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# An environmental Life Cycle Assessment of rooftop solar in Bangkok, Thailand

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## ABSTRACT

This study quantifies the environmental burdens created by a planned rooftop photovoltaic (PV) solar installation on a university campus in Bangkok, Thailand, and models the potential of rooftop solar to meet the country's renewable energy goals. Impacts are evaluated using Life Cycle Assessment and recommendations made for upstream purchasing decisions according to different scenarios. Results indicate that main contribution to impacts occurs in manufacturing by stage and from PV modules by component. Impacts generated by the mounting structure and inverters are also significant, and together these components constitute over 90% of environmental burdens. A climate change impact of 0.079 kg $CO_2$-eq/kWh is produced over the lifetime of the system. Energy Payback Time is calculated as 2.5 years, and the Economic Payback Period is 7.4 years. The system is estimated to avoid 1.00E+06 kg $CO_2$-eq over its lifetime. Installation of similar rooftop PV systems on 50% of university and government buildings in Bangkok could result in a net reduction of 4.80E+09 kg $CO_2$-eq. Domestic production of components and recycling of materials is identified as a best-case scenario, with alleviations across all impact categories. Economic analysis suggests on-site electricity consumption paired with a net-metering policy scheme is the best way to incentivize PV solar energy installations.

## 1. Introduction

As both population and GDP are on the rise, Thailand must be able to satisfy its increasing energy demands. The electricity sector is key to enforcing Thailand's continued economic development, and efforts to decarbonize the electricity supply raise the standard for government planning programs and greener power systems. Thailand is the largest producer of solar energy in Southeast Asia, and the majority of installed capacity is in the form of utility-scale solar farms [1]. In 2015 alone, newly installed solar capacity grew by more than 50% from the previous year [2]. As of 2015, solar represented 3.6% of total installed electricity generation capacity [3].

As smaller centers begin to prioritize environmental responsibility as part of institutional standards, more focus is brought to how small-scale renewable energy, specifically rooftop solar, can reduce environmental impacts. Similarly, King Mongkut's University of Technology Thonburi (KMUTT) in Bangkok, Thailand plans to install a 52.7 kWp rooftop solar system on its Multipurpose Building as part of its energy conservation policy, where a domestic supplier is under contract. By 2020, KMUTT's initiative intends to increase renewable energy supply by 5% according to the 2010 baseline of total university electrical energy use. In 2016, solar energy accounted for 245 kWp, or 2%, of KMUTT renewable energy capacity compared to the 2010 baseline [4].

This study estimates environmental impacts of the 52.7 kWp rooftop installation, including the solar modules and its significant balance of system components. Many previous Life Cycle Assessment (LCA) studies limit their system to the modules, mounting frame, and inverters [5–7]. However, these analyses are relatively incomplete because they do not account for all of the components

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necessary for electricity production. A more complete balance of system provides better understanding of the environmental burdens created by rooftop PV. This study is more inclusive by accounting for additional components often excluded from PV solar LCAs. By analyzing the installation from a life cycle perspective, this study creates a broader discussion of rooftop PV systems and their environmental impacts. It also addresses the potential of rooftop solar by analyzing how future installations of similar systems in Bangkok can meet Thailand's renewable energy targets.

Previous life-cycle studies suggest solar energy production has fewer overall environmental impacts than traditional electricity production, where life cycle emission factors can vary from 13 to 190 kg $CO_2$-eq per MWh of energy generated [7]. Energy payback times from multicrystalline rooftop systems vary from 2 to 7.5 years [5,8] Variability in emission factors and payback times arise in the manufacturing stage due to local grid mixes, as the largest contributions to impacts occur from module manufacturing [7,9]. Studies typically include a mounting support, inverter, and cabling in its balance of system components, where the maintenance stage is often excluded from the study scope.

## 2. Materials and methods

### 2.1. System energy generation

The rooftop system's lifetime electricity production was modeled utilizing HOMER Pro microgrid software with component and installation site-specific parameters. Module specifications included total rated capacity of 52.7 kWp, temperature coefficient of $-0.43\%/{}^{\circ}C$, rated efficiency of 16.2%, and nominal operating temperature of $45\,{}^{\circ}C$. Panel alignment azimuth was measured as $-14^{\circ}$ west of south at the installation site. After calculating multiple potential electricity outputs, an optimal panel slope of 16 is suggested. Irradiance variations in the software, from 1983 to 2005, account for radiation and clearness index fluctuations over Bangkok. Average monthly temperatures from 2009 to 2016 were used to account for temperature effects on PV module performance, where recent years' data better represent current trends in temperature rise [10]. Maximum Power Point Trackers were omitted from the model, as their performance framework in the system is unknown. Inverter specifications included rated efficiency of 98%, a capacity of 30 kW, and an assumed fifteen-year lifetime. Electricity produced by this system is to be consumed on site, and not sold back to the grid.

