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Technoeconomic Analysis of Dye Sensitized Solar Cells (DSSCs) with WS_2/Carbon Composite as Counter Electrode Material

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Abstract: Exploration of clean and renewable energy materials is necessary due to the coming energy crisis and environmental problems. Solar energy is one of the favorable energy sources because of the continuous energy reservoir and its affluence. Silicon-based solar devices are expensive due to their complicated production process, which limits this technology for urban and other commercial applications. Among the third generation of solar cells, Dye-Sensitized Solar Cells (DSSCs) have attracted widespread attention as potential cost-effective alternatives to silicon-based solar cells. In this paper, the commercializing potential of the DSSCs is investigated. A module is introduced where the materials, equipment, and distribution of direct manufacturing costs are calculated. The manufacturing costs and the Levelized Cost of Energy (LCOE) of these DSSCs for a system lifetime of 25 years were determined to be USD 22.40 per m^2 and USD 0.0438 per kWh and the module price of this technology is USD 0.18 per W and the total installed system cost is USD 0.88 per W in Kansas which suggest that this PV technology could challenge other leading PV technologies.

Keywords: technoeconomic analysis; dye-sensitized solar cells; counter electrode; WS_2

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1. Introduction

In 1991, O'Regan and Gratzel brought the international research community's attention to their dye-sensitized solar cell (DSSC) with a power conversion efficiency (PCE) of 7% [1]. A DSSC presents three important steps to convert sunlight into electrical energy: It relies on the visible photo-excitation of dyes triggering an electron transfer into the conduction band of the metal oxide semiconductor (generally TiO_2), followed by regeneration of the oxidized dye molecules by the electron donation from the redox couple in the electrolyte, and finally migration of electron through the external load to complete the circuit [2,3]. The entire operation takes place with the help of all the components of DSSC [4,5]. The schematic diagram of a DSSC with various components in shown in Figure 1. The counter electrode, as a crucial component of DSSCs, performs two critical functions: it collects the electrons flowing from the external circuit and catalysis the reduction of I_3^- to I^-, thereby realizing the regeneration of the sensitizer. Although Platinum (Pt) deposited on fluorine-doped tin oxide (FTO) conductive glass is an effective counter electrode (CE) for DSSCs, the limited availability and high cost of Pt have restricted further development of DSSCs. An alternative is to replace Pt with an economical catalyst that is endowed with both high catalytic activity and ready availability. It has been established that transition metal dichalcogenides (TMDs) have several benefits, including the durability of the covalent bond, the high melting temperature, and the good electrical and thermal conductivities of the transition metals. Inexpensive oxide nanoparticles and complexes besides organic dyes that are the main parts of DSSCs make the fabrication process needless to neither high temperature nor vacuum processing. Besides, many research groups found it easy to enter and contribute to progressing works on DSSCs where there have been more than 10 publications per year in 1992, 100 in 2001, and 1000 in 2010 [6]. Therefore, solar cells based on transition metal dichalcogenides (TMDs) have appeared as a promising low-cost technology for high-efficiency photovoltaics over the last few years. DSSCs have emerged as a potential rival to other solar cells due to the well-speed rise in photoconversion efficiency. Consequently, commercializing this promising technology could be of great interest in the near future which requires large-area processing. There is no doubt that evaluating the economics of the manufacturing process of DSSCs to produce electricity is of great importance. Here, in this report, a detailed techno-economic model based on production processes is presented to evaluate the minimum sustainable manufacturing price (MSP) and the Levelized cost of energy (LCOE) for DSSC modules. Therefore, the most critical factors that play significant roles in final costs are identified to find out where DSSCs are being placed in the competition with other PV technologies.

Some important factors are essential to achieve a low LCOE that could compete with the energy cost of energy from conventional sources. High efficiency, low cost, and stability, in the long run, are some of these factors. Over the last few years, there has been a large number of studies focusing on DSSCs to improve their PCE from 3% to about 15%. Alongside the rapid rise in efficiency of DSSCs, there is a potential to reduce manufacturing costs in order to commercialize this type of solar cell due to the simplicity of manufacturing processes through various solution-based and low-temperature deposition methods. Additionally, the manufacturing process could be time-efficient with the potential for roll-to-roll manufacturing. The fact that DSSCs are safe technologies and have the minimum environmental impacts brings even more attention to this technology hence there are more concerns about the future of the earth and using clean energies. The shorter important energy payback time (EPBT) metric is another criterion that makes DSSCs comparable with other PV technologies. Despite all of these advantages, there are some concerns regarding the lack of durability as well as operational instability of this PV technology on a commercial scale. Therefore, it is essential to address the degradation and instability issues to be able to utilize DSSCs in a field.

