Article

Solar Photovoltaic Development in Australia—A Life Cycle Sustainability Assessment Study

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Abstract: Australia possesses the highest average solar radiation of any continent in the world, but solar energy in total contributes less than 1% to Australia's primary energy consumption. This study intends to assess whether solar photovoltaic (PV) is really a sustainable option for Australia's energy transition on the project level. A life cycle sustainability assessment (LCSA) was conducted on a 1.2 MW flat-roof mounted PV solar array called UQ Solar, and the results suggested UQ Solar performed well in environmental aspects, except for emissions of several criteria air pollutants. It was economically feasible only with the grant provided by the Queensland government and the levelized cost of electricity (LCOE) was more or less the same as the LCOE of offset electricity. However, its social performance was not as good as expected. Large-scale PV installations can be sustainable in Australia on several conditions. PV manufacturers should be more responsible for reducing the use of hazardous materials; end-of-life treatment should be taken good care of; government should truly support the deployment of large-scale PV installation by providing more incentives and infrastructures; substantial subsidies for fossil fuel power stations should phase out; more awareness and training activities should be organized to promote social acceptance.

1. Introduction

Australia is a country with abundant energy resources, and more than three quarters of energy resources is exported [1]. While substantially utilizing vast amount of fossil fuels, various renewable energy resources are largely undeveloped in Australia, except for hydro and wind [1]. A transition to lower-emissions fuels is expected to take place to tackle severe impacts of global warming. Among various kinds of renewable energy, solar energy has great potential to be an abundant, clean and reliable energy resource. Australia, in particular, has great advantages of deploying solar energy, as she possesses the highest average solar radiation of any continent in the world [2]. However, in fact, solar power in total contributes less than 1% to Australia's primary energy consumption [3], and it is predominantly used for solar thermal water heating [1].

Photovoltaic (PV) is the direct use of solar radiation to generate electricity. Different types of PV installations have been exploited for several decades in Europe, which has proven the reliability of the technology itself. However, large-scale diffusion of PV installations in Australia is still very limited. It is, therefore, of strategic importance to figure out whether solar PV is really (can be) a sustainable option for Australia's energy transition. Life cycle sustainability assessment (LCSA) was selected in this study with the aim to analyze the sustainability of the PV system in Australia on the project level. The deliverables of this study are helpful in realizing current environmental, economic, and social hotspots of PV installations in Australia on the project level. Feasible solutions were proposed as well to help to achieve large-scale diffusion in the near future. In addition to that, this study was an attempt to put LCSA into practice. Both merits and limitations were disclosed, which would possibly enhance further development of LCSA methodology by learning lessons from practical application.

Developed from ISO standard life cycle assessment (LCA), LCSA is more inclusive and comprehensive as it covers more aspects relating to sustainability, which reflects the paradigm shift from environmental protection towards sustainability [4]. However, research community in the area of LCA has not reached consensus on what LCSA actually constitutes and how LCSA should develop in the future. Three main streams are observed: the first stream is influenced by Kloepffer's [5] definition on LCSA, which only highlights the inclusion of all three pillars of sustainability; the second stream is oriented at CALCAS (Coordination Action for Innovation in Life Cycle Analysis for Sustainability) project, which understands LCSA in a broader scope and in further detail [6]; and the third stream is developed by Halog and Manik [7], which emphasizes interrelationships and system dynamics in the assessment. To make this study feasible to conduct, LCSA guidelines developed by the UNEP/SETAC life cycle initiative [8] were employed. Similar to Kloepffer's definition, three dimensions of sustainability were assessed respectively from the life cycle perspective before they jointly formed a holistic LCSA. Each dimension went through four interdependent and iterative phases, which were goal and scope definition, life cycle inventory analysis, life cycle impact assessment and interpretation.

As a relatively new methodology, very few researches have been conducted to apply LCSA to solar PV systems. Most previous studies have only focused on LCA of solar PV systems and the results are various in terms of primary energy consumption, greenhouse gas (GHG) emission, and energy payback time (EPBT). Alsema [9] reported, under Southern European conditions, the primary energy consumption for rooftop mounted multi-Si PV modules with the efficiency of 13% was 4200 MJ/m^2, which corresponded to the EPBT of 2.5 years, and GHG emission of 46 g CO_2-eq./kWh. Meijer *et al.* [10]

reported a slightly higher energy demand of 4900 MJ/m^2 for multi-Si modules with the efficiency of 14.5%, and the corresponding EPBT was 3.5 years under the Netherlands' conditions. Jungbluth [11] estimated, under the environmental conditions of Switzerland, for various multi-Si PV modules, the GHG emissions ranged from 39 g CO_2-eq./kWh to 110 g CO_2-eq./kWh and the EPBT was 3–6 years, depending on configuration of the PV systems. With material-inventory data from industry, Alsema and de Wild-Scholten [12] demonstrated much lower primary energy demand and GHG emission of complete rooftop Si-PV systems. Fthenakis and Alsema [13] also reported the GHG emission of a rooftop multi-Si application was 37 CO_2-eq./kWh in 2004–2005, and the corresponding EPBT was 2.2 years under Southern European conditions. De wild-Scholten [14] updated these estimates in 2009 based on thinner modules and higher efficiency. An EPBT of 1.8 years and GHG emission of 30 g CO_2-eq./kWh for both multi- and mono-Si PVs were reported.

By conducting LCSA on a representative solar PV project in Australia, this study is expected to find out principal problems regarding solar PV's environmental bearability, economic viability and social equitability [15], and hopefully, the results can be helpful for large-scale diffusion of solar PV system in the near future.

2. Case Study

A LCSA was carried out on a 1.2 MW photovoltaic solar array named "UQ Solar". It is located at St. Lucia campus of the University of Queensland, and it was selected for several reasons. First of all, Queensland State is also known as "Sunshine State", and it is the state that has the highest installed PV generation capacity in Australia [16], thereby choosing one case coming from Queensland makes more sense. Second of all, this solar array is Australia's biggest flat-panel PV power system, which is almost 25% larger than any other rooftop system in Australia [17], indicating it well represents this type of solar PV system in Australia. Thirdly, grid connected distributed PV systems have represented the largest share (>97% in 2012) in Australia since 2009 [18], and UQ Solar falls into this category. Lastly, this project is easily accessible for the author to collect necessary information and data.

More than 5000 polycrystalline silicon solar panels covering 8200 m^2 of roof space have been installed across four major buildings: the UQ Centre, two adjacent multi-level car parking buildings, and the Sir Llew Edwards Building. It also has a small experimental array on the Prentice Building and a novel concentrated PV tracking array alongside Sir Fred Schonell Drive [17]. For the purpose of simplification, only solar panels on the four major buildings were considered in this assessment.

The UQ Centre has the University's largest PV installation rated at 433.44 kWp on its extensive and gently sloping roof area, and 1806 modules in total occupy 2956 m^2 of roof area [17]. When the peak output of the rooftop PV system exceeds the electricity demand of UQ Centre, power is exported and distributed to other nearby buildings using University's low voltage electricity network [17].

Taking up 4610 m^2, 2824 PV modules rated at 338.9 kWp have been installed on the undulating roof of multi-level carparks 1 & 2. Panels on the north edge of the building have been placed parallel with the roofline. To deal with the undulating roof and small differences in roof level, the other panels are placed on tilt frames [17].

Taking up 612 m^2, 374 PV modules rated at 89.76 kWp have been installed on the roof of Sir Llew Edwards building. Most of the solar panels were laid flat or parallel to the roof. A small installation of experimental panels has been placed on tilt frames [17].

To sum up, the defined PV system consists of 5004 Trina TSM 240-PC05 polycrystalline modules, 85 Aurora Power-One PVI-12.5-OUTD/-S inverters, and 6 Aurora Power-One PVI-5000-OUTD inverters.

3. Methodology

3.1. Environmental Life Cycle Assessment

Environmental LCA is a technique that is used to assess the environmental impacts associated with a product over its life cycle. As mentioned above, an environmental LCA should be carried out in four phases.

In goal and scope definition, assessment context needs to be provided, and detailed technical information needs to be specified, including functional unit, system boundaries, reference flow, allocation methods, assumptions and limitations [8].

In inventory analysis, all LCI data for the specific case are collected from the comprehensive Ecoinvent database version 3.1 [19], and the activity name is "electricity production, photovoltaic, 3 kWp flat-roof installation, multi-Si". This dataset is intentionally made for Australia, and necessary adaptations, which are mentioned in the assumptions supplemented in the end of this article, have been made.

In life cycle impact assessment, all data collected in inventory analysis are inserted into SimaPro 7.3. Primary energy consumption is calculated and CML 2 baseline 2000 V2.05 is employed to assess some mid-point environmental impacts.

In interpretation, energy payback time (EPBT) is calculated to indicate the number of years taken by UQ Solar to compensate for the energy that was consumed to manufacture the entire system.

3.2. Life Cycle Costing

Originally developed from a strict financial accounting practice, life cycle costing (LCC) is the oldest technique of the three. Traditionally speaking, LCC is an aggregation of all costs that are directly linked to a product over its entire life cycle. However, recently, it also takes into account external relevant costs and benefits that are anticipated to be privatized [8]. Like LCA, LCC is carried out in four phases.

In goal and scope definition, similar elements described in LCA need to be clarified in LCC.

In inventory analysis, three major types of data are collected: (1) Weather data: RMY Australia Representative Meteorological Year Climate Files [20] are used as the input to the weather data. Weather file of Brisbane is selected in particular for this analysis; (2) Technical performance data: technical datasheets of the specific PV module and inverters are used as references when entering relevant technical parameters. Even though the specific input variables (from CEC performance model) are not exactly the same as those put in the datasheets, the overall results are well simulated, indicating those trivial differences only have insignificant effects; (3) Financial performance data: Most of the financial input parameters and assumptions are collected from APVA [21] and Australian Bureau of Resources and Energy Economics [22]. Some reported data from AUSTELA [23] are also very useful. After collecting all necessary data, they are modeled into System Advisor Model (SAM 14 January 2014) to deliver all results. The SAM model has a performance model and a financial model. When inserting technical parameters and a set of weather data, the performance model can calculate the output of a

renewable energy system [23]. Based on the performance model and some financial parameters, the financial model can further calculate the financial performances of the studied system [23].

In life cycle impact assessment, a number of widely used financial metrics are calculated using SAM, including LCOE, electricity cost per year, net present value, payback, after tax cash flow, and cost per Watt.

In interpretation, grid parity is analyzed, followed by verification and limitation analysis.

3.3. Social Life Cycle Assessment

The UNEP/SETAC guidelines [8] state S-LCA conforms to the ISO 14040 framework with some adaptations. Again, four phases are carried out in an S-LCA.

In goal and scope definition, system boundary, stakeholders, subcategories, and limitations are stated.

In inventory analysis, information is collected based on stakeholders and subcategories identified, and the information basically comes from reports, websites and literatures.

Life cycle impact assessment is quite flexible in S-LCA, as UNEP/SETAC Guidelines [8] do not specify what should be done in this phase. This impact assessment can be either specific or general, depending on how much data is available. A nine-color qualitative assessment is adopted in this phase to assess the social impacts of UQ Solar.

Interpretation is given based on inventory results and impact assessment. Significant issues are identified, the study itself is evaluated and conclusions or recommendations are made.

