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# Introduction of SAM's Photovoltaic (PV) model for Utility Scale PV Solar Design and Analysis

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***Abstract*— System Advisor Model (SAM) developed by NREL (National Renewable Energy Lab) are used in modeling different types of renewable energy systems. Due to increase in demand of renewable energy sources (RES) the demand of engineers proficient in modeling RES has been growing. However, typical engineering curriculum focuses more on fundamental principles and other applications, not covering RES modeling. Employers desire and students yearn for hands-on, real-world, job read skills and proficiency. This study has explored and developed educational module for Large PV farms that could be incorporated into engineering courses. Such module(s) would help student awareness, understanding and proficiency to enable contribution within a growing area of demand within the job market.**

**Keywords—PV Solar, conventional power generation, utility scale, engineering professional.**

## I. Introduction

Distributed generation of utility-scale photovoltaic solar power involves integrating it into the distribution grid. The process of PV solar power generation involves converting sunlight into electrical energy using PV modules [1]. The amount of energy generated by the PV module depends on various factors, including POA solar irradiance, cell temperature, module efficiency, angle, and orientation of the module [2]. While the PV module generates DC power, the transmission and distribution systems operate on AC power, necessitating the use of an inverter to convert DC power to AC power. Besides, one or more types of transformers are required to convert low voltage AC to an appropriate voltage level for grid integration. To develop a utility-scale PV solar power plant, various design criteria must be considered. [3]

The knowledge of utility scale PV model has the potential to benefit numerous students pursuing a career in renewable engineering. With new renewable energy targets, there are increased opportunities for career growth, while also catering to the emerging workforce and educational requirements of global industries. However, the traditional engineering curriculum does not delve into the intricate design of the utility scale PV model. Typically, engineers and technicians gain the necessary knowledge and skills related to utility scale PV models outside of the formal electrical engineering curriculum. The curriculum primarily focuses on fundamental principles, with limited scope for specific applications such as PV models. However, there is a growing trend among students and employers towards acquiring job-ready skills. To address this need, this project aims to develop an educational module that can be integrated into engineering courses.

The selection of a suitable site for solar power generation primarily depends on the availability of sunlight. Thus, abundant sunlight availability is the foremost criterion in selecting a site. The second criterion is the availability of surplus land since the size of the PV power plant is directly proportional to the land area. The third criterion is the proximity of the site to the load center and existing power distribution or transmission lines.

Following site selection, the subsequent step is to select PV modules. The primary considerations when selecting PV modules are efficiency, cost per watt, and durability. As PV modules generate DC power that requires conversion to AC power to integrate into the power transmission or distribution line, the selection of an appropriate number and size of inverters is crucial. This selection should be based on the AC power required to be integrated into the grid.

While the inverter converts DC power to low voltage AC power, the transmission and distribution system is designed for high and medium voltage systems. Thus, selecting an appropriate transformer size is essential to convert low voltage AC to the required transmission or distribution voltage level. The transformer size selection should be based on the AC power to be integrated and voltage ratio.

To enable the integration of maximum PV power generation into the grid, the existing utility company must conduct an interconnection and integration study. An energy yield study is conducted to estimate the total energy generation expected during the project's operation period, which is equivalent to the revenue generated by the project.

Designing and analyzing utility-scale PV solar systems require meticulous planning, coordination, and expertise in solar energy, electrical engineering, and grid integration. Properly designed and installed systems can offer sustainable, cost-effective, and dependable power solutions to communities and businesses worldwide.

The project's scope does not encompass the study of grid integration as it is the responsibility of the utility company to carry out such analysis. Moreover, site selection is not a part of this project due to the inadequacy of relevant data. However, a site located in Burlington, MA, at coordinates (42.51, -71.20), has already been chosen. The developed project could be incorporated into engineering curriculum as foundation or elective courses. This initiative would help to enhance the awareness, comprehension, and job-ready skills of engineering students, preparing them for employment in various industrial fields.

## II. ELECTRICAL SYSTEM DESIGN

The design of an electrical system for a PV model involves several critical aspects, including the selection of appropriate PV modules and inverters, the calculation of string length, and the overall system design. In addition, the system design must comply with various industry standards, such as the National Electrical Code (NEC) and the American Solar Energy Society (ASES) standards. Creating detailed design analyses and incorporating industry codes into educational models can effectively prepare students for the industry.

