**Title: Modelling and Performing a Life Cycle Analysis of a Prospective Solar Farm**

**Authors:** Ryan Isaac Lazaroo 1, Munish Kumar 2

1 Nanyang Technological University, 2 Singapore University of Social Sciences

\*Corresponding author. Email: RYAN017@e.ntu.edu.sg

**Abstract:**

Solar energy is an increasingly cheap and potentially limitless source of energy that has been growing rapidly due to its modular and versatile nature. Solar power generation can be done on multiple scales, from large utility-scale projects that provide cheap electricity to smaller rooftop panel installations that help building owners offset their electricity bills. Given this ubiquity, solar has a large potential as an energy resource. As more solar developments are built, there is a need to study their environmental and financial impacts. There are currently a limited number of studies regarding the life cycle analysis of a solar farm as a whole – instead, most life cycle analyses focus on individual components such as the solar panels or power cables, for example. Many of these analyses are also done after the solar farm is operational. Once operational, it is difficult to mitigate the effects of high emissions costs. In this paper, we model and perform a life cycle analysis for a prospective solar farm in the earliest stages of conception. By this, what we mean is that the solar farm we are modelling is based on a real solar farm that is currently pre front end engineering and design (FEED) stage, and where no final investment decision (FID) has been made. Using analogues, careful assumptions, and public sources, we model the energy production, carbon emissions, and costs of a solar farm over its life cycle.

We learn from our modelling that battery decommissioning is the largest source of emissions followed by the manufacturing of solar panels and batteries, resulting in peak emissions at the start and end of the solar farm life cycle. The years where batteries replacement is modelled to occur also show high emissions compared to the lower baseline operational emissions. As batteries are a large source of emission, the number and deployment of batteries, if used at all, should be considered prior to commencing operations to reduce both emissions and costs through optimization. Finally, we evaluate the costs and payback period of the solar farm and find that the number of years before payback aligns with the 2-to-13-year period indicated by literature.

**One-Sentence Summary:**

We model and perform a life cycle analysis of a prospective solar farm at the early stages to identify possible mitigations in emissions and costs.

# Introduction

As an alternative energy source, solar energy is often touted as a ready replacement for fossil fuels. Its attractiveness lies in the fact that electricity generation from solar is carbon negative, and the sun is viewed as a limitless source of energy. Currently, solar energy already generates about 1000TWh worth of energy and continues to grow along with other forms of renewable energy such as wind. Part of this popularity stems from the modular and versatile nature of solar power generation, which comes in the form of large utility-scale projects down to local rooftop solar panel installations. Furthermore, external factors such as the ongoing war in Ukraine has heightened energy security concerns and accelerated the adoption of renewables like solar, such that some forecasts even estimate solar PV capacity to exceed that of natural gas and coal by 2027 (IEA, 2022).

However, despite its growing popularity as an alternative energy source, there are still challenges with solar developments. Depending on its end use, it is not an “on-demand” energy source and may require battery storage for greater flexibility of use. This means that, depending on how the solar development is planned and the amount and types of batteries used, its carbon footprint can vary widely. Batteries also add a significant Capital Expenditure (CAPEX) cost, which directly impacts the payback period of the project. As the number of solar developments around the globe increase, there is a need for novel approaches to analysing the energy production potential, greenhouse gas (GHG) emissions, and total cost of the development over its entire life cycle. It is especially important to evaluate these early in the development’s life cycle, ideally at the prospective stage, to optimise costs as well as plan for the mitigation of potential GHG emissions and the associated carbon taxes and costs they might incur. Thus far, early life cycle analysis has been a challenge due to the lack of data on exact energy production and emissions prior to commencing operations. However, we believe it is possible to use estimates of production, emissions, and costs from existing solar developments and component manufacturers to evaluate the full life cycle of solar development even at the prospective stage.

In this paper we discuss our approach to modelling and performing a life cycle analysis of a solar farm – evaluating the energy production, GHG emissions, and costs of a solar farm at the prospective stage. This hypothetical solar farm is based on an offshore equatorial island which requires subsea cabling to connect it to the onshore electrical grid where the power will be used up. Our model considers the full “cradle-to-grave” view of the development, where we consider: (a) the initial operational planning of the farm including installation of underground pipes and high voltage electrical cables groundwork, (b) logistics and shipping for major “off-the-shelf” parts and components like solar panels & inverters, and (c) the CAPEX, Operational Expenditure (OPEX), and Decommissioning Expenditure (ABEX) of the components. GHG contributions of each component within the value chain were then determined. Our method considers the uncertainty in which deterministic “Low-Best-High” outcomes of solar energy output were calculated (although only the results from the “Best” case will be discussed in this paper for simplicity). Finally, we evaluate the costs and payback period for the solar farm.

Our results indicate that while operational carbon emissions are low, there are periods of high carbon intensity during the installation and decommissioning phases under Scope 1 emissions, notably from battery decommissioning . Batteries also affect scope 3 emissions if the manufacturing of batteries, and more significantly, solar panels, are considered. The manufacturing process forms the bulk of all emissions due to the mining and purification processes involved. Overall, carbon emissions from battery decommissioning might negate the carbon emissions offset if solar energy over natural gas is used to produce the same amount of energy. In the following sections, we detail the methods and assumptions that have gone into these results.

