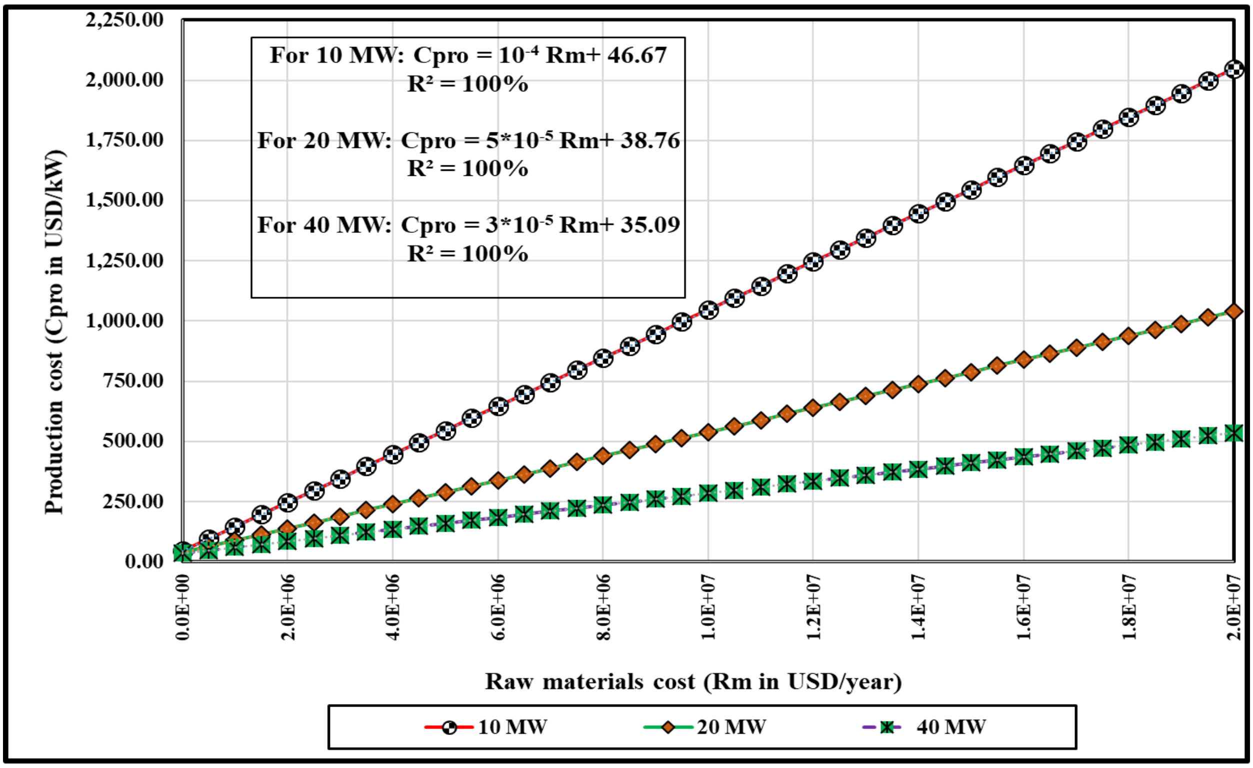

Figure 8 Impact of raw materials cost on the production cost.