One of the most significant challenges to investigating the potential for large-scale commercialization of DSSCs is the fact that a demonstrated manufacturing process is lacking and there are only a few numbers of companies that are currently working on the fabrication DSSCs from small cells (around 1 cm^2) to a large-scale. However, the manufacturing process of DSSCs might be very similar to other thin-film technologies which leads to getting a lot of attention from investors to consider this promising PV technology as a great potential for the near future.

Even though crystalline silicon (c-Si), cadmium telluride (CdTe), and copper indium gallium selenide (CIGS) devices have higher module efficiencies, the other benefits of DSSCs like low embodied energy and a shorter expected energy payback play an essential role in the functionality of DSSCs in the near future that lightweight and flexible products are of great importance. One of the reasons that DSSCs provide a good performance is the diversity of light absorption in various conditions including the high angle of incidence as well as partial shadowing and low light intensities. Additionally, DSSCs perform simlarly whether it is at room temperature or 50 °C in deserts. Consequently, considering all of the real outdoor aspects leads us to 10–20% higher electricity productivity of DSSCs yearly in comparison with c-Si at the same peak power [7]. It is undeniable that besides having a good performance through the various lightning condition, diversity in appearance performs a key role in building-integrated applications and that is where DSSCs are appropriate due to being semi-transparent, selected colors, and bifacial [8,9].

In order to commercialize DSSCs, sustainability of more than 25 years in building-integrated modules is required. This prevents the replacement or repair of the building setting where a lifespan of 5 years is recommended for portable electronic chargers integrated into accessories. Although DSSCs have a bulky sandwiched glass structure, they can benefit from the roll-to-roll method and make a flexible structure even though that consequent to a shorter lifespan. Some of the challenges are to increase the size of DSSCs as well as choosing the right metal interconnects in the cells based on how corrodible they are to the electrolyte. Moreover, there has to be a high degree of control over cell-to-cell reproducibility since the same current and voltage are required for all the cells. If all of these challenges would be faced correctly, then the commercial applications of DSSCs would surpass a lot of other PV technologies. G24i has produced 25 MW capacity from DSC modules in 2007 in Cardiff, Wales (UK) and there are a few other DSSC demonstration modules since then. However, the maximum outdoor aging test has still been a serious challenge where many reported to be up to 2–3 years [10].

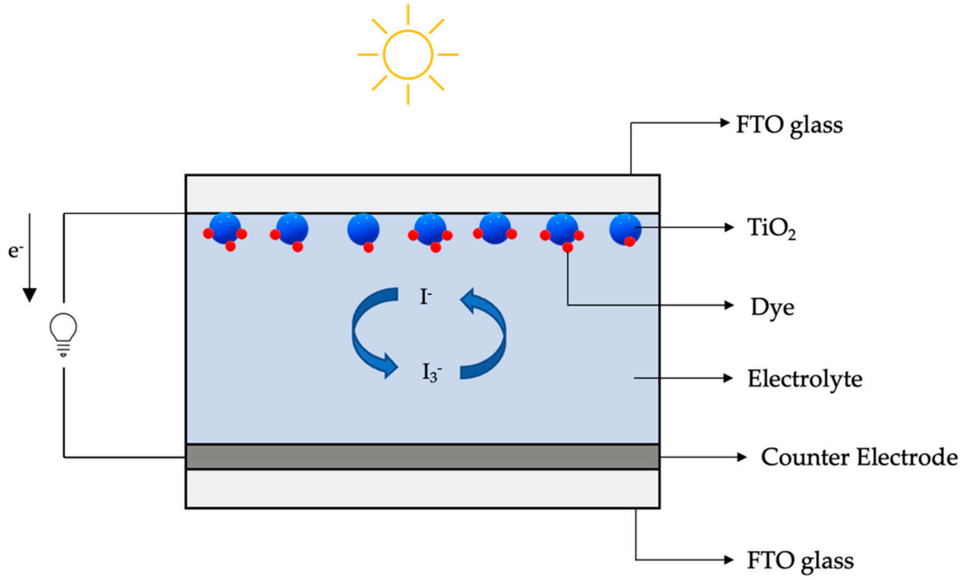

Figure 1. Schematic diagram of a dye sensitized solar cell.

Performance of DSSC with WS_2/Carbon Composite Counter Electrode

WS_2 can be used as a counter electrode is DSSCs by creating a WS_2/carbon composite. In 2013, Wang et al. created a WS_2/carbon composite to be used as a counter electrode by coating a thin layer of carbon on WS_2 surface [11]. It was observed that the presence of amorphous carbon layer increased the conductivity between WS_2 particles. The ratio of anorphous carbon (D-band) and the graphite carbon (G-band) was reported to be 0.87, which indicates that the carbon coated WS_2 structure is low crystalline [12]. The PCE of this carbon coated WS_2 counter electrode was reported to be 5.5%, which is comparable to the efficiency of DSSC with Pt electrode at 5.6%.

