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Guidelines for auditing Solar PV Installations

Techno Economic Evaluation for investors

MEMÒRIA

Autor:	William Wiseman
Director:	Björn Laumert
Ponent:	Cristóbal Voz
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Escola Tècnica Superior
d'Enginyeria Industrial de Barcelona

Abstract

Climate change is no longer a problem of the future. Climate change is global, rapid, and intensifying. A reality. The latest *Intergovernmental Panel on Climate Change* (IPCC) report highlights the Anthropocene is behind the unprecedent rising temperatures, leading to extreme weather events such as heatwaves, droughts, heavy precipitation, or tropical cyclones. Climate action must be taken.

The energy transition plays a fundamental role when considering the wellbeing of the planet. However, renewable energy finance has always been a challenge. To date, the energy transition has been regrettably underfunded. In 2018, the global energy system was below 50 % of the investment required to keep global warming below 1.5 °C and avert the worst consequences of the climate crisis [4]. This staggering statistic clearly shows that financial investment needs to either be redirected to the energy transition, or new financing channels must be open. Seeds Renewables, a California-based startup, has come up with a solution which has the potential to cover a portion of the energy financing deficit by enabling people to invest in renewable energy projects from as little as their spare change.

Before allowing their users to invest, Seeds carries out the due diligence of the projects to determine the feasibility of the installation. It is identified that there is a current lack of concise and public literature regarding the process required to determine the technical feasibility and economic profitability of projects. This thesis serves as a guide for lenders, such as Seeds Renewables, who aim to conduct techno-economic assessments on solar photovoltaic installations. This core objective is complemented by qualitative checklists for project development and legal due diligence to provide a comprehensive overview of the factors which surround the techno-economic analysis of solar arrays. Furthermore, the optimal software available in the market to carry out an analysis of solar photovoltaic installation is identified.

The thesis covers the background research conducted on solar photovoltaic systems, a compilation of project due diligence best practices, insights on renewable energy project finance and a literature review on photovoltaic analysis software tools which leads to the selection of two softwares. PVsol and PVsyst are compared by means of a Multi-Criteria Analysis.

A case study is conducted on a 63.3 kW solar photovoltaic array installed in 2016 to test the selected softwares. The array is located on the roof of Rinaldi Tile in Pajaro, California, United States of America. The array is replicated using PVsol and PVsyst. Consequently, the simulation predictions are compared to the real production data extracted from the system's inverter. The performance ratio from the real data, PVsol and PVsyst are 82.4 %, 85.9 %, 80.51 % respectively. The real quantity of power produced over a 5-year period of study is average of 82.24 MWh while the simulations by PVsol and PVsyst predict 93.49 MWh and 81.30 MWh respectively. The discrepancy between the real data and software results is due to limitations of both tools. After evaluating the accuracy of the solar PV simulation tools, the Multi-Criteria Analysis rates PVsyst as the more desirable tool.

Using this study, engineers or investors will have a clear framework to follow when carrying out the project due diligence on a solar photovoltaic installation and a rating of the available softwares to assess the viability of the solar arrays.

Keywords

Renewable Energy, Solar Photovoltaics, Due Diligence, Simulation tools.

Sammanfattning

Klimatförändringarna är inte längre ett framtidsproblem. Klimatförändringarna är globala, snabba och intensifierande. En verklighet. Den senaste Intergovernmental Panel on Climate Change (IPCC) rapporten visar att Antropocen ligger bakom de aldrig tidigare skådade temperaturerna, vilket leder till extrema väderhändelser som värmeböljor, torka, kraftig nederbörd eller tropiska cykloner. Klimatåtgärder måste vidtas.

Energiomställningen spelar en grundläggande roll när man överväger planetens välbefinnande. Finansiering av förnybar energi har dock alltid varit en utmaning. Hittills har energiomställningen tyvärr varit underfinansierad. År 2018 låg det globala energisystemet under 50% av investeringarna som krävs för att hålla den globala uppvärmningen under 1,5 ° C och avvärja de värsta konsekvenserna av klimatkrisen [4]. Denna häpnadsväckande statistik visar tydligt att finansiella investeringar antingen måste omdirigeras till energiomställningen eller att nya finansieringskanaler måste vara öppna. Seeds Renewables, en Kalifornienbaserad startup, har kommit fram till en lösning som har potential att täcka en del av energifinansieringsunderskottet genom att göra det möjligt för människor att investera i förnybara energiprojekt från så lite som deras växel.

Innan de tillåter sina användare att investera, utför Seeds projektets due diligence -analys för att avgöra genomförbarheten av installationen. Det identifieras att det för närvarande saknas kortfattad och offentlig litteratur om processen som krävs för att bestämma projektens tekniska genomförbarhet och ekonomiska lönsamhet. Denna avhandling fungerar som en vägledning för långivare, till exempel Seeds Renewables, som syftar till att göra tekno-ekonomiska bedömningar av solcellsanläggningar. Detta kärnmål kompletteras med kvalitativa checklistor för projektutveckling och juridisk due diligence för att ge en övergripande överblick över de faktorer som omger den tekno-ekonomiska analysen av solsystem. Dessutom identifieras den optimala programvara som finns tillgänglig på marknaden för att utföra en analys av solcellsinstallation.

Avhandlingen omfattar bakgrundsforskning på solcellssystem, en sammanställning av bästa praxis för aktsamhet, insikter om projektfinansiering för förnybar energi och en litteraturgenomgång om programvara för fotovoltaiska analyser som leder till val av två programvaror. PVsol och PVsyst jämförs med hjälp av en multikriterieanalys.

En fallstudie genomförs på en solcellsanläggning på 63,3 kW installerad 2016 för att testa de utvalda programvarorna. Arrayen ligger på taket av Rinaldi Tile i Pajaro, Kalifornien, USA. Arrayen replikeras med PVsol och PVsyst. Följaktligen jämförs simuleringsprognoserna med de verkliga produktionsdata som extraherats från systemets inverter. Prestandakvoten från de verkliga uppgifterna, PVsol och PVsyst är 82.4 %, 85,9% respektive 80,51%. Den verkliga mängden kraft som produceras under en 5-års studieperiod är i genomsnitt 82,24 MWh medan simuleringarna av PVsol och PVsyst förutsäger 93,49 MWh respektive 81,30 MWh. Skillnaden mellan de verkliga data- och programvareresultaten beror på begränsningar för båda verktygen. Efter att ha utvärderat noggrannheten i solcells-PV-simuleringsverktygen med multikriterieanalysen bedöms Multi-Criteria Analysis PVsyst som det mer önskvärda verktyget.

Med hjälp av denna studie kommer ingenjörer eller investerare att ha en tydlig ram att följa när projektet genomförs due diligence på en solcellsanläggning och en bedömning av de tillgängliga programvarorna för att bedöma matrisernas livskraft.

Nyckelord

Förnybar Energi, solceller, due diligence, simuleringsverktyg.

Acknowledgments

The thesis authors would like to extend a special thank you to Tony Armor at Day One Solar for providing the power production data for the solar PV array used in the case study. Without his contribution, this thesis would have lacked the control group necessary to benchmark the accuracy of the simulation tools.

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Stockholm, September 2021

William Wiseman

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List of acronyms and abbreviations

AHP	Analytic Hierarchical Process
CF	Cash flows
E_oT	Equation of time
EPA	Environmental Protection Agency
EP&C	Engineering. Procurement and Construction
FINRA	Financial Industry Regulatory Authority
FiT	Feed-in-tariff
GHI	Global Horizontal Irradiance
HRA	Hour Angle
ICT	Information and Communication Technology
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
IRR	Internal Rate of Return
ISO	International Organization for Standardization
ITC	Investment Tax Credit
JOBS	jumpstart our business startups
LT	Local time
LST	Local solar time
LSTM	Local standard time meridian
MCA	Multi-criteria Analysis
MPPT	Maximum Power Point Tracking
NREL	National Renewable Energy Laboratory
NPV	Net Present Value
PG&E	Pacific Gas and Electric Company
PR	Performance ratio
PV	Photovoltaic
SEC	Securities exchange commission
TC	Time correction factor
TMY	Typical Metrological Year
UL	Underwriters' Laboratories

UNIDO	United Nations Industrial Development Organization
WACC	Weighted Average Cost of Capital
WWW	World Wide Web

1 Introduction

In the past, financing the energy transition was a challenge. For a long-time renewable energy sources required government subsidies to be economically viable, although now economies of scale and perpetual learning have helped many solar photovoltaic (PV) installations and on-shore wind farms reach a levelized cost of energy price parity with conventional fossil fuels. [2]

While this pivotal tipping point will signal future investment potential, this has not been the case for the past or the present. To date, the energy transition has been regrettably underfunded. According to the International Renewable Energy Agency (IRENA), in the power sector, the global energy transformation would require investment of nearly USD 22.5 trillion in new renewable installed capacity through 2050. This would imply a doubling of annual investments compared to the current levels, from almost USD 310 billion to over USD 660 billion. [3] In 2018, the global energy system was below 50 % of the investment required to keep global warming below 1.5 °C and avert the worst consequences of climate the climate crisis. [4] This staggering statistic clearly shows that financial investment needs to either be redirected to the energy transition, or new financing channels need to be opened.

Seeds Renewables, a California-based startup, has come up with a solution which has the potential to cover a portion of the energy financing deficit by enabling people to invest in renewable energy projects from as little as their spare change. If the 7.6 million people who attended the global climate strikes on 2019 used Seeds to invest the spare change from their everyday purchases this would be equivalent to USD $ 1.25 billion per year invested in clean energy projects. This cumulative USD $ 1.25 billion per year of additional renewable energy investment would eliminate only a small portion of the global financing deficit, although it is a step in the right direction. A company analyzing $ 1.25 Bn/yr. of renewable energy projects will need a streamlined methodology to screen the technical and economic feasibility of available solar projects for investment.

1.1 Background

The basis for this thesis is the observation that there is not a comprehensive study or guide on completing a techno-economic analysis of solar PV arrays from the perspective of financial lenders. The authors of this thesis seek to create a single document which covers the technical and economic analysis which must be conducted to judge the financial viability to invest in a solar array. The quantitative processes undertaken to check the project's viability are complimented by qualitative framework which cover the necessary permits, land designations for development and much more. This study serves as a compilation of diverse topics upon which future academics can add more detail.

In addition, the authors have identified a software analysis tool which can be used to accelerate the speed of the techno-economic due diligence process. The tool is judged based on how well it performs regarding technical and economic accuracy while also considering secondary factors such as the learning curve, the time required to design the solar array and the cost of the tool. A literature review of the available solar PV analysis tools is conducted to determine their strengths and weaknesses. Two tools are selected, and their simulation accuracy is compared against the real power yields of the solar array. A Multi-Criteria Analysis (MCA) is developed so that the software tool selection criteria can be weighed appropriately. From there, each tool is rated on its performance and the superior tool is identified.

1.2 Problem statement

Seeds Renewables (hereby Seeds) aims to build an environmental FinTech mobile app that uses crowdfunding to combine many micro-investments into project finance loans for bankable renewable energy projects, providing users with a competitive return on investment. The startup is seeking to outline the project due diligence process to be able to assess the feasibility of solar PV installations from a lenders' perspective and minimize the risks for their investors. When standardized, the due diligence process can reduce costs and leverage the learning experience acquired. [5]

The questions that this research aims to answer are the following:

1. What does the due diligence procedure for a solar PV installation from the lender's perspective imply?
2. Which of the softwares used to carry out the due diligence of solar PV installations available in the market is best in terms of overall performance, price, level of complexity, time intensity, input data required and user interface?
3. Which is the optimal due diligence process flow which fits best Seeds Renewables' business model?

1.3 Purpose

Seeds will apply the results of this degree project to carry out the due diligence of their first pilot projects. Furthermore, Seeds will use this document as the introductory document upon which its due diligence process will be continually refined and improved. Through this study, a solar PV analysis software tool is selected to be used in follow on project due diligence. The accuracy with which the solar analysis tool can predict the energy yields and the accompanying financial performance is critical to the success of Seeds' investments.

1.4 Goals

The goal of this thesis is to outline and design the process of project due diligence for solar PV installations from a lender's perspective, the lender being a renewable energy investment crowdfunding platform. The goal has been divided into three objectives:

1. Develop a framework for solar PV project due diligence processes with an emphasis on the technical and financial analysis.
2. Review, analyze and make a comparison of solar PV softwares and identify the optimal solar PV software through an MCA.
3. Identify the optimal process flow for the renewable energy investment platform – Seeds Renewables.

1.5 Research Methodology

The research for this thesis starts with a comprehensive literature review of a wide array of topics including but not limited to solar PV installations, Engineering Procurement and Construction (EP&C) best practices, renewable energy project finance, simulation tools, technical and financial assessment of projects and, briefly, legal due diligence. The research of this broad range of topics is necessary to gain a comprehensive overview which then led the study to focus on the points of utmost importance to make an informed decision on the technical and economic viability of the solar array.

The technical and economic foundations acquired are used to design a framework for the solar PV project due diligence. Furthermore, this study compares two software tools' overall performance, costs, learning curve, input data and user experience to be used during the assessment. After a thorough review of the available solar PV analysis tools, the two software tools selected for the comparison, based on their merits and functionalities, corresponds to PVsol and PVsyst. The study creates a holistic perspective of an engineer's experience while completing the project feasibility and investment assessment. These factors are weighted for use within an Analytic Hierarchical Process (AHP). AHP is a type of MCA. Based on their relative importance to the results of the due diligence and the effect it will have for the lending firm. Finally, the findings are used to identify the optimal process flow for the renewable energy investment platform, Seeds.

1.6 Delimitations

To date, Seeds is at a pre-seed stage. The company was founded in October 2020. Seeds is currently developing the app, going through the compliance process with the *Financial Industry Regulatory Authority* (FINRA) and building the project pipeline. Seeds aims to finance renewable energy projects including a wide range of technologies, operating at a global scale. However, considering the company's stage and the legislation requirements to operate in other countries, only projects located in the United States are considered. Regarding technology, Seeds will start financing solely solar PV installations. The main drivers behind the decision of starting with solar projects are the comparatively low technical risk of construction and operation, the reliance on large volumes of mass-produced component parts available in the global market, and the opportunity to develop distributed generation projects on residential housing and communities. These characteristics set solar projects apart from other technologies and make them a safer option. [6] Both the boundary of the United States as a country and solar PV as a technology imply that further investigation must be carried out when including other locations and projects due to country dependent regulations and the features of the technology selected.

When looking into the project due diligence, the process is divided into the following categories: technical, economical, and legal. Because of lack of background, qualifications, and expertise in the field the legal due diligence only a very brief overview of the requirements is given. Moreover, there is a wide range of software tools available in the market, while this report focuses on an in-depth comparison of two of them.

1.7 Structure of the thesis

Chapter 2 benchmarks relevant background information about solar PV installations, project due diligence best practices, an introduction to project finance as well as the startup and goes through major related work. Chapter 3 presents the methodology used for this research project, being mainly a thorough literature review and the MCA, gives an overview of solar PV softwares and an analysis and comparison through literature review until landing on two, which is explored more thoroughly. Once selected, in Chapter 4, the project due diligence of an example solar PV installation in the United States is carried out using the two previously identified softwares. The two softwares are compared using the AHP method (subtype of MCA) and the findings of possible business models for Seeds are outlined. Chapter 5 includes the major results as well as a reliability and validity analysis and discussion. Finally, Chapter 6 concludes this degree project with the major learnings, limitations, and future work.

1.8 Authors' work

William Wiseman has co-authored this thesis with Alba Forns. It is worth noting the authors of this thesis evenly collaborate when carrying out the study. Both contribute to the research and writing of the introduction, literature review, result compilation and conclusion.

Wiseman carries out the simulation of the solar PV installation in California using PVSol. When analyzing the real data of the Rinaldi Tile project and comparing it to the simulation results, William Wiseman leads the techno economic analysis.

2 Background

This chapter provides basic background information about solar PV installation components (Section 2.1), describes the process of project due diligence (Section 2.2), and contains a brief introduction to renewable energy project finance and the startup Seeds (Section 2.3). In Section 2.4, major related work will be commented.

While this thesis covers the high-level background and equipment involved in a solar array, the reader may need to inform themselves on the underlying physics of PV energy to have a comprehensive understanding of this case study. Additionally, a basic understanding of project finance will be beneficial for understanding the financial analysis portions of this report. Keeping in mind that the audience of this thesis are professionals in the engineering sector rather than experts in the financial space, the authors intentionally kept the finance sections high level to avoid a digression into material which falls outside the scope of this case study.

2.1 Solar PV Installation components

Solar energy plants can be divided into solar thermal, solar thermodynamic and solar PV plants. PV's scalability and adaptability to regional conditions together with the dissemination and successful implementation of this technology worldwide are the technology's unique selling point. Moreover, economies of scale have led to a fall in PV system costs. For instance, module prices have decreased by 8 % from $ 0.53 /W to an average of $ 0.49 /W in 2019 in 5 years' time. [7] The aim of this section is to introduce solar PV systems, providing a brief overview of the main components of a PV installation, system performance and cost considerations.

Solar PV systems generate electricity through the PV effect, converting radiant energy from the sun into electrical energy. PV systems can or not be connected to the grid. [8] The three main types of grid-connected solar installations which supply power to users correspond to residential applications (3 kW), commercial (100 kW), and industrial (500 kW). [9]. PV installations which provide power at utility level are known as PV power stations or utility-scale solar and are in the MW range. The largest built was commissioned on March 2020 in India and has a nominal power of 2245 MW. [10]

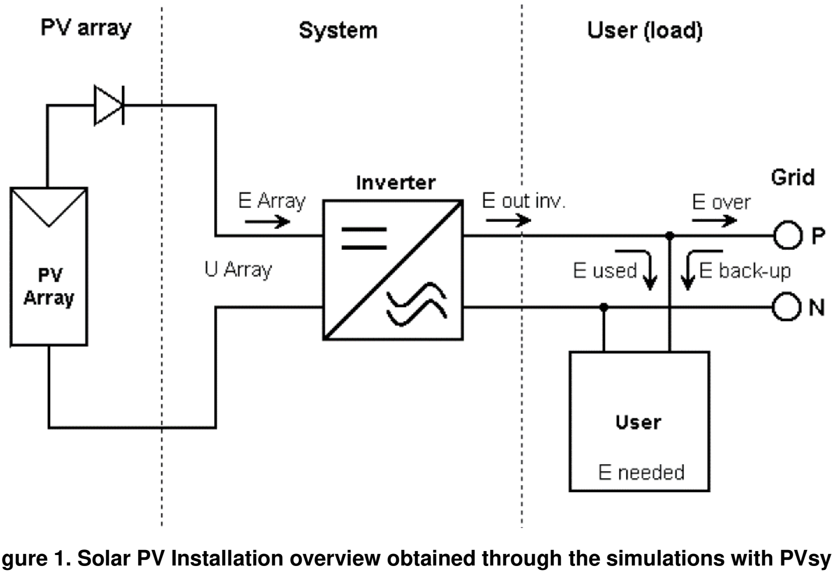

Figure 1. Solar PV Installation overview obtained through the simulations with PVsyst

The points outlined in this section relate to grid-connected systems and can be applicable to different scale projects, though the focus of this report are commercial installations. The main components of a grid connected installation correspond to the PV modules and the balance of system (BOS) which encompasses inverters, transformers, mounting structure, cabling, protection systems, transmission line, and the monitoring system, as well as the weather station. Storage will not be considered because the system is grid connected. Figure 1 provides a simple schematic of a solar PV system which includes some of the previously mentioned components.