4. Results

4.1. UQ Solar LCA

4.1.1. Goal and Scope Definition

The following parameters were collected according to Fthenakis *et al.* [24]:

(1) Location and on-plane irradiation level
   The approximate location of this system is (153°E, 27°S), and the yearly average irradiation collected by modules is 186 W/m^2. Annual average power produced per area is 146.6 W/m^2 [17].
(2) Module-rated efficiency: 14.7% [25]
(3) System's performance ratio: 0.75 [26]
(4) Time-frame of data: June 2010–June 2040
(5) Expected lifetime and degradation ratio for PV and balance of system (BOS)
   PV module warranties: 30 years with 2% of modules repaired and 1% reject [25]
   Degradation ratio for PV: 0.7% per year [25]
   Inverters: 15 years with one repair in the lifetime [26]
   Electric installation: 30 years [26]
   Mounting structure: 30 years [26]
   Manufacturing plants (capital equipment): 30 years [26]
(6) Average grid electricity mix
   Although UQ Solar is located in Brisbane, Australia, PV modules used are produced in China. Therefore, China average grid electricity mix (79% hard coal + 16% hydro + 3% oil + 2%

nuclear) [27] is used to analyze environmental impacts generated from PV modules production, while Queensland average grid electricity mix (72% black coal + 15% natural gas + 10% coal seam methane + 1% bagasse + 1% hydro + 1% photovoltaic) [27] is used to assess other life cycle processes.

System boundary includes raw material acquisition, material processing, product manufacturing, installation, operation, maintenance, end-of-life treatment and disposal for both PV modules and BOS. Transportations between each of the unit processes are also included.

The main function of a solar PV system is to produce electricity. The functional unit is thus 1 kWh of electricity produced by UQ Solar.

Referring to 1 kWh of electricity produced by UQ Solar, the amount of materials, products and systems needed are calculated in Figure 1. A 3 kWp module has been chosen as the basic module. Larger system can easily be scaled from the 3 kWp module without producing a significant error [27].

Ordinary by-products are allocated between products based on their economic values, heating values or mass values. For recyclable materials, the primary producer does not receive any credit for the provision of any recyclable materials. For wastes, the treatment of wastes is completely allocated to waste producer, and the producer does not receive any credit for recycling products generated out of waste treatment [28].

Due to the time restriction and budget limitation, most of the data are collected from existing databases with appropriate adaption to Australian situations. However, still, there are some mismatches between the data in databases and the data in real case, besides the assumptions made. For example, the cell efficiency in fact is slightly higher than the one assessed in the database, which indicates the emissions should be slightly lower in reality; the capacity in the database is 210 Wp [27] while in real case it is 240 Wp [17]; annual average solar irradiation in fact is 186 W/m^2 [17] which is higher than the assumption made in the database; electricity production assumption in database is 1407 kWh/kWp [27], while in fact it is 1475 kWh/kWp [17].

Therefore, the results of this life cycle assessment should be read with great caution, even though the simulation has been designed as case-specific as possible.

4.1.2. Life Cycle Inventory Analysis

Table S1 presents the mass of criteria air pollutants and greenhouse gases released at every stage of the life cycle of the 1.2 MW PV system. In this inventory table, carbon dioxide biogenic, land transformation, carbon monoxide biogenic, and methane biogenic are excluded. It is evidently clear that, except for CO and SO$_X$, the production of PV modules caused the highest amount of air emissions among all life cycle stages. Table S2 presents emissions avoided (or increased) due to the installation of UQ Solar by comparing emissions of two electricity generation systems that are UQ Solar PV system and conventional Queensland electricity grid system. Emissions generated from UQ Solar system were obtained from Ecoinvent database version 3.1 with the activity name of "electricity production, photovoltaic, 3 kWp flat-roof installation, multi-Si", while the emissions of conventional grid system were derived from AusLCI database, and the comparison was made on the basis of 1 kWh of electricity generation. Figure 2 demonstrates the emissions of two systems in relative terms [29]. For each type of air emission, 100% is assigned to the system that emits more. It is easy to observe UQ Solar has higher emissions of

As, Cd, Cr, Pb and C_6H_6 along its life cycle, while conventional Queensland grids have higher emissions of Hg, CO, PM_{10}, NO_x, SO_x, CO_2 and CH_4. A possible explanation could be PV modules production consumes more hazardous materials of certain kinds [30].
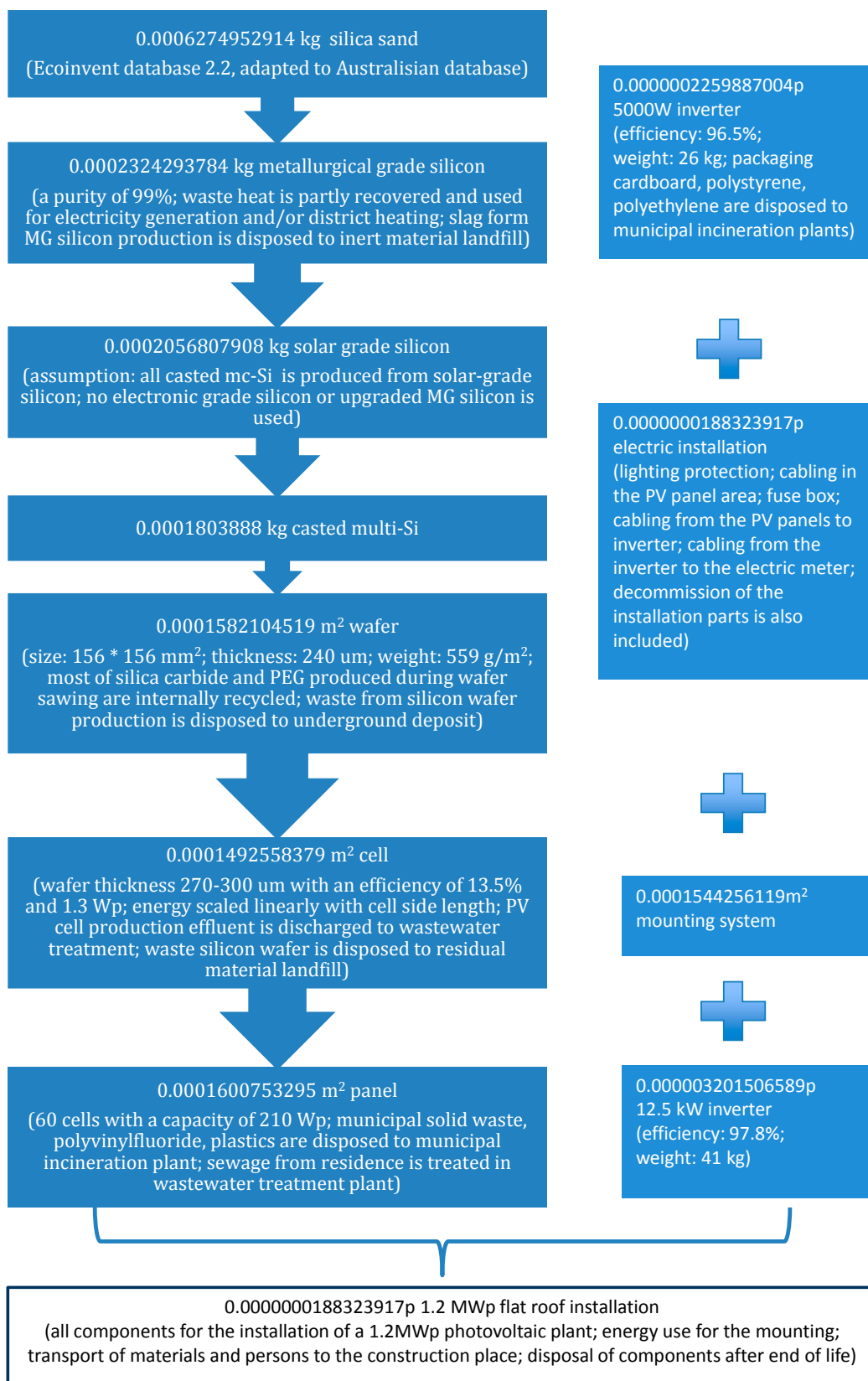

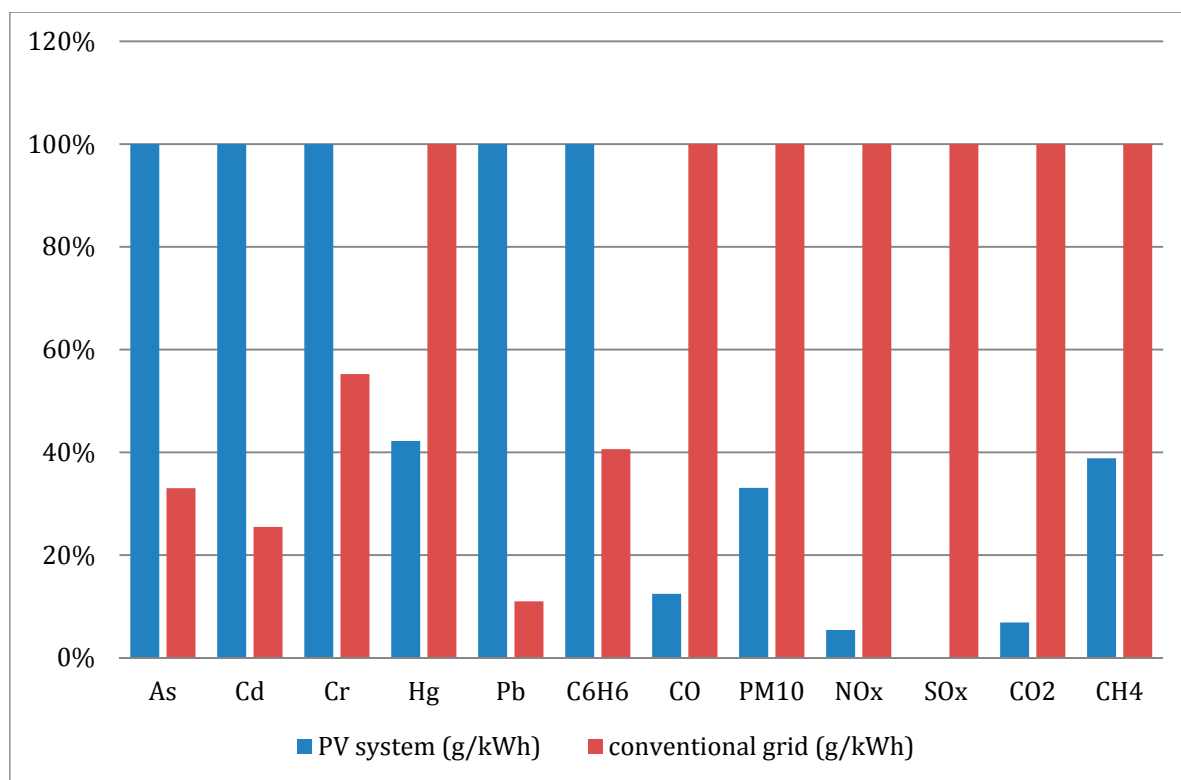**Figure 1.** Reference flow in life cycle assessment of UQ Solar.

Figure 2. Air emission comparison between two electricity generation systems.

4.1.3. Life Cycle Impact Assessment

The primary energy demand for the defined PV system consists of modules manufacturing, mounting system production, inverters production, electric installation, transportation energy, operation and maintenance energy, as well as end-of-life energy demand. They are modeled using SimaPro 7.3, and the total primary energy (or equivalent primary energy) consumption (after neglecting operation and maintenance energy) of the PV system is 4.92×10^7 MJ, 82.3% (4.05×10^7 MJ) of which is for PV modules production. One module consumed approximately 8094 MJ primary energy, and each module occupies 1.6368 m^2; therefore, 1 m^2 module needs 4945 MJ primary energy, and 21 MJ primary energy is consumed per peak power.