Shen et al. prepared a counter electrode by sulfurization of mesoporous WO_x/carbon film [13]. The carbon layer helped in electron transfer and electrolyte diffusion in the 3D WS_2 framework which resulted in higher electrocatalytic activity and faster reaction kinetics for the redox reaction of I_3^-/I^-. for this WO_x/WS_2/carbon composite counter electrode, PCE was reported to be 7.71%.

2. Results and Discussion

2.1. Manufacturing Cost

Figure 2A illustrates the direct manufacturing cost distribution and the materials cost (as shown in Table 1) breakdown of the reference module with a total manufacturing cost. We calculated the manufacturing cost of the reference model as USD 22.4 per m^2, which consists of 16.5 per m^2 for associated BOM components (glass, frame, laminating film, junction-box, and testing) and USD 5.9 per m^2 for processing the DSSC cells (utilities, labor, depreciation, maintenance) as can be seen in Tables 2 and 3, respectively. In comparison, the processing and associated BOM components costs for perovskite cells are USD 8 per m^2 and USD 29 per m^2, respectively. Note that the perovskite processing cost is much lower than some other PV technologies such as CIGS and CdTe cells with the processing costs of USD 29 per m^2 and USD 27 per m^2 (excluding BOM, in 2016 dollars), respectively. Therefore, we can confidently mention that the lower costs for DSSC cells are due to lower energy needs, less capital-intensive manufacturing process, and the use of lower-cost materials similar to the perovskite PV module [14].

Table 1. Materials costs for the reference module.

Component	Raw Material	Price (USD/kg)	Weight (g/m^2)	Material Cost (USD/m^2)
Glass	3 mm Glass	0.8–1.1	7500	7.0000
FTO	FTO	550–900	1.790	1.2980
Counter Electrode	AC	0.60–5.50	40	0.0240
Counter Electrode	WS_2	10–50	20	0.2000
Photo Electrode	TiO_2	2–4	16	0.0320
Photo Electrode	N719 $C_{58}H_{86}N_8O_8RuS_2$	2–5	4	0.0080
Electrolyte	Iodine	20–50	0.45	0.0090
Electrolyte	Lithium iodide	12–20	0.15	0.0017
Electrolyte	4-tert-Butylpyridine $C_9H_{13}N$	7–8	1.68	0.0118
Electrolyte	$C_8H_{15}IN_2$	29–80	7.10	0.2058
Electrolyte	CH_5N_3CHNS	10–30	0.26	0.0026
Electrolyte	C_5H_9N	10–25	5.3	0.053
Electrolyte	CH_3CN	5–10	29.65	0.1482
Junction Box	-	-	-	7.500

Table 2. Equipment costs.

Equipment	Footprint (m × m)	Unit Price (USDk)	Power (kW)	Operating Time (min/Module)
Glass cutter machine	2.9 × 1.8	2–9	3	2
FTO sputtering	10 × 2.5	1000–3000	500	30
Screen Printing	6 × 2.5	20–80	10	3
Furnace	6 × 2.5	150–360	30	60
Dye adsorption	6 × 2.5	20–80	25	20
Electrolyte injection and sealing	2 × 1	20–60	1.5	10
Soldering system	2.5 × 5	120–140	10	2
Testing table	2.5 × 1	10–15	0.5	1

Table 3. Distribution of direct manufacturing cost in each step.

Process	Utilities (USD/m^2)	Labor (USD/m^2)	Depreciation (USD/m^2)	Maintenance (USD/m^2)
Front Glass	0.259	0.231	0.158	0.011
Sputter FTO	0.394	0.116	0.900	0.232
Print TiO_2	0.066	0.270	0.203	0.023
Dye	0.062	0.502	0.236	0.032
AC coating	0.058	0.077	0.223	0.023
WS_2 coating	0.058	0.077	0.223	0.023
Electrolyte injection	0.008	0.009	0.191	0.019
Sealing	0.002	0.019	0.181	0.017
Back Glass	0.259	0.231	0.158	0.011
Junction-box	0.002	0.019	0.158	0.010
Testing	0.000	0.008	0.163	0.011

The materials costs are found to be the main cost segment of the DSSC module as can be seen in Figure 2A and are comprising 74% of the whole cost. Interestingly, only 5% of the total material cost is contributed to the materials in the DSSC cell structure (PE, CE, and electrolyte). The thin structure of the DSSC cell leads to saving materials and energy consumption reduction as well as high production throughput for the process. The remaining 95% of material costs belong to all other BOM categories including glass, FTO, and junction-box, as can be found in Figure 2B.

