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Life Cycle Considerations for Monocrystalline Photovoltaics in Thailand

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Abstract: Electricity from solar photovoltaics (PV) is gaining attention in Thailand, since the Ministry of Energy set forth targets to produce 25% of its electricity from renewable sources by 2021. Monocrystalline PV (mc-Si), the most energy-conversion efficient type photovoltaic module, is widespread as a solar technology in Thailand. Understanding the potential greenhouse gas emission reductions is increasingly important for evaluating renewable energies. This paper evaluates different parameters from a life cycle perspective that affect climate change mitigation. The primary objectives are to quantify the different life cycle effects on resulting greenhouse gas (GHG) emissions for electricity produced by mc-Si panels for grid-connected systems in Thailand. The study considers the effects of energy efficiency measures, location of production, installation, building-integrated options, and climatic effects. A life cycle assessment suggested that monocrystalline panels can generate electricity with approximately ten times fewer GHG emissions than Thailand's average electricity mix. The inclusion of building-integrated applications reduces the life cycle impact even further by a factor of 3. With potential for significant GHG emission reductions, mc-Si PV grid-connected electricity production can serve as a possible climate change mitigation strategy for Thailand. This paper outlines the ways that different parameters can alter life cycle GHG emission results.

Keywords: life cycle thinking, monocrystalline PV, climate change mitigation, Thailand.

1. Introduction

Life cycle thinking provides an objective assessment of different renewable technologies, which is an invaluable tool for both policymakers and engineers. Especially useful for the field of renewable energy, life cycle assessment can help objectively compare different types of renewable energy technologies or quantify the impacts of different environmental indicators including greenhouse gas (GHG) emissions [1-2].

Thailand seeks to increase its share of renewable energy by 2021 to 25% and this transition will require a multi-faceted approach incorporating various renewable energies including solar electricity [3]. Monocrystalline is one type of PV technology that has existed for more than 40 years [4]. The Very Small Power Producer (VSPP) policy mechanism in Thailand encourages the deployment of grid-connected solar electricity through subsidy adders, which has generated significant interest in solar electricity projects. To establish a climate change mitigation policy and adequately understand impacts associated with using grid-connected mc-Si photovoltaic technology, life cycle assessment becomes a useful and relevant tool. This paper explores the life cycle considerations that affect different outcomes of the evaluation, including energy efficiency during production, the location of production of the panels, installation and balance of system (BOS), building integration, and climate. It is important to note the potential outcomes for LCA studies within Thailand compared with similar life cycle studies conducted elsewhere based on different assumptions.

2. Life Cycle Assessment of Photovoltaics

Life cycle thinking requires the consideration of environmental impacts from the inception of the solar panel during the material extraction phase until the final disposal phase of the product. Life cycle assessments for mc-Si solar electricity vary largely based on both location of production due to the grid electricity, which is used in the factory, and location of the study because solar radiation varies across different climates. Some studies simplify results by averaging irradiation values to 1000 kWh/m^2/day [5]. The general process of designing a life cycle assessment for PV studies requires explicitly stated assumptions, a goal and scope, and methodology. A typical life cycle assessment breaks the photovoltaic electricity generation process into several steps as highlighted in Figure 1. Some studies reported that up to 80% of the embodied energy can be derived from manufacturing processes, composing a significant portion of the energy required for PV electricity generation [6]. Pacca et al. found that the net energy ratio is more sensitive to energy used during the production process energy as compared to that embodied in the materials for both thin film and crystalline modules [2]. Therefore, the location of production can play a significant role in determining the emissions, if the panel's materials are produced elsewhere. Additionally, energy efficiency gains in the process energy phase may yield more opportunities for emission reduction than the energy required to produce materials. Material production and component manufacturing account for more than 80% of the life cycle GHG emissions because during the use phase emissions are negligible and data related to the disposal stage are rather scarce and variable [7]. This encourages the focus of future improvements on the production phase to reduce life cycle GHG emissions.

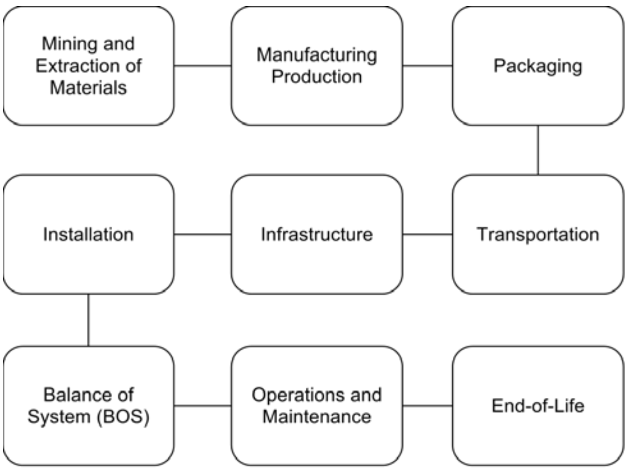

Figure 1. General steps considered in LCA studies of PV systems.