In addition, CML 2 baseline 2000 V2.05 is employed to assess some mid-point environmental impacts. Table S3 shows the results that are obtained after classification and characterization. For the majority of categories, PV modules production makes the biggest contributions. However, for fresh water aquatic ecotoxicity and marine aquatic ecotoxicity, electric installation contributes more. For human toxicity, mounting system also has significant impact, besides PV modules production and electric installation. Table S4 compares life cycle impacts imposed by UQ Solar and conventional grid electricity production. Figure 3 demonstrates the impacts of two systems in relative terms. For each category of impact, 100% is assigned to the system that generates severer impacts. It is observed, except for ozone layer depletion, conventional grid generates far more environmental impacts in all categories. In 30 years' lifetime, UQ Solar can reduce the global warming impacts by decreasing 40,345.84 tons of CO_2-eq emission.
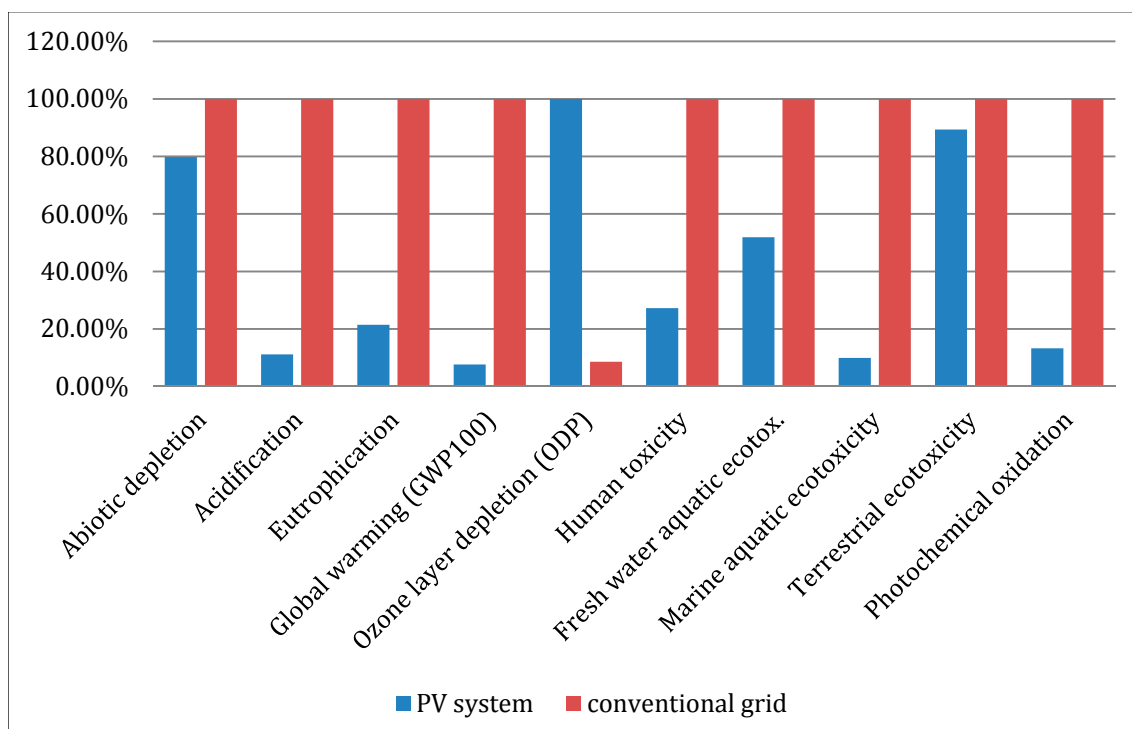
Figure 3. Life cycle impact assessment comparison.

4.1.4. Interpretation

It is known the total primary energy consumption is 4.92×10^7 MJ, and the annual energy output of the system is 1770 MWh (1 kWh = 3.6 MJ). If a degradation rate of 0.7% in cell output efficiency per year is taken into account, the EPBT is 7.91 years calculated by Microsoft Office Excel. In some cases, the electricity output at the demand side needs to be converted back to its equivalent primary energy by grid efficiency η_g before calculating EPBT. Assuming $\eta_g = 0.3$ [26], EPBT is then calculated with the following formula:

$$\text{EPBT (years)} = \frac{E(modules) + E(mounting) + E(inverter) + E(installation) + E(transportation)}{\frac{annual\ E\ (out)}{\eta g}}$$

In these cases, the EPBT becomes 2.33 years.

All in all, the results of UQ Solar LCA are comparable to the results given from previous studies. For example, the EPBT in our study is 2.33 years when taking grid efficiency into account, while the results of other literatures are between 1.8 years and 3.5 years [9,10,13,14].

4.2. UQ Solar LCC

4.2.1. Goal and Scope Definition

The main goal is to assess the economic performance of the system over its entire life. Main cost categories are quantified and opportunities for greater cost-effectiveness are identified. In addition, the results are compared with economic performances of conventional grid electricity generation. Benefits as well as losses are then determined.

The life cycle cost can be broken down into the following categories:

(1) Production of PV modules
(2) Production of Inverters
(3) Provision of BOS equipment
(4) Installation labour
(5) Installer margin and overhead
(6) Contingency
(7) Permitting
(8) Engineering
(9) Grid interconnection

As defined in environmental LCA, the functional unit adopted in LCC is also 1 kWh of solar PV electricity.

Levelized Cost of Electricity (LCOE) is used to calculate the life cycle cost of every 1 kWh of electricity generated by UQ Solar. It is equal to the net present value of the total lifetime system cost when assigned to every unit of electricity produced by that system [31]. When the LCOE of UQ Solar falls at or below the cost of purchasing electricity from the grid, the point of "grid parity" is reached and the studied PV system becomes economically competitive.

Some assumptions are given:

(1) If the effect of inflation is taken into account, the "nominal" discount rate is 10.29%/year. On the contrary, the "real" discount rate is 7.6%/year [21];
(2) Inflation rate is 2.5%/year [21];
(3) Escalation rate is essentially the same as the inflation rate;
(4) 10% of the total installed cost is assumed to be the salvage value;
(5) The base date of this project is 1 June 2010, the service date is 1 June 2011, and the study period is 30 years;
(6) The results of this study are independent of government subsidies (e.g., renewable energy certificates, rebates) and special feed in tariffs arrangements, because the inclusion of incentive is not consistent with the strict definition of LCOE [23];
(7) DC to AC ratio is set to be 1.1, and interconnection derate is 0.97 in total;
(8) The utility rate is going to increase 1.82%/year given no carbon tax is considered [21];
(9) Loan rate is 7.78%/year [21];
(10) Federal income tax is 30% [32];
(11) Contingency is assumed to be 5%.

4.2.2. Life Cycle Inventory Analysis

Main input values are summarized in Table S5. Defaulted values, zero values and automatically calculated values are not included.

4.2.3. Life Cycle Impact Assessment

The values of the main metrics are demonstrated in Table 1. From this table, it is clear to see LCOE of UQ Solar is 27.19 cents/kWh taking the inflation rate into consideration. If removing the effect of

inflation, the LCOE becomes 21.53 cents/kWh. In addition, the electricity cost per year is reduced with UQ Solar installation, which means UQ Solar can significantly reduce the amount of electricity that needed to be purchased from the utility grid previously by 23.21%.

Table 1. Main Metric Values of System Advisor Model (SAM) Simulation.

Metric	Value
Annual Energy	1771,513 kWh
LCOE Nominal	27.19 ¢/kWh
LCOE Real	21.53 ¢/kWh
Electricity cost without system	$1397,169.13/year
Electricity cost with system	$1072,829.13/year
Net savings with system	$324,348.28/year
Net present value ($)	−$1,304,143.13
Payback (years)	13.6769 years
Capacity Factor	16.84%
First year kWhac/kWdc	1476
System performance factor (%)	0.83
Total Land Area	2.10 acres

Net Present Value (NPV) is the sum of discounted future cash flows, both costs and revenues.

From Table 1, it is observed the NPV of UQ Solar is negative, which means the discounted lifetime revenues are less than discounted lifetime costs. In other words, UQ Solar is on its own not economically feasible. It is possible that NPV can become positive, if the utility electricity rate becomes higher or increases more significantly. If incentives or carbon taxes are taken into account, the NPV can possibly become positive as well. In this simulation, neither incentives nor grants are included in order to comply with the strict definition of LCOE. However, in actual case, the Queensland government provided 1.5 million Australian dollars to support this project, which suddenly turns the NPV into a positive value.

The payback (PB) period measures how long it takes for a project to recover the initial investment costs. It is a useful technique to weigh the additional capital costs against the time it takes for these costs to be recovered through savings or income during the operational period [33]. SAM calculates the payback period using non-discounted cash flow values [34].

Table 1 tells the PB for UQ Solar is 13.68 years, which indicates UQ Solar will recover its initial investment costs in about 14 years.

Apart from the metric table, there are some graphical presentations of this assessment. Figure 4 shows the after tax cash flow. It also proves NPV is negative in this case, and the final year revenue increases dramatically because salvage value is added. In terms of cost breakdown, Figure 5 shows that PV modules incur most of the costs, and the second and third biggest contributors are related to electric installation and inverters production, respectively.

In addition to various results mentioned above, SAM is so powerful that it can generate a financial report automatically, and this report is attached as appendix material.
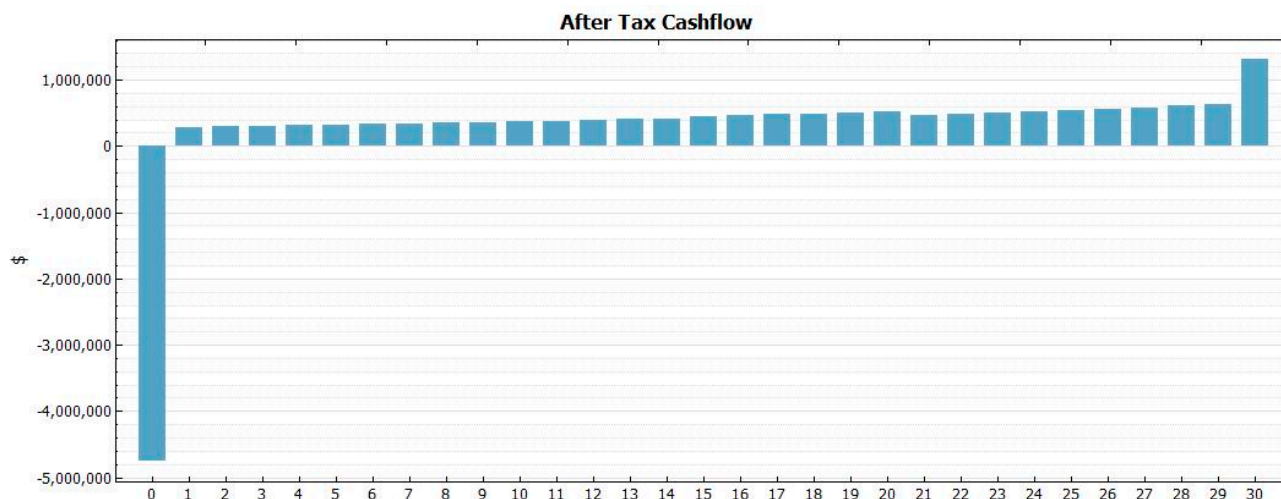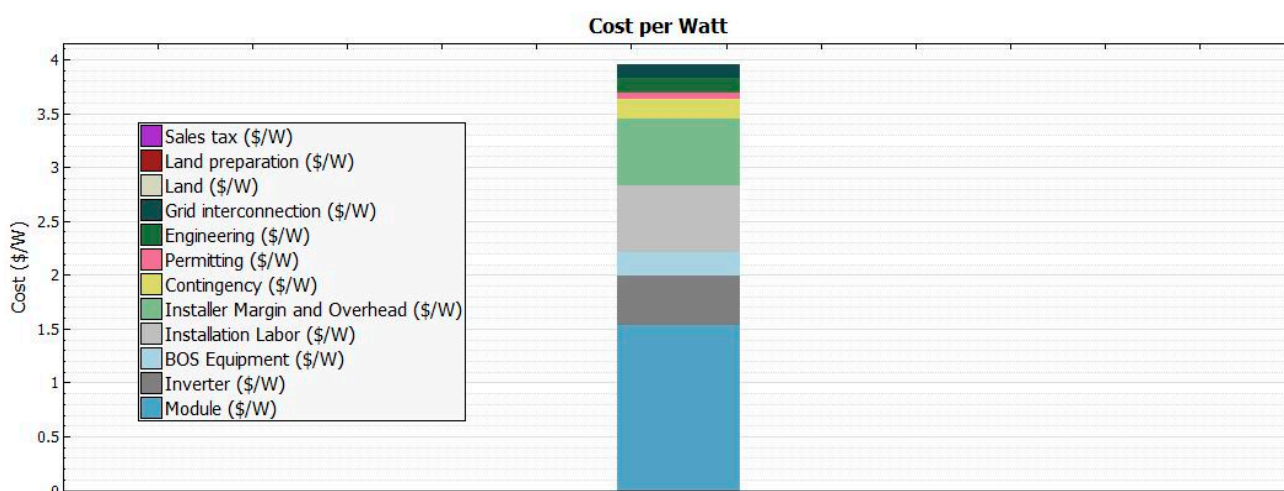
Figure 4. UQ Solar—after tax cash flow.