The second most dominant cost is related to depreciation that is accounting for 12% of the total cost. In general, depreciation costs are highly dependent on the process throughputs that are sensitive to the device architecture and design of processing. This is due to the expensive capital costs of the processing facilities. For instance, the throughput of 0.53 m^2 min^{-1} which is measured as relatively slow has been considered by Chang et al. for perovskite module cells due to its slow manufacturing process, such as thermal evaporation of Ag or Au as well as the sintering process of TiO_2 [15]. It has to be mentioned that a higher processing throughput leads to a reduction of the manufacturing cost. As an example, when the throughput is increasing from 0.5 m^2 min^{-1} to 1.4 m^2 min^{-1} the manufacturing cost is reduced by around 20%. However, this effect is less significant when throughput is increased to 2 m^2 min^{-1} and beyond that.

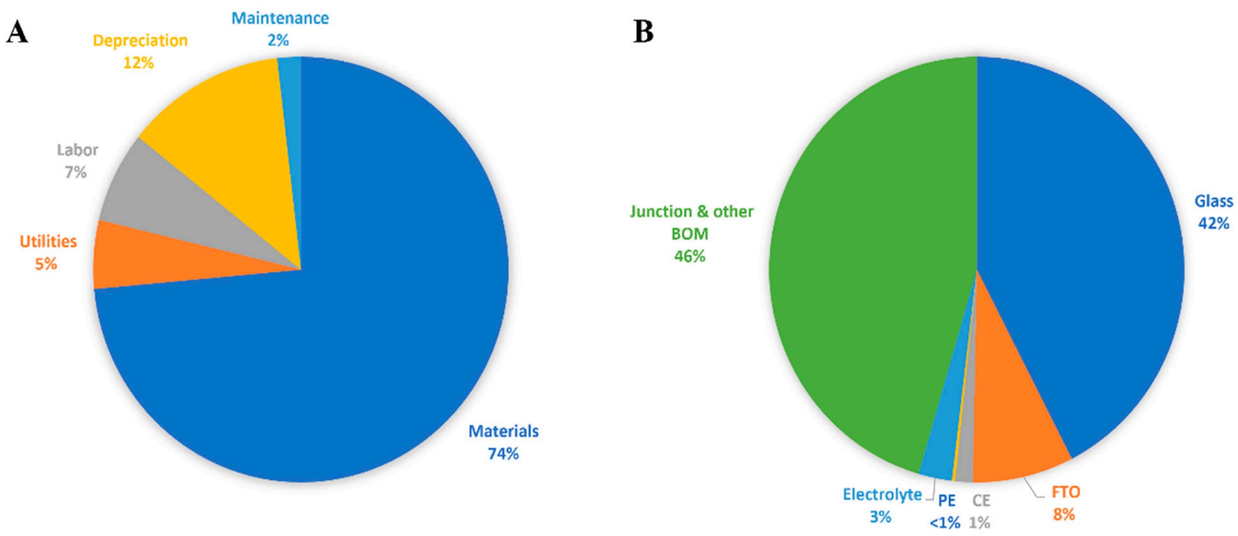

Figure 2. (**A**) Direct manufacturing cost distribution and (**B**) materials cost breakdown of the reference module with a total manufacturing cost of USD 22.4 per m^2.

2.2. Levelized Cost of Energy

To calculate the LCOE of DSSCs, the Levelized Cost of Energy calculator is being used provided by the national renewable energy laboratory's (NREL) website. This calculator provides information to estimate both utility-scale and distributed generation renewable energy technologies by comparing several other factors such as capital costs, operations and maintenance (O&M), performance, and fuel costs. However, this calculator does not consider some parameters including financing issues, discount issues, future replacement, or degradation costs.

There are some assumptions to estimate the LCOE. In the case of financing assumptions, we expect the project to be working for 25 years with a 3% discount rate. One of the important parameters is the capacity factor which is known as the ratio of the annual energy that the system produces to the amount of energy it would produce if that system operated at full nameplate capacity for the whole year. The capacity factor in this project is considered to be 15%. Some of the other assumptions regarding the renewable energy system cost and performance are the capital cost which is considered as USD 110 per kW, USD 7 per kW-year for fixed, and USD 0.002 per kWh for variable operation and maintenance costs. The heart rate is described as the amount of fuel burned for each unit of electricity produced and therefore this number is zero for renewable energy systems since PV technologies do not require fuel. The electricity price is assumed to be 12 cents per kWh and the cost escalation rate is 3%. Using all of these assumptions, the Levelized Cost of electricity for the energy system of this project is calculated as 1.2 cents per kWh. In the meanwhile, the Levelized or annualized cost of electricity from the utility assuming today's cost of electricity is measured as 17.1 cents per kWh. The distributed generation data used within this calculator is sponsored by the U.S. Department of energy's federal energy management program.

