Policy Proposals for Photovoltaic Waste Disposals of a Floating Solar Farm in Sirindhorn Dam, Thailand

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Thailand, the second-largest economy in Southeast Asia, is now facing an increase of energy demand in the next 20 years by 80% due to its population and economic growths[1]. Rather than increasing the consumption of oil and gas, this country has invested heavily in clean energy alternatives for electricity generation, one of which is photovoltaic (PV) solar. In early 2019, the first largest hydro-floating solar hybrid project was announced to be installed in Sirindhorn Dam, Ubon Ratchathani province, and currently, it is still in the midst of an installation process. This installation will be complete and the floating solar farm open for commercial operation in the middle of this year, 2021. With the life span of a solar panel is presumed to be 20-25 years[2], in the next few decades, these PV solar modules of this floating plant will be inefficient or unable to generate electricity anymore. This thesis, therefore, attempts to suggest recommendations for Thailand to manage PV solar waste properly. To do so, two SWOT analyses of two different countries - Thailand and China - will be used. China is another country chosen for this study due to its emerging characteristic to fight against pollution and starting to build a new floating solar plant in the abandoned mining area, Lianghuai[3]. With the comparison, Thailand can draw lessons learned from China on how to manage PV solar waste in an environmentally friendly manner.

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2) Sharma, A., Pandey, S. & Kolhe, M. (2019), *Global Review of Policies & Guidelines for Recycling of Solar PV Modules, 597-610.* doi: 10.12720/sgce.8.5.597-610
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タイ王国シリンドーンダムの水上太陽光発電廃棄物処理の政策提案

チャンサチャ ミアス

キーワード：フローティングソーラーPV、寿命末期のPV管理、PV廃棄物処理、SWOT、タイ、中国

東南アジアで2番目に大きな経済国であるタイは、人口と経済成長により、今後20年間でエネルギー需要が 80%増加することに直面しています。この国は、石油やガスの消費を増やすのではなく、発電のためのクリーンエネルギーの代替案に多額の投資を行ってきました。その 1 つが太陽光発電（PV）ソーラーです。 2019 年の初めに、最初の最大の水上フローティングソーラーハイブリッドプロジェクトがウボンラチャタニ県のシリントーンダムに設置されることが発表されましたが、現在、設置プロセスの最中です。この設置は完了し、フローティングソーラーファームは2021年の半ばに商業運転を開始します。ソーラーパネルの寿命は25〜30年と推定されており、今後数十年でこれらのPVソーラーモジュールはこのフローティングプラントの1つは非効率的であるか、もう発電できなくなります。したがって、この論文は、タイが太陽光発電廃棄物を適切に管理するための推奨事項を提案しようとしています。そのために、タイと中国の2つの異なる国の2つのSWOT分析が使用されます。中国は、汚染と戦うという新たな特徴と、廃鉱地域である梁淮に新しい浮体式太陽光発電所の建設を開始したことから、この調査に選ばれたもう 1 つの国です。比較すると、タイは、環境に優しい方法で太陽光発電廃棄物を管理する方法について中国から学んだ教訓を引き出すことができます。

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Chapter 1 Introduction

1.1. Thailand's Background

Geography

Thailand, with the 514,000 km^2 of land area, is ranked the 3^{rd} largest nation in Southeast Asia. This kingdom lies in the middle of mainland and a strategic crossroads of this region. It, topographically, introduces a diverse scenery of forested mountains, fertile river plains, dry plateaus, and sandy beaches. Ranges of mountains expand along the border of Myanmar and down to Malaysia. Another range divides the country into two from the north to the south.

The river of Chao Phraya has its origin in the north, and it flows to the south. This river waters the fertile rice fields of the Central Plain by a system of canals. It also serves as the major route of water transportation through the country's center. Finally, the river flows into the Gulf of Thailand about 35 miles southern part of its capital city, Bangkok.

With the location of 20 degrees in the north latitude, Thailand is usually hot and humid with a climate categorized as tropical monsoon. A rainy season is from July to October. In the duration from November to February, the northeast monsoon carries a cooler and drier period when humidity goes down from an average high of 95% to an average low of 58%. During this period, temperatures simply vary from the mid-60s in the dawn to the mid-80s during the daytime. Summer is generally from March to June and usually hot and humid. Bangkok's temperatures during this season can reach 100 ^{o}F or 38 ^{o}C.

Economy

Regionally, Thailand is the second biggest economy after Indonesia. With its status of an upper-middle income country, Thailand plays as an economic cornerstone for its developing neighboring countries. Its economy seems to be resilient; according to International Monetary Fund (IMF), Thailand is projected to progress at an average rate in spite of uncertainty of its domestic politics. Public investments, which grows over the last few years, is expected to continue to be a major driver together with the government's plans on infrastructure to attract private investment and a steady development of tourism sector. 2018 indicates the greatest outcome since the military-led government came into power in 2014; however, this growth started decreasing in 2019 to a projected 2.4% owing to the worldwide slowdown and the rising trade tensions between China and the United States. As stated by the newest projection of IMF, from April 14^{th}, 2020, GDP growth is likely to fall to -6.7% caused by the outbreak of a novel corona virus (COVID-19), but will increase to 6.1% in 2021, which depends on the world's post global economic recovery.

Energy

As many other Southeast Asian countries, Thailand intersects on the crucial path of its energy sector. It confronts with an increase in energy demand by almost 80% in the next 20 years, driven by economic and population growths (IRENA, 2017). This country is thriving to pursue 2015-2020 vision focusing on energy stability and this five-year plan is expanding to 2015-2036 under the Thailand Integrated Energy Blueprint (TIEB) (IRENA, 2017). This blueprint is constructed in 5 key energy plans: power, oil, gas, energy efficiency, and alternative energy development. The Alternative Energy Development Plan (AEDP 2015) sets a target to increase renewable energy, either in the form of electricity, heat, or biofuels to 30% of the final energy consumption of the country.

With AEDP 2015, Thailand attempts to trigger photovoltaic (PV) installation systems setting from 2017 – 2036. Those systems are categorized into ground-mounted PV, PV rooftop, and floating PV systems.

Particularly, for the floating solar systems, Electricity Generating Authority of Thailand (EGAT), Thailand's energy supply agency, will float 16 solar farms with a combined capacity of more than 2.7 gigawatts in 9 of its hydroelectric dam reservoirs by 2037. Among the 16 solar farms, a pilot hydro floating solar hybrid, 45MW power, located in Sirindhorn Dam, Ubon Ratchathani province, eastern part of Thailand, has been being installed and will be finished by this December.

Since the average life span of solar panels is between 25 (projected by EGAT), in the next few decades, Thailand will confront with the solar waste issue from these projects, which is why it is important for us to figure out how to solve this problem from this initial point.

Significance of the Study

According to Environmental Progress & Sustainable Energy (2017), by comparing solar waste to nuclear waste, solar panels generate 300 times more toxic waste per unit of energy than nuclear power plants. Thailand is the second largest economy in Southeast Asia and about to float the world's largest solar farms by 2030s, therefore it is crucial to dig deeper on how it can manage these farms and dispose of those solar panels environmentally guaranteed, so that it can be beneficial to the public health of Thailand itself as well as the region as a whole.

1.2. Global Photovoltaic Waste & Its Projection

While the use of solar photovoltaic (PV) technology has been accelerating and growing due to its advancements of technology and extreme reduction in capital costs, many countries in the world are urging toward the deployment of this clean energy. The expansion of solar PV has been rapidly increasing since 2000 and the global cumulation of solar PV capacity has extended to 633.7 GW in 2019, with 116.9 GW of newly installed PV capacity in that same year (Statista, 2020). The capacity of world's PV installation will further increase to 4,500 GW by 2050 (Chowdhury et al., 2020).

Although it is widely known that solar PV is one of the cleanest sources of energy as well as environmentally friendly technology; however, just like any other technologies, it degrades and unable to properly function with time. It is estimated that the lifetime of silicon-based PV modules is between 20-25 years and afterwards it eventually necessitates appropriate and proper disposals and decommissioning of solar PV components.

The global total amount of e-waste was reported as 41.8 million tonnes in 2016, while the world's cumulative PV waste was only 2.5 million tonnes, proportionating only 0.6% of total e-waste (Sharma et al., 2019). However, the contribution of PV waste module will consequentially increase in the forthcoming years. Two major international organizations, International Renewable Energy Agency (IRENA) and International Energy Agency (IEA), have estimated the current and future trends of the generation of PV waste by depending on the growth rates of world PV. IRENA's renewable energy's roadmap is used to predict PV waste module by 2030, while IEA's Technology Roadmap on Solar Photovoltaic Energy is to forecast the PV waste between 2030 to 2050, respectively. Inside these reports, scenarios of early and regular losses are examined for analysis purposes. The scenario of early loss is comprised of failures of solar PV components, such as back-sheet cracking, broken cells, or glasses, etc. Within this scenario, PV module with safety failures will be regarded for renewal, whereas other defects, module dis-coloration or the loss of power output are not considered. In the scenario of regular loss, both early and initial losses are not included.

Baldé et al. (2014) emphasizes that in the scenario of regular loss, solar PV module's waste generation will be accounted for 1.7 million tonnes by 2030 and it will increase further and possibly extend to roughly 60 million tonnes by 2050. For the scenario of early loss, an enormous amount of PV waste will be generated during the forecasted years of 2030-2050 in comparison to the previous case. The aggregate generation of PV waste will be 8 million tonne in 2030 and 78 million tonnes in 2050, respectively. This distinction can be caused by the high percentage of PV module failure has been included in the scenario of early loss by comparing to the scenario of regular loss. The future generation of PV module waste will be between both scenario projections (i.e. early and regular losses).

