Life Cycle Assessment of Emerging Technologies: Comparing Rooftop and Ground Installation Solar Photovoltaic in Indonesia

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Comparing Rooftop and Ground Installation Solar Photovoltaic in Indonesia

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Abstract

Solar photovoltaic (SPV) is a promising emerging technology for reducing green house gas emission and mitigating climate change. Past Life Cycle Assessment (LCA) studies have shown that SPV in general has less adverse climate change impact compared to conventional fossil fuel based electricity, even when including the energy intensive production phase. However, location-specific LCA is still lacking, as well as studies on environmental impacts other than climate change.

This thesis entails a comparative LCA of ground and rooftop SPV against the conventional energy mix in the context of Indonesia, where huge solar potential and growing electricity demand exist. Results show that both ground and rooftop SPV have less impact on the environment compared to the national grid in many categories. However, the magnitude of the mineral, fossil fuel and resource depletion impact, for which SPV has larger impact, is relatively larger than other impact categories after normalization. Ground installation has the least impact compared to the national grid and rooftop installation in most categories except for land use impact, but when the system duration is shorter than planned, the comparative advantage is lost. For stand-alone rooftop installation, the inefficiency and additional environmental impact of battery made SPV a less preferable option compared to conventional electricity. On-grid rooftop installation has smaller impact compared to stand-alone systems-- especially if the system duration becomes longer-- and may be the best preferred option since it avoids land use impact.

Further LCA research is necessary to incorporate the significance of converting forest land and potentially foreshortened end-of-life scenarios in developing countries.

Dedication

This thesis is dedicated to my husband Satoshi, who supported me throughout the intensive master's course, to my two daughters Sana & Ena, who constantly inspired me with their astonishing learning curves, and to my parents who were always anxious but believed in my decisions in the end.

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Acronyms

ADB	Asian Development Bank
BAU	Business as Usual
ENVI-PV	Environmental Impact Assessment Web Service for Photovoltaics
GHG	Green house gas
GHI	Global Horizontal Irradiation
GIS	Geographic Information System
IEA	International Energy Agency
IRENA	The International Renewable Energy Agency
JICA	Japan International Cooperation Agency
LCA	Life Cycle Assessment
MEMR	Ministry of Energy and Mineral Resources
NDC	Nationally Determined Contribution
NREL	National Renewable Energy Laboratory
PLN	Perusahaan Listrik Negara
SPV	Solar Photovoltaic
TIS	Technology Innovation System
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
WEEE	Waste Electrical and Electronic Equipment Directive

Chapter I

Introduction

External energy was a major driving force for development, better living and for lifting many out of poverty. The discovery of coal, oil and natural gas, along with the invention of accompanying engines were the source of ever-growing physical production, leading to exponential economic growth. However, the mining and burning of fossil fuel cause biodiversity and ecosystem depletion, irrecoverable water pollution, regional air pollution and serious health issues (Epstein et al., 2011). Moreover, the burning of fossil fuel releases carbon dioxide (CO_2) to the atmosphere, roughly accounting for 64% of the anthropogenic green house gas (GHG) emission and causing global warming (Sachs, 2015). Our society is already “beyond the safe operating space” of the planet’s capacity for GHG and loss of biodiversity (Rockstrom et. al, 2009). On the other hand,1.6 billion people worldwide still lack access to any source of electricity, hindering both economic and social development (The International Renewable Energy Agency, IRENA, 2015). In order to provide basic electricity to the growing population in developing areas while maintaining the supply in industrialized areas, the world is in need of alternative energy sources that can replace the conventional fossil fuel-based energy, while increasing energy efficiency (Sachs, 2015).

Solar photovoltaic (SPV), along with mini-hydropower, wind and geothermal, is an emerging renewable energy technology under rapid development (Sachs, 2015). SPV is increasing its share in newly installed energy sources with the help of the drop in price. One of the virtues of SPV is its flexibility in installation, enabling options such as the formation of a mini-grid in remote or rural areas, allowing the electrification of new areas and hybridizing or replacing existing diesel mini-grids. Life cycle assessment (LCA) studies encompassing GHG emissions have shown how SPV has less impact on the environment compared to conventional fossil fuel based electricity, even when taking into account the seemingly harmful production phase (Stoppato, 2008). However, for countries to make policy decisions, a more comprehensive impact assessment is needed that reflects the national energy grid, technology advancement, installation type, and end-of-life scenario (Fthenakis et al., 2011; Jungbluth et al., 2012). Therefore, this thesis applies a life cycle assessment approach to SPV installation in Indonesia, using existing LCA data to delineate system boundaries specific to the country context.

Research Significance and Goals

Among the 1.6 billion people who have no access to electricity worldwide, a large part of the population lives in the Asian region. Following India, 66 million are reported to live in Indonesia, mostly in rural areas on scattered small islands (IRENA, 2015). Indonesia is experiencing an annual 2% increase of grid electrification, but small islands are geographically difficult to connect to the central grid. With a national goal to increase rural electrification from present 70% to 90% by 2020, while reducing the reliance on diesel, the state-owned electricity company Perusahaan Listrik Negera (PLN) plans to install 620 MW of SPV by 2020, including the hybridization of existing diesel and other energy sources (IRENA, 2015).

In this thesis, I conducted a life cycle assessment (LCA) of several SPV options in the context of Indonesia, where current policy and geographical conditions show a growing potential for rapid diffusion of the technology. General LCA studies on SPV have shown that GHG emission and global warming potential can be drastically reduced compared to generating the same kWh electricity with conventional energy sources, even in areas with least favorable solar radiation (Stoppatto, 2006; Sherwani, Usmani & Varun, 2010). However, most of the LCA studies on SPV only concentrate on the GHG or climate change impact, and also tend to neglect the downstream process such as waste management. The national energy mix scenario, operational lifetime of the installed system and improper waste management can potentially reverse the broadly accepted positive result (Jacome Polit, Maldonado & Davalos, 2016).

SPV is an emblematic emerging technology, approaching its maturity in energy generation efficiency (Wender et al., 2014b). Technology is not merely the hardware; SPV technology cannot be understood merely by solar panels or batteries, but includes methods, processes, and practices (Brooks, 1980). Its formation is a social process (Williams & Edge, 1996), and in order to maximize the environmental benefits of the technological innovation, society and policy need to take into account the unintended consequences during its formation and diffusion period. Innovation has long been thought of as a priviledge of developed economies, due to the assumption that developing countries lack entrepreneurs and technological capacity, but recently developing countries are in search of ways to use existing technology while selecting original development pathways to bypass negative environmental and social impacts it may bring together (Juma, 2014)

The interpretation of LCA results may add value to the long-term renewable energy policies in Indonesia by informing on potential environmental impacts that otherwise could have been overlooked. This LCA practice is not intended to raise caution or oppose an emerging green technology, but rather to add information on potential development opportunities to mitigate unintended outcomes and instead create more positive impacts.

Background of LCA of SPV in Indonesia

SPV installation is growing rapidly in less developed areas as a new source of energy, and contributing to development while emitting less GHG compared to conventional energy sources. In this section, I will introduce the role of solar electricity in sustainable development, the results of past LCA studies on SPV, then explore its potential in Indonesia.

Solar Electricity for Sustainable Development

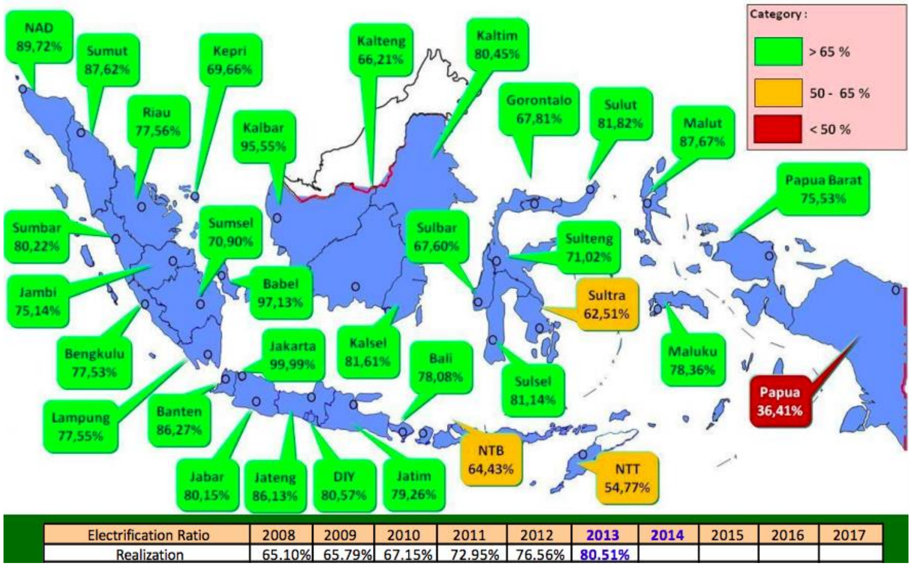
SPV has especially large potential in developing countries as a major means to provide electricity in rural villages or remote islands where it is economically or geographically not feasible to connect to a centralized grid (IRENA, 2015). For example, small island states in the Pacific region had a total generation capacity of 712 MW in 2012, of which 78% was from fossil fuels and 22% from hydropower. A major source of energy was diesel varying between 25kW-10MW in capacity. Tokelau already went 100% solar for a total 927 kW, and many other island states are vigorously planning to install SPV to replace the existing mini-grids (IRENA, 2015).

In addition to providing electricity to people presently lacking access, SPV can potentially hybridize or replace existing mini-grids that rely on diesel or gasoline energy. The replacement can bring social impacts such as longer study hours, longer working hours, access to entertainment, and improvement in housework for women, as well as a significant decrease in local air pollution and noise (Chakrabarti & Chakrabarti, 2000), which can lead to secondary social benefits such as slowing down rural to urban migration. Another aspect of SPV is that installation is done by actors such as NGOs and NPOs as well as local entrepreneurs and national electricity companies in less developed countries, creating spillover effects of technology learning and some installation jobs (Kebede, Mitsufuji & Islam, 2015). Technological "leap-frogging", or the adaption of a newer and less environmentally harmful technology is happening, such as the implementation of SPV in off-grid areas of Africa (infoDev, 2014).

Along with the growing number of installations in less developed areas with minimum or no technical maintenance capacity and infrastructure, however, is the possibility of unintended negative environmental impacts. Although not explicitly addressed in academic literature, project examples shown at conferences by NGOs and some researchers imply issues of abandoned SPV systems due to lack of technical expertise, as well as improperly disposed solar product donations or the lack of clear end-of-life scenarios for solar panels and batteries (Price, 2015; Bhopal, 2015). Both the positive and negative impacts of SPV need to be assessed in order to make better decisions.

SPV in the Indonesian Context

Indonesia relies heavily upon fossil energy: 46.08% oil, 30.9% coal, 18.26% gas and less than 5% of renewable energy, which are hydropower (3.21%), geothermal (1.15%) and biofuel (0.4%) (Tharakan, 2015). Among the world's 1.6 billion people still lacking access to electricity, the second largest population of 66 million lives in Indonesia. Although Indonesia's electrification ratio is growing at more than 3% annually, the electrification activity is concentrated on Java Island and several islands where economic growth is taking place, mostly on the west side of the country (Figure 1).



Electrification Ratio	2008	2009	2010	2011	2012	**2013**	**2014**	2015	2016	2017
Realization	65.10%	65.79%	67.15%	72.95%	76.56%	**80.51%**				

Figure 1. Electrification rate of Indonesia by region. (Directorate General of Electricity, 2014)

Total demand of the three major islands, Java, Madura and Bali ("JAMALI") is about 32 GW, accounting for 80% of the national electricity consumption and 60% of the population, followed by Sumatra and Kalimantan. Among these large consumption areas, PLN is planning an inter-grid connection toward 2019 and also aims to increase renewable energy sources (Tharakan, 2015)

The remaining population on remote small islands is geographically difficult or not feasible to connect to the main grid. The Directorate General of New, Renewable Energy and Mineral Resource set a goal of rural electrification from the current 70% to 90% by 2020 while decreasing the reliance to diesel power. The "1000 Islands" plan to install total 620 MW of SPV, including hybridization, is carried out by a state-owned electricity company PLN (IRENA, 2015). Recent legislation encourages the development of electricity infrastructure in remote regions. There are iconic pilot projects going on in Sumba (Sumba Iconic Island, 2016), Kupang and East Nussa Tengarra region (Mailoa & Pradipta, 2016). Yet to date, no scalable framework for off-grid supply exists, resulting in ad-hoc efforts by the private sector, funding only for installation and lack of financial or technical support by national agencies, leaving numerous failed projects behind (Asian Development Bank (ADB), 2016).