PV modules

Solar modules, often considered the most critical component of the installation, generate DC electricity via the photo-electric effect using irradiance energy from the sun. PV module performance parameters are evaluated based on I-V and P-V curves, I being current, V voltage and P Power. Curve tracking is the main method for PV performance analysis, determining the short-circuit current, open-circuit voltage, fill factor and maximum power point. Table 2-1 shows an overview of the main solar PV parameters. [7]

Table 2-1. Main solar PV module performance parameters, mathematical relation and description [7]

Parameters	Mathematical relation	Description
Open circuit voltage	V_{oc}	Voltage value measured under standard test conditions (STC) or real-time operating conditions by putting the cell terminals in open-circuit condition. V_{oc} generally exceeds the voltage achieved at the maximum power point (MPP).
Short-circuit current	I_{sc}	Maximum current generated when a solar PV cell is made to operate in STC or real time conditions. The cell terminals are short-circuited by means of a load. I_{sc} will be higher than the one attained at the MPP.
Power input	$P_{in}\,[KW] = Area \times I$	Solar energy potential available, product of the area of the PV module and the incident solar radiation, I.
Power output	$P_{out}\,[KW] = V_{MAX} \times I_{MAX}$	Product of the maximum current and maximum voltage at a given time.
Power conversion efficiency	$PEC[\%] = \frac{P_{out}}{P_{in}} \times 100$	Ratio of power output to power input.
Fill factor	$FF = \frac{P_{out}}{V_{oc} \times I_{sc}}$	Represents the quality of the PV cell. IT can be easily observed that FF is always <1. Normally the value for crystalline solar cells is around 0.7-0.8, the closer to unity the better the operation.

Commercial PV modules are commonly rated by their DC output power and range between 100 W – 320 W approximately, with a nominal efficiency under STC ranging from 8 % – 20 %. [11]

There are different kinds of modules available and the most common can be easily classified into Crystalline PV (including mono-crystalline and polycrystalline) and thin-film PV (including amorphous silicon (a-Si), copper indium gallium selenide (CIGS), and cadmium telluride (CdTe)). Other types can be found but will not be considered for the scope of this thesis due to their smaller market share.

Crystalline silicon solar technology were the first type of PV to be widely commercialized. Monocrystalline show higher nominal efficiency (~20 %) when compared to polycrystalline (~14-18 %). Thin-film technology consists in a thin semiconductor layer deposited on a low-cost flexible substrate. The lower use of silicon or other semiconductor material reduces the manufacturing costs but leads to lower efficiency (7-11 %). [11] The main drivers behind the selection of panels correspond to the technical aspects (which include the nominal efficiency in STC, and effects of the site temperature conditions and site irradiance to the performance) and the commercial aspects (including PV module manufacturers and the cost of the modules). A comparison between crystalline and thin fil panels taking into consideration the main technical and commercial aspects can be found in Table 2-2.

Table 2-2. Crystalline and Thin-film PV module technology comparison [11]

Concept	Comments	Crystalline	Thin-film
Nominal efficiency (STC)	Higher nominal efficiency leads to lower land area required at a given plant output capacity	Higher; suitable for sites with limited land area	Lower; suitable when no land constraints
Temperature conditions	Temperature conditions may affect PV module technology performance	Higher power loss under high temp. conditions	Lower power loss under high temp. conditions
Irradiance	PV module efficiency varies with irradiance	Poorer capacity to convert low irradiance into useful energy output	Better use of low irradiance resources
Manufacturer	More manufacturer options means more flexibility	More options due to higher track record	Less options
Cost	Solar panels account for 30-40 % of total CAPEX	April 2020 prices: Polycrystalline-Si: 0.160–0.290 USD/Wp, 0.177 USD/Wp average. High efficiency monocrystalline-Si: 0.185–0.380 USD/Wp, 0.200 USD/Wp average. A decrease in price of crystalline-Si modules to 0.150 USD/Wp is foreseen by 2025 [12]	April 2020: price of thin film modules was 0.200–0.320 USD/Wp, 0.221 USD/Wp average [12]

The quality of modules can significantly vary so due diligence has to be exercised. From a lender's perspective, reliable performance data is vital as minor deviations from the expected energy yield can have a great impact on the financial revenue of the project. [7] When it comes to testing and certification, there are standards which are considered of a higher priority and are almost considered a minimum requirement for use of a PV module. Most modules available on the market follow the *International Electrotechnical Commission (IEC)* certifications, a widely recognized quality standard throughout the solar industry for instance by the *World Bank* and the *United Nations Industrial Development Organization (UNIDO)*. [12] Other global safety certification companies are *Underwriters Laboratories (UL)* and the *International Organization for Standardization (ISO)*. UL is based in the United States and provides testing services and certifications, and ISO is an international standard-setting body with headquarters in Switzerland which has been used in this report to set the certifications that have to be complied by the module manufacturer's facility. It is important to bear in mind that both IEC and UL certify the module design but do not guarantee that the module will perform correctly during its lifetime. Table 2-3 is meant to serve as a generic checklist while selecting and procuring modules. The standards have been divided into first degree and second degree of importance. The first degree are considered a minimum in the industry and a common practice whilst the second-degree ones are applied in certain projects depending on the conditions. More in-depth due diligence can be carried out, if need be, on a project-to-project basis, but it is generally not the case when assessing the project from the lender's perspective.

Table 2-3. PV module certifications and tests [11] [13] [14] [15]

Subject of certifications	**Standards**
First degree	
Design qualification and type approval	
- **Terrestrial PV modules, design qualifications and type approval**	IEC 61215:2021
PV module safety qualification - **Part 1: Requirements for constructions** - **Part 2: Requirements for testing**	IEC 61730:2016
Standard for flat-plate photovoltaic modules and panels	UL 1703
Photovoltaic module safety qualification	UL 61730
Safety qualification of PV module	Safety class II
Second degree	
Agricultural environment: Ammonia testing	IEC 62716:2013
Environmental testing	IEC 60068:2021
Marine environment: salt mist corrosion test (to severity level 1 or 6)	IEC 61701:2020
Potential-induced degradation (PID) test	IEC 62804:2020 'System voltage durability test for crystalline silicon

	modules’
Damp heat test (extended)	Test under IEC 61215
Certifications of Module Manufacturer’s Facilities	
Certificate of the manufacturing unit.	ISO 9001:2015
Requirements for testing and calibration laboratories	ISO 17025:2017
Environmental management systems	ISO 14001:2015

The core standards that have to be met in almost every project correspond to *IEC 61215, IEC 61739 and UL 1703*. IEC 61215 lays down requirements for the design qualification of terrestrial PV modules suitable for long-term operation in open-air climates. The standard is intended to apply to all terrestrial flat plate module materials such as crystalline silicon module types including thin-film modules. The panels which comply with this standard have gone through stress tests and performed well in regard to quality, performance, and safety. Some of the tests performed to obtain this standard consist in electrical characteristics, mechanical load test and climate tests. IEC 61730 specifies the fundamental construction requirements for PV modules in order to provide safe electrical and mechanical operation, assessing the prevention of electrical shock, fire hazards, and personal injury due to mechanical and environmental stresses. In the states, UL 1703 is a mandate for solar panels sold and installed whilst IEC 61730 is internationally recognized and is more widely applicable to the global solar market. UL 1703 is an industry-standard ensuring both safety and performance. One of the most recent additions to solar panel testing corresponds to *UL 61730*, which essentially combines UL 1703 with IEC 61730, allowing for complete international approval. [15] Additionally to these standards, it is advised the qualifies for at least Safety class II.

Inverter

The grid network, in the majority of the cases, carries AC electricity. Given PV modules generate DC power, the role of the inverter is to work under the variable power output conditions of the panels and convert the DC power into AC for grid delivery. The most important parameters to bear in mind correspond to the inverter efficiency, the installation area requirements and maintenance requirements. Inverter efficiency is dependent on the losses associated with the DC to AC conversion, the maximum power point tracking (MPPT) and the auxiliary power consumption. MPPT is essential as the power output changes under different environmental conditions and the module voltage needs to be appropriately adjusted. Table 2-4 outlines the main differences between string and central inverters regarding the aforementioned criteria. There is a third type of inverter known as bidirectional inverter with energy storage application which is often used in grid-connected systems but that hasn’t been included in the comparison.

Table 2-4. Comparison between string and central inverters [11]

Parameters	String-inverters	Central-inverters
Maximum DC voltage	1000/1500 V for three-phase string inverters	1000/1500 V
AC power output range	<50 kW	100kW-1200 kW
Energy generation	Generate 2-3 % more energy than central-inverters while	

	providing redundancy	
Efficiency	More efficient for MPPT	More efficient when converting DC-AC (major factor driving overall inverter efficiency). Standard IEC 61683 inverters will have a European efficiency > 98 %
Area of the installation	Can be installed underneath PV modules – may not require additional area	Require a certain amount of site space
Failure and Maintenance	Easier reparation. Single inverter outage has less impact on the overall plan output	Failure and maintenance loss is much higher
Cost	More expensive BOS cost will also increase with string inverters Higher maintenance cost	More economical, especially for larger systems

In contrast with PV panels, inverters' primary reference when it comes to tests and certification are national codes, as compliance with the national grid code is a key requirement. Inverters manufactured for the international market and more in specific European countries often comply with the German *Association of Electrical Engineering*, in German *Verband der Elektrotechnik* (VDE) standards, reassuring that the inverter meets the quality, safety, and grid code standards. When looking into the standards needed for the states, the two which are more commonly accepted correspond to IEEE 1547 and UL1741. Standard IEEE 1547 is provided by the *Institute of Electrical and Electronics Engineers (IEEE)* and sets the criteria and requirements for interconnecting small generator equipment to the grid whilst UL 1741 sets the requirements for inverters and charge controllers in PV systems. [16]

Foundation and mounting structures

Foundation and mounting structures are designed to support the solar PV module positioning for the project lifetime which typically ranges between 20-25 years. The mounting structures can be fixed or tracking systems. Fixed systems have lower cost and require less maintenance. When looking into foundations, the most common are piled foundations though sometimes concreate spread footings are also used depending on the soil conditions and local material supply costs. [11]

Transformer

Transformers are electrical devices which transform electrical energy through the principle of electromagnetic induction by stepping up or down the voltage between two or more circuits. When connected to a solar PV system, transformers step up the low-level electrical power generated by solar PV to adequate it to grid voltage level. Some projects may require several transformer stages to achieve the desired output voltage. If the plan is connected to the grid with medium voltage (typically 22 kV or 33 kV) a single stage is used. When connecting to the grid at high voltage (69 kV or 115 kV) two stages are more appropriate. The latter will improve the overall cost but lead to higher losses. Transformers have two major loss types which correspond to load (copper) losses and no-load (iron) losses. [11] The cooling and insulation mechanism of transformers can be used as a criterion to classify them into dry and liquid (use mineral oil to insulate and cool the windings) transformers. Dry tend to have a higher cost, lower maintenance and are appropriate for both indoor and outdoor use whilst the liquid ones have a lower cost, higher maintenance and are a better fit for outdoor use.

In terms of certification, transformers are commonly manufactured domestically and expected to be made to IEC 60076 standard, to match the site conditions and usually offer 2–3-year warranty. Transformer supplier facilities should be certified ISO 9001 and ISO 14001. [11] It is preferred that the supplier track record includes reference to projects in the region.

Electrical cables

The electrical power between components is transmitted via cables. The size and type depend on the installation and when incorrectly sized can significantly increase losses and even cause cable fire. Cable insulation must be carefully selected for when not done appropriately can lead to current leakage. To minimize cable losses, copper cables are used for low voltage conductors. For medium voltage, both copper and aluminum are suitable. The named *solar cables* are commonly used in solar projects to connect the panels to the inverters as they can tolerate a wide range of temperatures and environmental conditions and provide resistance to UV radiation.

Transmission line

When located in remote areas, solar PV systems may not have access to transmission lines. In that case, the responsibility rests with the grid owner. The decision on the cost for new transmission will be decided between the two parties, being often covered by the project.

Monitoring system

Monitoring systems allow the owners and operators to compare, through the output power of the inverters, the real performance of the plant with the expected one. The expected one is calculated using actual weather conditions at site location including irradiation, temperature of the solar cells and ambient temperature.

2.2 Project due diligence for solar PV installations

The due diligence process aims to support business decision making by evaluating the projects and validating they are suitable for financing, offering the investor an adequate return. [5] The process can be divided into three blocks, technical, financial, and legal, in this order. The technical analysis aims to minimize the technical risks of the project by setting guarantees and evaluating the suppliers with whom the project is executed. Together with external experts, the documents needed are listed. The required documents depend on various factors, such as the underlying technology or country-specific renewable and energy efficiency regulation. The financial analysis goes through the financial plan of the project as well as information on ownership structures, securities, feed-in tariffs, and credit worthiness of the loan amongst others, assessing the financial risk and estimating the profitability of the project. The legal analysis consists of the validation of permits and contracts signed by the project owner and is normally carried out by a law firm, as previously mentioned, legal due diligence is out of the scope of this thesis. [17]

When funding simple technologies, given the necessary expertise in the lending company, many organizations decide to undertake the due diligence themselves. However, a report carried out through a third party can provide investors with an independent view which is often valued. It is common practice that the project owner pays the cost of the consultant.

Technical analysis

The objective when carrying out the technical feasibility analysis of a solar PV installation is to obtain the value of certain major performance parameters and ensure the values are in an acceptable range. In this section the formulas used to obtain this performance parameters are displayed.

Weather and Solar Irradiance

The first step will be to calculate the available solar irradiance resource at the selected site location. Getting an accurate resource evaluation for a typical meteorological year (TMY) is fundamental to determine the system's performance ratio (PR) and the power output per installed capacity [kWh/kWp], two key values when forecasting a system's yearly power generation. [18] An irradiance value for a TMY can be acquired in multiple ways, the two main options being to use empirical data or to calculate the value manually. Empirical data can be accessed through paid services such as *SolarGIS*, open-source tools such as the *Global Solar Atlas* or softwares such as *Meteonorm* [19] which can for instance be accessed through *PVsyst* and allows the data to be easily integrated when carrying out a simulation of the installation.

The theoretical potential irradiation at a location is known as the global horizontal irradiation (GHI). The GHI overestimates an available solar resource due to a number of real-world losses. When a PV panel is not on a mechanized solar tracking system, the irradiation will likely not strike the panel at a 90^{o} angle. The mismatch between the panel and solar angle creates losses to the theoretical potential irradiance value. Additional irradiance losses will be created due to scattering in the Earth's atmosphere. The scattered irradiation is known as diffuse radiation. [18]

The process to calculate the performance ratio requires calculating the GHI (G) received by the PV panel. Factors such as system location, panel orientation and module tilt effect the quantity of irradiation received. [18] The performance ratio is calculated internally by most software products although to fully understand the process the manual calculation is explained below. The total irradiation (G) received by a solar PV module is made up of both the direct irradiation (B) and the diffuse irradiation (D).

$$G = B + D$$

Equation 1. Total Irradiation

Where the direct irradiation is calculated with:

$$\begin{aligned} B = DNI(&\sin(\delta)\sin(\varphi)\cos(\beta) - \sin(\delta)\cos(\varphi)\sin(\beta)\cos(\psi) + \cos(\delta)\cos(\varphi)\cos(\beta)\cos(HRA) \\ &+ \cos(\delta)\sin(\varphi)\sin(\beta)\cos(\psi)\cos(HRA) + \cos(\delta)\sin(\psi)\sin(HRA)\sin(\beta)) \end{aligned}$$

Equation 2. Direct Irradiation

and the diffuse irradiation is calculated with:

$$D = DHI\left(\frac{180 - \beta}{180}\right)$$

Equation 3. Diffuse Irradiation

Where:

DNI = Direct normal irradiance (W/m^2)
DHI = Diffuse horizontal irradiation (W/m^2)
δ = Solar declination angle (°)

φ= latitude at system location (°)
β= module tilt (°)
ψ= module azimuth measured South to West (°)
and HRA = the solar hour angle

Solar Declination Angle

The solar declination angle (δ), is the seasonal tilt of the Earth's rotational axis from a vertical position. The Earth has a natural tilt of 23.45° which changes by ±23.45° throughout the year. The solar declination angle of 0° occurs on the equinoxes when the Earth has an equal quantity of day and night. [18]

$$\delta = -23.45° \times \cos(\frac{360}{365} \times (d + 10))$$

Equation 4. Solar Declination Angle

Where d = the day of the year with January 1st is d = 1.

Hour Angle (HRA)

In observing the sun from Earth, the solar hour angle is a translation of time into an angular measurement (°) from noon at which point the HRA = 0°. The HRA is denoted as a negative value before noon and as positive value after noon. The hour angle is a local measurement representing the displacement of the solar path east or west in comparison to the local meridian line. The HRA changes at a rate of 15° per hour, for example, at 10am the HRA would equal -30° (2 x -15°). [20]

$$HRA = 15°(LST - 12)$$

Equation 5. Hour Angle

$$LST = LT + \frac{TC}{60}$$

Equation 6. Local Solar Time

$$TC = 4(Longitude - LSTM) + E_0T$$

Equation 7. Time Correction Factor

$$LSTM = 15°\Delta T_{GMT}$$

Equation 8. Local Standard Time Meridian

$$E_0T = 9.87\sin(2B) - 7.53\cos(B) - 1.5\sin(B)$$

Equation 9. Equation of Time

$$B = \frac{360}{365}(d - 81)$$

Equation 10. Degree value

Where:

LST = Local solar time
LT = Local time
TC = time correction factor
LSTM = Local standard time meridian

E_0T = equation of time
ΔT_{GMT} = difference between PV system's LT from Greenwich Mean Time (GMT) in hours
B = a degree value where d = the day of the year with January 1st as d = 1

The equations listed above will be sufficient to calculate the real available solar resource when analyzing the selected solar PV generator site. The next section of this report will focus on the key performance indicators (KPIs) of the solar PV system design.