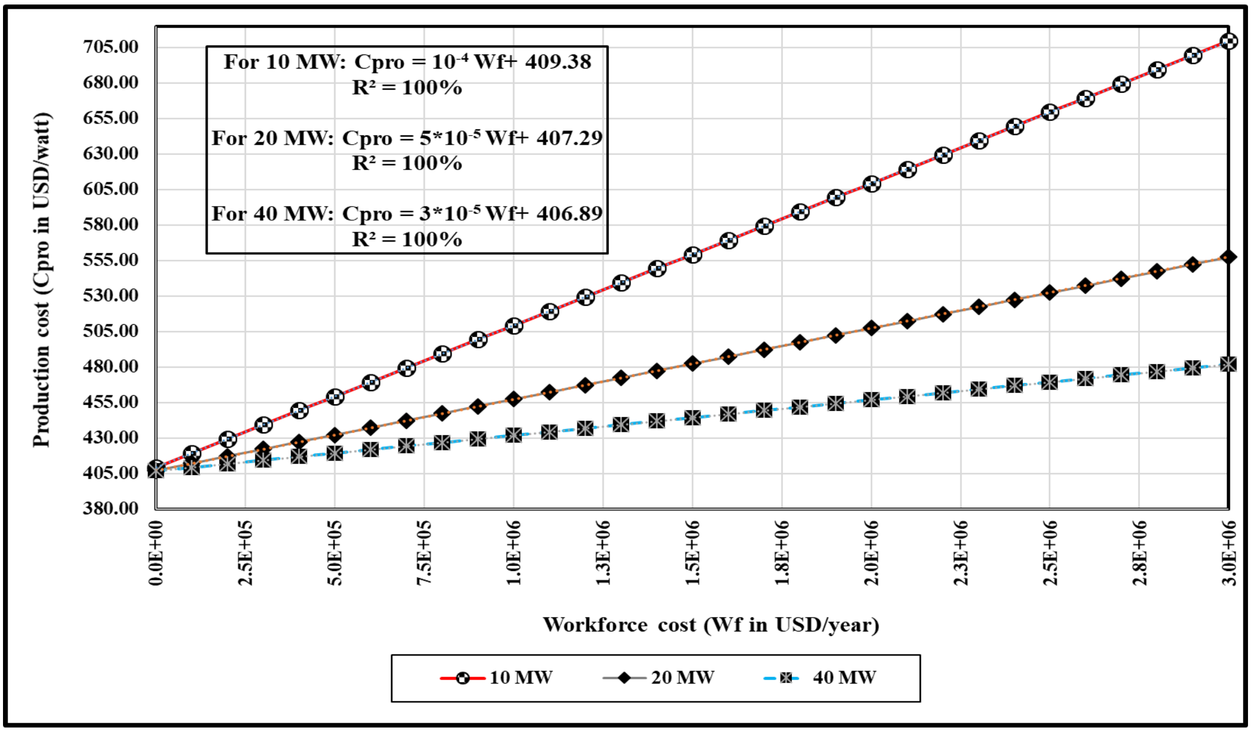

Figure 9 Impact of workforce cost on the production cost.

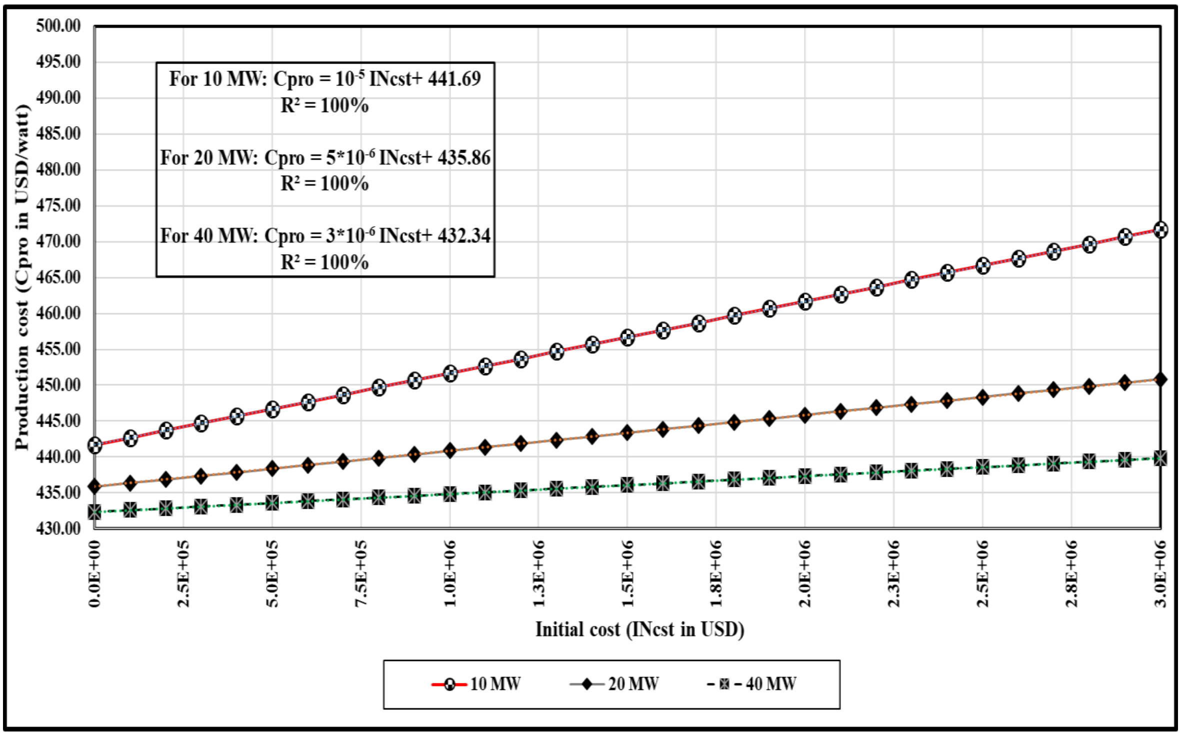

Figure 10 Impact of initial cost on the production cost.