Although Indonesia has a large potential for solar electricity throughout the nation, its geological landscape and current state present unique challenges. A more detailed picture of the country is required in order to understand the geographic complications of population density and solar radiation. A first challenge lies in Indonesia's mismatch of supply and demand, i.e., solar duration and population density.

Although generally higher compared to many parts of the world, the intensity and duration of sunlight vary from island to island. To examine by region, raster data based on the annual average Global Horizontal Irradiation (GHI) over 10 years at 3km resolution was obtained and visualized (VAISALA, 2016). Radiation is generally higher in the eastern half of the country (over 200 w/m2/day) including islands such as Bali, Lombok, Sumba, Sulawesi, Papua and lower (less than 200 w/m2/day) on the west side such as Java Island and Sumatra. (Figure 2).

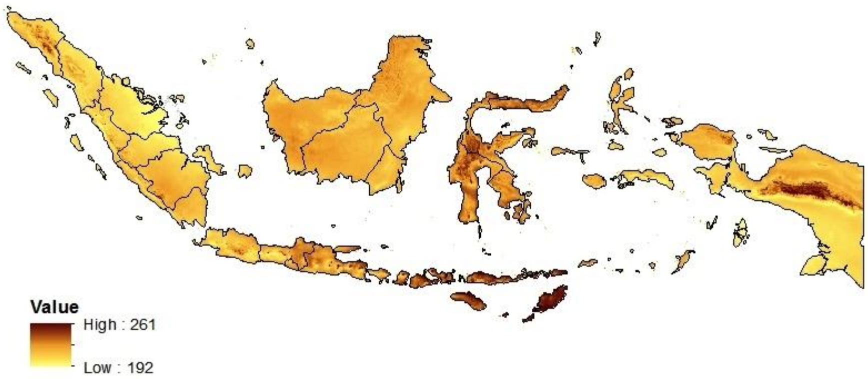


Figure 2. Solar radiation map of Indonesia (w/m2/day). Data source: IRENA & VAISALA, Global solar dataset, 2016.

Population is largely concentrated on Java Island, where the capital Jakarta is located, and also on Sumatra and Bali. Population density is higher on the west side of the country and more spread out as you move eastward (Figure 3). This means that the western islands with the largest electricity demand have lower solar capacity; eastern islands--where higher solar capacity potential exists-- have lower demand. Implementing an electrification plan requires consideration of such differences in population density. It is unnecessary to build a grid in areas where no population exists, and simple wire grids or standalone rooftop SPV may be the best option for low-density areas, making it difficult to create a nation-wide uniform policy.

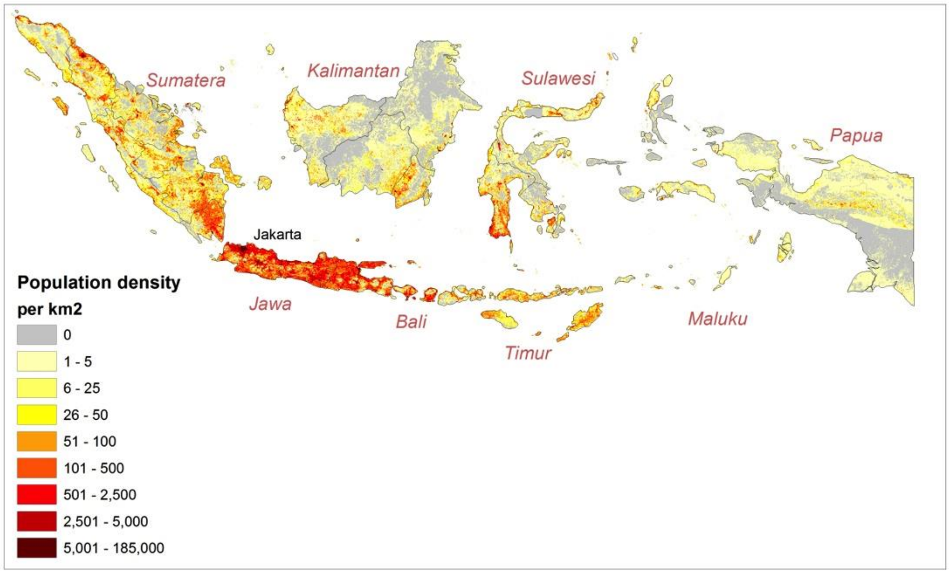


Figure 3. Indonesia population density per km2. Data source: Vector data, Oak Ridge National Laboratory, Earthscan 2015.

When mega-solar plants are discussed as a large-scale national energy source to support urban areas, one potential obstacle is the difficulty and high cost of land acquisition in areas within populated islands such as Java. Indonesia has large forest conservation areas which are protected by law (Figure 4). The high coverage of tropical forests and the need for land conservation limit potential sites of solar electricity projects.

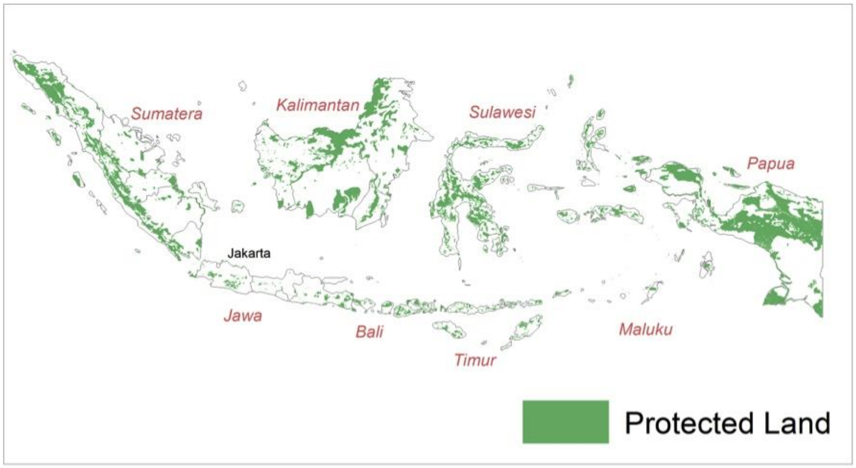


Figure 4. Legally protected forest land in Indonesia. Data source: Vector Data, WGS_1984, Global Forest Watch, 2016.

When solar electricity is discussed at a smaller scale as a back-up energy source for existing grids, price and technology are the two major obstacles. Indonesia relies heavily on oil, including diesel (50%), coal (26%), and, to a lesser extent, natural gas (20%) (Tharakan, 2015). Although the price of SPV systems has declined rapidly over the past decade, it is still not competitive compared to existing coal power plants. A feed-in-tariff system was introduced in 2015 (Kenning, 2016), however purchase contracts are frequently made based on business-to-business negotiation (Hutapea, 2017, personal communication). Recently the Minister of Energy and Mineral Resources (MEMR) issued the new “Regulation 12/2017 on the Use of Renewable Energy for the Provision of Electricity (Regulation 12)”, lowering the tariffs paid to electricity developers by capping the price to 85% of the local production cost and incentivizing PLN to purchase electricity from renewable energy sources (Horn & Sidharta, 2017). The effectiveness of the incentive is yet unknown. The second issue is technological, and is two fold. The first aspect is the basic technological capacity. Indonesia currently imports most of its solar components. MEMR has been working with bilateral agencies such as Japan International Cooperation Agency (JICA) for capacity building and companies for technology transfer, but its national technology innovation system for solar is in its infancy (Hutapea, 2017, personal communication). The second, more physical issue, is grid capacity. Grid capacity is generally low outside Java, making it difficult for the national grid to absorb solar generated electricity at times of high generation. The only digital grid is within Java, and the rest of the islands are partly or not covered, with analog grid. This means that the switching on and off of solar feeding needs to be done manually by phone calls, drastically reducing the efficiency of grid connected solar electricity (Rahadian, 2017, personal communication).

The double obstacles again create contradictions. For example in Kalimantan and Lombok, solar electricity is price competitive with diesel and oil, but the grid is less developed and cannot absorb the generated electricity. Currently there are no strong incentives for PLN to upgrade the grid to address this issue (Rahadian, 2017, personal communication). In order to implement solar at the national grid level, the whole country needs to be upgraded into a digital smart grid system. However the requisite financial scheme is unclear, which may be one reason why the nation is rather reluctant regarding solar electricity compared to conventional renewable energies such as hydropower and geothermal.

In terms of rural electrification, both MEMR and PLN have been using solar home systems, distributing one unit of solar panel, battery and lamp to each house to bridge the gap in the short term before they are connected to the grid. However, sustainable operation and financial systems have not been established yet (Tharakan, 2015). The second measure is to promote grid establishment outside of the national grid area, which just recently started under the MEMR law No. 38, 2016, issued in December 2016. The national grid in Indonesia is owned and managed by PLN, a single state-owned company. Any area within the PLN grid system is “on-grid”, while areas where PLN does not operate is called “off-grid” in the Indonesian context. The law allows private companies to establish a stand-alone grid system, including electricity generation, transmission and fee collection, in “off-grid” areas. The law is known under its informal nickname of “PLN Mini” because private companies are able to act like a small-scale version of the state-owned company PLN. The law does not limit the energy source to renewables, but implicitly favors renewable energy where possible. Private companies will partner with the regional government, and electricity fees are to be collected by “Badan Usaha Milik Daerah” (BUMD; regional government owned companies). MEMR law No. 38 states that when the price of electricity is larger than the PLN utility price, either the regional government will subsidize to match PLN or is allowed to sell at the higher price (MEMR, 2017). The third measure is small-scale solar plant implementation by MEMR in off-grid areas of eastern Indonesia. Starting from 2012, MEMR developed small-scale solar power plants of sizes from 1kw to 1MW, and handed the asset to local governments for operation. Although the local governments are mandated to report to MEMR on the plant conditions, the reporting process still face challenges (Finahari, 2017, personal communication).

One way of connecting smaller remote islands to mainland or islands with large electricity generation capacity will be by undersea cables. Technologically speaking, this is already possible for long distances, however the cost is still high and oftentimes will not make sense in the Indonesian context. Therefore, for archipelagic countries, it is more realistic to generate and supply electricity within each island. (Takahashi, 2017, personal communication). There are also issues specific to developing countries in the tropical region. The first is the need for conservation of forests. Indonesia declared their Nationally Determined Contribution (NDC) for the Paris Agreement in November 2016. While Indonesia declares new and renewable energy to account for at least 23% by 2025 and 31% by 2050 of the total energy source, within the 29% GHG reduction target by 2030, 17.2% is allocated to the forestry sector, 11% to the energy sector, and the remaining 0.8% to others such as waste, agriculture and industry sectors (United Nations Framework Convention on Climate Change, UNFCCC, 2016). Prevention of land-use change, along with the preservation of peat, is of equal importance both to the nation and for long-term climate change mitigation (Figure 5).

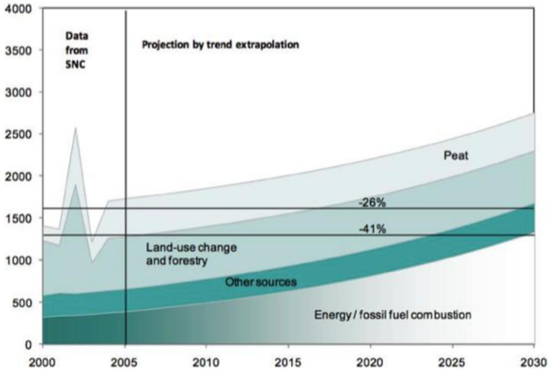


Figure 5. Emissions Projections from 2005- 2030 (million metric tons CO_2). (Tharakan, 2015)

The second is the issue of waste management for electric devices, also known as E-waste. Beyond solar panel and battery contexts, E-waste is generally becoming a major issue in South East Asian countries, including Indonesia, due to rapid increase in the amount of home appliances installed. Cheaper electronic devices are generally designed for low cost production, and have less recycling value. A major player in waste treatment is the informal sector, which is growing in capacity, yet has limited technological capacity and low safety standards. Direct health risks to the workers and their family (often operating in or close to residence), leakage to the environment, and risks such as explosion have been stressed (Honda, Sinha-Khetriwal & Kuehr, 2017). In the European Union, the Waste Electrical and Electronic Equipment Directive (WEEE) 2012/19/EU set the legal foundation for extended producer responsibility for the collection and recycling of SPV and batteries, and was transposed into national laws by February 2014 (PV Cycle, 2014). However this is not common elsewhere, and the possibility of SPV and batteries ending up in the informal sector cannot be ignored.