Array Yield

The array yield (Y_A) is a ratio, defined as the energy output from the PV array over a time period (day, hour, year, etc.) divided by the system's rated power capacity. [21] To calculate the array yield:

$$Y_A = \frac{E_{DC}}{P_{PV,rated}}$$

Equation 11. Array Yield

To take the array over a finite period, the previous equation can be adapted to the relevant period such as for a day array yield ($Y_{A,d}$) or for a monthly average array yield ($Y_{A,m}$):

$$Y_{A,d} = \frac{E_{DC,d}}{P_{PV,rated}}$$

Equation 12. Day Array Yield

$$Y_{A,m} = \frac{1}{N}\sum_{d=1}^{N} Y_{A,d}$$

Equation 13. Monthly Average Yield

Final Yield

The final yield is similar to the array yield although it considers the final AC power output of the system divided by the system rated power capacity. [21] Mainly, the final yield is considering the power output after losses in the inverter due to the DC to AC power conversion. It is important to note that the $P_{PV,rated}$ value is calculated at STC which entails a solar irradiance value of 1 kW/m^2 and an ambient air temperature of 25°C. This figure enables comparison of similar PV systems in a specific geographic region. The final yield is dependent on the mounting conditions (module tilt, roof or ground orientation, etc.) as well as geographic location. [22]

$$Y_{F,a} = \frac{E_{AC,a}}{P_{PV,rated}}$$

Equation 14. Final Yield

Similar to how the array yield can be calculated over a defined period of time, the final yield can be set up as a daily final yield ($Y_{F,d}$) and a monthly average final yield ($Y_{F,m}$):

$$Y_{F,d} = \frac{E_{AC,d}}{P_{PV,rated}}$$

Equation 15. Daily Final Yield

$$Y_{F,m} = \frac{1}{N}\sum_{d=1}^{N} Y_{F,d}$$

Equation 16. Average Final Yield

Reference Yield

The reference yield is the ratio of the total in-plane solar insolation H_t (kWh/m^2) divided by the array's reference yield at STC (1 kW/m^2, 25°C). The reference yield is also representative of the number of peak sun-hours the array will receive given as:

$$Y_R = \frac{H_t(kWh/m^2)}{1(kW/m^2)}$$

Equation 17. Reference Yield

Capacity Factor

The capacity factor (CF) in a simple analogy can be thought of as how often a generator is running at 100%. A generator with a capacity factor of 100 % would mean that it produced at maximum capacity for 24 hours per day, 365 days per year. Anything that reduces power generation including O&M maintenance, weather, losses, etc. will lower the CF. A CF of 100 % is impossible. According to the U.S. DOE the average CF for a solar array in 2019 is 24.5%. [23]

$$CF = \frac{E_{AC,a}}{P_{PV,rated} \times 24 \times 365} \times 100$$

Equation 18. Capacity Factor

PV Module Efficiency

The PV module is a variable representative of the electrical power generated divided by the total available irradiance on the planar area of the panel surface.

$$\eta_{PV} = \left(\frac{P_{DC}}{G_t \times A_m}\right) \times 100$$

Equation 19. PV Module Efficiency

Where:

G_t = the total in-plane irradiance (W/m^2)
A_m = the planar area of the solar PV module (m^2)

Inverter Efficiency

The inverter efficiency is representative of how well the inverter converts the DC power from the solar PV array into AC power which can be injected to the grid at the point of interconnection. The inverter efficiency is given as a single value although in reality the value changes depending on the voltage and DC power injected into the inverter. The inverter software includes a maximum power point tracking (MPPT) algorithm which enables the inverter to optimize the efficiency by adjusting the DC input voltage to track the PV panel's maximum power point and thus maximizing the AC power output. [24]

$$\eta_{inv} = \frac{P_{AC}}{P_{DC}}$$

Equation 20. Inverter Efficiency

System Efficiency

The system efficiency can be considered an accumulation of the efficiency losses throughout the entire system. Based on the equations presented above, the system efficiency would be:

$$\eta_{sys} = \eta_{PV} \times \eta_{inv}$$

Equation 21. System Efficiency

Additional efficiency losses may include cabling, shading, soiling from dust and dirt, thermal, and array mismatch losses. [25] These losses would be multiplied into the η_{sys} equation just like η_{PV} and η_{inv}. While individually small, the system losses can add up to a 20-25% loss in total system efficiency. [25]

Final Yield

The final yield (Y_f) of a solar PV array is expressed as the ratio of final AC power output (kWh) to the nameplate capacity of the array. The final yield allows an engineer to use a single normalized value to compare array power production to array size.

$$Y_f = \frac{final\ energy\ output\ (kWh)}{nominal\ DC\ power\ rating\ (kW)}$$

Equation 22. Final Yield

Reference Yield

The reference yield (Y_r) is the ratio of the total in-plane irradiance at the PV array location in comparison to the reference irradiance at STC (1000 w/m², 25°C). The reference yield is also referred to as the Peak Sun Hours (PSH). [18]

$$Y_r = \frac{local\ inplane\ irradiance\ (\frac{kWh}{m^2})}{STC\ reference\ irradiance\ (\frac{kW}{m^2})}$$

Equation 23. Reference Yield

Performance Ratio

The performance ratio (PR) is a value which is independent of location allowing the comparison of PV plants around the world using a single variable. The performance ratio is expressed as a percentage representing the actual power generation divided by the theoretical potential power generation. PR includes all production losses effecting the plant thus it is a useful tool when comparing the quality of solar resource, equipment selection, environmental factors, etc. The PR is sometimes alternatively named the quality factor. A PR of 100 % is unachievable due to losses which are unavoidable such as thermal losses. The PR upper range of a high-performance PV array may reach ~80 %. [26]

$$PR = \frac{Y_f}{Y_r} = \frac{Actual\ reading\ of\ plant\ output\ in\ kWh\ per\ annum}{Calculated\ nominal\ plant\ output\ in\ kWh\ per\ annum}$$

Equation 24. Performance Ratio

Financial analysis

A renewable energy crowdfunding portal will need to conduct a due diligence review on all submitted projects to ensure that all investment opportunities presented to the investor community are economically and technologically validated. This process shall consist of reviewing the following documents:

- Commitments of other financiers to the project and if they have performed a due diligence
- Project exploitation plan
- Financial plan, capex (at t=0), forecasted P&L, balance sheet and cash flow statement
- P&L of last 2 years (if available already).
- Relevant permits
- Contract for land use/ownership
- Engineering, Procurement, Construction contract
- Operations and Maintenance contract
- Relevant contract(s) guaranteeing revenues: feed-in tariff / power purchasing agreement
- Relevant tax/legal/subsidy documents, needed to realize/meet financial plan for realization/exploitation
- Finance agreements of key financiers
- Ownership structure overview
- Insurance contracts
- Warranties on critical hardware

Since the renewable energy cooperatives and project developers that Seeds would partner with are generally not companies with public debt ratings; the ratings will have to be calculate by Seeds in house using the financial multiples seen in Table 2-5.

Table 2-5. Moody's power company rating criteria [27]

Rating category	Aaa	Aa	A	Baa	Ba	B	Caa	Sub-factor rating
Cash flow interest coverage (10%) CFO pre-WC+interest / interest	$\geq 18.0x$	$12 - 18x$	$7.0 - 11.9x$	$3.6 - 6.9x$	$2.0 - 3.5x$	$1.0 - 1.9x$	$< 1.0x$	15.0%
Cash flow / debt (10%) CFO pre-WC / debt	> 90%	61 – 90%	36 – 60%	21 – 35%	13 – 20%	5 – 12%	< 5%	20.0%
Retained cash flow / debt (10%)	> 60%	45 – 60%	25 – 44%	15 – 24%	8 – 14%	3 – 7%	< 5%	7.5%
Free cash flow / debt	≥ 50%	35 – 50%	22 – 34%	12 – 21%	0 – 11%	(30) – 0%	< (30)%	7.5%

When analyzing the financial bankability of a project it is key to review the discounted cash flow and the coverage ratio of the loan interest and outstanding debt as can been seen in the first two rows of Table 2-5. The outsized importance of these values is highlighted by the subfactor weighting of 15 % and 20 % respectively.

Government Incentives

The MACRS is an important financial consideration as it allows the system owner to depreciate value of the asset more quickly. This depreciation is accounted for on a business' Profit and Loss (P&L) statement allowing that entity to reduce their taxable income by the quantity of the depreciation. Due to the time-value of money, the concept that the same quantity of money is worth more now than in the future, it is advantageous to claim the depreciation earlier in the asset's lifespan. MACRS depreciation does interact with the federal ITC. When a project takes the 30 % tax credit they must reduce the depreciable basis of the asses by half of the ITC, 15%. Thus, for example, if a system cost $ 100,000 and they claim the $ 30,000 ITC, then they can only depreciate $ 85,000 worth of system costs on their P&L.

Table 2-6. Applicable MACRS Depreciation Rate [28]

Year	1	2	3	4	5	6	Sum
% Rate	20.00	32.00	19.20	11.52	11.52	5.76	100.00

Net Present Value

The net present value is a way to calculate the future cash flows in terms of financial earnings today. The NPV looks at the projects cash flows (CF) and reduces their value based on the discount rate considered to be the market weighted average cost of capital (WACC). The absolute net return of the asset is calculated as follows:

$$NPV = -CO + \sum_{1}^{n} \frac{CF}{(1+k)^{j'}}$$

Equation 25. Net Present Value

Where CO = initial investment cost, CF = project cashflows, k = the discount rate at the time of initial investment, n = the lifetime of the investment. The NPV gives an analyst the value of a project in terms of today's dollars. The NPV specifically uses k which is the WACC considering the cost of capital of the investment company. The equation to calculate the WACC is discussed below. [29]

Internal Rate of Return

The IRR of a project is representative of the cost of capital which will cause the project to have a NPV = $0. In other words, the IRR determines the maximum WACC a project can accept to remain profitable. [29] The IRR can be calculated as follows:

$$0 = -CO + \sum_{1}^{n} \frac{CF}{(1+r)^{j'}}$$

Equation 26. Internal Rate of Return

Where r = the project's gross return. If $k > r$ then a project will have a NPV < 0, which is not investment worthy.

Weighted Average Cost of Capital

The weighted average cost of capital is a widely used tool in the financial industry to determine the evolution of cash flows over time. The WACC employs a weighted measurement of the company's sources of capital as follows:

$$WACC = \frac{k_e \cdot E + \, k_d \cdot D \cdot (1 - t)}{E + D}$$

Equation 27. Weighted Average Cost of Capital

Where k_e = the cost of equity (%), k_d = the cost of debt (%), t = the effect of tax savings through tax-deductible expenses such as interest on debt, while E and D are the levels of equity and debt in the company. In all cases a company will want to minimize their WACC. The WACC will be influenced by the market the company operates in and the risks associated with that market. Additionally, since each company will require different amounts of physical capital such as inventory, some companies will be better aligned with debt borrowing. [29]

There are two main methods used to calculate the k_e : the capital asset pricing model (CAPM) and by using a historical return analysis. The primary way to find k_d is based on historical returns as well. [29] While not necessarily complex, the detailed analysis of the underlying factors determining the WACC fall outside the scope of this thesis, thus a reference WACC value was found using data from NREL [30]. The WACC for a distributed PV project in the nearest available year to the Rinaldi project construction, 2018, is 5.6 %.

Legal analysis

The legal analysis and due diligence of a solar PV system is traditionally out of the scope of the lending company completing the techno-economic analysis. This is due to the legal and tax knowledge basis required to complete a thorough evaluation of the project. For the sake of the comprehensive nature of this project, the key documentation will be listed and briefly explained although they will not serve as evaluation criteria of the PV analysis software selection. The Permitting, Licensing and Authorizations (PLAs) represent a significant risk with the potential to derail a project through schedule delays, legal budget overruns, or failure to pass an assessment.

Corporate	**Description of the categorical due diligence**
Management body	Which company/person manages the SPV
Ownership titles	Who owns the equity shares of the SPV
Power of attorney	Who has been granted power of attorney on the project
Equity impairment	Processes for winding up the company and restoring net equity if project defaults on loan
Corporate books	Laws regarding consistent documentation of shareholders meetings in the Book of Minutes
Encumbrance	Obligations of the SPV shares to other parties
Agreements	
Credit facility agreement	Is debt owed? To whom, how much and when is it due?
Services agreement	Financial, tax and accounting services for the SPV. 5yr. plan w/ 5yr.

	Extensions, 1-month notice to cancel
Technical assistance	Technical maintenance. 5yr. Plan w/ 5-year extensions, 1-month notice to cancel.
Grid guarantee	Permits for grid access and interconnection w/ credit insurance.

Urban Planning	
Planning situation	Is the land classified as the proper type for energy project development?
Regulatory and Permits	
Grid access and connection permits	Access and connection permits issued by the DSO
Administrative Authorization (AA) and Project Authorization (AP)	Authorization to proceed by the local authorities
Archaeological prospection authorization	A study to confirm that project site does not hold items of archaeological value.
Environmental	
Permits, Licenses and Authorizations	Environmental impact assessment study
Litigation	
Litigation or sanctioning proceedings	Any outstanding lawsuits against the project or equity holders.
Real Estate	
Land Securement	Land deed for project is registered in the Land Registry. Notarial deed and agreement.
Existing right of way easement	A path through private property, if necessary, to reach public lands. Does not affect the ownership of the land that the right of way is made upon.

2.3 Renewable energy project finance

Renewable energy is often developed via project finance due to the high CAPEX costs to construct these assets. The money supplied for the development of these assets has been largely provided by commercial banks with government incentives to make these generators cost competitive with fossil fuel generators. The high upfront cost of renewable energy means that the borrow will need to source the lowest cost lender. Technologies that have been sufficiently de-risked like utility scale solar or onshore wind can acquire this funding relatively. In contrast, some technologies such as commercial or community solar, concentrated solar power and offshore wind power are still subject to higher capital costs due to a lack of standardization within the lending process as well as a lack of lending innovation. Wind and solar dominate the project development pipeline accounting for 82 %

of US installed capacity in 2020. [31] Annual energy investments will need to surge to $ 5Tn/yr. by 2030 to avoid the worst effects of climate change meaning that any available tool to increase current flow of investment is necessary. [32]

Traditional funding mechanisms

Looking into financial investment decision making, it has been identified that the decision on the valuation of renewable energy investment is based on the cost of capital, which is in turn influenced by the risk and the return profile of past investments and the opportunity cost of capital. The cost of capital is the required return necessary to make a capital budgeting project. It corresponds to the rate that the company must overcome before generating value. Depending on the mode of financing used, it is known as cost of equity if the business is solely financed through equity or cost of debt, if it is financed through debt. The weighted average cost of capital (WACC), explained in Section 2.2, takes both into consideration. [27] The energy sector shows that utilities prefer high risk/high return and low capital-intensive projects which leads to an underestimation of the attractiveness of investing in renewable energy projects, as they tend to have a low risk/low return prospects profile (for instance solar PV and wind power). See Table 2-7.

Table 2-7. Acceptable cost of capital range per investor type and decision rationale [27]

	Cost of capital level	Rationale
Utilities	High single-digit to double-digit range	– Previous activities in high-risk/high-return fossil fuel generation results in medium to high WACCs – Access to high-return investments results in high opportunity cost of capital
Institutional investors	Medium single-digit range	– Preference for low-risk investments and stable long-term cash flows
Private investors	Medium to low single-digit range	– Alternative investments with low return, low opportunity cost of capital

Inside institutional investors, it’s important to highlight commercial banks as they tend to focus on the lower end of the risk spectrum that being normally non-recourse project finance debt and most notably project finance loans. Non-recourse debt is a type of loan secured by a collateral (usually property). If the borrow defaults, the issuers can seize the collateral but cannot seek out the borrower for any further compensation. Up to date, the relationship between the commercial banking sector and the renewable energy industry has resulted in a high rate of development. However, banks’ regulation could lead to severe changes which would affect renewable energy and could cause as a result less availability of long-term funding. The funding gap in renewable energy projects and the misfit of traditional lending conditions with the risk-return profile of smaller renewable energy projects opens the doors of the energy space to new financial schemes. One of the most promising options being renewable energy crowdfunding.

Renewable energy crowdfunding

Crowdfunding presented itself as an alternative form of finance after 2008 financial crisis due to the credibility loss of traditional financial sources and the historical low interest on savings accounts. Since then, many innovation trends point towards the emergence of crowdfunding as a viable financial mechanism for moving funds into the clean energy industry. The emergence of technologies which improve digital trust such as blockchain and Smart Contracts enable marketplaces to connect capital and project developers in unprecedented ways. According to *Bloomberg New Energy Finance*, “Just 1 % of current US retail investment in savings accounts, money markets and US treasuries would provide US$90 billion for clean energy crowdfunding, with 0.5 % of the bond market adding a further US$190 billion.” [33] This cumulative USD 280 billion of additional renewable energy investment would eliminate 79 % of the financing deficit needed to meet the most ambitious global carbon reduction goals and limit the global temperature increase to 1.5°C while avoiding the most catastrophic environmental consequences.

