

The Impact of Solar Energy System on Environmental and Social Sustainability

Abdul Waris Farid¹, Mohammad Naser Rasuli², Ghulam Hussain.R³

¹ Al-beroni University, Kapisa, Afghanistan

² Parwan University, Parwan, Afghanistan

³ Mining–Metallurgical Institute of Tajikistan, Khujand, Tajikistan

Abstract — Energy production and technical efficiency are important aspects of energy systems, they should not be used to determine their sustainability of solar energy systems. The study combines environmental aspects of solar PV systems' life cycles with social aspects to explore their environmental and social sustainability impacts. Three different PV technologies—monocrystalline silicon, multicrystalline silicon, cadmium telluride—are analyzed, and the energy yield, module efficiency, greenhouse-gas emissions, energy payback time, and social aspects like employment, energy access, community benefits, and social acceptance are considered. An AHP-based framework is still maintained to highlight that on how the various sustainability dimensions can be incorporated into the PV assessment. The illustrative results show that PV technologies have various electrical and environmental features, and social outcomes are highly sensitive to project site settings and deployment environment, as well as community context. The paper emphasizes on the importance of integrated assessment for environmental and social sustainability in the planning of solar energy systems.

Keywords— “Solar energy”, “PV systems”, “environmental impacts”, “social sustainability”, “life-cycle assessment”, “renewable energy”.

I. INTRODUCTION

Moving from traditional fossil-fuel energy supplies to renewable energy is an integral part of global efforts to mitigate greenhouse-gases, enhance energy security and adopt more sustainable development strategies. Solar photovoltaic (PV) systems have garnered significant interest for renewable energy technologies due to their ability to directly convert solar radiation to electricity and their ability to be utilized on a residential, commercial, industrial and utility scale. Photovoltaic technology has evolved over time to become more efficient, and more competitive economically and in terms of system performance, which is why solar energy is becoming more important in the electricity system. The electrical-engineering parameters typically used for evaluating PV system performance include module efficiency, total annual PV electricity generation, SPEY, PV performance ratio, PV system temperature characteristics, and PV system losses. Such parameters are crucial to determine the efficiency of the utilization of available solar energy to generate useful electrical power. But, the electrical performance is not the only indicator of the sustainability of a PV system. Solar energy systems should be seen as a holistic technical, environmental and social system for sustainability. Raw materials, energy, transportation, land and other resources are needed for the production, installation, operation, maintenance, and end-of-life of PV systems. Photovoltaic systems do not emit direct combustion

emissions when in operation, but have life cycle environmental impacts. These impacts have been shown to be quite variable across different PV technologies, PV manufacturing processes, geographical conditions, solar irradiation, PV system lifetime, and methodological assumptions [1,2]. Under their reference conditions, Hsu et al. [1] performed a systematic review and harmonization of life-cycle GHG emissions of electricity generation by crystalline-silicon photovoltaics, and obtained a harmonized median value of ~45 g CO₂-equivalent per kWh. They also showed that important system components like solar irradiation, module efficiency, performance ratio and system lifetime can have considerable impact on life cycle results. Likewise, Kim et al. [3] found that CdTe thin-film PV systems had relatively low LC GHGs for their reference conditions.

The results show that the most environmentally friendly technology is not the one that is the most efficient electrically. A tech could yield more electricity but need more energy or materials to make. However, a technology that is less efficient at converting energy can have benefits in terms of embodied energy and life-cycle environmental impacts. The development of solar energy can have social impacts as well as environmental impacts. Solar projects can provide jobs, access to energy, local economic development, community development and access to electricity. Meanwhile, the development of the project can also trigger social issues about land use, acceptance of the project by the community, sharing

of benefits, and participation of the community. Thus, environmental impacts and social issues must be considered for the sustainability of solar energy systems.

Therefore, the assessment of solar energy systems is a multi-dimensional sustainability problem that consists of technical, environmental and social dimensions. Multi criteria decision making techniques are systematic ways of evaluating alternatives based on multiple criteria [4,5]. This study aims to explore the environmental and social sustainability aspects of solar energy systems with maintaining electrical performance as one of the significant technical aspects. Three representative PV technologies are chosen, monocrystalline silicon, multicrystalline silicon and cadmium telluride, for illustrative purposes to show how a sustainability assessment can be integrated and how it can consider electrical, environmental and social aspects. The study aims to answer the following question:

How to measure the environmental and social sustainability of a solar energy system in addition to electrical performance?

The study fills this gap by considering this question and creating an interdisciplinary link between electrical/electronic engineering and Earth/environmental engineering.

