A Feasibility Study for a Solar PV Farm on Langeland, Denmark

An Interactive Qualifying Project submitted to the Faculty of
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I. Abstract

In the transition to renewable energy, Denmark has relied on wind power. However, to achieve its goal of fossil fuel independence by 2050, Denmark needs to diversify its renewable energy sources. To aid in Denmark's transition, this project created a feasibility study for a solar photovoltaic farm on the Danish island of Langeland. We used prior feasibility studies to understand the development of a solar farm. From this background, the team used manufacturer quotes and site specific information including government regulations and environmental data to create a feasibility study, Python toolkit, and biodiversity plan for a solar farm on Langeland. Based on these deliverables the team recommended next steps to continue planning and development. LAUTEC sponsored this project.

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1.0 Introduction

With some of the most ambitious climate goals of any country, Denmark is at the forefront of sustainable development. Denmark has been known for its sustainable practices and renewable energy sectors for decades (International Trade Association, 2021). The country plans to reduce greenhouse gas emissions by 70% by 2030 and be completely free of fossil fuels by 2050 (Parajuli, 2012). According to the Danish Energy Agency, non-renewable sources only accounted for 38% of Denmark's energy production in 2019 with wind power supplying 58%, solar producing 4%, and >1% supplied by hydroelectric (Danish Energy Agency, 2020). While Denmark has been working to expand a wide range of renewable technologies, it is most well-known for wind energy.

The International Trade Association attributes Denmark's success with wind energy to its "significant experience" in the industry (International Trade Association, 2021). However, the International Trade Association also discusses the unpredictable nature inherent to wind power and the added infrastructure that is needed to expand offshore wind farms (International Trade Association, 2021). The installation of offshore wind power can affect local ecosystems. For instance, a study of coastal waters in Sweden found that construction and operation of offshore wind farms could potentially have negative effects on wildlife (Bergström et al., 2014). Furthermore, if Denmark were to only use one source of renewable energy (in this case wind), it would have to add at least a 400 MW offshore wind farm annually, from 2020 to 2050 in order to hit its energy goals (*Energy Scenarios for 2020, 2035 and 2050*, 2013). Based on energy production data published by the Danish Energy Agency, Danish based wind energy is not growing at this rate (Danish Energy Agency, 2020). If Denmark continues to rely only on wind, it will be susceptible to yearly trends in wind power and may have to turn back to fossil fuels in years with unexpectedly low wind speeds (*Energy Scenarios for 2020, 2035 and 2050*, 2013). Additionally, these speculations are based on assumptions of current electricity usage and do not account for the use of renewable energies in sectors such as transportation and heating, which will demand additional energy production (*Energy Scenarios for 2020, 2035 and 2050*, 2013). Although the benefits offshore wind power has provided are undeniable, Denmark will need to diversify its renewable energy production methods in order to responsibly hit its goal of cutting carbon emissions by 70% by 2030. One potential avenue for Denmark to diversify its energy sources is expanding its solar power industry.

Since 2015, the Danish company LAUTEC has been working to accelerate the transition to renewable energy. LAUTEC offers IT solutions and consulting services to enable the public and private sectors to “develop, execute, and operate renewable energy projects smarter, faster, and cheaper” (LAUTEC, 2015). LAUTEC consultants have worked on projects in Europe, Asia, Australia, and America and have focused on offshore wind power. To complement consulting services, LAUTEC has developed IT systems including geographic information system, quality assurance software, and daily progress reporting. Now looking to expand the company’s renewable energy consultation portfolio, LAUTEC is interested in exploring the feasibility of a solar farm on the Danish island of Langeland.

In order to aid LAUTEC in diversifying Denmark's renewable energy sources, the goal of this project was to create a feasibility study for a solar farm on Langeland. In order to achieve this goal, we pursued the following objectives:

1. Identify regulations that would impact a solar farm
2. Investigate impacts of a solar farm on the local environment
3. Estimate the power output of a solar farm
4. Estimate the costs of a solar farm
5. Prepare a feasibility study

This report details the research, analysis, and results of our study.

2.0 Background

Creating a feasibility study for a solar farm requires knowledge of the technical aspects of solar power as well as the local and environmental considerations needed to develop at a specific location. To give a broader understanding of solar PV farms and the Danish island of Langeland, the following sections discuss the principles of solar PV farms, including financial outlook and environmental considerations, as well as the island of Langeland.

2.1 Photovoltaic Energy

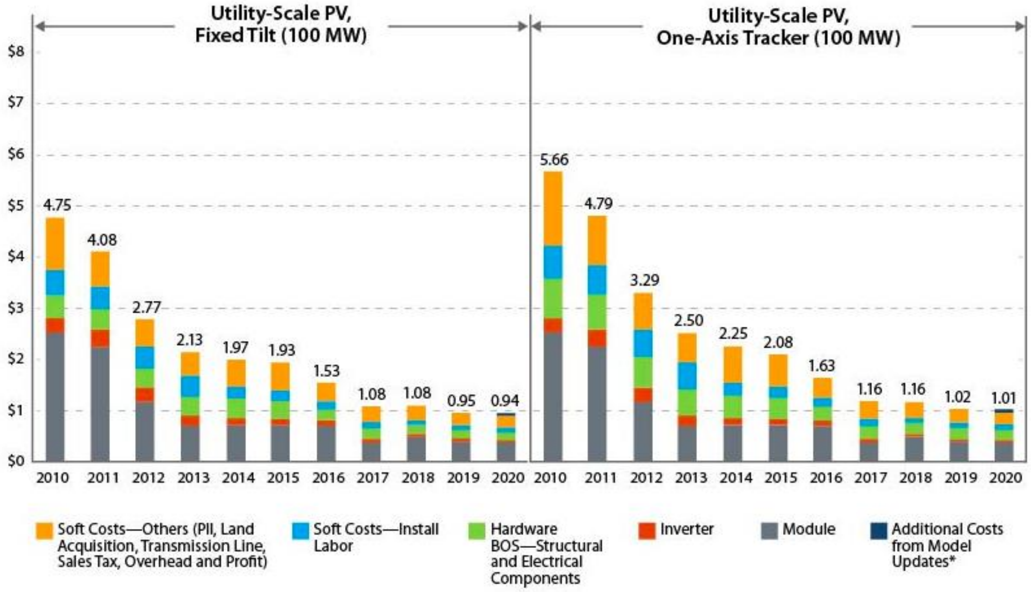
Photovoltaic energy is produced by the conversion of light from the sun to electricity. In the following section, we first explore the impacts of photovoltaic energy and the benefits of investing in this technology, specifically focusing on photovoltaic cells. Next we examine the hardware components needed in a solar PV farm and detail the tools used in determining the commercial viability of a solar PV project.

2.1.1 Benefits, Outlook, and Economic Analysis of Photovoltaic Energy

Photovoltaic is one of the “greenest” forms of energy sources (Aman et al., 2015). The benefits of photovoltaic energy compared to conventional and other renewable sources include low carbon and air pollutant emission, less water consumption, minimal land transformation, short payback time, few visual impacts, and low noise pollution (Aman et al., 2015). In contrast, several concerns remain, including the toxic chemicals used in the production of solar panels, ecological impacts of installation, and the recycling process of the panels (Aman et al., 2015). Although there are areas for growth, photovoltaic technology provides tremendous benefits when compared to conventional energy sources.

Photovoltaic energy is flexible and affordable. There are many methods to optimize solar power production, even in cloudy climates such as Northern Europe, as will be described further in section 2.1.3. In terms of cost, Figure 1 shows that improvements in technology are causing the cost of installation to decrease, while efficiency increases (“Documenting a Decade of Cost Declines for PV Systems,” 2021).

Figure 1



Note. Cost per watt given different variables for a utility-scale PV farm from 2010 to 2020 for fixed-tilt panels and one axis tracking panels. From Documenting a Decade of Cost Declines for PV Systems, by NREL, 2021, (https://www.nrel.gov/news/program/2021/documenting-a-decade-of-cost-declines-for-pv-systems.html). In the public domain.

Furthermore, low operation costs make photovoltaic energy a lucrative investment opportunity (IRENA, 2020). On average, operation and management costs for PV technology are approximately 15 USD/kW/yr. In comparison to other types, such as onshore wind (33 USD/kW/yr), offshore wind (100 USD/kW/yr), and hydropower (40 USD/kW/yr), solar technology is the cheapest to operate by a large margin (IRENA, 2020).

There are a multitude of different types of solar panels. The ones that are widely commercially available for solar farms include: mono-crystalline silicon, multi-crystalline silicon, triple junction amorphous silicon, and copper–indium–diselenide (CIS) solar panels. The highest efficiencies for the 2020 market solar panels are correspondingly, 25%, 20%, 15%, and 18% (Ahmad et al., 2020); MiaSolé Hi-Tech Corp., n.d.). Cutting-edge concentrating PV cells, such as triple and four junction solar cells, which use lenses to focus sunlight, currently have efficiencies of up to 40% with the potential to achieve over 50% efficiency (Ellabban et al., 2014; Yamaguchi et al., 2006). However, concentrating photovoltaic (PV) cells are currently too expensive for practical commercial use, and are still being developed (Ellabban et al., 2014; IRENA, 2020). Given this research we see that the efficiency of solar panels is continuously increasing.

2.1.2 Building a Solar Farm and Economic Models

A utility-scale solar power system consists of a core set of components. Aside from solar panels, other hardware includes inverters, batteries, transmission lines, and monitoring systems. The U.S. Office of Energy Efficiency and Renewable Energy gives descriptions for several key components, which are shown in **Table 1** (*Solar Systems Integration Basics*, 2022).

Table 1: Basic Solar Hardware Components and Descriptions (Solar Systems Integration Basics, 2022).

Component	**Description**
Solar PV Array	Interconnected PV modules that convert solar radiation into DC power
Racking and Mounting	Fixes solar panels to the ground at the optimal angle and mounts the inverters
Batteries	Technology that can capture electricity, store it as another form of energy (chemical, thermal, mechanical), and then release it when needed
Inverters	Converts direct current (DC), generated by a solar panel, to alternating current (AC), which is used by the electrical grid
Monitoring and Control	Measures the efficiency and energy production of the solar array as well as irradiation and temperature sensor
Cabling	Cables (low voltage), connectors, and combiner boxes that move the power from where electricity is generated to the grid

Grid connection	Includes medium voltage cables and connectors, switchgear and control boards, transformers, and substations

Battery storage technology is a potential solution to increase system flexibility in a power system (Utility-Scale Batteries Innovation Landscape Brief, 2019). Utility-scale battery storage systems have a typical storage capacity ranging from around a few megawatt-hours (MWh) to hundreds of MWh. They act as a reserve and are able to defer depositing excess energy into the grid (Utility-Scale Batteries Innovation Landscape Brief, 2019).

The total cost to build a solar farm is the summation of the hardware components, land, and labor for installation. Prices of each hardware component unit vary substantially by make, model, and manufacturer. Similarly, the quantity of each component is dependent on the size of the solar farm. The commercial viability of a solar PV project can be determined through financial analysis tools, which compare the predicted output with the expected costs. According to the International Finance Corporation, project financing is only possible when a solar PV array is capable of generating enough revenue to not only pay for debt obligations and the overall costs of operation and management, but also yield a reasonable return for the equity invested (Utility-Scale Solar Photovoltaic Power Plants). To assess the economic feasibility of a PV system, a simple payback is an attractive calculation as it is straightforward and easy to understand (Hay, 2016). Simple payback determines the number of years for the energy savings from the PV system to offset the initial cost of the investment. Simple payback in years can be calculated as

$$\text{Payback (years)} = \frac{Initial\ Cost\ (\$)}{Annual\ Production\ (kWh/year)\ x\ Value\ (\$/kWh) - Operation\ \&\ Management\ (\$/year)}.$$

Another economic model to optimize decision-making is Levelized Cost of Energy (LCOE). Investments in solar technology are important long-term decisions. Quality and security is valued over low initial investment thus the LCOE equation assesses the average lifetime costs of the energy provided from a solar PV system which is calculated as

$$\text{LCOE} = \frac{Sum\ of\ Cost\ over\ Lifetime}{Sum\ of\ Electrical\ Energy\ Produced\ over\ Lifetime}$$

(Levelized Cost of Energy (LCOE) Calculator, 2016).

Estimating return on investment (ROI) analysis takes into account the estimated total power output of a solar farm, and the costs of installation, components, and maintenance. This key performance indicator is important to determine profitability and is a useful measure to determine success over time. A positive ROI can be considered profitable as it yields more in revenue than it costs to pursue. A negative ROI can break a solar project. Calculating the estimated ROI of such a project before moving forward can help a business ensure that they are making the best possible uses of the resources available. A simple ROI is calculated as

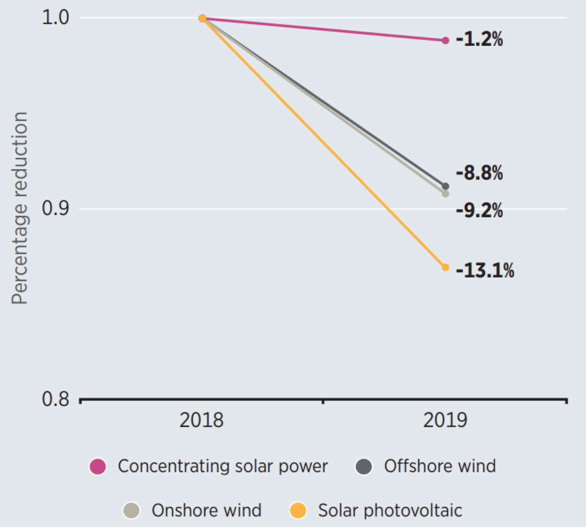
$$\text{ROI} = \frac{Net\ Profit}{Cost\ of\ Investment} \text{ x } 100$$

(*How to Calculate ROI to Justify a Project | HBS Online*, 2020)

From an economic standpoint, renewable energy increasingly out-competes fossil fuel. Driven by steadily improving technologies, economies of scale, competitive supply chains and growing developer experience, renewable power generation costs have fallen sharply over the past decade (IRENA, 2020). According to a 2019 International Renewable Energy Agency (IRENA) report, 56% of all newly commissioned utility-scale renewable power generation capacity provided electricity at a lower cost than the cheapest new fossil fuel-fired option (IRENA, 2020). As discussed above, a diversity of renewable energy production methods is key to cutting carbon emissions and securing the energy supply.

Specifically addressing photovoltaic energy, the global weighted-average LCOE of solar PV fell by 13% year-on-year in 2019 thanks to declines in panel prices and system costs (non-panel and inverter hardware, installation costs, and soft costs) whereas wind energy experienced a year-on-year decline of around 9% (IRENA, 2020). Figure 2 details the global LCOE from newly commissioned utility-scale renewable power comparing concentrating solar power, offshore wind, onshore wind, and solar photovoltaic.

Figure 2.



Note. Global LCOE from newly commissioned utility-scale renewable power. From IRENA Renewable Cost Database. From *Renewable Power Generation Costs in 2019* (p.21), by IRENA. Copyright 2020 by IRENA.

Photovoltaic energy outshines wind energy economically. Furthermore, wind energy is more degrading to the natural landscape, unpredictable in energy production, and contributes to higher levels of noise pollution.

2.1.3 Photovoltaic Energy Optimization

Certain types of solar panels are more efficient in cloudy climates (Amin et al., 2009). Mono-crystalline silicon and multi-crystalline silicon solar panels perform best when they are under direct sun; on the other hand, the copper–indium–diselenide (CIS) and amorphous silicon solar modules perform better when it is cloudy and sunshine is diffused (Amin et al., 2009).

Not only can the type of panel aid photovoltaic energy acquisition, but the tilt and orientation of the panels also play a vital role. In the northern hemisphere, the optimal orientation is due south (Armstrong & Hurley, 2010). Calculating the optimal tilt angle of the solar panel involves hourly direct radiation calculations (Armstrong & Hurley, 2010). However, since this radiation is split into direct beam and diffuse components when it is cloudy, a diffuse fraction correlation is used to help find the direct hourly radiation in partly cloudy and overcast days (Armstrong & Hurley, 2010). The radiation data on clear, partly cloudy, and overcast days is combined with the observed frequency of cloud conditions to find the total hourly direct radiation (Armstrong & Hurley, 2010). The hourly direct radiation can then be calculated for cloudy and clear conditions at different tilt angles to optimize the amount of solar radiation absorbed by the panel (Armstrong & Hurley, 2010). Higher cloud cover means a panel must have a lower tilt angle (Armstrong & Hurley, 2010).

In addition to cloud cover, average temperature can impact the efficiency of solar PV cells. As temperature increases the energy output of a PV cell decreases; thus, PV cells are more efficient in colder temperatures (Sproul & Green, 1991). Solar panel installations implemented at research stations with extreme latitudes have shown that solar panels can be effective at latitudes with reduced sunlight. Researchers at the Northern Research Institute in Narvik, Norway have developed robust systems with the goal of proving that solar power at extreme latitudes are "not only possible, but also profitable" (Nordic Energy Research, 2011). On the opposite pole, photovoltaic solar panels cover nearly every surface of Antarctica's Princess Elisabeth Station (International Polar Foundation, 2021). These research stations deal with temperatures well below freezing, high wind speeds, and in the winter, near constant snow and ice. If solar panels can be used successfully and efficiently in extremes such as these, they could thrive in the relatively moderate latitude of Denmark, which has less harsh conditions, but still colder temperatures, which make solar panels run more efficiently.