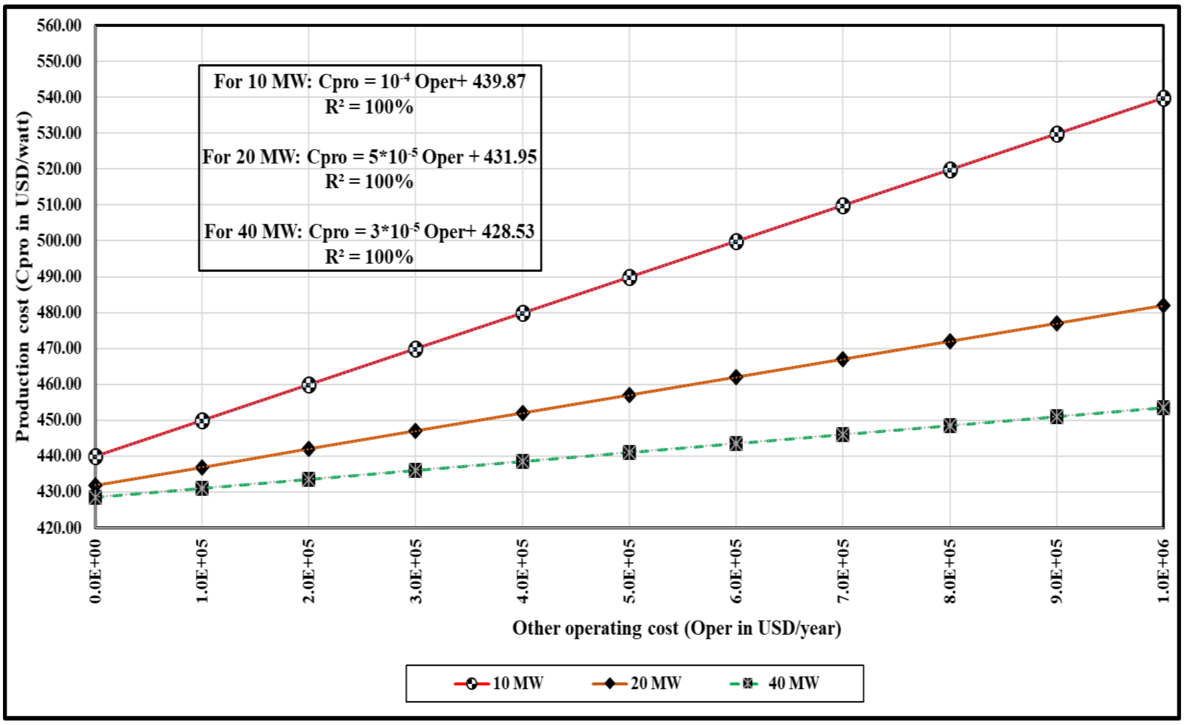

Figure 11 Impact of other operating costs on the production cost.

6. Conclusions

Initial and operating costs were developed in this paper for a plant in Sudan to produce 10 MW/year of solar PV modules in the base case, and the production was studied at higher scales of 20 MW/year and 40 MW/year. The simple payback period and net present value were used as economic indicators for the feasibility of producing solar PV modules in Sudan. Raw materials cost represented mainly by the solar cells is a significant contributor to the production cost. The raw materials cost dominates about 90% of the production cost in the base case, and 68% of that is by the solar cells cost. The reasonable payback period showed that the investment in the production of solar PV modules in Sudan is at low financial risk. The production capacity of 40 MW/year of solar PV modules in Sudan outperformed with a production cost of 434.29 USD/kW, and at a selling price of 450.00 USD/kW, the plant could achieve a payback period of 1.1 years. Future studies are recommended to investigate the high solar cells cost and to conduct research on the techno-economic feasibility of manufacturing these items locally for better sustainability of solar PV modules production in Sudan.

Author Contributions

The author has completed all the work.

Competing Interests

The author has declared that no competing interests exist.

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