According to the early case and regular case scenarios (from recent to 2030 and 2030-2050), Asia, Europe, and North America will generate the highest projected PV module waste. Nonetheless, Asia alone will share the proportion of 3.5 million tonnes of PV module waste, while Europe and North America 2 million tonnes and 1.1 million tonnes, respectively.

By 2030, among these three countries - China, India, and Japan - according to the future projection, the capacity of the installed solar PV in China will be the highest around 430 gigawatts, its maximum PV waste generation will be between 0.2 to 1.5 million tonnes, while Japan and India will follow by generating 0.2 million tonnes to 1 million tonnes and 0.3 to 0.5 million tonnes of PV waste, respectively.

For Europe, by 2030, Germany will share its installed PV capacity of 75 gigawatts, its projected PV waste will be between 0.4 to 1 million tonnes. Other European countries, Italy and France, will also contribute significantly in PV waste in the future.

For North America, the US will consist of 240 gigawatts of installed capacity of PV solar and will be the major contributor of PV waste in between 0.17 to 1 million tonnes by 2030. Other countries in North America, namely Canada and Mexico, will contribute 0.08 and 0.03 million tonnes respectively by that same year.

For other continents, Africa and Latin America, will also experience the growing of PV module waste generation in the prediction of the year 2030. South Africa and Brazil, with PV waste between 8.5 – 80K tonnes and 2.5 – 8.5K respectively, will be the significant contributors in PV waste. Other notable markets of PV module waste by this predicted year 2030 will be comprised of the Republic of South Korea and Australia, with PV waste generation of 25-150K tonnes and 30-145K tonnes, respectively.

Another scenario predicting from the year 2030 to 2050 also shows the result of China leading the world in generating the highest PV module waste, approximately from 13.5 – 20 million tonnes, followed by Japan, India and Germany, 6.5-7.5 million tonnes, 4.4-7.5 million tonnes, and 4.3 million tonne, respectively.

According to the projected PV waste, it is apparent that there are huge opportunities for establishing PV recycling industries across the world. Until now, there are only a few industries, who have expertise and competency in PV recycling plant establishment. Those countries are located in European Union (EU). For instance, Veolia, a giant waste management company, started operating a recycling practice plant in June 2018. This facility is expected to recycle 1,300 t of solar panel waste in the first year and up to 4,000 t by 2022. (Solar Quote, 2018). Another successful PV recycling project is located in Germany. According to the European Commission's Community Research and Development Information Service (August, 2018), a pilot solar panel recycling plant constructed in Germany has performed well. This pilot is conducted by a German engineering company Geltz Umwelt-Technologies under the ELSi project, which is an initiative of the EU. This facility can potentially process up to 50,000 solar panel per year (around 1,000 t of modules).

This process can reclaim 95% of materials from solar panels. According to the recent to 2030 and 2030-2050 scenarios of PV waste projections, there should be plenty of PV recycling industries established to deal with the enormous amount of PV module waste across the world.

1.3. The Literature

PV waste is a newly emerging issue generated by the solar PV industries. This issue has become a trend and attracted interests of many researchers around the world. The following is from the previous literature on PV module studies.

Operation and Production Phases of Solar PV

Scholars whose interests are on PV solar, tend to conduct their studies on the environmental impacts of energy technology during PV solar energy production.

Tsoutsos et al. (2005) studies on the environmental impacts from the solar energy technologies including PV, solar thermal and solar power using Environmental Impact Assessment. Their analysis demonstrates the prospective burdens to the environment, which include during the construction, installation and demolition phases, intrusion of noise and visuality, emissions of greenhouse gas, oil and water pollution, energy consumption, labor accidents, impact on archaeological sites or on sensitive ecosystems, negative and positive socio-economic effects.

Chen et al. (2016) conduct a study by assessing the environmental impact of monocrystalline silicon solar PV cell production in China. They evaluate the environmental burden, identified key factors, and explore approaches for potential improvement on the environment. The results indicate that the impact generated from the classifications of marine eco-toxicity, metal depletion, and human toxicity significantly contribute to the inclusive environmental burden due to glass consumption, silver (Ag) paste and electricity. By comparing with the coal-reliant electricity generation that utilizes ultra-supercritical technology, the environmental payback time in marine eco-toxicity, metal depletion, and human toxicity classifications are relatively high due to the direct air emissions of nickel, copper, mercury, arsenic, silver, and lead. Furthermore, the use of PV systems in areas of high solar radiation values has a significant potential environmental benefit from the PV systems.

Laleman et al. (2011) use six different LCA methods to figure out if the high cost of subsidy can be justified by the environmental benefits. The results show that PV systems have a relatively low environmental impact, even in regions with low solar irradiation, especially when compared to fossil-based energy sources. The light time energy production is at least 4 times and possibly 6 times higher than the lifetime energy consumption.

Rather than focusing on the subsidy cost, Bogacka et al. (2017) study on an environmental impact of PV cell waste scenario using LCA and they included three parameters into their study: efficiency, composition, and surface area. LCA analysis indicates that the negative impact of PV cell production on environment is twice lower than the environmental relief associated with the substitution of electrical energy produced in a coal-fired power plant. The production of PV panels incorporates with the usage of plenty of chemical materials and emissions are not neutral environmentally. They continue to conclude that PV cannot be considered as zero-emission technology. Their study also shows that the environmental relief caused by raw material recycling recovery and transportation processes are fairly small.

Srinivasan & Kottam (2018) focus on the environmental impacts of solar PV module production, use, and disposal. They also estimate the goodwill capital implanted in market evaluations of the 9 publicly listed firms of PV module manufacture. These goodwill scores are associated with the solar scores awarded by the Silicon Valley Toxics Coalition. The connection between such scores and the generated goodwill capital seems to be weak and inconclusive. The study also discovers no significant correlation between long-term capital revealed by these firms' managers, the environmental impacts of their processes and the goodwill generated among investors. Informing investors of the variants of solar PV technologies, and of the range of potential environmental consequences, could help internalize appropriately risks and rewards.

Muteri et al. (2020), review the hotspot issues in an environmental perspective, major parameters and methodological insights through the analysis of LCA studies of PV system, from the first to third generation. Their literature review indicates an equitable availability of LCA research work relevant to PV solar cells, particularly about third generation technologies. It reveals how the major aspects, such as the efficiency, the geographical location, the variety of PV cells, the technology utilized for PV production, the analysis of supplementary parts, the End-of-Life (EoL) stage (considering materials and recycling components), together with the distinguished methodological aspect picked by the LCA analysts, affects the results of different studies.

Rashedi & Khanam (2020) focus on the beginning-to-end of the four world's most used solar PV power generation technologies: mono-crystalline silicon (mono-Si), multi-crystalline silicon (multi-Si), amorphous silicon (a-Si) and cadmium telluride (CdTe). LCA method, ReCiPe, is used to evaluate which type of solar PV can generate more environmental impact during their energy production. As a result, CdTe maintains the lowest life-cycle impact value followed by multi-Si, a-Si and mono-Si PV technologies. Additionally, all the four PV technologies undertake the most negative impact to the damage classification of human health, followed by resources and ecosystems.

Impact of PV Module Recycling

Çağdaş Gönen & Elif Kaplanoğlu (2018) present environmental benefits and economic recoveries of recycling photovoltaic module in Turkey. They conclud that PV modules are renewable in terms of their production of energy, but are not properly managed when they reach their end-of-life period. Economically, recycling can be a positive gain for a country like Turkey. Since it is an EU candidate, it is presumed to construct its environmental, economic, and civil infrastructure to become a powerful and developed country. Furthermore, as one of the major EU suppliers for raw materials and semi-finished goods, low-price products would positively affect the producers to change their suppliers. With the recycled glasses and metals, Turkish producers can minimize costs of their products, so the prices for supplying their products into the EU market and the long-term strengthen the country's power of competition and development. Environmentally, if recycled materials are widely reused for producing PV modules, carbon emissions can be decreased and climate change effects can also be positively and gradually altered.

Lunardi et al. (2018) also conduct a review on recycling processes for PV modules. This review summarizes the potential PV recycling processes for solar modules, which include c-Si and thin-film technologies. The current processes, motivation, and legislation were also mentioned. They addressed that c-Si modules' recycling processes can result in a net cost activity comparing to the landfill by avoiding the true costs of the environment and potential externalities, but those processes can guarantee the sustainability of the supply chain in the long-run, increase energy and material recovery whilst decreasing emissions of CO_2 and energy payback time (EPBT) for the whole industry of PV. The current recycling methods can be unprofitable, but it does not necessarily mean that they should be ignored. The PV module waste management consists of potentialities to initiate new pathways for industry development and provides employment prospects to investors in public and private sectors. It is significant that specific regulation/legislation is instituted for the management of PV waste and recycling and this step is provided in advance of the amount of waste from EoL PV modules becomes frighteningly increasing as 2030 and 2050 projections. Legislation will be useful, but it is not the only option. The economic feasibility should be as well accomplished. If a recycling process for PV waste can run smoothly with positive revenues, then it will happen whether or not the legislation is in place.

Eskew et al. (2018) quantifies the environmental burdens created by a rooftop PV solar installed on one university's campus in Bangkok, Thailand, and models the potential of rooftop solar to comply with the country's goals of renewable energy. Life Cycle Assessment (LCA) is used for the evaluation and recommendations have been created for upstream purchasing decisions according to various scenarios. The results show that major contribution to impacts occurs in manufacturing by stage and from PV modules by component. Impacts generated by the mounting structure and inverters are also important, and simultaneously these elements constitute over 90% of environmental burdens. Local production of components and recycling of materials is determined as a best-case scenario, with alleviations across all impact categories. The economic analysis suggests on-site electricity consumption paired with a net-metering policy scheme is the best way to incentivize PV solar energy installations.