# Background Information

Our approach to a life cycle analysis of a solar farm is based on a solar evaluation that we carried out for a pre-FEED solar development on a small offshore island in Southeast Asia. We have worked under the assumption that land available for solar energy use will gradually be made available over a period of 5 years, ultimately providing approximately 70 hectares for solar cells deployment in total. The land was generally flat; we have assumed that there is no elevation of terrain and that most solar panels can be deployed with minimal land clearance. A nearby floating solar farm was used as an analogue for this development as well, given its proximity to this development and recent commencement of operations which allows for a proven comparison of solar capacity for a given area using similarly efficient solar cells.

For this development, besides the typical solar farm considerations, subsea cabling is an important aspect for the life cycle analysis as produced power from these solar cells must be delivered to end-use electrical grids onshore. This requires trenching to bury subsea cables several metres below the deepest point of the seabed, based on regulations from relevant authorities. Given that the area in close to busy shipping lanes, the cable must be buried under sufficient depth such that it is resistant to anchor drops from large ships. A conservative water depth of 30m is assumed for this study. Additionally, to have a clearer idea of what materials and costs go into our models, we also considered how the cables would be buried. If deep burial is utilised, an injector tool with a “lay and burial” method is needed to lay the submarine cable down in an 8m trench depth. The other alternative is dredging, using a “pre-lay burial” method, but the maximum trench depth achievable would only be 5m. As we do not have information on the soil type, nor do we have a full bathymetric assessment of the sea bed, we assumed that a lay and burial” method is used. For cable protection, we assumed a large diameter pipe (48”) with 0.5”-thick walls, with the pipes being filled with absorbent material like gravel, sand, or expanding foam to further protect the inner contents. All these aspects will be considered in later sections on GHG emissions and cost modelling.

## GHG Methodology

For the preparation of GHG emissions, we have used the following standards: 2009 American Petroleum Institute (API) Compendium of Greenhouse Gas Emissions Methodologies for the Oil and Natural Gas Industry, 2011 Petroleum Industry Guidelines for reporting Greenhouse Gas Emissions (IPIECA, API & IAOGP), 2018 ISO 14064 - International Standards for environmental management, to quantify, monitor, report and verify greenhouse gas emissions, and the 2020 Australian Government (Dept of Industry, Science, Energy & Resources) National Greenhouse Accounts Factors.

Based on the guidelines, we consider scopes 1, 2, and 3 as direct emissions, indirect emissions, and indirect emissions not covered in scope 2 respectively. The principal GHG generated by the combustion of fuels for energy is carbon dioxide (CO2), and the quantity of it produced depends on the fuel’s carbon content and the degree to which the fuel is fully combusted. Smaller amounts of methane (CH4) and nitrous oxide (N2O) are also produced from incomplete burning and reactions between nitrogen and oxygen in the combustion air respectively. All three gases are accounted for as uniform CO2 equivalents (CO2-e), which can be done using suitable conversion factors such as the global warming potentials listed in various IPCC assessment reports. One gas which has not been modelled is SF6 – a GHG much more potent than CO2. This gas is primarily used in electrical switchgears and emissions are likely to be from leaks or fugitive emissions. Depending on the maintenance regime, this could range from 0.5% to 3% per year.

# Development Stages

Before delving into the life cycle analysis, it is necessary to look at stages of development for a solar development to understand the different activities at each stage and what can be accounted for in evaluations at an early stage. Table 1 below shows the development process that we have assumed for any proposed solar development. Within this framework, the life cycle analysis that we are carry out comes at the prospective stage, or Stage 0, before FEED and FID for the project is sourced and hence represents a desktop study at the highest level of assessment of the project. While more accurate analysis can be done when projects are in a more advanced stage (Stage 1, 2, or 3), this Stage 0 study uses minimal resources and fundamentally aims to provide stakeholders with a quick “go-no go” result. In other words, conducting the life cycle analysis before any of these stages allows stakeholders to evaluate if the prospective solar farm is even worth allocating resources to for further development.

Table 1: Project development stages for a solar farm. IL=institutional lender, JV=joint venture, TC=technical consultant, EPC=engineering, procurement, and construction

|  |  |  |  |
| --- | --- | --- | --- |
| Project Stages | Stages | Main Activities | Participants |
| Prospective Stage | | | |
| Early Life Cycle Analysis | Stage 0 | Identify possible costs and emissions of prospective development | JV + TC |
| "Red Flag" Review | | | |
| Initial site identification | Stage 1 | Identification of potential final site | JV |
| Funding for project development | IL + JV + TC |
| Development of rough technical concept | TC |
| Due Diligence | | | |
| Pre-feasibility Study | Stage 2 | Assessment of technical concepts | JV + TC |
| Approximate Cost / Benefit | JV + TC |
| Permitting needs | JV |
| Market assessment | TC |
| pre-FEED | | | |
| Feasibility Study | Stage 3 | Technical and financial evaluation of selected concept | TC |
| Assessment of financing options | IL + JV + TC |
| Initiation of permitting process | JV |
| Development of rough technical concept | TC |
| Involvement of Project Development Team | | | |
| Financing & Contracts | Stage 4 | Permitting | JV + Legal + IL + TC |
| Contracting strategy |
| Supplier selection |
| Financing of project |
| FEED and FID | | | |
| Finalisation of Design | Stage 5 | Preparation of detailed design for all relevant lots | EPC |
| Preparation of project implementation schedule |
| Finalization of permitting process |
| Financial Control | | | |
| Construction | Stage 6 | Construction supervision | EPC + JV + TC |
| Independent Review | | | |
| Commissioning | Stage 7 | Performance testing | EPC + JV + TC |
| Post Commission Independent Audit | | | |
| Audit | Stage 8 | Audit & independent review of performance | IL + JV + TC |

# Solar Energy Production

Modelling the energy production from the solar farm is one of the most important parts of this life cycle analysis since it affects other aspects such as the payback period of the development. We have estimated the installed solar capacity on the development based on the land area available for solar cell deployment (~70 ha total). We also assume the land available will be developed gradually over four years in the best case as shown in Figure 1 below. Estimated capacity will depend on the exact solar panels used, but for this study we have assumed that small panels with a footprint of 2m2 per module and with 330Wp capacity will be used. If compared to the nearby floating reservoir as a benchmark, we note that the hypothetical development should be able to accommodate 73MWp of solar capacity in the second year of development, when the land area developed is roughly equivalent.