Guiding Innovation for Sustainable Development

The concept of innovation as a means of spurring sustainable development is gaining increasing attention among developing countries. Innovation, which can be technological, social, organizational or institutional, is an endogenous evolutionary process that spurs economic transformation (Schumpeter, 1934). The process of new emerging actors revolutionizing the economic structure discontinuously and replacing incumbents is a source of economic growth. It is important to note that this process known as "creative destruction" does not necessarily need completely novel technology, as can be seen in the example of the railroad which only used existing technology but completely replaced horse and carriers (Schumpeter, 1950).

Innovation has long been thought of as a priviledge restricted to developed economies, due to the assumption that developing countries lack entrepreneurs and technological capacity. However, recently developing countries have searched ways to use existing technology while selecting original development pathways, thereby bypassing negative environmental and social impacts it would have otherwise incurred (Juma, 2014). To pursue sustainable development, merely importing the production technology of an environmental product is insufficient. For example in the case of China, the rapid success of the SPV industry was for exporting to outside markets, and did not result in increase of solar energy use inside China (de la Tour, Glachant & Meniere, 2011).

Crude technology transfer of modern large-scale technology from developed to less developed countries carried out without consideration of the local context was predominantly unsustainable for the environment and society. Schumacher (1973) identified "intermediate technology" as a less top-down, more human centered and needs-based approach to technology; more recently, this approach has been termed "appropriate technology". Recently, "south-south cooperation" is bringing in a new type of appropriate technology. High-tech instruments are entering less developed countries at increasing frequencies from middle-income countries such as China and India. These technologies are more affordable and less quality intensive, although sometimes questionable in terms of their impact on the environment (Kaplinsky, 2011).

In a world where simply pursuing economic development at the cost of environmental degradation is not affordable anymore, nations require that their innovation policies move beyond solely maximizing industrial goals of increased national competitiveness. Environmental Kuznets approaches predict that, as a function of rising per capita income, environmental deterioration will follow an inverted U-shaped curve, implying that economic development alone will solve environmental problems. In practice, this development trajectory is not automatic. Appropriate regulations and policies, as well as international support are crucial to reverse environmental deterioration and thus change the course of the curve (Faure, Goodwin & Weber, 2010).

Technology has benefits, but comes with side effects. Negative effects of technologies are the result of collectively choosing the cheapest available technology to achieve a given production process; the “unwillingness” to pay can prevent use of cleaner technology (Rosenberg, 1971). There are at least three reasons why relying solely on market and the private sector will not automatically enhance sustainable innovation. First, the voice of marginalized populations may not be included in the formation of a new technology, due to lack of political power or lack of financial resources (Mowery & Rosenberg, 1979). This is problematic since global trade, funding, international agreements, national government and local community are increasingly affecting each other in the shaping of innovation systems, often with a knowledge and funding asymmetry. Moreover, sustainable development is a difficult process of considering equality both between generations and among generations, and it is impossible to engage future generations in this process (Solow, 1993). Second, environmental issues have the "double externality" problem. Negative environmental impact by a firm will be shared by the broad society (a negative externality), bringing little incentive to innovate. On the other hand, any positive impact created by investment will again be shared by the society (a positive externality) and gives back little return to the investment, again, discouraging innovation (Rennings, 2000). Thirdly, technologies have path dependencies, and once established they can form technological paradigms or a "technology regime" (Dosi, 1982; Nelson & Winter, 1977). The path dependency creates a lock-in effect, and the best innovative technology may not be chosen only because it doesn't fit in the dominant technology path, shaping future selection of technology (Arthur, 1989). Modern development has taken place within the technology regime of fossil fuel energy, and because of the significant past investment in its development and infrastructure, as well as the industrial and legal structure formed around the capital intensive technology, achieving its replacement by new technologies, such as renewable energy, is difficult (Kemp, Schot & Hoogma, 1998). Historically, stringent regulation is effective in creating the market for radical innovation of less polluting technologies, while weak regulations may lead to mere fine-tuning of existing technology (Ashford, Ayers and Stone, 1985; Yarime, 2007).

Orienting technology innovation to address the challenges of sustainable development requires regulation, economic instruments and directed public funding, and also the bottom-up engagement of stakeholder and broader actors to collectively consider the broadest possible range of technology options. An incremental approach can help to increase the number of people involved in the critical evaluation of technology, and to use the evaluation for further technological development (Kuntz, Meyer-Krahmer and Waltz, 1998). Life cycle assessment (LCA) is a tool for understanding potential environmental impacts of products, services and newly emerging technologies to inform stakeholders and policy makers of its potential positive and negative effects. LCA, by quantifying intended and unintended environmental impacts, can guide the decision of the direction of innovation (Bian et al., 2016).

Past LCA studies on SPV

At its purest definition, United Nations Environment Programme (UNEP) defines LCA as "a technique that is used to assess the environmental aspects associated with a product over its life cycle", with the following four steps, which are standardized in the ISO 14040 and 14044 (UNEP/SETAC Life Cycle Initiative, 2011).

(1) Define the goal and scope of study

Context of the assessment needs to be explicitly stated. The functional unit, which is the quantitatively or qualitatively defined product or service to be studied, system boundaries, which is the extent to which inputs and outputs to produce the product or service are included in the study, along with related assumptions and methods are to be stated in the beginning.

(2) List inventory of resources use and emissions

Elementary flows that cross the system boundary, which are consisted of all emissions released into the environment and resources extracted from the environment within the system boundary, to produce one functional unit, will be listed as inventory.

(3) Impact assessment

The inventory is translated into environmental impact categories either at the midpoint or endpoint levels. Midpoint categories measure the potential impacts of the studies system, while endpoint categories measure the potential damages to the human health and ecosystems (Vymard & Botta-genoulaz, 2016).

(4) Interpretation

The impact category data by itself is difficult to interpret. Normalization is an optional step, to divide each impact category results by a reference value, to compare with each other the significance of impact. Conclusions and recommendations are discussed. Another optional step is a sensitivity analysis, where assumptions are challenged to test the robustness of the conclusions (UNEP/SETAC Life Cycle Initiative, 2011).

Basic life cycle of SPV starts from raw material acquisition, goes through production, installation and usage, then eventually ends by decommissioning and disposal

(Frischknecht et al., 2011b) (Figure 6).

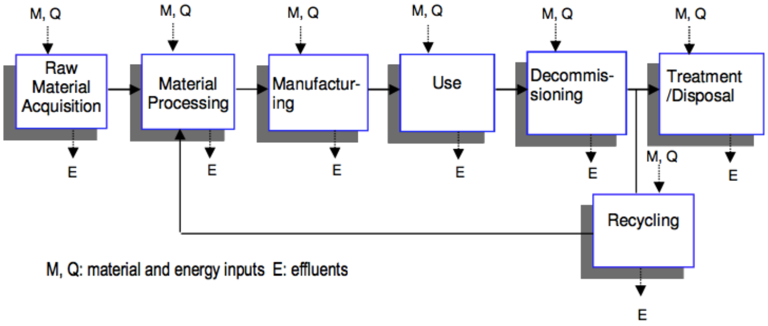


Figure 6. Life cycle of SPV (Frischknecht et al., 2015. Fig 1 Flow of the life-cycle stages, energy, materials, and effluents for PV systems)

Multiple LCA studies on SPV show that the phase that generates the most negative environmental impact is the production phase, and that with a long usage period, even in areas with worst solar radiation, SPV is better than conventional energy (Stoppatto, 2006; Sherwani, Usmani & Varun, 2010). A review of 400 studies showed that GHG emission impacts are 60-70% in the production phase, 21-26% in the operational phase, and 5-20% in the downstream phase. The impact from the production phase is still significantly smaller compared to the large emissions from the operational phase of fossil fuel energy, although results vary depending on the assumption and chosen method (National Renewable Energy Laboratory (NREL), 2012).

However, the energy payback time, or the time it takes for SPV to compensate for the initial high energy usage and start producing green energy, can vary depending on the national energy mix scenario. Also, if PV modules are disposed of by regular methods such as landfill or shredding in hammer mills, considering the chemicals used, environmental impacts other than GHG may become problematic (Jacome Polit, Maldonado & Davalos, 2016). SPV is unquestionably an environmentally sound technology to address climate change, but the sole focus on GHG emissions may cloud our views from unintended impacts. LCA of other environmental impact categories, taking into account the usage and downstream process needs more exploration.

In addition to solar panels, batteries are a challenge. A comparative LCA of four types of major batteries, lithium-ion, sodium-sulfur, lead-acid and vanadium-redox-flow, found that environmental impacts for producing 1 MWh of electricity depend on the usage period. When batteries are disposed earlier than full usage time, in this case 20 years, the potential candidate for best efficiency will change from lithium-ion to other options. The authors propose the development of innovative strategies to utilize the complete cycle life of batteries in order to get the best environmental effect of installation (Hiremath, Derendorf & Vogt, 2015).

With growing needs of a comprehensive method for quantifying photovoltaic life cycle impacts by practitioners, the International Energy Agency (IEA) published a set of guidelines in 2011 (Fthenakis et al., 2011a). The accompanying calculation of life cycle inventories for different types of technology enabled researchers and practitioners to calculate the production and installation phase using already established industry standards with actual global distribution shares and future scenario uncertainties incorporated (Fthenakis et al., 2011). Standard LCA practice for the production and installation is well established (Jungbluth et al., 2012), however its application in different locations and operation conditions needs more exploration. In order to make policy decisions that fully take advantage of the characteristic of SPV, environmental impact depending on the installation conditions, such as plant size, solar radiation and grid type need to be identified.

In addition, a new concept of handprinting merits investigation. Traditional LCA calculates the footprint of a product or service through the supply chain, and thus will always result in a negative impact on the environment, no matter how hard we try to reduce it. Handprinting considers the positive environmental impact of a decision we take that is different from BAU, which is accounted by both the direct reduction in the footprint, and positive changes that can occur outside our own footprints (Norris, 2013). An individual, company or government entity would switch from BAU energy to renewable energy with the mind of making a positive impact on the environment. The positive effect of switching the energy source shall also be considered.

Potential Island to Pilot Solar Options

With the opportunities and obstacles identified, Lombok and surrounding islands were chosen as a potential site for hypothetical data collection, due to their central location within the nation, where population density is sufficiently high and solar radiation is abundant. Lombok is located on the east of Bali Island, and agriculture and tourism are the major industries. The main island is fueled by three oil plants as of 2016, and is operating on an analog grid (Figure 7) (PLN, 2013).

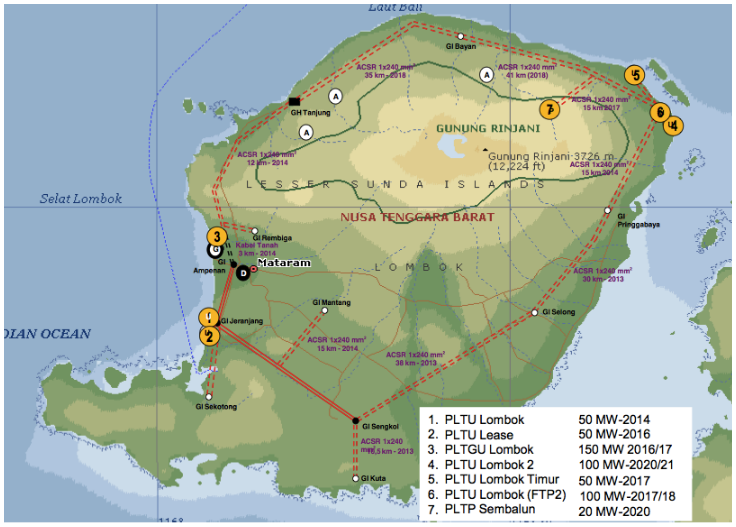


Figure 7. Electricity development plan of Lombok (RUPTL 2013-2022)

It also has a 600kWp solar power plant in Giri Trawangan, one of the three small neighboring tourism islands on the northwest side of main island Lombok (Figure 8).

Figure 8. Photos of the 600 kWp solar power plant on Giri Trawangan, Lombok.

As the aerial photograph shows, the solar power plant is built on mountaintops where it does not conflict with other land use such as agriculture and residence (Figure 9). This factor needs to be taken into account when conducting LCA in the Indonesian context. One past study shows that the surface area required to build a 570kWp solar power plant was 4273.5m2 (Jungbluth et al., 2012). The impact of converting this surface area of forest can be significant, especially for tropical forests.

