# EPRI Project Report

Date: May 3, 2024

**Project Title**: Sizing Renewable Microgrid for Net-Zero and Resilient Electric Vehicle Charging Satiations of Texas Through 2040

**Project PI:** Dr. Tongdan Jin, Ingram School of Engineering (ISOE), Texas State University, (tj17@txstate.edu)

**Collaborator:** Dr Michelle Londa, Ingram School of Engineering, Texas State University (michelle.londa@txstate.edu).

**Senior Industrial Engineering Students:**

- Valentina Mora Casallas, Senior Student of Industrial Engineering of ISOE, graduate in Spring 2024, (valemorac@txstate.edu).
- Joy Saha, Senior Student of Industrial Engineering of ISOE, graduating in Spring 2024, (j_s1239@txstate.edu).
- Arslan Abbasi, Senior Student of Industrial Engineering of ISOE, graduating in Spring 2024, (pox11@txstate.edu).

**Project Outcomes:**

1) The project trained 3 senior undertreated students with the capability of modeling and designing EV charging stations subject to random EV arrivals and power demand. They are Valentina Mora Casallas, Joy Saha, and Arslan Abbasi.

2) The three students are capable of sizing and siting WT and PV generation systems in charging station for attaining net-zero energy performance across 7 regions of Texas. They accomplished capstone design project "*Design of Net-Zero Electric Vehicle Charging Infrastructure of Texas Through 2040*." The EPRI funded project as the industrial engineering capstone design project began from 9/2023 to 5/2024 spanning two semesters. The student team completed the project tasks, and presented their design on April 30, 2024 in the ISOE school-wide capstone design event. The capstone design event showcases all the capstone projects from industrial engineering, electrical engineering, manufacturing engineering, and civil engineering teams with over 150 attendees. See Appendix A for the team's capstone design poster of spring 2024.

3) The student team also developed a conference paper accepted by the 2024 Annual Conference of Institute of Industrial and Systems Engineers (IISE 2024 Conference). The conference will be held from May 18 to 21 in Montreal, Canada. All three students will attend the conference and present their findings in the upcoming conference. The travel

cost including registrations, hotel and airfare will be covered by the EPRI fund. See Appendix B for the accepted IISE conference paper.

4) The PI Dr. Tongdan Jin incorporated data analytics, decision-making, and machining learning algorithms in courses such as IE 4310/IE5310 Design of Experiment and IE4330/IE5310 Reliability Engineering course. Over 40+ engineering MS and MS students took these classes in fall 2023 and spring 2024. See Appendixes C and D for the course project description of IE4310 and IE4330 as example.

We are very appreciative of the EPRI support to our students' senior design and curriculum enhancement. Students were able to gain cutting-edge EV knowledge as well as networking through capstone design event and upcoming IISE conference in Montreal. This guides and motivates them to pursue careers in the emerging EV manufacturing, EV charging infrastructure, and more broadly e-mobility and transportation electrification industry.

Texas State faculty and team look forward to future potential collaborations with EPRI. We will continue to explore the interface of power engineering, renewable energy, sustainable transportation, and empower our students and new generation of working force with data science and machine learning skills.

Report Prepared by Tongdan Jin

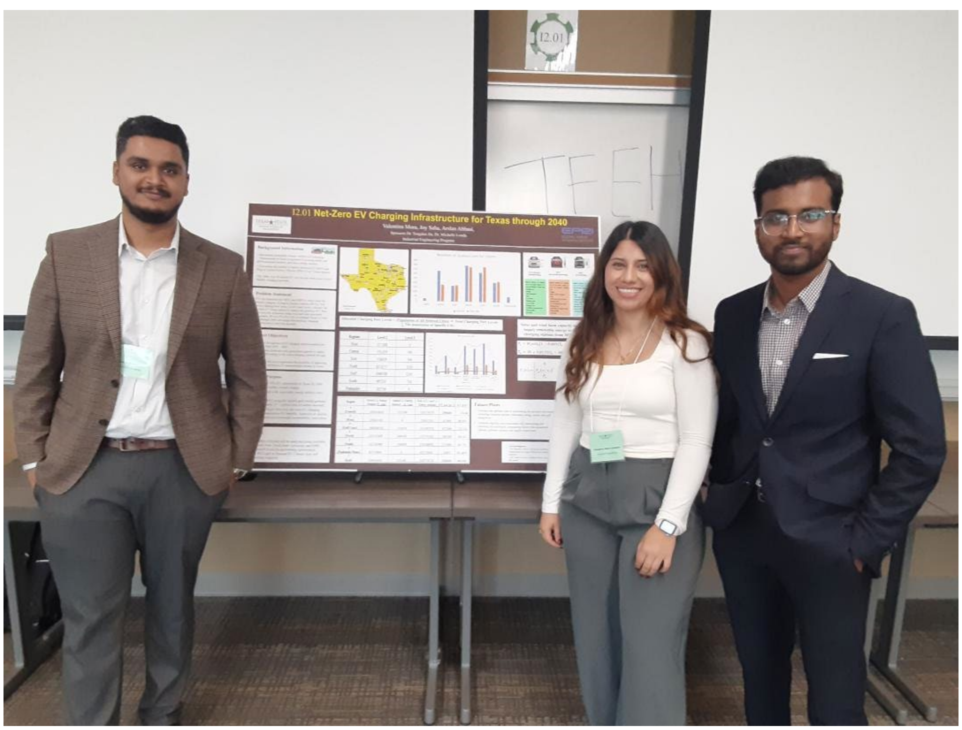
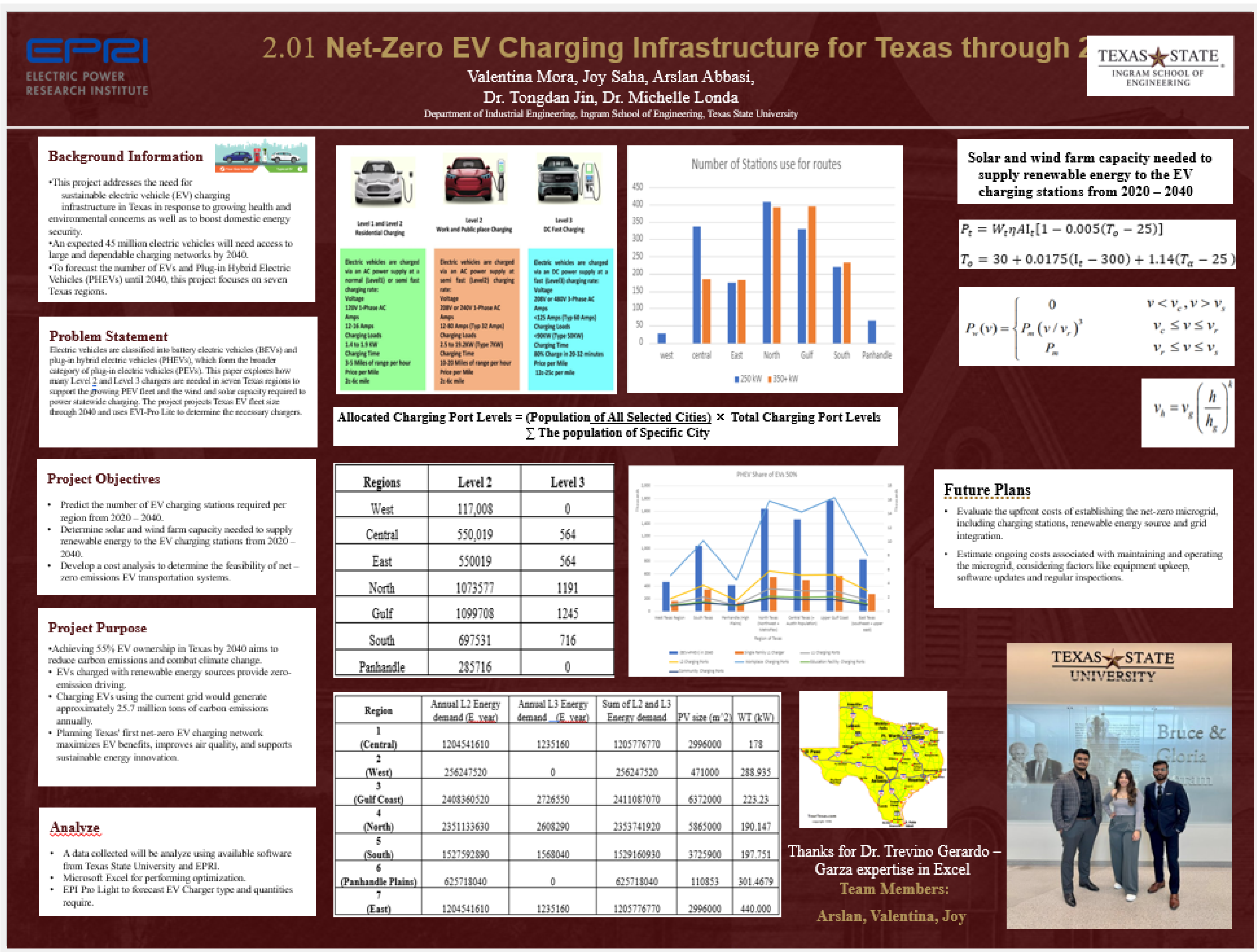



Figure 1: Arslan, Valentina, and Joy in Design Day of April 30, 2024 (Left to Right)

# Appendix A

# Capstone Design project Poster of Spring 2024



# Appendix B

# Accepted IISE 2024 Conference Paper

*Proceedings of the IISE Annual Conference & Expo 2024*
*A. Brown Greer, C. Contardo, J.-M. Frayret, eds.*

# Planning for Net-Zero Electric Vehicle Charging Infrastructure in Texas through 2040

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## Abstract

In the decade to come, it is imperative to deploy a ubiquitous charging infrastructure that ensures efficient and sustainable electrification of transportation. This research focuses on planning Texas's net-zero energy electric vehicle (EV) service network to accommodate the projected 45 million EV by 2040. The research aims to facilitate Texas' transition to a net-zero transportation paradigm. First, the number of battery-powered EV and plug-in hybrid electric vehicles (PHEV) is forecasted through 2040. Second, based on the projected fleet size, we use EVI-Pro Lite to determine the required number of Levels 1, 2 and 3 chargers. Finally, the sizing and sitting of solar and wind generation systems to power the state-wide stations is obtained. We choose 54 cities in Texas whose population exceeding 100,000 and allocate stations and chargers within cities and across highways and major intersections between adjacent cities. Two scenarios of EV-charging infrastructure deployment plans are proposed depending on charging demand, fleet composition, and home charger accessibility. Reducing emissions, minimizing charging congestion, and enhancing user experience are the design criteria when sizing and siting charging stations and renewable generation.

## Keywords
Net-zero energy, electric vehicle charging infrastructure, wind and solar generation, power resilience.

## 1. Introduction

Today about 96 percent of transportation energy used in the US is in the form of petroleum, 2.6 percent in natural gas, and less than 1 percent in biomass, electricity, or other forms of fuels. Electric transportation is a promising solution to reduce the dependency on fossil fuel energy. Additionally, vehicle-to-grid operations can play an important role in energizing critical loads in contingency, and achieving power resilience against extreme weather, such as the winter storm of 2021 in Texas. For this reason, the expansion of electric vehicle (EV) fleet and the deployment of ubiquitous charging infrastructure will provide a sustainable mobility solution against climate change.

The significant surge in EV adoption in the past decade presents a unique opportunity to reduce carbon emissions, provided the vehicle batteries are charged from renewable energy sources. However, power from wind- and solar-based generation is intermittent in addition to relatively high upfront investment cost. This study is to plan, design, and implement a net-zero statewide EV charging infrastructure in Texas, which not only meets the growing EV fleet but also integrates wind and photovoltaics (PV) generation units into the charging infrastructure. In this paper, net-zero means the annual electricity for charging the EV fleet is 100 percent offset by wind and PV generation. Renewable generation will reverse the climate change and enhance power resilience as well. Our research goals are to create a blueprint for a sustainable charging infrastructure that can support the EV growth in Texas through 2040, offering reliable, eco-friendly, and cost-effective charging services. By achieving these goals, we will contribute to Texas' sustainability efforts, reduce carbon footprint, and set a precedent for future EV charging infrastructure deployment.

## 2. Problem Description

The existing light-duty electric vehicles can be classified into two categories: pure battery electric vehicle (BEV) and plug-in hybrid electric vehicle (PHEV). PHEV differs from BEV in that it hosts an internal combustion engine alongside a rechargeable battery and electric motor. It has more flexibility than BEV in terms of requesting charging stations. Both BEV and PHEV fall into a more general category called plug-in electric vehicle (PEV). This paper aims to address two research questions as follows:

- To meet the growing charging demand in Texas, how many publicly available Level 2 and Level 3 chargers should be installed in seven regions of the state? Level 2 chargers with output power of 150-250 kW are typically installed at work or public sites. Level 3 is DC fast chargers with output power up to 350 kW.
- What will be the required WT and PV generation capacity in each region to meet the power load of the state-wide charging infrastructure?

Figure 1 shows the seven regions of Texas: Upper Gulf Coast, West Texas, South Texas, Panhandle, North Texas, Central Texas, and East Texas (tpwd.texas.gov/education). To address both questions, three research tasks will be carried out. First, the EV fleet size of Texas through 2040 is projected based on three different EV adoption rates. Second, we leverage EVI-Pro Lite tool to determine the amount of Level 2 and Level 3 to support the growing charging demand. As shown in Figure 2, EVI-Pro Lite is a simplified version of the Electric Vehicle Infrastructure Projection Tool that was developed through a collaboration between the National Renewable Energy Laboratory and the California Energy Commission. Third, sizing and siting wind and PV systems to meet the power demand based on meteorological data of each region.

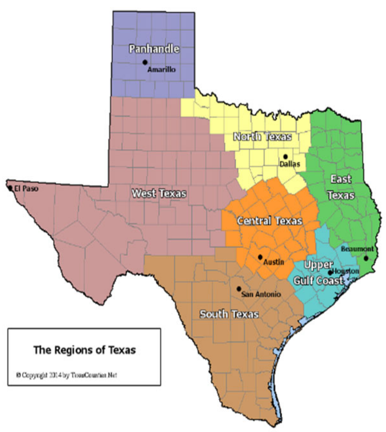


Figure 1. Texas with 7 Regions

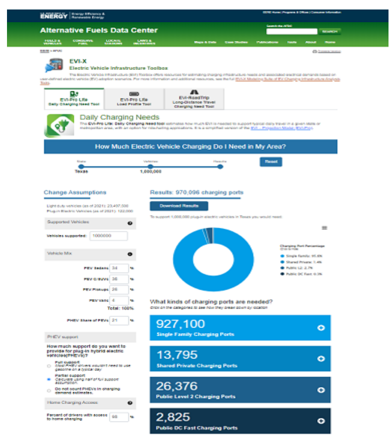


Figure 2. EVI-Pro Lite Tool Interface


Figure 3. Major Cities and Routes of Texas

## 3. Related Research

There exist systemic studies on net-zero energy systems incorporating renewable energy and transport electrification at national, regional, and community levels [1], [2]. Recent reviews on technologies, challenges, and mitigation strategies of EV charging infrastructure planning can be referred to the works in [3] and [4]. EV charging infrastructure planning models can be broadly classified into two categories: network design, and individual station establishment. Below we revisit those net-zero planning models.