2.1.4 Solar Panel Disposal

An important aspect of developing a solar farm is handling the associated waste. Europe is dedicated to researching methods of solar panel recycling (Chowdhury et al., 2020). In Europe, manufacturers are required to gather their panel waste after their lifetime (Sinvula et al., 2021). Solar panel recycling aims to preserve important parts of the panel for reuse. There are three different types of recycling methods: thermal, chemical, and physical (Chowdhury et al., 2020; Sinvula et al., 2021). Thermal recycling involves the process of heating the panel to collect the crystalline silicon, glass, and metal fractions (Chowdhury et al., 2020). Chemical recycling involves using acid leaching or solvents to isolate specific elements such as copper and tin and also can effectively restore the efficiency of panels by removing layers and replacing them (Chowdhury et al., 2020). Physical recycling involves dismantling the panels by removing the frames for repurpose and shredding other components examining their toxicity (Chowdhury et al., 2020). It is typical for a recycling strategy to combine these methods in order to most effectively reuse a solar panel. The junction box is what typically fails first on a solar panel due to contact defects (Chowdhury et al., 2020). If the junction box is located on the outside of the panel, it is easily replaceable and will help increase the output power of the older panels (Chowdhury et al., 2020). However, over time solar PV panels will lose efficiency over time therefore new panels will usually be necessary after their warranty expires (Chowdhury et al., 2020). Storage of depleted solar panels as well as the handling of waste needs to be considered before building a solar farm.

2.2 The Island of Langeland

Langeland is an island located in the center of Denmark with a population of 12,316 (*Population at the First Day of the Quarter - StatBank Denmark*, n.d.). Langeland is known for its vacation houses and activities, which during the summer months can cause the population of the island to double (Borchardt, n.d.). In Figure 3, Langeland is highlighted in red.

Figure 3

Note. Location map of Langeland. From Wikimedia Commons by LOS688, 2009, File:Location map Langeland.svg (https://commons.wikimedia.org/wiki/File:Location_map_Langeland.svg). CC-BY 3.0

Langeland currently produces 177% of the island's electrical needs by renewable energy (*Grøn Energi | Www.Langeland.Dk*, n.d.). Since the island is producing more power than it needs, it is exporting the excess to other parts of Denmark. Only 8% of Langeland's renewable energy production is due to photovoltaic energy, while the other 92% is generated by wind based renewable energy (*Grøn Energi | Www.Langeland.Dk*, n.d.). The municipality of Langeland pushes for more green energy based projects such as sustainable construction, and has joined sustainability agreements that will carry the municipality into the later 2020s (*Bæredygtighed Som Forretningspotentiale*, n.d.).

Langeland's high latitude (54.82° N) causes the average sunlight that Langeland receives to be lower than the continental USA and drastically differ season to season. For reference, the city of Humble (54.82° N), on the island of Langeland averages 1765 hours of sunlight yearly (*Average Monthly Hours of Sunshine in Humble*

(Syddanmark), Denmark, n.d.), whereas Worcester, Massachusetts (42.27° N), averages 2629 hours (*Average Monthly Hours of Sunshine in Boston (Massachusetts), United States of America*, n.d.). Langeland receives the least amount of sun during the winter, averaging only 7.2 hours of sunlight daily in the month of December (*Humble, Denmark Weather in March*, n.d.). This limits the production of solar power in Langeland during the winter months. Conversely, the summer months average 17 hours of sunlight a day allowing for large amounts of solar power production (*Humble, Denmark Weather*, n.d.).

Solar energy production on Langeland is also limited by frequent cloud cover. Langeland averages roughly 25% cloud cover during the winter and upwards of 50% in the summer (*Humble, Denmark Weather in March*, n.d.). This summer cloud coverage counteracts the increased sunlight hours and also increases the chances of shading based power loss. When a cloud passes overhead and blocks sunlight from certain parts of the panel, it will cause a loss in current (*Shading | PVEducation*, n.d.). If the panel is connected in series with other solar panels, then the loss of current from one panel will create a loss in current across the entire output (*Shading | PVEducation*, n.d.). If a singular panel is half shaded, then the total current of the system will drop proportionally (*Shading | PVEducation*, n.d.). Thus, cloud cover will limit the amount of energy being produced by a solar farm.

Langeland has made improvements to its electrical grid to allow for greater security of its power supply. The island has laid all of the grid connections underground to limit failure from the weather and other conditions (Borchardt, n.d.). The island has also reinforced the connections and lines in the grid, to better protect the grid from failures with redundancies so that if one connection is not secure, the entire grid will not fault (Borchardt, n.d.). The grid of Langeland is also connected to neighboring islands of Funen and Ærø. This prevents complete power outages if the renewables on Langeland fail (Borchardt, n.d.).

2.3 Environmental Considerations of Solar PV Farms

When developing a solar farm, it is important to not only consider the environmental benefits of clean energy, but also the potential impacts of the solar farm at the local level. This section details several important factors to consider when developing a solar farm.

As with any large development project, solar farms can have numerous effects on the local environment, both positive and negative. The major environmental concerns for large-scale PV installation include land use and hazardous materials. Many researchers cite benefits, such as reduced global emissions, of solar farms over conventional fossil fuel plants as enough to warrant their use; however, solar farms can cause significant changes and detriments to local ecology and biodiversity that cannot be overlooked (Tanner et al., 2021). Many of these effects can impact local human populations: improper land development can detriment recreational habitats and scenic areas, rise in temperatures can harm crucial pollinator species, and hazardous materials can enter the local food and water supply (Fthenakis & Kim, 2009). Comparing the impacts of solar farms and other power sources on the local ecosystems is often difficult, as understanding biodiversity is complex and few metrics exist to quantitatively compare sites (Fthenakis et al., 2011). Instead, it is reliant on the developer to consider all aspects of the local ecology they are working in and plan proactively to mitigate negative effects on the local ecosystem (Fthenakis et al., 2011).

Impacts of Land Use of Solar Farms on the Local Environment

The greatest environmental concern for utility-grade solar farms regards the use of the land that the facility is built on (*Solar Energy Development Environmental Considerations*, n.d.). Although solar PV farms occupy less land in their life cycles than coal-fired power plants as well as the least amount of land among renewable energy options, developing land for solar farms can still be detrimental to the local ecosystems (Fthenakis & Kim, 2009).

For instance, installation of a solar farm requires extensive soil modification and removal, which takes several years to recover (Fthenakis et al., 2011). This can significantly alter the physical and chemical properties of the site, including mineral nutrition content, microorganism structures, water flow, and carbon dynamics (Choi et al., 2020). However, reintroducing native vegetation after installation can help restore the soil (Choi et al., 2020). A study of a revegetated PV farm and an adjacent ecosystem in Colorado, United States found that the PV arrays changed the moisture distribution of the soil and that the carbon and nitrogen content was still lower in the soil of the PV site compared to the adjacent ecosystem, seven years after revegetation (Choi et al., 2020). The researchers noted that considering the redistribution patterns of moisture from the panels when revegetating could help maximize the plant growth and minimize soil erosion (Choi et al., 2020). Additionally, PV installations need to be evaluated for their potential impacts on nearby wildlife habitats and resources such as grazing or breeding territories (*Solar Energy Development Environmental Considerations*, n.d.).

Extensive clearing of undeveloped land or forests is an obvious source of habitat loss that can cause death or injury to individuals; however, less destructive installations can also substantially impact local ecosystems (Fthenakis et al., 2011; Tanner et al., 2021). Most solar farms are enclosed by fences, which can impede the movement of most animals (Fthenakis et al., 2011). While some fencing may be unavoidable, adding openings for small animals and making sure the fences will not snare larger animals, are easy options to limit the impact of fencing on the local fauna (Fthenakis et al., 2011). Proximity to wildlife sanctuaries and fragile ecosystems, must be considered and the potential impacts of the site should be consistently monitored and mitigated if a solar farm is developed in the vicinity of these locations (Fthenakis et al., 2011).

Further habitat loss can arise from the removal of vegetation as this can impact predator-prey dynamics as well as food and shelter availability (Fthenakis et al., 2011). Shading and water redistribution from the panels themselves can create disturbances in the microenvironment, which can impact plant growth (Tanner et al., 2021). Adding raised platforms that leave room under the solar panels could help limit the impacts on local plant and small animal life (Fthenakis et al., 2011). However, some plants do worse in excess shade, even with undisturbed soil, so understanding the local biodiversity is crucial to implementing an effective strategy for each individual site (Tanner et al., 2021). Solutions can help not only mitigate local environmental effects but create positive change that helps the native biodiversity thrive. For instance, developers of a solar farm in Wiltshire, UK planted native species around solar panels to provide habitats and food for native pollinators (Moore-O’Leary et al., 2017).

Impacts of Hazardous Materials Released from Solar PV Farms

Photovoltaic cells can also be potential sources of hazardous contaminants (*Solar Energy Development Environmental Considerations*, n.d.). Photovoltaic cells are manufactured with hazardous materials and although these are sealed under normal operating conditions, extensive wear or damage can cause these materials to leach into the environment (*Solar Energy Development Environmental Considerations*, n.d.). Additional contaminants can enter the environment through the installation process or through waste materials used to package or protect the components of the photovoltaic cells during transportation (*Solar Energy Development Environmental Considerations*, n.d.).

3.0 Methodology

The goal of this project was to develop a feasibility study of a utility-scale solar PV farm on the Danish island of Langeland. In order to achieve this goal, we pursued the following objectives:

1. Identify regulations that would impact a solar farm
2. Investigate impacts of a solar farm on the local environment
3. Estimate the power output of a solar farm
4. Estimate the costs of a solar farm
5. Prepare a feasibility analysis

In this chapter, we describe the methods to gather and analyze input from literature review and how the results of that analysis are drawn upon to develop a feasibility study of a solar farm on Langeland for LAUTEC.

3.1 Investigate Regulations that Would Impact a Solar PV Farm

Our first objective was to investigate and understand the regulations that would impact a utility-scale solar PV farm on Langeland. These include tax, zoning and land development, environmental, and electrical grid regulations.

Tax Regulations

We sought information on tax regulations to ensure that the solar farm owner is tax compliant and aware of the municipality and federal tax laws on the land and electricity produced as they develop and operate the solar PV farm (Northeastern University, 2020). We communicated via email with the Plan Coordinator of the Technology and Environment Department from Langeland Municipality. To gather information on the associated federal taxes, we contacted the Business Department of the Danish Tax Agency, an agency under the Ministry of Taxation.

Zoning & Land Development Regulations

In order to investigate regulations, we gathered information regarding zoning and land development regulations. Zoning allows authorities to regulate land-property and determines how a piece of land can be used, ensuring that the intended use for the land takes every regulation into account (Zoning and Land Use Planning | Urban

Regeneration, 2015). Zoning is important as it can restrict the use of the property and/or set standards in the size, placement, and construction of the solar PV farm (HG.org, 2022). Land use permits are needed to ensure that current or proposed land use is in compliance with the municipality and that it considers all viable factors such as environmental constraints, commerce, and roadway capacity (Land Use Regulatory Permitting, 2020). Although The Ministry for Business and Growth is the federal body responsible for creating policies, Langeland Municipality is the most important actor in local zoning and land development as they carry out and enforce said policies. To investigate Langeland's zoning and land development regulation, we contacted the Plan Coordinator of the Technology and Environment Department and Nykredit, one of Denmark's leading bank and mortgage providers.

Environmental Regulations

To minimize disruption to the local environment and even improve the local biodiversity, we sought information on the environmental regulations in Denmark. Environmental considerations have been brought to the forefront of developing in Denmark by public sentiments and increasing regulations. In order to understand the environmental regulations, the team contacted the Legal Specialist for Landscape and Forest at the Danish Environmental Protection Agency.

Electrical Grid Regulations

We researched information regarding electrical grid regulations as it is important to understand and ensure robust grid integration to maximize the cost-effectiveness while maintaining or increasing system stability and reliability (*Overview of Grid Integration Issues*, 2022). Energinet is the independent public enterprise owned by the Danish Ministry of Climate that owns, operates, and develops the transmission systems for electricity and natural gas in Denmark. We used published information from Energinet to guide our investigation of the requirements for grid connection. Additionally, we emailed Fonden Langelands Elforsyning (LEF) which is the electrical utility company on Langeland.

Response Rates

Communication via email was chosen as our inability to speak Danish limited the ease of phone conversations. We were successful in contacting the Plan Coordinator of

Langeland Municipality and the Landscape and Forest Legal Specialist from the Danish Environmental Protection Agency. Unfortunately, the Danish Tax Agency was overwhelmed due to tax season and we did not receive any information. Additionally, we were unsuccessful with our communication with Nykredit and LEF. The contact information for the Technology and Environment Department of the Langeland Municipality, the Danish Tax Agency, the Danish Environmental Protection Agency, Energinet, and LEF is found in the IQP Report Appendix A: Contact Information

3.2 Investigate Impacts of a Solar Farm on the Local Environment

Our next objective was to investigate and understand the impacts a possible solar farm installation would have on the local wildlife in order to make recommendations that will promote local biodiversity. We found examples from solar projects in similar ecosystems and used environmental data collected from the area to understand and make suggestions to reduce the negative effects of a solar farm on the wildlife and environment.

Understand Local Ecology

In order to understand and mitigate potential environmental impacts, solar developers must understand the dynamics of the local environment and ecology. Since we could find little available data regarding the specific ecology of Langeland, information regarding the critical and endangered species that could be in the area was gathered by parsing data from the IUCN Red List (*The IUCN Red List of Threatened Species*, 2022). The species on this list are the critical species throughout Denmark that are found in similar ecosystem types as those around the site. Therefore, species of local conservation interest may have been omitted and some species that are not present or not at risk in these ecosystems may have been erroneously included.

To determine the ecosystems present on each site, we used satellite data and onsite-surveys. To get an accurate understanding of the specific flora and fauna that make up the surrounding ecosystems, we prepared procedures for ecological surveys for several taxon groups including birds, bats, non-volant mammals, flora/fungi, reptiles/amphibians, pollinators, and ancient trees (information regarding survey techniques can be found in Chapter 5, Recommendations for Biodiversity Management

Plans.

Biodiversity Management Recommendations

After collecting data about the local ecology, we drafted recommendations for a Biodiversity Management Plan (BMP), a document that developers create that outlines their plans to protect and manage the local ecology. We used BMPs published from other solar developments to guide our investigations and recommendations. Additionally, information about the native flora helped us make suggestions for reseeding the areas surrounding the solar farm with species that will attract pollinators and promote biodiversity. The overall ecological data allowed us to make recommendations for creating new ecosystems around the site to improve the biodiversity of the surrounding area.

3.3 Estimate the Power Output of a Solar Farm

Another primary goal was to calculate the power output of a solar farm. Since the power output of a solar farm determines the financial return of the farm, the power output is the driving force that makes a solar farm financially feasible to the developer. We developed a Python toolkit for the total photovoltaic energy output based on component efficiencies, solar farm size, and irradiance data as well as costs and returns, which will be discussed in the IQP Report Section 3.4: Estimate the Cost of a Solar Farm.

Table 2: Key Variables to Determine Solar Power Output

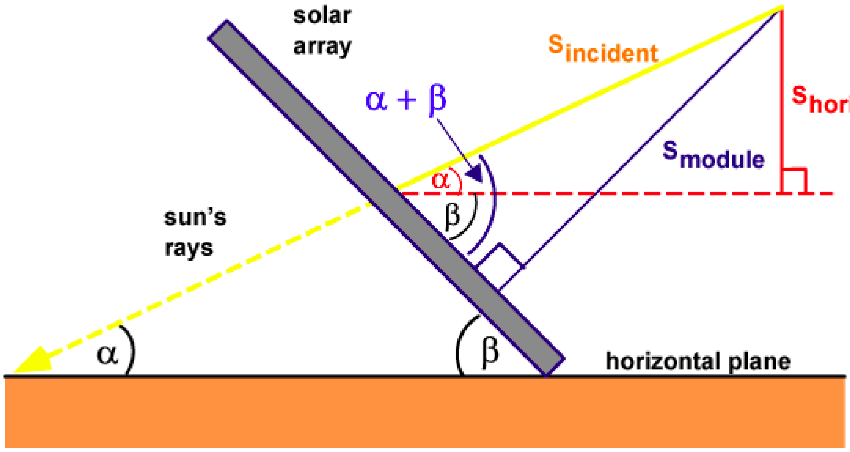
δ	Declination angle
α	Elevation angle
d	Day of the year
ϕ	Latitude
β	Panel tilt
ε	Percent efficiency of panel
A	Area of panel (m^2)

N	Number of panels
λ	Percent of total energy output loss due to malfunction, soiling, temperature, etc.

Solar Irradiance

To calculate solar irradiance for the site, we used irradiance data from nasa.gov, downloaded as a CSV. Specifically, we used daily all sky surface shortwave downward irradiance (kW-hr/m^2/day) specific to our site on Langeland. This represents the solar irradiance during all sky conditions. For the following calculations, we used generalized equations to provide accurate estimates of each calculated variable. We found this provided sufficient precision without involving complex calculations. The calculations were computed in a Python toolkit, the documentation for which can be found in the IQP Report Appendix B: Python Toolkit Documentation.

Figure 4



Note. From Solar radiation on a tilted surface [image], by C.B.Honsberg and S.G.Bowden, 2019, (https://www.pveducation.org/pvcdrom/properties-of-sunlight/solar-radiation-on-a-tilted-surface) Reprinted with Permission.