Besides the obvious benefit of averting climate change, renewable energy crowdfunding distributes the profits of the energy transition to regular people as opposed to institutional investors and international banks. As an alternative to traditional funding mechanisms which are focused primarily on the financial bottom line; renewable energy crowdfunding brings the additional social benefit of community involvement and improvement. As an example, a solar installation on a local school could help reduce the electricity bills of the school, provide jobs to local electricians, distribute the loan profits to the community and help diffuse the NIMBY (“not in my backyard”) phenomenon. [4] Additionally, projects that receive widespread community support are more likely to receive preferential treatment with respect to permitting and legal complications which can threaten to derail any project. A more subtle benefit of renewable energy crowdfunding may actually be the most interesting facet of the financing model; democratic investing. Once a project’s financial viability is verified by the responsible crowdfunding platform, it is up to the investors to choose which projects get funded thereby promoting the projects with the largest social impact. This fascinating evolution of project finance will couple profits with the ethical implications of the project and “If this perspective proves accurate and mass production of the 20th century gives way to greater personalization in the 21st, then it is hard to see the world of finance avoiding a comparable transformation of its own. New mechanisms like crowdfunding that are disintermediated, personalized and ethical will be well poised to challenge the centralized and opaque structures of old.”[27] With the growth of renewable energy crowdfunding, the energy and financial industry are poised to make simultaneous evolutions. [4]

Despite its potential, renewable energy crowdfunding presents some limitations. To date, renewable energy crowdfunding has only accounted for a small fraction of total crowdfunding globally. Crowdfunding is location dependent and is primarily centered in developed countries with North American and Europe accounting for over 90 % of the 2012 total. However, despite its concentrated nature, the potential is still enormous. Additionally, crowdfunding is dependent on country regulations which specify the workability and fundraising ceiling. The campaign ceilings for general Regulated Crowdfunding in the US and EU limits the ability to fund projects such as utility scale solar and offshore wind which tend to have the fastest payback rate. A change in the *Jumpstart Our Business Startups (JOBS)* act by the *Securities and Exchange Commission (SEC)* in March 2021 now enables American Regulated Crowdfunding portals to raise up to $ 5,000,000 per company within a 12-month period in comparison to the previous $ 1,070,000 limit. This ceiling increase will stimulate growth in the U.S. renewable energy crowdfunding industry which will hope to catch up to the European renewable energy crowdfunding industry. The campaign limit in the European Union is capped at 5,000,000 €. [34] The US market does have the distinct advantage of having more complex tiers of crowdfunding called Regulation D, A, and A+ which have $ 10M, $ 20M and $ 75M limits which could be used for utility scale project development. [35] The inability to easily liquidate investments also poses a challenge. Investments in renewable energy infrastructure tend to be medium to long-term investments of 5-20 years. This can be a significant deterrent to investors who may need to liquidate their assets in the short to medium-term. To eliminate this obstacle, some renewable energy crowdfunding sites have worked to develop a secondary market, essentially a stock market, which would allow their users to buy and sell their shares within the community. Operating a secondary market comes with significant additional financial oversight and development costs so, to date, no company has perfected this concept.

Just as no technology can single-handedly prevent climate change, it cannot be assumed that renewable energy crowdfunding will be the saving grace for humanity, although it could be a significant step in the right direction. Mitigating humanity's impact on the environment will require a diverse aggregation of technologies, business models and social movements. Each of these will represent a uniquely shaped puzzle piece that helps construct the plan to save the world; crowdfunding may just be a piece that nobody expected. Preventing a climate disaster will require a dynamic evolution of human society. Crowdfunding offers an opportunity to positively reform the financial system during a time of global adaptation. If people work together and "If people take back control of their own money and invest it transparently and tangibly in the real economy, ethics can be reintroduced into financial decision-making." [27] Using crowdfunding to build renewables creates a virtuous cycle of finance to the public will help democratize and decentralize the energy transition. [4]

Renewable Energy Crowdfunding platforms

A recent paper published by the *International Journal of Sustainable Energy Planning and management* [36], compares 23 crowdfunding platforms in the renewable energy sector and analyses there exposure and mitigation of investor risk. The study shows risk is highly dependent on the policy support schemes (determined by location) and on the financial instrument selected. Countries with the most favorable platform conditions have policies based on feed in tariffs (FiT) and/or market premium schemes – feed in premium (FiP) –* which enable and guarantee long term cash flows (i.e. Netherlands and Germany). Policy uncertainty or projects relying solely on sales (UK, Spain) have a clear disadvantage and a higher risk exposure. The Netherlands is considered the most mature and equalized market, home of the eldest platforms and country with the highest volume per capita invested. Surprisingly, the only spanish-based crowdfunding platform considered in this analysis, *Ecrowd*, despite having no favorable schemes, offers the lowest fees on the market (2-4 %+1-1.5 % annually). Other relevant numbers obtained from *Wouter De Broeck's* [36] paper relevant for this research are that all 23 platforms studied conduct project due diligence, 56.5 % of the platforms understudy include additional banking financing, 3/23 platforms have a secondary market exposing the investors to liquidity risk and all platforms but *TRINE* base their revenues on a success and management fee. The risks that platforms judge most probable to affect their RES-projects are finance risk (60 %), technical and management risk (50 %) and administrative risk (40 %). [37]

Seeds Renewables

Seeds is an environmental FinTech mobile app that allows users to invest in community energy projects and cleantech scale-ups through crowdfunding with as little as their spare change. Seeds' mission is to create the people's financial network for climate action, helping achieve the sustainable development goals set by the United Nations. Seeds uses a round up technology that identifies the investors' everyday card transactions, rounds the purchase up to the nearest $ and automatically

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* FiT are fixed electricity prices paid and guaranteed for a certain period of time or amount of full-load hours of electricity to renewable energy producers for each unit of energy produced and injected to the grid lowering the project's risk exposure. FiP consist in paying a premium on top of the market price of the electricity production when sold in the spot market to renewable energy producers. It can be fixed, when independent of market prices, or sliding, variable depending on the market price. [53] The fading of FiT and rise of market premium rise the business risk.

invests that spare change into the impact project of their choice. For instance, when buying a coffee for $ 1.60, this amount will round up to the nearest dollar ($ 2.00) and the $ 0.40 difference would be automatically invested. By asking very little from each individual and leveraging the rapidly growing environmental movement, Seeds empowers everyday people to benefit from the energy transition and changes the role of the public from a neutral bystander to an active stakeholder. The Seeds app will offer a gamified experience encouraging interaction between users as well as learning tools to help users make educated decisions regarding sustainability and their financials. By including achievements, bonuses, and leaderboards Seeds will encourage users to increase their impact and thus increase their total investment.

In order to source a pipeline of projects Seeds has established partnerships with renewable energy project developers and cooperatives which, as mentioned in the previous section, are traditionally underserved by commercial banks due to the scale of their projects. The scale of community energy projects fit crowdfunding legislative regulations perfectly creating a synergy where retail investors and the environmental movement can quickly finance bankable projects with high added social value. Renewable energy cooperatives foster community engagement, use local labor, and contribute to the wellbeing of their clients by providing low-cost electricity. For the collectives Seeds offers finance as a service. Once the projects are funded, constructed, and are generating revenue, the investors will receive annuity repayments[*] including interest. Seeds aims to finance renewable energy projects of different technologies at a global scale. However, considering the company's stage and the legislation requirements to operate in other countries priority is given to projects in the United States. Regarding technology, Seeds wants to start with solar PV installations. The main drivers behind the decision of starting with solar projects are the comparatively low technical risk of construction and operation, the reliance on large volumes of mass-produced component parts available in the global market, and the opportunity to develop distributed generation projects on residential housing and communities. These characteristics set a solar project apart from other technologies and make them a safer option. [1]

To date, Seeds is still at an early stage. The company was founded in October 2020 and is currently developing the app, going through the compliance process with the United States FINRA and in the process of building the project pipeline, amongst others. One of the most pressing needs of the company at this point is to outline the project due diligence process in order to be able to assess the renewable energy projects from a lenders' perspective and minimize the risks for the investors.

2.4 Related work

2.4.1. Renewable Energy Finance

The renewable energy project finance Section 2.3 has been inspired in a must read for professionals in the project finance space, *Renewable Energy Finance - Powering the future, by Charles W.Donovan.* [27] The book describes the best practices and trends in clean energy investing with contributions from leading global experts in energy finance, serving as a real-world examination of the key issues in developing capital towards sustainable investments. Chapter 3 of the book gives an excellent overview of investor-specific cost of capital and renewable energy investment decision.

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[*] payments made at equal intervals

2.4.2. Renewable Energy Crowdfunding

Renewable energy crowdfunding can be considered an alternative financial process and sub-tier within the renewable energy finance topic covered in Section 2.4.2. The literature review portion on this subject was conducted by William Wiseman, thesis co-author, in preparation for publishing a journal article in conjunction with the 7th Environmental Protection and Energy conference where he presented on the topic. The article, titled *Is Crowdfunding the Missing Puzzle Piece to Achieve Rapid Decarbonization* [4] was later published by InnoEnergy's CommUnity platform and on Seeds' blog. Within Section 2.3, the subsection which details the benefits of renewable energy crowdfunding leans heavily on this earlier publication while also updating the statistics. The macro-level benefits remain the same and thus the section quote's *W. Wiseman's* work since concepts remain the same. *Wiseman's* article references articles published by the EU providing best practices regarding renewable energy crowdfunding [38], economic journals such as *Cairn* [39], and Bloomberg New Energy Finance. [33]

2.4.3. Supporting Reports on Solar PV Software Tools

This thesis leverages the work of *N. Umar and B. Bora's* study *Comparison of different PV power simulation softwares: case study on performance analysis of 1 MW grid-connected PV solar power plant* [40] which provides a comprehensive comparison of the leading 10 solar analysis software tools. This study lays out the strengths and limitations of each tool as well as the costs . By using the results of this study certain tools such as Helioscope could be eliminated from the viable tools since it cannot complete a financial analysis of a solar PV generator. Later in *Umar et al.,* the methodology for conducting a solar resource analysis by hand is explained. This explanation is necessary for understanding which variables may play a role in power output sensitivity. Many of the equations in chapter 0 come from *Umar et al.* and were verified in *S. Bhatia* [20], *Ayompe et al.* [21], *L. Clavadetscher* [22], *Park et al.* [24], *S. Ekici and M. A. Kopru* [25], and *SMA Solar Technology AG* [26].

To corroborate the conclusions of the strengths and limitations of available solar PV analysis softwares the article *Review and Analysis of Solar PV Softwares* by *D. Sharma, V. Verma* and *A. Singh* [41] is especially useful. This article studied PVsyst, RETscreen, HOMER, TRNSYS, INSEL, PV F-Chart, National Renewable Energy Laboratory's (NREL) SAM, Solar Design Tool, ESP-r, Solar Pro, PV DesignPro-G and PVsol. The author evaluated each tool based on the following criteria: 1.) their commercial and educational availability and cost, 2.) the working platform, 3.) the working capacities, 4.) the scope and output as well as 5.) the updatability. *D. Sharma, V. Verma* and *A Singh* also mention other PV software analysis and planning tools such as pvPlanner, Solmetric PV Designer, DDS-CAD PV, Polysun, REA System Sizing Tool, Solarius-PV, and Matel Grid. The report concludes that PVsyst was the superior product due to its ability to accurately calculate the system yield very quickly using just a handful of general system characteristics.

2.5 Summary

Any extensive literature review covered how to technically analyze a solar PV array coupled with the tools which can most efficiently and accurately assess the project. Afterward, a thorough foundation of renewable energy project finance was created when both co-authors read the book Renewable Energy Finance: Powering the Future by Charles Donovan. [27] By reading Donovan's book the co-authors understood the underlying principles of project finance with which they supplemented using 8 other publications. To further educate themselves the co-authors continued to research the opportunity of crowdfunding to help fill the global funding deficit for renewable energy by reading another 6 publications. All of this research created the necessary educational foundation to confidently complete the study detailed in Chapters 3-6.

3 Methodology

The purpose of this chapter is to provide an overview of the research methodology used in this thesis, outlined in Figure 2. The research process to determine the key considerations for conducting a techno-economic analysis starts with a literature review culminating with the summation of the key background information discussed in Chapter 2. Equipped with this understanding, the focus is shifted to which tools were available and which would meet the needs of this use case. The literature review of software tools is described in more detail in Section 2.4.3. Once the pool of viable software tools is reduced thanks to the reports by *N. Umar, B.Bora* [18] as well as by *D. Sharma, V. Verma and A. Singh*. [41], a comparison trough MCA of the two most prominent softwares is carried out. The report's findings regarding operating system compatibility and requirements are verified on the tool hosts' sites.

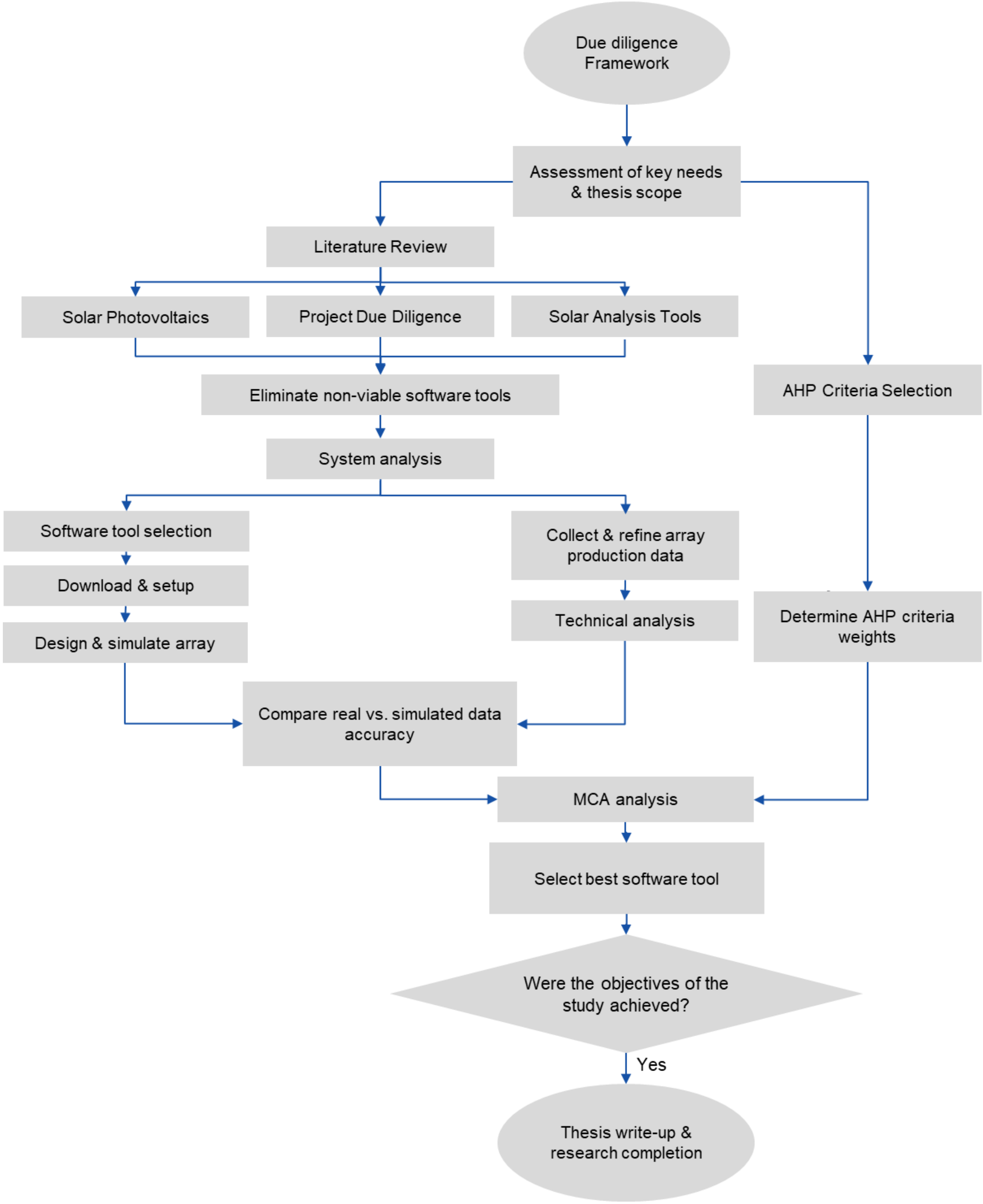

Figure 2. Methodology flow chart

3.1 Review analysis and comparison of PV softwares

As mentioned in Section 2.4.3, this report relies heavily on the work and insights provided in the reports by *D. Sharma* [41] and *N. Umar and B. Bora* [18] to help narrow the field of viable software tools. The first criteria when reviewing PV analysis tools was whether the tool can provide a technical and economic analysis of the project. For example, PVcalc.org provides a free and open-source tool for conducting the economic analysis of a project but without the technical side of the analysis the due diligence wouldn't be considered to be thorough enough to make an investment decision. Additionally, PVCalc lacks the ability to input a utility's rate schedule. This limited functionality eliminates a tool like PVCalc. In contrast, a technical tool like HelioScope cannot conduct a financial analysis which eliminates the viability of it to be selected for this study. [18] The software tools which were considered when doing the research of this project include Aurora, SAM, PVsyst, HOMER, PVsol, RETscreen, Solarius PV, HelioScope, Solar Pro, PV F-Chart, Solar Design Tool, and PV DesignPro-G.

Based on thesis authors' previous use of SAM and HOMER it was eliminated due to its lack of technical capability to replicate the project in a CAD model. While a CAD model is more time and labor intensive it is key when conducting a shading analysis which can significantly affect the output of an array if poorly planned. HelioScope and Solar Pro were eliminated due to their limited financial analysis capabilities. PV DesignPro-G was eliminated from the study since its features and functionality are tailored for research purposes with a high level of solar expertise. While the technical capabilities of PV DesignPro-G may be suited for this thesis, the intention of the MCA explored in Section 3.2 is also to balance the technical capability with the usability for analysts other than professional PV system designers. Additionally, updates to PV DesignPro-G were discontinued in 2010 making the tool obsolete. Similar to PV DesignPro-G, Solar Design Tool is a specialized used for rapidly generating permitting proposal packages to government agencies, not for conducting a techno-economic analysis.

RETscreen, PV F-Chart and Aurora were eliminated from the study because they were cost prohibitive for the authors to purchase. Aurora was contacted about the opportunity to partake in the study and to offer a student discount although they declined. The RETscreen, PV F-Chart and Aurora each cost $ 869 CAD/yr., $ 600 USD/yr. and $ 2640 USD/yr. for their premium products, respectively.

After eliminating the non-viable software tools, the remaining options were Solarius, PVsol and PVsyst. Due to the extensive scope required from the literature review and the work required to simulate the array using each tool, the authors decided to narrow the software simulations to two software tools. Considering the previously states reasons, the extensive troubleshooting forum communities, and their industry reputations - PVsol and PVsyst were selected to conduct the simulation.

Table 3-1. PV Analysis Software Tool Analysis

Software	Free/Paid	Strengths	Weaknesses
System Advisory Model (SAM)	Free	Shows levelized cost of electricity, operating cost, capital cost and maintenance costs. Shows the peak and annual system efficiency, system energy output and hourly system production.	No detailed technical design capability with CAD tools. Capable of a high-level economic analysis but lacking the detail for financial analysis.