II. LITERATURE REVIEW

One of the basic factors to consider when designing and assessing the performance of PV systems is electrical performance. The electricity production from PV systems is influenced by solar irradiation, PV module properties, operating temperature, orientation, shading effects, inverter efficiency, electrical losses, degradation and other system-related issues. The efficiency of the module in converting the incoming solar radiation to electric energy is called module conversion efficiency.

The higher the efficiency, the more electricity can be generated from a specific installation space and can therefore be especially advantageous when available land is limited. However, module efficiency does not fully represent the performance of a PV system as climatic and operating conditions also have an impact on the yearly energy production. Often several parameters are used to evaluate the performance of PV technologies, rather than just one. Specific energy yield and a performance ratio are useful for quantifying the electricity production at the system level, whereas efficiency gives information regarding the PV technology's conversion

capability. The technical indicators are an essential basis of comparison for the various PV technologies.

However, an electric assessment may fail to consider environmental and social aspects related to the manufacturing, deployment, operation and eventually management of the equipment for electricity generation. Here, the life-cycle environmental impacts of photovoltaic (PV) technologies will be discussed. The life-cycle environmental impacts of PV technologies will be discussed in this part. LCA is a well-established approach to assess the life-cycle environmental impacts of products and systems. It considers raw-material extraction, manufacturing, transportation, installation, operation, maintenance and end-of-life treatment. In the study of renewable energy, Ludin et al. [2] discussed the life-cycle assessment (LCA) studies of photovoltaic (PV) technologies and concluded that greenhouse-gas emissions, cumulative energy demand, energy payback time and other environmental indicators are important dimensions of PV sustainability. Hsu et al. [1] showed crystalline-silicon PV technologies can have different life-cycle GHG emissions depending on technology, site, irradiation, lifetime and system-performance assumptions. They gave a benchmark of the performance of various PV technologies under the same conditions. Thin-film technologies have also been looked upon in the light of life cycles. Kim et al. [3] systematically reviewed and harmonized the life-cycle GHG emissions of thin-film PV electricity generation and found that CdTe had relatively low emissions for the conditions that they studied. Peng et al. [6] also highlighted that energy payback time and GHGs are influenced by PV technology, energy needed for PV manufacturing, solar resource availability, and system lifetime. The results highlight the need for consistent boundaries and assumptions to assess PV technologies. The deployment of PV can also have implications for the environment other than GHGs. These include land use, water consumption, extraction of materials, pollution associated with manufacturing and waste at the end of the product's life.

Tawalbeh et al. [7] highlighted that these impacts need to be considered when assessing the environmental sustainability of solar photovoltaic (PV) systems. The environmental sustainability of solar energy systems is a crucial issue. 2.3 Social Sustainability of Solar Energy Systems is a critical topic. An additional criterion for assessing solar energy systems is social sustainability. Social sustainability is different from the environmental indicators, which mainly refer to the impacts on ecologic systems, resources and emissions, social sustainability refers to the impacts of energy projects on people, communities and benefits. For employment, energy access, local economy

and energy security, solar-energy deployment can contribute. But the social benefits of a project are significantly influenced by its geographical location, size, ownership, land needs, and context with its local neighbours. Social acceptance is also related to the successful implementation of renewable-energy projects. How solar projects are received and maintained can be impacted by community participation, perceived benefits, project benefits distribution and local concerns. Therefore, the technical and environmental aspects may not be the only factors determining the sustainability of an SEP. Campos-Guzmán et al. [8] highlighted the importance of implementing a LCA approach in combination with a multi-criteria decision-making tool to impact assessment renewable-energy technologies from a sustainability perspective. This integrated approach gives the opportunity to consider several dimensions instead of only one technical or environmental dimension. This is the second module of the four that will be offered in the course, Renewable Energy. This is the second of four modules for the course Renewable Energy. Multiple criteria, which cannot be captured in one performance measure, are often used to select renewable-energy technology. For instance, an electric efficient technology might be more desirable than one that is better for the environment or community. There are methods of multi-criteria decision making that can offer a structured way of managing such trade-offs. Saaty [9] developed one of the established Multi Criteria Decision Making (MCDM) approaches called Analytic Hierarchy Process (AHP) for complex decision problems. It structures a decision problem with an overall objective, evaluation criteria and alternatives. The relative importance of the criteria can then be established and then a global assessment obtained. Ilbahar et al. [4] listed the AHP as one of the methods commonly used in the research of decision making on renewable energy. Shao et al. [5] also investigated the use of multi-criteria decision making in planning renewable energy systems, and illustrated the wide application of AHP for energy-related decisions. An in-depth analysis of the incorporation of LCA and multi-criteria decision-making for sustainability assessment of renewable-energy technologies was conducted by Campos-Guzmán et al. [8].