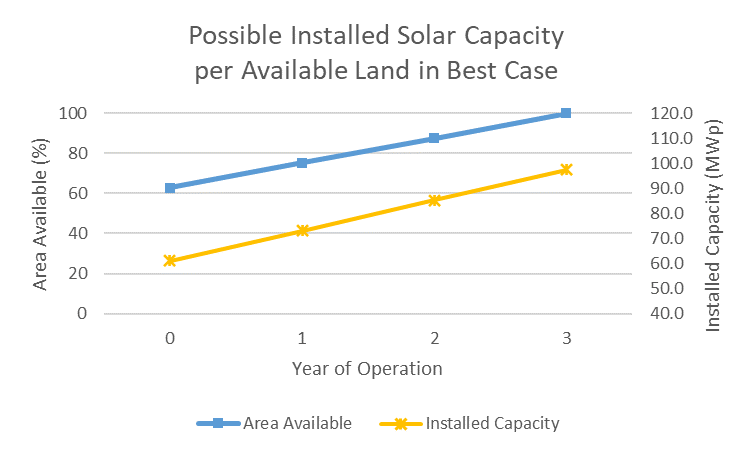


Figure 1: Possible installed solar capacity based on available land

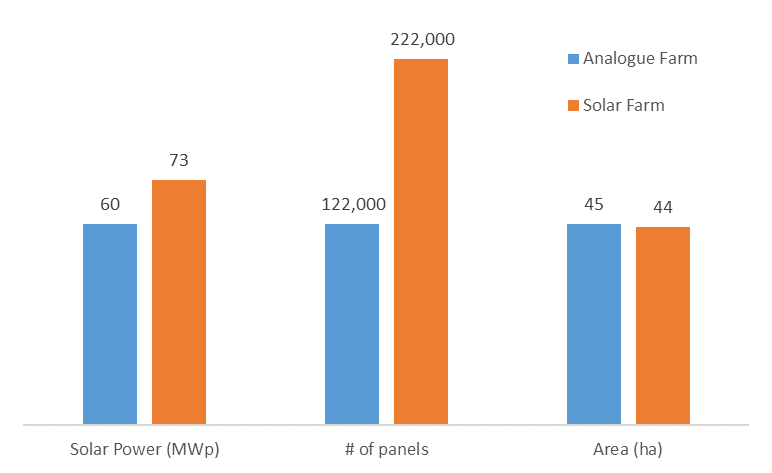


Figure 2: Comparison of solar power between analogue (from real operational farm) and model solar farm

Aside from the initial estimates of installed capacity, we also estimated the annual output from the development, assuming a 25-year production profile. We calculated low, best, and high case estimates by varying 3 key parameters in the estimation of annual production (i) Area available, (ii) the operating factor (which is meant to account for meteorological conditions), and (iii) system inefficiencies.

All cases factor in a decreasing solar module efficiency of 0.5% per year. For the low case, we assume some delays in area available for installation, operating factor of 60% and overall system efficiency of 70%. For the best case, we assume no delay in area available for installation, operating factor of 75% and overall system efficiency of 80%. For the high case, we assume additional space available for installation, operating factor of 90% and overall system efficiency of 90%. As the farm will likely be out of operation for several months during the first few years of development and installation, we estimate the days of operations during these years to be 100, 200, and 300 respectively in the low, best, and high cases. Finally, we assume an average of 4.38 hours of peak sun hours throughout the year for this development.

As seen in Figure 3, production peaks in year 4 when the full area of land is available for solar use. It can also be observed that solar output decreases over time, as increasing inefficiencies in the solar panel and overall system renders some components performing below full capacity. If large swaths of solar panels need full replacement periodically due to a system-wide failure, projected outputs would drop even further. Such scenarios could be modelled probabilistically to capture the randomness of such an event.