Khan et al. [5] evaluates the economic and environmental performances of building integrated photovoltaics (BIPV) with EV charging system for a residential house in Canberra, Australia. Different load scenarios are simulated to optimize BIPV system size in terms of payback period and levelized energy cost. Khan et al. [6] also compare mono- and bifacial- PV modules at three different roof slopes 15°, 30° and 45° for on-site renewable energy generation and EV charging in a Sweden building. It is found that bifacial PV system with a roof angle of 45° results in the shortest payback period of 7.3 years. Guov et al. [7] present a multi-objective optimization model to predict the sizing and cost of deploying battery-powered freight rail charging stations integrating distributed energy sources. Th optimal sizing of on-site energy storage and renewable generating units are obtained by simulating the charging station behavior using realistic input data. These studies are usually carried out at the individual station level.

At the network level, Haleh Moghaddasi et al. [8] propose a net-zero community (NZC) concept for the joint coordination of grid power, onsite renewables, and EV charging service. The authors highlight NZC design guidelines, including energy efficiency, vehicle electrification, and onsite wind and solar integration to achieve the net-zero target. The energy load analysis model used by Kannan [9] has unique features, which are paramount to the transport sector and the electric grid for renewable integration. For example, the authors include higher intra-annual time resolution variability of intermittent wind and solar power, mobility-related infrastructure such as fast-charging station, trip-based charging options, and vehicle-to-grid, among others [10]. The scenario analysis was adopted for the whole energy system with the emphasis on decarbonization strategies for the e-mobility sector.

The review shows there is a lack of study that addresses the technical and environmental aspects of EV charging infrastructure planning in a stateside scope. This paper aims to investigate these aspects by focusing on wind and solar energy integration into a regional EV charging network. We compare the cost and benefit over the 16-year horizon from 2024 to 2040, which generalizes the stationary planning models in the literature.

## 4. Methodology

### 4.1 Allocating Levels 2 and 3 Chargers

Based on the projected EV fleet size through 2040, we look at crucial details like how far each vehicle model can go on a single charge, which was on average 224 km, and the average battery size of 45 kWh. Part of our study is to predict how popular EV will be in different regions of Texas, finding that about 30-50% of the fleet will be PHEV, and the remaining vehicles are BEV. We use a tool called EVI-Pro Lite to figure out what levels of EV charging stations would be needed in various places, such as homes, apartment buildings, workplaces, schools, community centers, transport stations, offices, and parks. In addition to analyzing 53 cities with populations above 50,000, our research delves into the intricate network of highways that crisscross Texas shown in Figure 3. Through meticulous examination of traffic data, historical usage patterns, and expert consultation, we focus on the key highways that facilitate intercity travel within Texas. By scrutinizing the geographical distribution of these highways and overlaying them with populous cities, we gain insights into the optimal station placement along the major thoroughfares.

In our quest to optimize the efficiency and performance of our solar energy generation, we meticulously harnessed data from Weather Underground to enhance the precision of renewable power predictions and planning. Armed with daily insights into wind patterns and temperature fluctuations across different cities, we fine-tuned our strategies to account for the dynamic interplay between environmental conditions and solar irradiance. Leveraging PV generation equation, we calibrated our PV systems to capture the maximum solar energy potential inherent in each location.

The allocation of charging ports for each city is determined by a ratio-based formula, where the population of a specific city is divided by the aggregate population of all selected cities. This quotient is then multiplied by the total levels of charging ports available. Mathematically, the formula is expressed as:

$$\text{Allocated Charging Port Levels} = \left(\frac{\text{Population of All Selected Cities}}{\sum \text{Population of Specific City}}\right) \times \text{Total Charging Port Levels} \tag{1}$$

Two assumptions are made on the above equation. First, the amount of required charging ports in a city is directly correlated or proportional to the city's population size. Second, an assumption is also made on the correlation between the required charging ports of the highway and the two adjacent cities connected by the highway. That is, the demand for charging ports along the highway is not only influenced by the population of the cities but also by the populations along the route. Table 1 summarizes the results of chargers allocated in the seven regions of Texas.

Table 1. Results of Charger Allocation in Seven Regions of Texas through 2040

| Regions | West | South | Panhandle | North | Central | Gulf | East |
|---|---|---|---|---|---|---|---|
| Level 2 Chargers | 117,008 | 697,531 | 285,716 | 1,073,577 | 550,019 | 1,099,708 | 550,019 |
| Level 3 Chargers | 0 | 716 | 0 | 1191 | 564 | 1245 | 564 |

### 4.2 Modeling Solar PV and Wind Generation

Table 2 lists the key parameters for solar PV and wind generation. Weather Underground (www.wunderground.com/) provides historical data of hourly and daily weather conditions and wind speed. By integrating data-driven insights from Weather Underground and applying established equations, we refine our estimation of $P_t$, the actual output power of the PV system, while accounting for the dynamic interplay between weather conditions and the PV operating temperature $T_o$. This comprehensive approach enhances our ability to forecast PV generation accurately. The PV generation model is given below [11]

$$P_t = W_t \eta A I_t [1 - 0.005(T_o - 25)] \tag{2}$$

with

$$T_o = 30 + 0.0175(I_t - 300) + 1.14(T_a - 25) \tag{3}$$

Table 2. Parameters of PV and Wind Generation Models

| Notation | Explanation | Notation | Explanation |
|---|---|---|---|
| $P_t$ | PV output power at time $t$ (Unit: kW) | $P_{WT}(v)$ | Output of a WT at wind speed $v$ (kW) |
| $A$ | Area of a PV system (Unit: m$^2$) | $P_m$ | Power capacity of a WT (kW) |
| $W_t$ | Weather condition coefficient at time $t$ | $v$ | wind speed (m/s) |
| $T_o$ | PV operating or skin temperature (Unit: $^oC$) | $v_c$ | Cut-in speed (m/s) |
| $T_a$ | Ambient or air temperature (Unit: $^oC$) | $v_r$ | Rated speed (m/s) |
| $I_t$ | Solar irradiance at time $t$ (unit: kW/m$^2$) | $v_s$ | Cut-off speed (m/s) |

Table 3. Hourly Climate Data of Austin, TX from Weather Underground (6am to 1pm)

| Date | Time | Temperature | Humidity | Wind Dir | Wind Speed | Weather Condition |
|---|---|---|---|---|---|---|
| 4/22/2023 | 6:53 AM | 47 °F | 93 % | CALM | 0 mph | Sunny |
| 4/22/2023 | 7:53 AM | 52 °F | 86 % | CALM | 0 mph | Mostly Cloudy |
| 4/22/2023 | 8:53 AM | 57 °F | 69 % | ENE | 6 mph | Mostly Cloudy |
| 4/22/2023 | 9:53 AM | 60 °F | 57 % | E | 8 mph | Haze |
| 4/22/2023 | 10:53 AM | 62 °F | 58 % | ENE | 7 mph | Partly Cloudy |
| 4/22/2023 | 11:53 AM | 66 °F | 50 % | E | 7 mph | Partly Cloudy |
| 4/22/2023 | 12:53 PM | 69 °F | 42 % | SE | 9 mph | Sunny |

Table 3 shows the hourly climate data of Austin, TX on 4/22/2023 retrieved from Weather Underground portal. The wind speed and weather conditions are used for WT and PV generation estimation. Weather coefficient $W_t$ varies between 0 and 1 to model the sunshine condition with "1" being the sunny and "0" for snow coverage. The purpose is to emulate the diverse range of weather states encountered at time $t$. As outlined in Table 4, it encompasses nine major states, each representing a distinct weather condition. By utilizing $W_t$ in our analysis, we capture the variability of weather patterns, enabling us to adjust PV output through Equation (2), ensuring power resilience in the EV charging infrastructure albeit the uncertain weather.

Table 4. The Value of $W_t$ under Different Weather Conditions

| State No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| Weather Condition | Mostly Sunny | Partly Cloudy | Cloudy | Mostly Cloudy | Scattered Shower | Foggy | Rain | Snow | Thunder-storm |
| $W_t$ | 1 | 0.7 | 0.5 | 0.3 | 0.1 | 0.1 | 0.1 | 0 | 0.2 |

To accurately determine the output of a wind turbine (WT) at various wind speeds, a cubic power curve model is adopted to capture the relationship between wind speed $v$ and the corresponding output power of WT. As shown in Equation (4), it delineates four distinct operational phases of WT based on different speeds, with parameters including the cut-in speed $v_c$, rated speed $v_r$, and cut-off speed $v_s$. Note that $P_m$ is the WT power capacity in kW or MW.

$$P_{WT}(v) = \begin{cases} 0, & 0 \le v < v_c,\ v > v_s \\ P_m (v / v_r)^3, & v_c \le v \le v_r \\ P_m, & v_r < v \le v_s \end{cases} \tag{4}$$

Since the wind speed from Weather Underground is measured at the ground height of $h_g$=10 meters, while the WT tower height is typically $h_t$=80 meters, we also convert the measured speed $v_g$ into the tower height speed $v_h$ using $v_h = v_g (h_h / h_g)^\kappa$ where $\kappa$ is the exponent with 0.27 to 0.32 depending on the terrain and local environment.

# 5. Results and Discussion

## 5.1 Results of EV Charger Projection

We use EVI-Pro Lite for making the projection of EV chargers across Texas, and the results are shown in Figure 4. The projection tool generates the total amount of chargers needed in each region of Texas, and also gives us the number of distinct types of chargers as well (i.e., Levels 1, 2, and 3). Also, from the number of chargers allocated for retail stores, we use those charger ports between the routes of cities. After obtaining those numbers, we create a chart, and with the help of Equation (1) we were able to predict the number of chargers needed in each city of Texas based on population size of the city.

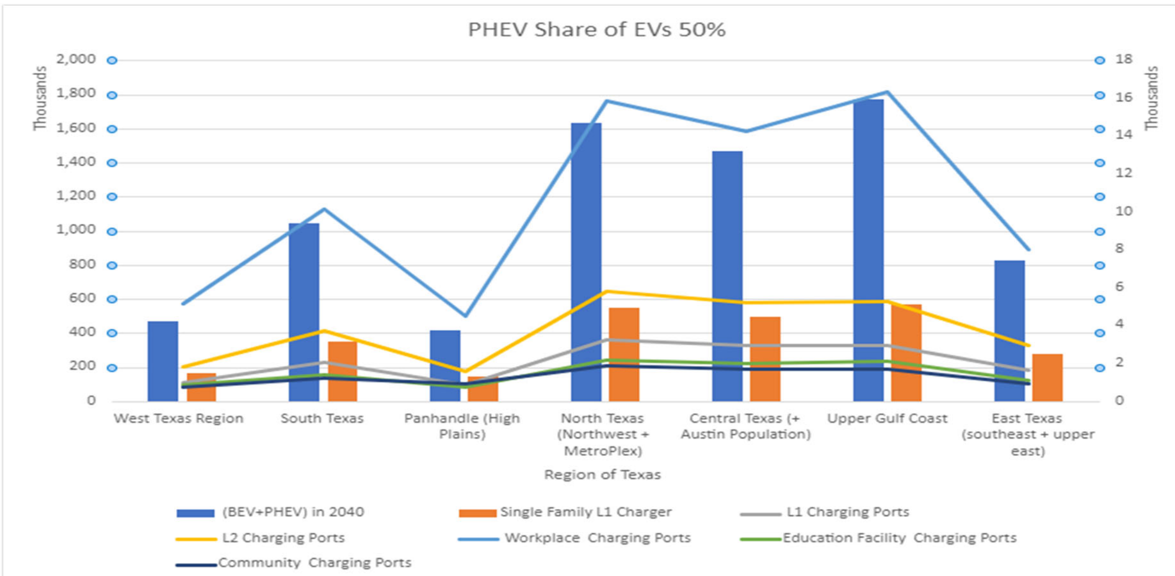


Figure 4. EV Charger Projection through 2040 with 50% of PHEV Share

## 5.2 Results of Solar PV and Wind Turbine Sizing

To determine the total yearly energy use of the EV charging infrastructure across seven regions in Texas, the annual energy consumption of Level 2 and Level 3 chargers is determined by the equations as follow:

$$\text{Level 2 Charger (or L2) Energy Consumption} = 250 \text{ kW/charger} \times 6 \text{ hours/day} \times 365 \text{ days/year} \tag{5}$$

$$\text{Level 3 Charger (or L3) Energy Consumption} = 350 \text{ kW/charger} \times 6 \text{ hours/day} \times 365 \text{ days/year} \tag{6}$$

The same logic applies to the aggregate energy estimation, where the energy consumption per charger of Equations (5) and (6) is multiplied by the number of Levels 2 and 3 chargers deployed in a region to determine its total annual energy use of the charging infrastructure.

Table 5. EV Annual Charging Demand (kWh) and Required PV and WT Sizing

| Region | .2 Energy Use (kWh) | L3 Energy Use (kWh) | L2 and L3 Energy (kWh) | PV (kW) | WT (kW) |
|---|---|---|---|---|---|
| West | 256,247,520 | 0 | 256,247,520 | 167,154 | 73,130 |
| South | 1,527,592,890 | 1,568,040 | 1,529,160,930 | 997,496 | 436,404 |
| Panhandle | 625,718,040 | 0 | 625,718,040 | 408,166 | 178,573 |
| North | 2,351,133,630 | 2,608,290 | 2,353,741,920 | 1,535,383 | 671,730 |
| Central | 1204,541,610 | 1,235,160 | 1,205,776,770 | 786,547 | 344,114 |
| Gulf Coast | 2,408,360,520 | 2,726,550 | 2,411,087,070 | 1,572,790 | 688,096 |
| East | 722,724,966 | 741,096 | 723,466,062 | 471,928 | 206,469 |

Without loss of generality, the daily climate data of 2023 are used for renewable generation analysis. After $W_t$ from 0 to 1 is assigned depending on the weather condition of that day, we use air temperature $T_a$ to estimate the PV skin temperature $\underline{T_o}$ using Equation (3). Finally, we were able to estimate PV and WT output power day-by-day using

Equations (2) and (4), respectively. By adjusting the value of $A$ and $P_m$, we can match the renewable throughput with the energy consumption of the charging infrastructure in a year. The results are summarized in Table 5.

## 6. Conclusion

This paper presents a strategic planning model to design the first-ever electric vehicle charging infrastructure in the state of Texas through 2040. The study also represents a new research direction for distributed facility planning in terms of allocating electric vehicle service equipment under uncertainty. We forecast the fleet size of BEV and PHEV in optimistic and most-likely scenarios, respectively. The forecast is based on 53 cities each having a population over 50 thousand, taking into account the variations of demographic factors. Using the projected fleet size, the number of Levels 2 and 3 chargers are estimated by running the EVI-Pro Lite. This online tool allows the planner to customize the key parameters, such as vehicle composition, charging support level, and home charger availability. After obtaining the number of chargers required for each city, we choose one typical city from each region to represent the typical wind and weather condition. Based on the daily climate condition, we determine the size of solar photovoltaics and the capacity of wind turbines such that the renewable generation can meet the total energy demand of the charging infrastructure, thus achieving net-zero energy performance. The primary computing tools and resources used include MS Excel, Matlab and EVI-Pro Lite. For future study, we would like to perform sensitivity analysis on the key model parameters, such as daily charging duration, BEV and PHEV composition, and wind and solar generation granularity. As such, it will provide in-depth or more comprehensive information to the infrastructure planners and policymakers while reducing the uncertainties over the long-term planning horizon.