Faircloth et al. (2019) shed light on the environmental and economic paybacks that could materialize from recycling solar panels. They compare the environmental impacts of landfilling of end-of-life crystalline silicon panel with two distinctive recycling methods. With this comparison, they found that landfilling of solar panels, besides from the depletion of metals, does not pose a prominent environmental burden. Nonetheless, the burdens which can be steered clear by recovering materials from the panels are more substantial than the burdens from the fuel and energy that it requires to collect, disassemble and recover them. The results indicate that recycling c-Si PV waste is beneficial environmentally and has the potential to become economically plausible.

Cyrs et al. (2014) use a screening-level risk assessment tool to estimate possible human health risk associated with disposal of CdTe panels into landfills. Until recently, there is no published quantitative assessment of the potential human health risk relevant to the leaching of cadmium from cadmium telluride (CdTe) PV panels disposed in a landfill. They also try to contrast the potential high risks from PV panel disposal in landfills to those from PV panel recycling. The results demonstrate that a potential risk comparison cannot be done yet by this time. Relying on the human health risk estimation generated for PV panel disposal, their assessment showed that landfill disposal of CdTe PV panels does not raise any danger to human health at the current amount of PV waste production, though they indicated the significance of the management of end-of-life PV panels.

Tao & Yu (2015) investigates three kinds of recycling pathways which include waste recycling, disposed module remanufacturing and recycling. The results indicate that recycling technologies for PV manufacturing wastes and end-of-life modules are wildly explored and some are available commercially, though some challenges still exist in the efficiency process, reduction in process complexity, energy requirements, and use of chemicals. Some research has been conducted on remanufacturing and reuse of PV modules. The ease-to-disassembly design can possibly enhance the reusability of valuable components. The results also indicated that PV module manufacturing waste recycling and end-of-life module recycling have significant positive impacts on the reducing environmental burdens, economic viability of PV module recycling is still unfavorable and policies are required to encourage producer responsibility not only in the PV manufacturing sector, but also in the entire energy industry, and an efficient collection network should be important to the economic viability of PV module recycling business.

Agathe Auer (2015) concentrate on decommissioning and recycling PV module. He conducts his studies by investigating the benefits received by PV significant stakeholders, such as power plant owners, manufacturers, and governments. His study indicates that the major benefits for manufacturers to recycle are image enhancement and profit maximization. By adding a strategy of recycling into the process of manufacture, this practice can increase competitiveness with PV business. He suggests that to raise awareness for PV waste, it is recommendable to include PV modules' decommissioning time into Giant Charts which can possibly convince PV owners to buy modules that can be recycled after they reach their life span. Like many other researchers in the previous studies, Auer foresees that the future key development is to see recycled materials to be reused for new PV products and substituting materials that can harm human health as well as the environment.

Xu et al. (2018) review the world status of PV solar waste. They attempt to provide a quantitative basis to support the PV panel recycling and to suggest future PV waste management guidelines for public policy makers. Presently, they find that from the technical point of view, the research on solar panel recovery is still confronting with many issues and further development of non-toxic and economically feasible technology is required. They also discover that the management of solar PV at the end-of-life is starting in many countries, but there is still a demand for further extension and advancement of producer responsibility.

Sharma et al. (2019) review policies/guidelines specifically on three different continents: European Union (EU), Asia, and Africa. As for the review and PV waste speculation, from recent to 2030 and 2030 to 2050, Asia will be the top continent to produce PV waste following by EU and Africa, although the amount of PV waste in Africa is not quite significant and not an alarm yet. Among countries in the three continents, only countries in EU, Germany and France, take the initiative to include the management and collection of PV module waste by complying with the Waste Electrical and Electronic Equipment Directive (WEEE Directive).

The majority of the above-mentioned solar photovoltaic (PV) studies lie in the review of global guidelines/policies, operation and production phases with the emphasis on energy requirements of these processes indicating a significant contribution to environmental impacts.

The evaluation on countries' PV solar waste project by addressing strengths, weaknesses, opportunities and threats is still limited among the PV waste studies.

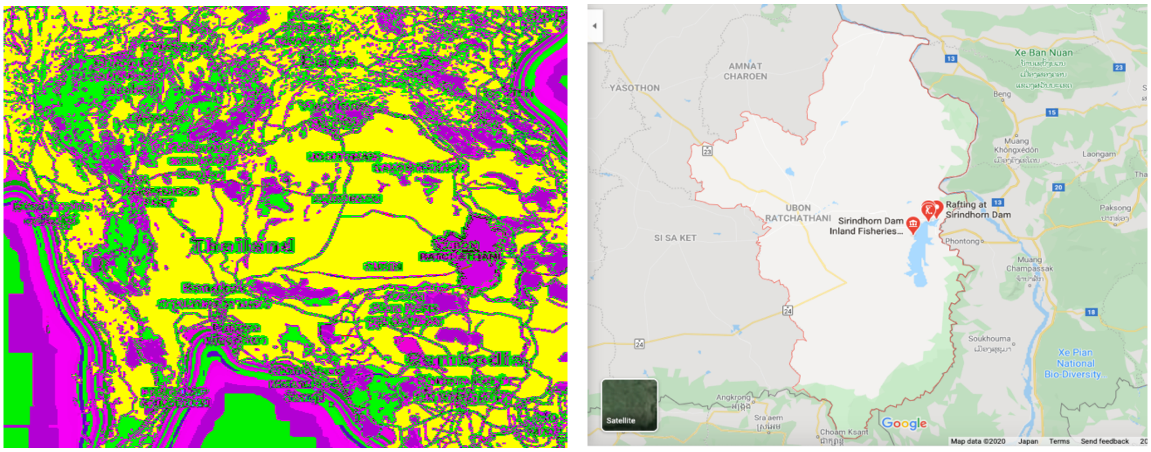
1.4. Objectives of the Thesis

PV waste management is like any other waste management which involves disciplines that are aligned with control of generation, collection, storage, transfer, transport, or disposal in a way that most advantageously addresses the aesthetics, conservation, public health, economics, and other environmental deliberations (LeBlanc, 2017). With this regard, the management of PV waste requires many elements to consider in order to ensure the safe and sufficient practice in Thailand as well as other countries around the world. Those elements include economic, political and social considerations which are needed to be involved in this study analysis.

In this thesis, 2 SWOT analyses of two countries, Thailand and China, will be compared in order to find similarities and differences of their floating solar projects and seek for better policies/practices for the end-of-life PV of the projects. China is another country chosen to compare in this context due to its capacity of solar PV usage and will be the biggest contributor of PV waste in the coming decades. Hence, it is crucial to compare Thailand, a newly emerging country in installing PV solar nationwide and capture the positive lessons from China to be absorbed and implemented in its own country.

Chapter 2 Research Sites

2.1. Sirindhorn Dam, Thailand



Source: Google Earth

Sirindhorn Dam is located in Sirindhorn District, Ubon Ratchathani province, easternmost of Thailand and nation's leading rice-producing province earning more than 10 billion baht annually from selling rice. Sirindhorn dam is one of Thailand's largest bodies of water, laying from north to south for more than 50 km, with a width of around 15 km at its largest point. Its reservoir's area consists of 288 km^2 with a storage capacity of 1,966.5 million m^3. The dam was built across the Lam Dome Noi River and is owned by the Electricity Generating Authority of Thailand (EGAT). It, then, has been commissioned to serve as a facility of hydropower and irrigation supply source since 1971. Electricity generated by this dam is intended for local demands.

Photo: Sirindhron Dam, Source: EGAT Official Website

Sirindhorn Solar Cell's first project was started in 2007 and completed in 2009. This plant takes up to 25 rai (4 hectares) of water surface with the number of 7,476 installed solar cells and a total electric capacity of 1.012 MW. Two different systems of solar panels have been installed: fixed and solar weight tracking systems. The electricity generation by these solar panels can replace the consumption of bunker oil about 348,000 liters per year which reduces the emissions of CO_2 up to 851.1 tonnes per year.

Photo: 1 MW Solar Plant, Source: Siam Cement Group Chemicals

In January 2019, EGAT announced that the first 45 MW floating solar hybrid project is to be installed in Sirindhorn Dam as well. This project is a Thai-Chinese consortium which contract has been signed to construct the world's largest hydro-floating solar hybrid. This project notably originates synergy between solar and hydropower which represents a significant step in the green energy development and also resolves an uncertainty of electricity supply from renewable energy in the country.

Photos: Hybrid Floating Solar Farm, Source: EGAT's Official Website

Both of this hybrid hydro-floating solar and the aforementioned solar power plant generate power during the day from sunlight under the output control of the Energy Management System (EMS), allowing uninterrupted generation of electricity which improves the reliability of the overall power supply of Thailand.

The solar panels chosen for the hybrid project are crystalline double glass module claimed to reduce 47,000 tonnes of CO_2 per annum (EGAT, 2020). The installation area of the surface water is 450 rai (72 hectares) by sharing facilities with the existing systems, such as transmission, transformers, and high-voltage substations, and can supply up to 18,200 households (EGAT, 2019) According to EGAT director of Hydro & Renewable Energy Power Plant Development Division, Mr. Chatchai Mawong, this project is 66% complete and planned to open for commercial use around the midst of 2021.

2.2. Lianghuai, China

Laignhuai used to be a coal mining area in the city of Hauinan, Anhui Province, China, until it was abandoned when it was overexploited, collapsed, and finally flooded. It should be noticed that half of the world's coal is consumed by China every year (International Energy Agency, 2018) making China's the top coal consumer in the world. Burning coal for decades contributes economic success to China, but also brings back with enormous costs of health and environment. The emissions of organic chemicals, toxic trace substances, and particulate matter from the incomplete combustion of the coal leads to serious health damage, such as lung cancer in women and black lung disease among miners (Finkelman and Tian, 2018). Coal combustion also release greenhouse gases in the atmosphere which substantially results in climate change (Liu et al., 2015). Consequentially, while the air quality in China is so toxic, about 17% of total deaths or 1.6 million deaths every year are caused by the air pollution this country (Pouran, 2018).