PVsyst	Paid	Strong forum and troubleshooting community Includes lifecycle GHG impact of power and equipment	Lacking the detail for financial analysis Lacking most utility rate schedules No net metering option
HOMER	Paid	Many kinds of renewable generators in the library which would allow Seeds to finance more than solar.	No CAD modeling of the system enabled. Can be very complex for an analyst who isn't an energy system designer.
PVsol	Paid	Strong forum and troubleshooting community Platform includes CAD modeling, financial analysis and proposal generation Extensive equipment database	Only for Windows – can be used with a virtual machine. CAD modeling isn't fast Lacking most utility rate schedules
RETScreen	Paid	Can perform feasibility, performance, energy, cost, emission, financial and severity/risk analysis. [18]	Not functional for Mac. No options for educational license.
Solarius	Paid	Has CAD tool and shading calcs. Cheap in comparison to other tools	Doesn't support advanced feasibility analysis
HelioScope	Paid	Recent UI/UX improvements No need to download software	Recently added financial analysis capabilities. Accuracy endorsed by Wells Fargo.
PV F-Chart	Paid	Offers technical and financial analysis Includes GHG reduction calculations	Can generate graphs but can't export them [18] More expensive for students than citizens
PV Design Pro-G	Paid	Extensive technical reporting	Updates discontinued in 2010. Software is obsolete and not user friendly

3.2 Multi Criteria Analysis (MCA)

Ex ante[*] approach and *ex post*[†] have always been part of decision-making processes. However, it was not until the beginning of the 20th century that these processes turned into more rigorous procedures. In the course of time, an increasing number of techniques and tools have been born, aiming to ensure more informed decisions. These methods can be classified in several ways, one of them being the number of objectives and decision criteria. Following this classification, we can distinguish between *mono-criterion* methods and *multi-criteria* methods. *Mono-criterion* asses a

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[*] Latin for "before the event".

[†] Latin for "after the event".

plan against a single objective whilst *multi-criteria* evaluate a plan taking into consideration various factors, including several objectives and different decision and criteria metrics. [42]

MCA itself comprises various classes of methods and techniques with different degrees of complexity which consider multiple factors in decision making process. Although these methods can differ from one another, there are certain aspects in common which exhibit a framework, commonly including the following elements: *option* (alterative), *objective* (goal), *criterion* (measurable qualitative or quantitative indicators of the performance of an option in relation to the objective), *performance score* (performance of an option against a specific objective or criterion) and *criterion weigh*t (coefficient intended to represent the level of importance of an objective and corresponding criterion relatively to the other objectives). Typically, one or more project options are assessed against a number of different objectives for which a set of criteria have been defined.

Table 3-2. MCA Method Classification [42]

Formal Methods ***Based on elaborated procedures, rigorous rules, and often advanced mathematical principles***	**Continuous Methods** ***Infinite number of alternatives, mathematical approach***		– **Linear Programming** – **Goal Programming** – **…**
	Discrete Methods *Limited number of alternatives, reflect real-world problems*	Full Aggregation Methods *Synthesis into a single global score*	– MAUT Methods – SMART/SMARTS/SMARTER – AHP – BWM – …
		Partial Aggregation Methods *Comparison of options on a pairwise basis*	– ELECTRE Methods – PROMETHEE Methods – REGIME – EVAMIX – …
Simplified Methods ***Practical, higher risk of errors***			– Simple Additive Weighted Model – Simple Summary – Charts – Checklists – Basic Lexicographic – Orderings – …

Table 3-2 shows a classification of the different MCA methods available. The category which fits best the objective of this thesis corresponds to the *discrete* methods, as the matter addressed is a real-world case scenario with limited number of alternatives. The *full aggregation* and *partial aggregation* methods represent two different schools of thought, the former corresponding to the American MCA school whilst the latter represents the European (French) MCA school. [42] Given this report aims to be make an analysis on behalf of an American startup, the first method has been selected, but both options would be equally as valid if well performed.

Analytic Hierarchical Process (AHP)

The Analytic Hierarchical Process (AHP) method has been selected for the scope of this work. AHP has particular application in group decision making. It provides a comprehensive framework for structuring a problem, representing, and quantifying its elements and relating those elements to overall goals whilst evaluating alternative solutions. By reducing the problem to a series of smaller analyses, AHP allows the decision-maker to determine the relative importance of different criteria with respect to the goal and finds the decision that best suits the objective and the understanding of the situation. [43]

The first step is to develop a hierarchical structure, level 1 corresponding to the goal, level 2 to the criteria and level 3 to the alternatives. The second step consists in determining the relative importance of the criteria with respect to the goal by means of a pair-wise comparison matrix. The relevance of the criteria is translated into quantitative scores by using a discrete scale, ranging from 1, the two criteria are of equal importance, to 9, one criterion is preferred very strongly over the other one. Once the comparison matrix is built, the following step is to retrieve weight of each criterion, named the *criteria weights*. To do this, several approaches can be taken, the most rigorous but in its turn more computationally demanding consists in calculating the normalized principal eigenvector. For the scope of this project, an approximate alternative which gives sufficiently close results will be used. This is a common practice given the difference between the exact value obtained through using the priority vector (eigenvector) and the one obtained through the approximation is less than 10 %. [44]

In order to calculate the *criteria weights*, the normalized pair-wise matrix has to be built. For that, each column of the pair-wise matrix is summed and the values in each column are divided by the sum of each corresponding column, the normalized pair-wise comparison matrix is obtained. The *criteria weights* for each row are obtained by calculating the average of each row, Equation 28.

$$Criteria\ weight_n = \frac{\sum_{m=1}^{m} Xvalue_{nm}}{m}$$

Equation 28. MCA Criteria Weight

Being:

n: number of rows
m: number of columns
$Xvalue_{nm}$: cell value of normalized pair-wise matrix, row n, column m

A *consistency ratio* has to be calculated to verify the *criteria weights* have been correctly obtained. To do so, the *weighted sum value* has to be first obtained by taking the non-normalized pair-wise matrix and multiplying the *criteria weights* of each row per the values in the corresponding column, row one per column one and so on. Once each column is multiplied by the *criteria weight* value, the rows are added, giving the *weighted sum value*. Once the *criteria weights* and *weighted sum values* are obtained, the next step is to divide the *weighted sum value* by the *criteria weights* in order to obtain the ratio between them. The average of these ratios is named *lambda max* (λ_{max}), which is used to calculate the *consistency index* (C.I.), Equation 29.

$$Consistency\ Index = \frac{\lambda_{max} - n}{n - 1}$$

Equation 29. Consistency Index

Being:

n: number of rows, which is equal to number of criteria

The *consistency index* is used to calculate the *consistency ratio,* Equation 30. For this, a *Random Index (RI)* is needed. The random index is the *consistency index* of randomly generated pair-wise matrixes. The table below shows the RI for up to 10 criteria. If the value of the *consistency ratio* is smaller than 0.10, it can be assumed that the matrix is consistent, and the criteria weights can be used for the decision-making process.

Table 3-3. Random Index (RI) for up to 10 criteria [43]

n	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

$$Consistency\ Ratio = \frac{Consistency\ Index}{Random\ Index}$$

Equation 30. Consistency Ratio

Once the comparison of the different criteria on a pairwise basis has been carried out, the same process can be followed in order to obtain the so-called *priorities*. Priorities are the same as the criteria weights but for the alternatives instead of the objectives. Once the priorities have been obtained and validated using the consistency ration, the priorities and the criteria weights are used to calculate the overall priorities to reach the objective understudy.

4 Project due diligence of a solar PV installation

The project due diligence of an installation located in California, USA, has been carried out using the two identified most promising softwares in the market, corresponding to PVsol and PVsyst. After the simulation, the results obtain have been compared through an MCA.

4.1 Project description

As the basis of this study, the thesis authors received the original project proposal and design of the Rinaldi Tile installation, courtesy of Tony Armor, CEO and President of Day One Solar, a local solar installation firm in Santa Cruz, California, USA. The solar system project proposal contains the roof layout and financial summary, the PV system description, annual energy savings, project costs, future savings, environmental benefits and cashflow details. [45] William Wiseman, co-author of this thesis, helped install the array during his early career while employed with Day One Solar. William's hands on perspective of the array gives a personal touch and deeper understanding of the project from beginning to end. An additional benefit of analyzing this array was that the team was able to access the past five years of system energy production data, enabling the comparison of the modeling software predicted power output to the real-world power output data. An image of the installation can be seen in Figure 3.

Figure 3. Rinaldi Tile 63.3kW Solar PV Installation

The original proposal to Rinaldi Tile outlines a 61.6 kW array although this was later upgraded to the final 63.3 kW array used in this study. In 2016, this 63.3 kW array was installed on the rooftop of Rinaldi Tile, a commercial tile manufacturing business located in Pajaro, California at the coordinates 36.898434°,-121.749114°. The opening hours of Rinaldi tile corresponds to 7:30 am – 16:00h pm on weekdays and consumption per month during an example year can be observed in Figure 4.

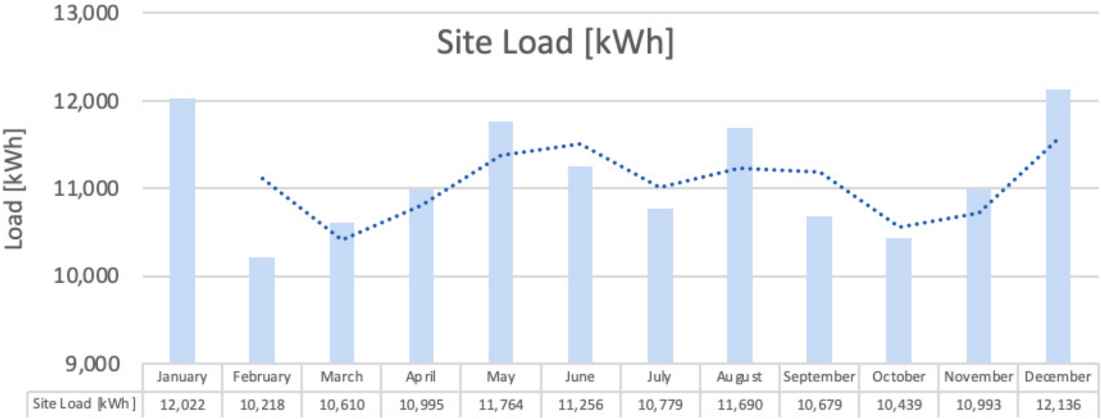


Figure 4. Monthly Site Load

Array Technical Specifications

The 63.3kW array consists of 201 *REC Solar REC315TP* PV Modules and 2 *SMA Sunny Tripower 30000TL-US-10 (480V)* Inverters. The PV module and inverter specifications can be seen below in Table 4-1. The roof has a 22.6° tilt angle on both the Main Module Area and Tower Side.

Table 4-1. Rinaldi Tile Solar PV Array Equipment Datasheet

REC Solar REC315TP PV Module [34]		SMA Sunny Tripower STP30000TL-US Inverter [40]	
Module Type	Polysilicon	**Max array power**	45 kWp STC
Nominal Voltage V_{mpp}	33.9 V	**Rated MPPT voltage (DC)**	500-800 V
I_{MPP}	9.31 A	**Maximum DC voltage**	1000 V
P_{MPP}	315 W	**MPPT op. voltage range**	150 – 1000 V
I_{sc}	10.09	**Min. DC voltage**	150 V
V_{OC}	40.5 V	**Max Isc per MPPT / string input**	53 A / 53 A
$\boldsymbol{\beta}$	-0.35% / °C	**Max operating input current / per MPP tracker**	66 A / 33 A
$\boldsymbol{\alpha}$	0.04% / °C	**Output side voltage (AC)**	480 / 277 V WYE, 480 V Delta
$\boldsymbol{\gamma}$	-0.27% / °C	**Rated AC power**	30 kW
NOCT	44°C (±2°C)	**AC voltage range**	244-305 V
Module Area	1.67 m^2	**Max output current**	36.2 A
Module Weight	18 kg.	**Output frequency**	50 or 60 Hz
Efficiency	18.9%	**Inverter Weight**	55 kg. (121 lbs.)
Annual Degradation	0.5%	**Max Efficiency**	98.6%

* Where β = temperature coefficient of V_{OC}, α = temperature coefficient of I_{SC}, and γ = temperature coefficient of $P_{MPP.}$

The panel tilt corresponds to the tilt angle of the roof where the installation is placed, 22.6° and the azimuth corresponds to 117.9°. [46] Using the equipment specified in Table 4-1 and the project design schematic, it was possible to recreate the system using PVsol. Inverter #1 has 6 strings with 16 panels in series whilst inverter #2 has 6 strings, 3 of which have 16 in series and the other 3 having 19 panels in series. Figure 5 below shows the specifics of the number of panels in series per string, which strings are connected to each inverter and the number of modules installed in each region of the rooftop.

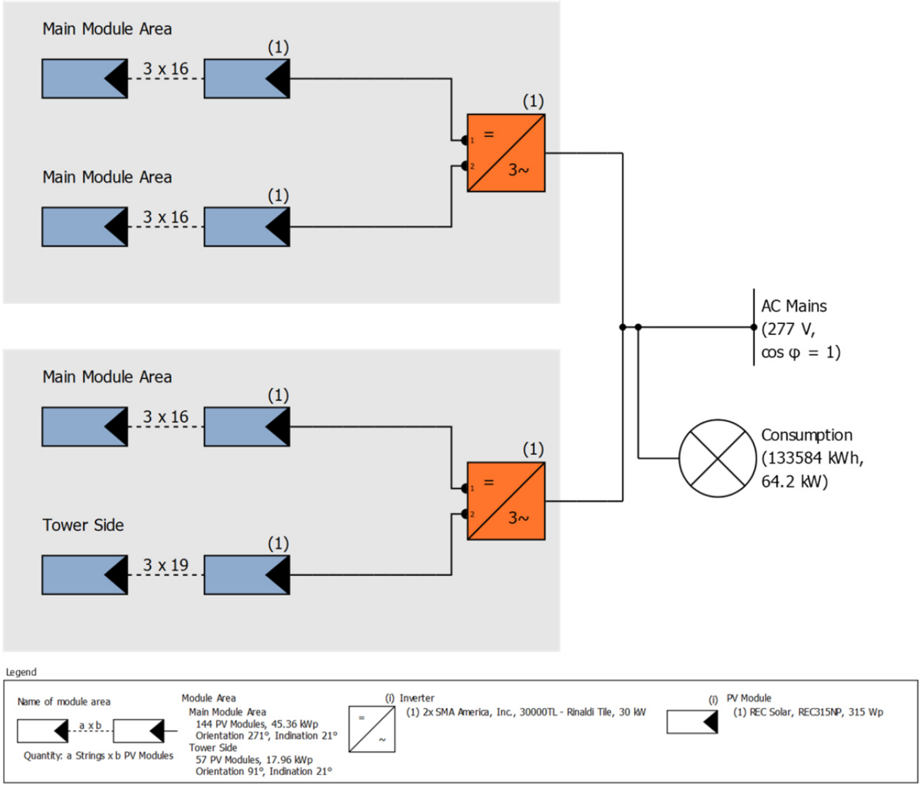


Figure 5. Rinaldi Tile Electrical Schematic from PVsol

4.2 Technical due diligence

To begin the technical due diligence process, an engineer must assess the resource availability and quality at a proposed location (36.898434°,-121.749114), which is given as an input to both softwares. As mentioned in the *Weather and Irradiance* section, an open-source solar resource map can be used to determine the GHI and the annual power output in kWh per kW of installed capacity. The specific PV power output [kWh/kW] and the GHI [kWh/m2] at the array location have been obtained. The specific PV power output and GHI provided by PVsyst and PVsol are listed below in Table 4-2. The results obtained in both simulations are very close to one another.

Table 4-2. Solar Resource at Array Location

	PVsol	PVsyst
Specific Photovoltaic Power Output [kWh/kWp/yr.]	1,482.0	1,466.0
Global Horizontal Irradiance [kWh/m2]	1,818.0	1,808.2

Both softwares share the same input data but the way of inputting the data and the order in which it is required varies slightly, so the technical simulation processes of both softwares will be explained individually in more detail.

PVsol

The process of analyzing a solar PV installation in PVsol requires the engineer to design the building and surrounding obstructions in a 3D model which is built within PVsol, Figure 6. Qualitatively, this process can be complex and time intensive even with previous Computer-aided design (CAD) experience. This 3D design process requires site blueprints to properly replicate the building upon which the array will be installed. Once the building is replicated, the panels must be placed according to the original installation blueprints including obstructions such as chimneys and free zones as dictated by local fire code. The ease of the panel placement phase is dependent upon whether the proposed panel is still being manufactured. If the panel is still available then the selection is as easy as searching the archive, although if the panel is out of production, or not in the *PVsol* database, then it will have to be entered manually which is time intensive although not complex. The same applies to the inverter. The specifications for both the *REC Solar 315TP* modules and the *SMA Sunny Tripower STP30000TL* inverters had to be entered manually the from their accompanying data sheets. [40][34] The next step required was to specify the number of panels wired in series per string and which strings were connected to the specified inverter which can be seen in Chapter 4, Figure 5. A final factor of safety check is performed by *PVsol* for the equipment configuration then it is ready for simulation. The monthly load was distributed over Monday-Friday and during Rinaldi Tile's operational hours 7:30am-4Pm. Unfortunately, PVsol can only add load profiles in 1 hr. increments so the load was evenly distributed from 8am-4pm. Zero load was entered during the hours when the manufacturing shop was non-operational. The Rinaldi load profile can be seen in Figure 4 in Section 4.1 Project description.

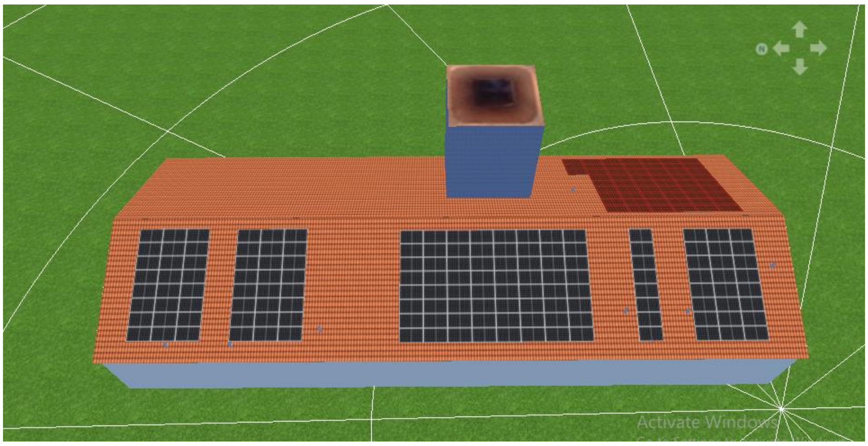


Figure 6. PVsol 3D CAD Design of Rinaldi Tile

PVsyst

Whet starting the simulation using PVsyst, the first step is to create a new project and select the location by inputting the coordinates or project site. Once the location has been selected, the monthly meteorological data, which can be obtained by using various data sources, has to be given. For the Rinaldi Tile system, the data source used corresponds to *Meteonorm 8.0 (1991-2005),* the values can be found in Table 4-2. Once this information is given, the user must proceed to create the first basic variant of the project by defining the orientation and system components with the option of defining later on the system losses, self-consumption, near shading and the economic evaluation, which is going to be analyzed in more depth in Section 4.3.