It is crucial for students pursuing a career in renewable engineering to understand the importance of following industry standards and regulations when designing and implementing electrical systems for PV models. Educational models that provide in-depth analysis of the various aspects of electrical system design, such as PV module and inverter selection, string length calculation, and compliance with industry codes, can equip students with the necessary knowledge and skills to develop effective and efficient electrical systems for PV models. This can help prepare them for the challenges and requirements of the industry, as well as promote safety and sustainability in the field.

### A. PV Module Selection

The selection of PV modules is a crucial step in the design process as it determines the project cost, string size, and energy yield. For this project, the Heline 144HC M10 Bifacial Module 540Wp has been chosen, which possesses the following characteristics:

TABLE I: PV Model Electrical Characteristics

| Electrical Data (STC) | |
|---|---|
| Peak Rated Power (W) | 540 |
| Maximum Power Voltage (V) | 42.32 |
| Maximum Power Current (A) | 12.77 |
| Open Circuit Voltage (V) | 50.22 |
| Short Circuit Current (A) | 13.50 |
| Module Efficiency (%) | 20.90 |

TABLE II: PV Model Temperature ratings

| Temperature Ratings | |
|---|---|
| Nominal Operating Cell Temperature (degC) | 45 |
| Temperature Coefficient of Pmax (%/degC) | -0.36 |
| Temperature Coefficeint of Voc (%/degC) | -0.28 |
| Temperature Coefficent of Isc (%/degC) | 0.034 |

### B. String Length Calculation

For utility-scale PV solar projects, the string length refers to the number of PV modules that are connected in series to form a string, without exceeding 1500 Vdc at the lowest temperature, as per NEC 2020 690.7 [4]. NEC 690.7(A)(1)-(3) provides guidelines for ensuring that the series connected DC voltage does not exceed 1500. In this project, the string length has been calculated using NEC 690.7(A)(1).

According to the ASHRAE website, the lowest temperature recorded at the selected site in the last 50 years has been -29.50°C. The open circuit voltage of the module at the lowest temperature, considering the temperature correction factor, is as follows:

$$V_{oc@T_{min}} = V_{oc@25}(1 - \frac{\beta}{100}(25 - T_{min})) \quad (1)$$

$$V_{oc@-29.50} = 50.22(1 - \frac{-0.28}{100}(25 - (-29.50)))$$

$$V_{oc@-29.50} = 57.88\,V$$

$$String\ Length = \frac{1500}{57.88} = 25.91 = 25$$

$$V_{string@-29.50} = 25 * 57.88 = 1{,}447\,V$$

Based on the calculations mentioned above, the string length is 25, and the maximum open circuit voltage of the string is 1,447 V.

### C. Inverter Selection

The selected 2 MWac capacity PV project is relatively small in size, and the Chint Power Systems 125kW (CPS SCH125KTL-DO/US-600) string inverter has been chosen to minimize the losses. The selected string inverter has the following characteristics:

TABLE III: String Inverter

| DC Input | |
|---|---|
| Max. PV Power (kW) | 185.5 |
| Max. DC Input Voltage (V) | 1500 |
| Max. Power Point Tracker Voltage Range (V) | 870-1300 |
| Number of Max. Power Point Trackers | 1 |
| AC Output | |
| Rated AC Output Power (kW) | 125 |
| Max. AC Output Power (kVA @ pf>0.95) | 132 |
| Rated Output Voltage (V) | 600 |
| Max. AC Output Current @ 600 Vac (A) | 127 |
| System | |
| Topology | Transformer less |
| CEC Efficiency (%) | 98.5 |

### D. System Design

Once the PV module and inverter are selected, and the string length is defined, the PV power plant can be designed. The designed system has been summarized in the following table:

TABLE IV: System Design

| System Information | |
|---|---|
| AC Power (MW) | 2.00 |
| DC Power (MW) | 2.59 |
| DC/AC Ratio | 1.29 |
| String (#) | 192 |
| String Power (kW) | 13.50 |
| Equipment Description | |
| Inverter Power (kW) | 125 |
| Module Power (Wp) | 540 |
| Equipment Quantity | |
| Inverter (#) | 16 |
| Module (#) | 4800 |

## III. Simulation In Software

The primary objective of this project is to incorporate the use of the System Advisor Model (SAM) into the engineering curriculum. SAM is a valuable open-source techno-economic software model developed by the National Renewable Energy Lab (NREL) [5], which is widely used by professionals in the renewable energy industry to make informed decisions. By integrating SAM into the coursework, students will gain industry-level experience in utilizing this software and be better prepared for potential employment opportunities in the renewable energy sector. This will equip them with practical skills and knowledge that are in high demand from employers in the industry.