In 2014, a Chinese Premier, Li Keqiang, announced China's war on pollution, "We will resolutely declare war against pollution as we declared war against poverty" (Pouran, 2018). A year after this declaration, Chinese government formally began implementing its revised Environmental Protection Law (EPL) with the hope of sustaining its economic growth through a clean energy. That is how floating solar farms on flooded coal mine areas started.

In 2017, the world's largest floating solar plant was officially put into an operation in Lianghuai, a mining subsidence in Huainan city situated in the north-central of Anhui province, China. This project is operated by China Energy Conversation and Environmental Protection Group (CECEP), a state-owned energy cooperation and a renewable energy project developer.

Lianghuai solar plant's surface is 63.6 hectares, floated on the 148.4-hectare, a total flooded area surface. This plant consists of 194,700 solar panels with electricity's generated capacity of 70MW (Pouran, 2018). The electricity generated from this plant can supply more than 21,000 households.

Altering from coal mines to floating solar farms indicates how China is working toward sustainability and literally in a battle against pollution, which is one of the worst killers that take lives of hundreds of thousands of people annually (Pouran, 2018).

Lianghuai Area in 2012 & 2015 (Source: Google Earth)

Lianghui Area in 2016, 2017 (Source: Google Earth and Pouran, 2018)

Chapter 3 Floating Solar PV Technology

3.1. Overlook

There are 5 types of solar PV applications: ground-mounted, roof-top, canal-top, offshore, and floating (Nguyen, 2017). The following table lists a comparative advantages and disadvantages of the different solar PV installations

Applications	Advantages	Disadvantages
Ground-mounted	- Suitable for small and large-scale systems - Easy to operate and maintain	- Limited land resources in urban areas - Solid foundations and stable structure required to protect from storms and high winds - Longer construction time needed for civil works
Rooftop	- Space optimization by utilization of rooftop areas - Increases the lifetime value of covered roof	- May have shading losses due to structure obstacles - Roof may not properly fit to the required system capacity

	- Easier and faster to install than ground-mounted systems	
Canal	- Land conservation - Save canal water from evaporation - Higher module efficiency compared to land-based systems due to water cooling effect by evaporation	- Lack of availability canals - Complicated and lengthy structures to accommodate modules - Difficult for maintenance - Panels, structure etc. may lead to contamination issues of fresh water
Offshore	- Reduce the land dependence - Higher module efficiency compared to land-based systems due to water cooling effect by evaporation - Almost no shading effect	- Erosion of PV panel caused by seawater may require higher panel cost - High maintenance cost required
Floating	- Land conservation - Reduction of water evaporation - Improved water quality by reducing photosynthesis and algae growth	- Potential erosion of PV components - Obstruction to fishing and transportation activities

Source: Alok Sahu, Neha Yadav, K. Sudhakar (2016)

Floating PV system, in particular, is a newly developed technology that is designed for areas that are crowded with overpopulation or lack of land. Its system is comprised of four main components: underwater cables, mooring system, floating system, and the PV system.

- Underwater cables: Transfer the generated power from land to the PV system
- Mooring system: Can adjust to water level fluctuations while maintaining its position in a southward direction
- Floating system: a floating body, including floater and structure, allows the PV module installations available
- PV system: PV generation equipment are PV modules installed on the top of the floating system, inverter, controller, substation and distribution line

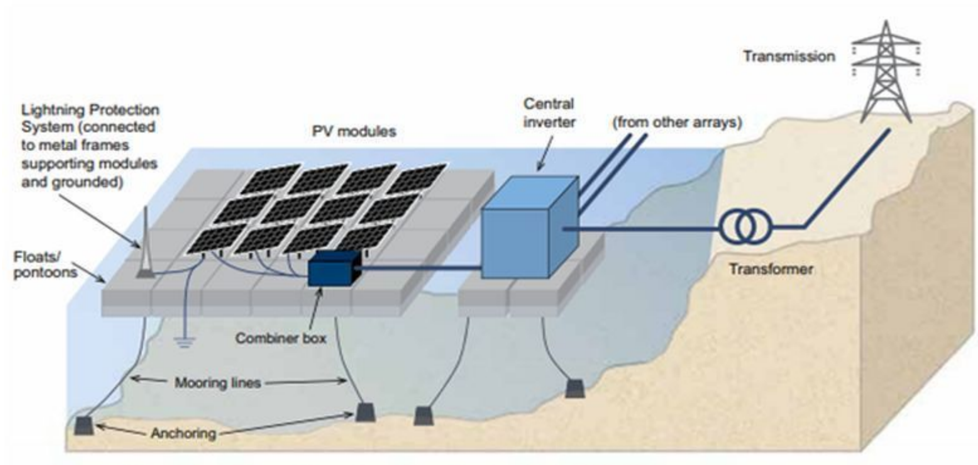


Figure 1: Layout of a Floating PV System
(Source: Solar Energy Research Institute of Singapore at the National University of Singapore)

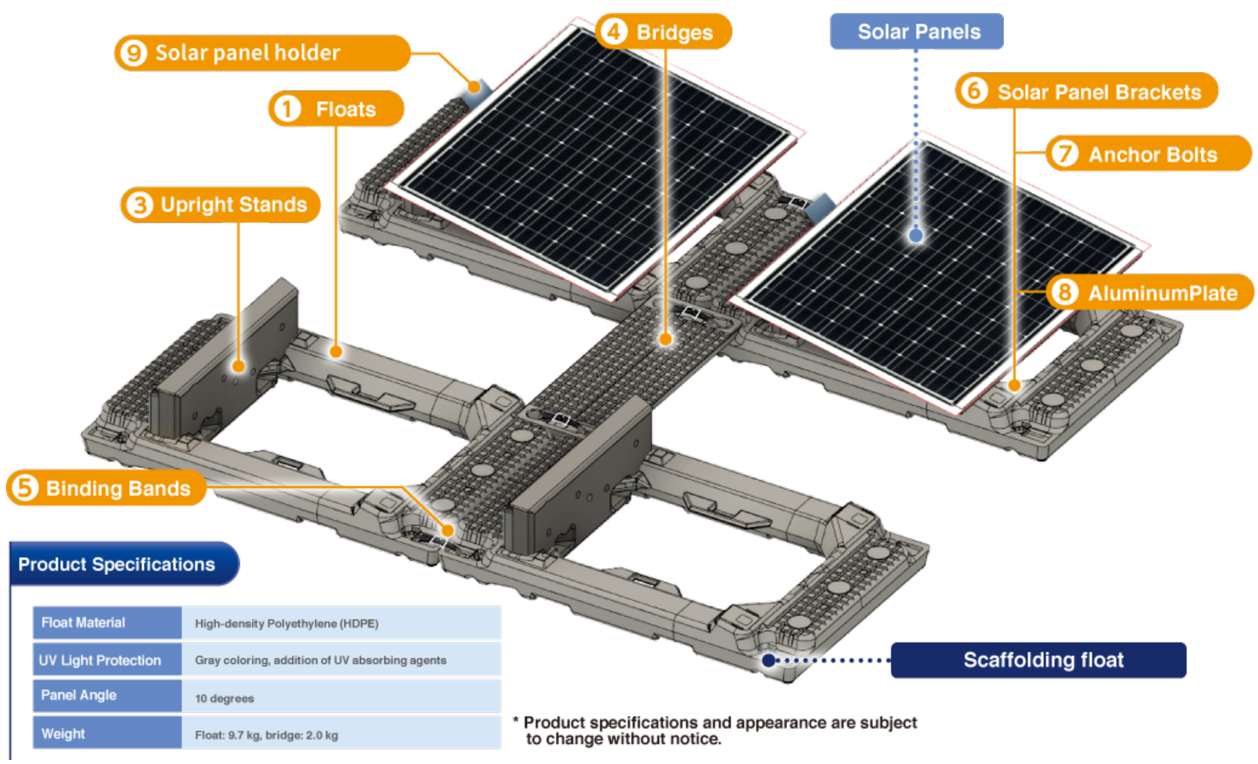


Figure 2: A Sample of Floating PV Product by Sumitomo Mitsui
(Source: https://pv-float.com/english/)

Figure 3: Floating PV System Overview
(Source: https://pv-float.com/english/)

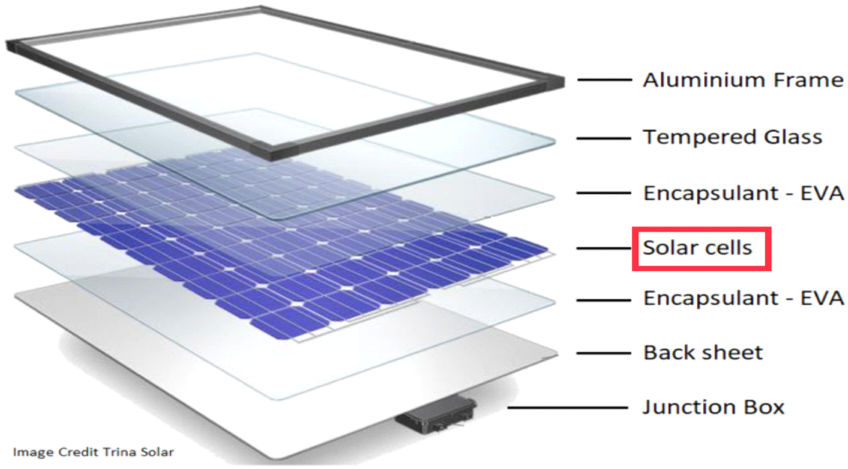


Figure 4: PV Components

3.2. End-of-Life PV

PV Waste Classifications

Solar PV panels, with a life span between 25-30 years, generate unique challenges when it comes to manage their end-of-life ones. Besides EU, the treatment of end-of-life PV requires all countries around the world to establish waste regulations dedicated on PV rather than considering it as regular waste.