The site location corresponds to the coordinates 36.898434°,-121.749114° and the orientation of the panels have a tilt angle of 22.6° and an azimuth angle of 117.9°, as previously mentioned. When entering the system components, the PV modules and the inverters can be selected from an existing database and the specifications can be modified to match the ones of the installation. When defining the connections, 3 sub-arrays have to be built. One for the inverter that is connected to 6 strings of

16 modules in series and two for the inverter that is connected to 3 strings with 16 modules in series and 3 strings of 19 modules in series. The second inverter is defined as two independent inverters with half the nominal power as PVsyst assumes that an inverter with 2 MPPT inputs behaves as 2 identical inverters of half the power. Once the orientation and the system components are defined, the simulation can be run and the fields of system losses, self-consumption, near shading and economic evaluation can be completed further on.

When outlining the system losses, some of the input data might not be easily available, thus the software allows the user to use default values. When defining the consumption of the system, it can easily be set by defining monthly values or daily values. As the load profile affects is affected by the seasonal grid tariffs, a more precise input has been given by uploading a CSV file in which the kWh/h have been defined. It is a time intensive procedure which could be avoided by adding more flexibility and options to input in the software. The values for the monthly loads that have been used for the simulation correspond to the consumption during an example year can be found in Figure 4. The daily consumption has been allocated considering an equally hour distribution during the operating hours of Rinaldi Tile using the monthly values. To define the near shadings, the installation has to be modeled, this can be done through PVsyst, or the files can be imported. The simulation is also time intensive, so it is recommended, if possible, to import the files from the developers.

4.3 Financial Due Diligence

The total cost of the installations amounts to $ 196,504.00 which was paid for in cash. No loan was issued for the installation of the array. 30 % of the cost is covered through tax credits which equals $58.951.20. From the total contract price, $ 57,950.00 correspond to the depreciable assets.

Two key factors when conducting the financial analysis are to understand how the power generated will be billed and which government incentives can be claimed for the system. The utility billing structure corresponds to the *Pacific Gas and Electric Company (P&E)* Net Metered Small General Time-of-Use Service, also known as *Schedule A-6*. [47] The time-of-use structure of the service plan adds considerable complexity to assessing the value of the energy generated by the array. PVsol had the A-6 schedule included in their rate archive allowing the net-metering rates to be correctly allocated whilst in PVsyst it has been defined manually.

The available incentives for the Rinaldi Tile installation correspond to the *federal investment tax credit* (ITC) - Rinaldi Tile array received an equal to 30% of the total system value for $1:$1 tax reduction and the federal depreciation method *modified accelerated cost recovery system* (MACRS) with a half year period which allows the assets to be depreciated more quickly over a 6-year period instead of the 20-yearbook value. Through the economic assessment, the *Net Present Value (NPV)* and *Internal Rate of Return (IRR)* are calculated to determine the profitability of the solar array. Again, the inputs used for this section have been the same in both softwares, but a more in-depth discussion will be done individually to be able to make a detailed comparison in the results section.

PVsol

To accurately model the financial savings and the cumulative cashflows of the Rinaldi array, the business' load profile had to be entered so that PVsol could account for self-consumption. By entering the business load and maximizing self-consumption, Rinaldi Tile hedged their cost of electricity to the LCOE of the solar system in 2016 while reducing their exposure to the increasing electricity costs from the grid. It was assumed that the electricity cost from the grid would increase at 5% per annum. The monthly load profile of Rinaldi Tile was acquired from the original Day One Solar proposal provided during the bidding process.

The financial analysis of the Rinaldi Tile array proved to be highly problematic using PVsol. As will be mentioned later in Chapter 5 within the section called *Limitations*, the PVsol utility rate base archive is very limited although it did include the PG&E A-6 TOU rate schedule which provides an accurate pricing schedule for any power consumed or re-sold to the utility via net-metering. The inputs for PVsol fall into 2 primary categories: Economic parameters and Net-metering tariffs. The economic parameter section is further divided into 4 sub-categories: general parameters, income and expenditure, financing, and tax. Each sub-category includes the following variables and the variables used in this simulation are indicated with their input in brackets:

1) General Parameters
    a) Lifetime of the project – [25 years]
    b) The WACC – 5.6% although this input isn't relevant since the array is paid in cash.
    c) Value added sales tax – all entries are: A. gross or B. net. Option A was chosen.
2) Income and Expenditure –variables can be entered using $, $/kWp, % of investment or $/a
    a) Tax deductible outgoing cost of system setup, parts and labor – [$196,504]
    b) Non-tax-deductible outgoing cost of system setup parts and labor – [$0]
    c) Incoming subsidies – [30% of investment]
    d) Outgoing annual operating costs – [$0/a]
        i) Day One Solar confirmed they do not clean the panels.
    e) Annual consumption costs – [$0/a]
    f) Outgoing other annual costs – [$0/a]
    g) Detailed entry – miscellaneous costs can be added in this tab
3) Financing
    a) Number of loans – [**No Loan** – 3]
        i) Loan capital – $
        ii) Payment installment as % of Loan Capital
        iii) Term - [Years]
        iv) Repayment Free Initial Period – Years
        v) Type of loan – Installment or Annuities
        vi) Loan Interest - %
        vii) Repayment period – monthly, quarterly, half-yearly, yearly
4) Tax
    a) Allow for Tax
        i) Marginal rate for income/corporation tax – [35%]
    b) Allow for change in marginal tax rate
        i) Change tax rate after ___ years
            (1) New tax rate [%]
    c) Depreciation

        - i) Depreciation period – [6 years]
            - (1) Linear (straight line)
            - (2) Degressive (reducing balance)

The full simulation datasheet with all variables and outputs can be reviewed in detail in Annex B. The net-metering section is as simple as selecting the tariff from the PVsol archive and entering the inflation rate for energy (5 %). As was previously mentioned, it was lucky that the PG&E A-6 TOU rate schedule was included with PVsol although this would not be the case for any other utility. Utility rates which are not included in the archive can be entered manually.

PVsyst

Compared to the technical assessment, the financial assessment that can be carried out with PVsyst is more vague and less accurate as the options offered by the software are very basic. The first step taken when starting the economic evaluation consists in defining the system CAPEX and OPEX. The total capital investment is given, 85 % of the total system costs being depreciable assets. When defining the operational costs, a yearly expense of $1000 during year 1 which increases with inflation a 2% yearly has been defined. This is an approximation that has been used to account for changing the inverters in the original system in year 15. In PVsyst, there was no option to input an expense at a certain year for the inverter change so this alternative was the only option to account for the extra expense. This is not ideal, as it increases the payback period of the project. No other operation and maintenance costs have been added as they were not contemplated in the original system.

When looking into the financial parameters, the lifetime of the project is set at 25 years, starting in year 2016. The inflation and discount rate are 2 and 3 %/year respectively and the production variation considers a linear aging of 0.5 %/year. There is only one income dependent expense which corresponds to an income tax of 35 %. Lastly, the depreciation of the assets has been defined by setting manually a declining balance depreciation with a depreciation period of 6 years and a depreciation coefficient of 2 to replicate the half-year MACRS of the original system, as PVsyst doesn't have the option to select the MACRS depreciation methodology. The yearly depreciation percentages displayed by PVsyst do not coincide with the ones that should be obtained through the MACRS methodology, but these values have been used as no other options were available. The yearly percentages used in PVsyst for the 6-year declining balance depreciation correspond to 33.33 %, 22.22 %, 14.81 %, 9.87 %, 9.87 % and 9.87 % whilst the ones that should be used instead are 20 %, 32 %, 19.2 %, 11.52 %, 11.52 %, 5.76 %. This will also affect the project payback period.

The financing structure correspond to 70% of the total installation covered by own funds with a 30% covered by the ITC tax incentive. When looking at the utility billing structure, which corresponds to the PG&E Net Metered Small General Time-of-Use Service, also known as Schedule A-6, PVsyst has also encountered major difficulties. PVsyst only offers the option of defining a feed in tariff and does not consider any net metering solutions. That being said, the A-6 Schedule cannot be given as an input and it has to be set manually as self-consumption savings. Once all these inputs are given, the financial results, including the NPV, LCOE, payback period and the ROI, as well as the carbon balance of the system are obtained. The following list summarizes the system inputs just described in a more visual manner:

1) Investment and charges
    - a) Installation costs
        - i) Total installation costs – [$ 196,504]
        - ii) Depreciable assets – [$ 67,028.4 – 85 % of total installation costs]

  b) Operating costs (yearly)
    i) OPEX starting at $1000 in year 1 which increases with inflation a 2% yearly

2) Financial parameters
  a) Simulation period
    i) Project lifetime – [25 years]
    ii) Start year – [2016]
  b) Projected variations
    i) Inflation – [2 %/year]
    ii) Discount rate – [5 %/year]
    iii) Production variation (aging) – [Linear: 0.5 %/year]
  c) Income dependent expenses
    i) Income tax– [35 %/year]
  d) Depreciation
    i) Declining balance method, depreciation coefficient: 2, depreciation period: 6
  e) Financing
    i) Own funds – [70 % of total investment]
    ii) Subsidies – [30 % of total investment]
3) Tariffs
  a) Pricing strategy: variable seasonal tariff with hourly peak/off-peak tariff
    i) Self-consumption saving
4) Financial results
5) Carbon balance

4.4 Software limitations

PVsol

PVsol has a handful of technical limitations which prove to be time intensive although not fundamentally restraining. The primary limitation to the software is the depth of the equipment and electricity rate archive. When a piece of equipment is not accessible from the database it is possible to create a custom equipment file and manually enter the operational characteristics. It is notable that both the SMA Sunny Tripower 30000 inverter and REC 315TP modules needed to have their operational characteristics manually entered from their datasheets. The process of data entry for both sheets took 2 hours. If an analyst is regularly conducting due diligence on an EP&C which consistently purchased from a single supplier that was not entered in the database this would be an insignificant quantity of time, although if a wide array of equipment suppliers is being checked it could add up to a significant time usage.

Another limitation is the lack of customization regarding the wiring plan. The Day One Solar blueprint and the simulated wiring plan on string #12 are different because of the system rigidity. The Day One plan minimizes the total cabling length while the PVsol model does not accommodate this change. When the string is successfully replicated, the system does not accept the change. Little documentation is provided in the PVsol guidebook and additional forums acknowledged this limitation. While the cost savings in copper wire for the Rinaldi Tile case are insignificant, this limitation could be more significant when considering a multi-megawatt project.

When looking into the financial analysis, the largest limitation for PVsol is the database of available utility rates. PVsol included the PG&E Time-of-Use Schedule A-6 rate plan in the available plans. The A-6 was only 1/2 options available for the United States. The A-6 rate schedule is very complex including on-peak and off-peak rates for summer and winter with different rates for various generators and suppliers. The rate schedule is difficult to accurately replicate for the simulation and leads to considerable error on the financial analysis. PVsol only has a database of utility rates for the United States, Poland, Slovenia, Mexico, Germany, and Brazil for a total of 12 rate plans on file. Mexico holds the most with 6 documented rates while Germany, Poland and Slovenia only have example utility rate files. For PVsol to be useful across a wide variety of projects, this is the single largest limitation.

Another limitation that stood out while using PVsol is the inability to alter the depreciation rate of the solar asset in any other way than with a linear or degressive (reducing balance). The limitation of the depreciation settings results in PVsol not accurately incorporate the MACRS depreciation rate. PVsol can change the depreciation period (years) so that the PV array can still be fully depreciated within the accelerated period although the annual rate will have a slight undervaluation in years 1 and 2, with a slight over estimation in years 3 to 6. The range of error will vary depending on whether the linear or degressive balance is used.

PVsol is also limited by the fact it is not possible to enter timed individual expenses in the financial modeling such as the replacement of an inverter. A workaround for this can be to enter an ongoing O&M cost which divides the cost of the inverter over the lifetime of the project. This method does not account for the time value of money and must have an inflation rate applied to the cost.

PVsyst

The main limiting factor on the technical side is that no inputs can be given in the section of the near shading analysis without carrying out a full 3D representation of the PV system. However, the major limitation encountered corresponds to the load definition. When defining the consumption, it could easily be set by defining monthly values or daily values. However, when trying to define a more precise load profile the only option available was to upload a CSV file in which the kWh/h had to been defined. It was a time intensive procedure which could be avoided by adding more flexibility and options to input in the software. Another limitation, similarly, to PVsol, would be the inability to customize the wiring plan, but this has not been considered a major drawback as the aim of this thesis is to carry out the due diligence from a lender's perspective.

In regard to the financials, when defining the operating expenses in the investment and charges section, the cost of replacing an inverter on a certain year cannot be accounted for. Instead, the cost of the replacement was distributed throughout the lifetime of the project, which affects the payback period of the installation. When looking into the depreciation of the assets, PVsyst does not have the option to select any depreciation methodology so for instance, the MACRS depreciation could not be inputted. The alternative closest to the MACRS depreciation consisted in selecting a declining balance 6-year depreciation with a coefficient of 2. The yearly depreciation percentages displayed by PVsyst did not coincide with the ones that should be obtained through the MACRS methodology, affecting the payback period of the project. Additionally, PVsyst only offers the option of defining a feed in tariff and does not consider any net metering solutions. That being said, the A-6 Schedule that Rinaldi Tile project is following cannot be given as an input and had to be set manually as self-consumption savings.

4.5 Software comparison

When comparing the two softwares used to carry out the simulation of the Rinaldi Tile solar PV installation, the AHP method has been used. The full disclosure of the methodology can be found in Section 3.2. First of all, the three-level hierarchical structure has been built, see Figure 7. The goal (level 1) of this analysis is to identify the best software simulation tool for solar PV installation project due diligence from a lender's perspective. The criteria (level 2) correspond to the overall performance of the software, price, level of complexity, time needed to run the simulation, input data required and the user interface. The alternatives (level 3) are PVsol and PVsyst, which have been identified after carrying out a literature review, see Section 3.1.

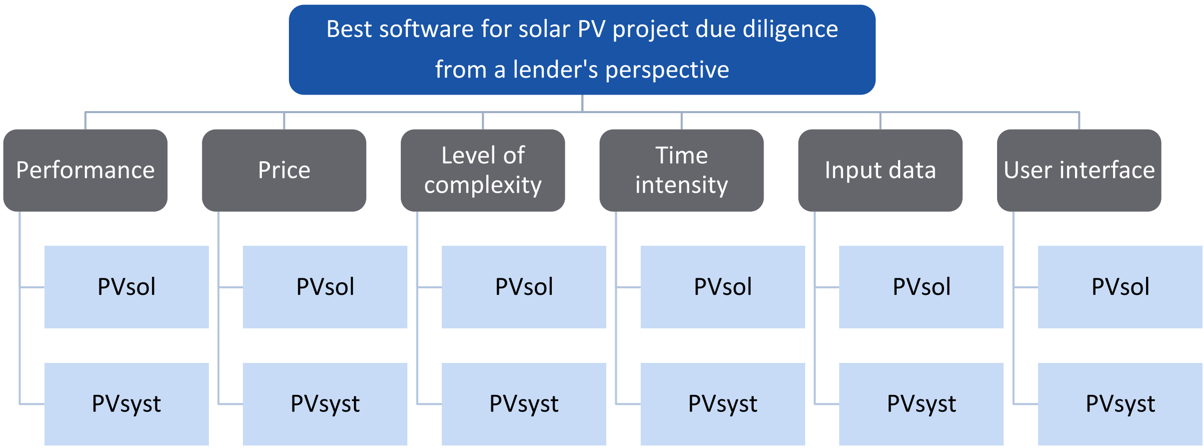


Figure 7. Three-level hierarchy AHP

The relative importance of the criteria with respect to the goal has been determined by means of a pair-wise comparison matrix, see Table 4-3. The diagonal of the matrix is set to 1 as it corresponds to the comparison of criteria of the same importance. Once the pair-wise comparison matrix has been built, the criteria weights are obtained. The validity of the weights has to be ensured. For this, the consistency ratio has to be calculated. To do so, the weighted sum value, lambda max and the consistency index have to be obtained. The random index value used for the calculations is 1.24 given we have 6 criteria. The criteria wights, weighted sum value and the ration between them are displayed on Table 4-4 and the formulas used to obtain these numbers can be found in Section 3.2. The values of lambda max, the consistency index and the consistency ratio are 6.45, 0.09 and 0.07 in this order. The consistency ratio is smaller than the tolerance of (0.07<0.10), so it can be assumed that the matrix is consistent and that the criteria weights can be used for the decision making-process. That is to say, for instance, the performance of the software has a contribution of 41% to the goal whereas the user interface has a contribution of only 3 %.

Table 4-3. Pair-wise comparison matrix with 6 criteria

	Performance	**Price**	**Complexity**	**Time**	**Input data**	**Interface**
Performance	1	5	4	3	4	5
Price	1/5	1	1	1/2	3	6
Complexity	1/4	1	1	1/2	3	6
Time	1/3	2	2	1	5	7
Input data	1/4	1/3	1/3	1/5	1	3
Interface	1/5	1/6	1/6	1/7	1/3	1

Table 4-4. Weighted sum value, criteria weights, and consistency ratio

Weighted Sum value	**Criteria weights**	**Ratio**
2.73	0.41	6.74
0.87	0.13	6.49
0.89	0.14	6.46
1.47	0.22	6.60
0.41	0.07	6.22
0.22	0.03	6.15

Once the criteria weights have been obtained, the same procedure is followed with the alternatives in order to obtain the priorities (which are the equivalent to the criteria weights for the alternatives). This is done by building a pair-wise comparison matrix to compare the alternatives for each of the criteria. In this case study, it results in building 6 matrixes. Table 4-5 is an example of the pair-wise comparison matrix between the two alternatives for the criterion *performance*. It also contains the result of the priorities.