The comparative photovoltaic Levelized cost of energy calculator (comparative PV LCOE) is used to determine the LCOE of our DSSC photovoltaic system [16]. In this method, the baseline and the proposed technology are being compared to each other based on cost, performance, and reliability inputs. Here, we compare our DSSC with two different baseline technologies that are mono-Si and CdTe. All three technologies are considered to have a glass-glass structure and have fixed tilt in utility-scale systems. The closest location to Wichita, Kansas that is available for this calculator is Hutchinson in Kansas and this location is considered for these three different PV technologies. The discount rate of all three technologies is considered 3%.

The first baseline cell technology is the mono-Si cell and the cost of front and back layers were calculated as USD 4.06 and USD 3 per m^2, respectively. The non-cell module and cell costs are USD 18 and USD 34.40 per m^2, respectively. The total operation and maintenance cost of the mono-Si cell is USD 15.40 per kWDC (kilowatts direct current) per year. The balance of system (BOS) cost is reported as USD 0.33 per W for power-scaling and USD 55.70 per m^2 for area-scaling. The performance of the mono-Si PV technology is reported as 19% with an energy yield of 1572 kWh per kWDC. In the case of reliability, the degradation rate of this PV technology is 0.36% per year for a total service life of 25 years. Therefore, the LCOE of mono-Si PV technology is measured as USD 0.0475 per kWh while the module price of this technology is USD 0.36 per W, and the total installed system cost is USD 0.98 per W.

The second baseline is the CdTe-based PV technology, and the cost of front and back layers is calculated as USD 4.06 and USD 3 per m^2, respectively. The non-cell module and cell costs are USD 18 and USD 30 per m^2, respectively. The total operation and maintenance cost of the mono-Si cell is USD 15.40 per kWDC per year. The balance of system (BOS) cost is reported as USD 0.33 per W for power-scaling and USD 55.70 per m^2 for area-scaling. The performance of the CdTe PV technology is reported as 16% with an energy yield of 1611 kWh per kWDC. In the case of reliability, the degradation rate of this PV technology is 0.40% per year for a total service life of 25 years. Therefore, the LCOE of CdTe PV technology is measured as USD 0.0499 per kWh while the module price of this technology is USD 0.40 per W, and the total installed system cost is USD 1.07 per W.

The third system is our DSSC technology, the cost of front and back layers is measured as USD 8.298 per m^2 each. The non-cell module and cell costs are USD 7.5 and USD 0.6961 per m^2, respectively. The total operation and maintenance cost of this DSSC is calculated as USD 9.74 per kWDC per year. The balance of system (BOS) cost is reported as USD 0.31 per W for power-scaling and USD 63.04 per m^2 for area-scaling. The performance of this DSSC is assumed as 16% with an energy yield of 1475 kWh per kWDC. In the case of reliability, the degradation rate of this PV technology is considered as 0.648% per year for a total service life of 25 years. Therefore, the LCOE of DSSC technology is measured as USD 0.0438 per kWh while the module price of this technology is USD 0.18 per W, and the total installed system cost is USD 0.88 per W.

By comparing the results of each technology, the PV LCOE of DSSC is 8% and 12% cheaper than that of mono-Si and CdTe technologies. The module cost of DSSC is also 50% and 55% lower than the module cost of mono-Si and CdTe technologies, respectively. The total installed system cost of DSSC that is calculated by the NREL calculator is 10% and 18% lower than that of mono-Si and CdTe technologies. Therefore, based on these results there is no doubt that DSSC as the proposed technology is very cost-effective in comparison with the mono-Si and CdTe technologies.

3. Methodology

3.1. DSSC Module Cost

The techno-economic cost analysis was performed for a hypothetical DSSC manufacturer located in the United States, starting operation in 2030. The manufacturing cost is calculated using an internally developed spreadsheet calculator based on the "bottom-up cost modeling" as used by Powell, [17] Goodrich, [18] and Woodhouse et al. [15]. In short, we consider the mass-scale manufacturing of DSSCs modules with a production volume of 200 MWp per year. Projections of potential perovskite module costs have been made following the standard engineering cost estimating methodology in the literature [15,19,20]. To provide a realistic and accurate estimation, we chose a relatively conservative approach (see assumptions below) for developing a cost estimation and analyzed the uncertainties of the most sensitive assumptions.