Waste regulations depends on waste classification. Such classification is created due to waste composition specifically concerning any part deemed dangerous to the environment. Waste classification tests ascertain authorized and banned shipment, treatment, recycling, disposal pathways (IRENA, 2016). Therefore, it is crucial for every government to design the waste classification that is appropriate and suitable to implement safe waste management practice in their countries when it comes to managing end-of-life PV.

Table 1 Market Proportion of PV Panels classified by groups (2014-2030)

Technology		2014	2020	2030
Silicon-based (c-Si)	Monocrystalline	92%	73.3%	44.8%
	Poly- or multicrystalline			
	Ribbon			
	a-Si (amorph/micromorph)			
Thin-film based	Copper indium gallium (di)selenide (CIGS)	2%	5.2%	6.4%
	Cadmium telluride (CdTe)	5%	5.2%	4.7%
Other	Concentrating solar PV (CPV)	1%	1.2%	0.6%
	Organic PV/dye-sensitised cells (OPV)		5.8%	8.7%
	Crystalline silicon (advanced c-Si)		8.7%	25.6%
	CIGS alternatives, heavy metals (e.g. perovskite), advanced III-V		0.6%	9.3%

Source: International Renewable Energy Agency (IRENA, 2016)

To accomplish optimal waste treatment for various PV product classifications, the composition of PV panels requires to be considered. PV panels can be categorized as shown in Table 1. The distinctive types differ according to the materials used in their production and may contain different levels of hazardous elements that must be considered during treatment.

PV Waste Management Alternatives

Rather than waste regulations in general, different approaches have been specifically established for managing end-of-life PV panels. The following sections provide a summary of general principles of PV waste management together with examples demonstrating voluntary, public-private-partnership and regulated approaches.

Waste Management Principles for PV Panels

Life Cycle Methodology

All approaches of waste management follow the life cycle phases of a specific product.

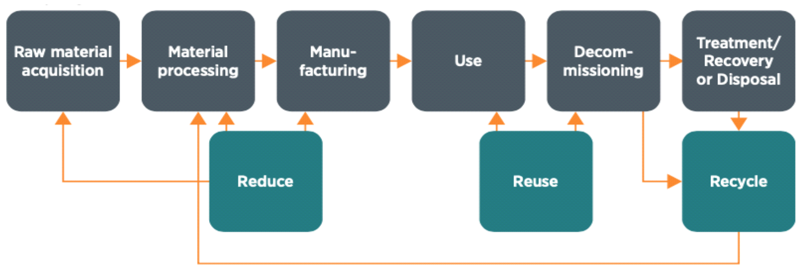


Figure 5: Diagram of a Process Flow of the life cycle phases for PV panels and generating opportunities for reducing, reusing, or recycling (Fthenakis, 2000); Source: IRENA (2016)

Stakeholders and Responsibilities

The responsibilities for end-of-life waste-management activities downstream (waste generation, collection, transport, treatment, and disposal) are generally involved by the following major stakeholders:

- **Society:** End-of-life management is supported by society, with government organizations in charge of managing and controlling operations, financed by taxation. This may generate revenue for municipalities and eliminate the fixed costs of building a new collection infrastructure while maintaining economies-of-scale benefits. Downsides may include a lack of competition and slower cost optimization.

- **Consumers:** The consumer that produces panel waste is responsible for end-of-life management, including the proper treatment and disposal of the panel. The consumer could try to minimize costs, which can contain a negative effect on the development of proper waste collection and treatment. Since the producer is not involved, there might be less motivation to produce recyclable and 'green' products. Currently, this approach remains the dominant framework in most countries for the management of end-of-life PV panel.

- **Producers:** The management of end-of-life PV is based on the extended-producer-responsibility (EPR) principle. This holds producers financially and physically responsible for the environmental impact of their products through end-of-life and provides incentives for the development of greener products with lower environmental impacts. This principle can also be used to create funds to finance sound collection, treatment, recycling, and disposal systems. Although producers are responsible for financing the waste management system, the additional cost can be passed through to consumers in the form of higher prices.

Costs and Financing

A decision has to be made on which of the three stakeholders abovementioned (society, consumers, producers) to take financial responsibility for end-of-life management. All approaches of waste management which includes e-waste, associate with incurring costs. This is equally accurate for end-of-life PV panel management. The costs can be broken down into the following three interconnected systems outlined below:

- A physical system of collection, storage/aggregation, treatment, recovery, recycling, and disposal: This system collects PV panels, for example, from separate waste generation locations and transfers them to a more central site where first-level treatment can begin. After this phase, which normally separates the waste product into material sorts (e.g. glass, metals, mixed plastic, etc.), further processing of the different material streams is necessary for recovery and recycling. This step removes potentially dangerous impurities and materials from recycling materials because they prevent recycling. Eventually, the disposal of non-recoverable, non-recyclable fractions is also required to be taken care of in the physical system. The costs of operating these physical systems are a function of several factors, which include the geographical and economic context, the selected number of collection and processing locations and the complexity of dismantling and disassembly processes (first-level treatment). A final factor is the value/costs involved with final processing of the different material streams of recycling or disposal.

- A financial processing system: This system counts the volumes of varieties of materials recovered from the process of recycling and the involved revenues and costs to the system.

- A management and financing system: This system accounts for the overhead costs of operating an e-waste system of PV panels, for instance.

To provide the financial foundation for recycling end-of-life products, serval fee models have been initiated and implemented globally. Part of these fees is put aside to finance the system of waste treatment when end-of-life products are transferred to the collection points operated by municipalities, dealers, wholesalers, producers, or their service providers. The fees are normally structured to follow several principles to ensure they are fair, reasonable, based on actual program costs and include regular revisions:

- The funds generated from the fees collected should cover the system costs and accomplish clear environmental goals.
- The fees should be a function of the return on investment, technical and administrative costs. The revenues generated from the collection, recycling, and treatment fees should be sufficient to cover the costs of implementation.
- The fee structure should be implemented without rendering the PV sector uncompetitive with international markets. Social care should be taken to avoid free riders.
- The fee structure should be simple to implement.

- The fee structure should be viable for the PV products covered by the regulation.

Table 2: Financing Models for Collection, Treatment, Recovery, Recycling, and Disposal of PV panels

Producer-financed compliance cost	Consumer-financed upfront recycling fee
Under this model, the producer finances the activities of the waste management system by joining a compliance scheme and paying for its takeback system or stewardship program. It covers two sorts of wastes. The first is orphan waste (from products placed on the market after implementation of the waste management system by producers that no longer exist and cannot be held liable). The second is historic waste (waste from products placed on the market before the waste management system was established). The costs are generally shared between producers. All costs are revised regularly and charged per panel or weight based on the actual recycling costs and estimates of future costs.	This fee is paid to collect funds for the future end-of-life treatment of the product. Consumers pay the fee at the time of the purchase of the panel. The fee is set according to estimates for future recycling costs but many also be used to offset current recycling costs.
	Consumer-financed end-of-life fee (disposal fee)
	The last owner pays a fee for the collection and recycling costs to the entity in charge of the recycling of the end-of-life product.

Source: IRENA (2016)

The implementation of these different financial approaches can vary considerably from country to country owing to different legal frameworks, waste streams, levels of infrastructure maturity, and logistical and financial capabilities. In most countries, with e-waste management systems, a combination of the producer-based and consumer-based approaches is incorporated into the compliance scheme (e.g. in the EU). Nonetheless, each such scheme should be adapted to the unique conditions of each country or region.

Enabling Framework

Adjusting or developing an end-of-life management scheme for PV panel waste requires the balancing of a number of factors, namely collection, recovery, and recycling targets. These three targets become the main driver of waste management policies. Waste management schemes or approaches require to consider different alternatives for collection systems (e.g. pick-up versus bring-in systems). They also require to consider the nature and design of products to manage end-of-life and recycling processes adequately (e.g. PV panels are often classified as e-waste). Therefore, waste management also leads naturally to a motivation to change the design of products themselves in favor of easier waste treatment, for example.

- **Voluntary approach:** Producers often depend on their internal environmental management systems to organize all their company's environmental responsibilities, including the end-of-life of their products or services. One example is found in the International Standards Organization ISO 14000 family of international standards on environmental management. ISO 14040: 2006 specifically deals with the principles and framework for life cycle assessment of a company's products and operations (ISO, 2006). Within this or other frameworks, some PV panel manufacturers have established individual voluntary takeback or product stewardship programs that allow defective panels to be returned for recycling on request. The management of such programs can be borne directly by the company or indirectly through a recycling service agreement outlined in more below details:

- ◊ **Direct management:** the manufacturer operates its own recycling infrastructure and refurbishment or recycling programs to process its own panels, enabling it to control the entire process (e.g. First Solar, 2015).

- ◊ **Indirect management:** the manufacturer contracts service providers to collect and treat its panels. Different levels of manufacturer involvement are possible based on the contract details.

In the indirect management option, producers could outsource part or the entire management and operation of their recycling programs to a third party. The members of such an organization can be entirely producers or can also include a network of government entities, collectors, or recyclers. As another option, it can be a single entity established by the government to manage the system. The activities carried out by third-party organizations and other compliance schemes can vary from country to country and based on specific legislative requirements and the services offered to members.

- **Public-private approach:** Established in 2007, PV CYCLE is an example of a voluntary scheme that includes both a 'bring-in' and 'pick-up' system based on the principle of a public-private-partnership between industry and European regulators. The association was established by leading PV manufacturers and is fully financed by its member companies so that end-users can return member companies' defective panels at over 300 collection points around Europe. PV CYCLE covers the operation of the collection points with its own receptacles, collection, transport, recycling and reporting. Large qualities of panels (currently more than 40) can be picked up by PV CYCLE on request. In some countries, PV CYCLE has established co-operatives and it encourages research on panel recycling. PV CYCLE is being restructured to comply with the emerging new regulations for end-of-life PV in the different EU member states (PV CYCLE, 2016).