We calculated the declination angle (δ), the angle between the center of the Earth and the center of the sun from the equator. Since the declination angle varies as the earth revolves around the sun, it is calculated separately for each day in the year (1-365), indicated by the variable d. From the declination angle and the latitude (ϕ), we then calculated the elevation angle (α), which is the angle at which the sun's rays hit the solar panel. We then used the elevation angle and the daily all sky surface shortwave downward irradiance to calculate the daily direct normal irradiance. We then calculated irradiance on a tilted panel using the direct normal irradiance, elevation angle, and optimal tilt angle (β**)**. The equations and data used to calculate this radiation and the optimal tilt angle are found in the IQP Report Appendix C: Calculations of Site-Specific Solar Radiation. A diagram portraying these angles is shown in Figure 4.

The tilted irradiance is the expected radiation absorbed by one tilted panel each day. To get the panel output, we multiplied the tilted irradiance by the panel efficiency percentage (ε) and the area of a panel (A) (taken from the manufacturer specification sheet for the solar panel). We then took the summation of these daily values to find the yearly output of a panel at this site. These calculations were all computed with our Python toolkit and can be recalculated for any site by changing only the irradiance data input.

Energy Dependent on Spacing

To limit panels shading other panels, the solar arrays must be spaced a minimum distance apart. The minimum spacing can be calculated from the adjusted height of the tilted panels, the minimum solar elevation angle (at the winter solstice for the northern hemisphere), the optimal tilt angle, and the azimuth correction angle (which corrects the tilt based on the position of the sun towards the north/south). The width of a row can then be calculated by adding this spacing to the length of a tilted panel. The equations used to calculate these values can be found under the “Calculate Module Spacing” and “Calculate Row Width” section of IQP Report Appendix B: Python Toolkit Documentation.

Energy Dependent on Land Area

The total solar output of the farm is the product of the number of panels and output of each panel. To calculate the number of panels on a usable site, we first had to make several assumptions about the shape of the plots. Computing the exact number of solar panel arrays that can fit in a non-rectangular area of land in the proper orientations involves complex algorithms (Hegedüs, 1982). However, calculating the number of solar panel arrays that can fit in a rectangular area of land is fairly easy; the number of panels is the product of the area's length divided by the row width and the area's width divided by the panel's length. Rather than implementing a complex packing algorithm, we extrapolated rectangular areas over each site in QGIS and calculated the number of solar panels that could fit into these rectangular areas by the method described above. We then estimated the number of panels in the actual plots by computing the product of the number of panels in the rectangular plot and the ratio of the actual site area over the rectangular area. Finally, we calculated the total yearly output of the farm by multiplying the total number of panels by the output of one panel.

3.4 Estimate the Costs of a Solar Farm

In order to create a feasibility study for a solar farm on Langeland in Denmark, we evaluated the associated financial and social costs. We analyzed the direct and indirect costs of developing a solar farm in Table 3:

Table 3: Direct and Indirect Cost of Developing a Solar PV System

Category	Description
Direct Costs	
PV Array	Interconnected PV modules that convert solar radiation into DC power
Racking and Mounting	Fixes solar panels to the ground at the optimal angle and mounts the inverters
Inverters	Converts direct current (DC), generated by a solar panel, to alternating current (AC), which is used by the electrical grid
Batteries	Technology that can capture electricity, store it as another form of energy (chemical, thermal, mechanical), and then release it when needed
Engineering, Procurement, and Construction (EPC)	Development and installment of the solar PV farm, from early concept to the construction (mechanical installation, electrical installation, and inspection)

Indirect Costs	
Land	Cost to lease an acre of land per year
Taxes	Cost associated to be tax compliant
Incentive Application	Cost related to compliance in order to benefit from support policies
Operation & Maintenance	Includes the cost of labor to operate and maintain the solar farm over time

Furthermore, we considered the ethical sourcing of materials for the farm when deciding what equipment to suggest.

Direct Costs

PV Array

First, we conducted a cost analysis of different types of panels by reaching out to manufacturers including: Risen, Trinasolar, Astronergy, CanadianSolar, JinkoSolar, SunTech, Jolywood, JASolar, Longi Solar, Maxeon, MiaSolé. Contacting manufacturers allowed us to get current market quotes of panels that fell within our specifications. This combined with literature review of different panel types, allowed us to decide on a specific panel type. We investigated social costs by ensuring that panels were ethically sourced. This was accomplished when we reached out to the manufacturers; we also requested information on how and where the panels were manufactured.

Inverters

To estimate the cost for inverters we found listed costs on the manufacturer's websites. To determine the amount of inverters we used a standard ratio of 1:1.25 (Inverter Max Power : Panel Max Power) to find the total amount of inverters necessary. We found the information on max power by investigating specification sheets provided by manufacturers.

Batteries

To estimate the cost for batteries we made a loose assumption based on other battery solutions provided by manufacturers, such as Tesla and Siemens. The amount of battery storage needed was assumed by the total estimated power output of the farm and literature review.

EPC

After we calculated component cost we contacted various renewable energy engineering companies to estimate the cost of an EPC. However, we never got a specific value from any of them. Therefore, we estimated the value for EPC cost based on installed cost from the International Renewable Energy Agency (IRENA) (IRENA, 2021). Installed cost includes labor, transport, component cost, etc. We took the installed cost value and subtracted our calculated component cost to get a rough estimate of the EPC cost.

Indirect Costs

Land Cost & Property Tax

We estimated the cost of renting the land based on input from our collaborator and similar development projects. Property taxes for solar farms value the farm based on 250 DKK per MW. To get the property tax we reached out to the Danish Tax Agency. This allows us to estimate the yearly operation costs associated with land use. However, it was challenging to contact the Danish Tax Agency and get an exact rate as it was during the tax season. Instead we assumed a property tax rate of 2.5% on the value of the solar farm.

Income Tax

As the sale of electricity will be subject to income tax, we loosely assumed that value from literature review of corporate income tax which is 22%.

Incentive Application

Incentives were estimated from literature review.

Operation and Management Costs

In order to find operation and maintenance costs we conducted literature review to discover what is required to operate and maintain a solar farm. To estimate the associated costs, we reached out to operation and maintenance companies for information and quotes. We used this information to propose methods for operation and maintenance of the solar farm. However, only one operation and management company got back to us, European Energy, so our results may not accurately reflect the average current market value of operation and maintenance.

As discussed in the IQP Report Section 3.3: Estimate the Power Output of a Solar Farm, we developed a Python toolkit to calculate solar output and financial projections. To make said financial projections comparing the costs and benefits of a solar farm, we compiled data from a variety of sources including manufacturer quotes and similar projects. The Python toolkit takes variables for all costs discussed above and the solar power estimates as described in Section 3.3. From these values, the toolkit creates a financial projection that calculates the total costs and return over the lifespan of the solar farm. Unforeseen costs and the unpredictable nature of economic factors such as inflation and electricity cost limit the overall accuracy of the model.

The challenges we faced while gathering this information was responsiveness, small-scale vs. large-scale solar farm feasibility, and accuracy due to estimates. Manufacturers were non-responsive and required multiple emails before we got any response. This reduced the amount of quotes we received, making our findings less broad and precise. In literature review, the academic research available for comparing different solar technologies was mostly for small-scale (>1MW) farms. Therefore, when it came to estimates regarding cost, they did not take into account small-scale manufacturing vs. large-scale manufacturing. The information gathered did not meet our needs, as a result we received our quotes for the solar panels directly from manufacturers. For other components, cost was gathered from the manufacturer's websites.

3.5 Prepare a Feasibility Study

Our final objective was to conduct a feasibility study for a proposed solar PV farm on the island of Langeland. This involved compiling all of our data and previous research to evaluate the feasibility of a solar farm and make suggestions regarding its implementation in a standalone document. In our feasibility study, we outlined the components of a solar PV farm and the process of development including site selection, performance and optimization, operation and maintenance strategies, decommissioning, and economic performance. To not only aid LAUTEC in determining the feasibility of this project, but also future projects, we created a reusable Python toolkit to determine the economic viability of a solar farm at any location. Using this toolkit, we estimated the costs and returns of the solar farm and ran several financial scenarios to determine the likely return on investment. Finally, we discussed the future of photovoltaic energy including trends in energy price and evolving technologies such as multijunction solar cells and Power-to-X.

4.0 Feasibility Study of a Solar PV Farm on Langeland, Denmark

As the first step in evaluating a potential renewable energy project, a feasibility study examines the financial, technological, and environmental viability. The goal is to limit project risks and identify challenges early. A thorough and accurate feasibility study lays the foundation for a successful solar energy installation project.

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1 Background and Introduction

As fossil fuels from conventional energy sources are burned, large amounts of greenhouse gasses are released and trapped in the Earth's atmosphere, increasing the global surface temperature, thus causing damage to air quality, water, land, and wildlife. To combat the negative effects of fossil fuels, many countries have decided to invest in sustainable and renewable power. Denmark is at the forefront of sustainable development and plans to reduce greenhouse gas emissions by 70% (from 2020 levels) by 2030 and be completely free of fossil fuels by 2050 (Klimaloven, 2020; Parajuli, 2012). Regarding current renewable energy sources, wind power accounts for 58% of Denmark's energy production, while solar only accounts for 4%.

Thanks to increasing efficiency, and declining panel prices and system costs, there is untapped potential for photovoltaic energy. Photovoltaic energy technologies are not only advantageous as a renewable energy source but also for the following environmental and socio-economic reasons:

- Less water consumption compared to conventional power plants
- Minimized land transformation
- Shorter payback time
- Fewer visual impacts and low noise pollution
- Increased regional/national energy independency
- Diversified and secure energy supply

There are also environmental concerns, including the toxic chemicals used in the production of solar panels, ecological impacts of installation, and the recycling process of the panels (Aman et al., 2015). However, these unfavorable effects can be minimized by appropriate mitigation measures.

Since 2015, the Danish company LAUTEC has been working to accelerate the transition to renewable energy. LAUTEC offers IT solutions and consulting services to enable the public and private sectors to "develop, execute, and operate renewable energy projects smarter, faster, and cheaper" (LAUTEC, 2015). Now looking to expand the company's renewable energy consultation portfolio, LAUTEC is interested in exploring the feasibility of a solar farm on the Danish island of Langeland.

LAUTEC selected several agriculture sites on Langeland for a feasibility study of solar PV farm installations. Farmland presents a good opportunity for solar installation, as it has already been cleared, limiting financial and legal risks associated with clearing land. Frequent tilling also decreases the need for grading to flatten the land, which can be expensive.

Langeland is a Danish island situated between the larger islands of Funen and Zealand. The island consists of one municipality, which has a population of 12,446, and consists of 285 km^2 ("Langeland," 2021). The climate of Langeland consists of frequent cloud cover and precipitation, with temperatures ranging from 3 to 25 degrees Celsius. Additionally Langeland's high latitude (54.82° N) causes the island to receive as little as 7 hours of sunlight a day in the winter months and up to 17 hours a day in the summer months (*Humble, Denmark Weather in March*, n.d.).

Figure 1

Note. Location map of Langeland. From Wikimedia Commons by LOS688, 2009, File: Location map Langeland.svg (https://commons.wikimedia.org/wiki/File:Location_map_Langeland.svg). CC-BY 3.0

This report presents the results of an investigation of the feasibility of solar PV farms on several agricultural sites and provides estimates of cost and performance.

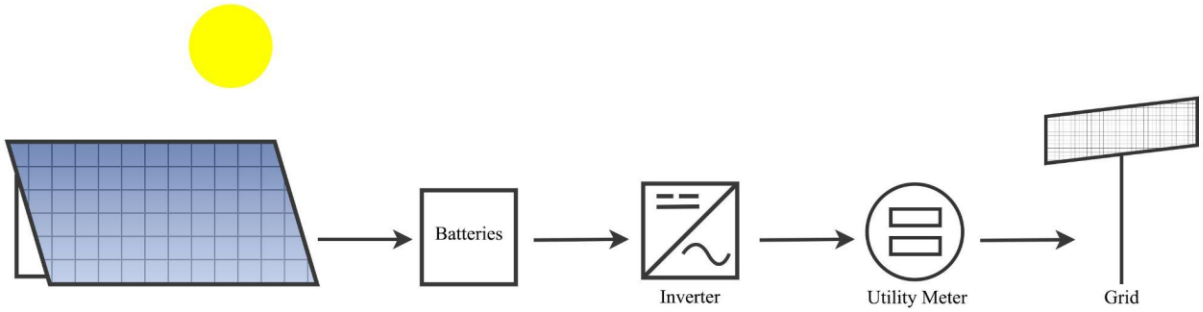
2 Photovoltaic (PV) Systems

In this section, we give an overview of photovoltaic solar farms, including their components, operation and maintenance, and performance. We then provide our recommendations for a conceptual solar farm on Langeland.

2.1 Solar PV System

Solar farms are large-scale, ground-mounted solar installations, where thousands of photovoltaic (PV) solar panels are arranged in the favorable position to absorb energy from the sun, convert it into electricity, and send the electricity to the power grid for distribution and consumption. Solar panels generate direct current (DC) power, which an inverter converts to alternating current (AC) power for use by the electrical grid as shown in Figure 2.

Figure 2



Note. Layout of grid connected photovoltaic system.

2.2 PV System Components

A utility scale ground mounted solar PV farm consists of a core set of components, shown in Table 1 (Solar Systems Integration Basics, 2022).

Table 1: Basic Solar Hardware Components and Descriptions (Solar Systems Integration Basics, 2022).

Component	**Description**
Solar PV Array	Interconnected PV modules that convert solar radiation into DC power
Racking and Mounting	Fixes solar panels to the ground at the optimal angle and mounts the inverters
Batteries	Technology that can capture electricity, store it as another form of energy (chemical, thermal, mechanical), and then release it when needed
Inverters	Converts direct current (DC), generated by a solar panel, to alternating current (AC), which is used by the electrical grid

Solar PV Array

There are three major types of solar panels used in utility-scale solar farms: monocrystalline, polycrystalline, and thin-film panels (Kiwi Energy, 2020). Within each major category, there are different panels that vary in composition and have unique advantages and disadvantages. An improvement of the traditional monocrystalline panel is Passivated Emitter and Rear Cell (PERC) panels. Variations in thin-film panels include Copper Indium Gallium Selenide (CIS) panels (*Comprehensive Guide to Solar Panel Types - Aurora Solar*, 2021). Key factors when selecting solar panels are the cost of panels, solar efficiency, lifespan, reliability, and size. Table 2 details a few of these attributes for different types of solar panels.

Table 2. Monocrystalline PERC and CIS panel information (Qarony et. al., 2017; MiaSolé Hi-Tech Corp., 2019)

Panel Type	Efficiency	Shadow Tolerance	Typical Warranty
Monocrystalline PERC	25%	Low	-12 years enhance product warranty on materials and workmanship -25 years linear power performance warranty
CIS	18%	High	-5 year workmanship -10/25 year warranty against power loss

Other factors, such as temperature and climate can affect a panel's ability to generate energy. For instance, monocrystalline silicon solar panels perform best under direct sun, while CIS solar modules perform better under cloudy conditions (Bostan et al., 2017). Furthermore, CIS panels suffer less power loss from high temperatures compared to other panel types (Kumar et al., 2015) Ultimately, the choice of solar panels comes down to the specific property, condition settings, and cost.

Racking

Panel arrays are supported by racking systems. The main types of racking systems are fixed tilt, single-axis tracking, and dual-axis tracking. Fixed tilt racking consists of fixed angle panels that do not shift over time (Barbón et al., 2021). Single-axis tracking allows for movement of panels on one axis to follow sunlight and move to an optimal angle throughout the year. Dual-axis tracking allows for movement both vertically and horizontally over time to increase solar irradiance through the year.

Batteries

Battery storage technology is a solution to increase system flexibility in a power system; however, high costs limit their use to specific scenarios (Utility-Scale Batteries Innovation Landscape Brief, 2019). Utility-scale battery storage systems have a typical storage capacity ranging from around a few megawatt-hours (MWh) to hundreds of

MWh. They act as a reserve and are able to defer depositing excess energy into the grid (Utility-Scale Batteries Innovation Landscape Brief, 2019).

Inverters

Inverters are electrical components that take the DC power created by the solar array and transfer it to AC power, which is the type of power that is transmitted on the electrical grid. For a solar farm, two types of inverters exist, micro inverters and string inverters. Micro inverters are a 1:1 ratio with inverter to panel, while string inverters are connected to a string of panels based on a standard 1:1.25 (inverter max power : panel max power) ratio.

Development and Construction

On large-scale and complex infrastructure projects such as a utility scale solar PV farm, clients typically enter into a contract with an Engineering, Procurement, Construction (EPC) company. EPC is responsible for performing the engineering design, then procuring the necessary materials needed for construction, and finally construction which includes mechanical installation, electrical installation, and inspection.

2.3 Operation and Maintenance

Operation and maintenance of a solar farm is the process of maintaining the solar farm throughout its life and includes cooling, dust removal, and performance checks. Since panel efficiency decreases by 0.5% for every degree increase in temperature from 0 to 75 degrees Celsius, cooling strategies can be effective methods to increase output in certain climates (Moharram et al., 2013). For instance, a study in Mâcon, France showed an increase of 6% of the standard efficiency after implementing a cooling strategy (Fraisse et al., 2007). Furthermore, soiling losses are the percent losses of the panel’s power output due to dust and dirt accumulation on the solar panels surface. A study researching soiling losses for 250 solar farms concluded that soiling accounts for 1.5 to 6.2 percent of losses depending on location (Iftikhar et al., 2021). The study also found that rain does not always clean the modules; at least 20 mm of rainfall is required to properly clean off the modules (Iftikhar et al., 2021). A light shower can make mud on the panels, worsening the soiling condition (Iftikhar et al., 2021). As temperatures and dust accumulation are highly dependent on climate, the necessity of cooling and dust removal strategies are unique to each location. Other forms of maintenance include preventative maintenance, corrective maintenance, and operational services. A full list of these services, provided by European Energy, a company that offers operation and maintenance services for solar farms, is given in Chapter 4.0 Appendix A: Operation and Management Services.