Figure 9. Aerial photograph of the solar power plant in Giri Trawangan, Lombok. Source: CNES/Airbus, Google Map, Extracted on July 2, 2017.

Research Question, Hypotheses and Specific Aims

In this thesis, the environmental impacts of three options for SPV installation at Lombok were calculated and compared with each other, and against the Business As Usual (BAU) scenario, which is the national grid energy mix. The first option is to add a ground installation to the existing national grid to supplement the fossil based power plants. The second option is to introduce roof-top solar panels in residential areas connected to the grid, assuming that the national grid will be upgraded to a smart grid system. The third option is to install standalone rooftop SPV with battery to households. This can be an option in rural areas or surrounding islands difficult to connect to the national grid.

Past LCA research have mostly selected 1kWh of electricity production as the functional unit, and focused on climate change impacts (Stoppatto, 2006; Sherwani, Usmani & Varun, 2010) . Study results showed less negative impact for solar electricity compared to conventional fossil fuel based electricity production (NREL, 2012). However, a comprehensive LCA study that covers other potential environmental impacts is still lacking. It must also be noted that the difficulty of solar energy, along with other renewable energy sources, is that the daily or seasonal production patterns cannot be controlled, and also can be very different from the daily demand pattern (van der Veen, 2011). This is no exception in Indonesia (Figure 10). To better understand this constraint, a detailed LCA with a more realistic functional unit: "electricity consumption of 1kWh under the condition that electricity is supplied for 24 hours-year-round" needs to be explored.

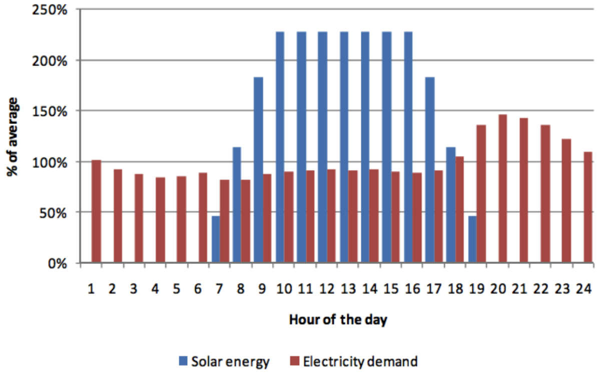


Figure 10. Electricity demand and solar energy generation pattern in Sumba (van der Veen, 2011, pp29, Figure 4-16 Indicative solar pattern and demand pattern – day patterns)

Hypothesis

Comparison of environmental impacts of different types of SPV projects and BAU may not necessarily favor SPV. My hypotheses regarding the above research questions were the following.

1) Hidden environmental impact of batteries will favor hybrid plants of SPV and conventional power plants over stand-alone SPV at this point of technology development, although this may be subject to change with further innovation.
2) SPV will not always have less significant impact on the environment, other than the GHG or climate change category.
3) Indonesia has a high coverage of tropical forests, and ground installation can potentially be a threat to these forests. Potential negative impact of forest clearance to enable ground installation will drastically offset the benefit of SPV, therefore favoring rooftop SPV options.

Specific Aims

From the above hypothesis, the following specific aims are generated.

Specific aim 1: To define a working system boundary that reflects the context and technology in Indonesia. Instead of using the conventional “per kWh of electricity production”, a new methodology of “per kWh electricity consumption” with the condition that the household is supplied electricity 24hours-year-round, will be tested.

Specific aim 2: To calculate the full environmental impact of different solar electricity project options. Options will be compared against conventional fossil fuel based energy and between each other. The aim is to compare the installation type and project size at the screening level for policy decisions, and not to consider specific sites or businesses.

Specific aim 3: To examine two additional impacts specific to the country—the conversion of forest to a large-scale solar power plant; and the end-of-life scenario.

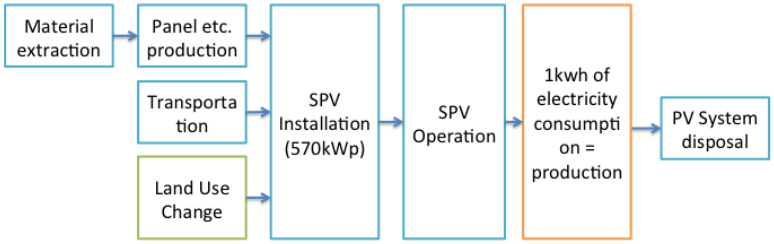
LCA cannot predict the future, but it can be a tool for quantifying potential negative and positive impacts to guide innovation in an environmentally sound direction (Wender et al., 2014a; Sharp & Miller, 2016). The study may lead to different selection of installation options and policy in Indonesia. Moreover, Indonesia is a unique country consisting of over 10,000 islands. Worldwide estimation shows that there are 2,056 islands with 1,000 to 100,000 residents, with a total electricity demand of 53 TWp per year. Islands in the Asia-Pacific region, where more than half of the island population is located, have a high potential of 3390 MWp SPV power generation even without battery storage systems, with a 19% increase enabled by battery storage systems (Blecheinger et. al, 2014). Good practice in Indonesia has the potential to mitigate potential negative impacts characteristic of tropical climates, and encourage the collective island market for solar electricity.

Furthermore, technology innovation is an important factor to achieve the Sustainable Development Goals (United Nations, 2015). The thesis may add insights to further understand the application of LCA for the governance of technology innovation toward sustainable development; development that raises basic standards of living of those in need, realizes equitable social inclusion and management of the natural environment without further degradation (UN General Assembly, 2012).

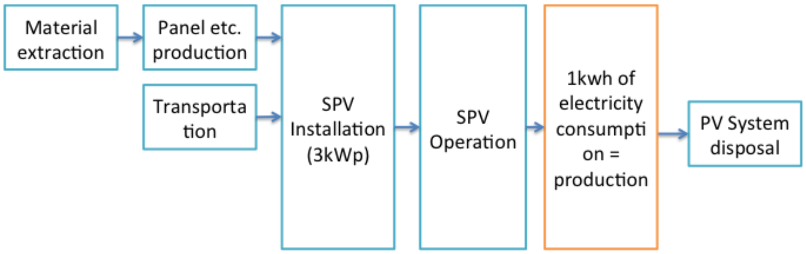
Chapter II

Methods

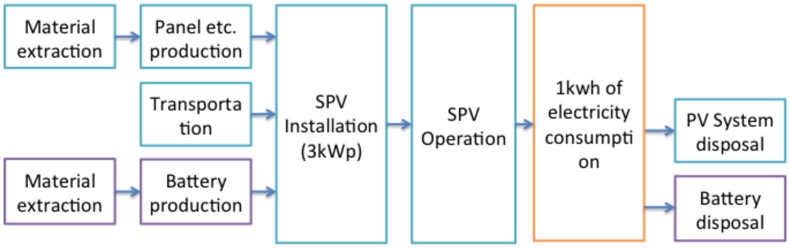
The functional unit of the LCA study is defined as "1kWh of electricity consumption" of different installation that can provide electricity to households for 24 hours year-round, instead of a commonly used functional unit, 1kWh of production. The simplified system boundaries for each of the three options are shown in the following diagrams (Figure 11). Note that the consumption matches production for the first two grid-connected options, since it will be fed into the grid and consumed elsewhere.



Option 1. SPV ground installation connected to the national grid



Option 2. SPV rooftop installation connected to the national grid



Option 3. SPV rooftop installation with battery, off-grid

Figure 11. System boundaries for the three SPV installation options.

Impact Inventory Data Collection and Calculation

Lifelong environmental impact for each SPV installation option was first obtained. Per household impact was then calculated. To simplify, when solar electricity production is larger than demand, solar electricity is used; when demand is larger than solar electricity, in the case of grid-connected systems the national electricity mix is used, and for the stand-alone system, battery storage is used.

SPV System

Lifelong and per kWh production impact inventory was collected using an interactive web-based calculator tool “Environmental Impact Assessment Web Service for Photovoltaics (ENVI-PV)” (http://viewer.webservice-energy.org /project_iea/). This tool was developed based on the latest updated life cycle inventories by IEA Task 12 published in 2015 and solar irradiation data from NASA SSE database, taking into consideration the full life cycle of a grid connected SPV system for both roof-top and ground installation (Perez-Lopez et al., 2016).

The location for calculation was set to an anonymous point in Lombok (latitude: -8.587810745935997, longitude: 116.35345458984372) as the solar irradiation value of 20 randomly sampled point across the island showed the same results., while other parameters were assumed for each installation option; installation method (roof top or ground), size (3kWp or 570kWp), technology (current or prospective), slant (0-90degrees), system duration (0-30 years), performance ratio (0-100%) (Table 1. ENVI-PV parameter settings.). Impact inventory for all options and the BAU was collected for ILCD 2011 Midpoint category (Table 2).

Table 1. ENVI-PV parameter settings.

	1 Grid-connected ground installation	2 Grid-connected Roof-top installation	3 Stand-alone roof-top installation
Installation method	Ground	Roof-top, mount	Roof-top, mount
Size	570kWp	3kWp	3kWp
Performance ratio	80%	80%	65%
Duration	30 years	20 years	20 years
Technology	Current	Current	Current
	Mono-Si	Mono-Si	Mono-Si
Slant	0	0	0

Table 2. Impact Categories for ILCD 2011 Midpoint (European Commission, 2013; European Commission, Joint Research Centre, Institute for Environment and Sustainability 2012; Frischknecht et al., 2016)

Impact category	Summary	Reference Unit
Acidification	Change in acidity in the soil due to deposition of sulphates, nitrates and phosphates in atmosphere.	molc H+ eq
Climate Change	Greenhouse gas emission is calculated as an equivalent of Co2 with a 100 year time horizon.	kg CO2 eq
Freshwater ecotoxicity	The impacts of toxic substances on aquatic	CTUe

	ecosystems.	
Terrestrial eutrophication	Nitrogen (N-compounds) emitted to air, since nitrogen is the limiting factor.	molc N eq
Freshwater eutrophication	Phosphorus (p-compounds) emitted to freshwater, since phosphorus is the limiting factor.	kg P eq
Marine eutrophication	Nitrogen (N-compounds) emitted to water.	kg N eq
Human toxicity, cancer effects	Cardiovascular impacts of toxic substances on human health, including the exposure risk in workplaces.	CTUh
Human toxicity, non-cancer effects	Non-cancer impacts of toxic substances on human health, including the exposure risk in workplaces.	CTUh
Ionizing radiation HH (human health)		kBq U-235-eq
Land use	Soil organic carbon (SOC) lost through transformation and occupation of land.	kg C deficit
Mineral, fossil & renewable resource depletion	kg of antimony-equivalent per kg extraction for rare earths, Gallium, Magnesium and per kg MJ for fossil fuels and Uranium.	kg Sb eq
Nuclear waste		m3 HAA eq
Ozone depletion	Ozone depleting substances.	kg CFC-11 eq
Particulate matter	Fate and intake of particulate matters.	kg PM2.5 eq
Photochemical ozone formation	Emission-weighted combination of the characterization factors of Non- methane VOCs (generic) and of CH4	mg NMVOC eq

Battery

The ILCD 2011 Midpoint impact inventory of battery was calculated using Open LCA and ecoinvent database, based on the input data of a 6kWh lead acid battery cell production, provided in a previous LCA study of a 3kWp rooftop solar system (Table 3, Table 4). Since inverter and wire are already included in the SPV inventory, and the data for a charge controller was not provided, these are excluded. Following the study, an assumption is made that the battery will last for 10 years, and at the end-of-life, 94% of lead input and 65% of sulphuric acid input are recycled while the rest go to landfill (Balcombe, Rigby & Azapagic, 2015). This end-of-life assumption is reviewed in the sensitivity analysis. The ecoinvent database did not give results for the Nuclear Waste impact category, thus this is assumed to be 0.

Table 3. Life cycle inputs for battery cell production and transport per 6kWh pack.

	Input	Quantity
Materials	Electricity, medium voltage	1318.2 MJ
	Heat, natural gas	709.8 MJ
	Lead	107.64 kg
	Water	28.08 l
	Sulphuric acid	17.16 kg
	Polypropylene	6.24 kg
	Glass fibre	6.24 kg
	Antimony	1.56 kg
Transport	Materials Lorry (>16t)	138.84kg x 200km
	Manufacture Lorry (>16t)	138.84kg x 200km
	Maintenance Passenger car	1person x 200km

Table 4. End-of-life inputs of battery cell per 6kWh pack, recycle.