- **Regulatory approach:** The EU is the only jurisdiction that has developed specific regulations and policies addressing the end-of-life management of PV.

Chapter 4 Value Creation from End-of-Life PV Panels

Chances for value creation exist in each part of the PV value chain, which includes the end-of-life stage. The following gives an overview of value creation opportunities associated with reductions in material use, choices for repair and reuse and lastly recycling and treatment deliberations for end-of-life PV panel. In the first segment, PV panel recycling is assigned in the context of renown waste-reduction principles: reduce, reuse, and recycle. The second segment explains how socio-economic and environmental value is acquired from end-of-life PV panels.

4.1. Opportunities to Reduce, Reuse, and Recycle PV Panels

The framework of a circular economy and the typical waste reduction principles of 3Rs (reduce, reuse, and recycle) can be used for PV panels. The preferred alternative among the two is the reduction of material in PV panels resulting in increasing in efficiency. Strong market growth, shortages of raw materials and downward pressure on prices of PV panels are allowing more efficient mass production, reduced material use, material substitutions and new and more advanced technologies. This functions towards decreasing materials use per unit of generation. The reuse alternative follows the reduce alternative. This covers distinct repair and reuse modalities. Recycling is the least preferred alternative (besides from disposal) and only occurs after the first two alternatives have been exhausted. It generates for the processing and treatment of PV panels and can create raw materials for manufacturing new PV panels or other products. (see Figure 6).

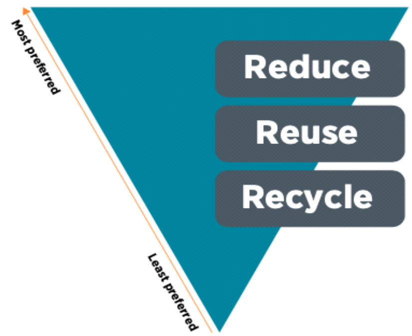


Figure 6: Preferred Alternatives for PV Waste Management (Source: IRENA, 2016)

PV panel material savings through R&D (reduce)

This segment includes a projection of changes in PV panel composition between currently and 2030. The below analysis gives summary of potential "reduce" alternatives for the material components used in distinct PV technologies.

The material mixture within PV panels has not significantly altered in the past. Nonetheless, considerable material savings have been accomplished as a consequence of increased resource and material efficiency. For example, materials savings and even substitutions have been and are maintaining to be researched for selenium, cadmium, and lead, so that the quantity of hazardous materials can be decreased. For other materials used for different technologies of PV panels, research predominantly concentrates on minimizing quantity per panel to save costs. Since the total consumption of valuable and rare materials will increase as the PV market grows, prices and availability will drive reduction and substitution efforts. Contemporary studies agree that the availability of PV materials is not a main concern in the short term although crucial materials may impose limitations in the long run. Additionally, increasing prices will enhance the economics of recycling activities and drive investment for more efficiency in mining processes. This comprises the metal extraction in PV manufacturing process, such as tin, copper, silver, and aluminum (IRENA, 2016).

PV R&D has specifically prioritized topics for material use reduction or substitution for distinct components usually use in current PV panels including for:

- c-Si panels: glass, polymer, silicon, aluminum, silver, lead, and others;
- CIGS panels: glass, polymer, aluminum, cadmium, gallium, indium, selenium, and others;
- CdTe panels: glass, polymer, cadmium telluride, nickel, and others.

Moreover, considerable R&D is concentrated on new materials and material replacements. The following is an explanatively set:

- **Indium:** New transparent conducting oxide layers incorporating more plentiful and thus cheaper compounds like fluorine doped tin-oxide can replace indium-tin-oxide as front electrodes. This reduces the use of indium in indium-tin-oxide available in some thin-film PV technologies as transparent conducting oxide.

- **Glass:** Additional optimization of glass composition, thickness, anti-reflective coating and surface structures will increase the transmission of the front glass panes by another 2% by 2024. The use of glass two millimeters thick or even less in a single-pane laminate will require further mechanical stabilization effort which might be achieved by double-glass panels with a thin encapsulation layer. These are proven constructions deployed for decades in thin-film PV panels and could lead to significant material reductions by substituting the need for a backsheet (IRENA, 2016).

- **Polymers:** Encapsulants and backsheet foils are not recycled today because the duroplastic materials that dominate the market cannot be dissolved or melted for recycling without decomposition. Research is figuring out at reducing or replacing the number of polymers, especially for backsheets that use a polyethylene terephthalate foil. They contain up to a few hundred parts per million of antimony used as polymerization catalyst (IRENA, 2016). For instance, the research project led by the Energy Research Center of the Netherlands and PV CYCLE (CU-PV) will develop and demonstrate options to current practices. One example is the use of thermoplastics, which are more convenient to separate, as encapsulant. Another is the elimination of encapsulant use together (IRENA, 2016).

- **Silicon:** Thinner cells can reduce the amount of silicon used in c-Si cells. For example, by moving to a back-contact cell design, the use of silicon could be reduced by half, and energy consumption could be cut by about 30% (IRNEA, 2016).

- **Silver:** About 95% of c-Si solar cells are now produced with screen-printed silver contact lines on the front side covering roughly 6%-8% of the cell area. A significant reduction of silver on cells is expected by 2018 according to International Technology Roadmap for Photovoltaic (ITRPV) study owing to recent progress in inkjet and screen-printing technologies. This allows the use of other metals like copper in combination with nickel and aluminum. Use of rear-contact or bifacial cells can help further reduce silver consumption per watt (W) by strengthening cell efficiency.

Diverse contemporary technologies for cells, backsheets, coatings and encapsulation materials have been implemented, resulting in over 50,000 panel types (Photon, 2015 and 2016). Tracking all materials for the purposes of waste treatment and recycling is challenging and will continue to be that way. Establishing world information flow systems with panel and material databases may facilitate the objective of long-term end-of-life management systems that minimize material recovery.

Repair of PV Panels (Reuse)

The majority of PV systems were installed in the last six years (from 15GW in 2008 to 222 GW in 2015), meaning that these have reached to an early loss of 20% of the anticipated average lifetime (30 years) today. If deficiencies are found during the early stage of a PV panel's life, customers may try to claim guarantees or warranties for repair or replacement provided the contract partner still in place. Insurance companies can be involved to compensate for some or all of the replacement/repair costs within the agreements of the contracts. In this case, the ownership of the panels usually changes to the insurance company. Most defective panels are therefore normally returned to the contract partner, a producer service partner, or the producer itself for examination and repair.

In order to retrieve some value from a returned panel via resale, quality tests have to be done mostly on power output and electrical safety. A wet leakage test and a flash test function is one illustration. When repairs can be both practical and needed, they usually involve applying to a new frame, a new junction box, diode replacement, new plugs and sockets, etc. Solar cells can also be substituted and panels get delaminated. This is close to the 'B-spec' and 'C-spec' qualities in panel products that may be sold into special projects or relabeled to another brand name in some cases in pre-marketing processes (IRENA, 2016). Consequently, the product is given a new label with a new warranty (in accordance with national laws).

The repaired solar PV panels can be resold as replacements. Otherwise, they can be resold as used panels at about 70% of an original market price of a new panel (IRENA, 2016). Partially, repaired parts or panels could be sold in a second-hand market. A low-key use panel market as already made an appearance, supporting by virtual internet platforms, such as www.pvXchange.com and www.secondsol.de (IRENA, 2016). Accompanied by more PV installed worldwide, such second-hand markets will soon increase, providing a market for their use.

According to the Weibull statistics applied to the PV forecast in IRENA report, a proportion of installed panels may remain whole even after 30 years, an average lifetime of the panels. If a PV system is taken apart after its average lifetime, these panels might be reused after a quality inspection and refurbishment. This establishes a great opportunity for an emerging secondary market of used panels and new repair service jobs in the future.

Panels which cannot be repaired or reused will be dismantled and after that transferred to local waste treatment companies for further processing according to local regulations (IRENA, 2016).

Decommissioning and Treatment of PV Panels (Recycle)

Dismantling and Disassembly

The sizes and types of PV systems installed contain significant implications for future waste management. For instance, the rapid growth of tremendously dispersed, small rooftop PV systems can add on more costs to disassembly, collection, and transport of end-of-life PV panels. In the contrary, the management for utility-scale end-of-life PV is logistically more convenient.

It is beneficial to differentiate scenarios for the collection of end-of-life PV panels due to size and geographical location:

- Home single-panel system (< 500 W), small rooftop (< 5 kW) and large rooftop system (>5 kW);
- Utility Scale (> 100 kilowatts – kW)

Since this study mainly focuses on the governments' installed PV systems, Thailand's 42 MW and China's 70 MW, only the scenario of utility scale will be discussed.

Utility-scale systems (> 100 kW) are typically ground-mounted, on which they are kept track and serviced regularly. Floating solar system, on the other hand, is a newly emerging technology created for floating on the water surfaces, such as ponds, dams, lakes, fish farms, canals, reservoirs etc. and this technology can be integrated with other facilities, such as irrigation, hydro power, water treatment and thermal power. The solar panels are typically kept on the floats, a buoyant body that lays above the water and also acts as a solar panel installation base.