### 2.2. Life Cycle Assessment

### 2.2.1. Goal and scope definition

This LCA evaluates the environmental impacts of the planned 52.7 kWp solar installation to be made on KMUTT campus. The intended purpose is to indicate how rooftop solar PV systems in Bangkok can offset environmental burdens from conventional electricity generation while reaching national renewable energy targets. The intended audience is university and government entities who want to meet sustainability goals through rooftop solar installations. Results are not considered applicable to specific suppliers or large-scale utility solar farms. Geographic and temporal limitations are defined as Bangkok, Thailand over the next 30 years.

*2.2.1.1. Functional unit.* The functional unit is the rooftop PV solar system's modeled electricity production of 2,190 MWh over the next 30 years. It was defined according to Thailand specific inputs in HOMER Pro software and various supplier specified rated efficiencies [11]. The reference flow is 326 $m^2$ of module area from 170 multi-crystalline PV solar modules, six 30 kW inverters, eight circuit breakers, the mounting structure, direct-current (DC) cabling, cable conduit, and thirty-nine fuses and fuse holders.

*2.2.1.2. System boundaries.* Balance of system components include the mounting structure, inverters, circuit breakers, DC cabling and conduits, fuse bodies, and fuse holders. Components excluded from the system are the surge protector, pyranometer, digital indicating controller, uninterruptible power supply device, and computer monitoring system. The pyranometer and computer monitoring system serve research purposes for KMUTT and are not essential for electricity production in typical systems. Exact material compositions of the other excluded components were unavailable.

The impacts from extraction to end-of-life disposal are considered for the system detailed above. Impacts for all stages were quantified using ecoinvent data and SimaPro LCA software. In the ecoinvent database utilized, raw material extraction and material processing stage impacts cannot be separated. Manufacturing information was not complete for all components, so some estimations of energy consumption were applied. No environmental burdens for manufacturing were quantified for the fuses, cable conduits, and circuit breakers, as they were considered to not significantly affect the results. To justify this exclusion, data was supplemented from the environmental burdens of components with similar compositions and scaled down according to the relative components' masses. Using this approach, the results showed that the manufacturing of fuses, circuit breakers, and cable conduit would each contribute less than 1% to the overall burdens in each impact category of the entire system. All infrastructure processes are outside the scope of this study and were excluded from calculations.

### 2.2.2. SimaPro software

In order to quantify environmental impacts generated from the entire life cycle of all system components, LCA standards specified by ISO 14040/44 methodology [12,13] were followed. This LCA assesses the impacts associated with the following stages: extraction and materials processing; manufacturing; transportation; and end-of-life. Impacts from use and maintenance stage were considered minimal, and thus excluded from the study. Impacts were calculated using the ecoinvent 3 database within SimaPro software, where data have been adapted to Thailand and according to ReCiPe version 1.13 and hierarchist methodology for ten indicators: climate change [kg $CO_2$-eq], ozone depletion [kg CFC-11-eq], terrestrial acidification [kg $SO_2$-eq], freshwater eutrophication [kg P-eq], human toxicity [kg 1,4-DB-eq], photochemical oxidant formation [kg NMVOC-eq], particulate matter formation [PM10-eq], water depletion [$m^3$], fossil depletion [kg oil-eq], and metal depletion [kg Fe-eq]. The impacts are also normalized and aggregated to create damage indicators of human health [DALYs], ecosystem [species*year], and resource depletion [$] based on the same methodology.

Multiple life cycle scenarios were evaluated for consideration of current processes as well as potentially more sustainable methods of rooftop solar implementation in Thailand. For the system analyzed, the mounting structure is produced in Australia and the inverter and DC cabling in India. After manufacturing, these components require transportation to Thailand. Currently, Thailand has no recycling infrastructure for PV modules. The "worst-case scenario" is then the current situation, of international production with general waste treatment. Benefits of domestic production of all components and use of recovered recycled materials are quantified in the "best-case" scenario.