2.4 PV Performance

Key factors of PV performance include: solar irradiance, tilt angle, and shading. Solar irradiance is the amount of light radiation that impacts a surface and, in the case of a solar panel, it is the energy available to be absorbed. The solar irradiance absorbed can be optimized by manipulating the tilt angle and orientation of the solar panel. In the northern hemisphere, the optimal orientation of solar farms is due south (Armstrong & Hurley, 2010). However, changes in land slope can impact the angle at which the panels must be placed, so it should be confirmed that the angle remains consistent with the horizontal by measuring the incline of the ground and adjusting the angle accordingly.

Furthermore, solar PV systems should be installed in locations with no obstructions and limited shade. Shading leads to serious power generation losses in the array due to differences in electrical characteristics, or mismatching, between modules.

Including shading, a list of forms of energy loss includes:

- **Clipping** - Power loss due to inverter input voltage and output power limits
- **Shading** - Loss caused by shading from rack rowes casting shadows and weather patterns
- **Dust and Dirt** - Loss due to debris buildup from the environment
- **Reflection** - Power loss due to reflectivity of panel
- **Array Mismatch** - Power loss due to component manufacturing defects
- **Irradiation** - Power loss due to low solar irradiance causing inverter not to turn on (Portal, 2018)

By understanding reasons for power loss, developers and operators can mitigate and maintain the facilities to obtain the maximum amount of power from a solar PV array.

2.5 System Recommendations for Langeland

We recommend monocrystalline PERC panels.
For utility-scale solar farms, monocrystalline PERC is the leading panel type. An example of a potential solar panel would be the CanadianSolar HiKu 7 (CS7N-MS 640-670 Watts), priced for mass bulk order at $0.30/W or approximately $205 per panel. Monocrystalline PERC is recommended over Copper Indium, and Selenium (CIS), due to PERC's higher efficiencies and lower cost of energy. Even though CIS performs better in cloudy conditions, its lower efficiency and limited manufacturing make it unsuitable for utility-scale farms.

We recommend string inverters.
For large scale utility farms, we recommend string inverters, as they are more cost efficient than micro inverters. Micro inverters are currently less cost efficient and large-scale manufacturing has not been developed yet.

We recommend a battery solution that allows for instantaneous high-power output with a low-power long term output to improve efficiency and limit power losses.
Batteries can be useful for sustaining level power output or for collecting extra power output during low times in usage. A battery solution can be beneficial if a PPA has been created, as batteries allow for stable energy output. Battery solutions for utility scale solar farms are customizable to suit specific tasks. Multiple manufacturers, such as Siemens, Tesla, General Electric Energy Storage, and Fluence, develop battery solutions for utility-scale solar farms. Options for solutions include high MW output over a short amount of time, lower MW output over a longer amount of time, or a combination system that allows for instantaneous high-power output with low-power long term output. We recommend investigating the combination system as the potential battery solution due to the frequent cloud shading that is caused by the climate of Langeland.

We recommend a fixed-tilt racking solution with panels at a tilt of 53 degrees from the horizontal and orientated due South.
Compared to single-axis and dual-axis tracking systems, fixed-tilt racking is more affordable, has a lower maintenance cost, and has the lowest levelized cost of energy

(Barbón et al., 2021). Depending on the optimization of panel tilt and placement, fixed-tilt racking is more cost efficient than tracking based racking systems (Barbón et al., 2021). Tracking systems are prone to mechanical failure due to the incorporation of moving parts and non-fixed components (Barbón et al., 2021). For the optimization of panel tilt and placement, in the northern hemisphere, the optimal orientation of solar farms is due south (Armstrong & Hurley, 2010). And according to calculations based on irradiance data from NASA, the optimal tilt angle is 53 degrees from the horizontal, 37 degrees from the vertical racking. See *Calculator Documentation* for relevant calculations.

We recommend the optimal spacing of panel arrays to be 4.37 meters.
Panel spacing is also an important characteristic of a solar farm. Optimal panel spacing can lead to higher power and cost efficiencies. By spacing the panels optimally, shading is limited and total solar panel amount/price is lowered. Using the calculator described in the IQP Report Appendix B: Python Toolkit Documentation, we calculated the optimal spacing of panel arrays to be 4.37 meters.

We recommend hiring an Operation and Maintenance firm.
Hiring an operation and maintenance (O&M) firm can increase the overall output of a solar farm over time due to mitigation of environmental and physical losses. The firm will monitor output and conduct preventative and responsive maintenance when necessary, such as snow and soiling removal. It is important to consider the effect of soiling and snow on the panel's output before implementing a cleaning campaign (M. Kolkenbrock, personal communication, April 11, 2022). If power output losses due to snow or soiling are excessive, it may be economical to implement a cleaning/clearing strategy (M. Kolkenbrock, personal communication, April 11, 2022).

We do not recommend a cooling strategy.
While cooling can be effective in warmer climates, the temperature on Langeland does not exceed the recommended operation temperature of any type of panel; therefore adding a cooling mechanism would not be financially advisable.

3 PV Site Locations

This section describes the considerations for site selection on Langeland. To understand the surrounding land and factors such as grid capacity, pre-visit screenings were conducted. We used site visits to select usable sites. Factors for site selection include electrical grid feasibility and tie-in locations, land elevation, terrain, and habitat, as well as the nearby residents' opinion on the land sites.

3.1 Pre-Site Visit Feasibility Screening

Grid capacity and distance to electrical substations on Langeland may limit the feasibility of the creation of a utility scale solar farm.
Langeland contains three electrical substations and an underground connected power grid. According to the plan coordinator of Langeland municipality, the current grid of Langeland is too oversaturated to sustain a utility scale solar farm, so the upgrade of existing substations or creation of a new substation and potentially the upgrading of the grid would be necessary. In the year 2020, the Danish government passed the Climate Agreement for energy and industry of 22 June 2020. The agreement shifts the cost of grid installment from a standard cost to a variable cost based on geographical location starting in 2023. The additional costs of upgrading the grid will be pushed to the renewable energy producer, which will cause extensive cost increases. (*High Uncertainty Surrounding Grid Connection Costs*, 2021)

The plots with flat land or slight southward slopes are optimal for solar farm feasibility. Hills and other changing terrain features can cause shading and installation issues. Shading occurs when an obstruction casts shadows over a solar panel, which causes a significant drop in power output. Since hills can cause shading at certain hours of the day, flat land is generally preferred. However, southern facing hills can improve power output as the panels will not have terrain blocking the direct light thus increasing the solar irradiance absorbed. Many of the sites in the Eastern plot have gentle southern facing slopes that allow for power creation without shading.

Farmland is the best choice for potential plots due to low environmental impact and cost efficiency.

Factors such as previous disturbances, small obstructions, low biodiversity, and ease of access make a site easier to develop. For instance, developing a PV system on forested land requires significant financial and environmental expenses to clear the land thus disturbing the local biodiversity. As farmland has been continuously disturbed for years, has no obstructions (e.g., trees), little biodiversity, and plenty of access roads it is much easier to develop than nearly any other habitat type. Most of the available land for use on Langeland is farmland.

Solar installations could cause disruption of migratory bird habitats and destruction of marshlands on Langeland.
Even when using land with low ecological value, solar installations can cause lasting ecological changes including changes in soil chemistry, ecosystem dynamics, and injury/death to animals during development. The most likely environmental impacts to consider on Langeland would be disruption of migratory bird habitats and destruction of marshlands. To limit the effects on the environment, we advise that checks be conducted at the beginning and throughout construction to ensure no animals are close to machinery. Additionally, care should be taken to ensure no damage is done to trees or brush surrounding the site. Further recommendations for sustainable development and strategies to improve the biodiversity of the site can be found in *5.0 Recommendation for a Biodiversity Management Plan.*

3.2 Site Visit

Local landowners hold strong opinions about the possible locations of a solar farm.
Community opinions on solar farms can be influential to the feasibility of a solar farm, especially on Langeland. Based on discussion with the landowners of the potential sites, the nearby inhabitants are favorable to solar installations, but do not want a large solar farm detracting from the island's natural beauty. Because of this, the site landowners request that the solar farm be put on land distanced from other inhabitants of Langeland. Local opinions impact feasibility, as the landowners will reject offers if they feel as if the solar farm will detract from the appearance of their land. The landowners are also concerned that the value of land surrounding the solar farms could decrease or be unusable. To limit this, sites that do not fragment usable farmland are ideal and unused or less productive farmlands should be favored over

highly desirable lands. Solar farms are still feasible on land that is not directly on the main sightlines of other nearby inhabitants.

Nearby forests and saltmarshes can lead to elimination of potential sites on Langeland.
There are several areas of forest surrounding the potential solar sites. As these areas are of high ecological importance and development would be expensive, development of these habitats should be avoided. There are also several areas of "Christmas Tree Farms," which consist of spruce monocultures. These areas present greater biodiversity than traditional farmland and likely provide shelter to a variety of organisms and should also be avoided. Additionally, several sites include areas of saltwater marshland habitats. These habitat types are fragile and important to many species. Efforts should be made to preserve and restore these habitats as they are also accessible to the public and offer an opportunity to garner public support for solar development in an area that is highly concerned with landscape aesthetics.

3.3 Selected Potential Plots

Through the use of pre-site visit feasibility screening and visiting the site, we were able to narrow down the potential plots to a selection. The criteria we used consisted of land slope, habitat, and the nearby residents' opinion on the land sites. Shown in Figure 3, the red sections denote the areas of the sites where we believe placement of a solar farm would be feasible.

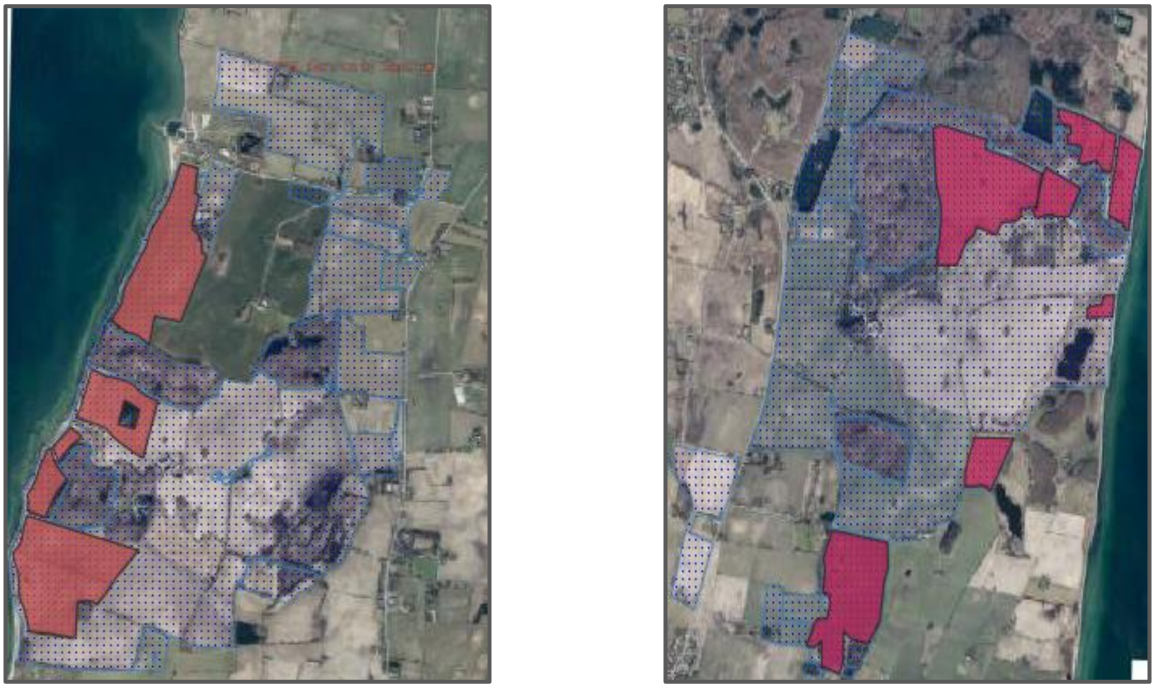
To start the filtering of potential sites, we selected sites that contained level terrain and southern facing slopes. This eliminated northern facing slope plots where issues could arise from installation as well as shading caused by the natural features and the difference in elevation from the solar arrays.

Next we decided to eliminate sites that had environmentally diverse habitats, such as forests and saltwater marshes. This eliminated many potential sites as a great percentage of the possible land contained forests where the razing of forest habitats would be too costly environmentally and financially. We decided on farmland as it was the most environmentally and financially efficient habitat type.

Finally we utilized landowner opinion to further eliminate potential sites. Through discussion with landowners, we determined that land on main roadways and by nearby residents would not be feasible for a solar farm, as nearby resident opinions on the natural beauty of the island would prevent the development.

After the filtering and elimination of potential sites, we were left with approximately 340 acres of usable land which is shown in Figure 3.

Figure 3



Note. The Western (left) and Eastern (right) potential plots of land. The dotted blue areas show the total area of the potential sites provided by LAUTEC, while the solid red areas are the plots deemed usable.

4 Economics and Performance

This section discusses the economic costs of a solar PV farm as well as the value generated through the sale of produced power. All assumptions are described to allow for rough predictions of economics and performance. Documented in the IQP Report Appendix B: Python Toolkit Documentation, we generated return on investment models to estimate the value output and the energy output over time.

4.1 Assumptions and Input Data for Analysis

To understand the economics of a solar farm on Langeland, we made assumptions based on evidence from literature reviews and data collection as shown in Table 3. We estimated the initial cost and operating cost of a solar PV farm based on all of these factors.

Table 3: Certainties, Informed Assumptions, and Loose Assumptions for Economic Analysis

Certainties	Informed Assumptions	Loose Assumptions
• Solar Panel Specifications and Cost • Inverter Specifications and Cost • Nonexistence of Government Incentives	• Installation Costs • Land Costs (per year) • O&M Costs • Energy Value	• Tax Value • Grid Infrastructure Upgrade Cost • Battery solution Cost

The following analysis depends on numerous assumptions.

To create an economic analysis, we used data based on information we could find, and assumptions on information we could not. Table 3 provides a list of the variables and estimates that we have considered in the economic analysis of the study. Split into three sections, the variables are defined by categories of certainties, assumptions, and unknowns.

Certainties

Our certainties include solar panel information, inverter information, and government incentive information. We were able to find panel and inverter specifications and costs through manufacturer data sheets as well as correspondence with manufacturers. We found that Denmark does not offer government incentives for solar development through the research of government websites and documents.

Informed Assumptions

Assumptions were crucial to the analysis as many of the costs associated with a solar farm can change or are not solidified.

- **Installation Cost:** Found by taking the average cost of a solar farm installation per MegaWatt and then deducting the included cost of components from that average to find an estimate for the installation of the components. The value for the assumption of installation was approximately $360 per MegaWatt, derived from the total installation including component cost of $850 per MegaWatt.
- **Land Cost (per year):** Assumption made by communication with a source familiar with Langeland, and assumed to be $1,200 per year per acre.
- **O&M Cost:** Derived by communication with an Operation and Maintenance firm was the O&M cost of $4600 per MegaWatt yearly. This value is subject to change greatly by O&M strategies and contracts.
- **Energy Value:** We started with an assumption of $0.214 per kWh based on Q4 2021 electricity value and multiplied it by the kWh expected of the estimated solar farm to receive a value of energy produced per year of approximately $29 M USD. The price of electricity is always changing and can increase and decrease based on numerous reasons. One reason we recommend investigating a PPA would be to limit the fluctuation of energy prices and to have a stable rate at which electricity can be bought.

Loose Assumptions

Two important factors remain unknown. One factor is the tax value on the land as the land will increase as it transitions from agricultural tax to industrial tax value. We contacted the Plan Coordinator of Langeland Municipality to receive information about the tax change increase, but were unable to get the answers we were looking for. Determining the potential taxation of the land is a recommended next step. For the purposes of making preliminary projections, we assumed a tax rate of 2.5% on an expected $35 USD per MW value of the solar farm.

Another significant unknown factor is the grid infrastructure upgrade cost. Through discussion with the Plan Coordinator of Langeland, we were made aware that the current electrical grid could not sustain a utility scale solar farm. A grid infrastructure upgrade would be necessary for the feasibility of a utility scale solar farm, and the upgrade could greatly vary. We assumed two scenarios, one scenario where the current grid infrastructure can be upgraded for $5 million (USD) and another scenario where a new transformer station would be $30 million (USD).

Battery solution costs can vary wildly based on individual solution needs. For the loose assumption made for battery cost we assumed a cost of $1 million (USD) for a 3MWh battery. For a utility scale solar farm, we assume the need for multiple batteries per battery solution so the overall cost of a battery solution was assumed to be roughly $15 million (USD).

The initial cost of the solar farm is approximately 3.5 times as much as the total yearly cost for the lifespan.

The bulk of the cost associated with a solar farm is the cost of hardware components and the cost of installation. These costs are upfront costs that will have to be recovered over time by the energy value output of a solar farm. Additional smaller costs include the yearly Operation and Maintenance cost and the yearly land cost. Compared to the total yearly costs of the solar farm, the installation cost is approximately 3.5 times as much. For 340 acres (the total utilization of the feasible land) the installment cost is roughly $126 M USD and the total yearly cost is roughly $36 M USD.

Component costs without a battery solution can vary from $17 M USD to $35 M USD.