## Acknowledgements

This research is supported by the Electric Power Research Institute (EPRI) under GridEd Design Project Program. The student authors express their appreciation to Dr. Gerardo Trevino for Excel expertise assistance.

## References

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# Appendix C

# IE 4310 Project Description, Spring 2024

Instructor: Dr. Tongdan Jin

Ingram School of Engineering
Texas State University

**Project Guidelines:**

1) Students should team up to work on the project. At the end of the project, each project team completes the following:
2) Submit a 10-12 pages (font 12 double space including necessary tables or charts if have) report. The report shall consist of project abstract (100-150 words), project background/motivation, methodology used, data analysis, recommended solutions, sensitivity analysis/discussion, and conclusion.
3) Use tables, charts and other graphical tools to illustrate the results.
4) Each team will make a 10-minute presentation at the end of the semester. This means your presentation package should not be more than 10 PPT slides. Each team member will have 3-4 minutes to present his/her part of the work.
5) Your project will be evaluated and graded based on: (a) quality of the report, (b) the solution and methodology, (c) the contribution of individual students, and (d) individual presentation.
6) Note: The project is open-ended, and covers a broad spectrum of knowledge in renewable and sustainable energy such as wind power, and solar photovoltaics. You can adjust the project title in your final report to reflect the actual theme of your work. But all the questions stated in the project shall be addressed appropriately.

**Basic Formulas and Facts of Electric Power and Energy System**

- Voltage: $V=I\times R$ (Ohm's Law)
- Power Demand: $P=V\times I$ (Direct current power formula)
- P=5-20 kW/home, for a typical US house
- P= 10-30 MW for a university campus, factory and data center
- 1GW=1,000 MW=1,000,000 kW=1,000,000,000 W

- Energy=Power×Time (just like Distance=Speed ×Time)
- 1 kWh allows 1 window A/C for running for 0.5-1 hour
- Battery Capacity of Nissan Leaf of the 1st generation is 24-40 kWh, and the battery capacity of a Tesla EV in a range of 60kWh to 100 kWh
- 1 TWh=1,000 GWh=1,000,000 MWh=1,000,000,000 kWh=1,000,000,000,000 Wh

# Project Title

# Sizing Solar Photovoltaic System for Green Manufacturing using Design of Experiments

## 1. Background of Solar Photovoltaics Systems

**(from https://en.wikipedia.org) Photovoltaics** (**PV**) is the conversion of sun light into electricity using semiconducting materials that exhibit the photovoltaic effect. PV panel installations may be ground-mounted, rooftop, wall mounted or floating on the sea/water surface. The mount may be fixed or use a solar tracker to follow the sun over the time. PV has become an affordable source of electrical power supply in regions with a high solar potential, with price bids as low as $0.016/kWh in 2020 (typical utility retail price is $0.05-$0.1/kWh). Including materials and installation overhead, the current PV capacity cost is $2-3/W as opposed to $5-6/W ten years ago. A home installing 2 kW PV capacity is now costing as low as $4,000 compared with $12,000 decade ago.

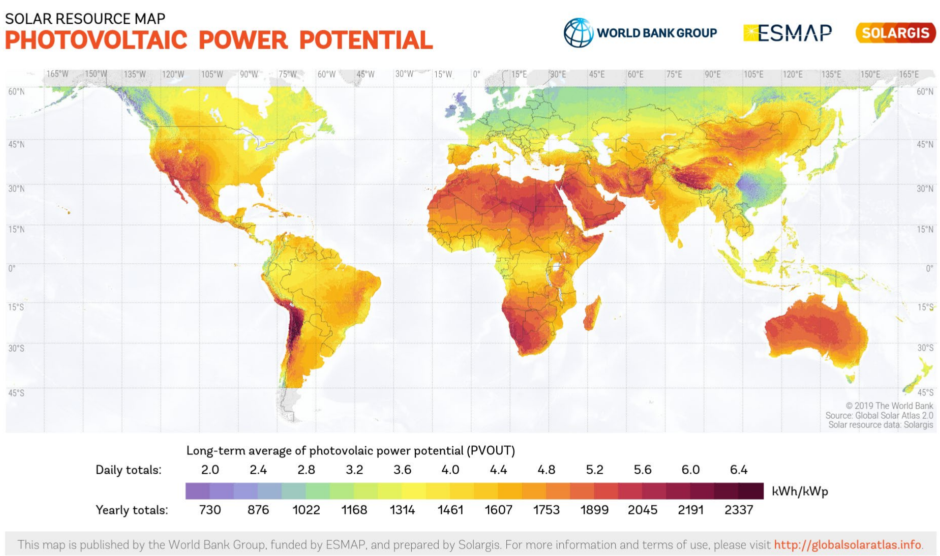



Figure 1: Solar PV Energy Potential in the Globe (note: kWp=kW in peak)

The sun provides abundant solar energy to us during the course of a year. Figure 1 shows the annual solar insolation across different regions of the world. In certain areas, the annual solar insolation reaches 2,000 kWh/m$^2$ over the year. If a home consumes 20 kWh electricity a day, the annual power demand is about 7,300 kWh. In a perfect situation that all the local solar insolation is harvested by the PV panel, only a size of 3.65 m$^2$ (or less than 40 square feet) PV panel is sufficient to power the house day-by-day. Today the PV efficiency can achieve 20-25%, and the performance degradation of power generation is typically 0.5% a year. Thus the actual PV size shall be larger than 3.65 $m^2$ with a size of 15-20 $m^2$ to achieve this amount of energy production.

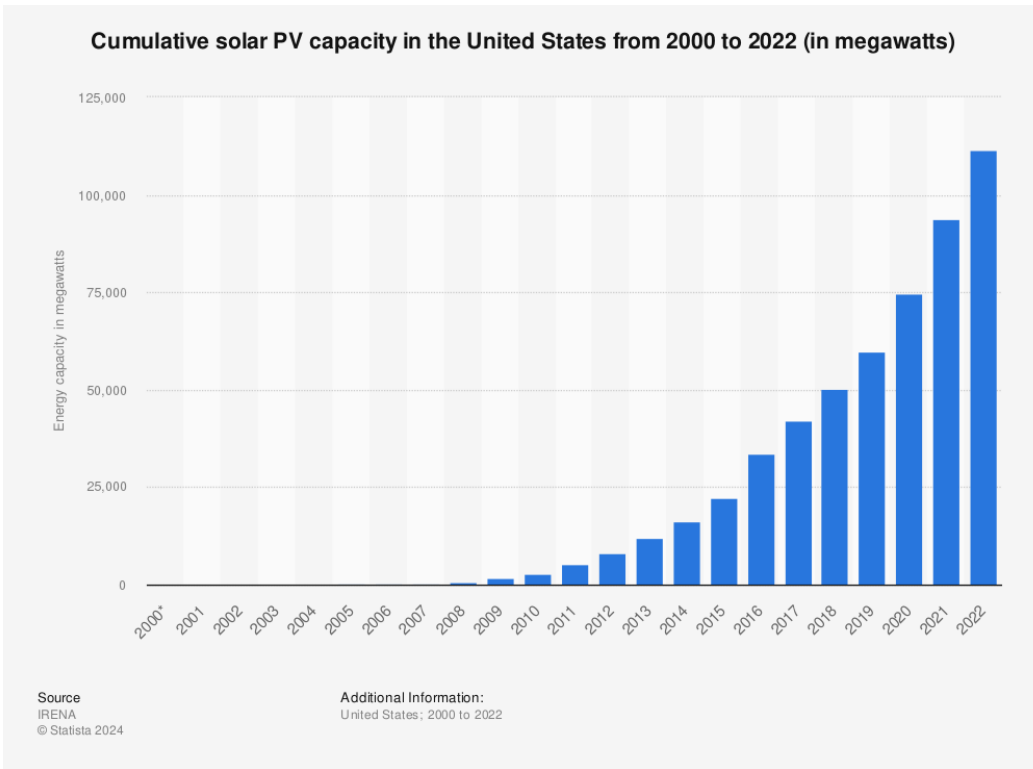



Figure 2: Solar PV Installation in the US through 2022

Driven by the cost reduction and environmental sustainability, the PV installation increases on average 15-20% per year. Figure 2 shows the installed PV capacity in the US from 2000 to 2022. As of 2022, the cumulative PV installation reaches almost 120 GW. This PV installation, if in full-scale generation, can power 3,000 campuses like Texas State University. Given 330 million US population, each person possesses 363 Watt (W) solar capacity on average through 2022.

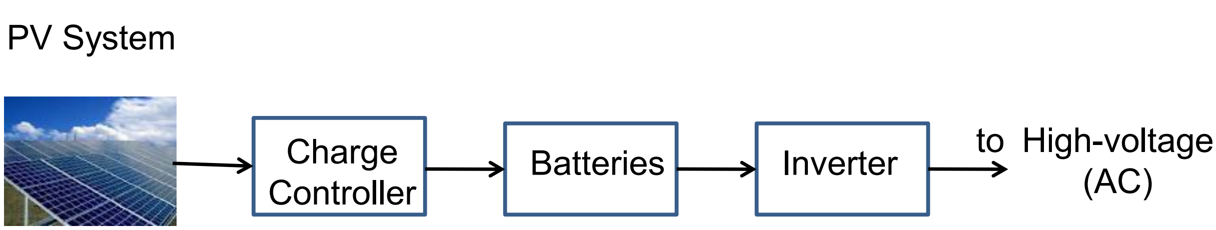



Figure 3: Decomposition of Wind Turbines

A PV system typically consists of solar panels, charging controller, battery storage, inverter, and load (e.g., home). The battery pack keeps the surplus PV energy in daytime and release it in the night when solar generation is not available. The energy stored in the battery is in direct current (DC) form, hence the purpose of the inverter is to convert the DC into alternating current (AC) power at 120 to 220 V that is used by most home appliance, such as washing machines, dish washers and air-conditioning units. However, electric vehicles (EV) and your PC/Laptop directly use DC power, instead of AC.

**2. Desert Sunlight Solar Farm in California: An Example**

Solar PV systems can be installed by connecting hundreds of thousands of individual solar panels in series and parallel to form a huge power plant. For instance, Figure 4 shows a large solar park, **Desert Sunlight Solar Farm,** located in California with capacity of 550 MW. The total farm footage exceeds 1,000 acres or twice of the San Marcos campus.

Figure 4: Operating a 550MW capacity, Desert Sunlight Solar Farm is located in the Riverside County in California and in 2015 it is tied in second place with Topaz Solar Farm.

Assuming the capacity of a single PV panel is 250 W. Then the number of panels used by this solar park is

$$n = \frac{550MW}{250W} = \frac{550\times 10^6 W}{250W} = 2{,}200{,}000 \ \text{(panels)}$$

Assume that the size of each panel is 2 m$^2$, the total areas occupied by the solar park is

$$A = (2{,}200{,}000)(2) = 4{,}400{,}000(m^2) = 1{,}087 \text{ (acres)}$$

The actual footage of the solar park is larger than 1,087 acres because sufficient spacing must be kept between rows of the PV panels to maximize the receipt of solar irradiance as well as to facilitate the maintenance services, such as surface cleaning.

## 3. Modeling PV Generation Considering Uncertain Weather

The output power of a PV system depends on multiple factors that are summarized in Table 1. Unless specified, the unit of all angles is radian (rad).

Table 1: Key Parameters in PV Generation

| No. | Factor | Symbol | Explanation |
|---|---|---|---|
| 1 | weather coefficient | $W_t$ | between 0 and 1 |
| 2 | PV size (m$^2$) | $A$ | PV system area |
| 3 | PV efficiency | $\eta$ | 15-25% for commercial PV |
| 4 | calendar date | $d$ | $d \in \{1, 2, \ldots, 365\}$ |
| 5 | solar hour (rad) | $\omega$ | related to the local hour |
| 6 | PV skin temperature (°C) | $T_o$ | operating temperature of the panel |
| 7 | latitude of PV (rad) | $\phi$ | depends on location |
| 8 | PV azimuth angle (rad) | $\alpha$ | if facing the south, $\alpha$=0 |
| 9 | PV tilt angle (rad) | $\beta$ | between PV and the ground |
| 10 | Solar zenith angle (rad) | $\varphi$ | between the zenith and the Sun's ray |
| 11 | solar incident angle (rad) | $\theta$ | Between the norm to PV and the Sun's ray |
| 12 | local hours | $t$ | $t$=1, 2, …, 24 |
| 12 | ambient temperature | $T_a$ | The temperature of the air |

We present a three-step procedure to estimate the output power of a PV system based on the study of Cai et al. (2010). The following derivations are made on the assumption that PV is installed in the northern hemisphere. In the southern hemisphere, simply set $\alpha=\pi$ and change latitude $\phi$ into a native value (for example, the latitude of Wellington, New Zealand is 41.29 degree in southern hemisphere, so $\phi$=-0.72 rad). These steps are summarized as follows

**Step 1:** For PV facing the south, the sunrise and sunset times (unit is rad not degree) in day $d \in \{1, 2, \ldots, 365\}$ are given by

$$\cos(-\omega_{rise}) = \cos(\omega_{set}) = -\tan(\phi - \beta)\tan\delta\,, \tag{A5}$$

with

$$\delta = 0.40928\sin\left(\frac{2\pi(d+284)}{365}\right), \qquad \text{for } d \in \{1, 2, \ldots, 365\} \tag{A6}$$

where, $\omega_{rise}$ and $\omega_{set}$ are, respectively, the sunrise and the sunset angles in day $d$ perceived from the PV panel, and $\delta$ is the declination angle. PV has no power output before sunrise, and after sunset.

**Step 2:** Estimating the solar irradiance incident on the PV surface, denoted as $I_t$, at local hour $t$ in date $d$ under clear sky condition,

$$I_t = 1370\left(0.7^{(\cos\varphi)^{-0.678}}\right)\left(1+0.034\cos\left(\frac{2\pi(d-4)}{365}\right)\right)\left(\cos\theta+0.1\left(1-\frac{\beta}{\pi}\right)\right), \qquad \text{(A7)}$$

where

$$\cos\varphi = \cos\delta\cos\phi\cos\omega + \sin\delta\sin\phi, \qquad \text{(A8)}$$

$$\begin{aligned}\cos\theta &= \sin\delta\sin\phi\cos\beta - \sin\delta\cos\phi\sin\beta\cos\alpha + \cos\delta\cos\phi\cos\beta\cos\omega \\ &\quad + \cos\delta\sin\phi\sin\beta\cos\omega\cos\alpha + \cos\delta\sin\beta\sin\omega\sin\alpha\end{aligned} \qquad \text{(A9)}$$

Here $I_t$ is the solar irradiance (W/m$^2$) received by the PV at hour $t$ of day $d$. The solar zenith angle $\varphi$ is estimated by Equation (A8). The solar hour angle $\omega$ is determined by local hour $t$. Starting from $\omega$=-$\pi$/2 at 6am, and it increases 15 degrees (or 0.1617 rad) every hour until reaching $\omega$=$\pi$/2 at 6pm. To maximize the energy yield, the PV panel faces the South and its tilt angle shall be equal to the local latitude, namely $\alpha$=0 and $\beta$=$\phi$, then equation (A9) can be simplified as

$$\cos\theta = \cos\delta\cos\omega \qquad \text{(A10)}$$

For example, the latitude of Austin, TX is $\phi$=30.267 degrees or $\phi$=0.528 rad, then the PV tilt angle should be $\beta$=0.528 rad as well. Such setting in general can maximize the overall intake of solar irradiance during the entire year.