	Input	Quantity
Recycle	Lead (credit for recovery)	101.18 kg
	Sulphuric acid (credit for recovery)	11.15 kg
Gate	Lead- Lead in car scrap incinerate	6.46 kg
	Sulphuric acid- Hazardous material incinerate	6.0 kg
	Polypropylene- Landfill, polypropylene	6.24 kg
	Glass fibre- Landfill, glass	6.24 kg
	Antimony- Hazardous material incinerate	1.56 kg
Transport	Metals recycling sorting freight rail	138.84kg x 200km
	Recycling Lorry (>16t)	138.84kg x 200km

Calculating the impact per kWh consumption

As mentioned before, for options 1 and 2, consumption matches production. The total electricity production data was obtained from ENVI-PV. For option 3, unused electricity is stored in the battery and used, however the amount that is not used over one day is assumed to be wasted. Therefore, the total lifetime environmental impact of the SPV system and two lifetimes of batteries are divided by the total consumption up to the point where consumption exceeds production. The average annual electricity consumption of an electrified household in Indonesia is 1723 kWh as of year 2014 (World Energy Council, 2016). If the current growth rate of 2.6% continues, this will be 2285 kWh by the year 2025, and 4377 kWh in the year 2045 (Figure 12). The total electricity consumption over 20 years has been calculated based on this projection.

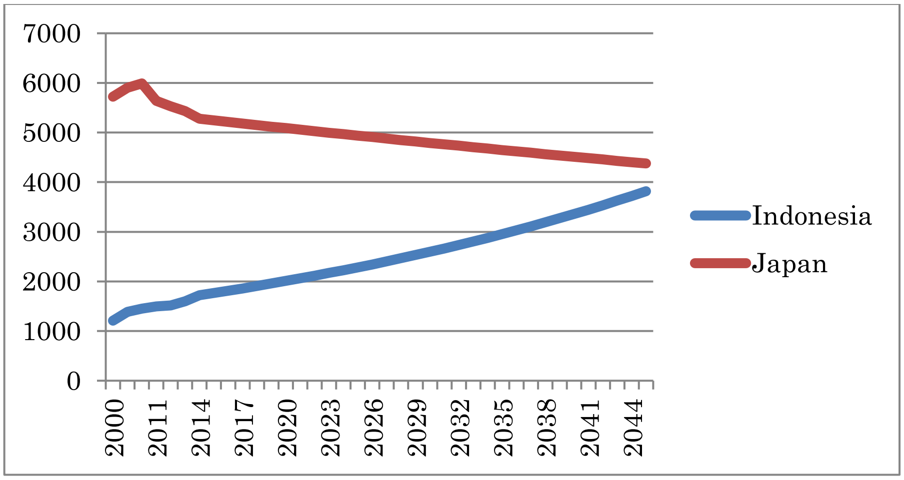


Figure 12. Average electricity consumption of an electrified household in Indonesia and Japan, following current growth rate. Assumption was made that the current growth and negative growth rate as of year 2014 continues.

Normalization and Sensitivity Analysis

The impact inventories themselves can be difficult to interpret. Normalization and sensitivity analysis are optional steps in the ISO standard 14044 to assist the results interpretation process. Both were conducted to support better results interpretation and discussions.

Normalization

Normalization is a step to convert the raw figures of largely different environmental impact categories of different measurement units into a comparable value, by dividing each impact category result by a reference value (Aymard & Botta-Genoulaz, 2016). The equation used for normalization was the following:

$$Ni = Si / Ri$$

where i is the impact category, Ni is the result of normalization, Si is the impact of the impact category of the solar system under study, and Ri is the impact of the reference system. Ideally, the reference value should be specific to Indonesia or the ASEAN region, however, due to data restrictions, the most recent EU-27 normalization value suggested by ILCD was used as base for calculating proxy values (Benini et al., 2014). Assuming that the level of GHG emission roughly reflects the size of other impact categories, each ILCD factor was multiplied by the ratio of per capita GHG emission of EU and Indonesia. The annual GHG emissions per capita were calculated using the World Bank database, which resulted in 9.1928 kg CO2 eq for EU and 2.9893 kg CO2 eq for Indonesia, which means that the per capita emission of Indonesia is 0.3252 times that of EU. Results are shown in Table 5. The magnitude of the impacts from each solar installation option were compared and discussed based on normalized values. Data was not provided for the impact category Nuclear Waste, thus left out of the normalization results.

Table 5. Normalization factor per person (Benini et al., 2014)

Impact Category	Factor (EU)	Factor (Indonesia)	Unit
Acidification	4.73E+01	1.54E+07	mol H+ eq.
Climate Change	9.22E+03	3.00E+06	kg CO2 eq
Freshwater Ecotoxicity	8.74E+03	2.84E+06	CTUe
Terrestral eutrophication	1.76E+02	5.72E+07	mol N eq.
Human toxicity, cancer	3.69E-05	1.20E+04	CTUh
Human toxicity, non-cancer	5.33E-04	1.73E+05	CTUh
Ionizing radiation- human health	1.13E+03	3.67E+05	kBq U235 eq
Land Use	7.48E+04	2.43E+04	kg C deficit
Mineral, fossil and resource depletion	1.01E-01	3.28E+04	kg Sb eq.
Nuclear Waste	No data	No data	No data
Ozone depletion	2.16E-02	7.02E+06	kg CFC-11 eq.
Particulate matter	3.80E+00	1.24E+06	kg PM2.5 eq
Photochemical	3.17E+01	1.03E+07	kg NMVOC eq.

Sensitivity analysis

Sensitivity analysis is another optional step to further analyze the results using different parameters or assumptions. Sensitivity was examined for the following two items; battery end-of-life scenario and the number of years of usage of the SPV system.

Battery recycling is mandatory in the EU (Balcombe, Rigby & Azapagic, 2015), however this is not the case for Indonesia. Therefore, the assumption was challenged by comparing the results when disposed batteries are simply disposed in landfills. Since battery life is assumed to be 10 years, two sets of batteries will be disposed over the lifecycle of one rooftop SPV. The alternative inputs are shown in Table 6.

Table 6. End-of-life inputs of battery cell per 6kWh, without recycling.

	Input	Quantity
Gate	Lead- Lead in car scrap incinerate	107.64 kg
	Sulphuric acid- Hazardous material incinerate	17.16 kg
	Polypropylene- Landfill, polypropylene	6.24 kg
	Glass fibre- Landfill, glass	6.24 kg
	Antimony- Hazardous material incinerate	1.56 kg

The lifespan of SPV is set at 30 years for ground installation and 20 years for rooftop installation, assuming that commercial usage secures better maintenance compared to household usage. This is an assumption based on different maintenance criteria between residential usage and large-scale ground installation (NREL, 2015). However in developing countries, abandonment of commercial SPVs is observed due to financial reasons or poor maintenance. This uncertainty is challenged by shortening the longevity of ground installation to 20 years. The environment impact inventory was collected under this new assumption using the ENVI-PV, and relative results and normalization results were recalculated.

Handprinting effect

Finally, an alternative perspective of “handprinting” was examined. While ordinary LCA focuses on the environmental footprint, we can also look at the same data to see how much positive impact a certain decision different from BAU can create. In this thesis I considered the handprinting effect of an individual person switching the energy source to rooftop SPV from the national grid. The per capita normalization factor in Table 5 was used as the annual footprint of an average Indonesian. First, direct credit was given for reduction in the footprint of oneself and neighbors connected to the grid in the case of on-grid installation. Secondly, the potential credit for influencing others was estimated. This was not applied to ground installation, since it is difficult for an individual to make a decision on using electricity from ground-installed SPV, other than by moving into neighboring areas or supporting through monetary or political means.

Research Limitations

The research mainly focused on the conceptual understanding of how different SPV installation methods affect the environment both positively and negatively. Therefore, the LCA calculation used hypothetical data based on global production share and industry standards, instead of actual projects. This limits the data to only two well-used installation options, which are 3kWp rooftop mount and 570kWp ground installation.

For battery, the best technology option may have been the newly emerging Lithium Ion, otherwise a sensitivity analysis using different batteries could have been useful. However due to lack of data, I focused only on the most popular lead acid battery.

This research and discussion is limited to environmental impact analysis of solar electricity for households. In the real world, policy decisions are made based on existing energy mix and cost analysis, which are not part of this research. Furthermore, daily household demand is proxy data, which does not drastically affect the overall conclusion but is too rough to make informed policy or investment decisions.

Chapter III

Results

Environmental impact inventory data at the ILDC mid-point level were collected using ENVI-PV and Open LCA for the BAU national energy mix and three solar installation options, which are: ground installation connected to grid, rooftop installation connected to grid, and rooftop installation standalone with battery. Inventory data were then analyzed by relative results and normalized results, and finally robustness was tested through a sensitivity analysis on alternative assumptions.

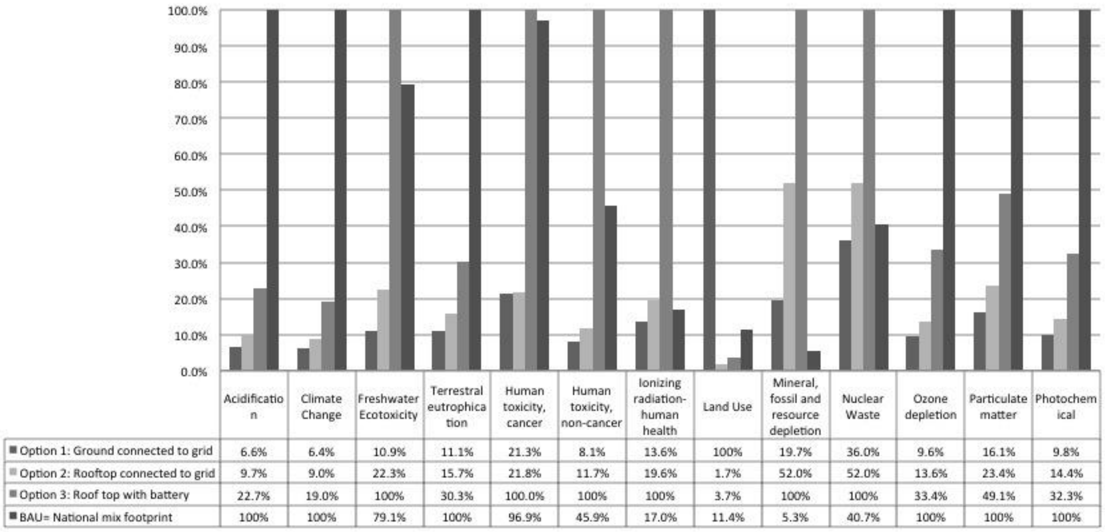
Environmental Impact Inventory

Based on the system diagram and set of assumptions, environmental impact inventory data per 1kWh of electricity consumption was calculated using data extracted from ENVI-PV and Open LCA. The simple results are shown as LCIA results in Table 7. Units have been modified to show the results effectively. Then, the relative magnitude for each impact category was visualized by setting the maximum result within the category to 100% and displaying the remaining results in relation to the largest figure (Figure 13).

Table 7. Life Cycle Inventory per kWh of electricity consumption.

Impact Category	Unit	Option 1	Option 2	Option 3	BAU
Acidification	u03bcmolc H+ eq	569.05	836.90	1948.47	8593.45

Climate Change	g CO2 eq	65.08	91.58	194.80	1023.10
Freshwater Ecotoxicity	*10^-3 CTUe	56.87	116.91	523.41	414.26
Terrestrial eutrophication	u03bcmolc N eq	829.35	1172.38	2256.84	7446.25
Human toxicity, cancer	*10^-9 CTUh	1.58	1.61	7.40	7.17
Human toxicity, non-cancer	*10^-9 CTUh	11.69	16.89	143.74	65.97
Ionizing radiation-human health	Bq U235 eq	2.88	4.17	21.24	3.61
Land Use	kg C deficit	5.63	0.10	0.21	0.64
Mineral, fossil and resource depletion	mg Sb eq	8.66	22.85	43.98	2.33
Nuclear Waste	mm3 HAA eq	0.07	0.10	0.18	0.08
Ozone depletion	u00b5g CFC-11 eq	1.79	2.55	6.27	18.74
Particulate matter	mg PM2.5 eq	91.38	132.56	277.83	566.15
Photochemical	mg NMVOC eq	229.36	336.35	752.53	2333.34



	Acidification	Climate Change	Freshwater Ecotoxicity	Terrestral eutrophication	Human toxicity, cancer	Human toxicity, non-cancer	Ionizing radiation-human health	Land Use	Mineral, fossil and resource depletion	Nuclear Waste	Ozone depletion	Particulate matter	Photochemical
■ Option 1: Ground connected to grid	6.6%	6.4%	10.9%	11.1%	21.3%	8.1%	13.6%	100%	19.7%	36.0%	9.6%	16.1%	9.8%
■ Option 2: Rooftop connected to grid	9.7%	9.0%	22.3%	15.7%	21.8%	11.7%	19.6%	1.7%	52.0%	52.0%	13.6%	23.4%	14.4%
■ Option 3: Roof top with battery	22.7%	19.0%	100%	30.3%	100.0%	100%	100%	3.7%	100%	100%	33.4%	49.1%	32.3%
■ BAU= National mix footprint	100%	100%	79.1%	100%	96.9%	45.9%	17.0%	11.4%	5.3%	40.7%	100%	100%	100%

Figure 13. Relative results of solar installation options and BAU.