3.1.1. Reference Module Assumptions

To estimate the module manufacturing cost, we selected a monolithic module geometry based on a rigid glass substrate as the reference module. Currently, a variety of device structures and alternative materials for DSSCs are reported in the literature.

The DSSC module is constructed with the reference DSSCs and other components that are essential for the module production. The latter, so-called balance of module (BOM) components, include glass plates, interconnection busbars, sealant, lamination film, edge-sealing frame, a junction-box, and wiring. This glass–glass design should provide excellent protection against water-induced degradation, [21] is compliant with the environmental regulatory codes and standards [14] and is widely used in the conventional design of commercial thin-film (CdTe [22] and CIGS [15]) PV modules. This glass–glass module configuration also lowers the probability of emission of toxic contents to the environment [23] and eases the environmental concerns associated with using water-soluble Pb-based perovskite materials [24].

3.1.2. Manufacturing Processes

DSSC materials and module architectures must be amenable to low-cost, high-throughput processing, in addition to being efficient and stable. Details of manufacturing lines are not widely available because of the obvious commercial importance to their owners. Manufacturing processes will also vary significantly depending on whether DSSC modules are rigid or flexible, the module architecture, and the substrate material. Materials and manufacturing steps must be well-matched. The dye, di-tetrabutylammonium cis-bis(isothiocyanato)bis(2,2′-bipyridyl-4,4′-dicarboxylato)ruthenium(II) (N719) molecules are sensitive to a temperature above 100 °C, so any high-temperature processing should be completed before dyeing. It is possible to seal cells and leave small fill holes for subsequent, dyeing, rinsing, and electrolyte filling. With this procedure, the design of the filling system and the module is critical. Sastrawan et al. at Fraunhofer ISE have designed meander-type parallel current collecting modules with partially interdigitated current collectors that minimize the number of cells that need to be independently filled [25]. Further details regarding the processing advantages of different module designs were described by Tulloch [26].

For DSSCs to compete with the current PV technologies and reach future targets in terms of cost, manufacturing line speeds of more than 20 m/min are required [8]. Processing in the research lab for small cells is commonly performed by hand and without regard for time; however, suitable automated and high-speed protocols must be developed for manufacturing. For example, TiO_2 nanoparticle films are commonly sintered at 450 °C for 30 min and dyeing is routinely done overnight. These procedures would require exceedingly long process lines to accomplish. Alternative materials and processes such as fast-curing TiO_2 [8,27] and dyeing procedures requiring only minutes [28] have already been developed.

Cells prepared in labs usually have active area of less than 1 cm^2. In scaling up this area to a larger active area of more than 10 cm^2, performance of cell is limited by the sealing process of the device and the sheet resistance of the substrate [29]. Limitations due to sheet resistance can be overcome by making smaller dimension cells and connecting them in various patterns [30]. There are four possible ways of connecting cells: parallel connection [31], Series monolithic connection [32], series W-type connection [33] and series Z-type connection which gives the best electric performance [34,35]. Z-type connection facilitates high voltage output and ability to pre and post treatment of electrodes [36]. Z-type connections provide reliable, uniform output over large areas at various temperatures and light conditions [37]. Figure 3 shows the design and fabrication scheme for DSSCs. The Z-type design requires preparation of two separate substrates, i.e., photo electrode and counter electrodes, which are then assembled to get the DSSC module.