**Step 3:** Now the actual output of a PV system considering the uncertain weather can be estimated as

$$P_t = W_t\eta A I_t\left[1-0.005(T_o-25)\right], \qquad \text{(A11)}$$

where

$$T_0 = 30 + 0.0175(I_t-300) + 1.14(T_a-25) \qquad \text{(A12)}$$

where $P_t$ is the actual output power of the PV system (unit: Watt) at hour $t$ of day $d$. Note that $T_o$ is the PV operating temperature or known as skin temperature. Equation (A12) is due to Lasnier (1990). $T_a$ is the ambient or air temperature, and $T_o$>$T_a$ because power generation creates thermal heats increasing the skin of PV panel temperature (*Reference: Lasnier F. (1990), Photovoltaic engineering handbook, Springer Publisher*). For example, the ambient temperature is 20°C, the temperature of the PV panel could reach 40 or 50°C because of the power generation. If PV has no power output, its skin temperature is the same as the ambient temperature.

Note that $W_t$ is a weather coefficient that varies from 0 and 1 to mimic the nine major states of the weather condition shows in Table 2. Note that SC=scatted cloud, PC=partly cloud, and MC=mostly cloudy.

Table 2: Weather Condition Coefficients $W_t$ under Different Weather States

| No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|

| State | Clear Sky | SC | PC | MC | Overcast | Rain | Fog | Storm | Snow |
|---|---|---|---|---|---|---|---|---|---|
| $W_t$ | 1 | 0.7 | 0.5 | 0.3 | 0.2 | 0.1 | 0.1 | 0.1 | 0 |

Below we examine how the PV skip temperature influences the power out. By referring to Equation (A11), we set $A$=1 m$^2$, $I_t$=1000 W/m$^2$ (around noon time), and η=25%. We let the temperature change from 0ºC to 100ºC. The results are plotted in Figure 4B. Note that $W_t$=1 represents the sunny weather and $W_t$=0.5 represents the partly cloud weather. For instance, at $T_o$=25, the PV produces 250 W power under sunny condition. If $T_o$=0, the power increases to 280 W, however if $T_o$=100, the power drops and becomes150W. Similar interpretation can be applied to the partly cloud condition.

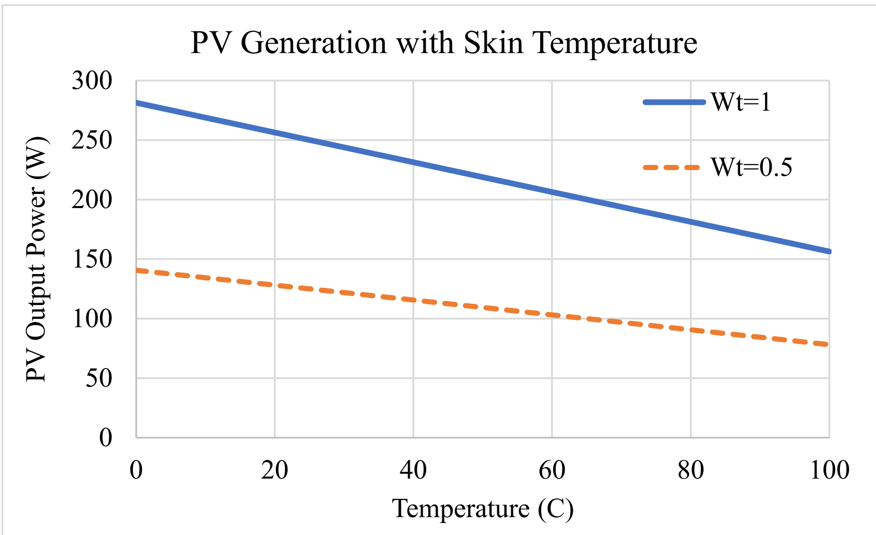



Figure 4B: PV Output Power under Different Skin Temperatures

**The capacity factor** of a PV system, denoted as $\lambda_{PV}$, represents the ratio of actual PV output versus the PV capacity (or the maximum/possible power output). The value is 0≤ $\lambda_{PV}$ ≤1. In the night, there is no sunshine, the PV output is zero, hence $\lambda_{PV}$ =0. At noon time of a sunny day, the PV can generate the maximum power, hence $\lambda_{PV}$ =1. The capacity factor of a PV system can be estimated by

$$\lambda_{PV} = \frac{P_t}{P_{\max}} \tag{A13}$$

Where $P_{\max}$ is the capacity of a PV system, and $P_t$ is the actual power generation at hour $t$ of day $d$ given in Equation (A11).

**For example**, At 10am in the morning of a day, the PV produces 90 W under the direct sunshine with no cloud. If $P_{\max}$ =100 W, then $\lambda_{PV}$ =90/100=0.9. However, if the weather at 10am is mostly cloudy, then the actual generation $P_t$=0.3×90=27 W where $W_t$=0.3 (see Table 2). In that case, $\lambda_{PV}$ =27/100=0.27, and the capacity factor is much smaller than the one under sunny weather given the same PV panel.

The value of $\lambda_{PV}$ varies in a day. During the noon time in a clear sky day, $\lambda_{PV}$ reach the highest and close to one. When sun rises or sets down, $\lambda_{PV}$ becomes 0. See the chart below for example.

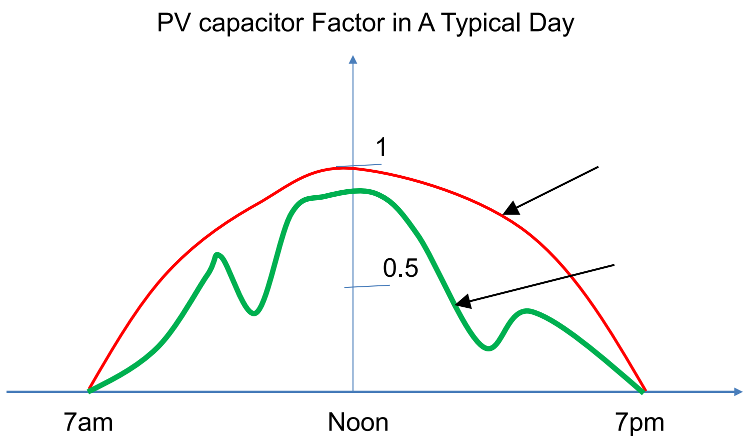



Figure 5: Capacity factor varies with the hour during a clear sky day and cloudy weather

Let $P_{\max}$ be the PV system capacity in unit MW. The PV energy generation model is given as follows

$$E = \lambda_{PV} \tau P_{\max} \tag{A14}$$

Where $E$ is the energy produced by PV during time period $\tau$, and $\lambda_{PV}$ is the capacity factor. If the unit for power is MW, the unit of $\tau$ is hour, then the unit of $E$ is MWh.

**4. Solar Irradiance in Winter and Summer Seasons of Austin and NYC**

Given a sunny day, solar irradiance changes with the clock time. Here is the data for the hourly solar irradiance in Austin, TX and New York City (NYC), NY. For each city, two data sets are provided: one represents winter season, and other represents summer season. For instance, in summer of Austin with no cloud, the solar power incident on the PV is 1033W per square meter (m$^2$) at noon time. Without loss of generality, winter season is defined from January to March, and from October to December, and Summer is defined from April to September.

Table 3: Solar Irradiance in Winter and Summer Seasons of Austin and NYC

| Season Hour | Austin Winter $W/m^2$ | Austin Summer $W/m^2$ | NYC Winter $W/m^2$ | NYC Summer $W/m^2$ |
|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 |
| 2 | 0 | 0 | 0 | 0 |
| 3 | 0 | 0 | 0 | 0 |
| 4 | 0 | 0 | 0 | 0 |
| 5 | 0 | 0 | 0 | 0 |
| 6 | 0 | 0 | 0 | 0 |
| 7 | 75 | 200 | 60 | 170 |
| 8 | 346 | 454 | 277 | 386 |
| 9 | 582 | 688 | 465 | 585 |
| 10 | 764 | 874 | 612 | 743 |
| 11 | 880 | 992 | 704 | 844 |
| 12 | 920 | 1033 | 736 | 878 |
| 13 | 880 | 992 | 704 | 844 |
| 14 | 764 | 874 | 612 | 743 |
| 15 | 582 | 688 | 465 | 585 |
| 16 | 346 | 454 | 277 | 386 |
| 17 | 75 | 200 | 60 | 170 |
| 18 | 0 | 0 | 0 | 0 |
| 19 | 0 | 0 | 0 | 0 |
| 20 | 0 | 0 | 0 | 0 |
| 21 | 0 | 0 | 0 | 0 |
| 22 | 0 | 0 | 0 | 0 |
| 23 | 0 | 0 | 0 | 0 |
| 24 | 0 | 0 | 0 | 0 |

**Note:**
Winter Data is applicable to Oct, Nov, Dec, Jan, Feb and March.
Summer Data is applicable to April, May, June, July, August, September

## 5. Wind Power Generation Model

A wind turbine (WT) operates in four phases based on the wind speeds. Let $P_w(v)$ be the output of a WT unit at wind speed $v$. Then according to Thiringer and Linders (1993), the cubic power curve is given as

$$P_w(v) = \begin{cases} 0 & v < v_c, v > v_s \\ P_m\left(v / v_r\right)^3 & v_c \le v \le v_r \\ P_m & v_r \le v \le v_s \end{cases} \tag{5.1}$$

Where $v_c$, $v_r$, and $v_s$ are the cut-in speed, the rated speed and, the cut-off speed, respectively. $P_m$ is the power capacity of the wind turbine in Megawatt (MW) or Kilowatt (kW) depending on the size of the wind turbine. Figure 6 shows the typical operational characteristics of a WT based on various wind speeds. From cut-in speeds, $v_c$, between 2 m/s to 12 m/s, the power output increases. At rated speed, $v_r$ =12 m/s, the power output reaches the maximum and remain stable until 25 m/s. WT is shut down for protection if the wind speed exceeds $v_s$=25 m/s.

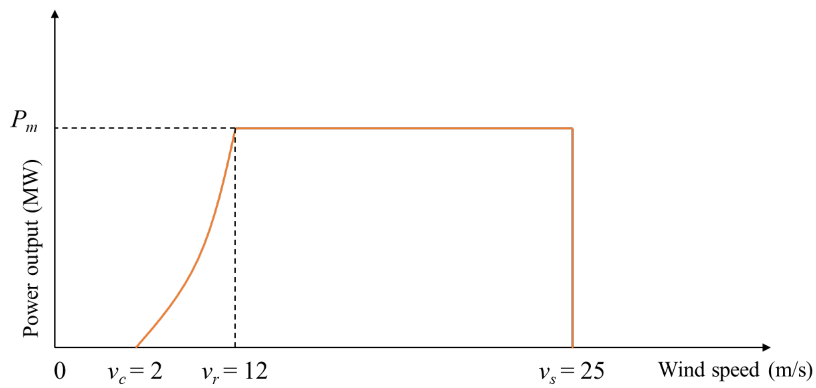



Figure 6: Wind turbine power curve

An Automated Surface Observing Systems (ASOS) usually is installed 8-10 meters above the ground to track the wind speed in airport. Assume $h_g$ is the ground-level (i.e., 8-10 meters) to measure wind speed $v_g$ (m/s). Heier (2005) estimates the wind speed at turbine tower height $h$ as follow,

$$v_h = v_g \left( \frac{h}{h_g} \right)^k \quad ; \qquad \text{for } h \ge h_g \tag{5.2}$$

Where '$k$' is the Hellman exponent whose value depends on the terrain and geographical location. A value of 0.27 to 0.34 is assumed for $k$ in populated areas (Blackadar and Tennekes, 1968; Heier, 2005).

**For example,** the wind turbine tower height is $h$=100 meters, the wind speed measured on the ground at height $h_g$=10 meter is $v_g$=3 m/s. If we choose $k$=0.27, then the actual wind speed at the height of the turbine tower is

$$v_h = v_g \left( \frac{h}{h_g} \right)^k = 3 \times \left( \frac{100}{10} \right)^{0.27} = 5.59 \,\text{m/s} \tag{5.2b}$$

Using these parameters, the WT capacity factor can be calculated. The capacity factor of a WT is the actual output over a given period of time to the maximum possible output over the same period of time and can be expressed as,

$$\lambda_w = \frac{P_w(v)}{P_\text{m}} \tag{5.3}$$

Where $P_m$ is the rated WT power capacity. The capacity factor $\lambda_w$ is in the range [0, 1]. Note that wind speed usually follows the Weibull distribution Justus et al. (1978), Seguro and Lambert (2000), Dorvlo (2002), Yeh and Wang (2008). The probability distribution function $f_w(v)$ and the cumulative distribution function $F_w(v)$ is as follows.

PDF $$f_w(v) = \frac{k}{c}\left( \frac{v}{c} \right)^{k-1} e^{-\left( \frac{v}{c} \right)^k} \quad ; \qquad \text{for } v \ge 0 \tag{5.4}$$

CDF: $$F_w(v) = e^{-\left( \frac{v}{c} \right)^k} \quad ; \qquad \text{for } v \ge 0 \tag{5.5}$$

Where $c$ and $k$ are Weibull scale and shape parameters, respectively. The unit of $c$ is m/s and no unit for $k$.

## 6. Project Scope

Achieving low-carbon manufacturing operations is a primary goal of Industry 4.0 for the sake of environmental sustainability. Figure 7 show shows the traditional power is supplied to a factory, and Figure 8 shows the next generation of industrial facilities (including factory and warehouse) powered by wind, solar and distributed energy storage in conjunction with main grid to achieve eco-friendly operations.