Normalization

While the relative results already help visualize the comparison of the electricity options within each impact category, the information is still insufficient to make decisions on whether solar electricity has a comparative advantage in terms of environmental impact over BAU, and on which installation option actually has the least environmental impact.

Normalization results are shown in three ways using the same data set. The impact category Nuclear Waste is not applicable in all three graphs, due to lack of reference data. Figure 15 compares the three solar installation options against the BAU. Figure 15 compares the 3 solar installation options. Figure 17 excludes the rooftop with battery option, and compares the two on-grid solar options with BAU.

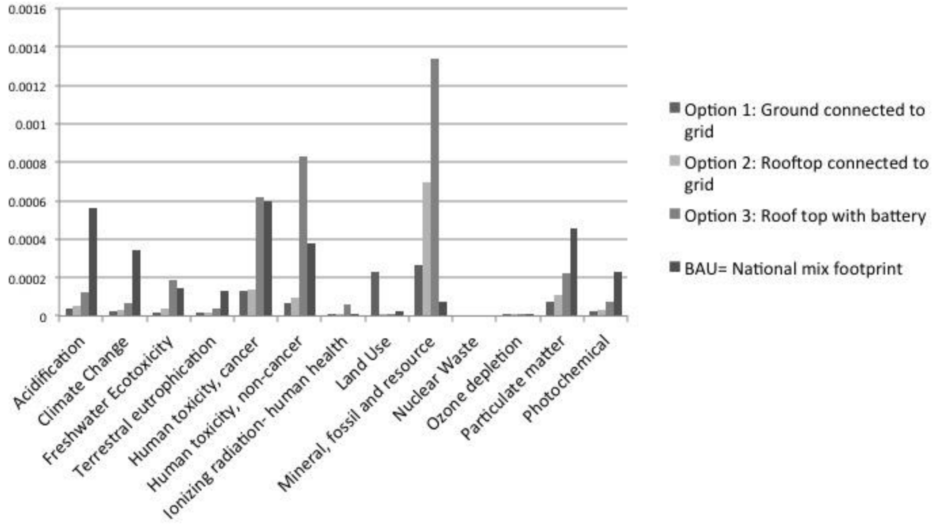


Figure 14. Normalization results including BAU.

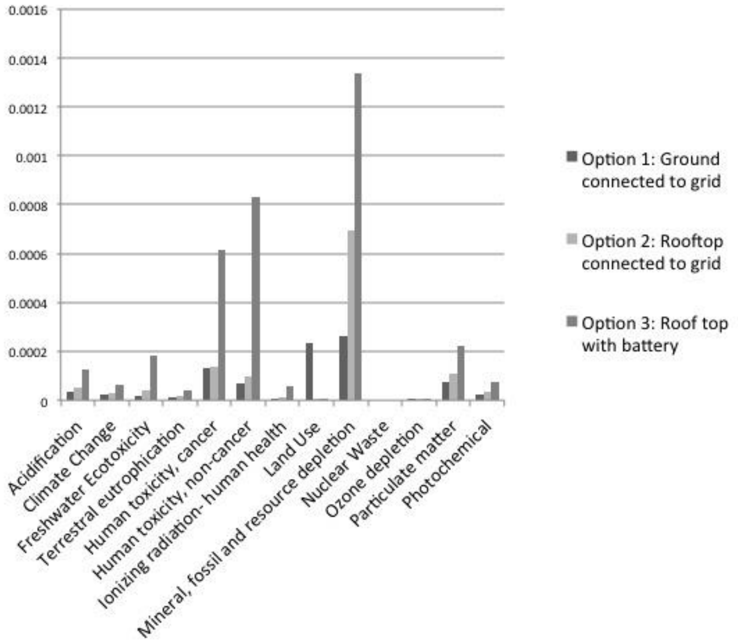


Figure 15. Normalization results comparing the 3 solar installation options.

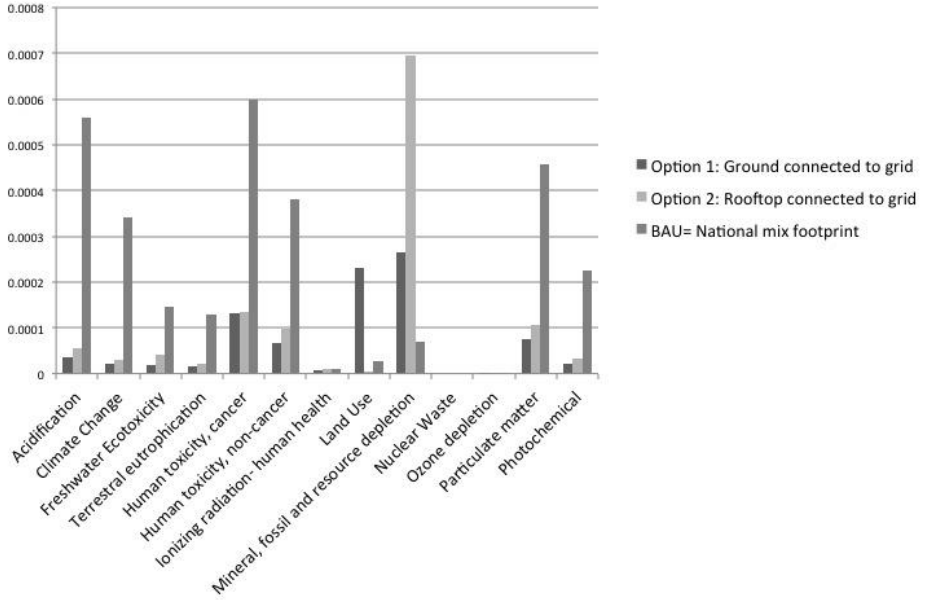


Figure 16. Normalized Impact of On-grid Solar Installations and BAU.

Sensitivity Analysis

The robustness of above results was tested by two sensitivity analyses. The assumptions that batteries are recycled at the end-of-life and that ground installation has a longer lifespan compared to rooftop installation were challenged.

Battery end-of-life sensitivity

The normalized impacts of rooftop installations between grid connected installation (no batteries), off-grid installation with batteries which are recycled at end-of-life, and off-grid installation without recycling at end-of-life, are shown in Figure 17. For the difference of two impact categories-- Human toxicity Cancer and Human Toxicity Non-cancer--, screenshots of process contribution from Open LCA results are shown below as supporting data (Figure 18).

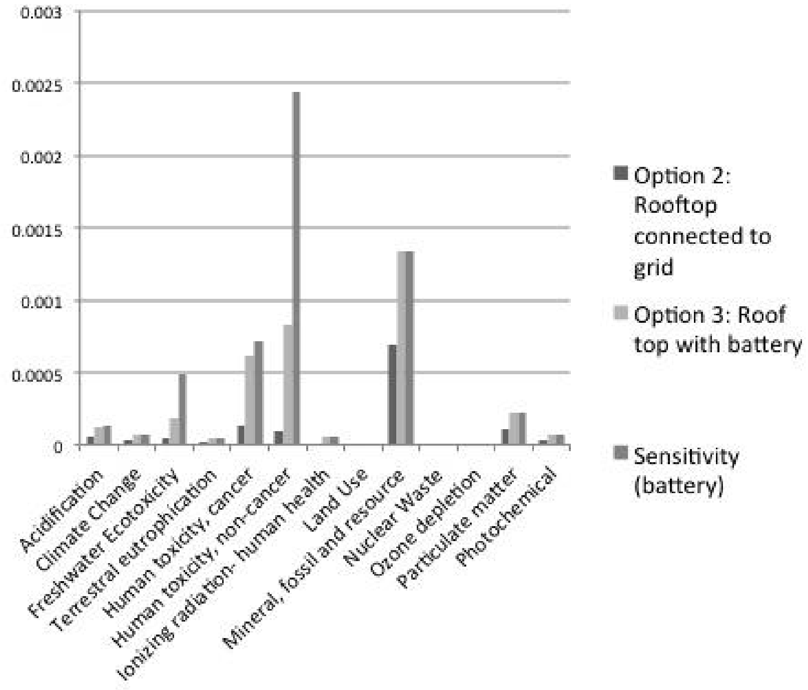
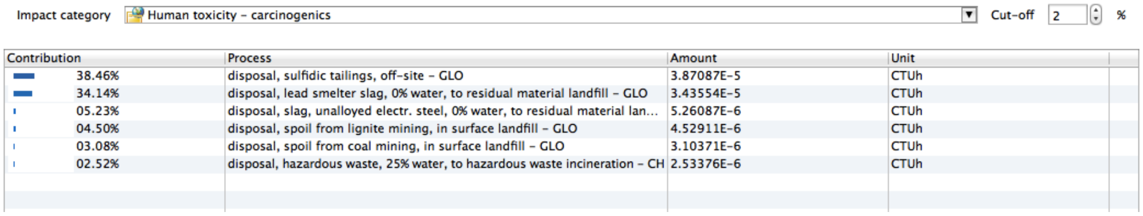


Figure 17. Normalized impact of battery recycled and non-recycled

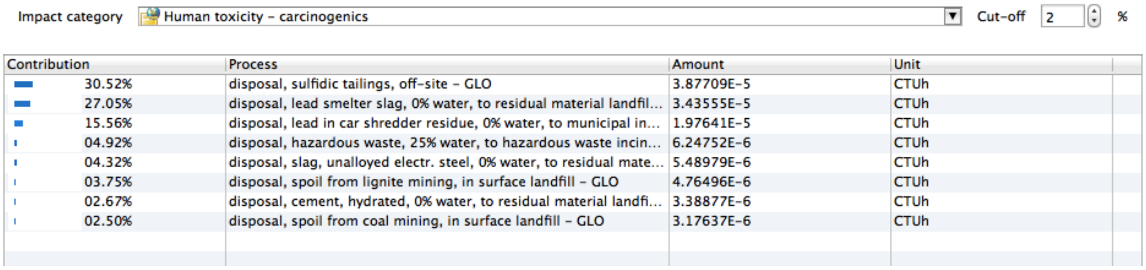
(a) Human toxicity – cancer process contributions (with recycling)



Impact category: Human toxicity – carcinogenics | Cut-off: 2 %

Contribution	Process	Amount	Unit
38.46%	disposal, sulfidic tailings, off-site – GLO	3.87087E-5	CTUh
34.14%	disposal, lead smelter slag, 0% water, to residual material landfill – GLO	3.43554E-5	CTUh
05.23%	disposal, slag, unalloyed electr. steel, 0% water, to residual material lan…	5.26087E-6	CTUh
04.50%	disposal, spoil from lignite mining, in surface landfill – GLO	4.52911E-6	CTUh
03.08%	disposal, spoil from coal mining, in surface landfill – GLO	3.10371E-6	CTUh
02.52%	disposal, hazardous waste, 25% water, to hazardous waste incineration – CH	2.53376E-6	CTUh

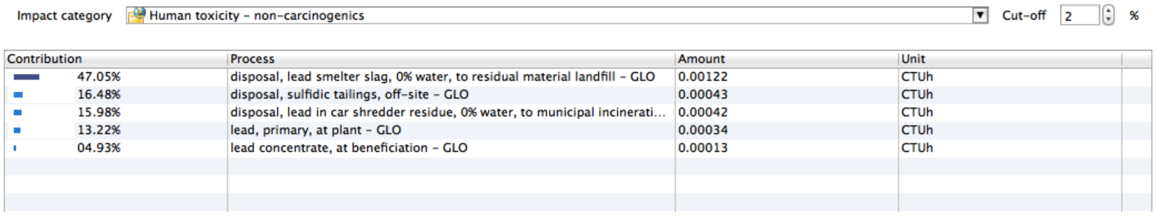
(b) Human toxicity – cancer process contributions (no recycling)