Figure 5. UQ Solar—cost per watt.

4.2.4. Interpretation

According to the results calculated by SAM, the real LCOE of UQ Solar is 21.53 cents/kWh, and the nominal LCOE is 27.19 cents/kWh. Cost per watt is about 3.96 dollars.

(1) When comparing these values with the utility electricity rates paid by UQ to the Queensland electricity network provider, which is about 12.5 cents/kWh [17], UQ Solar is not an attractive investment at present if there are not any incentives, grants, or carbon taxes.

(2) When comparing real LCOE value with Queensland average residential time of use (TOU) tariff, which is about 22.07 cents/kWh [35], grid parity has been reached. Especially when feed-in-tariff and renewable energy certificates apply, PV installation seems more appealing.

(3) When comparing these values with LCOE offset electricity, which is about 28 cents/kWh in 2012 [21], it can be concluded UQ Solar is more or less economically competitive.

(4) When considering projections of these two systems, it is reasonable to predict PV installation will become more and more beneficial because LCOE of PV will be continually decreasing while LCOE of grid electricity will be generally increasing.

In order to verify the conclusions of this study, the results are compared with the results obtained from other studies.

(1) The LCOE is 26.5 cents/kWh for a 100 kW commercial polycrystalline PV installation in Sydney in 2011 [21], which is very similar to the result of this study.

(2) From the UQ Solar website, it is known the initial cost of the studied system is 4.746 million, the cost per watt is approximately 3.955 dollars, and the payback period for this project is 10–12 years [17]. These results are also similar to the results of this study. While the UQ Solar website considers government grants, this study does not.

This study mainly makes use of SAM to simulate the UQ Solar project. Since SAM is basically accommodated to US conditions, this simulation cannot be very precise. In addition, many assumptions are made due to the lack of specific data. Therefore, the deliverables may not be reliable. Uncertainty analysis should be conducted to clarify this problem.

4.3. UQ Solar S-LCA

4.3.1. Goal and Scope Definition

The main goal is to qualitatively assess the social performances of UQ Solar from different stakeholders' perspectives. Main social impacts are analyzed and critical interpretations are delivered.

The boundary of this intended system is delimited at an organizational level, starting from the organizations producing PV modules to the organizations dealing with end-of-life treatment. In each stage of the life cycle, different stakeholders/organizations are involved, and the assessment is made against different stakeholders' interests in each stage (Figure 6).

➢ Stakeholders

Major stakeholders involved and their respective roles are marked in Figure 6.

➢ Subcategories

Subcategories are assigned to several stakeholders who potentially have significant impacts. These subcategories are selected against each stakeholder's main roles and interests, and they can be found in the life cycle inventory analysis and life cycle impact assessment.

➢ Limitation

Due to very limited data availability, the complex social assessment has to be a generic, qualitative and subjective one. Only main stakeholders are selected, and the information collected is neither completely unbiased nor comprehensively inclusive. Therefore, all the conclusions need to be read with caution. However, it can be considered as a good starting point to conduct more profound and advanced social assessment.
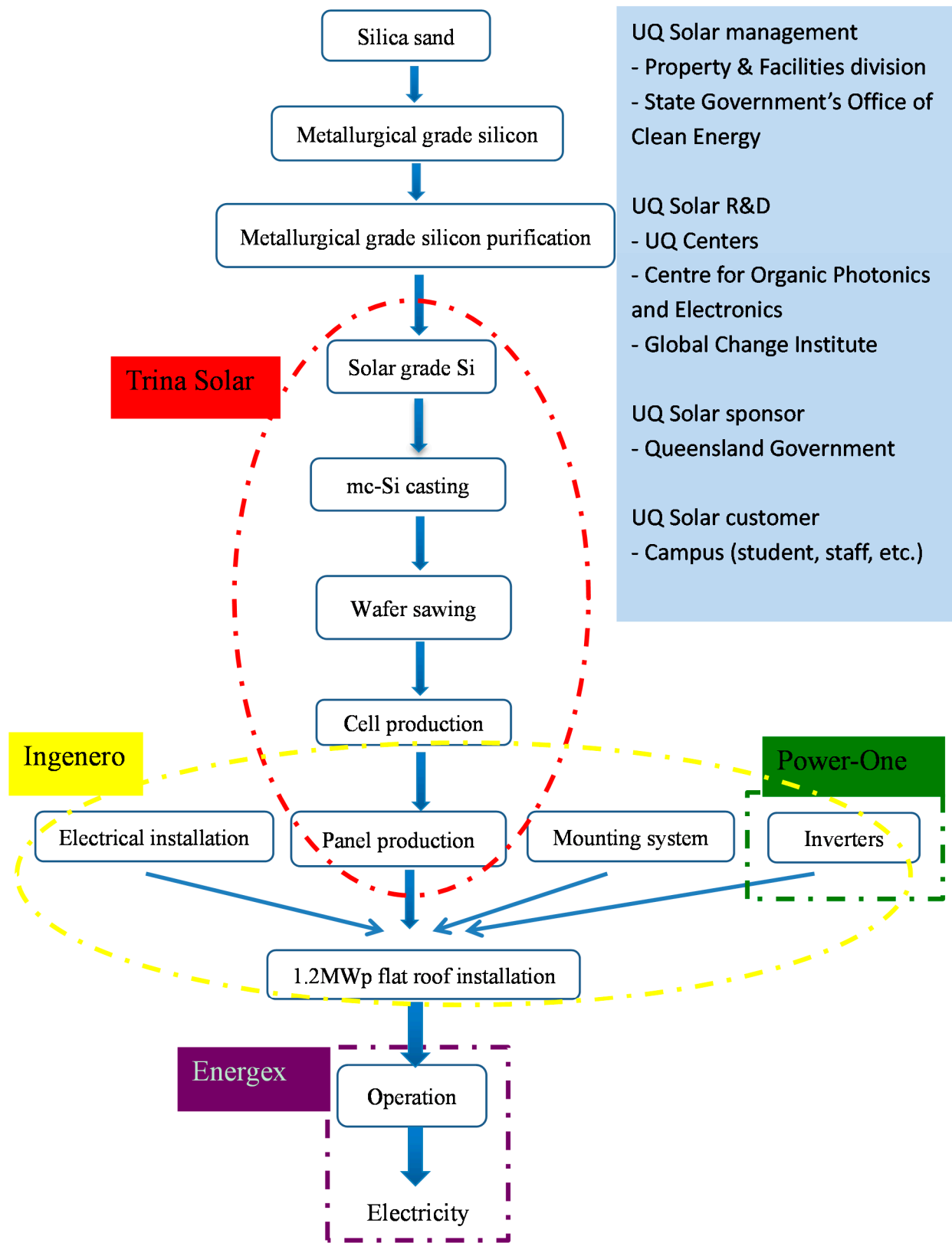
Figure 6. S-LCA system boundary and principal stakeholders.

4.3.2. Life Cycle Inventory Analysis

Information is collected for every subcategory to build up the inventory analysis.

➢ Trina Solar

• Business ethics

Trina Solar has established the "Code of Business Conduct and Ethics", in which it highlights anti-corruption, integrity and compliance, reporting mechanism, and high business ethical standards with suppliers and partners [36].

• Supplier relationships

In order to improve the social responsibility performance of suppliers, Trina Solar exerts some influence on them. Trina Solar carries out risk assessments annually to list key suppliers who comply with its requirements on sustainable development. Trina Solar has implemented Supplier CSR Management Procedure. Key suppliers are required to sign a commitment letter in order to strengthen communication and cooperation between different suppliers. In 2012, 18 key suppliers had been through EHS/CSR audits, among which 11 are conditionally accepted and three are disqualified [36].

• Care for employees

Following laws and regulations, employees' rights are protected: no forced labor or child labor; men and women are equally paid; no discrimination incidents; various insurances, funds and benefits are guaranteed [36]. However, in fact, it is recognized the enforcement of law in China is not very strict, and the inspection can be very superficial.

In 2012, the amount of employees reached 12,000, 67.3% of which had joined a labor union. Female employee ratio is 36.5%, and 100% of employees' salary is higher than the stipulated minimum. Total recordable rate is 0.56 per million working hour. There is no work-related fatality, and the average training hours is 33 h per employee per year. US$4.568 million had been invested in safety and occupational health management [36].

• Health and safety

Trina Solar has implemented both an Environmental Health and Safety policy and Product Stewardship policy to ensure the commitment to designing and manufacturing solar photovoltaic modules with overall lower impacts on the environment, and employees' health, safety and well-being. In November 2012, Trina Solar had passed Occupational Health and Safety management system (OHSAS 18001) verification [36].

However, it is known that during the manufacturing and disposal phase, many toxic and hazardous metals and chemicals can be generated to harm workers who work around them. For example, sawing c-Si wafers may generate silicon particulate matter that can pose inhalation problems [37]. Especially, in China, the problems would get more serious as environmental regulatory enforcement is low. Therefore, it is not indubitable to conclude Trina Solar has no problems in dealing with health and safety problems.

• Contribution to society

Apart from doing business, Trina Solar contributes to the society development in many ways. Trina Solar established an international school to support education, and it donated solar PV modules to universities for demonstration and education, *etc.* [36].

- End of life management

Trina Solar encourages Extended Producer Responsibility (EPR), and it collects end-of-life PV modules sold in Europe through PV Cycle initiative [38]. In Europe, the end-of life or defective PV modules are recycled at facilities with certified environmental management systems.

By and large, Trina Solar is a social responsible company and it is ranked No. 1 for its environmental and social performances in the 2012 Solar Scorecard among 40 companies globally [38].

➢ UQ R&D

- Contribution to technology development

The establishment of UQ Solar has facilitated the research activities in UQ regarding photovoltaic development.

UQ Center proactively carries out many researches on renewable energy system, and UQ Solar can provide the opportunities for many efficiency improvement experiments. Centre for Organic Photonics and Electronics are developing emerging PV technologies. Although UQ Solar does not utilize any new technologies, it is still a good establishment for comparative research, and emerging technologies can also be added to this establishment for pilot-scale research. The Global Change Institute is conducting researches that are, in particular, using UQ Solar. They are working on the storage devices, the concentrated PV installation and the shading effects [17].

- Contribution to research collaboration

As the largest flat panel installation in Australia, UQ Solar can be regarded as a demonstration project, which may attract many researchers in other universities, institutes, and industries to work together to improve the overall performances of PV system. Not only can scholars in science and engineering fields participate, experts in social science and economics are also encouraged to make contributions.