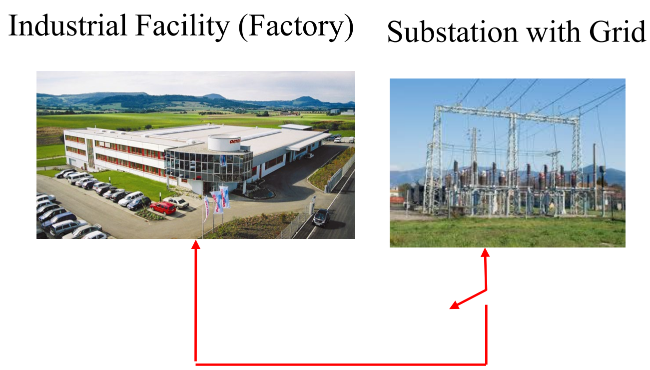



Figure 7: Traditional Power Supply to Industrial Facility

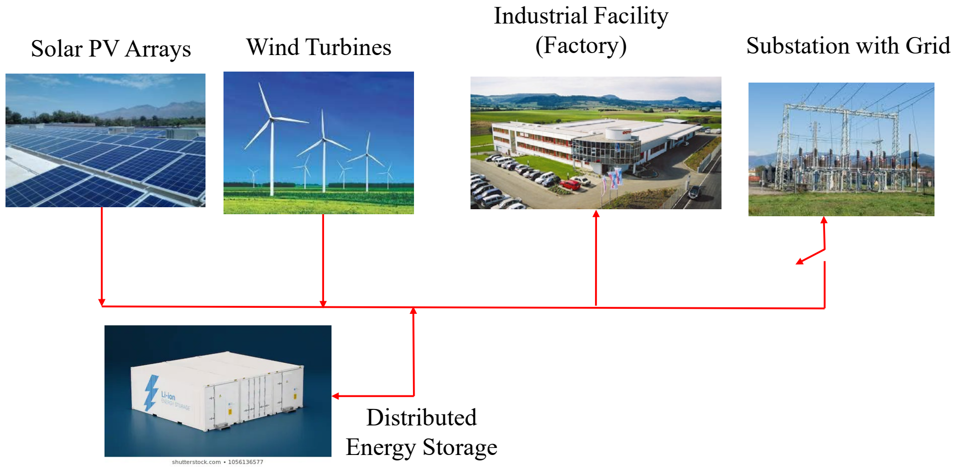



Figure 8: Power Supply to Industrial Facility using Grid-tied Microgrid

This project is centered around PV and/or Wind generation and installation. Figure 9 graphically shows the interactions between various factors and the response variables for the installation and generation of the renewable power system.

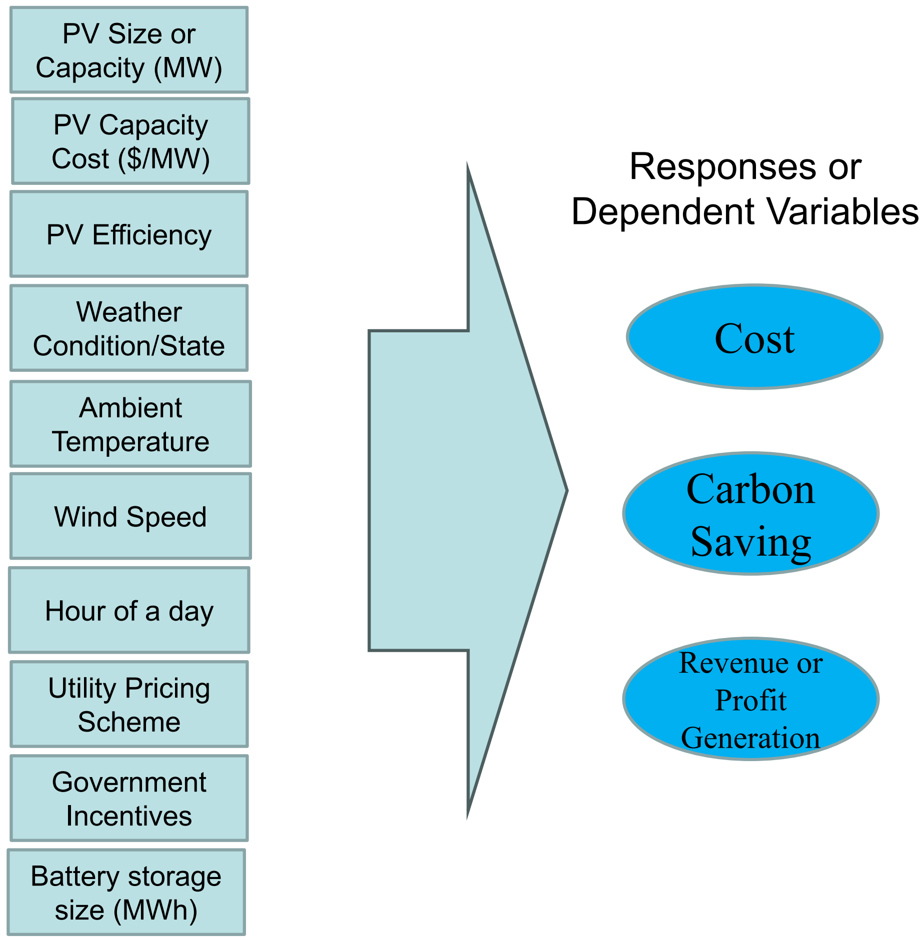



Figure 9: Factors and Responses of PV System Installation and Operations

**Factor 1: The Size of PV system**
PV size is an influential factor because a larger PV system always produces more power and energy. The size of PV called capacity is measured by MW or kW.

**Factor 2: PV Capacity Cost**
The cost of installation cost of PV continues to decline in the past 10 years. The total cost of installing 1-W PV is now between $2-3 as opposed to $5-6 per Watt ten years ago. It is anticipated that the cost will continue to drop by 5-10% per year on average.

**Factor 3: PV Efficiency**
Among all the solar radiation received by the PV surface, only certain amounts of solar energy are converted into electric power. The current commercial PV efficiency varies between 20% and 25%. The efficacy keeps increasing driven by the technological advancement, and in the lab setting, we are able to achieve 45% conversion efficiency using multiple P-N junctions in PV cells.

**Factor 4: Weather Condition**

This is perhaps one of the most significant factors influencing the PV generation. See equation (A11) as well as the solar irradiance data in Table 3 in the clear sky condition. The weather conditions change hourly, daily, and seasonally.

**Factor 5: Ambient Temperature**
Ambient temperature has the direct impact on the PV skin temperature shown in Equations A12. In general, a low PV operating temperature yields more power output of a panel.

**Factor 6: Wind Speed**
Wind speed will have an indirect influence on PV generation. For instance, a larger wind speed can quickly cool down PV cells, resulting in a lower PV operating temperature, hence increasing the PV power output (see Equations A11 and A12).

**Factor 7: Hour of a Day.**
Since the solar radiation incident on the PV surface changes from hour to hour. The irradiance is lowest in sunrise and sunset hours, and the PV receives the strongest irradiance during the noon time in a clear sky condition. Hence the hour of a day affects the PV generation (also see Table 3).

**Factor 8: Utility Pricing Scheme**
To stimulate the PV adoption, various pricing programs have been proposed by utility companies, such as net metering, time-of-use rate, critical peak price, real-time price, and feed-in-tariff (FIT), among others. The idea behind these schemes is to offer a favorable payment scheme to the PV owner if surplus renewable energy is sold or fed to the main grid.

**Factor 9: Government Incentives**
To stimulate the PV adoption, various incentives programs are provided by the governments around the world, such as tax rebate, carbon credits, and equipment subsidies, among others.

**Factor 10: The Battery Capacity/Size**
The battery size or capacity is an influential factor because a larger battery system can store more energy. The size of battery is measured by MWh. For instance, a 100 MWh battery can provide 1 MW power for 100 hours, or it can provide 2 MW for 50 hours, or provide 4 MW power for 25 hours. The discharging duration depends on the discharging power for a fixed battery size.

## 7. Project Questions

The project tasks are articulated below, and you shall solve/address each problem using the knowledge learned from the DOE class along with other courses if needed.

### 7.1 Characterizing the Distribution of Wind Speed
Three-year data of Austin for 2014 to 2016 are provided, but you can choose any year data to analyze (only need to choose one year).

**Question 1**: What is the mean wind speed, the standard deviation of wind speed in daily of the year, weekly of the year, monthly of the year?

**Question 2**: Use relevant software like Minitab/Matlab/SPSS to fit the wind speed data, and examine whether the hourly wind speed fits to specific distribution function, such as normal, log-normal, exponential, and Weibull distribution? What is P-value of the best fit of the distribution?

Since the hourly data is huge with 8760 records, it is suggested you break them into 12 months, and you preform the hourly data fitting month by month.

**Question 3**: Perform the hypothesis testing, and examine whether the hourly, weekly, monthly mean wind speeds are significant different between two adjacent months? Also perform the hypothesis testing to examine whether the variances of the wind speed differ between two adjacent months.

Note: you can randomly choose two adjacent months, for example June and July or March and April. You do not need to consider all pairs of adjacent months, just one pair from the 12 months.

### 7.2 Estimating WT and PV Power Generation

**Question 4**: Based on the hourly wind speed of Autin, estimate the hourly power output of a wind turbine installed in Austin. We assume the turbine height is 80 meters, and the WT capacity is $P_m$=1 MW. Based on the hourly power generation, also compute the total energy generated by this WT in a year. How many homes can be powered using this WT if each home consumes 7,300 kWh/year. To solve this problem, you need to use Equations (5.1) and (5.2).

**Question 5**: Based on the hourly weather condition of Austin, estimate the hourly power output of a PV system stalled in Austin. We assume the PV system size is $A$=1,000 m$^2$. All panels face the south, and the tilt angle equals the latitude of Austin. In addition, the PV efficiency is $\eta$=25%. Based on the hourly power generation, also estimate the total energy produced by this PV system in the year you have chosen. Use the hourly solar irradiance data of Austin in Table 3 to perform the computation and analysis. To solve this problem, you need to use Equations (A11) and (A12).

### 7.3 Regression Models of Wind Speed Forecasting

Forecasting the wind speed is of importance as the prediction data allow us to estimate the future wind power generation if wind turbines are installed. Wind speed also allows us to estimate the PV operating temperature. In this section, your task is to use a regression model to forecast the hourly wind speed of Austin.

**Question 6:** Forecasting the wind speed on an hourly basis, forecasting the daily average wind speed, forecasting the monthly average wind speed for the year you have chosen. You can choose any year data from 2014 to 2016 for solving this problem.

### 7.4 Using DOC to Minimize the Cost of a PV system

In this section, we deign a PV system to power a manufacturing plant. Figure 10 shows a production plant is energized by PV and energy storage units. During the daytime, PV produces power for the plant and excess energy is stored in a local battery energy system. In the night, the battery discharges the energy to power the factory or plant.

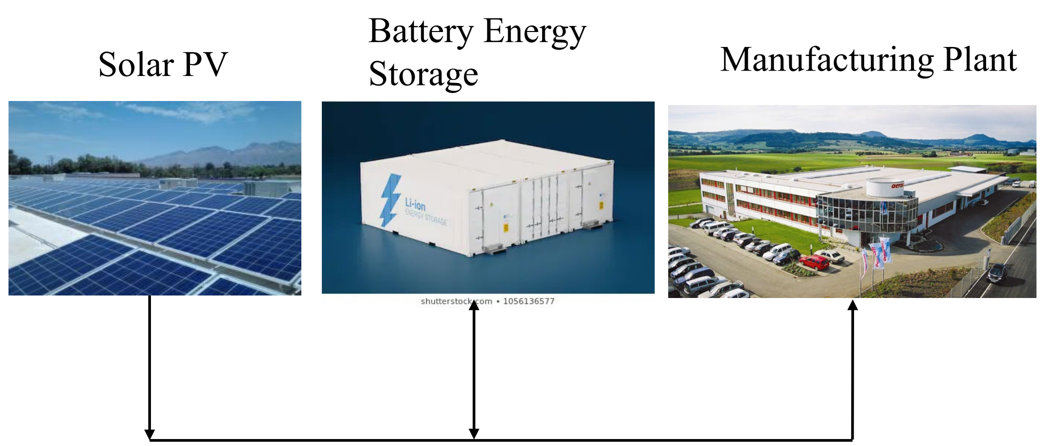



Figure 10: A manufacturing plant is powered by PV and battery energy storage system

Assuming the PV system size (i.e., area) is fixed with $A$=1200 $m^2$, three factors are taken into account in performing the DOE of the PV generation output: the weather condition, the tilt angle of the PV panels, and the months of the year.

For the weather condition, the experiments are conducted in sunny, partly cloudy, and overcast conditions.

For the tilt angles, the PV is oriented at 25 degrees and 40 degrees, respectively.

For the months of the year, the experiments are conducted in Jan, April, July and October, respectively.

The results of the experiments are summarized in Table 4 below.

Table 4: The Results of Experiments for the PV System Generation (Unit: kW)

| **Tilt Angle (degree)** | **Month** | **Jan** | **April** | **July** | **Oct** |
|---|---|---|---|---|---|
| 25 | Sunny | 121 | 141 | 157 | 135 |

| | | | | | |
|---|---|---|---|---|---|
| 25 | Sunny | 124 | 138 | 163 | 132 |
| 25 | Sunny | 120 | 143 | 162 | 140 |
| 25 | Sunny | 120 | 139 | 157 | 132 |
| 25 | Sunny | 124 | 140 | 158 | 141 |
| 25 | Partly Cloudy | 90 | 101 | 113 | 93 |
| 25 | Partly Cloudy | 83 | 101 | 106 | 91 |
| 25 | Partly Cloudy | 83 | 106 | 110 | 100 |
| 25 | Partly Cloudy | 87 | 103 | 114 | 96 |
| 25 | Partly Cloudy | 85 | 95 | 105 | 103 |
| 25 | Overcast | 45 | 41 | 53 | 52 |
| 25 | Overcast | 40 | 41 | 56 | 48 |
| 25 | Overcast | 41 | 44 | 55 | 47 |
| 25 | Overcast | 42 | 52 | 55 | 48 |
| 25 | Overcast | 40 | 43 | 52 | 46 |
| 40 | Sunny | 120 | 136 | 156 | 142 |
| 40 | Sunny | 124 | 144 | 151 | 137 |
| 40 | Sunny | 123 | 145 | 156 | 134 |
| 40 | Sunny | 126 | 143 | 158 | 133 |
| 40 | Sunny | 120 | 145 | 156 | 135 |
| 40 | Partly Cloudy | 91 | 101 | 119 | 102 |
| 40 | Partly Cloudy | 83 | 101 | 108 | 93 |
| 40 | Partly Cloudy | 82 | 98 | 118 | 95 |
| 40 | Partly Cloudy | 90 | 104 | 107 | 94 |
| 40 | Partly Cloudy | 86 | 107 | 110 | 98 |
| 40 | Overcast | 36 | 46 | 48 | 50 |
| 40 | Overcast | 44 | 51 | 51 | 42 |
| 40 | Overcast | 40 | 42 | 48 | 40 |
| 40 | Overcast | 45 | 44 | 47 | 47 |
| 40 | Overcast | 35 | 49 | 56 | 46 |

**Question 7:** Perform ANOVA and determine which factors are significant, which is (are) not? Also generate the response surface model. This model contains the significant factors and/or their interaction terms. The response variable is the output power of the PV system.

**7.5 Lifecycle Cost Analysis**

**Question 8**: Based on the outcome of Question 7, in this section you are going to perform lifecycle cost analysis of the PV system (No battery). When you perform such analysis, you may need the knowledge of Engineering Economics learned from ENGR 3315. The PV system lifecycle cost comprises of

1) Equipment Installation Cost

2) Annual operating Cost
3) Maintenance and Repair Cost
4) Decommission or Disposal Cost
5) Assuming the PV system lifetime is 20 years
6) The discount rate or interest rate for PV and battery is 5% compound annually.\
7) If revenue of selling 1 kWh is $0.15/kWh.