Impact category: Human toxicity – carcinogenics | Cut-off: 2 %

Contribution	Process	Amount	Unit
30.52%	disposal, sulfidic tailings, off-site – GLO	3.87709E-5	CTUh
27.05%	disposal, lead smelter slag, 0% water, to residual material landfil…	3.43555E-5	CTUh
15.56%	disposal, lead in car shredder residue, 0% water, to municipal in…	1.97641E-5	CTUh
04.92%	disposal, hazardous waste, 25% water, to hazardous waste incin…	6.24752E-6	CTUh
04.32%	disposal, slag, unalloyed electr. steel, 0% water, to residual mate…	5.48979E-6	CTUh
03.75%	disposal, spoil from lignite mining, in surface landfill – GLO	4.76496E-6	CTUh
02.67%	disposal, cement, hydrated, 0% water, to residual material landfi…	3.38877E-6	CTUh
02.50%	disposal, spoil from coal mining, in surface landfill – GLO	3.17637E-6	CTUh

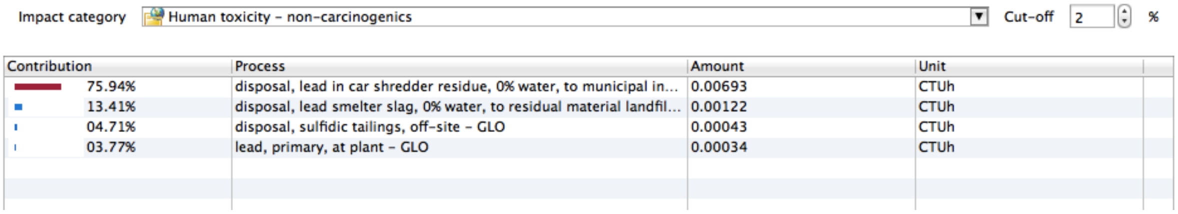
(c) Human Toxicity – non-cancer process contributions (with recycling)



Impact category: Human toxicity – non-carcinogenics | Cut-off: 2 %

Contribution	Process	Amount	Unit
47.05%	disposal, lead smelter slag, 0% water, to residual material landfill – GLO	0.00122	CTUh
16.48%	disposal, sulfidic tailings, off-site – GLO	0.00043	CTUh
15.98%	disposal, lead in car shredder residue, 0% water, to municipal incinerati…	0.00042	CTUh
13.22%	lead, primary, at plant – GLO	0.00034	CTUh
04.93%	lead concentrate, at beneficiation – GLO	0.00013	CTUh

(d) Human Toxicity – non-cancer process contributions (no recycling)



Impact category: Human toxicity – non-carcinogenics | Cut-off: 2 %

Contribution	Process	Amount	Unit
75.94%	disposal, lead in car shredder residue, 0% water, to municipal in…	0.00693	CTUh
13.41%	disposal, lead smelter slag, 0% water, to residual material landfil…	0.00122	CTUh
04.71%	disposal, sulfidic tailings, off-site – GLO	0.00043	CTUh
03.77%	lead, primary, at plant – GLO	0.00034	CTUh

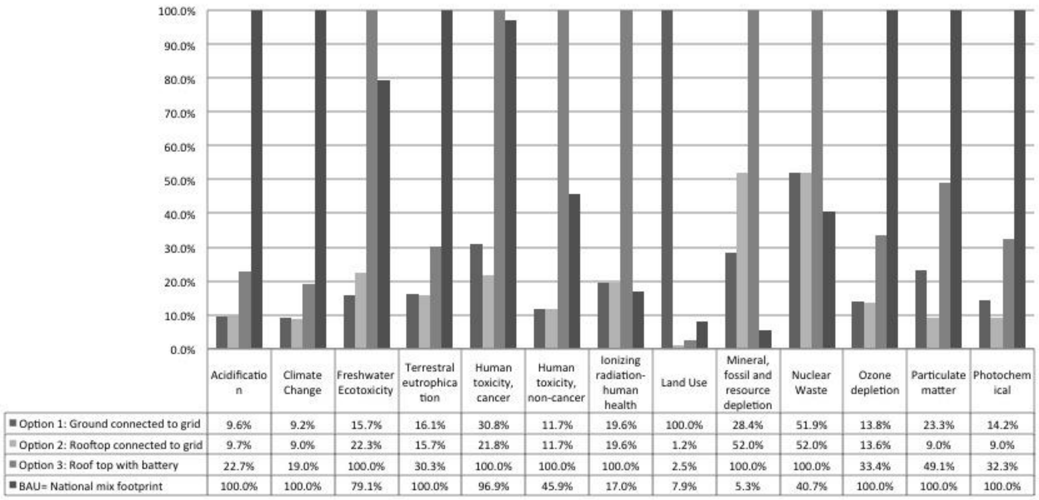
Figure 18. Screenshots of process contributions to each impact category.

Ground installation lifespan sensitivity

When the assumption of the lifespan is changed from 30 years to 20 years for the ground installation option, lifelong electricity production was reduced from 24,702,972.98 kWh to 17,110,165.29 kWh, which is actually higher than 2/3, reflecting the fact that system efficiency becomes lower as it becomes older. The Life Cycle inventory is shown in Table 8, relative results are shown in Figure 19 and normalized results are in Figure 20.

Table 8. Life Cycle Inventory of Ground Installation with 20 years duration.

Impact Category	Unit	Ground installation, 20 years duration
Acidification	u03bcmolc H+ eq	821.5753932
Climate Change	g CO2 eq	93.9625628
Freshwater Ecotoxicity	*10^-3 CTUe	82.09991883
Terrestral eutrophication	u03bcmolc N eq	1197.388292
Human toxicity, cancer	*10^-9 CTUh	2.28185986
Human toxicity, non-cancer	*10^-9 CTUh	16.882336
Ionizing radiation- human health	Bq U235 eq	4.157628806
Land Use	kg C deficit	8.126746277
Mineral, fossil and resource depletion	mg Sb eq	12.49917142
Nuclear Waste	mm3 HAA eq	0.095860908
Ozone depletion	u00b5g CFC-11 eq	2.586694273
Particulate matter	mg PM2.5 eq	131.9262382
Photochemical	mg NMVOC eq	331.1440217



	Acidification	Climate Change	Freshwater Ecotoxicity	Terrestral eutrophication	Human toxicity, cancer	Human toxicity, non-cancer	Ionizing radiation-human health	Land Use	Mineral, fossil and resource depletion	Nuclear Waste	Ozone depletion	Particulate matter	Photochemical
■ Option 1: Ground connected to grid	9.6%	9.2%	15.7%	16.1%	30.8%	11.7%	19.6%	100.0%	28.4%	51.9%	13.8%	23.3%	14.2%
■ Option 2: Rooftop connected to grid	9.7%	9.0%	22.3%	15.7%	21.8%	11.7%	19.6%	1.2%	52.0%	52.0%	13.6%	9.0%	9.0%
■ Option 3: Roof top with battery	22.7%	19.0%	100.0%	30.3%	100.0%	100.0%	100.0%	2.5%	100.0%	100.0%	33.4%	49.1%	32.3%
■ BAU= National mix footprint	100.0%	100.0%	79.1%	100.0%	96.9%	45.9%	17.0%	7.9%	5.3%	40.7%	100.0%	100.0%	100.0%

Figure 19. Relative results of 3 installation options and BAU with 20 years duration for ground installation.

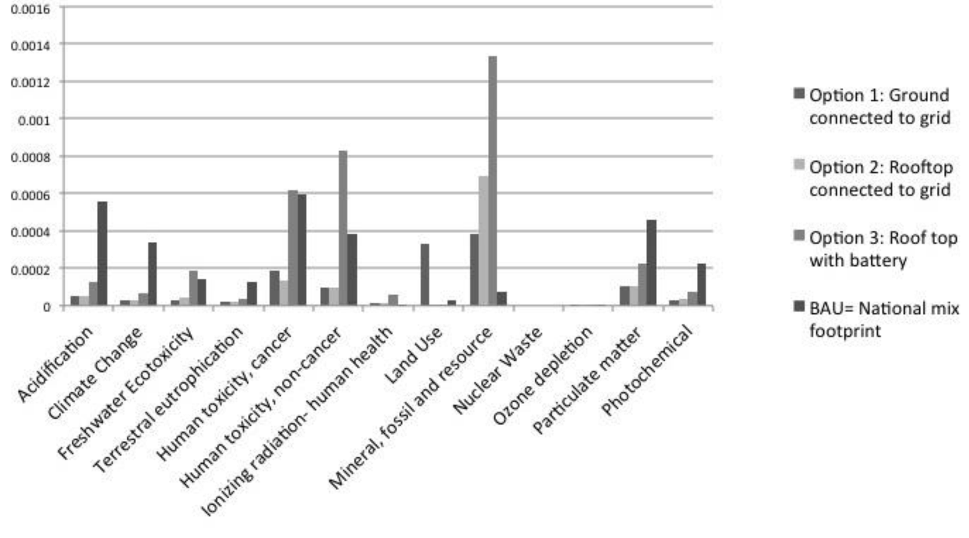


Figure 20. Normalization (Ground installation duration 20 years).

Handprinting Effect

Finally, the handprinting effect of installing one rooftop SPV, either connected to the grid or off-grid with battery was calculated. Table 9 shows how much impact was reduced per category compared to BAU, the resulting annual footprint, and the % of the handprinting effect compared to the original footprint of the person.

Table 9 Handprinting effect of installing one rooftop SPV

			Rooftop connected to grid			Rooftop off-grid		
Impact Category	Unit	Annual Footprint	Handprint	Total footprint	Reduce by X%	Handprinting	Total footprint	Reduce by X%
Acidification	u03bcmolc H+ eq/kWh	15,380,938	16,335,666	-954,728	Net positive	15,545,603	-164,664	Net positive
Climate Change	g CO2 eq/kWh	2,998,145	1,981,142	1,017,003	66%	1,937,772	1,060,373	65%
Freshwater Ecotoxicity	*10^-3 CTUe/kWh	2,842,059	442,733	2,399,326	16%	-255,352	3,097,411	-9%
Terrestral eutrophication	u03bcmolc N eq/kWh	57,231,398	12,141,295	45,090,104	21%	12,140,372	45,091,027	21%
Human toxicity, cancer	*10^-9 CTUh/kWh	11,999	9,532	2,467	79%	-531	12,530	-4%
Human toxicity, non-cancer	*10^-9 CTUh/kWh	173,320	78,285	95,035	45%	-181,938	355,258	-105%
Ionizing radiation-human health	Bq U235 eq/kWh	367,452	-10,335	377,787	-3%	-41,249	408,700	-11%
Land Use	kg C deficit/kWh	24,323	1,055	23,268	4%	1,014	23,309	4%
Mineral, fossil and resource depletion	mg Sb eq/kWh	32,843	-97,432	130,275	-297%	-97,435	130,278	-297%
Ozone depletion	u00b5g CFC-11 eq/kWh	7,023,853	32,366	6,991,487	0%	29,180	6,994,674	0%

Particulate matter	mg PM2.5 eq/kWh	1,235,678	727,617	508,061	59%	674,522	561,156	55%
Photochemical	mg NMVOC eq/kWh	10,308,155	3,944,270	6,363,885	38%	3,698,237	6,609,918	36%

Chapter IV

Discussion

Life Cycle Assessment results provided data to analyze my initial hypothesis from multiple environmental impact categories, instead of one criterion of climate change impact. Drawing from the findings, I will discuss some implications on policy in Indonesia and general recommendations for SPV technology development. Finally, I discuss limitations of the study and suggestions for future research in the area.

LCA Results Interpretation

While SPV seems to be unquestionably more ‘environmentally friendly’ compared to a BAU national energy mix when focusing only on Climate Change impact, a full range life cycle impact assessment shows a different and more complex picture.