➢ Queensland government

- Consistency with Federal government

Australia has Federal, State and local governments, and they all have different priorities, jurisdictions, incentives and motivations. In order to respond to climate change, the Federal government has set several greenhouse gas emission reduction targets for different periods, and the transition to more renewable energy deployment is taking place. However, current policies still favor more mature and cheaper technologies such as hydro and wind, which have little thing to do with solar photovoltaic. Some non-renewable but "greener" fossil fuels (e.g., natural gas, coal seam gas) are considered as critical contributors to emission reduction. In addition, some emission intensive and trade-exposed industries (steel, alumina, coal fired power stations, *etc.*) are privileged, subsidized and protected from participating in renewable energy targets and carbon pricing in order to balance social concerns regarding jobs and competitiveness. More seriously, many practical barriers exist in implementing renewable energy policies, such as lengthy and complicated permitting procedures, costly and non-transparent grid connection, uncertainty of returns, *etc.* In summary, all the above-mentioned factors undermine the potential environmental, economic, and social contributions of emerging renewable energy industries, and renewables are actually not competing on an equal playing field [39].

Globally speaking, Queenslanders emit the highest amount of greenhouse gases, and Queensland is a major exporter of coal and gas [40]. However, very few down to earth initiatives have been implemented to tackle this urgent problem. The Queensland government has set many strong renewable energy targets, and it has also outlined some funding strategies. However, no sufficient details are proposed to address the barriers existing in renewable energy development. On the contrary, large sums of subsidies are still provided to support conventional fossil fuel industry, and some policies still promote rapid expansion of coal/gas mining to increase export sales. With regard to solar photovoltaic development, the Queensland government did exceptionally well in promoting the uptake of residential solar PV systems, however, the major challenges still lay in deploying large-scale PV installations [41]. After the change of government in the Queensland election in March 2012, almost all renewable energy funding was cancelled, which substantially hinders the deployment of renewables as they largely rely on regulatory intervention to be commercially viable [39].

As far as it is known, the Queensland government is consistent with the Federal government in dealing with renewable energy transition, however, in discouraging ways.

- Commitment to carbon emission reduction

With particular respect to UQ Solar, the Queensland government has provided AU$1.5 million to support this project, which, to some extent, indicates its intention to reduce carbon emissions. However, such a small contribution is not convincing enough to express its commitment.

- Social influences

UQ Solar is not very helpful to government to exert influences on society to use more renewable energy. It is more academic-oriented, and it is a big challenge to make the project widely known.

➢ Electricity distribution network

- Compatibility and stability

In Australia, the majority of electricity is firstly generated by large centralized generators, and then it is transmitted at high voltage through transmission networks, after which distribution networks take over at low voltage before reaching end consumers [39]. This centralized system is both cheap and efficient, but it also faces many challenges nowadays due to changing demand patterns and deteriorating environmental problems. The prevailing "top-down" structure needs to be transformed to a "bottom-up" structure as consumers may have a number of alternatives to choose from [42].

However, for UQ Solar only, the electricity distribution network is readily available so that no extra efforts or costs need to be paid to expand the current network.

- Profitability

For electricity network provider Energex, the establishment of UQ Solar can be both good and bad. When peak demand cannot be met, UQ Solar can provide a reliable energy backup. However, when UQ Solar provides too much electricity, it will reduce electricity use and electricity utility revenues.

➢ Customers (local community)

- Health and safety

During the operation of UQ Solar, it is not likely to generate any toxic/hazardous materials or noises; therefore, it is quite a safe renewable technology during its operation. However, if some unexpected accidents happen, exposure to toxic materials can be very harmful.

- Feedback mechanism

There is no extensive feedback mechanism available to students and local communities, as they are not much affected by UQ Solar. However, for the Property & Facility Division of UQ, a feedback mechanism is available, because there should be some feedback on how good the system runs, what problems it brings and how to address them.

- Transparency

It is quite a transparent project because a data acquisition system (DAS) has been installed on a data display screen. Real-time output of the PV system can be displayed.

- Awareness and training

For general students and local communities, UQ Solar is not well exploited for awareness enhancement and training.

- Community engagement

The community is not actively engaged, as they are not directly/seriously affected.

- Local employment

The solar energy sector has the potential to provide hundreds of thousands of jobs in fields of manufacturing, construction, installation, and maintenance. However, this environmentally sustainable industry may end up with unsustainable jobs, which keep workers and their families in poverty [43]. Besides, the creation of jobs in solar industry indicates fewer jobs are needed in the conventional electricity industry.

4.3.3. Life Cycle Impact Assessment

In the life cycle impact assessment, a nine-color scale is employed to qualitatively assess the social impacts of UQ Solar based on the information gathered from inventory analysis (Figure 7).
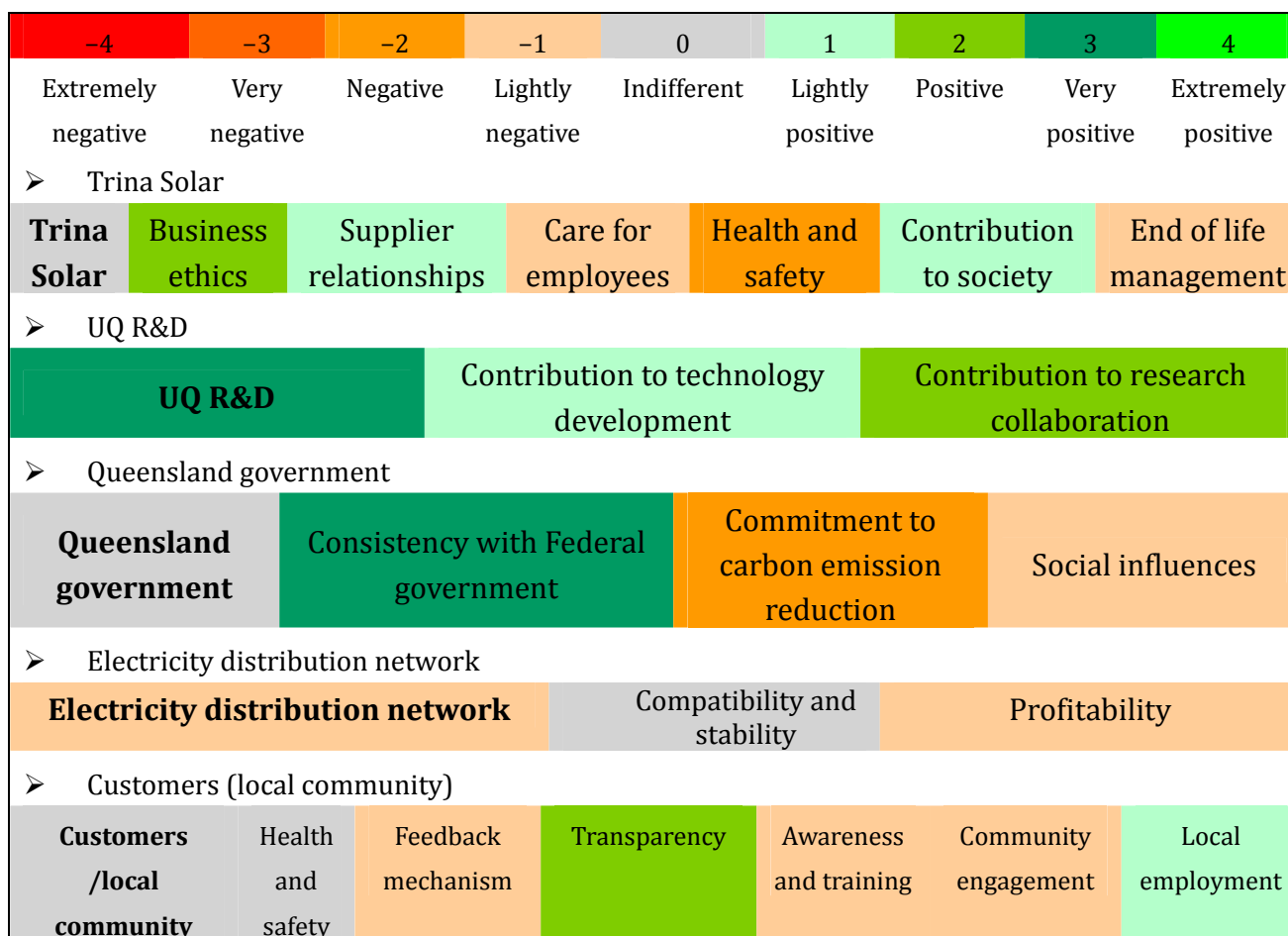
−4	−3	−2	−1	0	1	2	3	4
Extremely negative	Very negative	Negative	Lightly negative	Indifferent	Lightly positive	Positive	Very positive	Extremely positive

➢ Trina Solar

Trina Solar	Business ethics	Supplier relationships	Care for employees	Health and safety	Contribution to society	End of life management

➢ UQ R&D

UQ R&D		Contribution to technology development	Contribution to research collaboration

➢ Queensland government

Queensland government	Consistency with Federal government	Commitment to carbon emission reduction	Social influences

➢ Electricity distribution network

Electricity distribution network	Compatibility and stability	Profitability

➢ Customers (local community)

Customers /local community	Health and safety	Feedback mechanism	Transparency	Awareness and training	Community engagement	Local employment

Figure 7. Nine-color scale qualitative assessment for the S-LCA of UQ Solar.

4.3.4. Interpretation

From the impact assessment, the overall score of Trina Solar is indifferent. To be more specific, Trina Solar performs better in business ethics, supplier relationships, and contribution to the society, while there are some problems in caring for employees, health and safety, and end of life treatment. The main challenges underlying PV modules production are toxic/hazardous materials emissions. In order to reduce and eventually eliminate this problem, several stakeholders should work together.

Solar PV manufacturers should be responsible for the lifetime impacts of PV modules through Extended Producer Responsibility (EPR). Starting from the design stage, PV manufacturers should make sure PV modules as well as components can be easily and safely recycled; during production process, manufacturers should protect workers and the environment from toxic exposure, and they should also monitor supply chains to ensure safe and just practices; during operation stage, manufacturers are expected to protect community health and safety by informing of the potential risks in using solar modules; during end-of-life treatment, manufacturers should establish effective take-back policies for solar modules. Federal and State policymakers should also provide corresponding policies and legislations to support/enforce these implementations. In addition, consumers can make big differences with the power of the market [37].

UQ Solar is a very good establishment for R&D activities and the overall result is quite positive. In order to maximize the efficacy of UQ Solar, more collaboration with outside stakeholders is encouraged.

The Queensland government is indifferent to the overall result of the project because, although its policies and initiatives are consistent with the Federal government's, both do not attach importance to renewable energy deployment. There are many challenges in exploiting renewable resources, including immature technologies, higher costs, institutional inexperience, incompatible with exiting transmission and distribution networks, *etc.* [39]. Government should introduce carbon pricing to internalize environmental costs that are associated with conventional electricity generation, and more importantly, the costs should be borne by the industry itself rather than taxpayers. Non-renewable but "greener" fossil fuels should be excluded when considering carbon emission reduction measures. In addition, free credits or direct subsidies for emissions intensive and trade-exposed industries should be phased out. Administrative and regulatory issues regarding renewable energy deployment should be streamlined to save on the costs of deployment.

In the case of UQ Solar, the electricity distribution network is slightly negatively affected. Assuming a larger-scale PV installation in remote area, which has not been integrated into the existing distribution network, the negative impacts will become more significant, because higher grid connection costs will ensue and the electricity utility revenue will decrease. In order to alleviate the negative impacts, government should invest more in building up/expanding electricity infrastructure.