## 8. Project Schedule and Deliverables

Table 5: Project Timeline and Deliverables (subject to minor adjustments)

| Deadline | Action and Deliverables |
|---|---|
| From now to 2/20 | Form the project team |
| From 2/20 to 3/7 | Complete questions 1-4 |
| 3/19 Tuesday class | Present the preliminary results of questions you have done as of that day using PPT slide. Each team has 10 minutes to talk. |
| From 3/19 to 4/25 | Complete the remaining questions<br>Writing report and preparing power point slides |
| On 4/30 (date to be finalized) | Final report due and oral presentation |

## 9. References


1. Fu, R., Feldman, D., Margolis, R., Woodhouse, M., Ardani, K. (2018) The U.S. Solar Photovoltaic System Cost Benchmark: Q1 2017. National Renewable Energy Laboratory Report. Available at https://www.nrel.gov/docs/fy17osti/68925.pdf, (accessed on September 4, 2019).
2. Fu, R., Remo, T., Margolis, R. (2018) The 2018 U.S. Utility-scale Photovoltaics-Plus-Energy Storage System Costs Benchmark. National Renewable Energy Laboratory Report. Available at https://www.nrel.gov/docs/fy19osti/71714.pdf, (accessed in September 4, 2019).
3. Pham, A., Jin, T., Novoa, C., Qin, J. (2019) A multi-site production and microgrid planning model for net-zero energy operations. International Journal of Production Economics, vol. 218, December issue, pp. 260-274.
4. Cheng, F., Ettl, M., Lu, Y., Yao, D. D. (2012) A production-inventory model for a push-pull manufacturing system with capacity and service level constraints. Production and Operations Management, vol. 21, no. 4, pp. 668-681.
5. Drake, D. F., Kleindorfer, P. R., Van Wassenhove, L. N. (2016) Technology choice and capacity portfolios under emissions regulation. Production and Operations Management, vol. 25, no. 6, pp. 1006-1025.

# Appendix D

# IE4330 Project Description, Fall 2023

## Ingram School of Engineering
## Texas State University

**Project Guidelines:**

1) Students is teamed up to work on the project. At the end of the project, each project team completes the following:
2) Submit a 10-12 pages (font 12 double space) report. The report shall include the following sections: project abstract, project background/motivation, methodology, data analysis, sensitivity analysis, recommended solutions, and conclusion.
3) In the report, please use tables, charts and other graphical tools to illustrate the results and justify your conclusion.
4) Each team will make a 10 minutes presentation including minutes for questions (this means your presentation package should no more than 10 PPT slides including the cover page). Each team member will have 1-3 minutes to present his/her part of the work.
5) Your project will be evaluated and graded based on the quality of the report, the responsibility of individual students, the completeness of data collection, the solution methodology, and individual presentation.
6) **Note:** Your team can choose one of the three projects listed below.

# Project 1:
# Reliability and Lifecycle Cost Analysis of Electric Vehicles

## 1. Project Background

Driven by the climate change coupled with volatile fuel price, electric vehicles (EV) are emerging as a promising technology to replace gas-powered automobiles in transportation/mobility industry. The first EV was introduced to the commercial market in 1906. Over the one hundred years, battery technologies have advanced rapidly in terms of energy density and recharge speed, making the load capacity and the drive range dramatically increased. Battery-powered EV are compelling due to their high reliability, low operating costs, and zero tail-pipe emissions. Today lithium-ion battery cost is down to $200-300/kWh. This price was over $500 prior to 2015. For instance, a battery pack of 40kWh for Nissan Leaf II costs $12000. The basic configuration of Tesla Model 3 costs less than 30K, yet with a drive range of 272 miles (https://www.tesla.com/model3/design#overview). Energy costs of a battery-powered EV is at $0.05 per mile, compared with a diesel or gas counterpart at $0.10 to $0.2 per mile for passenger vehicles. Figure 1 shows the EV market trend through 2030. It is projected that the market will reach 27 million in 2030 as opposed to 3.27 million in 2019. This is about 8 times increase.

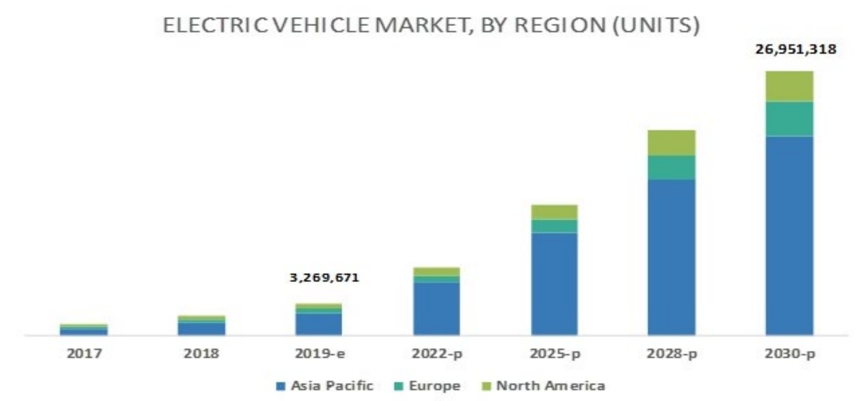



Figure 1: EV Market now and Projection in 2030 (source: Electric Vehicle Market)

## 2. Market Drivers of EV Adoption

- **Favorable government policies and subsidies**: many governments are providing incentives and subsidies to encourage EV sales or purchase.
- **Heavy investments from EV automakers:** for instance, (original equipment manufacturers) OEMs offer different segments ranging from small hatchbacks such as Nissan Leaf to high-end sedans like Tesla Model 3. The wide product offering has attracted many consumers.
- **Reverse the climate change:** The use of EV reduces the dependence on fossil fuels.

- **Increased vehicle battery capacity and drive range**: Tesla Models S and X cars now are capable of a maximum of 370 and 325 miles, respectively, using 100 kWh battery pack. (note: 1 kWh energy can run window A/C for about 30 minutes).
- **The growing accessibility of charge points and charge station stations**: Tesla is deploying a charge infrastructure in the US, East Asia and Europe (see the figure below)

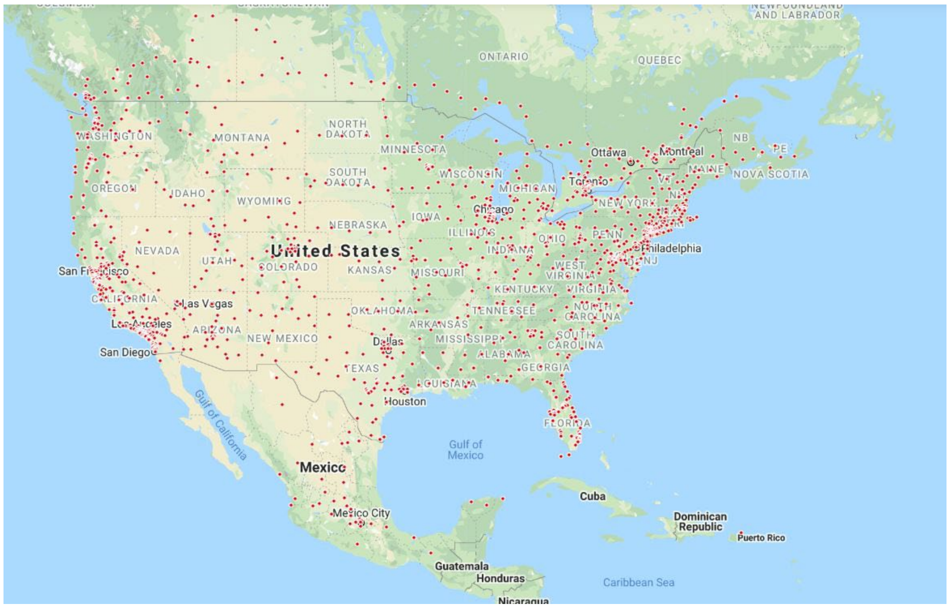



Fig 1.1: Tesla Super Charging Network in North America as of 2019

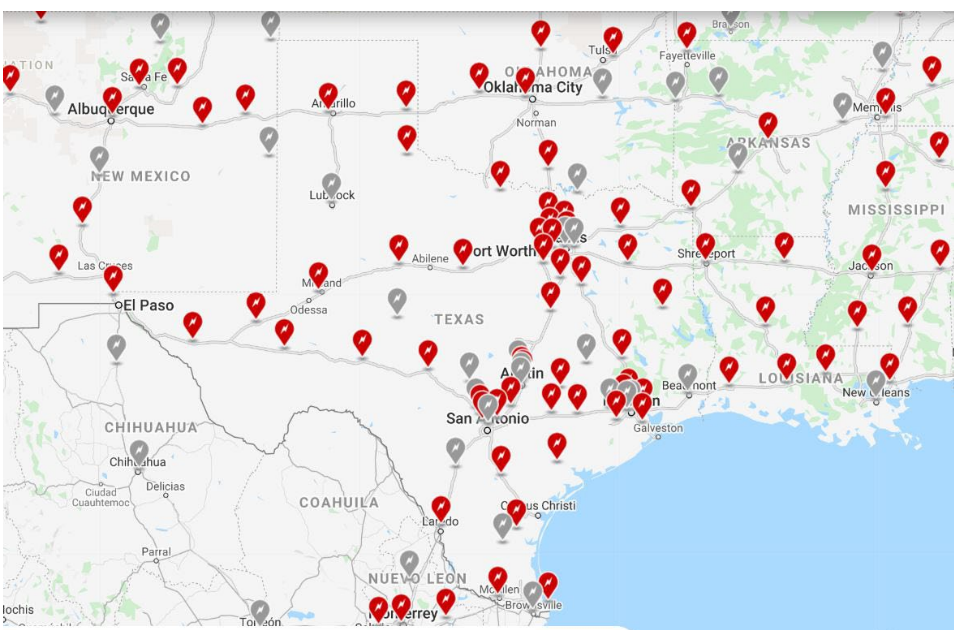



Fig 1.2: Tesla Super Charging Station Network in Texas as of 2019


Fig 1.3: Tesla Super Charger

**3. Charging Standard and Level**

The first EV charging standard is the Japanese CHAdeMO which combines alternating current (AC) and direct current (DC) charging in a single connector/inlet. Hence it requires two separate connectors/inlets, one for AC and one for DC. Later the U.S. Society of Automotive Engineers (SAE) proposed the SAE J1772 standard to regulate the EV charging process by covering the connector and charging cable based on 120V and 240V. The SAE J1772 is a commercial standard coupler for all DC faster chargers such as home/family and public charging stations. SAE J1772 also developed a combo coupler variant of the J1772-2009 connector with additional pins to accommodate fast DC charging at 200-450V and up to 90 kW. The SAE J1772-2009 has been adopted by the car manufacturers, and used in the third generation of the Chevrolet Volt and Nissan Leaf as the early models. Table 1.1 lists the voltage, current and power range at three different charging levels prescribed in SAE J1772-2009. Tesla proposed its own charge standard with power capacity over 125 kW denoted as Level 4. Level 4 is not part of SAE J1772-2009.

Table 2: Voltage, Current and Power Parameters at Different Charging Levels

| Level | Location | Voltage and Current | Power (KW) | Estimated Time to Charge (based on 24-40 kWh battery) |
|---|---|---|---|---|
| 1 | Residential | 110V, 15 A | 1.4 | 12-18 hours |
| 2 | Residential/ Public | 220V, 15-30 A | 3.3-6.6 | 4-8 hours |
| 3 | Commercial | 480V, 167 A | 50-70 | 20-50 minutes |
| 4 | Tesla Supercharger | 480V, 260-300 A | 125-150 | 10-25 minutes |

## 4. Restraints Towards the Transportation Electrification

- Lack of standardization of charging infrastructure. For standardization of charging infrastructure, a world-wide shared vision is significant, and the attainment of such goal requires the industry collaboration and government regulation. Efforts to improve the user experience of charging infrastructure have been made by promoting interoperability, both for drivers and charging network operators.

## 5. New Opportunities of Electrifying Transportation

- Vehicle-to-grid (V2G) charging is a system that realizes bi-directional power flow between EV and the power grid. V2G technology enables EV to sell or discharge batter energy to the grid in contingency. This is important when the power outage happens following the hurricanes, earthquakes, or man-made attacks. V2G allows the residential home to be powered temporarily and gives sufficient time to the utilities to restore the grid power.
- EV charging stations can be powered by renewable energy through roof-top solar panels or onsite wind turbines. Due to the easier installation of solar panels, photovoltaic powered charging stations have become ideal for homeowners or commercial buildings.

## 6. Detailed Course Project

The EV project consists of 6 tasks described below

### 6.1 Task 1: Survey the main EV Models in the World

The task here is to survey the EV models in the global market, including passenger EV and EV trucks. The latter is used for logistics and long-haul food or goods transportation.

Please pay attention to the following technology aspects/features (but not limited to)

- drive range
- battery technology (lithium-ion or lead acid)
- estimated battery recharge time (depending on charge level)
- EV cost or price,
- EV capacity, such as the number of passengers a car can accommodate or the shipping load or total weight of E-truck.
- The name of the EV manufacturer, etc.
- Puer battery-powered EV vs. hybrid EV (battery plus gasoline engine)

The purpose of this survey is to give you an overall landscape of EV commercial market in the world.

### 6.2 Task 2: Reliability Block Diagram of EV

The task here is to understand the working principle of an EV. Like gasoline engine car, an EV or HEV, consists of tires/wheels, drivetrain, battery, electric motors, AC/DC and DC/AC converter, power supply system, brakes, and control systems, among others. Figure 1.2 simply shows one such configuration of an EV.

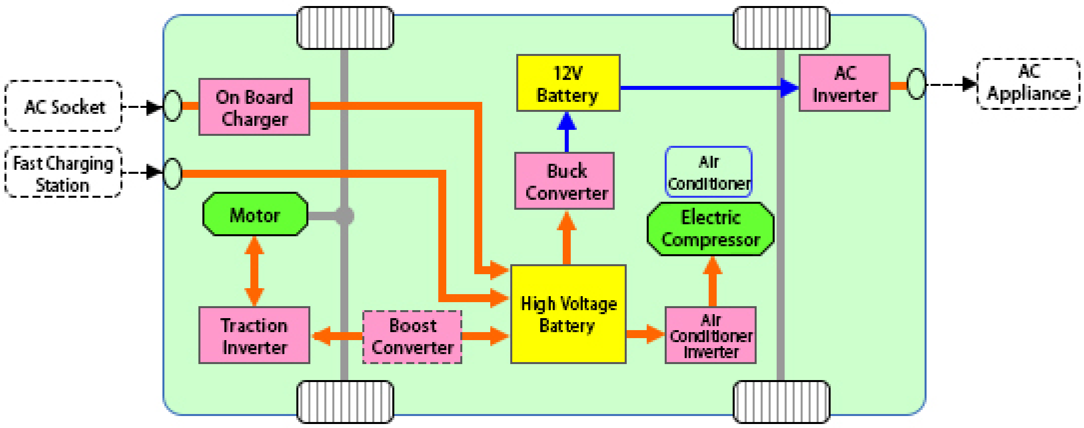



Figure 1.2: Layout of an EV system
(source: https://www.mitsubishielectric.com/semiconductors/application/automobile/index.html

You are expected to present the reliability diagram of EV. First, please identify the key subsystems or components used in an EV. Second, by considering their function and relationship, you decide whether a series configuration, a parallel configuration, a mixed series-parallel, mixed parallel-series block diagram, or even a network configuration should be adopted to develop the EV reliability diagram. Please also provide a brief explain on the configuration.