While most of the GHG emissions associated with PV occur during the manufacturing and production phase, understanding the GHG impacts of all stages involved in the PV production process would spawn innovation for improved PV technologies in the future and help policymakers better understand the various contributors to GHG emissions and options for optimized environmental performance.

3. Energy Efficiency in Monocrystalline Production

The most direct way to reduce GHG impacts from the production of mc-Si solar panels is to reduce the embodied energy. However, there are different strategies to reduce the energy required to construct a mc-Si solar cell. Figure 2 summarizes the approximate embodied energy for different steps in the production of grid-connected mc-Si PV.

The Czochralski (CZ Step) Process comprises the bulk of the energy required for production of mc-Si modules (34% of the embodied energy), while silicon purification and cell process energy also contributes a large portion (a combined 44% of the embodied energy). The Inverter and Balance of System (BOS) may contribute approximately 6% of the embodied energy, but this value varies depending on the location of deployment and necessary infrastructure to complete the grid connection process. Steps are highlighted with potential for life cycle GHG emission reduction.

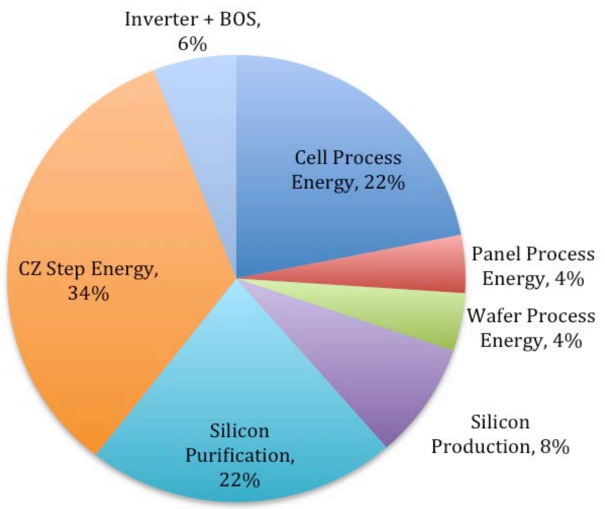

Figure 2. The distribution of embodied energy requirements for mc-Si PV [8].

3.1 Czochralski Process

The Czochralski Process constitutes the most significant portion of production energy to create mc-Si modules consuming nearly 34% of the primary energy. The streamlined process remains generally the same as when it was developed during the 1970s [9]. Embodied energy has not significantly decreased over the past 40 years, therefore room to improve efficiency is limited with regard to the purification of silicon. Other aspects of the production process should be further researched to improve energy and CO_2 payback times. Silicon must be heated to at least 1500°C for decarburization to purify the silicon, therefore cleaner forms of energy to heat the silicon would be an important option to consider to reduce GHG emissions [10].

3.2 Silicon Purification and Cell Process Energy

The purification process for solar cells slightly differs from that of electronic-grade silicon made to produce semiconductors using a "modified" Siemens process [11]. Future reductions in the silicon purification process have been documented by using a Fluidized Bed Reactor to deposit the silicon from chlorosilane or silane on the order of 70% lower than for using the Siemens process. Experiments are being conducted to increase energy efficiency in the silicon purification step and cell process energy. The use of non-solar grade or electronic-grade silicon typically is more energy intensive. Because of the standard process to create monocrystalline solar cells spanning for over forty years, it is likely that changes in the efficiency will result from using fewer input materials, which would imply a decreased requirement for energy.

3.3 Wafer Sawing

The wafer sawing gap controls the amount of silicon needed to create a mc-Si photovoltaic solar cell. Up to 60% of raw silicon ingot consumed during manufacturing is wasted [4]. Smaller gap space maximizes the raw silicon per wafer and minimizes the quantity of waste material. Reducing the number of necessary cuts and shortening the sawing gap would contribute to reduce both energy and resource consumption [9]. Wafer thickness has decreased to 180 μm in some panels where it previously was 200 μm [12]. Future decreases in thickness could potentially enable reducing the overall embodied energy required to produce mc-Si PV 2-4%. It is not clear exactly how much of a wafer reduction is required to make the embodied energy nearly negligible for monocrystalline PV, because it has not been adequately studied. The Swiss Ecoinvent database contains a monocrystalline panel that decreased the sawing gap by 9 μm yielding only a life cycle electricity use of 0.19 kWh/wafer compared to 0.3 kWh/wafer [9]. Many studies combine the life cycle inventory for wafer sawing gap and thickness together, making it difficult to extract the difference and variations in factory location and age further reduce objectivity [8-9].