Relative results analysis

The relative results showed that in 6 out of 13 impact categories (Acidification, Climate Change, Terrestrial Eutrophication, Ozone Depletion, Particulate Matter and Photochemical), BAU has relatively larger impact on the environment compared to the three solar options. It can be noted that for the Climate Change category, which oftentimes gather the most attention, options 1, 2 and 3 all have much less impact compared to BAU; their impacts are 6%, 9.4%, and 19% of BAU, respectively. However, also in 6 categories (Freshwater Ecotoxicity, Human Toxicity-Cancer, Human Toxicity-Non-Cancer, Ionizing

Radiation-Human Health, Mineral, Fossil and Resource Depletion and Nuclear Waste), option 3: rooftop installation with battery has the largest impact. Also, option 1: ground installation has the largest impact in the Land Use category. This means that when we widen our perspective on solar energy outside climate change effects, SPV, especially standalone rooftop installation with battery, may not always be the option with least environmental impact. Data also show that larger scale SPV has less per kWh impact in all categories except Land Use. This is due to the economy of scale of mounting and the assumption that ground installation for commercial purpose has longer system duration compared to household installation.

Normalized results analysis

Normalization gives insights for further analysis, by comparing each impact category of each electricity option with the environmental impact of one person per year (Aymard & Botta-genoulaz, 2016). The results show the magnitude of impact that the selection of each installation option or the BAU has for one person. The larger the normalized value, the more importance the decision has on the environment impact category.

First, I compared the three solar installation options and the BAU (Figure 14). Within the 12 impact categories (excluding Nuclear Waste which is lacking reference data), the most significant value was for the Mineral, Fossil and Resource Depletion, with the highest value for the standalone rooftop with battery option, and significantly large values for the two other solar options compared to BAU. The second outstanding impact was the

Human Toxicity-Non-Cancer, again with the highest value for the standalone rooftop with battery option, but with the BAU ranking second. The third largest value is for the Human Toxicity-Cancer, again with the highest value for the standalone rooftop option, and with BAU ranked second with small difference. For the lower magnitude impacts, Acidification, Particulate Matter, Climate Change and Photochemical, BAU has a significantly higher impact compared to all solar installation options. However, for Land Use, option 1: ground installation connected to grid has a significantly larger impact compared to BAU and rooftop solar options, and for Freshwater Ecotoxicity again the standalone rooftop with battery option has the highest value.

The second result compared between the 3 solar installation options (Figure 15). It can be observed that in all impact category except for Land Use, the standalone rooftop with battery option has a significantly higher impact compared to the two grid connected options. The reason of high impact per kWh for off-grid rooftop installation compared to the other two installation options was because of the low production efficiency set at 65% compared to 80% for grid connected systems, the battery impact, and also the wasted electricity due to larger electricity production than household demand. This was partly due to research limitations. Data were only available for a 3kWp installation, which is sufficient for a household in a developed country, capacity too large for an average Indonesian household. However, this may reflect reality to a certain extent. A stand-alone solar system may at first sight seem to reduce the footprint of the individual household, yet from a wider perspective it is not the most efficient option.

The third comparison removed the least likely rooftop with battery option, and compared the two on-grid solar options with BAU. This time, in 8 out of 12 categories, BAU has a significantly larger impact compared to solar options. However, again the Mineral, Fossil and Resource Depletion impact has a high magnitude, with the largest value for the rooftop option. Land Use impact is again largest for ground installation. The magnitude of the Ionizing Radiation and Ozone Depletion impacts are very small compared to other impact categories.

The results make it difficult to make a clear-cut decision. Indeed, both ground and rooftop, when connected to the grid, have significantly lower environmental impact compared to BAU in the important impact categories. Since it is natural that the preferred system does not necessarily have lower impact in every single category, it can be concluded that solar installations are the better option compared to BAU. However, Mineral, Fossil and Resource Depletion impact is high, possibly due to the rare metal used in the components. This is an implication for future technology development, through means such as investing in innovation to create different materials and / or designing SPV that can be recycled to reuse all components many times. Increasing the electricity production efficiency is also a necessary precondition. The Land Use category has its implication too. ENVI-PV results are calculated based the data assumption of transforming European average land (a mixture of arid, forest, agricultural, urban, traffic, mining etc…) into industrial use. Indonesia has abundant tropical forests, and converting forest areas into ground installed solar power plants can do more harm than good. Ground and rooftop installation have pros and cons, yet while rooftop has only one category that is significantly larger than BAU, ground has two, with possibly higher impact in the Indonesian context. Under the assumption that a smart grid will be installed either as the national grid or by an independent mini-grid, the rooftop installment connected to the grid seems to be the better option.

Sensitivity analysis of battery end-of-life

Before concluding which solar installation option is the most suitable, the two sensitivity analyses need to be considered. As for the end-of-life scenario of batteries, since Indonesia is still at an early stage in terms of general e-waste, there is a risk of batteries being disposed and incinerated or landfilled without recycling. The sensitivity analysis aimed to quantify the significance of this possible scenario.

The normalized impacts of rooftop installations between batteries recycled at end-of-life, no recycling at end-of-life, and also with without battery, are shown in Figure 17. It can first be observed that the difference of impact between on-grid (option 2) and standalone rooftop installation (option 3) in many categories are attributed to the lifelong kWh consumed. While the grid connected option is assumed to be consumed all of its lifelong production of 90,054 kWh, this research assumed that the standalone system will only consume the demanded 46,789 kWh. Since the lifelong environment impact of SPV is the same for both options, it is natural that the impact of a standalone option will be about twice as large as the grid connected option in all impact categories. However, as the graph showed, Freshwater Ecotoxicity, Human Toxicity-Cancer, Human Toxicity-Non-cancer are three categories where the battery is producing additional impact.

The difference in end-of-life treatment does not affect the less significant impact categories such as Acidification, Climate Change, Terrestrial Eutrophication, Ionizing Radiation, Land Use, Mineral, Fossil and Resource Depletion, Ozone Depletion, Particulate Matters and Photochemical. However, batteries disposed without recycling increase the impact in large magnitude for impact categories such as Freshwater Ecotoxicity, Human Toxicity-Non-cancer, and to a lesser degree, Human Toxicity-Cancer. The process that contributes to carcinogen Human Toxicity impact was 100% the disposal process (Figure 18 (a)(b)). Similarly, over 99.5% of the non-concinogen Human Toxicity impact is attributed to disposal, and the remaining to lead production (Figure 18 (c)(d)). Disposal of battery without recycling will place a significantly larger impact on public health. Moreover, in the Indonesian e-waste context, the actual LCA results may be worse, since the modeling in the Ecoinvent database does not account for improper waste management, and ENVI-PV assumes that solar panels will be recycled. Although not compared in this study, batteries will play an important role if the national energy is to switch from fossil based to renewable energy sources. A strong recycling system, including legislation, institutions, technology and business models will be necessary to prevent this potential harm.

Sensitivity analysis of ground installation system duration

Sensitivity analysis on the duration of the ground installation can possibly tip the decision. Ground installation, with the assumption that it will operate for 30 years, had the least environment impact among the three solar options in 12 out of the 13 impact categories except for Land Use. It also had smaller impact compared to BAU in all categories except for Land Use and Mineral, Fossil and Resource Depletion. However, once the operation time is reduced to 20 years, the results are very different. Relative results show that compared to the initial analysis the comparative magnitude of impact has increased in several categories (Figure 19). Originally in 8 out of 13 categories (Acidification, Climate Change, Terrestrial Eutrophication, Human Toxicity Non-Cancer, Ionizing Radiation, Nuclear Waste, Ozone Depletion, and Photochemical), the impact was smaller compared to option 2: rooftop installation connected to grid. But the sensitivity analysis shows that when the system duration is set as short as the rooftop options, the per kWh consumption impact is now about the same. In other categories such as Human Toxicity Cancer and Particulate Matter, the impact is now larger than those of rooftop connected to grid.

When the results are normalized, it can be seen that now the impacts are almost the same with option 2 for Acidification and Terrestrial Eutrophication, while the significant impact of Land Use remains larger compared to the other options (

Figure 20). This indicates the importance of utilizing an originally installed SPV to the end of its duration, both for rooftop and ground installment. Flipping it around, this also means that if rooftop installation can receive good maintenance and be used for 30 years, it will tip the decision for best option to grid-connected rooftop installation, which in fact has the least impact in all 3 significant categories after normalization.

Handprinting effect

The largest reason for an individual to install a rooftop SPV may be to reduce the climate change effect. By switching from the BAU (national grid), both grid-connected and off-grid rooftop options show a huge handprinting effect, by directly reducing 66% and 65% of the annual footprint, respectively. We can stop the analysis here, saying that both SPV options have a positive impact on climate change, and that by also convincing one more person to install a rooftop SPV, one can actually offset the annual footprint and heal the planet.

However, the results are more complex. For Acidification, again both options have big handprinting effects, offsetting the annual footprint of an individual. Terrestrial Eutrophication, Land use, Particulate Matter and Photochemical are categories that also show handprinting effects. However, the off-grid option actually has negative effects in categories such as Freshwater Ecotoxicity and Human toxicity. It needs to be noted that again, Mineral, fossil and resource Depletion category shows negative impact for SPV.

From this result, two observations can be made. First is that the option with battery cannot be considered to have the same positive impact as the grid-connected option, although, it is nonetheless a very useful and important tool for addressing electricity accessibility issues in remote areas. Secondly, the handprinting effect of grid-connected installation can potentially be much larger, due to its connectivity. Already one person's decision to install SPV is having spillover effects for other households who benefit from the surplus electricity. In order to create a net positive handprinting effect, if a person installs one rooftop SPV on their house and convinces 1 more household to do the same every year, it will offset the annual Climate Change and impact of the person for the next

20 years. Of course in reality this is not as simple as it seems, since there is no economic incentive for a household to install SPV to provide electricity to others without a proper FIT system, and the nation also needs to upgrade its grid. Also there is no incentive to invite others to invest in SPV. However, if the handprinting effect of inviting just one more household to install a rooftop SPV already offsets a person's annual Climate Change effect, a policy promoting two households to buy together could be a realistic way of creating a rippling effect in the country. On the other hand, installing a stand-alone SPV system on one's house, especially in a grid-connected area can be a very strong message to show how the house is dedicated to become grid-independent. However, this excludes the others from benefiting from the solar potential, and may be a less engaging message in terms of handprinting.

Research Limitations and Caveats

This study has limitations and caveats. Comparing different electricity production technology is much more complicated than comparing the production process of physical products. Although it is following the IEA guideline to the extent possible, the science of electricity provision, including the efficiency, capacity and grid technology is not fully accounted in this study. The recurring effect that the additional solar electricity will cause on the national energy mix is not considered either.

Also, further data are needed to fully analyze the country-specific conditions. At the LCA level, ideally the normalization factor should be specific to the country, but due to lack of data, it is a proxy data based on EU-29 factors, possibly affecting the normalized results. It is also lacking Nuclear impact category. Truly country-specific data on e-waste and forest transformation are also missing, therefore the true impact of the sensitivity analysis is still unknown.

Questions for Further Research

This thesis was a comparative LCA of SPV installation options that may be considered as effective in the Indonesian context. The research focused on addressing the overall picture using existing life cycle inventory data. In the future, a more detailed study is suggested for the following two directions.

The first is the significance of converting forest land to solar electricity farms. Environmental benefit in many categories, even when normalized, seem to indicate that ground installation has the least impact, and possibly better when the size is bigger due to better efficiency and economy of scale. However, for the Land Use category, ground installation had a significantly larger impact compared to the other options including BAU. This is due to the land transformation that solar power plants require. In Indonesia, the country has a high coverage rate of tropical forests, which plays a significant role in biodiversity conservation, climate change mitigation and general ecological regulation service provision among other benefits. As in the case of Giri Trawangan power plant, a new solar power plant has a possibility of being built in forest areas instead of residential or agriculture areas, which already have an economic value. The ENVI-PV calculation is based on the assumption that ground installation transforms average land use of Europe to industry area. If the origin of the land is a tropical forest, the Land Use impact can become much more significant.

The second is the direction of technology innovation. Increase in energy production efficiency can reduce the per kWh impact, however it will not be enough to drastically improve the Mineral, Fossil and Resource Depletion category. A detailed study on different directions of innovation can help guide future scientific research; can it be addressed by recycling more efficiently, or do we need to come up with a different material? The same can be said for the battery. In this research I only studied lead acid battery, but the emerging group of Li-Ion or other batteries that can be used both for vehicle and household purpose can reveal a new direction. Recycling technology may have a potential of improving many impact categories as well.

Regarding handprinting effects, the analysis is still very simplified and hypothetical. Policy decisions, such as either incentivizing business entities to build ground SPV, or incentivizing individuals to install rooftop SPVs, may represent further ways of comparing the handprinting effect at the policy level.

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