Disassembly, packing, transport, and recycling can be conveniently contracted for parts of or the entire system. Disassembly and pick-up services for transport to the recycling facilities will often be defined during the contractor bidding processes and supervised and performed by skilled workers. The processes of tendering could include the whole disassembling of the plant or parts of it based on the intended use of the area afterwards. It can be assumed that comparatively high-quality standards will be applied in such a case. The parts of the PV plant will be separately stored: panels, cables, electronics (inverters, charge controllers, transformers, monitoring electronics etc.), metals (aluminum, steel), usually buildings and construction demolition waste etc. The quantities of the different waste are reasonably high and can easily be separately collected at a fair cost for transport to specialized recyclers or landfill sites. According to the local regulations, some parts – normally some batteries or power transformers – can be considered toxic or hazardous waste. Logistics costs may become decisive in takeback systems for PV panels in remote areas such as rural areas or islands.

Damage to PV panels should be avoided during disassembly, transport and storage to support well-constructed waste treatment with best available technologies and greatest possible results. Cables, junction boxes, and frames should not be removed during disassembly. These can require special attention for their secondary material value and possibly in line with local legal requirements.

Recycling

Currently, since only limited PV waste quantities exist on the world waste market, there are not adequate quantities or economic incentive to establish dedicated PV panel recycling plants. End-of-life PV, therefore, simply processed in existing recycling plants in general. In those plants, the mechanical separation of the main components and materials of PV panels is the core focus. This still accomplishes high material recovery by panel mass though some higher value materials (which are small-scale in mass) could not completely be recovered. This current approach provides legal compliance without the demand of investment for new PV-specific recycling facilities. Nevertheless, in the long run, establishing dedicated PV panel recycling plants may increase treatment capacities and maximize revenue due to output quality. Additionally, it may increase recovery of valuable components.

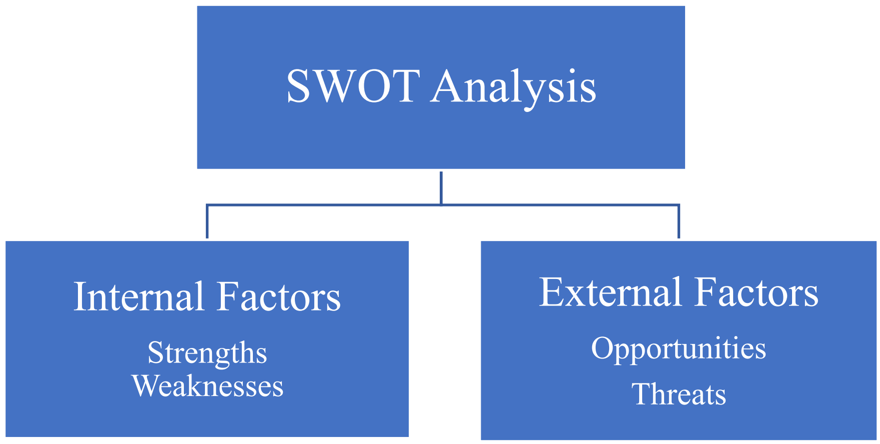
Recycling Crystalline Silicon (c-Si) PV Panels

The main parts of c-Si panels, which include aluminum, copper, and glass, can be retrieved at accumulative yields more than 85% by panel mass through an entirely mechanical separation. Without a combination of chemical, thermal, or metallurgical stages, impurity levels of the required components should be adequately high to reduce resale price.

Separation of the main parts of the panels, such as laminated glass, metal frames, wiring and polymer is the initial step in the first-generation and current recycling processes. Recycling the laminated glass part of c-Si panels is a reasonably low-cost process which flat-glass recycling companies can implement with just little more investment. This process works in batches to enable adjustment of parameters and is reckoned for the moderate quantities available for nowadays' process. Regular equipment for removing impurities, such as polymer (glue) residues or screws from the glass cullet, includes crushers, magnets, eddy-current devices, optical sorters, sieves, inductive sorters and exhaust systems. The remaining crushed-glass fraction, which can still be heavily contaminated with metals, silicon, and polymers, may be blended with other recycled glass as thermal insulating material in the glass-fiber or glass-foam industries. A blend composition which includes 15%-20% of PV panel glass is thereby achievable. Nonetheless, with the growing volume of PV waste streams, this market can become saturated, and investments in new technologies of recycling will be needed.

Chapter 5 SWOT Model

5.1. SWOT Framework



Source: Emet GÜREL & Merba TAT (2017)

5.2. Conceptual Framework

"SWOT Analysis is a simple but powerful tool for sizing up an organization's resource capabilities and deficiencies, its market opportunities, and the external threats to its future" (Thompson et al., 2007). The acronym SWOT stands for 'strengths', 'weakness', 'opportunities' and 'threats'. It assesses the internal strengths and weaknesses, and the external opportunities and threats in a project or organization's environment. The internal analysis is used to point out the resources, capabilities, core competencies, and comparative advantages built-in the organization. The external analysis spots opportunities and threats that either the other party outside of the organization would create or the organization itself that is the agent who make them happen. SWOT analysis' objective is to use the knowledge an organization possess about its internal and external environments and to establish its strategy accordingly.

5.3. Development and Applications

Originally, SWOT was created and used to in the field of business or market research for a product sale. However, as it evolves, this simple but powerful tool has been widely used in any fields ranging from social sciences to natural sciences, from practical to social policy research as well. For this thesis, SWOT has been chosen to evaluate the potential of solar PV in two different countries, Thailand and China, and how their SWOT can be used and dealt with in their floating PV solar projects.

5.4. Data Collection

This study uses two sets of data: primary and secondary data. For the primary data, 6 officials (1 from the head office of EGAT and 5 from Sirindhorn Dam, EGAT's branch) were interviewed. For Lianguai, China, the primary data could not be collected due to time limitation and global pandemic (COVID-19). For the secondary data, Thai government's documents, reports of public national and international agencies of Thailand and China, and previous research studies were reviewed and taken into data collection.

Chapter 6 Analysis, Results and Discussion

6.1. Sirindhorn Dam

Strengths

- Floating solar power generating systems typically generate more electricity than rooftop and ground-mounted systems due to water's cooling effect (Sudhakar, 2019).
- The platforms of floating solar systems are engineered and designed to resist the physical stress which includes storm and typhoon conditions (Sudhakar, 2019).
- Installations of a tracking Liquid Solar Array (LSA) reduce water evaporation and algae growth by shading the water (Sudhakar, 2019).
- Geographically, any water bodies with abundance of sunlight radiation can be used to install floating solar plants (Sudhakar, 2019).
- Located in Southeast Asia, Thailand has a great solar potential, especially the northern-eastern part of the country, which benefits from strong levels of solar radiation all year round. By comparing Thailand's radiation levels with other countries, Thailand has better potential than other countries in the region and only falls behind Australia and the United States (Netherlands Embassy in Bangkok, 2016).
- Thailand takes advantages of hydro and solar powers by building a 45MW floating solar farm to generate electricity (EGAT, 2019)
- The floating solar farm can generate energy about 87.53 million kwh/year which can supply up to 18,200 household nationwide (Mr. Chatchai Mawong, Director of Hydro and Renewable Power Plant Development Division).
- Floating solar panels are 100% recyclable, utilizing high-density polyethylene, which can resist ultraviolet rays and withstand corrosion (Sudhakar, 2019).
- More modules can be installed compared with other systems (Sudhakar, 2019).
- Non-use (and disturbance) of land which conserves the local environment (Sudhakar, 2019).
- Easy to erect and faster deployment (Sudhakar, 2019).

Weaknesses

- Long-term maintenance requirements and durability of floating solar PV is yet to be seen (Sudhakar, 2019).
- There can be ecological and adverse impacts on water ecosystems (Sudhakar, 2019).
- This floating PV system is still young and immature technology (Sudhakar, 2019).
- Experts and engineers can still be lack of experience and knowledge of floating PV systems (Sudhakar, 2019).
- Thailand is lack of clear framework/guidelines to dispose of PV solar waste.
- The department responsible for PV solar waste disposals is not the one that is responsible for the floating solar installment. Therefore, further knowledge, skills and PV solar waste guidelines need to be discussed, planned, and shared transparently between relevant institutions.
- There are no specified disposal sites. This can imply that the disposal practices of PV solar waste can get lost without a defined direction.

Opportunities

- If this pilot project is successful, more hybrid floating PV can be installed and operated.
- Innovations in floating technology can be growing (Sudhakar, 2019).
- Great potential and growing awareness for floating PV systems (Sudhakar, 2019).

- Availability of water bodies and land issues are main accelerators for floating PV solar panels (Sudhakar, 2019).

- Floating PV increases its efficiency over Land PV installed (Sudhakar, 2019).

- Availability of trained manpower and government policies have boosted investors' confidence (Sudhakar, 2019).

- Stable floating PV platforms result in minimum operation and maintenance cost (Sudhakar, 2019).

- Thailand is a new emerging market and investment for floating solar PV (Sudhakar, 2019).

- Solar energy is known as one of the most sustainable, long-term, and high return investments. Thus, with proper studies and plans, in the long run, Thailand can be better off with its PV solar potentiality.

- With this solar energy, Thailand can reduce a huge amount of CO_2 emission generated by the energy sector by 47,000 tones/year (EGAT, 2021).

- EGAT has assume that the life span of this floating solar PV is 25 years. Therefore, until these panels become inefficient or unusable, Thailand can have more time to develop effective PV waste disposal guidelines/regulations to manages this PV waste.

- R&D (Research & Development) of PV can be potentially included into the national research program and can be beneficial to further development and installation of next PV projects of the country.

Threats

- Lack of testing and standard procedures of floating solar (Sudhakar, 2019).

- This floating PV technology is not tested for the long run (Sudhakar, 2019).

- There are no promotion and support through a separate policy in Thailand (Sudhakar, 2019).

- The concerns focus on the cost and the lack of financial resources (Sudhakar, 2019).

- Floating PV systems can be unwieldy to repair and maintain (Sudhakar, 2019).

- The end-of-life PV solar will be likely distributed to the landfill site (Mr. Chatchai Mawong, Director of Hydro and Renewable Power Plant Development Division).