The next step in the process is to simulate the system using appropriate software to determine the energy yield. The model's detailed PV option consists of 7 tabs that are used to define the system: a) Location and Resource, b) Module, c) Inverter, d) System Design, e) Shading and Layout, f) Losses, and g) Grid Limits.

The typical meteorological year (TMY) data has been downloaded for the project location coordinate (42.51, -71.20) in the Location and Resource tab. The Perez model was used to convert the Direct Normal Irradiance (DNI) and Diffuse Horizontal Irradiance (DHI) into front and rear Plane of Array (POA) irradiance. The selected module is bifacial, which means it can receive irradiance from the rear side as well. Therefore, the albedo value of the site location is crucial to reflect the rear side irradiance from the ground. The software will use the available albedo value in the weather file for the simulation.

The Module tab in SAM's detailed PV model option was used, and the "CEC Performance Model with User Entered Specifications" was selected. The selected module data was entered in accordance with the datasheet for the bifacial module. The transmission fraction of 0.025, bifaciality factor of 0.70, and ground clearance height of 2.10 meters were entered for this particular module.

The "Inverter Datasheet" option has been selected in the Inverter tab to input the selected inverter data. The maximum AC output power and weighted efficiency for the inverter, according to the datasheet, are 125,000 W and 98.50%, respectively. The nominal AC voltage is 600 V, the maximum DC voltage is 1500 V, the maximum DC current is 275 A, and the maximum power point tracking voltage range is 870 – 1300 V for operating parameters.

In the System Design tab, the number of inverters has been specified as 16, modules per string as 25, and strings in parallel as 192. A single-axis tracker has been chosen for tracking and orientation, assuming a flat site with zero slope angle in the north-south direction. The tilt angle has been set to 0 degrees. The Ground Coverage Ratio (GCR), which is the ratio of module width to the pitch in tracker row spacing, has been selected as 0.4, which is a typical value. The tracker angle has been set at 60 degrees, allowing it to rotate from -60 degrees to +60 degrees. Backtracking has been enabled, and the tracker control's backtracking algorithm ensures that there is no shading due to rotation of the tracker row behind its row.In the Shading and Layout tab, module orientation has been set to portrait and it is 1 module in the portrait. Number of strings in one tracker row has been assumed as 4. Therefore, 100 modules in a row have been set. Module aspect ratio is the ratio of length to width.

The Losses tab includes the following inputs: average annual soiling loss set to 2%, module mismatch loss to 1.5%, DC wiring loss to 1.5%, AC losses to 1.5%, transformer loss at load and no load to 0.5%, and transmission loss to 0.2%.

In Grid Limits tab, grid interconnection limit has been set to 2000 kWac.

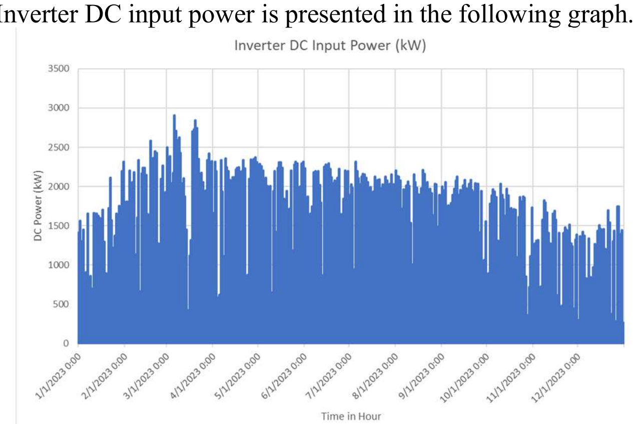
## IV. Result

The simulation and analysis have utilized TMY 2020 data, and the summary of the results is provided in the table below:

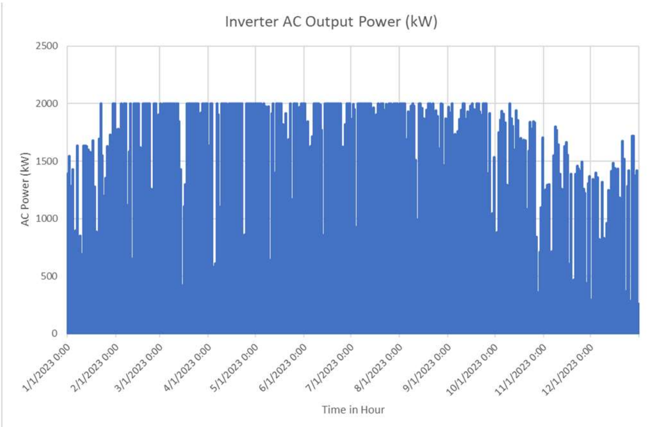
TABLE V: Results Summary

| Output Summery | |
|---|---|
| Annual AC Energy in Year 1 (MWh) | 4,387.93 |
| DC Capacity Factor in Year 1 (%) | 19.30 |
| Energy Yield in Year 1 (kWh/kW) | 1692.00 |
| Performance Ratio in Year 1 | 0.87 |

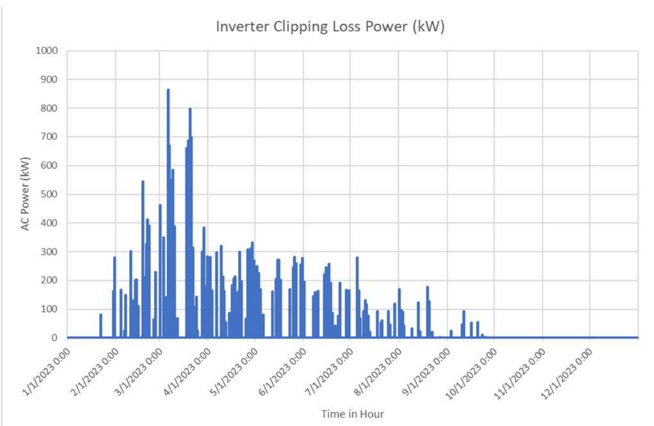
Inverter DC input power is presented in the following graph.



Inverter AC output power is presented in the following graph.




The inverter clipping loss AC power limit is presented in the following graph:




The inverter DC input energy, inverter AC output energy, and inverter clipping loss energy are presented in the following table:

TABLE V: Energy Generated

| Generated Energy | |
|---|---|
| Inverter DC Input Energy (MWh) | 4,750.59 |
| Inverter AC Output Energy (MWh) | 4,570.09 |
| Inverter Clipping Loss Energy (MWh) | 109.24 |

According to NEC 2020 690.8(A)(1)(a)(1), the maximum current of the PV source circuit is determined as 125% of the short circuit current of the PV module. Hence, the maximum current of the source circuit for this project is 13.5 x 1.25 = 16.88 A since each string will be connected to the inverter input. As per NEC 2020 690.8(A)(1)(e), the maximum current for the continuous output of the inverter is the output current limit. Therefore, the inverter's maximum output current for this project is 127 A.

According to NEC 2020 690.9(B)(1), the DC input and AC output fuse of the inverter should be sized such that the fuse rating is not less than 125% of the maximum current. Hence, the DC fuse rating must be the next highest available rating of 16.88x1.25 = 21.10 A, which is 25A, and the AC fuse rating should be the next highest available rating of 127x1.25 = 158.75 A, which is 175A.

## V. Disccussion and Conclusion

The project's rated DC power is 2,592 kW under STC conditions, but the actual DC power generation may sometimes exceed this value due to variations in irradiance. However, the installed inverter has a maximum AC output power of 2,000 kW, making it a power-limiting device. Any power that is lost due to the inverter's capacity limitation is referred to as clipping loss.

The total DC energy input to the inverter is 4,750.59 MWh, while the inverter's AC energy output is 4,570.09 MWh, resulting in a clipping energy loss of 109.24 MWh. This clipping energy loss represents 2.29% of the DC energy input. If the goal is to minimize this clipping energy loss to 2.29%, the inverter size, AC cable, and transformer will need to be upsized, increasing the overall project cost.

As federal and state renewable energy targets have increased, employers are seeking engineers with knowledge of the renewable sector. Teaching students about PV model designs would be beneficial for their engineering careers. These learning modules could be integrated into engineering courses to enhance students proficiency [6]. The engineering curriculum would need to be periodically updated to prioritize the most important information for students. As students advance in their skills, labs, lectures, and assignments would gradually allow for more creative freedom to encourage independent thinking and personal investment in projects.

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