UQ Solar has positive impacts on transparency and local employment, but it does not make many differences in terms of awareness enhancement and community engagement. It should be noted that social acceptance and willingness are indispensible for solar photovoltaic development. As customers tend to rely on technologies they are more familiar with, a lot of effort should be taken to enhance public awareness and training of solar photovoltaic technology.

4.4. UQ Solar Integrated LCSA

Based on the life cycle assessments on all three pillars of sustainability, we can make conclusions about the sustainability performances of UQ Solar. The overall results suggest UQ Solar performs well in environmental aspects, and it is economically feasible with grants provided by the Queensland government. However, its performance in social aspects is not as good as expected, although no serious adverse impacts are detected. This study assumes each dimension weighs equally, and if one stands for worst performance and five stands for the best performance, the overall sustainability performance can be illustrated using Figure 8.
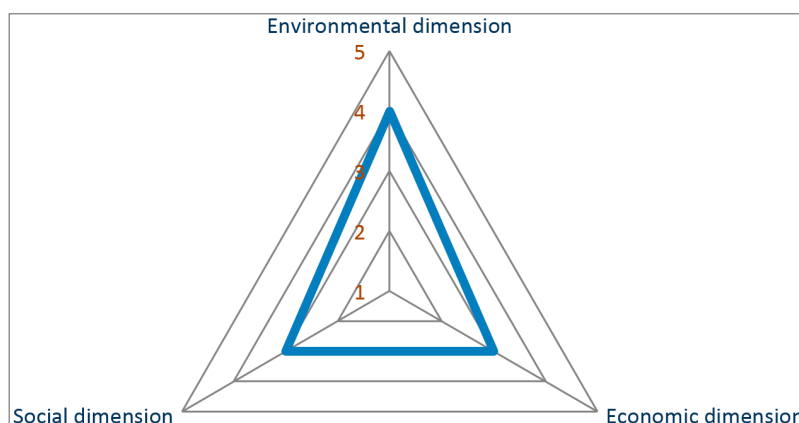

Figure 8. UQ Solar Sustainability Dashboard.

5. Discussion

5.1. Problem Identification

In this section, problems are identified according to the three dimensions separately.

5.1.1. Environmental Dimension

In the environmental aspects, UQ Solar performances quite well, except for emissions of several criteria air pollutants (As, Cd, Cr, Pb and C_6H_6). During the life cycle of UQ Solar, PV modules' production contributes most to environmental impacts, followed by the mounting structure and electrical installation.

5.1.2. Economic Dimension

The LCOE of UQ Solar is more or less the same as LCOE of offset electricity, although this value is far higher than the utility rate currently paid by UQ. However, the NPV of UQ Solar is negative without considering Government grants, which makes it economically infeasible. PV modules production takes up the largest share of the cost.

5.1.3. Social Dimension

Generally speaking, UQ Solar does not generate very serious adverse social impacts. However, it does not fulfill its expected social functions fully. Not many people are aware of this project, thus no educational or training purposes are reached. The most serious potential impact could be the health and safety problems caused by modules' production and end-of-life treatment. Besides, governments on different levels are not truly supportive of deploying large-scale renewable energy installations, and the lack of necessary infrastructure facilities is another big challenge.

5.2. Recommendations

In this section, recommendations are proposed according to the three dimensions separately.

5.2.1. Environmental Dimension

Since PV modules' production contributes most to environmental impacts, it is the manufacturer's responsibility to address this problem.

Solar PV manufacturers should be responsible for the lifetime impacts of PV modules starting from design stage to the end-of-life treatment. PV manufacturers should work together with research institutes to find out more material efficient and less energy intensive production processes; Any toxic or risky materials should be reduced and even eliminated from the manufacturing process; Any new materials or components should be carefully tested in order to know their toxicity and safety before using them; Manufacturers should protect workers and the environment from toxic exposure through strict management systems; Manufacturers should also monitor supply chains to ensure safe and just practices; During operation stage, manufacturers are expected to protect community health and safety by informing of the potential risks in using solar modules; During end-of-life treatment, manufacturers should establish

effective take-back policies for solar modules to recycle them easily and safely. Federal and State policymakers should also enforce corresponding policies and legislations to support these implementations.

5.2.2. Economic Dimension

At present, government support (incentives, subsidies, grants) is indispensible for large PV installations to be economically viable. In order to make PV systems more economically competitive, conventional utility electricity rates should be increased more significantly. In addition, consumers can exert much influence on the economic performances of PV installation through the power of the market.

5.2.3. Social Dimension

As a matter of fact, the problems existing in the social dimension are closely related to environmental problems and economic problems. More efficient and responsible production can effectively ease the impacts on health and safety. Government should truly support the deployment of large-scale PV installation by providing more funds and infrastructure. Subsidies provided for fossil fuel power stations should be phased out, and more awareness and training activities should be organized to promote social acceptance.

6. Conclusions and Prospects

6.1. Key Messages

Australia possesses the highest average solar radiation of any continent in the world, and the annual solar radiation is approximately 10,000 times more than Australia's annual energy consumption. However, solar energy so far has not been largely developed. This study intends to investigate the sustainability of current solar PV installations in Australia on the project level in order to know why solar photovoltaic is not favored, what the problems are and how to possibly solve them.

Life cycle sustainability assessment is conducted on a specific case called UQ Solar, and the basic conclusion is that PV installations can be sustainable in Australia, but several environmental, economic, and social problems need to be addressed first. PV manufacturers should be assigned more responsibility in reducing and, eventually, eliminating toxic/hazardous materials used in PV modules production; End-of-life treatment should be taken good care of by manufacturers to make sure solar modules/components/materials can be reused/recycled/recovered; Government should truly support the deployment of large-scale PV installation by providing more incentives/funds/infrastructures; Substantial subsidies for fossil fuel power stations should be phased out; More awareness and training activities should be organized to promote the social acceptance of solar PV installations.

6.2. Limitations

Due to time constraints and budget restrictions, this study has many limitations that need to be improved in future studies.

(1) As the main objectives of this study are to know whether current solar photovoltaic deployment is sustainable in Australia and how to make large-scale installation more sustainable in the future, it is not sufficient to assess just one case on the project level.

(2) Life cycle sustainability assessment is such a complex topic that it is not sufficient to just assess three dimensions of sustainability separately.

(3) UQ Solar is selected in this study because it is the largest flat roof PV installation in Australia and it is easily accessed. However, some social and economic problems cannot be properly examined in an academic-oriented establishment.

(4) The limitations mentioned in each section of the assessment emphasize the limitations of data quality in this study. Not all data are case specific, and the interpretation of results, to a large extent, depends on the assumptions made.

(5) When discussing a complex problem regarding sustainability, expert review and stakeholder participation can be very helpful, sometimes necessary, to grasp a comprehensive picture of this problem.

6.3. Prospects

Although there are many limitations of this study, it is still a good starting point for many further studies.

(1) With the aim of achieving sustainable large-scale PV installation in Australia, additional macro-level or landscape level systems need to be investigated to complete multi-level perspective analysis. It is helpful to employ adaptive and dynamic mechanisms.

(2) Life cycle sustainability assessment is such a complex topic that more integrated frameworks should be adopted. It is recommended to take system interrelationships as well as dynamics into account.

(3) In order to know what the social and economic problems really are, cases selected for study should cover different technologies adopted in different sizes of systems at different locations. The more representative the cases are, the more convincing the study is.

(4) Further studies should concentrate on case-specific data gathering. At present, most of the data collected are based on European conditions, so it is crucial to improve Australian life cycle databases to find out problems that are urgently taking place in Australia. Sensitivity and uncertainty analysis should be conducted to make the results more reliable.

(5) If possible, experts and stakeholders should actively take part in sustainability assessment. Their opinions should be considered during the whole life cycle assessment and adjustments should be made accordingly.

Acknowledgments

Author Contributions

Appendix

Assumptions of UQ Solar LCA

In order to achieve the goals, several assumptions are made based on literature review and mathematical inferences.

(1) Delivery of various system components via road transport, including the transport of construction workers, is assumed to be 100 kM [27];

(2) The existing database only has data on the inverter with a capacity of 2500 W, while in fact 5000 W and 12.5 kW inverters are used, therefore the data are correspondingly scaled using mass ratio 1.4 (2.3) [44] and energy ratio 2 (5) for 5000 W (12.5 kW) inverters;

(3) For electric installation, most of material use can be assumed to be proportional to the installed capacity;

(4) It is known 1800 MWh of electricity is generated per year for 1.22 MWp PV installation [17], so it is assumed 1770 MWh of electricity, in proportion, is generated per year for 1.2 MWp installation;

(5) In database, the data is made for 3 kWp installation [27], while in fact the system is 1.2 MWp. So, every value is multiplied by 400 to fit in the studied system;

(6) The whole defined PV system is uniformly simplified as flat roof installation;

(7) The electricity supplied to UQ campus by conventional Queensland electricity grid does not have significant transmission—distribution losses;

(8) All casted mc-Si is produced from solar-grade silicon; neither electronic grade silicon nor upgraded MG silicon is used.

Table A1. UQ Solar life cycle emissions of criteria air pollutants and greenhouse gases.

	Unit	PV Modules	Mounting System	Electric Installation	Inverter	Transportation	Total
Air Pollutants							
Carbon monoxide (CO)	kg	1872.5	2200	108	188.75	394.28	4763.62
Hydrocarbons (HC)	kg	19.70	3.23	0.67	1.18	1.00	25.78
Lead (Pb)	kg	8.99	0.163	2.95	1.33	0.03	13.46
Nitrogen Oxides (NO_x)	kg	9190	514	171	272.4	432	10,581.2
Particulate Matter (PM_{10})	kg	1922.94	272	126.24	101.24	25.28	2447.77
Sulfur Oxides (SO_x)	kg	24.8	0	0.901	57.37	0	84.33
Greenhouse gases							
Carbon dioxide (CO_2)	kg	2,690,000	285,000	44,700	76,610	59,180	3,155,877
Methane (CH_4)	kg	15,441.4	599	122.246	147.699	69.54	16,380.32

Table A2. Air pollution comparison between two electricity generation systems.

		PV System (g/kWh)	Conventional Grid (g/kWh)	Net Emission (g/kWh)
Metals	Arsenic (As)	4.28×10^{-5}	1.41×10^{-5}	-2.87×10^{-5}
	Cadmium (Cd)	1.34×10^{-5}	3.42×10^{-6}	-1.00×10^{-5}
	Chromium (Cr)	5.15×10^{-5}	2.84×10^{-5}	-2.30×10^{-5}
	Mercury (Hg)	2.34×10^{-6}	5.54×10^{-6}	3.20×10^{-6}
Criteria Air Pollutants	Lead (Pb)	2.53×10^{-4}	2.79×10^{-5}	-2.26×10^{-4}
	Carbon Monoxide (CO)	8.96×10^{-2}	7.20×10^{-1}	6.30×10^{-1}
	Particulate Matter (PM10)	4.61×10^{-2}	1.39×10^{-1}	9.32×10^{-2}
	Nitrogen Oxides (NO_x)	1.99×10^{-1}	3.67	3.47
	Sulfur Oxides (SO_x)	1.57×10^{-3}	2.73	2.73
Greenhouse gases	Carbon Dioxide (CO_2)	5.94×10^{1}	8.64×10^{2}	8.05×10^{2}
	Methane (CH_4)	3.08×10^{-1}	7.92×10^{-1}	4.84×10^{-1}
Air Toxics	Benzene (C_6H_6)	4.07×10^{-4}	1.65×10^{-4}	-2.42×10^{-4}

Table A3. Life cycle impact assessment of UQ Solar (CML 2 baseline 2000).