### 6.3 Task 3: Reliability Block Diagram of EV Charger Install (To be Completed)

Table 3: The State-of-the-Art Tesla Superchargers for Different Power Output (https://en.wikipedia.org/wiki/Tesla_Supercharger)

| Version | Image | Max power | Features / Notes |
|---|---|---|---|
| V1 |  | 100 kW | Power output reduced when another vehicle is plugged into the neighboring, paired charger. |
| V2 |  | 150 kW | Power output reduced when another vehicle is plugged into the neighboring, paired charger.<br>Max power output gradually upgraded from 120 to 150 kW via software updates. |
| Urban |  | 72 kW | Smaller form-factor, lower power device offered for urban installations. |
| V3 |  | 250 kW | Equipped with thinner, lighter cable that uses liquid cooling. |
| V4 | | 615 kW<br>(limited to 250 kW) | Equipped with longer cable and credit card reader for charging non-Tesla vehicles.<br>As of March 2023, the maximum power output is limited to 250 kW at 400 V. |

Reliability Analysis of the Supercharging Network in Texas (by referring to Figure 1.2)

## 6.4 Task 4: Modeling and Estimate EV Reliability

The task here is to perform survey and literature review, and choose the right data source and determine the reliability of individual key subsystems or components of EV, those include battery pack, motor, wheel, energy manage system, AC/DC and DC/AC, just name a few. In short, based on the reliability block diagram you developed in Section 6.3, the focus is to perform reliability modeling and analysis of individual components.

Ideally, you shall consider to use Weibull distribution for analyzing individual components or subsystems, though exponential lifetime distribution is fine. Or possibly, mixed use of Weibull, exponential or other distributions for modeling the reliability of key components of EV.

Finally, you are able to estimate the reliability of the entire EV system based on the reliability of individual subsystems or components.

What interested to us is the reliability of EV at mileage of 100K miles, 150k miles, or at the age or 5, 10 and 15 years of a vehicle, etc.

## 6.5 Task 5: Maintenance and Spare Parts provisioning of EV Fleet

There are two roles imposed on the EV manufacturer: product delivery and after-sales service. The latter is mainly associated with the supply of spare parts for maintenance and failure replacement across the lifecycle of an EV. For instance, Nissan Leaf 1$^{st}$ generation was released to the market in December 2010. And the 2$^{nd}$ generation Leaf was introduced in 2017 to the market. Though the first generation may be no longer in production, the supply of spare parts to keep the first generation to run is still necessary at present and in the future, so does the 2$^{nd}$ generation. The process of managing spare parts is called after-sales service supply chain and logistics.

Global sales totaled over 470,000 Leaf for first and 2$^{nd}$ generation by May 2020. Assume 60% are 1$^{st}$ generation Leaf, meaning **28,2000 Leaf** first generation are on road. The company may have stopped producing the 1st generation model in 2017 upon the introduction of the 2$^{nd}$ generation. Hence the question is how to support this amount of 28,2000 Leaf in the next 10 years or even longer because these early version cars will continue to operate by customers.

The analyses in this section are suggested as follows

- Estimate the spare parts per component type needed to support the operations of the fleet of 28,2000 Nissin 1st generation car in next 10 years from 2018 to 2027 (2017 is assumed to the stop of 1st generation).
- Compute the inventory capital and holding cost of keeping these spare parts during 10 years. Please consider the discount rate because of the time value over 10 years.
- Discuss your strategy of saving inventory cost while meeting the service level of spare parts supply. Service level is typically measured as the probability of delivering the part upon requested by customers.

**6.7 Task 6: Lifecycle Cost Analysis of EV**

Today EV is still relatively expensive compared with the counterpart of gasoline engine car. But it might be interesting to look at the lifecycle cost equation by considering the initial purchase cost, maintenance and repair, operations and the carbon savings. The task here is to answer the following questions or similar:

- Given two identical or similar cars (EV and gasoline powered), what is the total lifecycle cost assuming the annual mileage is 12,000 miles, and their lifetime is 10 years. (you can also assume 12 years or 15 years by considering more scenarios).
- What is the environmental impact during the 10 years, if running an EV vs. gasoline car and the annual mileage is 12,000 miles? In other words, how much carbon is saved if operating an EV?

**7. Project Schedule and Deliverables**

The following Project Timelines are Suggested (subject to minor changes)

| Time | Action and Deliverables |
|---|---|
| From now to 9/4 | Form the project team |
| From 9/5 to 10/23 | Complete about 50% of the tasks |
| 10/23 (Monday) | **Submit 1-2 pages mid-term report stating the completed or almost-completed tasks** |
| From 10/24 to 11/30 | Complete the remaining tasks<br>Writing report and preparing power point slides |
| On 12/4 | Final report due and oral presentation |

# Project 2:
# A Lifecycle Approach to Wind Turbine Reliability Management

## 1. Project Description

Wind power emerged as a clean and sustainable energy resource to meet the growing electricity needs in 21th century. According to U.S. Department of Energy, by 2030, the total wind power capacity in the U.S. will reach 300 GW, comprising 20% of the electricity market. To meet this target, it is anticipated that every 10 hours, 7-8 new wind turbines (WT) will be installed in the U.S. in the next 20 years in order to meet the capacity goal. Figure 1 shows the cumulative installed wind generation capacity in the US by 2019. It reaches approximately 100,000MW or 100GW. Assuming the average wind turbine size is 2MW, it means 100,1000/2=50,000 wind turbines running in the US as of today. Given the target capacity of 300GW by 2030, it is anticipated that 100,000 new wind turbines will be installed in next 11 years.

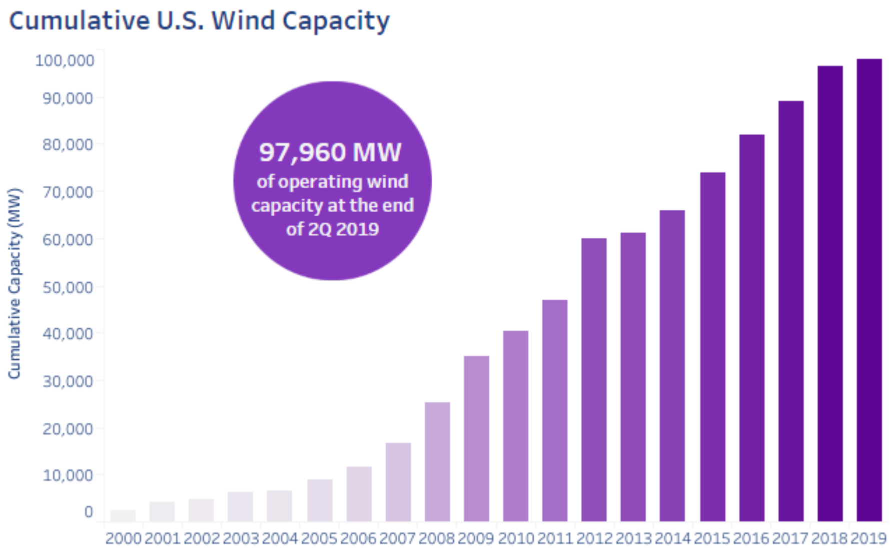



Figure 1: Cumulative Wind Turbine Installation Capacity in the US. (https://www.awea.org/wind-101/basics-of-wind-energy/wind-facts-at-a-glance)

Figure 1.5: Off-shore Wind Turbines

The rapid deployment of WT creates tremendous challenges in equipment design, maintenance, repair and overhaul services. The actual situation may be worse as wind farms are often located in remote areas or offshore sites, making it difficult to access these giant machines and perform maintenance activities. Given 50,000 wind turbines installed in the U.S. by the end of 2019, every day 120 turbines will fail based on 10,000 hours MTBF (mean-time-between-failures) per turbine. This means, every 12 minutes a wind turbine calls for a maintenance/repair action. The issue will become more pronounced as the number of installations continues to grow for reaching 300 GW in 2030. A simple math will reveals the total number of WT by end of 2030. Assuming each turbine capacity is 3MW. Then the number of turbines=300GW/3MW=100,000 turbines.

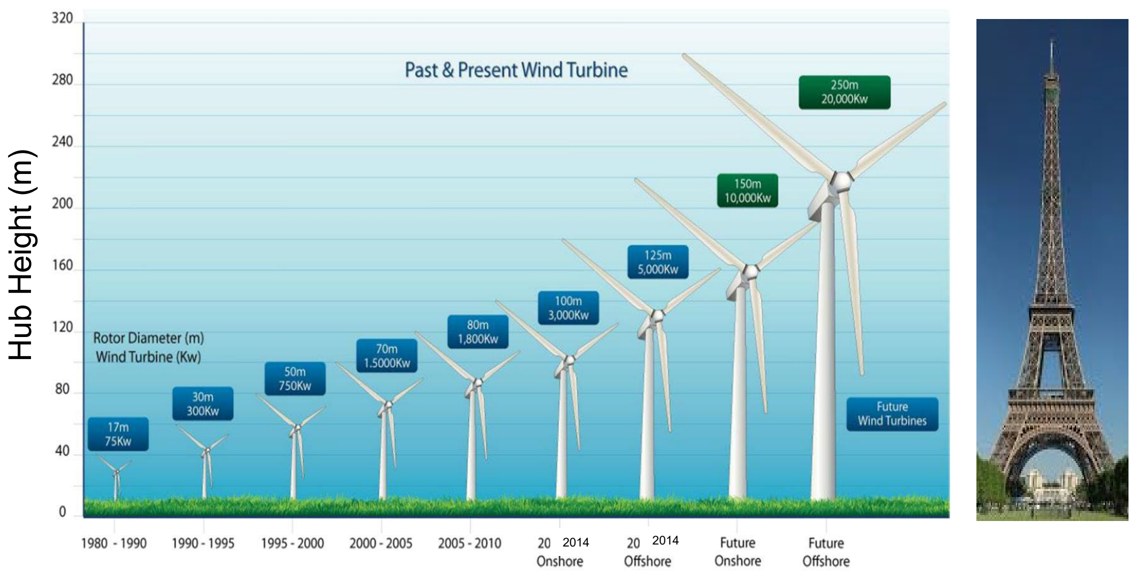



Figure 2: Capacity Growth of Individual Wind Turbines

Wind turbines are complex aerodynamic, electro-mechanical equipment incorporating sophisticated subsystems including gearbox, rotor, power electronics, and control modules. Gearbox failures account for the largest amount of downtime, maintenance cost, and loss of power production. It is estimated that when a $1,500 bearing fails unnoticed, it can lead to power interruption and revenue loss including an unscheduled replacement of a $100,000 gearbox and an unscheduled crane cost of up to $70,000 to access the failed components. These costly failures can consume 15-20% of the price of the turbine itself, making gearbox maintenance a high priority. Coupled with the intermittent wind speeds, the actual energy throughput of a WT will be dramatically compromised if the turbine availability is not kept at a high level.

Three strategies are often used for equipment maintenance: corrective maintenance, preventative maintenance, and condition-based maintenance. Regardless of maintenance strategies, a key process to support the maintenance and repair is timely supply and delivering of spare parts upon the request. If the wind turbine fleet size is large, a wind farm may maintain its own spare parts pool. Since turbine spare parts are usually costly, to avoid the excessive capital investment, many wind farms contract for maintenance services with original equipment manufacturer(OEM) who undertakes the equipment maintenance and repair.

The purpose of this project is to estimate the WT reliability, estimate the expected number of failures during its lifetime, and predict the spare parts needed for failure replacement, and finally perform lifecycle cost analysis of wind power technology. The average lifetime of a wind turbine is expected to be 20 years.

## 2. Project Tasks

### 2.1 Estimate Wind Turbine Component Reliability

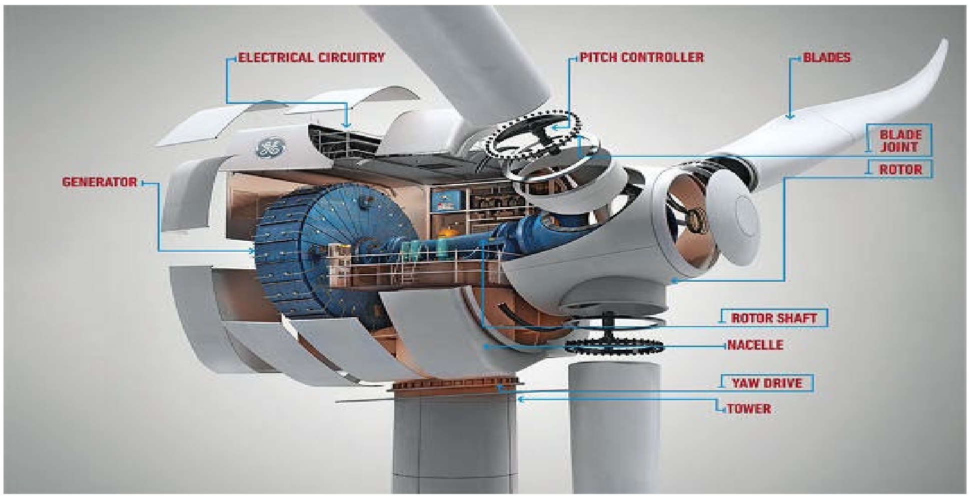



Figure 3: Decomposition of Wind Turbines

A WT system typically consists of blades, rotor, main bearing, drive train, gear box, generator, transformers, AC/DC and DC/AC converters, and other electrical and mechanical units or subsystem.

In this phase, your task is to find the reliability of individual subsystems mentioned above. You do not need to exactly follow the above classification. But regardless of the technology and manufacturers, the following subsystems are pretty standardized: blades, main bearing, generator, gearbox, and power electronics.

We are looking for two types of data pertaining to individual subsystems: (1) MTBF (mean-time-between-failures); and (2) exponential or Weibull models to model the reliability of individual subsystems.

About the source of the data: actual reliability data of components or subsystems are considered as confidential to OEM. Several suggestions for obtaining the data: 1) using the internet to search directly; 2) looking at the technical papers; 3) look at the US Renewable Energy Research lab (NREL) report.

### 2. 2 Estimating the System Reliability

Based on the reliability of individual subsystem, the next question is what is the system reliability? System reliability can be expressed as MTBF or represented as time-dependent function comprising the functions of subsystem reliability function.

**2. 3 Predicting the Number of Spare Parts**

Capital-intensive equipment such as wind turbines is often designed in modularity to facilitate maintenance and repair. Upon failure, the defective module (or subsystem) will be removed and replaced with a spare part so that the turbine can quickly return to the production. Therefore, supplying spare parts in a timely manner is the key to the sustainment of high equipment availability during its useful lifetime.