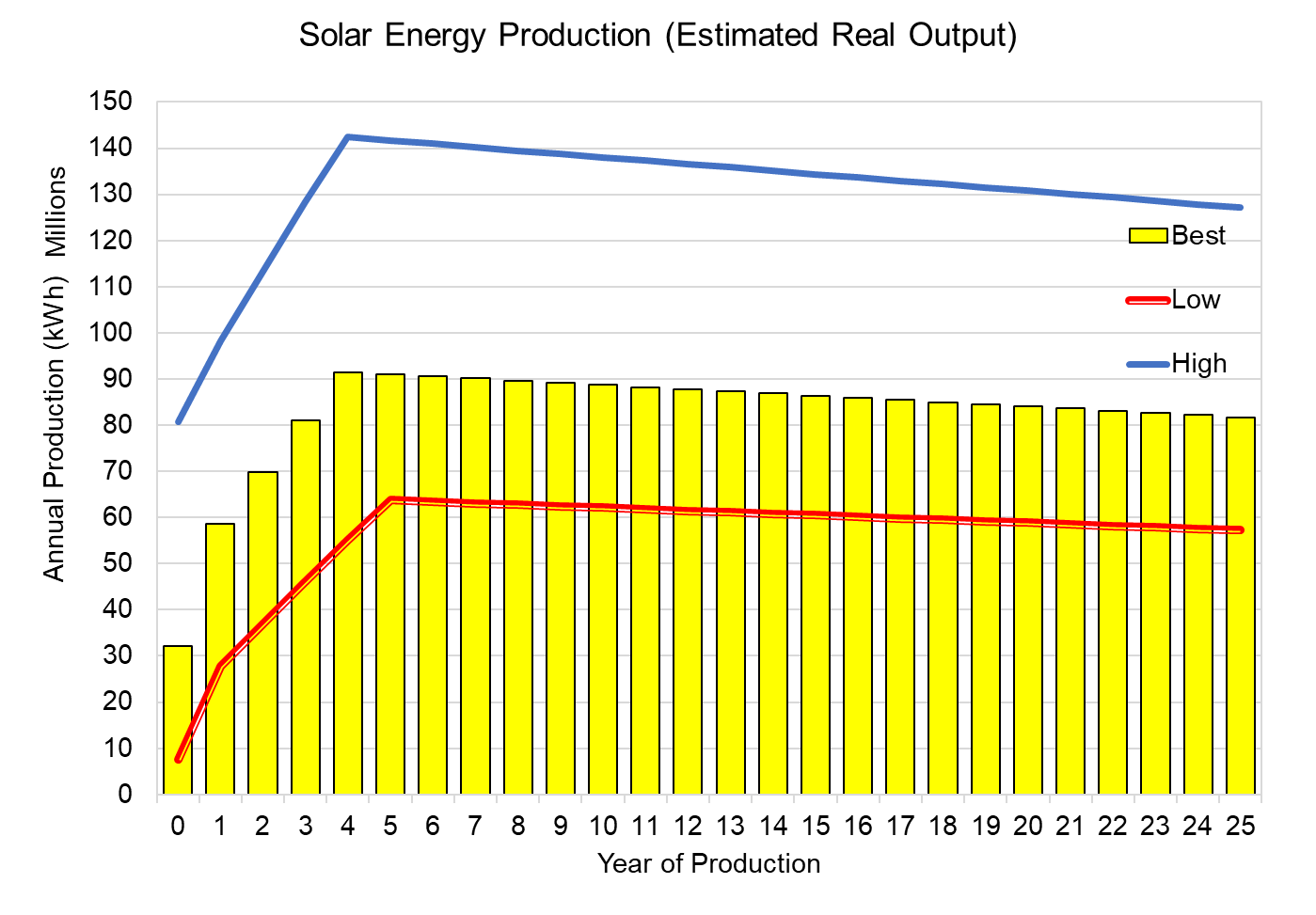


Figure 3: Low, best, and high cases of solar energy production throughout the solar farm’s assumed 25-year lifetime

# GHG Emissions

## Emissions, Energy Content Factors, and Carbon Intensities

To model emissions, we gathered data on emissions factors (EF), energy content factors (ECF), and carbon intensities for various parts in a solar farm based on publicly available data. Some of this data is shown in Table 3, which lists the carbon intensities for materials, fuels, and components that contribute to the emissions of a solar farm over its entire life cycle. This includes the emissions given off during manufacturing, transportation, installation, operation, maintenance, and decommissioning. The key components at each of these stages are highlighted in Figure XX, along with the emissions source for each component. Most of the carbon intensities are from the manufacture and decommissioning processes, as onshore operation processes for components (aside from fuelling and yearly maintenance works) are considered negligible here.

Emissions from fuel consumption were calculated using appropriate EFs and ECFs using Equation 1 below.

|  |  |
| --- | --- |
|  | Equation 1 |

The EF and ECF values used in our calculations are listed in Table 2 below.

Table 2: Energy content and emissions factors for different fuels based on Australia’s 2022 National Greenhouse Accounts Factors (2022)

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Fuel Type** | **Energy Content Factor** | | **Emission Factor**  (Tonnes CO2eq/GJ) | | |
| Value | Units | CO2 | CH4 | N2O |
| Diesel | 38.6 | GJ/kL | 0.0699 | 0.0001 | 0.0002 |
| Natural Gas (Unprocessed) | 0.0393 | GJ/m3 | 0.0514 | 0.0001 | 0.00003 |