For a solar farm utilizing 170 Acres, or 50% of the total feasible land, the component cost is approximately $17 M USD, and for a solar farm utilizing 340 acres, or 100%, the component cost is approximately $35 M USD. Based on these values the total cost of solar panels necessary for the solar farm can range from $10 M USD to $20 M USD, with a single panel costing an estimated $205. The total cost of inverters necessary for the solar farm can range from $4 M USD to $9 M USD, with a single inverter costing an estimated $4,000 USD. Other component costs were assumed to range roughly from $3 M USD to $6 M USD accordingly. The estimates for individual component cost assumptions can be found in Table 4.

Table 4: Assumed Costs

Cost per Component	Example Cost (USD)	Retrieved from
Panel Cost (x1)	$205	Direct quote from Canadian Solar
Inverter Cost (x1)	$4,000	Manufacturer website
Battery Solution Cost (x1)	$1,000,000	Comparable Solutions
Acre Cost (x1)	$1,200	Provided by sponsor
Installment (per MW)	$360	Literature review
O&M (yearly per MW)	$4,600	Direct quote from European Energy

There are no incentives in Denmark to offset the costs of solar developments.
As of April of 2022, there are no federal or municipality incentives to make the PV system more cost effective.

A Power Purchase Agreement (PPA) is recommended to provide financial certainty for a long term project.
A PPA is a long-term contract that governs the sale and purchase of power between the renewable energy producer and the purchaser(*Power Purchase Agreements for Variable Renewable Energy*, 2018). It provides financial certainty to the project developer thus removing a significant roadblock to building new renewable facilities (RWE, 1 C.E.). The agreement works by having a solar contractor own, operate, and maintain the system while the utility company purchases the electricity generated by the system (Salasovich, et al. 2011). The main benefit of a PPA is that it provides a fixed, predictable cost of electricity for the duration of the agreement (*Solar Power Purchase Agreements | SEIA*, 2012).

4.2 Return on Investment

Estimating for return on investment (ROI) analysis takes into account the estimated total power output of a solar farm, and the costs of installation, components, and maintenance. Given the high installation cost of a solar farm, the return on initial investment is a key parameter to determine project viability.

Technological Parameters

To estimate the return on investment, we calculated the power output of the farm. We used irradiance data from NASA and the specifications of the Monocrystalline PERC panel to calculate the theoretical output of each individual solar panel. However, the theoretical maximum power generated by a PV array is impossible to achieve due to energy losses. For our case study, we used a value of 17.9% percent losses provided by a source who developed a 60MW solar farm in Iowa (Benton et al., 2016). We then subtracted approximately 5% for temperature losses which were calculated separately based on temperature data on Langeland.

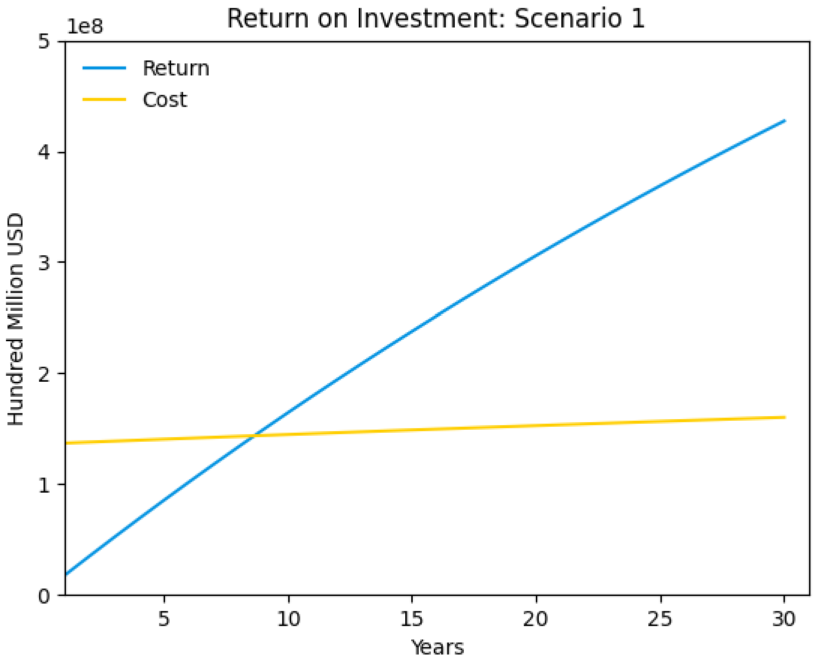
Introduction to Scenarios

Based on assumptions detailed in Section 4.1 of the Feasibility Study, we generated simple economic models. As explained earlier, there are 340 usable acres of land of which a 105 MW solar farm could be built upon. Two scenarios are highlighted below for different assumptions regarding grid upgrades. Both scenarios assume a rate of 1.5% for inflation and a corporate income tax of 22% on the net profits over the lifetime of the farm.

Scenario 1

For the first economic projection, we assumed a $30 million USD substation upgrade. Figure 4 is Return on Investment graph with the blue line representing return and the mustard line representing cost over the solar farm lifespan of 30 years. The intersection of those lines is the point at which the project breaks even and begins to turn a profit for the solar farm owner. From Figure 4, this occurs after roughly 9 years, with an initial investment of about $136 million USD or 952 million DKK. This model will return an estimated 4.4% per year for about $210 million USD or 1.47 billion DKK in the solar farm’s 30-year lifespan.

Figure 4

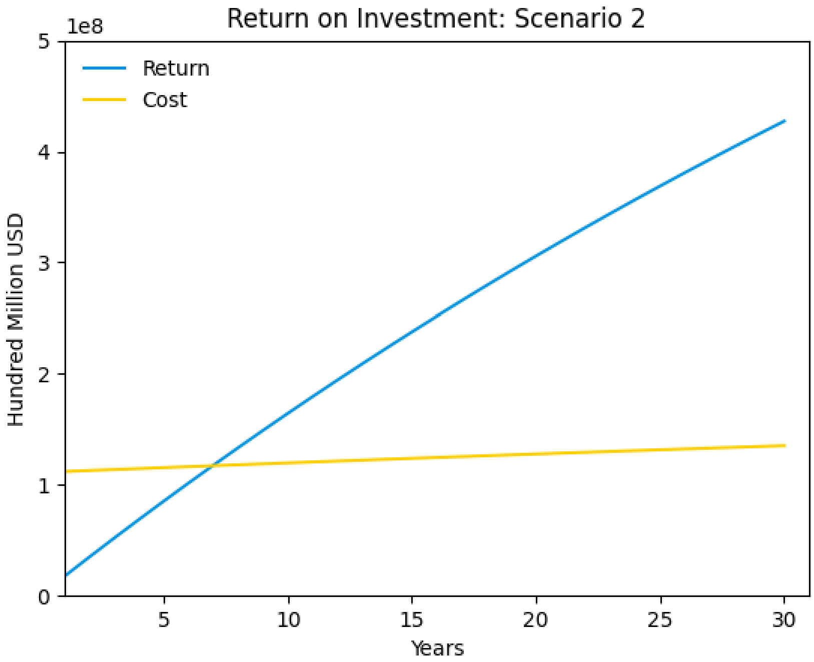


Note. Return on Investment Scenario 1.

Scenario 2

Scenario 2 assumed 5 million USD for a multi transformer upgrade. Similarly to above, Figure 5 shows a Return on Investment projection. The start-up cost of this economic projection is $110 million USD which will return an estimated 5.7% per year. It will become profitable in about 7 years and will deliver a net profit of $230 million USD or 1.61 billion DKK in the solar farm's 30-year lifespan.

Figure 5



Note. Return on Investment Scenario 2.

5 End of Life

When solar farms are ready to be decommissioned, at either the end of the panel warranty or the end of a contract, the solar farm will need to be dismantled and the components recycled. The Waste Electrical and Electronic Equipment Directive (WEEE Directive) is a law in the European Union that regulates the handling of electrical and electronic waste at the end of its life cycle (PV Cycle, n.d.). This directive promotes the practice of "Extended Producers Responsibility" for solar panels meaning that the producers, or manufacturers, of the modules, are responsible for collecting and disposing of them at the end of their life cycle (PV Cycle, n.d.). Solar farm owners/developers will not have to pay to dispose of the PV modules; in fact, all manufacturers of PV panels who supply components to the European market must pay a recycling fee and provide solar farm owners with instructions to give back the modules (PV Cycle, n.d.).

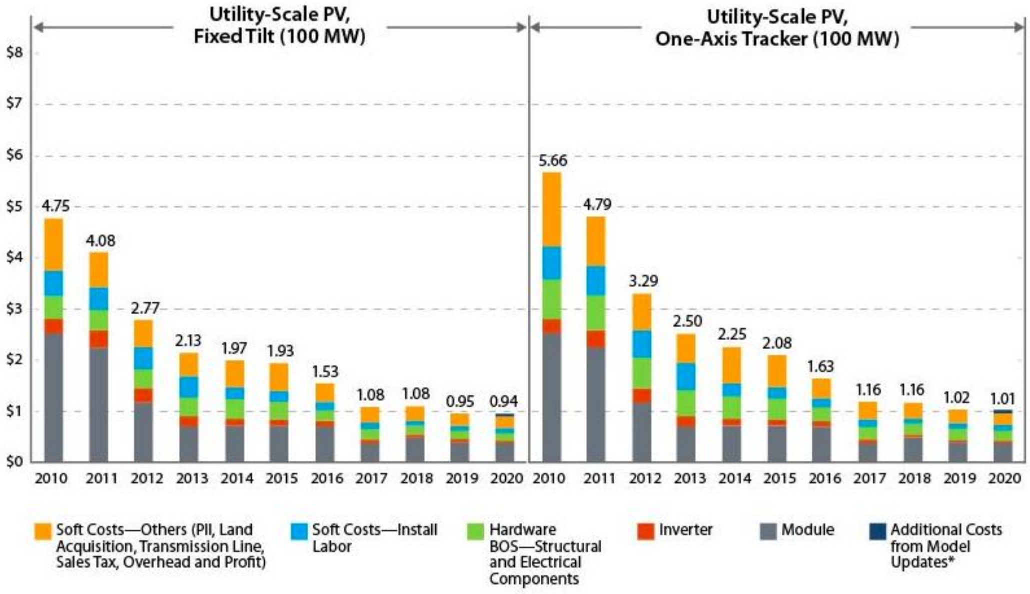
At the end of life of the solar farm, the land will need to be reclassified as farmland to ensure the landowners get the proper tax rates associated with the land usage. Since some landowners have had difficulties reclassifying their land, we recommend facilitating an agreement between the local government and the landowners to ensure the land has a smooth transition back to farmland after the end of life of the solar farm.

6 The Future of Solar Power

In this section we outline the trends in solar power technologies over time relating to both cost and efficiencies and provide estimates on how these trends will continue. We discuss the current state of solar research including thin-film solar panels, multijunction solar panels, and Power-to-X systems. The future of solar power provides several avenues that LAUTEC can explore.

Between 2010 and 2020, the efficiency of solar panels has consistently increased while the cost per panel has decreased. We can see in Figure 6 that the module price is on an exponentially decreasing trend. We expect the price of the module will continue to decrease at a slowing non-linear rate.

Figure 6



Note. Cost per watt over time for racking solutions. From ("Documenting a Decade of Cost Declines for PV Systems," 2021), by NREL, 2021, (https://www.nrel.gov/news/program/2021/documenting-a-decade-of-cost-declines-for-pv-systems.html). In the public domain.

As for efficiency, cutting-edge concentrator PV cells, such as triple and four junction solar cells, which use lenses to focus sunlight, currently have efficiencies of up to 40% with the potential to achieve over 50% efficiency (Ellabban et al., 2014; Yamaguchi et al., 2006). However, concentrator PV cells are currently too expensive for practical commercial use and are still being developed. For thin film panels the technology is currently on the market for small-scale farms, but it is not yet developed enough for large-scale farms.

Power-to-X

Power-to-X (PtX) is an umbrella term for a number of technologies that are based on using electricity to produce a number of chemicals (Danish Ministry of Climate, Energy and Utilities, 2021). PtX technologies make it possible to use renewable sources of energy to produce fuels and chemicals that are currently produced from fossil fuel sources thus reducing greenhouse gas emissions (Danish Ministry of Climate, Energy and Utilities, 2021). Additionally, such plants generate large amounts of surplus heat and thus can contribute in providing heat for district heating.

Not only will PtX be able to contribute to the realization of the objectives in the Danish Climate Act, there is considerable interest in PtX and green hydrogen abroad, making it an attractive foreign investment (Danish Ministry of Climate, Energy and Utilities, 2021).

7 Conclusions

To determine if a solar PV farm is feasible on Langeland, this study considered factors such as regulations that would impact a solar farm, impacts of a solar farm on the local environment, estimated power output of a solar farm, and estimated costs of a solar farm. **Based on this cumulative assessment, we conclude that a solar PV farm may be feasible on select locations on Langeland, but future investigations would be necessary to determine overall feasibility.** Site characteristics and economic analysis are influential in determining the feasibility of the sites. Some important factors to consider when developing at these sites include the site viability based on criteria of slopes, terrain, habitat, and land owner opinion, as well as the economic analysis of construction, grid upgrade cost, and estimated power output.

8 Recommended Next Steps

This Feasibility Study illustrates the potential for a solar PV farm on Langeland. IWe recommend using it as a platform to continue developing a conceptual analysis. We have highlighted key areas where our work can serve as a basis for continuation. Our recommendation for future work focuses on areas where our study was incomplete or based on simplistic assumptions. The Feasibility Study in tangent with the Recommendations for Biodiversity Management Plan and Calculator/Documentation can provide guidance to LAUTEC in pursuing further work.

Further Investigate Tax Implications

We recommend that LAUTEC secure a quote regarding the tax rate change of installing and operating a solar PV farm. The per acre lease rate of a solar land lease must be understood in the wider context of the tax liabilities associated with a solar PV farm. The sale of electricity will likewise be subject to income tax as well. It is suggested that the solar farm developer initially contact the Business Department of the Danish Tax Agency and follow up by consulting a tax advisor familiar with the taxation of a PV system.

Further Investigate Infrastructure Upgrade Costs

From our communication with the Plan Coordinator of Langeland Municipality, we learned that there is currently not enough grid capacity for a utility-scale solar PV system on Langeland. To shed light on this, we recommend that the solar farm developer research whether the substations on langeland would need upgrading or a complete new substation would be necessary. If a new substation needs to be installed, then we recommend investigating the feasibility and financial undertaking of developing, installing, and operating a substation. It would be useful for the solar farm developer to contact and collaborate with Fonden Langelands Elforsyning (LEF), the electrical utility company on Langeland.

Langeland Municipality & Zoning and Land Development

We suggest that the solar farm developer begin communication with the Plan Coordinator of Langeland Municipality regarding zoning and land development. This factor is immensely important in the feasibility of a utility-scale solar PV farm on Langeland as the municipality can restrict the use of the property and/or set standards in the size, placement, and construction. This aspect can take more than a year as there are a large number of factors at play. Opening communication will set the tone of the partnership between the solar farm developer and Langeland Municipality for years to come.

Confirm Cost of Hardware Components, Installation, and O&M

We recommend that the solar farm developer confirm the cost of the hardware components, installation, and O&M. Having an accurate upfront cost can determine the financial feasibility of such a project. Additionally, it forecasts the expected return on investment as well as outlines any financial risks.

Investigate the Monitoring, and Safety and Security Costs

We recommend further investigation into the monitoring costs, as well as the safety and security costs associated with a solar farm. Monitoring costs include monitoring systems that create understanding and awareness of energy output. Having a monitoring system will allow for better maintenance time turnaround if there are disturbances in the energy output. Safety and security costs include the measures taken to prevent disturbance to the solar farm.

Explore the Permitting and Zoning Regulations

We recommend exploring the permitting and zoning regulation. The purpose of zoning is to allow authorities to regulate and control the land property market. Ordinance determines how a piece of land can be used and ensures that the intended use for the piece of land takes every regulation into account (Zoning and Land Use Planning | Urban Regeneration, 2015). Zoning is important as it can restrict the use of the property and/or set standards in the size, placement, and construction of the solar PV farm (HG.org, 2022). Land use permits are needed to ensure that current or proposed land use considers all viable factors and is in compliance (Land Use Regulatory Permitting, 2020).

Develop an Environmentally-Sound Strategy and Identity Associated Costs

Using the *5.0 Recommendations for a Biodiversity Management Plan*, we suggest the solar farm developer create an environmentally-sound strategy to address and mitigate the environmental impacts of developing and operating a solar PV farm. This includes identifying any associated costs with this endeavor. We recommend hiring a company or working with a university and contacting an ecologist to provide expertise and support.

Further Investigate Safe and Lawful Disposal of Batteries and Inverters

We suggest the solar farm developer research how to safely and lawfully dispose of the batteries and inverters. Diverting batteries and inverters to the appropriate disposal areas is important to ensure metals and toxic chemicals do not leak into groundwater or harm the ecosystems. Battery and inverter manufacturers could possibly provide information on this matter.

Appendix

A. Operation and Maintenance Services

Preventive Maintenance:

- Site Inspections (incl. Fence, Signage, Gates & Keys, General Observations, Grounds, drains)
- Preventive Maintenance LV Electrical (incl. Inverter Maintenance, LV cabling (DC/AC), Fuse Holders)
- Preventive Maintenance Auxiliary Electrical (incl. Communication, Equipment, Auxiliary transformers, Cameras)
- Preventive Maintenance HV (incl. service of transformers, substation building, switchgears)
- Preventive Maintenance Structure (incl. Toque checks, Lubrication per Manual)
- Greenkeeping of grounds, two cuts per year or grazing with additional manual cut

Corrective maintenance:

- Corrective maintenance of all items of below scope up to 4 h / MWp included
- Further CM at additional cost
- Spare parts handling included
- Inverter Warranty Claims included
- Consumables included

Operational Services:

- Daylight monitoring
- Monthly production & performance reporting
- Incident reporting
- Operational communication to direct trader & grid operator

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5.0 Recommendations for a Biodiversity Management Plan

Table of Contents

List of Figures

1 Introduction

This document is designed to supplement the *Feasibility Study for a Solar PV Farm on Langeland* conducted for LAUTEC on two sites in Langeland. The document provides LAUTEC with an overview of a Biodiversity Management for solar PV farms, as well as examples of management strategies and recommendations based on our conceptual analysis for the Langeland sites.