Impact Category	Unit	Inverter	Electric Installation	Mounting System	PV Module	Transportation	Total
Abiotic depletion	kg Sb eq	507.2442	349.7557	2116.7385	20,024.71	416.2695	23,414.71
Acidification	kg SO_2 eq	736.0431	926.10171	1305.7183	27,130.96	341.8155	30,440.64
Eutrophication	kg PO_4 eq	710.8017	1031.4202	476.21218	3597.214	81.6106	5897.259
Global warming (GWP100)	kg CO_2 eq	82,154.04	48,457.16	338080.4	3,153,394	61,980.09	3,684,066
Ozone layer depletion (ODP)	Kg CFC-11 eq	0.005396	0.0013523	0.0162321	0.295842	0.00905	0.327872
Human toxicity	kg 1,4-DB eq	500,004.4	935,956.42	1,150,067.6	1,643,401	21,015.72	4,250,445
Fresh water aquatic ecotoxicity	kg 1,4-DB eq	182,845.5	5,690,261	233,253.8	705,574.5	5944.029	6,817,879
Marine aquatic ecotoxicity	kg 1,4-DB eq	4.72×10^{8}	1.84×10^{9}	326,874,804	1.56×10^{9}	13,497,108	4.22×10^{9}
Terrestrial ecotoxicity	kg 1,4-DB eq	1375.375	2331.5322	2896.7959	12,883.78	123.399	19,610.89
Photochemical oxidation	kg C_2H_4 eq	63.3772	36.694604	109.93306	1099.181	21.09426	1330.28

Table A4. Life cycle impact assessment comparison.

Impact Category	Unit	PV System (kg/kWh)	Conventional Grid (kg/kWh)
Abiotic depletion	kg Sb eq	0.000441	0.000553
Acidification	kg SO_2 eq	0.000573	0.005129
Eutrophication	kg PO_4 eq	0.000111	0.000518
Global warming (GWP100)	kg CO_2 eq	0.069393	0.909119
Ozone layer depletion (ODP)	kg CFC-11 eq	6.17×10^{-9}	5.31×10^{-10}
Human toxicity	kg 1,4-DB eq	0.080053	0.29406
Fresh water aquatic ecotox.	kg 1,4-DB eq	0.128401	0.247349
Marine aquatic ecotoxicity	kg 1,4-DB eq	79.41658	800.2707
Terrestrial ecotoxicity	kg 1,4-DB eq	0.000369	0.000413
Photochemical oxidation	kg C_2H_4 eq	2.51×10^{-5}	0.000189

Table A5. SAM main input values.

| Input Variable	Value
Analysis Parameters/Analysis Period (years)	30
Analysis Parameters/Federal Income Tax Rate (%/year)	30
Analysis Parameters/Inflation Rate (%/year)	2.5
Analysis Parameters/Net Salvage Value (% of installed cost)	10
Analysis Parameters/Real Discount Rate (%/year)	7.6
Array/DC to AC ratio	1.1
CEC Performance Model with Module Database/Array height	One story building height or lower
CEC Performance Model with Module Database/Mounting standoff	Building integrated
CEC Performance Model/Columns of modules in array	10
CEC Performance Model/Gap Spacing (m)	0.05
CEC Performance Model/Heat Transfer Dimensions	Module Dimensions
CEC Performance Model/Material	Multi-c-Si
CEC Performance Model/Module Area (m^2)	1.618
CEC Performance Model/Module Name	SAM/CEC Modules/Trina Solar TSM-240PA05.38
CEC Performance Model/Module Width (m)	0.992
CEC Performance Model/Mounting Configuration	Rack
CEC Performance Model/Number of Cells	60
CEC Performance Model/Rows of modules in array	1
Depreciation/Federal Straight Line Depreciation Years	20
Inverter (Sandia)/Sandia Inverter	SAM/Sandia Inverters/Power-One Inc.: PVI-12.0-I-OUTD-x-US-480-y 480V [CEC 2011]
Inverter (Sandia)/Sandia Inverter	SAM/Sandia Inverters/SMA America: SB4000US 240V [CEC 2007]
Inverter Datasheet/ Manufacturer efficiency (%)	96
Inverter Datasheet/Maximum AC output power (Wac)	12441.6
Inverter Datasheet/Maximum DC current (Adc)	36
Inverter Datasheet/Maximum DC voltage (Vdc)	900
Inverter Datasheet/Maximum MPPT DC voltage (Vdc)	750
Inverter Datasheet/Minimum MPPT DC voltage (Vdc)	360
Inverter Datasheet/Nominal AC voltage (Vac)	400
Inverter Datasheet/Nominal DC voltage (Vdc)	360
Inverter Datasheet/Power consumption at night (Wac)	3.1104
Inverter Datasheet/Power consumption during operation (Wdc)	0
Inverter Datasheet/Weighted efficiency (%)	97.2
Inverter Part Load Curve/Maximum AC output power (Wac)	36,000
Inverter Part Load Curve/Maximum DC current (Adc)	150
Inverter Part Load Curve/Maximum DC voltage (Vdc)	600

Table A5. *Cont.*

Input Variable	Value
Inverter Part Load Curve/Maximum MPPT DC voltage (Vdc)	480
Inverter Part Load Curve/Minimum MPPT DC voltage (Vdc)	250
Inverter Part Load Curve/Nominal AC voltage (Vac)	240
Inverter Part Load Curve/Nominal DC voltage (Vdc)	310
Inverter Part Load Curve/Power consumption at night (Wac)	0.6
Inverter Part Load Curve/Weighted Efficiency Type	CEC efficiency
Loan Parameters/Debt Fraction (%)	0
Loan Parameters/Loan Rate (%/year)	7.78
Loan Parameters/Loan Term (years)	15
Location and Resource/Location	C:\Users\Fisher\Desktop\SAM weather data/AUS_QLD.Brisbane.945780_IWEC.epw
O and M Costs/Fixed Cost by Capacity ($/kW-year)	12
PV Array Self-Shading/Mask Angle Calculation Method	Average over Entire Array
PV Array Self-Shading/Number of Bypass Diodes	3
PV Array Self-Shading/Number of Cells along Width	6
PV Array Self-Shading/Number of Modules along Side	1
PV Array Self-Shading/Number of Strings along Bottom	1
PV Array Self-Shading/Orientation	Portrait
PV Array Self-Shading/Row Spacing (m)	5
PV Array Self-Shading/Width (m)	0.992
PV Array/AC wiring losses ((0..1))	0.97
PV Array/Desired array size (kWdc)	1202
PV Array/Mode	Specify desired array size
PV Array/Modules per string	40
PV Array/Monthly ground reflectance (albedo)	0.2
PV Array/Number of inverters	88
PV Array/PV Radiation Model (0 = Total&Beam 1 = Beam&Diffuse)	0
PV Array/PV Tilt Radiation Model (0 = Isotropic 1 = HDKR 2 = Perez)	Perez
PV Array/Packing factor	1.05
PV Array/Row offset (m)	0
PV Array/Step-up transformer losses ((0..1))	1
PV Array/Strings in parallel	125
PV Array/Use albedo in weather file if it exists	1
PV Capital Costs/Balance of System Equipment Capacity ($/Wdc)	0.219
PV Capital Costs/Contingency	5
PV Capital Costs/Engineering Cost, by Capacity ($/Wdc)	0.14

Table A5. *Cont.*

Input Variable	Value
PV Capital Costs/Grid Interconnect Cost, by Capacity ($/Wdc)	0.13
PV Capital Costs/Installation Labor, by Capacity ($/Wdc)	0.625
PV Capital Costs/Installer Margin and Overhead, by Capacity ($/Wdc)	0.625
PV Capital Costs/Inverter Cost	0.5
PV Capital Costs/Module Cost	1.53
PV Capital Costs/Permitting Cost, by Capacity ($/Wdc)	0.06
PV Inverter/Inverter Model Type (0 = CEC, 1 = DATASHEET, 3 = PARTLOAD)	1
PV Module Manufacturer Specifications Model/Approximate installation height	Two story building height or higher
PV Module Manufacturer Specifications Model/Cell type	Multi-Si
PV Module Manufacturer Specifications Model/Maximum power point current (Imp) (A)	6
PV Module Manufacturer Specifications Model/Maximum power point voltage (Vmp) (V)	30
PV Module Manufacturer Specifications Model/Module area (m2)	1.3
PV Module Manufacturer Specifications Model/Module description	Generic polycrystalline silicon module
PV Module Manufacturer Specifications Model/Nominal operating cell temperature ('C)	46
PV Module Manufacturer Specifications Model/Number of cells in series	60
PV Module Manufacturer Specifications Model/Open circuit voltage (Voc) (V)	37
PV Module Manufacturer Specifications Model/Short circuit current (Isc) (A)	7
PV Module Manufacturer Specifications Model/Standoff height	Ground or rack mounted
PV Module Manufacturer Specifications Model/Temperature coefficient of Isc	0.004
PV Module Manufacturer Specifications Model/Temperature coefficient of Voc	−0.11
PV Module Manufacturer Specifications Model/Temperature coefficient of max. power point (%/'C)	−0.41
PV Module/Module Model Type (0 = MPE 1 = CEC 2 = CECUSER 3 = SANDIA)	1
PV Subarray 1/Azimuth 1 (deg)	20
PV Subarray 1/DC wiring losses 1 (%)	0.98
PV Subarray 1/Diode and connection losses 1 (%)	0.995
PV Subarray 1/Ground coverage ratio 1	0.3

Table A5. *Cont.*

Input Variable	Value
PV Subarray 1/Mismatch losses 1 (%)	0.98
PV Subarray 1/Nameplate derate 1 (%)	1
PV Subarray 1/Self-shading mode for 1x trackers	Self-shaded
PV Subarray 1/Tilt 1 (deg)	4
PV Subarray 1/Tracker rotation limit 1 (deg)	45
PV Subarray 1/Tracking error 1 (%)	1
PV Subarray 1/Tracking mode 1	Fixed
Performance Adjustment/Year-to-year decline in output (compounded annually)	0.7
Sandia Inverter Model/Maximum AC power (Wac)	12,000
Sandia Inverter Model/Maximum DC current (Adc)	25
Sandia Inverter Model/Maximum DC power (Wdc)	12,363.9
Sandia Inverter Model/Maximum DC voltage (Vdc)	520
Sandia Inverter Model/Maximum MPPT DC voltage (Vdc)	470
Sandia Inverter Model/Minimum MPPT DC voltage (Vdc)	250
Sandia Inverter Model/Nominal AC voltage (Vac)	480
Sandia Inverter Model/Nominal DC voltage (Vdc)	374.028
Sandia Inverter Model/Power consumption at night (Wac)	0.4
Sandia Inverter Model/Power consumption during operation	69.199 (Wdc)
Sandia PV Array Performance Model/Material	Mc-Si
Sandia PV Array Performance Model/Module Area (m^2)	1.312
Sandia PV Array Performance Model/Module Name	SAM/Sandia Modules/Advent Solar AS160 [2006]
Sandia PV Array Performance Model/Module Structure and Mounting	Use Database Values
Sandia PV Array Performance Model/Number of Cell Strings in Parallel	1
Sandia PV Array Performance Model/Number of Cells in Series	72
Sandia PV Array Performance Model/Vintage	2006
Sandia PV Array Performance Model/a	−99
String Wiring	Horizontal
Utility Rate/Flat Buy Rate ($/kWh)	0.125
Utility Rate/Flat Sell Rate ($/kWh)	0.125
Utility Rate/Out-year Escalation (%/year)	1.82
Utility Rate/Year End Sell Rate ($/kWh)	0.0289

System Advisor Model Report
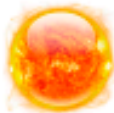
Photovoltaic System
Commercial