Table 3: Carbon intensities of different components in a solar farm

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Carbon Intensities** | | | | | |
| **Fuel** | | | | | |
| **Fuel Type** | **Value** | | | **Units** | **References** |
| Natural gas | 0.185508 | | | kgCO2eq/kWh | Calculated based on Table 2 |
| **Solar modules** | | | | | |
| **Process** | **Low** | **Best** | **High** | **Units** | **References** |
| Manufacturing | 1.32 | 2.01 | 2.7 | kgCO2eq/Wp | (Yue, You, & Darling, 2014) |
| Decommissioning | 1.5 | 1.65 | 1.8 | gCO2e/ kWh | (Frankl et al., 2005) |
| **Inverters** | | | | | |
| **Process** | **Value** | | | **Units** | **References** |
| Manufacturing | 44.3 | | | kgCO2eq/kW | (Huawei, 2020) |
| Decommissioning | 0.43 | | | kgCO2eq/kW | (Huawei, 2020) |
| **Battery** | | | | | |
| **Process** | **Value** | | | **Units** | **References** |
| Manufacturing | 83 | | | kgCO2eq/Kwh | (Emilsson & Dahllöf, 2019) |
| Decommissioning | 15 | | | kgCO2eq/Kwh | (Romare & Dahllöf, 2017) |
| **Cables** | | | | | |
| **Process** | **Low** | **Best** | **High** | **Units** | **References** |
| Manufacturing | 3 | 4.5 | 5.9 | kgCO2eq/kg | (Harrison et al., 2010) |
| **Pipes** | | | | | |
| **Process** | **Low** | **Best** | **High** | **Units** | **References** |
| Manufacturing | 1.77 | 2.3 | 2.82 | kgCO2eq/kg | (Harrison et al., 2010) |

Lastly, specifications for the different components were based on analogue products and models from various companies summarised below in Table 4. It is important to note that the selection of these components was purely arbitrary and does not represent any endorsement of these products as more ideal for solar farms. If the exact models that will be used in the solar farm you are modelling are known, specifications of those products should be used for more accurate models of GHG estimation.

Table 4: Product models used as analogues for various components

|  |  |
| --- | --- |
| **Component** | **Analogue Model** |
| Solar Module | FuturaSun FU 330P Polycrystalline Photovoltaic Module |
| IDT Inverter | ABB central inverters, PVS800, 100 to 500 kW |
| Inverter and Battery | Siemens & AES Fluence Sunstack |
| Pipe | Tioga Pipes |
| Transmission Cable | Sumitomo Electric |

## Scope 1

The assumptions for Scope 1 emissions are divided into the solar panel modelling, inverter modelling, IDT modelling, and battery modelling aspects. For solar panels, we assume solar panels have 330Wp and take up 2m2 each, resulting in a total of 185,000 panels which can be installed in available land in the first year. Installation of the panels is expected to require heavy vehicles and construction equipment; thus, we assume 5 units of heavy machinery will be used – each emitting 10 tonnes of CO2e per year. The installation is expected to be between one and six months long. Operations emissions are expected to be small and is estimated to be 2-8% of the emissions from installation. Depending on whether the panels are mono or multi-Si PV units, decommissioning emissions can be between 1.5-1.8 gCO2e/kWh respectively. Seasonality, cloud cover, and replacement of panels were not modelled, and hence future modelling work is needed to stress-test these assumptions.

Installation emissions for inverters, IDTs and batteries have been rolled up together with solar panel installations. 158 inverters are modelled, operating for 8 hours each day and being idle for 16. The power consumed during each period is 600W and 55W respectively. IDTs are assumed to emit the equivalent of 100-300 inverter units. We have assumed that battery storage will have enough storage capacity for the whole solar farm output. Batteries are assumed to not consume energy in daily operations, while any emissions from maintenance of them are rolled up with overall maintenance emissions on the farm. The end-of-life decommissioning emissions from batteries are at 15 kgCO2e/kWh, based on a 2017 IVL Swedish Environmental Research Institute study which considers both disposal and recycling of lithium batteries (Romare & Dahllöf, 2017).

As these battery emissions are significant, it is important to consider whether they will be used for the solar farm and to what extent. To analyse the breadth of scenarios, we model a solar farm for two cases: a “maximum flexibility” case where all generated power is stored in batteries, and a “minimum cost” case where no batteries are used, and power is consumed immediately. Both cases are compared to a “do nothing” case where power is simply generated from natural gas.