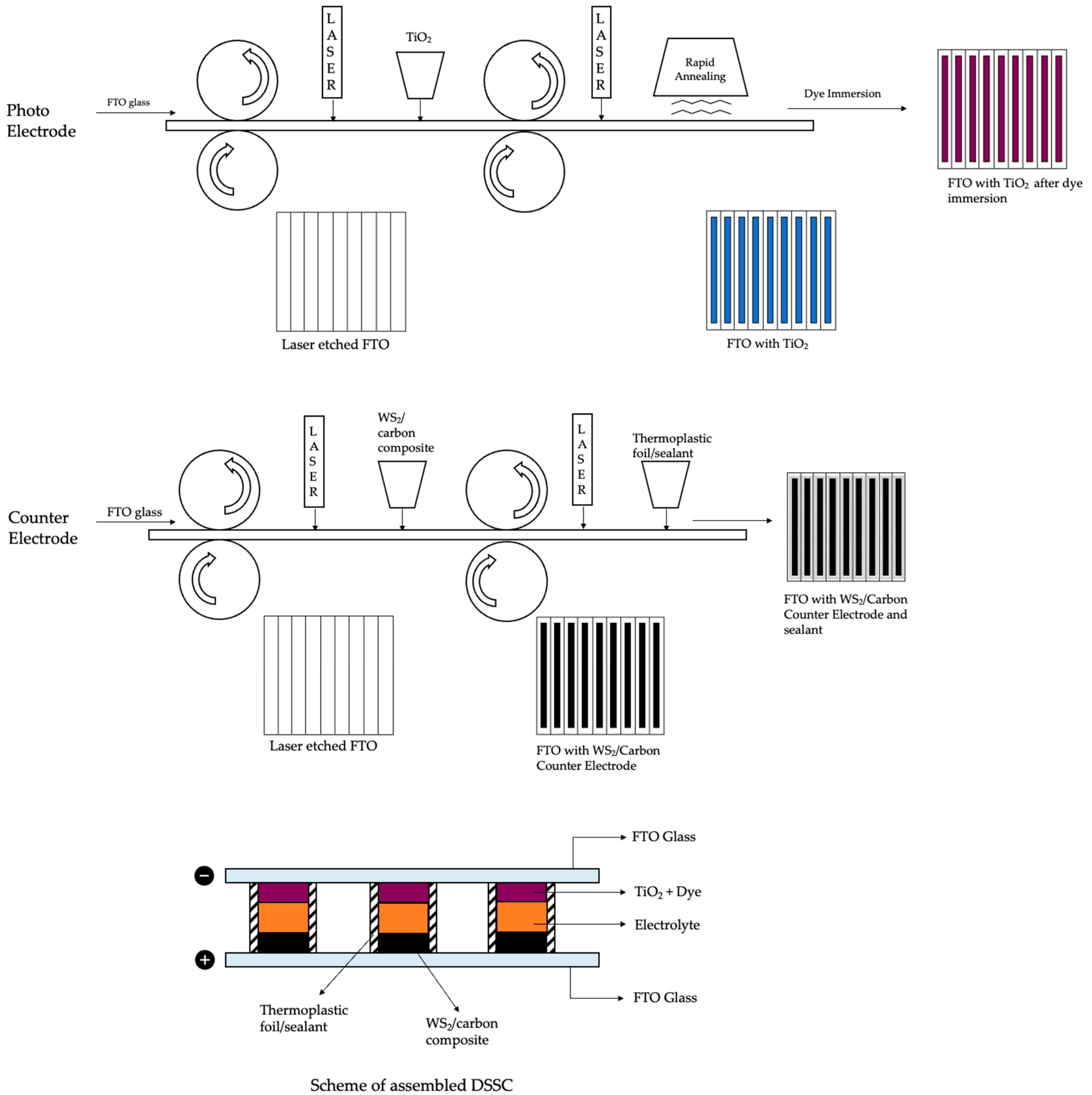

Figure 3. Preparation and assembly of DSSC module.

One of the advantages of DSSCs compared to crystalline silicon and thin films is low-cost, low-energy processing. Energy payback periods of less than one year are expected. No cleanroom, vacuum processing, or high temperatures (above 450 °C) are required. No new technologies need to be developed for DSSC manufacturing. High throughput processes can be borrowed from other industries including thin-film PV, printing, and laminating. For example, TiO_2 layers are typically deposited by screen printing and cured in an inline oven. The availability of standard equipment and processing will enable the fast development of new manufacturing lines for DSSC modules. Equipment for small-scale automation of many of the DSSC fabrication processes is already offered by Dyesol.

The first step of the manufacturing line is substrate preparation where the front and back electrodes are prepared by industrial-scale Fluorine-doped tin oxide (FTO) sputtering. The charge transport layer TiO_2 is then prepared by screen printing followed by a post-deposition heat treatment at an in-line oven. After the sintering process, the dye sensitization process takes place where dye is being applied to the surface to be adsorbed and dried. After that, the back glass which has gone through the FTO sputtering and WS_2/AC screen printing would be added to the front glass to make the sandwich structure of the PV cell. The next step in the manufacturing line is to hole drill and electrolyte fill the cells before the sealing and encapsulation process. The line will come to an end through the framing and electrical interconnection steps.

To calculate the manufacturing cost per unit area (USD per m^2) of the DSSC module (MC) the cost of each parameter during the manufacturing process should be summed up as shown in Equation (1).

$$MC = \sum_i (M_i + U_i + L_i + E_i + D_i) \quad (1)$$

where M_i stands for raw materials costs, U_i for costs of utilities, L_i for line labor costs, E_i for equipment maintenance costs, and finally D_i stands for the depreciation costs in the ith step of the manufacturing process. All of the mentioned costs are considered as being per unit area (USD per m^2). Therefore, the materials costs should be determined in the first place. Table 1 provides information about each component and the raw materials that are required for the manufacturing process while the material costs of each component are determined based on their price per unit of weight and the required weight per unit of area (m^2).