The goal of this chapter is to provide recommendations for a Biodiversity Management Plan to aid LAUTEC in responsible stewardship practices for solar farms and provide strategies to potentially increase biodiversity around solar PV farms.

What is a Biodiversity Management Plan?

A Biodiversity Management Plan (BMP) is a plan used to guide the identification, protection, and management of biodiversity resources in a development site (Warringah Council, 2009). These resources include local flora, fauna, and fungi taxa, habitats, ecosystems, and ecological features (e.g., hydrology, abiota, etc.). Some municipalities require Biodiversity Management Plans to be submitted for approval of a development project. Although Denmark and most European countries do not explicitly require Biodiversity Management Plans for solar development, many developers include these plans in order to promote local biodiversity, sustainable development, and garner local support. The BMP can also be used to maintain and describe compliance with any local environmental regulations, including the drafting of Environmental Impact Assessments (Warringah Council, 2009).

While specific plans vary across regulatory boards and developers, Biodiversity Management Plans typically include the following:

- general information about the site and its surroundings (including maps of the area)
- relevant environmental regulations
- assessments of the local ecology
- potential impacts to the local biodiversity
- impact mitigation methods
- management plans for the local flora and fauna
- monitoring methods

- strategies for end of life decommissioning

Biodiversity Management Plans can also include strategies for habitat creation and ecosystem engineering methods (e.g. veterinalization) to promote biodiversity (Cunningham, & Flenley, 2022).

European Union/Denmark Environmental Regulations

Danish environmental legislation is derived mostly from European Union legislation and, to a lesser extent, from international treaties. The Ministry of the Environment is composed of three agencies: The Environmental Protection Agency, The Danish Geodata Agency (GDA), and The Danish Nature Agency. The Nature Agency and its local entities ensure the overall protection of nature whereas the GDA is responsible for surveying, mapping, and land registration of all of Denmark. Environmental NGOs such as Greenpeace and the Danish Society for Nature Conservation also play a key role in ensuring the protection of the environment in Denmark.

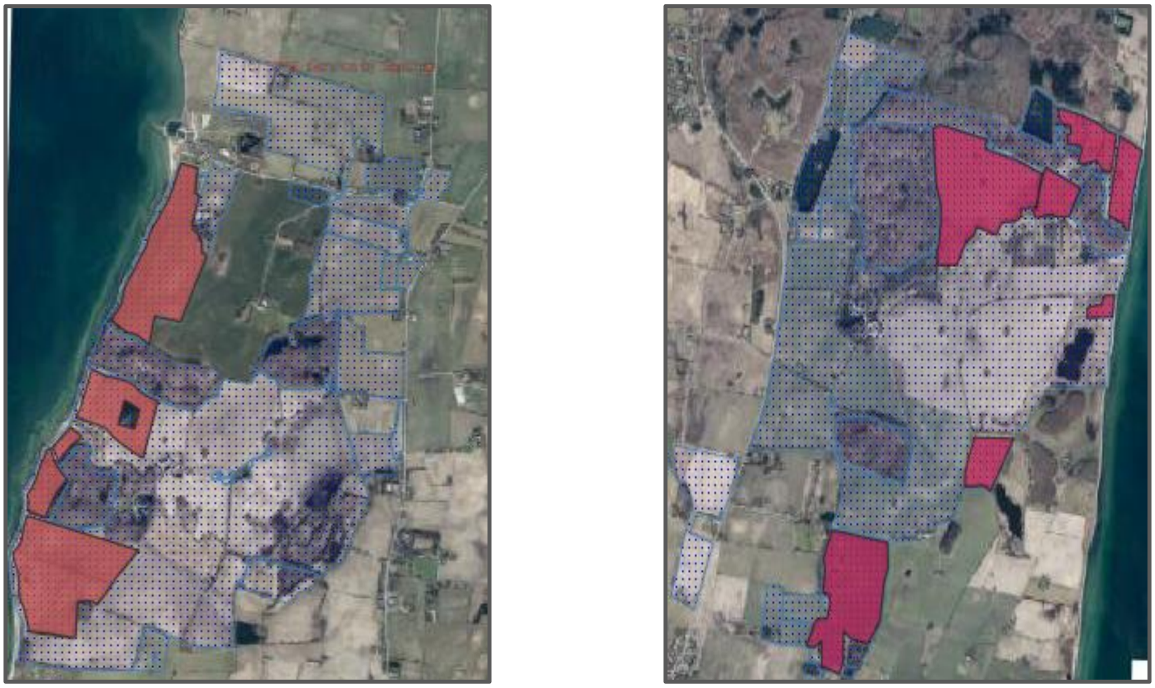
The main environmental law is the Environmental Protection Act (EPA) (*Consolidated Act no. 879, 26 June 2010*) set by the Environmental Protection Agency. The EPA is built on the concept of decentralization, with the goal of dealing with the problems as near as possible to the people involved. As a result, municipalities administer and execute the majority of centrally issued legislation.

Prior to construction, the two major documentation to secure is environmental permitting of the land and an Environmental Impact Assessment (EIA). Any industrial installation that causes significant pollution must be granted an environmental permit (*Environmental Law and Practice in Denmark: Overview | Practical Law*, 2013). Eight years after the permit is granted, the relevant supervisory authority can amend the terms of permission or ban the conduct of activity. If an operator fails to comply with the terms of the approval, the supervisory body may issue an injunction prohibiting the continuation of the activity. Regarding an EIA, project owners may be punished if the regulating authority is not notified or if construction begins before the required EIA is complete.

Site Description

The sites described in this document are located on the island of Langeland with approximate latitude and longitudes of 55 and 10. The total area of the sites is roughly 1000 acres consisting of 340 acres that we deemed feasible for solar PV farms. The land consists mostly of active farmland, with spruce monocultures (Christmas Tree farms), several forests, and coastline with areas of salt marshes. The coast of Langeland is accessible to the public and there are several hiking trails on the land adjacent to the coast.

Figure 1



Note. The Western (left) and Eastern (right) plots of land. The dotted blue areas show the total area of the potential sites provided by LAUTEC, while the solid red areas are the plots deemed usable in the Feasibility Study.

The Green Map of Denmark

The Danish Planning Act deals with the hierarchical planning framework for land development. Local plans must comply with municipal plans, municipal plans must comply with regional plans, and regional plans must comply with state plans (Land-Use Planning Systems in the OECD). In 2017, Danish legislatures passed an amendment to the Planning Act requiring municipalities to create plans for conserving nature as well as contribute to a Green Map of Denmark (Danish Environmental Protection Agency, 2020). The Green Map of Denmark is an interactive digital map that displays a variety of ecological data, including a Biodiversity Map of rare and endangered species, for all of Denmark. We used the Green Map to determine if any critical species were found within the potential sites.

Critical Species and Habitats

Each site consists of several stretches of coastline, some of which contain salt marsh ecosystems (shown in Figure 2). These ecosystems are fragile and are susceptible to erosion, pollution, and destruction from human activities.

To determine areas of critical species and habitats, we compared data from the Green Map of Denmark with the plots on QGIS. Based on the Green Map of Denmark, the Western Plot contains several areas where at least one localized population of a IUCN red-listed species has been observed. Additionally, the Eastern Plot contains large areas of habitats that are ideal for certain red-listed species; however, there is little or inaccurate occurrence data to conclude a population exists in these areas. These areas are isolated to forested areas that would be adjacent to the solar farm and will not be directly impacted by development. However, it is important that these areas be protected and efforts should be made to preserve the habitats. These areas are ideal candidates for the habitat and taxon surveys detailed in Section 3 of this chapter. Chapter 5.0 Appendix A: Endangered Animals of Denmark contains a list of the endangered animals of Denmark that could potentially be found on Langeland.

Figure 2

Note. Examples of the coastal marshland from the Western Site

Biodiversity Targets

Nature and the ecosystem are vital to all life on Earth and therefore, Denmark must ensure the availability of natural resources for present and future generations. Biodiversity is under pressure from threats that include the expansion of infrastructure and thus has suffered significant losses. To promote a more sustainable world, Denmark has brought forth initiatives to preserve and safeguard the further development of biological diversity.

2 Potential Impacts

The installation of a solar PV farm could cause several environmental impacts including habitat loss and fragmentation and disruption during construction

Habitat Loss

Since construction would be limited to cleared farmland, habitat loss would be minimal and solar panels would not cover a majority of the farmland. However, noise and vibrations from construction machinery can cause disturbances to the surrounding habitats. Before construction begins, on-site surveys should be conducted to identify nearby habitats and care should be taken to limit disturbances or habitat loss from cable trenches, inverter stands, access roads, and buildings.

Mitigation Efforts During Construction

In addition to habitat loss, individual organisms can be injured or killed during construction; however, it is likely that any disturbances during construction will be similar or less disruptive than the previous agricultural work.
We recommend hiring a trained ecologist to supervise the construction of solar PV farms and ensure the environmental regulations and strategies are adhered to.

Practices to limit the occurrences of injuries or death to individual during construction include (Cunningham, & Flenley, 2022):

- Pre-construction surveys for mammals or reptiles on the site
- Pre-construction surveys for birds during periods of peak activity (March through August)
- Screening for bird/bat roosts on any trees that are being removed
- Covering any excavation sites to prevent trapping any animals

3 Monitoring Strategies

In order to determine the impacts of the solar farm on the local ecology, a developer needs to be able to quantitatively assess the changes in biodiversity over time. This necessitates the use of monitoring assessment strategies to accurately determine biodiversity in the managed areas. Such strategies typically consist of accounting strategies to quantify and compare biodiversity, a baseline survey to determine initial biodiversity, followed by site surveys repeated at set intervals as well as monitoring physical characteristics of the sites, such as temperature.

Biodiversity Accounting Strategies

Since biodiversity is difficult to quantify, having effective accounting strategies is important to compare biodiversity between areas and over time. The Endangered Wildlife Trust developed a method for accounting biodiversity resources, specifically for businesses, called the Biological Diversity Protocol (or BD Protocol) (Endangered Wildlife Trust, 2020). These protocols are designed to account for all of the environmental assets and impacts of a company and their operations. To create a full accounting system using the BD Protocols, we recommend working with an environmental specialist, either a company such as Habitats, or a university such as the

Globe Institute, who have both created biodiversity account strategies for similar projects. However, a subset of the BD Protocol can be used to quantize the biodiversity observed at different sites and compare the biodiversity changes throughout the life of the solar farm.

This adjusted method involves multiplying the Defra Biodiversity Metric (shown in Figure 3), which rates the biodiversity of each site and the area of the site (typically in hectares) to get the biodiversity adjusted area. This adjusted area can be used to compare the total biodiversity across sites and changes in biodiversity after reassessment.

The BD Protocol used the Defra Biodiversity Metric 2.0, which ranks a location's biodiversity on a scale of 0 to 3 (varying by 0.5). However, Natural England (who writes and maintains the Defra Biodiversity Metric) recently released a third version of this metric that includes a workbook that walks the user through calculations of the biodiversity for a project (Natural England, 2022). Our analysis found the 2.0 Metric sufficient to compare biodiversity; however, the latest version was released in April of 2022 and we were not able to evaluate the new calculator.

Figure 3

Category	Score
Good	3
Fairly good	2,5
Moderate	2
Fairly poor	1,5
Poor	1
N/A - Agriculture	1
N/A - Other	0

Note. Defra Biodiversity Metric 2.0 (Endangered Wildlife Trust, 2020)

Baseline Assessments

In order to understand the solar farm’s impacts on biodiversity, baseline assessment should be conducted before development begins. Assessments should include site surveys that account for the biodiversity and habitat types of each site, as well as surveys to understand the local ecology. Specific surveys recommended for solar development are detailed in Chapter 5.0 Appendix B: Survey Techniques.

Ongoing Surveys

After baseline assessments are conducted, the necessary surveys should be reevaluated. If endangered or red-listed species are determined to be onsite, new mitigation strategies and surveys should be created to better protect and monitor these species. Assuming no endangered species are found onsite, surveys should be repeated at regular intervals to determine changes in biodiversity. Surveys should be conducted as often as is feasible, as more frequent surveys will be better able to catch any sudden changes in ecosystem health. However, surveying once every year or every other year is sufficient to accurately assess changes in biodiversity. **We recommend repeating surveys for groups that include either critical or highly prevalent species at least once a year, and repeating surveys for less critical or prevalent species every other year.**

Temperature Monitoring

A temperature monitoring system of the solar farm and surrounding ecosystems is advisable to ensure that temperatures do not drastically increase since PV farms can cause a rise in ambient temperatures in the wild ecosystem. This phenomenon, called the Photovoltaic Heat Island effect, is caused by the PV cells altering the landscape's albedo (Barron-Gafford et al., 2016). Solar farms have been found to increase ambient nightly temperatures around the plant by 3-4 °C compared to control environments (Barron-Gafford et al., 2016). Rising temperatures could potentially affect the surrounding ecosystems and human populations; especially vulnerable populations include birds and insects, which fly over the areas that experience the most drastic temperature increases (Barron-Gafford et al., 2016; Fthenakis et al., 2011). Regardless, this phenomenon is more common in arid or semi-arid climates, as they often have lower humidity and higher albedo relative to wetland or forest ecosystems; therefore a monitoring system should prove sufficient for mitigating impacts (Loarie et al., 2011). If significant temperature increases are recorded, a cooling system should be considered.

4 Habitat Restoration

Since the proposed sites are owned by private landowners, who would likely wish to use the land for agriculture after the lifespan of the solar farm, extensive habitat restoration or engineering will not be feasible for this project. However, if the landowners are interested in building wildlife areas, habitat creation can greatly increase the biodiversity of the area as well as add aesthetic value to the land. Potential new habitats depend on the specific site and can be almost any habitat type including orchards, wetlands, new hydrology (e.g. duck pond), forests, and grasslands.

Instead of creating new habitats, restoration methods can improve biodiversity and strengthen ecosystems. Examples of restoration techniques include planting native trees at forest's edge, removing invasive species, and defending coastal areas against erosion (Cunningham, & Flenley, 2022).

In addition to creating habitats and restoring plant life, providing artificial habitats or shelters can also improve the biodiversity of the land, without requiring extensive modification (Cunningham, & Flenley, 2022). Artificial habitats can be installed in forests or outside of the usable land. For development on Langeland (and most of Denmark) we recommend the following artificial habitats:

- bird/bat boxes
- bee banks
- hedgehog houses
- hibernacula
- invertebrate hotels

Public Access

Several of the potential sites are adjacent to Langeland's coast, which is open to the public. This simultaneously makes such sites susceptible to public scrutiny and ideal for habitat restoration. These coastal areas are fragile environments that are in danger from erosion, rising sea levels, and pollution. Protecting these areas will increase the biodiversity of the site and presents an opportunity to also increase the aesthetic value of land that is accessible to passersby, which will hopefully ease tensions over the PV farm.

Figure 4

Note Example area that could be used for public access. The coast, salt marshes, and northern facing areas unsuitable for solar panels make this particular area ideal for public access. The left figure shows the land specific features and the right figure shows the area in relation to the western site.

Since the land is privately owned, we recommend discussing options for public access with the landowners. If the land owners do not wish the land to be open for public use, the restored areas could be used by the landowners to host guests.

Our recommendations for potential improvements to the area include planting fruit trees, flowering shrubs, and/or wildflowers, placing picnic tables, cleaning up trash that washed ashore, installing fire pits or charcoal grills.

5 Management Strategies

In addition to mitigation and habitat restoration, there are many land management strategies that can be implemented to improve biodiversity for the site. Management strategies maintain and heal the land the panels are situated on. In managing the solar sites, we recommend ceasing any fertilizer or herbicide regimens to allow the chemical composition of the soil to recover during the life of the solar farm.

Grazing

To stop overgrown grass from shading the panels, solar farms generally incorporate mowing regiments, which typically use gas-powered lawn mowers. However, these traditional gas-powered lawn mowers release greenhouse gasses, offsetting the sustainability of the solar farm. To be as sustainable as possible, many solar developers are switching to ruminants grazing instead of mowing. Not only is cattle grazing sustainable, but it is also cheaper and gives back to the local community by supporting farmers (Cunningham, & Flenley, 2022). Typically, sheep are used for grazing as they are docile and do not cause damage to panels or wiring.

Reseeding

Reseeding the areas underneath the solar panels with native wildflowers is a simple method to add biodiversity to and beautify the landscape. Reseeding with wildflowers also provides food for pollinators and other animals. The species listed below are all native to Denmark and were chosen because they will either add beauty to the landscape (in the case of the wildflowers) or because they are preferred grazing plants for sheep.

- Red Deadnettle, *Lamium purpureum*
- Common Daisy, *Bellis perenis*
- Forbes' Glory-of-the-snow, *Scilla forbesii*
- Apple Mint, *Mentha suaveolens* (Prefered by Sheep)
- Red clover, *Trifolium pratense* (Prefered by Sheep)
- Perennial Ryegrass, *Lolium perenne* (Prefered by Sheep)
- Lady Orchid, *Orchis purpurea*
- Marguerite Daisy, *Argyranthemum frutescens*

Additionally, native trees or hedgerows can be planted around the solar farm to hide panels from view. However, care must be taken to not plant trees in areas that cause shading on solar panels.