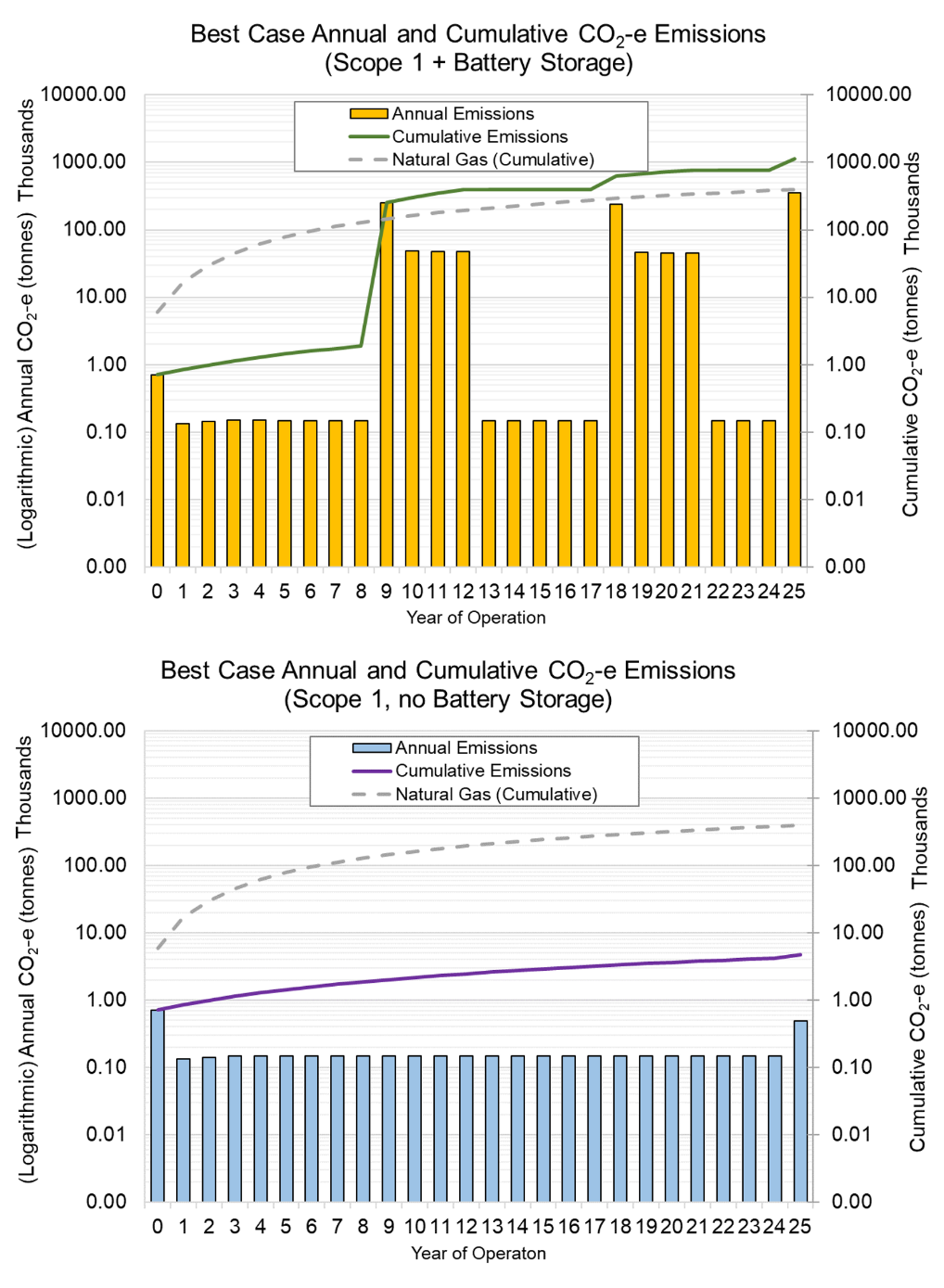


Figure 4: Scope 1 CO2-e emissions for the solar farm with batteries (top) and without batteries (bottom)

It is clear from Figure 4 that overall scope 1 emissions increase greatly with the addition of batteries. These large cyclical emissions arise mainly from battery decommissioning at the end of their lifespan, resulting in 350 kilotonnes of CO2e every 8 years. Without the batteries, emissions only peak at 0.7 kilotonnes of CO2e initially, mainly due to the installation of subsea cables. The rest of the yearly emissions increase gradually over time as solar production declines with time. These smaller emissions are mainly from energy consumed to power the inverter and IDT operations. The energy for these operations is assumed to come from natural gas as the inverters consume power even when idle and hence need a stable supply of energy. The peak at the 25th year is from decommissioning of all components except the subsea cables. Hence, the installation and decommissioning are the only two carbon intensive events in the solar farm life cycle in this case.

When compared to the “do nothing” scenario of using natural gas to produce the same power, the no-battery “minimum cost” scenario has nearly 84 times lower emissions. However, with batteries added for the “maximum flexibility” scenario, cumulative emissions from the solar farm exceed that of just using natural gas. It should be noted, however, that this is a very pessimistic scenario which assumes all power generated is stored in batteries, when likely only a fraction of it would be stored and the rest of the power consumed immediately upon generation. It is reasonable to infer therefore that with proper optimisation, solar farms with batteries can still have less emissions than electricity from natural gas combustion.

## Scope 2

Scope 2 emissions are mainly focused on electricity consumption post-generation and hence requires an understanding of the power consumption of the facility. As this information is unlikely to be known at the early prospective stage of the solar farm, we have not modelled scope 2 emissions in this study. Further along the development of the solar farm, data and estimates of office and facility electricity consumption can be covered in the scope 2 emissions when known. With scope 2 emissions included, however, the carbon intensity of solar farms will increase.

## Scope 3

Scope 3 emissions are emissions that are a consequence of activities of the company but not from sources owned or controlled by the company. This makes scope 3 the hardest category to estimate as it is highly dependent on the end user of the products from the solar farm. For simplicity, we model scope 3 emissions related to the manufacturing and transport of the components of the solar farm only.

Carbon intensities from the manufacturing of components are outlined in Table XX. Batteries were assumed to have an 8-year lifespan and hence three installation cycles were modelled for a 25-year solar farm life cycle. Transport of all components are modelled with one shipment per year, using a vessel which consumes 21kL of diesel per day. The number of days required for shipment per year likely varies due to prevailing weather conditions and factory output, but shipments are assumed to take 5, 10, or 15 days in the low, best, and high cases respectively.

The main source of scope 3 emissions is the manufacturing of solar panels, which contribute roughly 120 kilotonnes of CO2e in the first year of operations alone, when the bulk of solar panels are installed. Battery manufacturing is the next largest source, exacerbated by the fact they need to be replaced every 8 years. The manufacturing of both solar panels and batteries is an energy intensive process due to the mining and purification processes needed for the materials within these components. Consequently, their manufacturing footprint also depends on the energy mix where they were mined and produced. In China for example, solar panel manufacturing has twice the carbon footprint of Europe, as China’s primary mean of power generation is through coal combustion.