Table 4-5. Pair-wise comparison matrix between the alternatives for the performance criteria

A	**Performance**		**Priorities**
	PVsyst	PVsol	
PVsyst	1	8	0.89
PVsol	1/8	1	0.11

5 Results and Analysis

This chapter will discuss the answers to the questions formulated in the problem statement of this report. The findings include the guidelines for a sola PV project due diligence focusing on the technical and financial analysis and a comparison through MCA of the two softwares identified through the literature review. The optimal process flow for the company Seeds is identified. By comparing the real power production data from the Rinaldi Tile array and the simulated power forecasts from PVsol and PVsyst the accuracy of the models can be benchmarked against the results of real-world operation.

5.1 Major findings

Due Diligence Checklist

The following table has been built after carrying out a study on the project due diligence from a best practices both in Europe and the US and it is meant to serve as a high-level guide of the broad steps necessary to plan, develop, construct, operate and maintain a solar array. While this list may serve as a guide, it is not comprehensive since every project will come with its own unique complexities. From a lender's perspective, the aim is to check the boxes as this work has been previously done by the developers and not to necessarily conduct all the research. In Section 2.1 the standards that have to be met by the system components are summarized (see Table 2-3 for the system components). Making sure that the equipment used complies with the requirements is part of the technical due diligence.

Table 5-1. Solar Project Development Checklist [48]

Feasibility Analysis
Assess site for solar resource (see Section 2.2 - Technical analysis)
Secure control of property and/or site
Evaluate the solar resource (see Section 2.2 - Weather and Solar Irradiance)
Understand participant motivation
Conduct market research/focus groups/surveys
Investigate interconnection options
Research financing mechanisms
Gauge community receptivity and support
Project Development
Prepare a financial plan
Determine ownership structure
Develop operating agreement between host and project owner (if different)
Develop participant agreement
Obtain legal and tax consultation for contracts
Design system and other technical specifications

Finalize agreement for the sale of power
Complete permitting and environmental compliance requirements
Finalize interconnection agreement
Conduct a request for proposal (RFP) for the design and build
Construction
Prepare the site for construction: grading, road improvements, etc.
Dig trenches for cabling and install transformer(s)
Install fencing and site security features
Complete inspections and commissioning
Restore site and surrounding natural habitats
Complete paperwork for incentives (feed-it-tariffs, investment tax credits, etc.)
Operations and Maintenance
Schedule and perform panel cleaning
Create liquidity fund for inverter replacement
Monitor system output
Distribute incentives to participants (tax credits, incentives, etc.)
File tax returns
File annual business license requirements

This checklist must be supplemented with the legal due diligence checklist, particularly pre-construction. Each row of this checklist can be representative of a much larger work package as is indicative in “Assess the solar resource” which is actually representative of the entirety of the Technical analysis section.

Software comparison

In this section, the technical and financial results obtained through the simulation using PVsol and PVsyst will be compared to the real data from the Rinaldi Tile project. The real data and reports on the simulations can be found in Annex A, B and C.

Simulation results - Technical

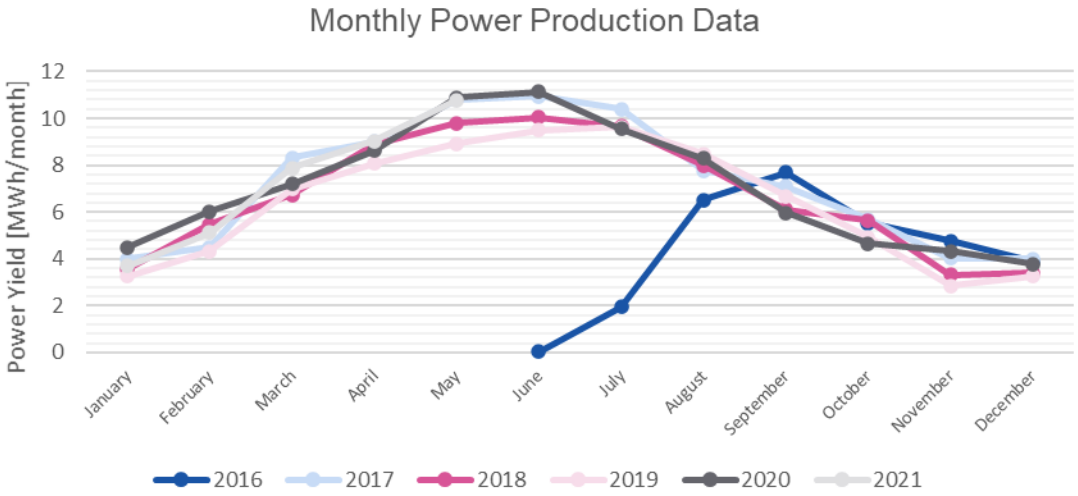
The *SMA Sunny Tripower 30000* inverters from the Rinaldi Tile array were able to export the array’s power production data, allowing the mapping of the monthly AC power generated by the array over time, see Graph 1. It is worth noting the year-to-year monthly variation. The power production data from the Rinaldi Tile array can be seen in Annex A. This shows the potential of localized weather to create significant deviation from the models.

An average of the monthly power generation values of the real production data and the two simulations can be seen below in Graph 2. This will be key in determining the percent error of *PVsol* and *PVsyst*. Comparing the real production data to the forecasts of PVsol and PVsyst enables the identification of over or underestimation trends over numerous years. The average monthly error can be calculated to identify months in which production error may be reoccurring. The average monthly error is calculated as indicated in Equation 31.

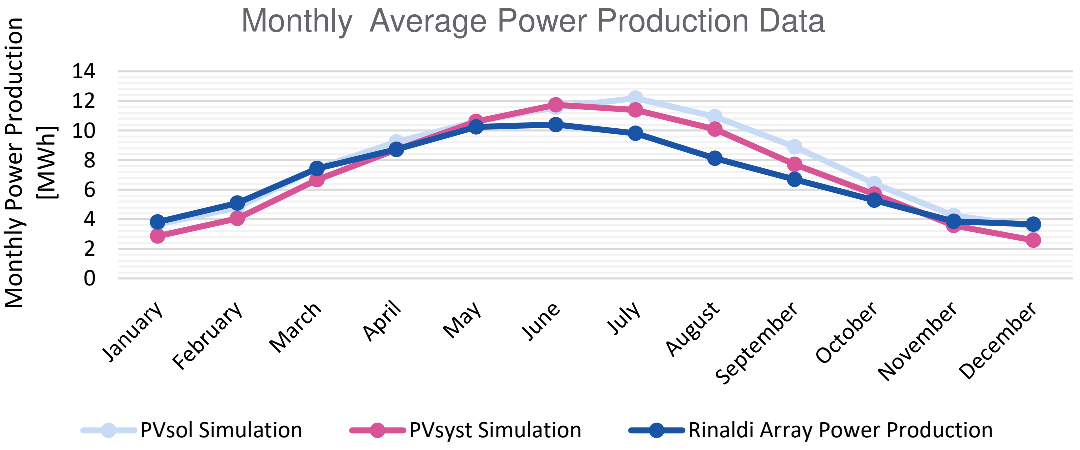
$$Error\ (\%) = \frac{(Predicted\ power\ output - real\ power\ output)}{Real\ power\ output}$$

Equation 31. % Error

The months of June, July and August 2016 were removed from the monthly error calculation since the array power output had not normalized as can be seen in Graph 1. Those 3 months are clear outliers from the rest of the data set and would have biased the monthly average error value. Using the inverter output data from September 2016 – May 2021, the average monthly power generation of the array in Megawatt hours can be calculated as seen below in the first row of Table 5-2, represented also in Graph 2.



Graph 1. Monthly Power Production Data 2016-2021 of Rinaldi Tile solar PV array

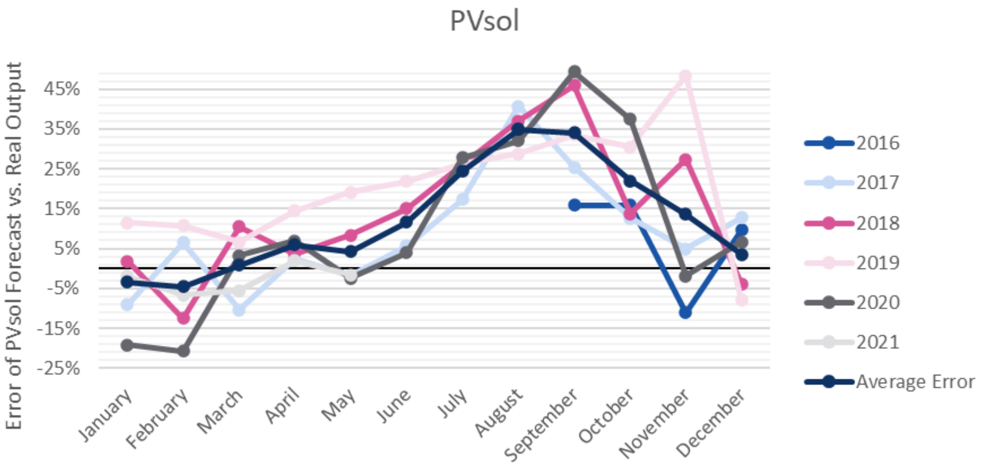


Graph 2. Monthly Average Power Production Data from PVSol, PVsyst simulations & real values

Table 5-2. Rinaldi Tile Power Production Data and Simulation Monthly Average Forecasts [MWh]

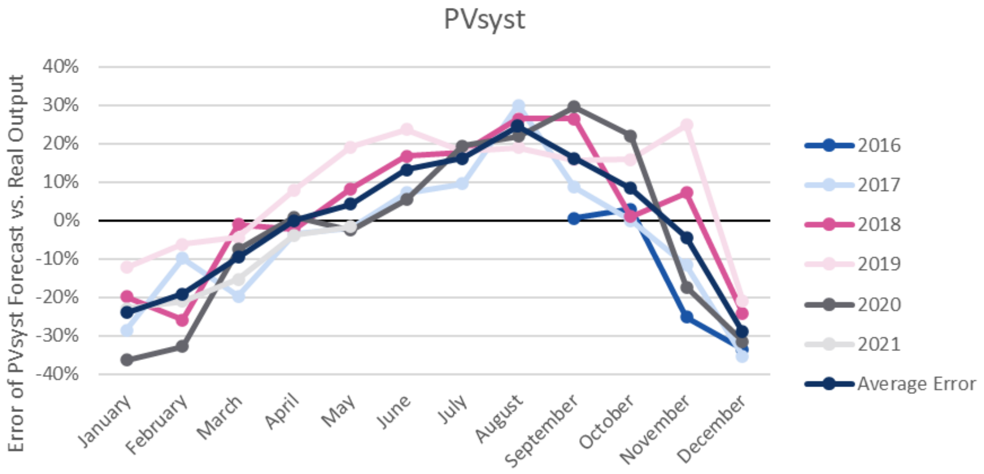
	Jan.	Feb.	Mar.	Apr.	May	Jun	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Total
Real	3.81	5.09	7.42	8.72	10.24	10.41	9.81	8.13	6.70	5.29	3.86	3.66	82.24
PVsol	3.63	4.78	7.44	9.21	10.61	11.56	12.18	10.93	8.90	6.41	4.24	3.54	93.47
PVsyst	2.86	4.05	6.67	8.70	10.61	11.74	11.39	10.10	7.72	5.70	3.57	2.58	85.69

Using the data from the Rinaldi Tile inverter, the error of PVsol and PVsyst could be calculated on a monthly basis and charted as seen below in Graph 3 and Graph 4. PVsol shows a high amount of forecast variability while PVsyst shows a tighter error band. These visual trend identifications are matched by the results where PVsol and PVsyst had an average monthly error of 12.22% and -0.30% respectively. The average monthly error of PVsol is clear since the majority of the error is above the x-axis representing an overestimation of power production. In comparison, PVsyst is more balanced where May – October has an overestimation while November – April balance the average monthly error by underestimating the power production. This monthly error is important to note both in terms of which months and the scale of the error. Month-to-month error can be negated by inverse error in the following months. The key characteristic will be the annual power production estimates which represents an accumulation of any simulation error.



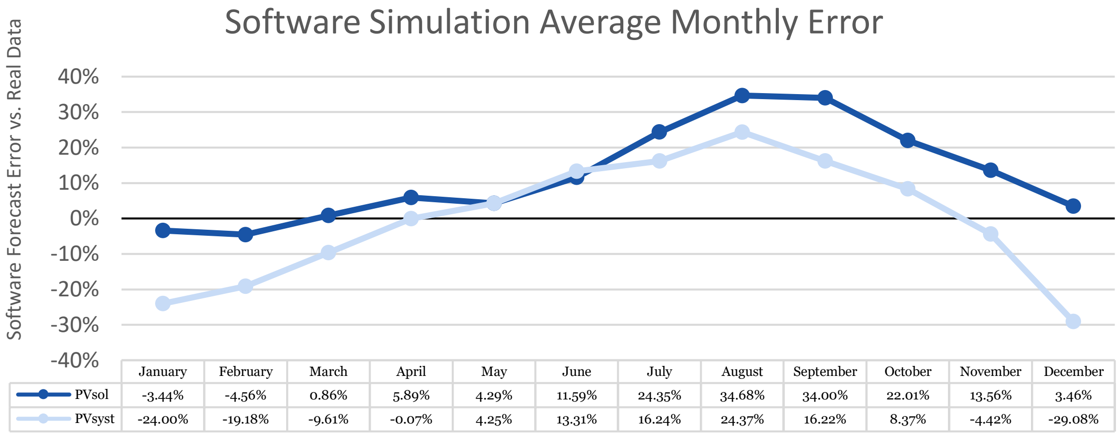
Graph 3. Error of Monthly Power Production Forecast - PVsol

The next step is to take the average error for each month across the operational lifetime of the Rinaldi array. The average monthly error and the error trendline can be seen in Graph 5. The largest percentage error for PVsol occurs in August while the largest error for PVsyst occurred in December. From a lender's perspective, an overestimation is much more dangerous than an underestimation. Overestimating the power yield will result in cash shortfalls and endanger the bankruptcy of a project. Underestimating the power yield of a project risks that the developers or financiers may decline to build the project in the first place. In this case study PVsol overestimates the power yield in 10/12 months while PVsyst strikes a balance - overestimating for 6 months and underestimating for 6 months.



Graph 4. Error of Monthly Power Production Forecast - PVsyst

In terms of total annual error PVsyst outperformed PVsol with an error of 4.20 % and 12.22 % respectively. Both overestimate the power production which is a serious risk when considering project viability. This risk can be mitigated by purchasing newly launched insurance products which guarantee an array yield, although this is not an excuse to neglect the technical error.



	January	February	March	April	May	June	July	August	September	October	November	December
PVsol	-3.44%	-4.56%	0.86%	5.89%	4.29%	11.59%	24.35%	34.68%	34.00%	22.01%	13.56%	3.46%
PVsyst	-24.00%	-19.18%	-9.61%	-0.07%	4.25%	13.31%	16.24%	24.37%	16.22%	8.37%	-4.42%	-29.08%

Graph 5. Average Error of Software Simulation Monthly Power Forecasts

Simulation results – Financial

When analyzing the results of the simulations 5 key criteria were selected: total earnings, the IRR, NPV of the project cashflow, the LCOE at Rinaldi Tile after installing the array and the time required to repay the system, see Table 5-3. The full results of the two simulations can be found in Annex B and C.

Table 5-3. Rinaldi Tile, PVsol and PVsyst Financial Key Results

	Cumulative Cash Flow	IRR	NPV	LCOE	Payback Period
Rinaldi T.	$662,575	19.26%	$309,837.81	$0.06/kWh	4.6 years
PVsol	$253,686	18.12%	$206,416.51	$0.13/kWh	6.7 years
PVsyst	$746,440	16%	$344,680.45	$0.126/kWh	7.7 years

It is immediately obvious that the simulations have a high level of inconsistency despite their identical input parameters. The payback period of both simulations is longer than the one forecasted by Day One Solar, the LCOE lower and the IRR higher. The disparity has been attributed to the software limitations, which will be commented in Section 6.2 and the fact that the data obtained from the project developers is somewhat outdated and is not as reliable.

PVsyst financial predictions are closer to the real data, especially regarding the cumulative cash flows and NPV. Surprisingly, PVsol forecasts that the array will produce only 22.5% of the total financial earnings of the PVsyst simulation even though PVsol predicts the array will produce 9.1% more power than the PVsyst array. This is despite having the same remuneration inputs through the PG&E schedule. The financial input values were the same including government incentives, utility rates and electricity price inflation rates.

It has been complex to understand where such a large variation in earnings is created when the two simulation tools each have nearly identical inputs. The original hypothesis was that there was a substantial difference the quantity of energy purchased from the grid between the two simulations. Looking below at Figure 8 and Graph 6, the annual energy flow graph and a monthly breakdown of the energy balance from PVsol shows the annual consumption per year is 133,581 kWh which remains the same for both simulations. 74,391 kWh are purchased from the grid which is nearly the same as the 80,060 kWh of electricity purchased from the grid in the PVsyst simulation as can be seen below in Figure 9. The average price of commercial electricity in California for May 2021 was $ 0.17/kWh. [49] Considering this the cost difference created by this grid injection imbalance would be equivalent to $ 964/yr and $ 24,093 over the 25-year lifespan of the PV array. This is less than 10% of the financial forecast imbalance. While significant, it is not the main driver of the error within PVsol. Looking more closely into the simulation reports, it has been identified that PVsol has constant savings prediction which might result in low cash flows. In both PVsol and the data from the real installation, the savings increase over the project lifetime due to the increase in the electricity bill whilst PVsol shows constant savings even though the yearly percentage increase was given as an input. It is also worth noting that PVsyst does not include tax refunds which are present in both the real project data and PVsol simulation.