1.2 DC MW Nameplate
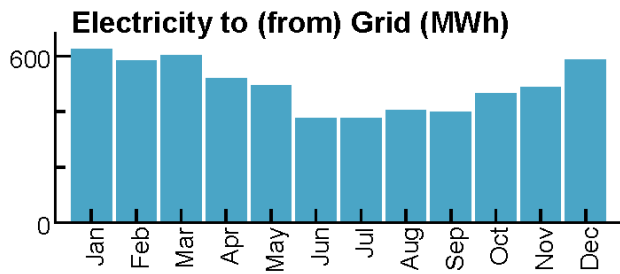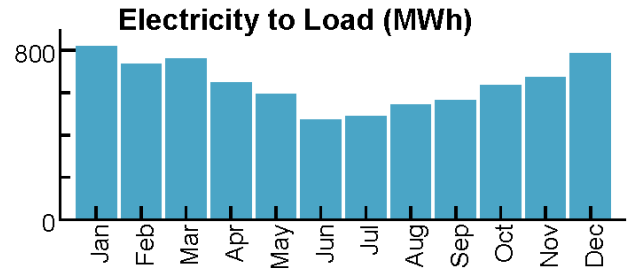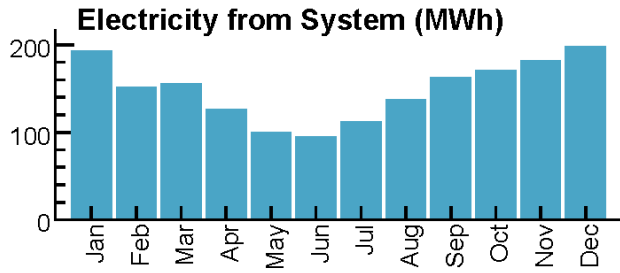$3.96/W Installed Cost

BRISBANE, -
-27.38 N, 153.1 E GMT +10

Performance Model

Modules

Trina Solar TSM-240PA05.38	
Cell material	mc-Si
Module area	1.6 m^2
Module capacity	239.9 DC Watts
Quantity	5,004
Total capacity	1.2 DC MW
Total area	8,096 m^2

Inverters

Custom (Inverter Datasheet Model)	
Unit capacity	12.4416 AC kW
Input voltage	360 DC V
Quantity	88
Total capacity	1.1 AC MW
DC to AC Capacity Ratio	1.10
AC derate factor	0.97

Array

Strings	278
Modules per string	18
String voltage (DC V)	547.2
Tilt (deg from horizontal)	4
Azimuth (deg E of N)	20
Tracking	fixed
Backtracking	-
Rotation limit (deg)	-
Shading	no
Soiling	yes
DC derate factor	0.96

Performance Adjustment

Annual	100, 100, 100, 100, 100...%
Year-to-year decline	0.7%/yr
Hourly factors	no

Annual Results (in Year 1)

Horizontal solar kW/m^2	1,834
Incident solar kW/m^2	0
DC GWh from array	1.967
Net to inverter	1,880,000 DC kWh
Gross from inverter	1,826,000 AC kWh
Net to grid	1,771,000 AC kWh
Capacity factor	16.8%
Performance factor	0.83

Financial Model

Project Costs

Total installed cost	$4,750,374
Salvage value	$475,037

Analysis Parameters

Project life	30 years
Inflation rate	2.5%
Real discount rate	7.6%

Project Debt Parameters

Debt fraction	0%
Amount	$0
Term	15 years
Rate	7.78%

Tax and Insurance Rates (% of installed cost)

Federal income tax	30%/year
State income tax	0%/year
Sales tax	0%
Insurance	0%/year
Property tax (% of assess. val.)	0%/year

Incentives

Federal Depreciation 20-yr Straight Line	
State Depreciation	None

Electricity Demand and Rate Summary

Annual peak demand 1,687.6 kW	
Annual total demand 7,646,295 kWh	
Flat buy rate $0.125/kWh, flat sell rate $0.125/kWh	
Annual rate escalation: 1.82%/year	

Results

Nominal LCOE	27.2 cents/kWh
Net present value	$-1,304,100
Payback period	13.7 years

Commercial | Flat Plate PV | CEC Module with Database | Inverter Datasheet

Figure A1. *Cont.*

Electricity from System (MWh)

Electricity to Load (MWh)

Electricity to (from) Grid (MWh)

Net Metering not Applicable

Monthly Electricity Purchases and Savings (Year 1 $)

Month	Without System	With System	Savings
Jan	146,063	111,347	34,716
Feb	130,926	103,677	27,249
Mar	134,841	106,979	27,862
Apr	114,507	92,169	22,337
May	104,985	87,431	17,553
Jun	88,722	70,757	17,965
Jul	91,256	70,266	20,989
Aug	102,252	76,449	25,802
Sep	105,085	74,850	30,234
Oct	120,132	88,113	32,018
Nov	119,061	86,806	32,254
Dec	139,331	103,979	35,352
Annual	1,397,167	1,072,829	324,338

NPV Approximation using Annuities

Annuities, Capital Recovery Factor (CRF) = 0.1087		
Investment	$-516,100	Sum:
Expenses	$-12,300	$-141,700
Savings	$68,300	NPV = Sum / CRF:
Energy value	$318,400	$-1,304,000

Investment = Installed Cost - Debt Principal - IBI - CBI
Expenses = Operating Costs + Debt Payments
Savings = Tax Deductions + PBI
Energy value = Tax Adjusted Net Savings
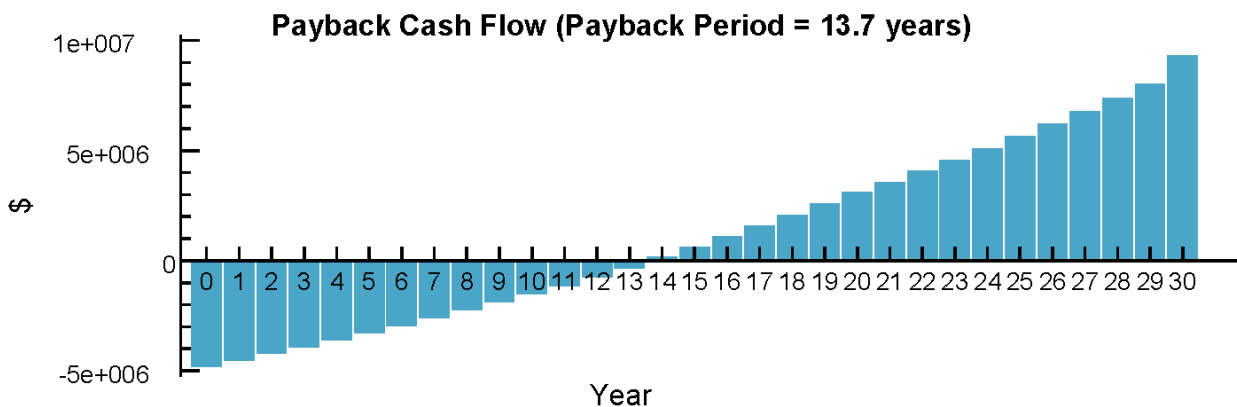Nominal discount rate = 10.29%

Payback Cash Flow (Payback Period = 13.7 years)

Figure A1. *Cont.*

Nominal POA Total Radiation
15,185,631 kWh

Operating Losses as % of Previous Valu

0.00% Shading

5.00% Soiling

POA after Shading and Soiling
14,426,350 kWh

Array Nominal Output at STC
2,138,595 kWh(dc)

8.00% Module Model

2.00% Mismatch

0.50% Diodes and Connections

2.00% DC Wiring

0.00% Sun Tracking

0.00% Nameplate

Array Output at MPP
1,880,097 kWh(dc)

0.00% Inverter Clipping

0.00% Inverter Power Consumption

0.00% Inverter Night Tare

2.86% Inverter Efficiency

3.00% AC wiring

0.00% Step-up Transformer

-0.00% Performance Adjustment

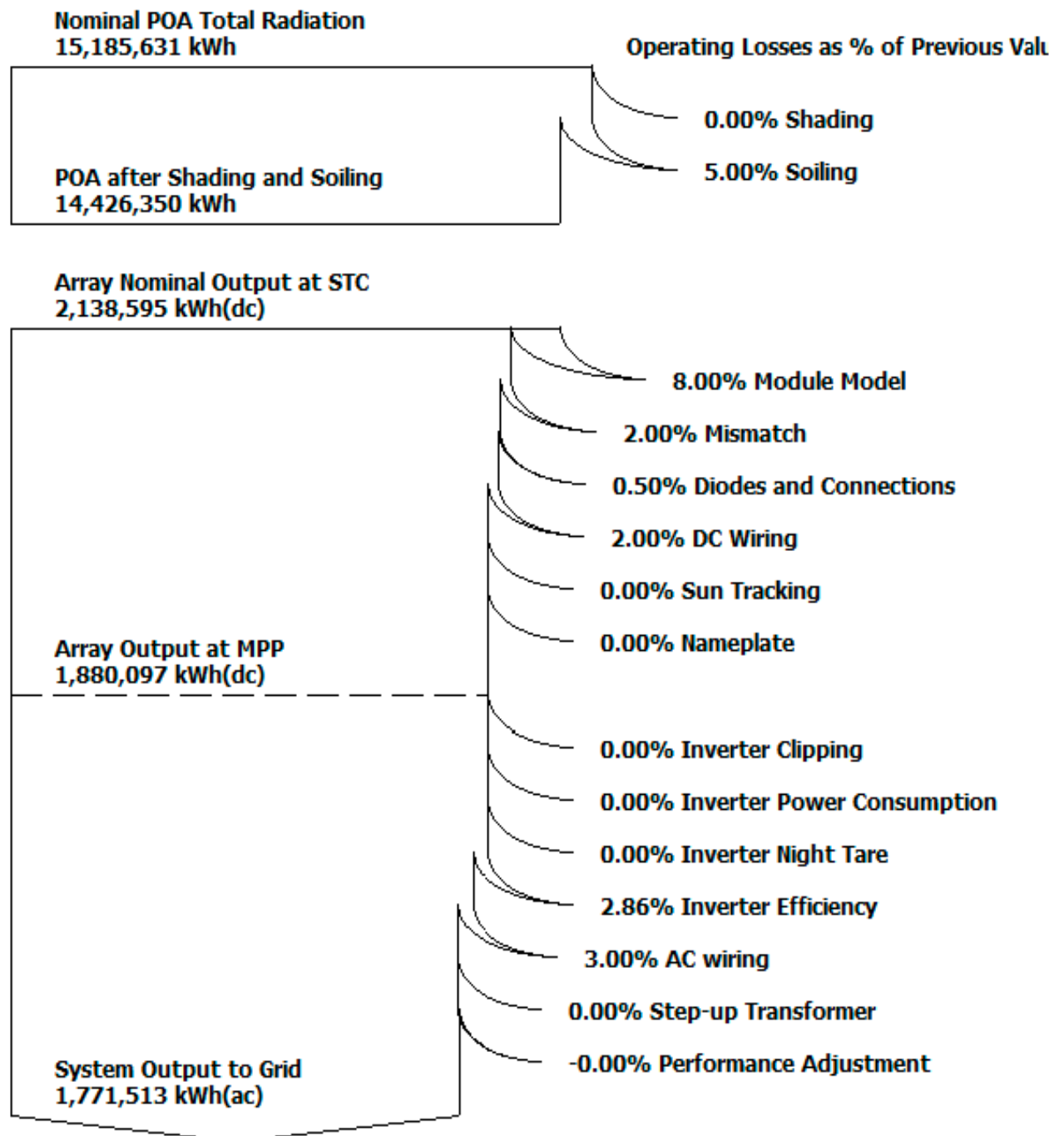**System Output to Grid**
1,771,513 kWh(ac)

Figure A1. System advisor model report for UQ Solar life cycle costing analysis.

Conflicts of Interest

The authors declare no conflict of interest.

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