3.4 Panel Process Energy

Aluminum is the primary metal used in mc-Si PV for the encapsulation step. Therefore if alternative materials exist or are developed, then the resource depletion and embodied energy to encapsulate solar cells could decrease the embodied energy as long as alternative materials have a smaller embodied energy than aluminum. Boron would be a possible interesting alternative to aluminum [13].

3.5 Inverter and BOS

Depending on the grid, type of module, size of module, and other necessary factors to connect panels to the grid, the inverter, which converts DC to AC, can typically consume between 1-10% of the primary energy inputs. Mason et al. found a 71% reduction in life cycle energy BOS requirements by using more advanced design, which implies the potential for near-zero life cycle GHG emissions with future development [14]. Previously, concrete support structures and aluminum metals were required as part of the frames to balance the PV system. Future "frameless" PV modules will decrease the amount of concrete and aluminum necessary in the BOS. The use of recycled aluminum also helps reduce GHG emissions from the BOS. The inverters and components rely on grid technology in Thailand. The lack of a "smart" grid in Thailand compared with other countries would likely result in additional components needed to connect inverters with the grid. There may be added transmission infrastructure that would be needed to support a rooftop PV system in Bangkok's metropolitan area or for large-scale PV farms in rural areas. The lifetime of the inverter would be another aspect to consider since it would influence the embodied energy and GHG impact results.

3.6 Disposal of PV

Without an official recycling infrastructure set up for PV disposal, most PV life cycle studies assume that discarded panels would go to a landfill. However, valuable aluminum and silicon scraps could potentially be recovered. For a large-scale installation, the collection of discarded PV panels would be easier than the collection of distributed generation rooftop installations. The process for recycling thin-film PV has been developed more thoroughly than that of mc-Si panels. Despite this lack of development and deployment, pilot scale recycling projects exist for mc-Si modules and it is reasonable to consider the future potential for recycling modules [15]. Especially for modules decommissioning in approximately thirty years better methods may exist in the future to extract reusable material. This recovery process could help improve PV's life cycle performance [5]. Previously, the pyrolysis of silicon wafer required a larger amount of energy that required heating to 1500°C rendering the recycling process energy intensive and unfeasible due to cost [16].

4. Location of Production

While transportation GHG emissions vary based on the location of the solar panel processing plant, a more significant portion of environmental life cycle GHG impacts result from the type of energy used for electricity to operate the plant and heat the silica wafer. Due to varied industrial standards in potential panel-exporting countries, the electricity mix helps determine life cycle GHG emissions. The results of this assessment use PVSYST software to model incoming radiation and suggest that mc-Si panels built in China shipped to Thailand could generate life cycle GHG emissions as high as 150 g-CO_2-eq/kWh whereas those produced in Thailand or Germany could be as low as approximately 60 g-CO_2-eq/kWh [17-18]. A harmonization study found that LCA studies of monocrystalline panels in the United States had an interquartile range of 39-49 g-CO_2-eq/kWh [7]. Because Thailand's own electricity generation portfolio emits approximately 561 g-CO_2/kWh, one may argue that panels will contribute lower GHG emissions than the current electricity grid regardless of location of production; however, these issues significantly affect the outcomes of life cycle assessments.

5. Building-integrated PV

Building-integrated applications of grid-connected mc-Si PV (BIPV) are photovoltaic modules that serve dual purposes as roof tiles or façades in buildings. Rather than simply placed on top of roofs, these modules replace conventional building materials in a life cycle assessment because they function as roof tiles or façades. In Thailand, many building roof tiles or façade materials are derived from concrete. This allows an expansion of system boundaries for LCA studies to include co-benefits of roofing or providing structure to a building, which displaces concrete. Therefore, adding building-integration can improve the performance of mc-Si installations by a factor of 3 compared to simple rooftop installations. BIPV applications range in GHG emissions from approximately 20-50 g-CO_2-eq/kWh compared to conventional solar arrays that may generate between 60-150 g-CO_2-eq/kWh [18]. On individual case bases, BIPV could provide additional co-benefits by using dead space or maintaining compact urban design, though this may be difficult to justify and attribute. Generally, BIPV systems can drastically alter the outcomes from the standard life cycle performance of a mounted system [19].