Fencing Solutions

For safety and security reasons, fences are planted around a solar site. Most fences are chain-linked but wild-life permeable fencing is recommended. Wild-life permeable fencing is made of welding wire with larger holes which allows movement for smaller animals. Moreover, small gaps at the bottom of the fence (30 cm x 45 cm) can be placed every 90 meters or so. Ideal fencing would have spacing large or small enough to allow certain small animals in, but also deter larger animals

Additionally, security fencing is an ideal surface for climbing vines. Alternatively, hedgerows can be planted outside of the fences which would increase the security value, provide a visual barrier, and provide habitat for wildlife. Hedgerows planted along the fence should be placed 3-5 feet away from the fence. A local biologist should be consulted in order to select a plant that would thrive in the site specific area. Agricultural style fences also blend more aesthetically with rural environments compared to chain-link fences.

6 Expected Outcomes and Recommendations

Our research showed that following the principles and strategies outlined in this chapter to develop a project specific Biodiversity Management Plan can significantly improve the biodiversity of the area as well as improve the fertility of the land for future agricultural use.

For onsite surveys and analyzing ecological data, we recommend hiring a company or working with a university. Goals for this third-party would be to design and carry out a full Biodiversity Management Plan, Environmental Impact Assessment and conduct on site surveys for any solar PV project. Additionally, we recommend having an on-site ecology manager to supervise any construction.

Appendix

A. Endangered Animals of Denmark

These are the critical species of all of Denmark; current data regarding the critical species specific to Langeland could not be found (Glenn, 2006). Therefore, this list may have included species not found on Langeland as well as omitted species that are regionally endangered on Langeland. Additional data was collected from a website that used database keyword searches to pull these species from a full database of all of the endangered species of Europe (Glenn, 2006). For a more complete and accurate understanding of the critical species on Langeland, on site ecological studies should be conducted.

Mammals:
- Bats:
  - Western barbastelle, *Barbastella barbastellus* VU
  - Bechstein's bat, *Myotis bechsteinii* ENP
  - Pond bat, *Myotis dasycneme* VU
- Beavers:
  - Eurasian beaver, Castor fiber,EN
- Mice:
  - Hazel dormouse, *Muscardinus avellanarius*, EN
  - Northern birch mouse, *Sicista betulina* VU
- Pigs
  - Wild boar, *Sus scrofa* CR

Birds:
- Balearic Shearwater, *Puffinus mauretanicus*, CR
- Black-browed Albatross, *Thalassarche melanophyrs*, EN
- Black-tailed Godwit, *Limosa limosa*, NT*
- Buff-breasted Sandpiper, *Tryngites subruficollis*, NT
- Corncrake, *Crex crex*, NT
- Egyptian Vulture, *Neophron percnopterus*, EN
- Elegant Tern, *Sterna elegans*, NT
- Eurasian Curlew, *Numenius arquata*, NT
- Eurasian Peregrine Falcon, *Falco peregrinus peregrinus*, EN
- Great Bustard, *Otis tarda*, VU
- Ivory Gull, *Pagophila eburnea*, NT

- Little Bustard, *Tetrax tetrax*, NT
- Red Kite, *Milvus milvus*, NT
- Saker Falcon, *Falco cherrug*, VU
- Sociable Lapwing, *Vanellus gregarious*, CR
- Sooty Shearwater, *Ardenna grisea*, NT
- Steller's Eider, *Polysticta stelleri*, VU
- White-headed Duck, *Oxyura leucocephala*, EN

Amphibians:

- European fire-bellied toad, *Bombina bombina*, NT
- Common spadefoot, *Pelobates fuscus*, VU
- Natterjack Toad, *Bufo calamita*, EN
- European green toad, *Pseudepidalea (Bufo) viridis*, EN
- Common tree frog, *Hyla arborea*, NT
- Moor frog, *Rana arvalis*, NT
- Marsh frog, *Pelophylax ridibundus*, EN

Reptiles:

- Sand lizard, *Lacerta agilis*, VU

Plants:

- Ojcow birch, *Betula oycoviensis*, VU
- Marsh Earwort, *Jamesoniella undulifolia*, VU
- *Orthotrichum scanicum*, VU (moss)

Arachnids:

- Great Raft Spider, *Dolomedes plantarius*, VU

Clams and Crustaceans:

- Freshwater Pearl Mussel, *Margaritifera margaritifera*, EN
- Broad-fingered Crayfish, *Astacus astacus*, VU

B. Survey Techniques

Habitat Survey:

First, an initial survey of the land should be conducted to determine which habitat types make up the site. This information can be used to decide how to adapt the basic protocols outlined below. Since the site encompasses a large area, a representative sample of each habitat type should be conducted and generalized to the surrounding habitat. Each site should be evaluated for its biodiversity according to the Defra Biodiversity Metric (either version 2 or 3) (Natural England, 2022).

Bird Surveys:

To understand the local bird population at the site, we suggest conducting transect surveys of the land. Transect surveys consist of an observer walking a path of defined distance through an area and recording the number of birds from each species they observe within a defined width. The protocol for a basic transect survey is outlined below (Hostetler, 2001):

After the habitat types have been identified, several transects should be picked from each type to be representative samples of the whole area. Transects should be 1 km long and include the area 20 m to each side of the transect. To gather consistent and comparable results, transects should be walked at a constant rate of roughly 1 km in 30 minutes (0.5 km/hr). To optimize bird activity, surveys should be conducted roughly 3 hours after sunrise for diurnal species and 3 hours after sunset for nocturnal species. All birds seen or heard in the area of observation should be recorded (use the full common name or record the codes used to match to the common name) and the features of any unidentifiable bird should be recorded for identification after the survey. Only individuals of a species should be recorded and care should be taken to avoid recording the same individual more than once. For large flocks of birds, the best estimate should be provided.

The general behavior of the birds in the area can also be noted (e.g. foraging, nesting, aggression/territorial, calling/singing, flying overhead, etc).

The location and behavior of ground nesting birds should be noted and any nests on or near the sites should be recorded. The GPS coordinates should be marked so they can be added to GIS.

Birds that Fly Through (FT) the transect (i.e. fly under the treeline but did not take off from or land in the transect) and birds that Fly Over (FO) the transect (i.e. fly over the treeline) should be recorded in the respective columns. Similarly, birds that are seen or heard Outside of the transect should be recorded in the Outside column. Additional notes can be recorded at the bottom of the tracking sheet.

When approaching the survey location it is crucial to wear mute colors as bright colors could attract or scare away certain birds. When arriving on the site make as little noise as possible and wait at least two minutes without moving before starting the transect.

Additionally, record the general weather conditions such as wind intensity, temperature, cloud cover. Avoid conducting surveys in the rain.

Plant/Fungi Survey:

Since many animals rely on certain plant species for food or shelter, biodiversity of an area is generally contingent on the plant life. To get an accurate estimate of the plant species in and around the site, quadrat surveys should be used. Quadrat surveys consist of defining quadrats, areas of equal area (generally circles or strips), and performing censuses of the species found in each quadrat. Quadrats from each habitat type should be randomly selected using a QGIS model. A census of the plant and fungi (including lichen) should be conducted of each quadrat. Circular quadrats are the easiest to conduct, as measuring each quadrat only requires a stack and a rope.

Bat Survey:

Since identifying and counting individual bats requires sophisticated equipment including ultrasonic sensors, we recommend seeking out a specialist to create specific survey methods.

Pollinator Survey:

To study the pollinator species in the sites, 100 m transects should be used throughout each habitat type. The transects should be walked slowly (roughly 4 minutes per transect), recording pollinator species within 3 m of each side of the transect. Pollinators should be denoted by scientific name if possible or by species type if not (e.g. bumblebee, honey bee, or butterfly) and any useful characteristics should be recorded for subsequent identification. Frequency of each taxon observed should be recorded. If a precise observation is not possible, record an approximation and note the unusual circumstances. If any hives are found, record the GPS locations and the qualities of the hive (e.g. active/abandoned, what is it attached to?, injured?). Include any additional notes at the bottom of the survey sheet.

Mammal Survey:

Langeland has several species of non-volant mammals ranging in size from moles to horses. While on site for other surveys and during construction, tracks, scat, and mammal activity should be recorded. Further surveying techniques are listed below, broken down by size of the mammals (“large”, “medium”, and “small”). Small mammals are any smaller than a hare, medium sized mammals range in size from hares to foxes, and large mammals are anything larger than a fox. Surveying the large mammals in the area should consist of notes taken during observation of other flora and fauna and several minutes of silent observation at the edges of the site. Since medium sized and small mammals are often the hardest to directly observe without trapping, surveys should mostly rely on scat and tracks and chance observations to get an idea of the species and their activity in the area.

Based on the observed activity of mammals, future surveys including trapping and/or camera systems should be considered.

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6.0 Conclusion

As the first essential step in creating a successful renewable energy project, a feasibility study examines the financial, technological, and environmental viability. The goal is to limit project risks and address issues early. A thorough and accurate feasibility study lays the foundation for a successful photovoltaic energy installation project. Our project aimed to accomplish this and provide directions for further work. Based on this cumulative assessment, we conclude that a solar PV farm would likely be feasible on select locations on Langeland.

This report, along with the associated Python toolkit and Recommendations for a Biodiversity Management Plan, can provide a roadmap for the next steps in exploring a solar farm on Langeland. We hope that these materials will help LAUTEC contribute to meeting Denmark's renewable energy goals.

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Appendix

A. Contact Information

Name	Position/Organization	Contact Information
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Electrical Grid Regulations		
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	Elforsyning (LEF)	

B. Python Toolkit Documentation

Overview

This appendix includes the documentation for the functions that are within the python toolkit. The documentation also details how certain values were derived and calculated.

Code Documentation Format

The Code Documentation Format of the document goes as follow:

Function

Description of Function

Parameters

- Input Parameter 1
- Input Parameter 2

Uses Global Variable(s):

- GLOBAL_VARIABLE

Returns

Describes what the function returns: “Returns the return of the function if the call succeeded.”

Site Data Structure

The toolkit utilizes a data structure of sites to calculate the number of panels for the site. The data structure includes a site index, rectangular length, rectangular width, and the actual site area. A global variable called usable_sites contains a list of all usable sites.

Functions

Calculate Max Temperature

Calculate Module Spacing

Calculate Row Width

Calculate Declination Angle of Sun

Calculate Elevation Angle of Sun

Calculate Irradiance on a Tilted Surface

Output Annual Radiation on Tilted Surface

Calculate Optimal Tilt Angle

Calculate Direct Normal Irradiance

Calculate Cell Temperature

Calculate Daily Cell Temperature

Calculate Panel Input

Calculate Total DC Output

Calculate Yearly Return

Calculate Installment Cost

Calculate Solar Irradiance

Calculate Total Panel Amount

Calculate Acres to Square Meters

Calculate Hectares to Square Meters

Calculate Total Usable Land

Calculate Cost of Panels

Calculate Amount of Inverters

Calculate Cost of Inverters

Calculate Estimated Cost of Total Land

Calculate Estimated Starting Costs

Calculate Estimated ROI Value

Calculate Extra Component Cost

Calculate Amount of Panels

Calculate Estimated Return of Basic ETF

Convert USD to DKK

Calculate Average Efficiency

Calculate Total Cost

Calculate Land Cost

Contributors: Jon Aronoff, Jake Mercier

Imports python libraries for use in the tool kit. The libraries imported consist of math, pandas, numpy, and matplotlib.pyplot.

```
# Imports
import math
import pandas as pd
import numpy as np
import matplotlib.pyplot as plt
```

We also imported the data set for location dependent irradiance from a csv file downloaded from https://power.larc.nasa.gov/data-access-viewer/.

We then used the pandas library to read the csv file ./Datasets/Radiation.csv and to

```
# Import Irradiance Data Set

# Location dependent, downloaded from
https://power.larc.nasa.gov/data-access-viewer/
# !!!!!!!!!!!Describe formatting options here!!!!!!!!!!!!!!!
irradiance = pd.read_csv("./Datasets/Radiation.csv")

irradiance.replace("-999.00", np.nan, inplace=True)
irradiance.dropna(subset=['ALLSKY'], inplace=True)
irradiance['ALLSKY'] = pd.to_numeric(irradiance['ALLSKY'])
```

We created a list of global variables, including site variables, solar panel variables, inverter variables, and other miscellaneous variables. These variables will be used as imports for functions throughout the toolkit. For our case study, we used a value of 17.9% percent losses provided by a source who developed a 60MW solar farm in Iowa (Benton et al., 2016). We then subtracted approximately 5% for temperature losses which were calculated separately based on temperature data on Langeland.

```
# Global Variables
# Site Variables
LATITUDE = 55  # Latitude of site
LONGITUDE = 10  # Longitude of site
```

```
SOLAR_ELEVATION_ANGLE = 11.5  # Minimum angle of solar elevation, taken from Solar Data Plot
# Azimuth Correction for this latitude, based on angle of the sun in the sky at the winter solstice
AZIMUTH_CORRECTION = 31.25

# Solar Panel Variables
PANEL_HEIGHT = 1.303  # Panel Height in meters
PANEL_WIDTH = 2.834  # Panel Width in meters
PANEL_AREA = PANEL_WIDTH * PANEL_HEIGHT
PANEL_TEMP_COEF = -0.0034  # Change in panel efficiency per degree Celsius over 25 degrees
PANEL_EFFICIENCY = 0.216  # Efficiency of Solar Panel
TOTAL_LOSSES = 0.13  # Total potential losses (except temperature losses, which are incorporated into the system)
TILT_ANGLE = 53  # Tilt Angle of the solar modules
NOMINAL_OPERATING_CELL_TEMP = 41  # NOCT of the Panel in degrees Celsius

PANEL_PMAX = 655  # Panel Power Max in Watts
PANEL_COST = 205  # Single Panel Cost in USD
# !!!!!!!!!!!!!!!!!!!! need other panel dimensions

INVERTER_PMAX = 25000  # Inverter Power Max in Watts
INVERTER_COST = 4000  # Single Inverter Cost in USD
INVERTER_EFFICIENCY = 0.981  # Efficiency of DC to AC energy conversion

LAND_COST = 1215 * 1.15  # Cost of one Acre for one Year with a 15% increase due to tax changes

BATTERY_COST = 0  # Battery Solution Cost

ELECTRICITY_COST = 0.2  # Estimated Price of Electricity per Watt


# INSTALMENT_COST = assumption but we can give a rough estimate

# OPERATION_AND_MAINTENANCE_COST = estimated quote
```

```
# Data structure for each site
# includes Plot index (string?) , rectangular length (meters), rectangular width (meters), and actual area (Acres)
class Site:
    def __init__(self, index, rect_length, rect_width, area):
        self.index = index
        self.rect_length = rect_length
        self.rect_width = rect_width
        self.area = area


# Global Variable that holds the Rectangular estimates for the usable sites
usable_sites = [Site(1, 480, 315, 27),
                Site(2, 191, 496, 13),
                Site(3, 723, 573, 68),
                Site(4, 356, 934, 61),
                Site(5, 389, 701, 51),
                Site(6, 258, 306, 13),
                Site(7, 182, 162, 3),
                Site(8, 970, 404, 77),
                Site(9, 212, 433, 13),
                Site(10, 385, 235, 14)]
```

Calculate Max Temperature

Calculates the max temperature that the area will reach given the irradiance data from the region.

Parameters

- irradiance["Temp"]

Uses Global Variable(s):

- None

Returns

Returns the maximum temperature in celsius and how often that temperature is reached if the call succeeded.

Calculate Module Spacing

Calculates the minimum spacing of the solar panel arrays.
First, we calculated the height of the tilted panel by the equation below (Diehl, 2020).

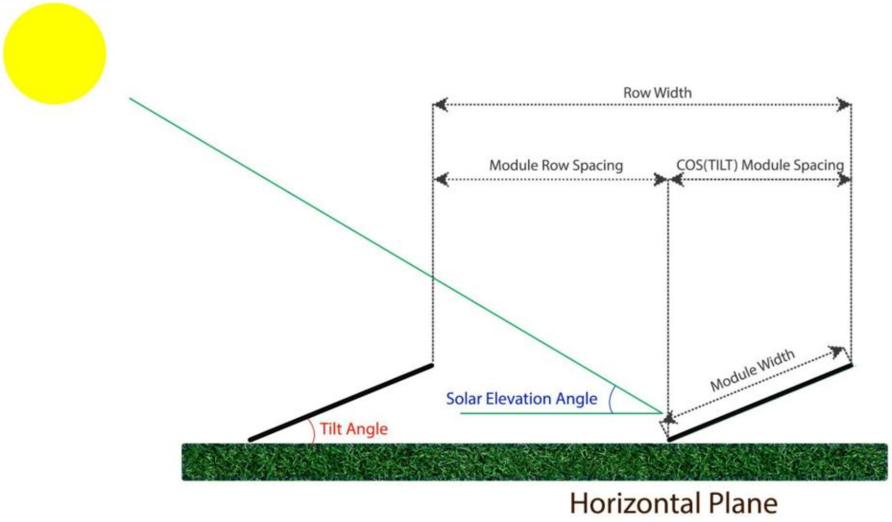
Height Difference = Sin (Tilt Angle) x Module Width

Next we used the solar elevation angle at the winter solstice at this latitude (11.5 degrees) to calculate the module row spacing (Diehl, 2020).