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Figure 5: Scope 3 CO2-e emissions for the solar farm with batteries (top) and without batteries (bottom)

## Overall emissions

In our emissions model, battery decommissioning from scope 1 and solar panel and battery manufacturing from scope 3 form the bulk of all emissions from the solar farm. The greatest uncertainty in GHG emissions thus comes from the presence of batteries, which add to the capital cost of the solar farm, in addition to the emissions. However, the added flexibility for operations that they provide might make the use of batteries worth the cost. In this case, careful optimisation of the number and deployment of batteries is needed to reduce emissions and maximise benefit. The emissions for solar farms with batteries being higher than emissions from natural gas for the same power is a testament to the importance of early life cycle analysis at the prospective stage. Such insight would let stakeholders decide if the project is still worth pursuing and, if it is, how can the project be optimised such that emissions and costs are reduced.

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Figure 6: Contribution of activities to the total CO2-e emissions of the solar farm

# Cost Modelling

## Weighted Average Cost of Capital (WACC)

To model costs, we calculate a WACC based on assumptions indicated in Table XX below. Using a 5-year historical average of the Uniform Singapore Energy Price (USEP), a Power Purchase Agreement (PPA) price of 88.7 SGD/MWh was estimated. A USD-to-SGD foreign exchange rate of 1.34 was assumed based on a historical 12-month average. Costs and prices were determined in real terms (as of the time of calculation), then inflated at a 2% rate per annum.

|  |  |  |
| --- | --- | --- |
| Variable | Assumption | References & Remarks |
| Beta | 1 | Assuming same risk as overall economy |
| Equity Risk Premium | 4.38% | Singapore equity risk premium estimate (Damodaran, 2021) |
| Debt Premium | 2.85% | 5-year Singapore bond yield 3Q22 forecast (OCBC, 2022) |
| Tax Rate | 17% | Singapore's prevailing corporate tax rate (IRAS, n.d.) |
| Inflation Rate | 2% | Assumption based on 2021 inflation rates for Singapore |

## CAPEX, OPEX, and Payback Period

Modelling the CAPEX and OPEX are important as they directly impact the profitability of the project. The cost analysis for this study utilises open-source information and industry averages – contractor margins, balance of system, civil and infrastructure costs, and others have not been factored. This therefore represents an optimistic outlook for the solar farm costs.

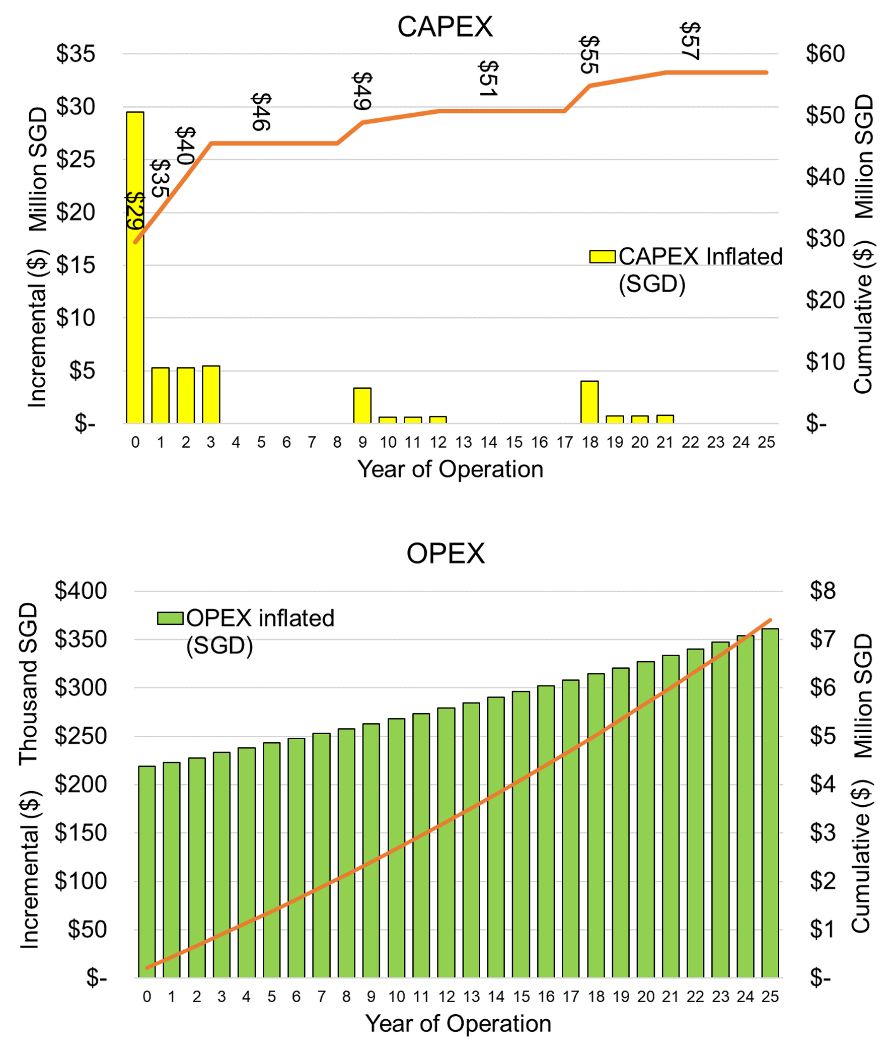


Figure 7: Modelled CAPEX (top) and OPEX (bottom) for the solar farm

Combining the CAPEX and OPEX shows a solar farm to be a highly capital-intensive endeavour, costing upwards of SGD$64 million over its lifetime. However, assuming a PPA price of 88.7 SGD/MWh, the generated revenue from the solar farm could be as much as SGD$250 million – more than enough to offset the costs within the 25-year timeframe.