- Economically, the materials that can be reused will be unlikely to be recovered. Thousands of USD will be lost with this method.

- Environmentally, there are many studies that claim the harms resulting from landfilled solar PV on human health as well as the ecosystems (Lunardi et al., 2018).

- PV waste modules can produce pollutants causing from the leaching of metals, such as lead and silver into the environment, affecting the water and soil (Fthenakis, 2000; Berger et al., 2010; Frisson et al., 2000; Choi et al., 2014; Gerbinet et al., 2014; Stamford & Azapagic, 2018; Zong et al., 2011).

6.2. Lianghuai

Strengths

- Floating solar power generating systems typically generate more electricity than rooftop and ground-mounted systems due to water's cooling effect (Sudhakar, 2019).

- The platforms of floating solar systems are engineered and designed to resist the physical stress which includes storm and typhoon conditions (Sudhakar, 2019).

- Installations of a tracking Liquid Solar Array (LSA) reduce water evaporation and algae growth by shading the water (Sudhakar, 2019).

- Geographically, any water bodies with abundance of sunlight radiation can be used to install floating solar plants (Sudhakar, 2019).

- Floating solar panels are 100% recyclable, utilizing high-density polyethylene, which can resist ultraviolet rays and withstand corrosion (Sudhakar, 2019).

- More modules can be installed compared with other systems (Sudhakar, 2019).

- Non-use (and disturbance) of land which conserves the local environment (Sudhakar, 2019).

- Easy to erect and faster deployment (Sudhakar, 2019).

- China has a rich potential of solar radiation throughout the country (Solangi et al., 2011). In 2017, China was the first country to pass 100 GW of total installed PV. By the end of 2020, it had 240 GW of all installed PV combined in the country (Pouran, 2018).

- The first action of China to fight against pollution is constructing a 70MW floating solar farm on the mining subsidence area, Lianghuai, as a substitution to the coal burning for energy generation (Pouran, 2018).

- This 194,700-solar-panel farm can supply more than 21,000 houses in the installed area (Pouran, 2018).

Weaknesses

- Long-term maintenance requirements and durability of floating solar PV is yet to be seen (Sudhakar, 2019).
- There can be ecological and adverse impacts on water ecosystems (Sudhakar, 2019).
- This floating PV system is still young and immature technology (Sudhakar, 2019).
- Experts and engineers can still be lack of experience and knowledge of floating PV systems (Sudhakar, 2019).
- In spite of the government's commitment in promoting clean energy usage from PV solar, there are no PV recycling facilities within China.
- No clear regulations/guidelines dealing with end-of-life PV (Chowdhury et al., 2020)

Opportunities

- Innovations in floating technology can be growing (Sudhakar, 2019).
- Great potential and growing awareness for floating PV systems (Sudhakar, 2019).
- Availability of water bodies and land issues are main accelerators for floating PV solar panels (Sudhakar, 2019).
- Floating PV increases its efficiency over Land PV installed (Sudhakar, 2019).
- Availability of trained manpower and government policies have boosted investors' confidence (Sudhakar, 2019).
- Stable floating PV platforms result in minimum operation and maintenance cost (Sudhakar, 2019).
- New emerging market and investments in China for floating PV systems (Sudhakar, 2019).
- China still maintains a strong solar radiation potential, which makes more floating solar PV available and keeps growing.
- Before the PV solar modules become old or no longer usable which would be in 20 - 25 years' time, China can invest in R&D in PV recycling so that it will manage PV waste in a proper way

Threats

- Lack of testing and standard procedures of floating solar (Sudhakar, 2019).
- This floating PV technology is not tested for the long run (Sudhakar, 2019).
- There are no promotion and support through a separate policy in Thailand (Sudhakar, 2019).
- The concerns focus on the cost and the lack of financial resources (Sudhakar, 2019).
- Floating PV systems can be unwieldy to repair and maintain (Sudhakar, 2019).
- If China continues to install PV solar without establishing a clear framework/regulations/guideline on end-of-life PV management, China tends to create more hazards to its own environment which will harm more human lives and ecosystems.

6.3. Comparison of the Results

According to the analyses in 5.1 and 5.2, Thailand and China have similarities and differences as the following:

Similarities:

- The strengths, weaknesses, opportunities, and threats of floating PV solar systems are so much similar in these two countries
- Both of them are rich in solar radiation
- They possess high potentialities in more PV solar installation on available water surfaces
- They have opportunities to invest in R&D of end-of-life PV solar management
- However, they do not have PV solar recycling facilities within the countries even though both governments are pushing hard towards PV solar energy.

Differences:

Thailand does not have serious issues on environment as China yet, but if Thailand does not balance between country's economic development and environmental conservation, the future of human health and ecosystems of Thailand cannot be anticipated with the unforeseeable future.

6.4. Policy Recommendations

After the SWOT analyses and the comparison between the two countries, policy recommendations for Thailand on managing floating solar PV waste is as the following:

1. Initiate the establishment of end-of-life PV management regulations and guidelines to implement in the country;
2. Invest in PV solar R&D and further study on how dangerous it can be for landfilling end-of-life PV solar modules and find approaches to manage PV waste efficiently;
3. Put aside the budget that can be saved for constructing PV recycling facilities;
4. Take a look at successful PV recycling countries, namely Germany and France, and learn what aspects can be taken into consideration and apply into its own PV solar waste management;
5. Strengthen the renewable energy cooperation nationally, regionally, and internationally and consult and seek for assistance in establishing and/or implementing renewable energy projects.

Chapter 6 Conclusion

As a green, clean, renewable source of energy, solar PV power is a vital pillar in efforts to combat climate change. However, when it comes to end-of-life PV, the safe and proper management of it is crucial to assure that PV waste does not provide negative impacts to the public health and ecosystems of a country.

Thailand has been heavily invested in solar PV and has prioritized the environmental conservation by turning to solar PV power rather than increasing the amount of oil and gas to generate its electricity within the country. With this commitment, Thailand should establish a clear framework on how to deal with end-of-life solar PV in advance before it is too late. Of course, studying further in PV waste impacts on the environment or constructing recycling PV facilities take time and efforts, but it is worth to initiate, so that countries in the region and around the world can take Thailand as an example in managing of PV waste and also turning to this clean energy for their countries' electricity generation as well.

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Appendix A

Interview questions and answers with 6 EGAT officials. Only one of them, Mr. Chatchai Mawon, a Director, Hydro and Renewable Power Plant Development Division, permits the author to reveal his name in this interview. This interview took place on November 13th, 2019 at EGAT Headquarter, Bangkok, Thailand.

Assessing Indicators/Criteria to Assess	Questions & Answers
Floating PV Power Generation	*How much energy does the plant generate*? The Floating Solar Plant can generate energy about 87.53 million kwh / year (Capacity factor 18.74%).
Number of PV Modules to be installed	*How many solar panels (in number) does the plant use to generate that amount of energy?* According to requirement stated in TOR, PV modules' output power shall be >= 325 Wp. Thus, the number of solar panels can be clarified by the Bidder but the Net power output of floating solar power plant shall not be less than 45 MWac.
Type and Structure of PV Modules	*What type of solar panel does the plant use? Is it monocrystalline, polycrystalline, or thin-film? Or any other than the mentioned types?* Type of PV module: Crystalline Silicon Structure of PV module: Double Glass
Life Span of PV Panels	*How many years does the plant expect the solar panels to last?* - The PV modules would be expected to have the lift time about 25 years. - According to requirement of TOR, it stated that the solar panels shall generate a power output not less than 97.5% of the peak power output (Wp) under STC condition for first year, thereafter 0.5% per year ending with 83% in the 30th year. - The contractor shall submit EGAT a copy of warranty certificate of power output for proposed PV modules before issuance of Provisional Acceptance Certificate (PAC).
Plan for PV Disposals	What are plans of the plant to dispose the solar panels when they reach their end-of-life utilization?

	- EGAT has to comply with Code of Practice (CoP) and Environmental Safety Assessment (ESA) during plant construction, plant operation and plant decommissioning. - After end of PV module life utilization, the PV modules will be sent to the disposal site authorized by the Department of Factory. - In Thailand, the PV modules will be sent to secure landfill or Incinerator plant or another deposal process under law.
Nearby Recycling Factory/Landfill Site to the Floating Solar Farm	*How far (in Km) is the closest recycling factory or landfill of the plant (if there is any)?* EGAT does not specify the location of deposal sites. The authorized disposal sites by Department of Factory will be concerned.
Households to be Supplied by Floating PV	*How many households can the plant supply?* About 18,200 households, Remark: average households in Thailand = 400 kWh/ month, 4,800 kWh/ year. *Does the plant plan to supply only in Ubon Ratchathani province or in other provinces too?* This plant generates electricity to EGAT's transmission system via 22 kV. EGAT's transmission system. Thus, the exact area cannot be identified.

Appendix B

AEDP	Alternative Energy Development Plan
Amorphous Silicon	a-Si
Cadmium Telluride	CdTe
COVID-19	Coronavirus Disease
EGAT	Electricity Generating Authority of Thailand
EPBT	Energy Payback Time
EoL	End-of-Life
EU	European Union
GDP	Gross Domestic Product
GW	Gigawatt
IEA	International Energy Agency
IMF	International Monetary Fund
IRENA	International Renewable Energy Agency
LCA	Life Cycle Assessment
Mono-Crystalline Silicon	mono-Si
Multi-Crystalline Silicon	multi-Si
MW	Megawatt
PV	Photovoltaic
Rai	A Unit of Area (Thai Measurement Standard on Land/Water Surface)
ReCiPe	A Method in Life Cycle Impact Assessment
SWOT	Strengths, Weaknesses, Opportunities, Threats
TIEB	Thailand Integrated Energy Blueprint
US	United States of America
WEEE Directive	Waste Electrical and Electric Equipment Directive

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