Module Row Spacing = Height Difference / Tan (11.5)

To calculate the minimum spacing we use the azimuth correction angle (Diehl, 2020).

Minimum Module Row Spacing = Module Row Spacing x Cos (Azimuth Correction Angle)



Parameters

- Tilt Angle (degrees)

- Solar Angle (degrees)
- Azimuth Correction Angle (degrees)

Uses Global Variable(s):

- PANEL_HEIGHT

Returns

Returns the minimum module spacing in meters if the call succeeded.

Calculate Row Width

This method uses many equations from the previous method however it outputs row width which is shown in the above figure.
Row Width = Minimum Module Row Spacing + Cos (Tilt Angle) x Module Width

Parameters

- Tilt Angle (degrees)
- Solar Angle (degrees)
- Azimuth Correction Angle (degrees)

Uses Global Variable(s):

- PANEL_HEIGHT

Returns

Returns the width of the row in meters if the call succeeded.

Calculate Declination Angle of Sun

We needed to calculate the declination angle (δ) shown in Equation 1 (Bowden et al., 2019). The declination angle is calculated via the days in the year (1-365), indicated by the variable d (Bowden et al., 2019).

$$\delta = \ 23.45° \cdot sin(360/365\ (284\ +\ d)) \qquad (1)$$

Parameters

- None

Uses Global Variable(s):

- None

Returns

Returns no value, but updates the irradiance Data Frame if the call succeeded.

Calculate Elevation Angle of Sun

The declination angle value relates to the elevation angle (α), shown in Equation 2, which is the angle at which the sun's rays hit the solar panel (Bowden et al., 2019).

$$\alpha = 90 - \phi + \delta \tag{2}$$

ϕ represents the latitude of the site for the solar farm. For our case, this value is 55 degrees.

Parameters

- None

Uses Global Variable(s):

- LATITUDE

Returns

Returns no value, but updates the irradiance Data Frame if the call succeeded.

Calculate Irradiance on a Tilted Surface

We used irradiance data from nasa.gov (NASA, 2021). Specifically, we used daily all sky surface shortwave downward irradiance (kW-hr/m^2/day) for our site on Langeland. This represents the incident irradiance from the sun in all sky conditions. To calculate the tilted irradiance, we first converted the downward irradiance into direct normal irradiance by multiplying the downward irradiance by the cosine of the elevation angle. The irradiance on a tilted panel could then be calculated by the equation below.

$$Smodule = (Shorizontal \cdot sin(\alpha + \beta))/sin(\alpha) \tag{3}$$

This equation includes the tilt angle of the solar panel from the ground represented by β (Bowden et al., 2019). S_{module} is the radiation on a tilted surface. $S_{horizontal}$ is the all sky surface shortwave downward direct normal irradiance we see in Table 1.

Parameters

- Elevation Angle (degrees)
- Tilt Angles (degrees)
- Direct Normal Irradiance (kW-hr/m^2/day)

Uses Global Variable(s):

- None

Returns

Returns solar irradiance (kW-hr/m^2/day) values if the call succeeded.

Output Annual Radiation on Tilted Surface

Adds the daily radiation and outputs the yearly radiation

Parameters

- Tilt Angle (degrees)

Uses Global Variable(s):

- irradiance

Returns

Returns annual radiation received on a tilted surface if the call succeeded.

Calculate Optimal Tilt Angle

Function to calculate the Optimal tilt angle for a solar farm at this location. The function uses calculations for solar irradiance on a tilted surface, inputs angles 0 through 90 to see which angle will produce the highest level of radiation, and then outputs the optimal tilt angle for the location.

Parameters

- Step between angles (degrees)

Uses Global Variable(s):

- None

Returns

Returns the optimal tilt angle of the solar panels if the call succeeded.

Calculate Direct Normal Irradiance

Function that calculates direct normal irradiance from NASA's All Sky Downward Direct Irradiance. It multiplies the All Sky Irradiance by the cosine of the elevation angle to get this value.

Parameters

- irradiance['ALLSKY'].size

Uses Global Variable(s):

- None

Returns

Returns the direct normal irradiance if the call succeeded.

Calculate Cell Temperature

Function to calculate the cell temperature of the panels. Takes the Air temp, nominal operating cell temp, and the irradiance data to return the cell temperature of the panel.

Parameters

- Air temp (degrees Celsius)
- Nominal Operating Cell Temp (degrees Celsius)
- Irradiance (kWh/m^2/day)

Uses Global Variable(s):

- None

Returns

Returns the temperature of the solar cells in Celsius if the call succeeded.

Calculate Daily Cell Temperature

Wrapper function to calculate the average cell temp for each day and the updated efficiency.
The cell temperature was calculated from the equation below where, Tcell is the cell temperature, Tair is the air temperature, NOCT is the Nominal Operating Cell Temperature, and S is the irradiance.

$$Tcell \quad = Tair\frac{NOCT-20}{800} \quad S$$

To calculate the updated panel efficiency, the difference between cell temperature and 25 degrees Celsius was multiplied by the temperature coefficient. This was then subtracted from the baseline efficiency and then recorded as the daily adjusted efficiency.

Parameters

- irradiance['Temp'].size

Uses Global Variable(s):

- NOMINAL_OPERATING_CELL_TEMP
- PANEL_TEMP_COEF
- PANEL_EFFICIENCY

Returns

Returns nothing, but updates the efficiency of the panels if the call succeeded.

Calculate Panel Input

Function to calculate the daily output of a single solar panel given irradiance, panel efficiency, and the panel area.

Parameters

- Irradiance (!!UNITS!!)
- Efficiency (percentage)
- Panel Area (square meters)

Uses Global Variable(s):

- PANEL_AREA

Returns

Returns the power output of a single solar panel if the call succeeded.

Calculate Total DC Output

Calculate Total DC Output of the farm by multiplying the Radiation on a single panel by the number of panels

Parameters

- Number of Panels (Number)
- Solar Radiation

Uses Global Variable(s):

- None

Returns

Returns the total DC Power output of the solar farm if the call succeeded.

Calculate Yearly Return

Calculate yearly return from the sale of energy; converts the DC power to AC power and accounts for the inverter efficiency, estimated cost of electricity, and the estimated losses of the system. The function takes the product of the estimated cost per kwh and the inverter conversion efficiency and then subtracts the estimated loss percentage from the output to get the estimated yearly return.

Parameters

- DC Power

Uses Global Variable(s):

- INVERTER_EFFICIENCY
- ELECTRICITY_COST

Returns

Returns the AC power of the solar farm and the gross yearly return of the farm if the call succeeded.

Calculate Installment Cost

Estimates Installation Costs based on the dc output of the system. The function returns an estimated installment cost for the solar farm by taking the product of the DC Power output in MegaWatts, conversion factor of 1000 to kilowatts, and the estimated cost of installment per kilowatt ($350 USD).

Parameters

- DC Power (kWh)

Uses Global Variable(s):

- None

Returns

Returns the installation cost of the solar farm if the call succeeded.

Calculate Solar Irradiance

Wrapper function to handle all calculations of Solar Irradiance. The function takes the Declination Angles for this Site, Elevation Angles for this Site, Direct Normal Irradiance for the Site, total radiation on a titled panel, Daily Cell Temperature and Adjusted Efficiency for a Panel to calculate the Power Output of a Panel in kW/year.

Parameters

- Tilt Angle (degrees) OPTIONAL - can be added for optimization code

Uses Global Variable(s):

- None

Returns

Returns the power output of a panel in kW/year if the call succeeded.

Calculate Total Panel Amount

Function to determine the total amount of panels for the size of a solar farm given the panel amount per site. The function sums the panel amounts from every individual site.

Parameters

- Tilt Angle (optional)
- Sites

Uses Global Variable(s):

- None

Returns

Returns the total amount of solar panels for the solar farm if the call succeeded.

Calculate Acres to Square Meters

Converts Acres to Square Meters. Returns the amount Square Meters by taking the product of acres and the conversion rate of 4046.86.

Parameters

- Acres

Uses Global Variable(s):

- None

Returns

Returns the area in square meters if the call succeeded.

Calculate Hectares to Square Meters

Converts Hectares to Square Meters. Returns the amount Square Meters by taking the product of hectares and the conversion rate of 8093.72.

Parameters

- Hectares

Uses Global Variable(s):

- None

Returns

Returns area in square meters if the call succeeded.

Calculate Total Usable Land

Calculates the total usable land using a summation of the usable land from each site.

Parameters

- Sites

Uses Global Variable(s):

- None

Returns

Returns total area of usable land if the call succeeded.

Calculate Cost of Panels

Calculates an estimated cost of panels for the solar farm. The function returns the product of the cost of a single panel and the total amount of panels needed.

Parameters

- Amount of panels (int)
- Cost of one panel (number)

Uses Global Variable(s):

- PANEL_COST

Returns

Returns the total panel cost if the call succeeded.

Calculate Amount of Inverters

Calculates an estimated amount of inverters for the solar farm. The function returns the amount of inverters by taking the 1:1.25 ratio of power max of panels to power max of inverters, and multiplying it by the amount of total panels necessary for the farm.

Parameters

- Amount of panels (int)

Uses Global Variable(s):

- PANEL_PMAX
- INVERTER_PMAX

Returns

Returns the total number of inverters if the call succeeded.

Calculate Cost of Inverters

Calculates an estimated cost of inverters for the solar farm. The function returns the product of the cost of a single inverter and the total amount of inverters needed.

Parameters

- Amount of inverters (int)
- Cost of one inverter (number)

Uses Global Variable(s):

- INVERTER_COST

Returns

Returns the cost of the total inverters if the call succeeded.

Calculate Estimated Cost of Total Land

Calculates an estimated cost of acres necessary for the solar farm. The function returns the product of the costs of one acre per year and the total amount of acres.

Parameters

- Amount of acres (number)
- Cost of one Acre per year (number)

Uses Global Variable(s):

- LAND_COST

Returns

Returns the estimated cost of the land over the years of the lease if the call succeeded.

Calculate Estimated Starting Costs

Calculates an estimated starting cost for a solar panel given the costs of components and installation, as well as costs associated with infrastructure upgrades potentially necessary for a solar farm. The function takes the summation of the costs of panels, inverters, battery solutions, installation, tax change, grid infrastructure upgrades, and other components.

Parameters

- Cost of Panels
- Cost of Inverters
- Cost of Batteries
- Cost of Installment
- Cost associated with Tax Change
- Cost of Grid Upgrade
- Cost of other Components

Uses Global Variable(s):

- None

Returns

Returns the estimated starting cost of a solar farm if the call succeeded.
Calculate Estimated ROI Value
Calculates an estimated return on investment for a solar panel given the starting cost, the estimated value of energy, the years of estimated lifespan of the solar farm, the land cost per year, the operation and management costs, and the DC output of the solar farm.
Also prints out the annualized percentage return on investment, as well as plots ROI graph with the return data.

Parameters

- Starting Cost (number)
- Value of energy (number)
- Years (number)
- Land Cost per year (number)

- Operation and management (number)
- Estimated DC Output (number)

Uses Global Variable(s):

- None

Returns

Returns ROI of expected, optimistic, and pessimistic scenarios if the call succeeded.
Calculate Extra Component Cost
Calculates the cost of extra components including cabling, monitoring systems, and racking using assumptions based on prices per MW.

Parameters

- DC Power (MWh) required

Uses Global Variable(s):

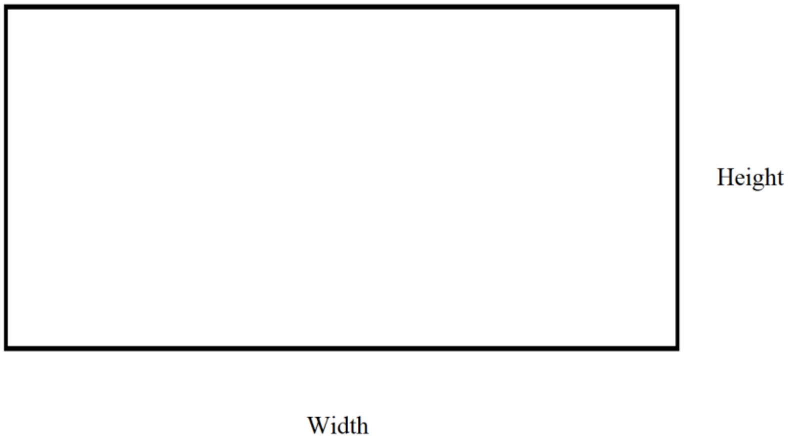
- None

Returns

Returns the cost of extra components if the call succeeded.

Calculate Amount of Panels

Estimates the number of panels that can be used in a given site. This function estimates the number of arrays that can fit in the site by extrapolating rectangles over each non-rectangular site, calculating the number of arrays that can fit in that rectangle, and using the actual area of the non-rectangular site to get a more accurate estimate.



The above figure shows the orientation of the height/width of a solar panel, which are referenced below.

Since panels are organized in linear arrays, they must fit in a certain orientation in a plot of land. If the site is perfectly rectangular, the amount of solar arrays can be calculated by dividing the length of the rectangle by the calculated row width (the width of the tilted panel plus the spacing in between each array). The amount of panels in each array can be calculated by dividing the width of the rectangular plot by the width of a panel. From this, the total number of panels is simply the product of arrays per plot and panels per array. However, most plots are not perfectly rectangular and this method will not give an accurate estimate of the amount of solar panels.

Accurately calculating the amount of panels/arrays that can fit in non-rectangular plots involves complex algorithms. Instead, we extrapolated the smallest possible rectangles over each usable plot of land, used the above method to calculate the amount of panels/arrays that could fit in that rectangle and then multiplied those numbers by the ratio of the actual site area over the area of the extrapolated rectangle. This gave us a fairly accurate assumption of the total number of solar panels without writing complex geometrical algorithms.

Parameters

- Site (Site)

Uses Global Variable(s):

- TILT_ANGLE

- PANEL_WIDTH
- SOLAR_ELEVATION_ANGLE
- AZIMUTH_CORRECTION

Returns

Returns the number of solar panels if the call succeeded.

Calculate Estimated Return of Basic ETF

Compares the return on investment of a solar farm to a basic ETF investment given the same starting cost, interest rate of the ETF, and inflation.

Parameters

- Interest_rate
- Starting_investment
- Inflation

Uses Global Variable(s):

- None

Returns

Returns the estimated return on investment of the starting cost in a basic ETF if the call succeeded.

Convert USD to DKK

Takes in an amount of US Dollars and converts the value to Danish Kroner based on the current exchange rate.

Parameters:

- USD

Uses Global Variable(s):

- USD_DKK_EXCHANGE_RATE

Returns

Returns the amount of DKK equivalent to the imputed USD if the call succeeds.

Calculate Average Efficiency

Function that computes the average of the “Efficiency” column in the irradiance DataFrame

Parameters:

- None

Uses Global Variable(s):

- Irradiance

Returns

Returns the average adjusted efficiency for a panel if the call succeeds.

Calculate Total Cost

Wrapper function that takes in the output of one panel at the site and calculates the total cost and return of a solar farm at this site, using the irradiance DataFrame and the usable_sites global variable.

Parameters:

- Panel Output (kWh)

Uses Global Variable(s):

- IRRADIANCE
- USABLE_SITES

Returns

Returns the starting cost of the solar farm if the call succeeds.

Calculate Land Cost

Calculates the amount of land taxes to be paid yearly, based on the size of the solar farm

Parameters:

- Solar Farm Size (MW)

Uses Global Variable(s):

- LAND_VALUE_PER_MW
- LAND_TAX_RATE

Returns

Returns the yearly taxes to be paid if the call succeeds

References:

Bowden, S.G. and Honsberg, C.B. (2019) Photovoltaics education website. www.pveducation.org

Benton, C., Dizdarevic, S., Ibrahim, A., & Mukumbilwa, M. (2016). *115 kV / 34.5 kV Solar Power Plant / Substation*.

Diehl, A. (2020, February). *Determining module inter-row spacing*. Determining Module Inter-Row Spacing. Retrieved April 20, 2022, from https://www.cedgreentech.com/article/determining-module-inter-row-spacing

NASA. (2021). *Prediction Of Worldwide Energy Resource*. POWER Data Access Viewer. Retrieved from https://power.larc.nasa.gov/data-access-viewer/

C. Calculations of Site-Specific Solar Radiation

To calculate the output of the solar farm and optimal tilt angle, we used irradiance data from nasa.gov. We used daily all sky surface shortwave downward irradiance (kW-hr/m^2/day) specific to our site on Langeland. This represents the solar irradiance during all sky conditions. We needed to calculate the declination angle (δ) shown in equation 3. The declination angle is calculated via the days in the year (1-365), indicated by the variable d. This value relates to the elevation angle (α), shown in equation 4, which is the angle at which the sun's rays hit the solar panel. We then calculated the direct normal irradiance from the all sky irradiance by multiplying the all sky irradiance by the sin of the elevation angle. The equations for which are shown below:

$$\delta = 23.45° \cdot sin(360/365\ (284\ +\ d)) \qquad (1)$$

$$\alpha = 90 - \phi + \delta \qquad (2)$$

ϕ represents the latitude of the site. For our case, this value is 55 degrees.

$$Smodule = (Shorizontal \cdot sin(\alpha + \beta))/sin(\alpha) \qquad (3)$$

Equation 3 includes the tilt angle of the solar panel from the ground represented by β**.** S_{module} is the radiation on a tilted surface. $S_{horizontal}$ is the all sky surface shortwave downward direct normal irradiance. To calculate the optimal angle, we used a Python function that varied the tilt angle between 0-90 degrees and returned the angle that produced the highest output. Once we found the optimal tilt angle, we calculated the radiation on a tilted surface by using equation 3 for each day.