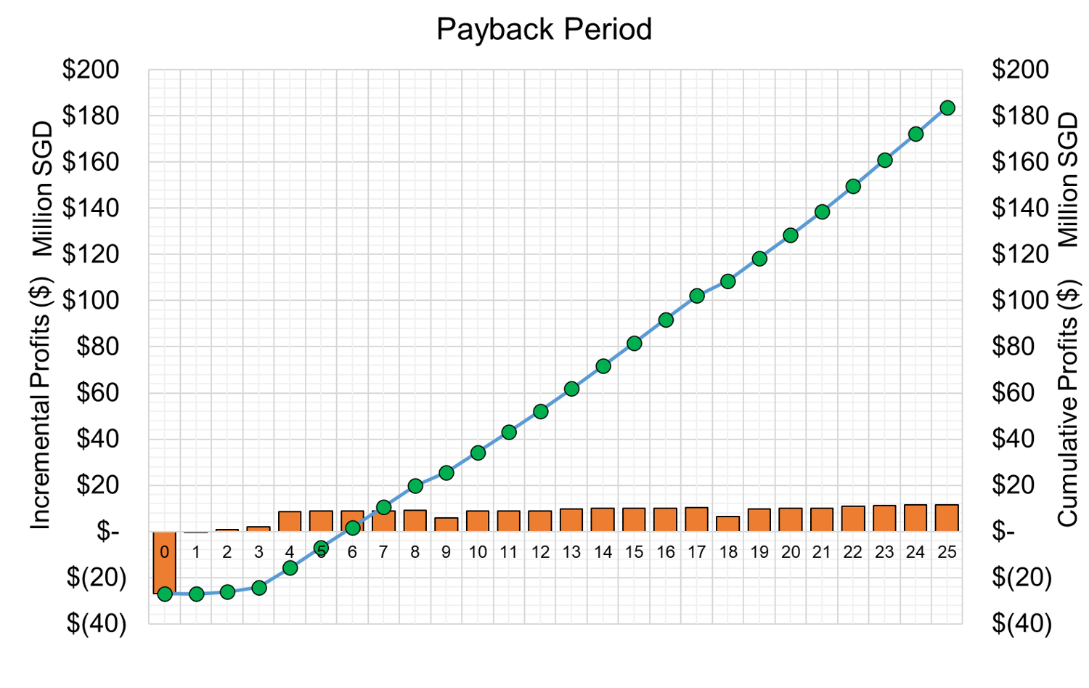


Figure 8: Annual profits and cumulative profits for the solar farm, showing its payback period of about 6 years

Based on the model, the minimum payback period is 6 years, with positive cash flow after. This is in line with payback periods from analogues in literature, which indicates 2 to 13 years before payback (Suphahitanukool, et al., 2018; Kessler, 2017; Marimuthu, Kirubakaran, & Rajasekaran, 2014; Paton, Tan, & Reindl, 2019). There are noticeable dips in the annual profits which are associated with capital costs during years where batteries need to be replaced. Note that solar panel replacement has not been modelled here and this may further extend the breakeven point.

# Conclusion

A high-level life cycle assessment of a prospective solar farm shows that benefits from solar can be negated depending on how extensively batteries are used as part of the development. In our model, we found battery decommissioning to be the most carbon intensive activity for the solar farm, followed by manufacturing of the batteries as well as solar panels. This thus creates peaks in emissions at the start and end of the project life cycle, as well as during any periods of battery replacements. Doing away with battery storage would dramatically decrease emissions and lower costs, but this would be at the expense of operational flexibility and thus optimisation of the number and deployment of batteries is recommended if that is what meets the needs of the project.

Another aspect of this work deals with the payback periods (PP) for these solar farms. We find that solar farms are highly capital intensive, but payback periods are generally in the earlier half of a solar farm’s assumed 25-year lifetime. We have shown that they are affected by the PP is affected by the replacement of solar panels and batteries. Hence, early life cycle assessments at the prospective stage are an important tool for investors and companies deciding if a solar project is worth moving forward with. Such a modelling exercise helps to identifying where the highest costs and emissions come from, and allow for multiple scenario modelling to optimise the solar farm, lower costs and increase environmental performance.

# Limitations

This study is limited by lack of data specific to any real solar farm, hence data and models used in this study rely on a medley of different public sources and analogues. Furthermore, many assumptions have been used in our calculations which may or may not reflect true conditions on an actual solar site. Nevertheless, the methods employed and considerations made can be repeated with better data in the life cycle analysis of other solar farms in their prospective stages.

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# Nomenclature

|  |  |
| --- | --- |
| **ABEX** | Decommissioning expenditure |
| **CAPEX** | Capital expenditure |
| **CH4** | Methane |
| **CO2** | Carbon dioxide |
| **CO2-e** | Carbon dioxide equivalents |
| **g** | gram |
| **GHG** | Greenhouse gas |
| **GJ** | Gigajoule |
| **ha** | Hectare |
| **HVDC** | High voltage direct current |
| **J** | Joule |
| **kg** | Kilogram |
| **kL** | kilolitre |
| **Kwh** | Kilowatt-hour |
| **L** | Litre |
| **m** | Metre |
| **MWp** | Megawatt peak |
| **N2O** | Nitrous oxide |
| **OPEX** | Operational expenditure |
| **Twh** | Terrawatt-hour |
| **Wp** | Watt peak |

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