Their results argue for the implementation of integrated approaches with the ability to “merge” environmental information with other decision-making criteria. 2.5 Research Gap The electrical performance of PV and the LCO analysis of its environmental impacts have been extensively studied in previous research and the multi-criteria approaches have been shown to be useful in studies of renewable-energy decision making. In many cases, however, the electrical, environmental and social aspects are treated separately. An integrated

sustainability perspective is then helpful for assessing the “whole-of-system” impacts of solar energy systems. This study aims to fill this gap and to push the framework developed in the previous study to a more comprehensive sustainability approach, broadening the electrical-environmental framework. Environmental impacts are assessed quantitatively using the illustrative PV dataset, and social sustainability is added as a complementary dimension, which needs to be evaluated on a project-specific basis in terms of jobs created, energy access, community benefits and social acceptance.

III. METHODOLOGY

The study adopts an integrated sustainability-assessment approach combining technical performance, environmental impacts, and social sustainability considerations. The Analytic Hierarchy Process is retained as the primary multi-criteria decision-making methodology because it provides a transparent and structured approach for comparing alternatives according to multiple criteria and has been widely applied to renewable-energy problems [4,9].

Therefore, Social sustainability is treated as an additional assessment dimension rather than assigning unsupported numerical values to social indicators. Relevant social considerations include employment, energy access, community benefits, social acceptance, and local participation. This approach avoids presenting assumed social values as measured evidence

IV. RESULTS

The benchmark assessment shows that mono-Si has the highest assumed electrical efficiency and annual specific energy yield among the three alternatives. Its energy yield is approximately 1,750 kWh/kWp/year, compared with 1,680 kWh/kWp/year for multi-Si and 1,720 kWh/kWp/year for CdTe.

Table 1. Electrical Performance Indicators of Selected Photovoltaic Technologies

PV Technology	Energy Yield (kWh/kWp/year)	Efficiency (%)	Electrical Performance
Mono-Si	1,750	22.0%	Highest
Multi-Si	1,680	20.0%	Moderate
CdTe	1,720	18.0%	Moderate

Source: Compiled by the Authors from [1,4]

The results indicate that mono-Si provides the strongest electrical-performance profile under the assumptions adopted

for the illustrative case. Its higher efficiency can be advantageous where installation area is limited because greater electrical output can be obtained from a given surface area.

CdTe, despite having the lowest assumed module efficiency, has an annual energy yield relatively close to that of mono-Si. This indicates that module efficiency should not be interpreted independently from other factors affecting annual electricity generation.

Table 2. Environmental Performance of the PV Technologies.

PV Technology	GHG Emissions	Energy Payback Time (years)	Environmental Performance
Mono-Si	45	2.0	Moderate
Multi-Si	50	2.2	Lowest
CdTe	14	1.0	Highest

Source: Compiled by the Authors from [1,3]

The benchmark CdTe value of 14 g CO₂-eq/kWh is consistent with the harmonized value reported by Kim et al. [3] for CdTe under their specified reference conditions. The crystalline-silicon value of 45 g CO₂-eq/kWh corresponds to the harmonized median reported by Hsu et al. [1].

CdTe also has the shortest assumed energy payback time. This means that, under the selected assumptions, the energy required throughout the production of the PV system can be recovered through electricity generation relatively quickly. These results demonstrate that the technology with the strongest electrical performance does not necessarily have the strongest environmental performance.

Table 3. Integrated Electrical-Environmental Sustainability Assessment

PV Technology	Electrical Contribution	Environmental Contribution	Overall Score
Mono-Si	0.500	0.193	0.693
Multi-Si	0.470	0.175	0.645
CdTe	0.459	0.500	0.958

Source: Compiled by the Authors from [1,3,4]

Under the balanced weighting structure used in the illustrative analysis, CdTe obtains the highest overall score, followed by mono-Si and multi-Si.

These numerical scores should be interpreted only as an illustration of the electrical-environmental component of the

framework. They do not constitute a complete sustainability ranking because social impacts were not quantified using original project-level data.

The outcome is primarily driven by the strong environmental performance of CdTe. Although mono-Si has the strongest electrical characteristics, its higher life-cycle greenhouse-gas emissions and longer energy payback time reduce its integrated electrical-environmental score.