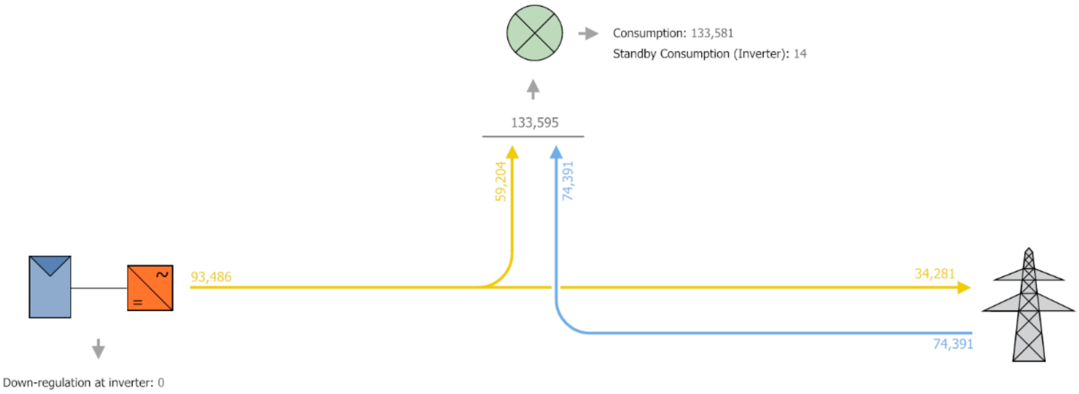
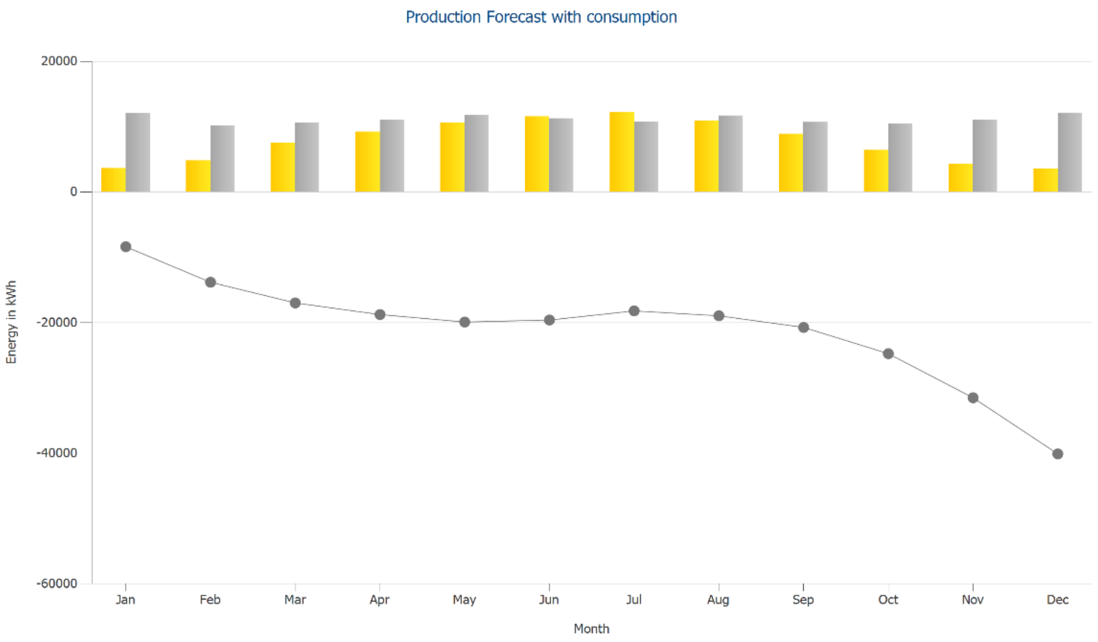
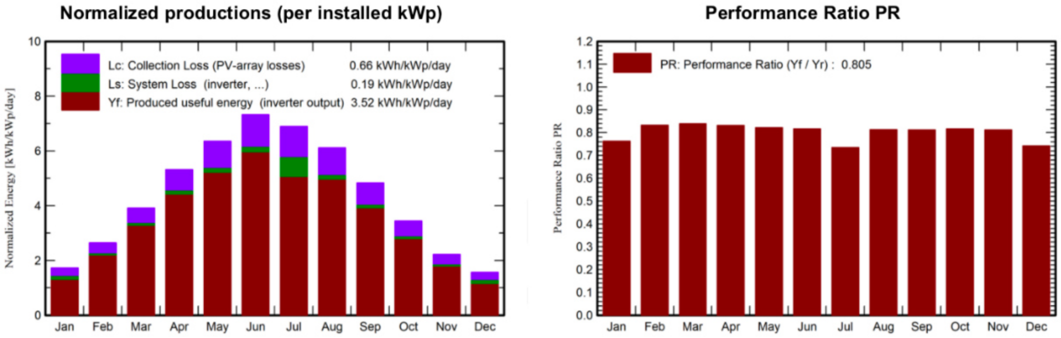


Figure 8. Energy Flow Graph - PVsol



Graph 6. Annual Energy Consumption - PVsol



Balances and main results

	GlobHor kWh/m²	DiffHor kWh/m²	T_Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray MWh	E_User MWh	E_Solar MWh	E_Grid MWh	EFrGrid MWh
January	69.2	29.25	10.01	53.4	48.3	2.86	12.76	2.080	0.497	10.68
February	90.9	41.99	10.63	74.0	68.5	4.05	10.07	2.816	1.087	7.26
March	138.2	60.66	11.89	121.4	114.4	6.67	10.57	4.205	2.243	6.37
April	179.5	63.01	12.60	159.6	151.5	8.70	10.78	5.526	2.877	5.25
May	212.3	71.55	14.28	197.0	187.5	10.61	12.07	6.630	3.618	5.44
June	232.5	66.23	15.55	219.6	209.5	11.74	11.03	6.793	4.555	4.24
July	230.4	66.77	16.60	213.8	203.7	11.39	10.71	6.177	3.775	4.53
August	210.2	57.16	16.85	189.5	180.2	10.10	12.14	6.634	3.123	5.51
September	170.5	45.44	16.89	145.0	137.0	7.72	9.97	4.674	2.780	5.29
October	128.3	42.09	15.54	106.5	99.3	5.70	10.84	3.992	1.513	6.85
November	82.9	34.72	12.11	66.6	60.6	3.57	11.29	2.448	0.977	8.84
December	63.3	28.92	9.96	48.6	43.5	2.58	11.35	1.546	0.737	9.81
Year	1808.2	607.78	13.59	1595.0	1504.0	85.67	133.58	53.521	27.782	80.06

Legends

GlobHor	Global horizontal irradiation	EArray	Effective energy at the output of the array
DiffHor	Horizontal diffuse irradiation	E_User	Energy supplied to the user
T_Amb	Ambient Temperature	E_Solar	Energy from the sun
GlobInc	Global incident in coll. plane	E_Grid	Energy injected into grid
GlobEff	Effective Global, corr. for IAM and shadings	EFrGrid	Energy from the grid

Figure 9. Monthly and Annual Energy Balance - PVsyst

Simulation results – Environmental

Solar electric systems provide significant environmental benefits. On average, the energy produced by the system in the first 0.5 - 1.5 years will fully offset the energy used to produce and install the system. [45] The environmental benefit of the installation can be calculated using both softwares and compared with the results from the real data obtained from the Rinaldi Tile project proposal.

Table 5-4. Environmental benefits of the Rinaldi Tile installation over the project lifetime

	t CO_2 avoided in 25 yrs
Rinaldi T.	1420.2
PVsol	1098.3
PVsyst	1073.2

The Rinaldi Tile original project proposal forecasts the PV system will eliminate as much greenhouse gas emissions as not driving 142,736 vehicle miles/year. According to the *United States Environmental Protection Agency (EPA)* [50], 3.98 x 10-4 tCO2E/mile, which has been used to determine the 1420.2 tCO2 avoided by the Rinaldi Tile installation over the project lifetime. Through the simulations, PVsol has made an estimation of 1098.3 tCO2 avoided whilst PVsyst, generally on the most conservative end, forecasts 1073.2 tCO2. These values, found in Table 5-4, do not account for the emissions generated by the installation. PVsyst simulation has a more complete CO2 balance section where the total avoided emissions are given together with the generated emissions by the system, which results in a total of 837.5 tCO2 avoided over the 25 years. The full disclosure of this calculations and the results can be found in the PVsyst simulation report, Annex C. On the other hand, PVsol only gives the yearly value of emissions avoided. It is important to highlight that the emissions avoided forecasted by Day One Solar are higher than the ones obtained by both simulations whilst the values given by the simulations are reasonably close to one another. The values obtained through the simulations have been considered to be more reliable as the forecast by Day One Solar correspond to an older version of the installation which might lead to errors in the estimation of the avoided emissions.

Multi-Criteria Analysis result

After carrying out the MCA the software which best fits Seeds' business model has been identified, corresponding to PVsyst. Through the AHP method, the criteria weights and priorities have been obtained and used to build Table 5-5, which shows the overall priority of each alterative. PVsyst has an overall priority of 62 % and PVsol of 38 %. The priorities reflect how the alternatives, which are the two softwares, relate to the criteria.

PVsyst has shown a better overall performance, as the results obtained through the simulation are the closest to the real data, both from a technical and financial perspective. This is why, an 8 has been given to PVsyst when compared to PVsol in regard to performance.

When looking into pricing, PVsol takes the lead and is rated with an 8 in respect to PVsyst. PVsol offers two version, PVsol and PVsol premium. The full license costs ~$ 1050 (onetime payment including 6 months of software maintenance support) with an annual maintenance fee of ~$190 including all program and database updates for PVsol and ~$ 1520 one-time payment with ~$270 annual maintenance fee for the premium version. The premium version contains all the features from PVsol with the addition of detailed 3D modelling. Because of the option of importing 3D files from CAD programs and 3D shading analysis, the premium version would be the version acquired by Seeds. [51] On the other hand, PVsyst offers a yearly subscription for $ 670 per year including unlimited features, unrestricted access to components database and updates. Discounts ranging between - 5-20 % can be obtained on grouped orders or some can be applied for non-profit use, such as educational licenses (-40 %), training (-20 %) and research (-20 %). Considering the software would be used by the company Seeds Renewables it is assumed that the entity would be paying the full yearly subscription with no discount. [52] After 4 years, the price of acquiring both softwares would be the same (considering PVsol premium and no discounts for PVsyst), however, in 5 years' time, PVsyst would be 14 % more expensive than PVsol and in 10 years, 36 %. The prices mentioned do not include taxes.

Both softwares have presented similar level of complexity. PVsyst has been preferred over PVsol, with a 3, due to the fact that in PVsol the 3D model has to be designed at the beginning of the simulation and in PVsyst it is only necessary for the near shading analysis.

PVsyst and PVsol have both been time intensive. The authors of this thesis have timed the installation of the software and the simulation of the array. The time spent to download PVsyst was minimal, corresponding to 5 minutes 25 seconds. This enters in contrast with the 72 hours needed to install PVsol due to problems with the virtual machine. The extra complexity of downloading PVsol is attributed to the computer's operating system (OS), as the engineer carrying out the simulation with PVsol was using MAC OS, whilst the engineer running the simulation with PVsyst was using Windows OS. As a result, and because the time to download both softwares is considered a one-time investment, the download has not been considered for the time intensity criterion. The time spent to learn the software and carry out the simulation was 16 hours, 54 minutes for PVsyst and 11 hours, 44 minutes for PVsol. The time spent with both softwares is similar and taking into consideration there might be a bias because two different people were running the simulations, the time intensity of the softwares have been considered equal.

When looking into the input data required, PVsol takes the lead with an 8. A perfect example would be, although PVsol's utility rate base archive is very limited it did include the PG&E A-6 TOU rate schedule whilst it is not possible in PVsyst. Moreover, net metering cannot be easily given as an input in PVsyst, which is a major drawback.

Lastly, the user interface of PVsyst is moderately better than the one of PVsol, awarded a 3. This criterion is the least objective one and might vary depending on the engineer behind the simulation. When using PVsol from Mac OS, the display screen was small and could not be maximized adding unnecessary complexity, but this has not been considered as it is OS dependent and might be the case with PVsyst as well when used in an OS other than Windows.

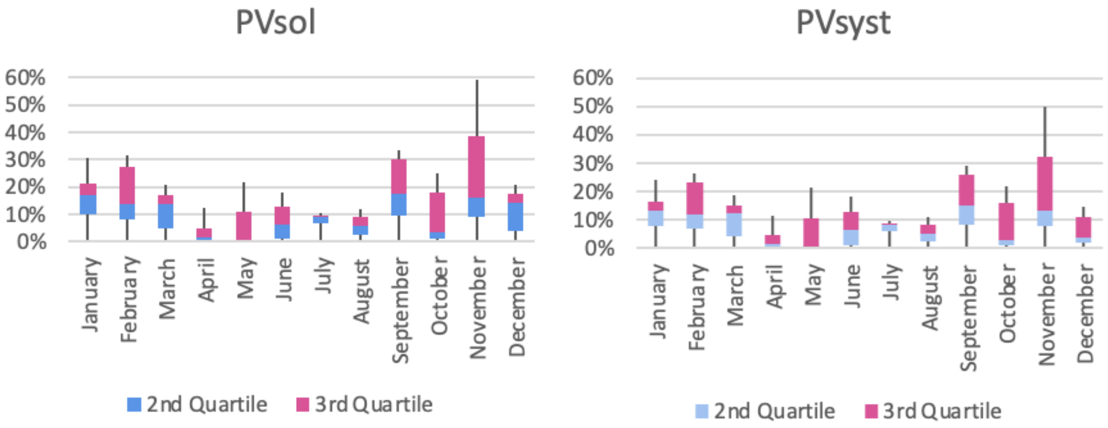
When all the priorities for each of the criteria have been obtained, the criteria weights and the priorities are multiplied and summed, adding to the overall priority of an alternative, Table 5-5. PVsyst has been selected as the best software for solar PV project due diligence from a lender's perspectives with an overall priority of 62 % in respect to PVsol, with a 38 %. The preference of PVsyst over PVsol has been driven by the better overall performance.

Table 5-5. Criteria weights and priorities used to calculate the overall priority of the alternatives

	Performance	**Price**	**Complexity**	**Time**	**Input data**	**Interface**	**Overall priority**
Criteria weights	0.41	0.13	0.14	0.22	0.07	0.03	
PVsyst	0.89	0.11	0.75	0.50	0.13	0.75	0.62
PVsol	0.11	0.89	0.25	0.50	0.88	0.25	0.38

5.2 Reliability Analysis

It is important to consider the reliability of the data to protect the study against statistical anomalies, especially when extrapolating the accuracy of a 25-year simulation against 4 full-years and 2 half-years of production data. To double check the reliability of the data and identify areas which are prone to error, the data was plotted by minimum, 2nd quartile, median, 3rd quartile and max, see Graph 7. By mapping the middle 50 % of the absolute error, PVsyst has a 10 % smaller maximum error in November. PVsol has an error of nearly 60 %.



Graph 7. Reliability analysis PVsol and PVsyst

6 Conclusions and Future work

In this chapter, the work of the thesis is concluded, followed by the limitations encountered and future work.

6.1 Conclusions

The goal of the thesis is to accurately set a framework for the tecno-economic assessment when conducting the due diligence processes from a lender perspective to finance the construction of solar arrays. Additionally, the thesis aims to identify the software analysis tool which best fits the investor profile of the Fintech company Seeds.

The first goal of this thesis has been met by elaborating a checklist for carrying project due diligence using the findings from the literature review. The guidelines include a list of the standards that have to be met by the solar PV installation components in the United States, technical and financial requirements and an overview of the main points that should be covered in the legal due diligence. The list is targeted to financers but can be used by engineers and project developers who seek to have a general understanding about what the process implies.

Meeting another objective, the optimal software tool which can analyze the bankability of a solar array and can be used by the company Seeds has been identified. To select the optimal software, the authors have, through related work, narrowed down the options to two softwares, PVSol and PVsyst. A comparison has been made through an MCA.

Through the AHP, the criterion that has been assigned the highest weight corresponds to performance, with an overall preference of 41%. In terms of both technical and financial accuracy, PVsyst clearly outperforms PVsol. PVsyst is able to forecast the electrical yield of the Rinaldi array with almost one third of the error of PVsol, 4.20 % and 12.22 % respectively. Moreover, PVsyst financial predictions are closer to the real data, especially regarding the cumulative cash flows and NPV. This has tipped the scale in favor of PVsyst. PVsyst has also received a higher valuation regarding complexity and user interface whilst PVSol is more competitive when looking into price and the input data required. Both softwares have been equally time intensive. This study concludes that PVsyst can meet the needs of a lender. However, it is work noting that the software has some limitations, the major one being PVsyst is better suited for projects based in Europe due to the database of utility rate schedules which effects the financial forecasts.

6.2 Limitations

They main limitation encountered during the elaboration of this thesis is the lack of the real financial performance data of the Rinaldi Tile array, which has hindered the accuracy of the software comparison. Since this case study does not have the real financial performance data to compare against, the financial projection in the proposal which was professionally prepared by Day One Solar is used as a benchmark to determine the range of the accumulated earnings. Considering this, Day One’s proposal estimated the cumulative savings to be $ 662,575 while PVsyst and PVsol projected $ 746,440 and $ 253,686 respectively. Notably, the financial forecast in the Day One proposal was based on a 61.6 kW system versus the final 63.3 kW system. If scaled linearly, this increases the output to $ 680,860 which is incrementally closer to the PVsyst prediction further reinforcing the conclusion that PVsyst is a better analysis tool for this application.

6.3 Future work

While this case study covers a broad range of material and synthesize it into a single comprehensive report; future work could use the information and methodology provided to test the accuracy of more software tools on the same or even a different array. In particular, Aurora, Helioscope, RETScreen and PV F-Chart should be compared for technical and economic accuracy with a similar methodology as conducted in this thesis and in the report by *N. Umar* and *B.Bora,* mentioned in the related work section. Additionally, for the company Seeds Renewables, providing alternatives and suggesting outsourcing options like working with a third party instead of doing the due diligence in house could have been added.

Another direction where future work could be relevant would be to complete a sensitivity analysis of the main variables both technically and economically to determine which have the largest effect on the energy yield or the financial earnings. Moreover, the work carried out in this study can be extrapolated to other projects and lenders, allowing the scalability of the findings. However, regarding the AHP method, the pair-wise comparison matrix would need to be redesigned, as for the scope of this study the ratings are made for the start-up Seeds, and they might not represent the preferences of other investors.

6.4 Reflections

The authors of this thesis hope that this synopsis can clarify the key considerations for anyone looking to assess the viability of solar for themselves or their business. Reports like this serve to consolidate and simplify the vast quantities of information which exist, but in silos. The details of a lender’s due diligence processes are often proprietary and partially disclosed which creates an information asymmetry between commercial firms and the average engineer or citizen. This report hopes to bridge the gap between the technical and financial worlds in a way that is clear to an outsider while containing enough detail to be representative of the scrutiny required to diligence and invest in a project.

The availability of knowledge is a privilege. As the world rapidly approaches a second industrial revolution, the availability of this knowledge for future engineers, scientists and scholars will be key. Deploying the necessary renewable energy generators and averting the worst effects of the climate crisis will require international collaboration between the next generations of engineers and financiers.

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