6. Installation

Installation affects performance in two ways, there are the direct infrastructure requirements to connect a photovoltaic system to the electrical grid and the proper site selection, which determines the amount of electricity generated by the system. This electricity offsets the energy required to produce the solar panel. Poor site selection may result in shadows or future buildings constructed that block PV arrays and therefore decrease the electrical output. Optimization of the electrical output is an important consideration to maintain GHG emission reduction.

7. Climatic Variation

The amount of solar radiation affects photovoltaic performance, and within Thailand, the Northeastern and Southern regions receive a larger amount of incoming solar radiation than the Central or North [20]. Pacca et al. found that irradiation and system lifetime affect greenhouse gas emissions more significantly than the efficiency of the module [2]. Additionally, Phowan and colleagues modeled the temperature effects of crystalline solar panels in Thailand on the electricity production; the results showed a decrease due to prolonged thermal exposure [21]. Proper placement and consultation of solar radiation maps will ensure that projects can achieve theoretical outputs based on irradiation predictions. The effects of thermal exposure on the crystalline panels can only become mitigated by technological progress, which would likely require different materials. The understanding of temperature effects on the panels provides more accurate emissions inventories.

8. Establishing Baseline Emissions

One important consideration for life cycle assessments conducted in Thailand is the verification and evaluation of baseline emissions. Often the studies that span a series of 10-30 years assume the electricity generation mix may remain constant. However, both the electricity mix and emissions will likely change over the next thirty years. Therefore, assessments should incorporate predictive modeling to estimate the future electricity generation mix. Another issue arises when studies assume that all electricity produced by solar electricity will replace electricity generated by a conventional source. However, with expected electricity demand to increase, it is unclear how much the electricity supply will increase and therefore whether solar will supplement the current electricity or displace the production of marginal electricity sources. These issues all affect the amount of GHG emissions offset by generating solar electricity and create different life cycle assessment results.

Future research may explore the life cycle impacts of solar electricity produced on rooftops versus those in large-scale commercial farm settings. There may be benefits by urbanizing electricity production compared to the use of extra land that could be used for agriculture or storing carbon in forest land. Changing land use to construct a solar farm could obstruct habitats and alter ecosystem services previously contained in that land. These considerations influence LCA of mc-Si PV for Thailand. Due to the VSPP program, investors are encouraged economically to construct large-scale farms that can produce up to 8 MWe [20] and the financial investment becomes attractive because the cost of land in Thailand is relatively inexpensive.

Renewable energy goals will play a role in understanding the scope of the reduced GHG emissions that mc-Si PV could provide as an alternative electricity source. The Power Development Plan target of 2 GW of solar electricity by 2021 [20] will likely be achieved with the current growth rate, underscoring the importance of environmental impact assessment to quantify GHG emission reductions.

9. Conclusions

A number of factors affect life cycle performance of mc-Si PV in Thailand, therefore the effects of energy efficiency measures, location of production, installation, building-integrated options, and climatic effects play a role in determining the outcome of such studies. Monocrystalline solar photovoltaics are one strategy for Thailand to pursue in reducing GHG emissions. We have detailed the factors that affect the quantification of GHG emissions and will serve to project a clear picture of the environmental effects of implementing mc-Si PV in Thailand so that PV can be evaluated objectively alongside other energy technologies. In the future, mc-Si will supplement Thailand's electricity grid as it will help fulfill the 2 GW solar electricity generation capacity target outlined in the Alternative Energy Development Plan, therefore practitioners should heed these considerations when understanding PV's effect on energy and the environment. Additionally, with locational variation affecting PV's GHG emissions, proper site selection should be conducted to maximize electricity output and ensure substitution of conventional energy sources. More than 80% of the embodied energy necessary to create mc-Si PV occurs during the production phase, which suggests shifting the focus of life cycle studies to analyze ways in which production can become more energy efficient. However, we also stress the importance of energy used in the production process as a GHG reduction strategy and raise the possibility of building-integration as a way to efficiently serve multiple building functions for rooftop solar applications. Without certainty that technological breakthroughs will push the efficiency of PV electricity generation much higher, reducing silicon waste and using cleaner forms of energy to produce the panels will contribute to the largest reduction of mc-Si PV's GHG impacts. Another issue for LCA studies is to generate better models that account for changing electricity trends over the entire PV life cycle. The potential for future recycling after decommissioning panels will allow for the reuse of some silicon and aluminum materials.

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