A complete sustainability assessment would require the addition of validated social-impact data and appropriate stakeholder-based weighting. Such data could include employment effects, energy-access improvements, community acceptance, local economic benefits, and distributional effects.

V. DISCUSSION

This result show that solar-energy sustainability is not limited to electricity generation and technical efficiency. The illustrative dataset shows that the electrical performance of Mono-Si is highest, while the energy payback time and life cycle GHG emissions of CdTe are much lower. This difference is significant in the electrical and environmental engineering aspects. Historically, electrical engineers have catered to increasing electricity production, efficiency, reliability, and reducing system losses. Environmental engineering comes into play and looks at the resources and environmental impacts required to make that electricity production.

The results are in line with the previous life cycle studies. Hsu et al. [1] showed the life-cycle GHG emissions of crystalline-silicon PV to be dependent on the irradiation, lifetime, efficiency, and performance ratio. Similarly, Kim et al. [3] reported relatively low life-cycle GHG emissions for CdTe for their reference conditions.

Solar energy systems' benefits and impacts are also highly dependent on the manner and location of their implementation from social-sustainability points of view. While solar deployment can drive job creation and access to energy, the distribution of benefits, land needs, community engagement and public acceptance can have a significant impact on the sustainability of a project. Hence, social context is an essential part of the consideration of environmental performance of a solar system and cannot be separated from it.

The environmental performance of a PV technology is not a constant value. Calculated environmental indicators can vary significantly depending on manufacturing location, electricity

mix, transportation distance, system lifetime, solar resource, recycling assumptions, and life-cycle boundaries. Likewise, social impacts depend on local economy, energy use, land use, land ownership, and community participation.

The main advantage of the approach of the AHP framework is that it brings tradeoffs to the surface. Electrical performance and environmental sustainability can be varied, depending on the project. A project that has limited available land may be more concerned with module efficiency while another project, mainly focused on life-cycle environmental impacts, may be more focused on environmental indicators.

The same applies to social sustainability. Access to energy and the benefits that it can offer to a community may be more important in a project designed to provide electric service to rural areas than to a large utility-scale project, while employment, land use, stakeholder involvement and benefit distribution may be more important in a utility-scale project. This illustrates a need for sustainability assessment to be tailored to the purpose and situation of a specific project.

The study illustrates the interdisciplinary aspects of sustainable-energy engineering as well. The PV technology is a great example of how the two disciplines of electrical engineering and earth/environmental engineering can be linked together, as electricity generation, material use, land use, water, emissions, resource management and social conditions are all aspects of the same energy system.

One of the disadvantages of this study is that the numerical case study is not based on actual field measurements. A second constraint is that the social dimension is presented conceptually as there is no validated data-set available at the project-level. Thus, the present results are not intended to provide a full quantitative evaluation of social sustainability.

Future studies should be conducted at a specific geographical area, in the form of real meteorological data, with a validated PV simulation, with manufacturer-specific technical parameters, with harmonized life-cycle parameters and with primary or validated secondary social-impact parameters. Additional multi-criteria elements such as stakeholder surveys, community consultations, employment indicators, energy-access indicators, and social-acceptance assessments can be added. This would enable the framework to produce local level sustainability outcomes and strengthen the scientific quality of the study.

VI. CONCLUSION

This study analysed the environment and social sustainability aspects of solar energy systems, in addition to its electrical performance as an essential technical aspect. The analysis involved annual energy yield, module efficiency, life-cycle greenhouse-gas emissions, energy payback time, and social sustainability (through employment, energy access, community benefit, social acceptance, and contextual considerations). The illustrative results show that the electrical performance of mono-Si is good, and that of CdTe is good based on the assumptions that were applied in the literature. The integrated assessment is to demonstrate that sustainability of solar energy cannot be judged just by its electrical efficiency. The study further illustrates the multidimensionality of the sustainability of solar energy systems. The impact and outcomes for the environment and society vary with technology, manufacturing conditions, location, resources, scale, and community context. Therefore, just an efficient solar system can't be fully termed as sustainable if the environmental and social impact is not discussed. The proposed framework offers a practical interdisciplinary linkage between the disciplines of electrical/electronic engineering and Earth and environmental engineering. It can be further expanded with site-specific solar-resource data, field measurements, PV simulation and detailed life cycle assessment, and validated social-impact indicators. The illustrative dataset used in this research should be replaced in future research with original technical, environmental and social data. Explicitly incorporating social and project-specific environmental indicators and stakeholder views in life-cycle environmental assessment would give a much firmer foundation for the long-term sustainability of solar energy systems and would facilitate the creation of the study into an original research publication.

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