Materials and utilities costs are two categories that are directly determined by the selection of the device structure and the manufacturing processes, while labor costs could be varying from place to place. Thanks to the automation of the production line, the labor costs are expected to be minimized in comparison with other recurring costs. The time of processing and the degree of automation for every step is used to evaluate the minimum labor cost. The maintenance cost is considered as a fixed percentage (20%) of the costs of equipment and buildings. That is to say, a fixed percentage of the expensive equipment will cause a higher cost to maintain and repair. The equipment costs can be found in Table 2. It is of great importance to mention that the manufacturing costs in the various periods of production could be changed based on the method of distributing depreciation costs. For instance, whether a company depreciates its physical properties in the early period or at the later stages.

The costs of depreciation, utilities, labor, and maintenance per m^2 are mentioned in Table 3. Note that the manufacturing cost can be considerably decreased after the depreciation cost is eliminated from the balance sheet. In this study, we selected the linear depreciation method to estimate the expected value of the module cost. In this method, the physical property costs are evenly distributed to each year of production throughout the lifetime of the factory. Since the available information on the costs and prices from DSSC companies are very limited, other assumptions and cost data were taken from the literature and online sources, including global trading websites, as well as from reports from governments and other organizations.

3.2. Levelized Cost of Energy Calculation (LCOE)

The Levelized Cost of Energy of a PV system employing DSSC modules has been estimated to evaluate the potential solar electricity cost of DSSCs. To have a reliable estimation of the LCOE, the system advisor model developed by the National Renewable Energy Laboratory (NREL) has been used. Generally, the ratio of the total lifecycle cost of a PV system to the total energy generated during the lifetime of the system is called the LCOE.

The LCOE of a single-owner PV power plant with the power of 100 MW that operates under the Purchase Power Agreement (PPA) and is installed in Wichita, Kansas is evaluated. It is of great importance to consider the fact that this new PV technology would take a couple of years at the development stage to be commercialized later. Therefore, the expected PV system cost inputs that are considered in this study are for the year 2030 in the calculation [38]. It has to be noted that since the development of future alternative energy generation technologies should be commercially viable without government incentives, several subsidies are being excluded in this study such as the investment tax credit or production tax credit.

4. Conclusions and Outlook

To commercialize any PV technology successfully, there are several requirements to meet. The most important combination of requirements is high efficiency, long-term stability, and low cost. Advances in DSSC stable performance for over 20,000 h of continuous illumination have made it practical to find this technology in small manufacturing facilities [39,40]. Thermal cycling and potential outdoor lifetimes beyond 20 years are some other signs of progress have made with DSSCs. Moreover, the material and manufacturing costs are playing a big role in the feasibility of this PV technology, where it can reach much lower price costs by increasing manufacturing volume and developing supply chains. There is a great potential for DSSC capacity while no material limitations prevent the production of hundreds of gigawatts of energy [8].

DSSCs are in a position to compete with other PV technologies based on their efficiency, lifetime, and costs. Despite the efficiency of DSSCs being lower than c-Si and CdTe, it is considered a great competitor to amorphous Si for low-cost and low-power markets, as G24i introduced the first commercial products in 2009. There is a great potential for to DSSCs reach efficiencies above 15% by optimizing the energetic alignment of cell components so this technology can challenge c-Si and CdTe cells. There are a vast variety of combinations for DSSCs based on the dye, redox couple, photoelectrode, and counter electrode that is being used to manufacture the cell and it is most likely to find the right combination of components. Therefore, to increase the efficiency of DSSCs significantly it is expected to change multiple cell materials simultaneously.

This analysis indicates the strong potential of DSSCs economically. However, there are several barriers to commercializing this technology on large scale. Barriers include aging and stability of cells on-site, and heat and illumination. There is also the manufacturing process that is derived from other PV manufacturing processes. These concerns will be further allayed by the development of the manufacturing process as well as improvements in the stability of the cells. Although these issues need to be addressed, determining the low manufacturing cost and LCOE for DSSCs provides enough reasons to be optimistic cautiously.

In this study, a techno-economic cost analysis is performed while investigating the bottom-up model of manufacturing DSSCs. The critical factors in manufacturing costs have been determined for DSSC modules and the manufacturing cost of USD 22.40 per m^2 is obtained. Moreover, the LCOE of DSSC is estimated to be USD 0.0438 per kWh while the module price of this technology is USD 0.18 per W and the total installed system cost is USD 0.88 per W in Kansas if a system lifetime of 25 years can be achieved. It is noted that the full potential of DSSCs will be significantly dependent on stability improvements. Therefore, if the advances in DSSC PV technology continue rapidly, there will be no surprise to see this technology as a low-cost leader over the PV technologies competition.

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