Downtime cost for WT systems are costly: loss of the electricity production, equipment depreciation, and the possibility of electricity outage due to insufficient power in the grid. Therefore, high operational availability is critical to supply reliable and secure energy to end consumers.

In this section, you are asked to perform spare parts logistics management. Based on the reliability individual subsystems, your tasks is to predict how many spare parts will be needed during the lifetime of the wind turbine.

**2. 5 Lifecycle Cost Analysis**

In this section, you are going to perform lifecycle cost analysis of wind turbines, and if want, you may also compare the cost the conventional generations (such as diesel engine, coal-fired power unit or gas turbine). When you perform such analysis, you may need the knowledge of Engineering Economics learned from ENGR 3315. Wind turbine lifecycle cost typically comprises

1) Equipment Installation Cost
2) Operating Cost
3) Maintenance and Repair Cost
4) Decommission or Disposal Cost
5) Revenue of selling renewable energy to the grid/utility company

As the revenue you made from these generation units is to selling the electricity (e.g. in unit of MWh) to end utility companies through whole sale price. For instance, a typical wholesale market price for selling 1 MWh wind electricity is around $50-70/MWh.

Therefore, the profit you obtained is the following

Profit=Revenue-Lifecycle Cost

Assuming the equipment is able to run 20 years. You need to convert the profit into an annual basis such as

What if the wind turbine system's lifetime is extended from 20 years to 25 years?

Annual Profit=Annual Revenue-Annual Cost

Let $P_c$ be a WT system capacity in unit MW. The WT power generation model is given as follows

$$E = \lambda t P_c$$

Where $E$ is the energy produced by the WT unit during time period of $t$, and $\lambda$ is the capacity factor, and it varies between 0 and 1. The unit of $t$ is hour, and the unit of $E$ is MWh. The value of $\lambda$ varies in a day because of the change in hourly wind speed. The following table capacity factor table shows how the wind capacity factor changes with the speed against the turbine blades.

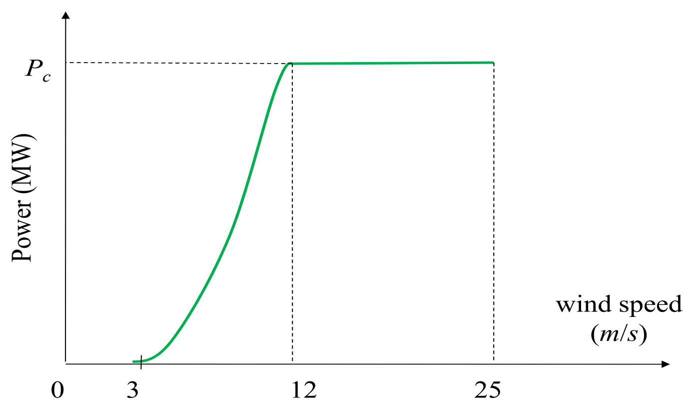



Figure 3.5: Wind Turbine Power Curve (if wind speed >25, the turbine is shut down for protection)

Table for Wind Turbine Capacity Factor

| wind speed (m/s) | Capacitor Factor | wind speed (m/s) | Capacitor Factor |
|---|---|---|---|
| 0 | 0 | 14 | 1 |
| 1 | 0 | 15 | 1 |
| 2 | 0 | 16 | 1 |
| 3 | 0.016 | 17 | 1 |
| 4 | 0.037 | 18 | 1 |
| 5 | 0.072 | 19 | 1 |
| 6 | 0.125 | 20 | 1 |
| 7 | 0.198 | 21 | 1 |
| 8 | 0.296 | 22 | 1 |
| 9 | 0.422 | 23 | 1 |
| 10 | 0.579 | 24 | 1 |
| 11 | 0.770 | 25 | 1 |
| 12 | 1 | 26 | 0 |
| 13 | 1 | >26 | 0 |

### 3. Project Schedule and Deliverables

The following Project Timelines are Suggested (subject to minor changes)

| Time | Action and Deliverables |
|---|---|
| From now to 9/4 | Form the project team |
| From 9/5 to 10/23 | Complete about 50% of the tasks |
| 10/23 (Monday) | **Submit 1-2 pages mid-term report stating the completed or almost-completed tasks** |
| From 10/24 to 11/30 | Complete the remaining tasks<br>Writing report and preparing power point slides |
| On 12/4 | Final report due and oral presentation |

# Project 3:
# A Lifecycle Approach to Solar Photovoltaic Reliability Management

### 1. Background of Solar PV Systems

The project scope of solar Photovoltaic (PV) is very similar to wind turbines. First, both are renewable energy generators by harassing clean and natural resources. Second, the generation of wind and solar is intermittent, depending on the climate condition. Third, to build a solar farm, you need PV panels, charge controller, DC/AC and AC/DC converters, battery storages. Fourth, the lifetime of PV system is also expected to be 20-25 years, similar to the expected lifetime of WT equipment. Figure 4 shows a typical PV-based power generation system.

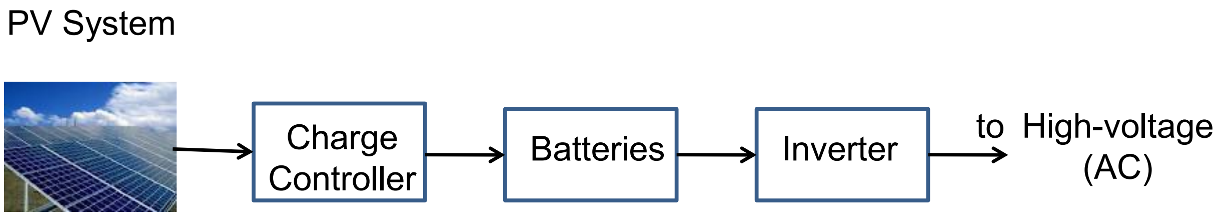



Figure 4: Decomposition of Wind Turbines

Figure 5: Japan's Offshore Solar Power Plant for the Future of Renewable Energy

Figure 6: Operating a 550MW capacity, Desert Sunlight Solar Farm is located in the Riverside County in California and tied in second place with Topaz Solar Farm.

Like WT, solar PV systems can be installed offshore (see Figure 5) and onshore (see Figure 6). For instance, Figure 7 shows a large solar park located in California with capacity of 550 MW. Assuming the capacity of a single PV panel is 250 W. Then the number of panel used for this solar park is

$$n = \frac{550MW}{250W} = \frac{550 \times 10^6 W}{250W} = 2{,}200{,}000 \text{ (panels)}$$

Assume that the size of each panel is 2 m$^2$, the total areas occupied by the solar park is

$$A = (2{,}200{,}000)(2) = 4{,}400{,}000(m^2) = 1{,}087 \text{ (acres)}$$

**The campus of Texas State University is 500 acres, and this solar park is twice of the Texas State University.** The actual area of the solar park is even larger than 1087 acres because certain space (distance) must be maintain between two rows of the PV panels to maximize the receipt of solar irradiance.

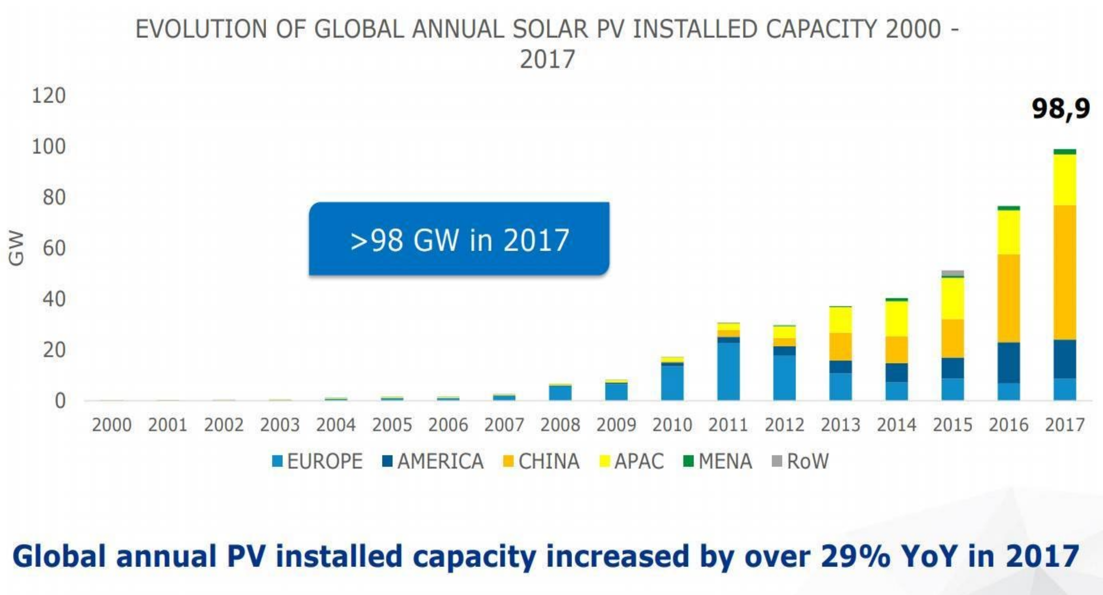
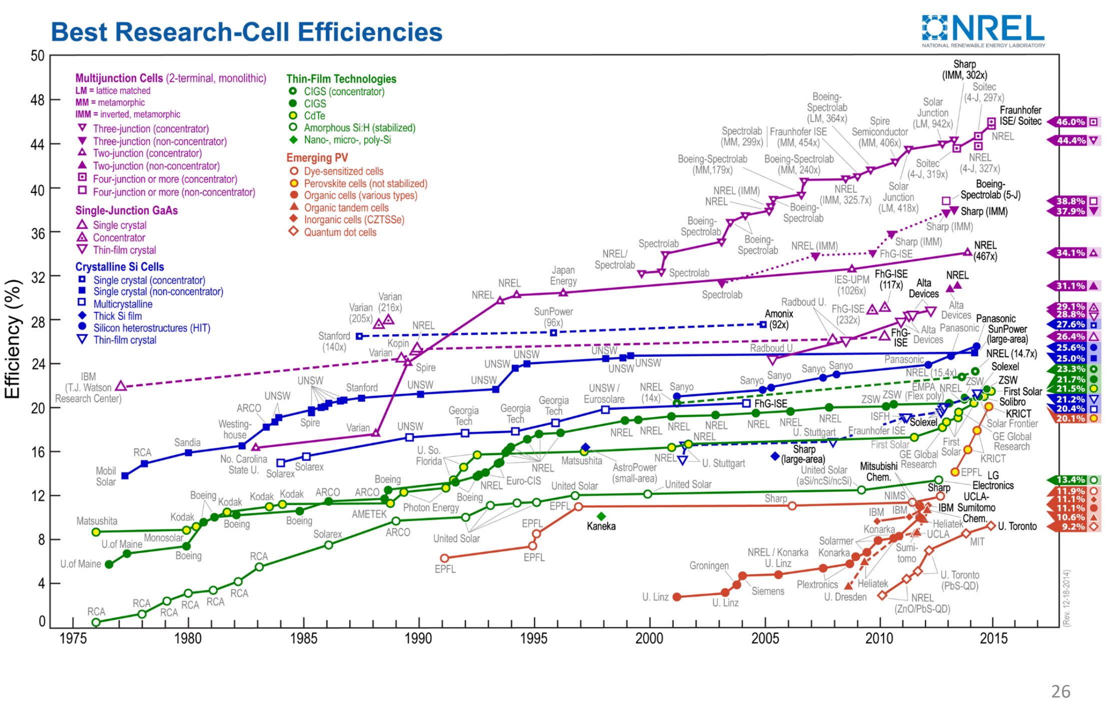



Figure 7: Cumulative Installed PV System Capacity in the World

If your team decide to work on the reliability problem of a large solar PV park, then you shall accomplish the following questions (similar to wind turbine project)




http://upload.wikimedia.org/wikipedia/commons/3/35/Best_Research-Cell_Efficiencies.png

Figure 8: The Continuous Growth of PV efficiency in the last 40 Years

## 2. Project Tasks

## 2.1 Estimate PV System's Component Reliability

A PV system (see figure 4) consists of solar panels, charge controller, DC/AC or AC/DC inverters, battery packs and other subsystems.

In this phase, your task is to find the reliability of individual subsystems mentioned above. You do not need to exactly follow the above classification. But regardless of the technology and manufacturers, the following subsystems are pretty standardized: solar panels, charge controller, DC/AC or AC/DC inverters, batteries.

We are looking for two types of data pertaining to individual subsystems: (1) MTBF (mean time between failures); and (2) exponential or Weibull models to model the reliability of individual subsystems of a PV system.

## 2. 2 Estimating the System Reliability

Based on the reliability of individual subsystem, the next question is what is the system reliability? System reliability can be expressed as MTBF or represented as time-dependent function comprising the functions of subsystem reliability function. In this case, we consider large solar PV park comprised of hundreds of thousands of PV panels, charge controllers, DC/AC, AC/DC, or batteries. So please use the Desert Sunlight Solar Farm in Figure 6 as the case study.

## 2. 3 Predicting the Number of Spare Parts

Downtime cost for PV systems are costly: loss of the electricity production, equipment depreciation, and the possibility of electricity outage due to insufficient power in the grid. Therefore, high operational availability is critical to supply reliable and secure energy to the end users.

Capital-intensive equipment such as a PV park is often designed in modularity to facilitate maintenance and repair. Upon failure, the defective module (or subsystem) will be removed and replaced with a spare item so that the PV can quickly return to the production. Therefore, supplying spare parts in a timely manner is the key to attaining high equipment availability during its useful lifetime.

In this section, you are asked to perform spare parts logistics management. Based on the reliability individual subsystems, your tasks is to predict how many spare parts will be needed during the lifetime of the solar park, such as PV panels, DC/AC and AC/DC inverters, charge controller, and battery packs.

## 2. 5 Lifecycle Cost Analysis

In this section, you are going to perform lifecycle cost analysis of solar Photovoltaics system, or if you want you can also compare the cost with conventional generation units like diesel engines, micro turbines and gas-fired power units. When you perform such analysis, you may need the knowledge of Engineering Economics learned from ENGR 3315. Wind turbine lifecycle cost typically comprises

1) Equipment Installation Cost
2) Operating Cost
3) Maintenance and Repair Cost
4) Decommission or Disposal Cost
5) Annual revenue of selling renewable energy to main grid or utility companies

As the revenue you made from these generation units is to selling the electricity (e.g. in unit of MWh) to end utility companies through whole sale price. For instance, a typical wholesale market price for selling 1 MWh PV electricity is around $60-80/MWh.

Therefore, the profit you obtained is the following

Profit=Revenue-Lifecycle Cost

Assuming the equipment is able to run 20 years. You need to convert the profit into an annual basis such as

What if the PV system's lifetime is extended from 20 years to 25 years?
Annual Profit=Annual Revenue-Annual Cost

Let Pc be the PV system capacity in unit MW. The PV power generation model is given as follows

$$E = \lambda t P_c$$

Where $E$ is the energy produced by PV during time period of $t$, and $\lambda$ is the capacity factor. The unit of $t$ is hour, and the unit of $E$ is MWh. The value of $\lambda$ varies in a day. During the noon time, $\lambda$ is close to one, and when sun rises or sets down, $\lambda$ becomes 0. See the chart below for example.

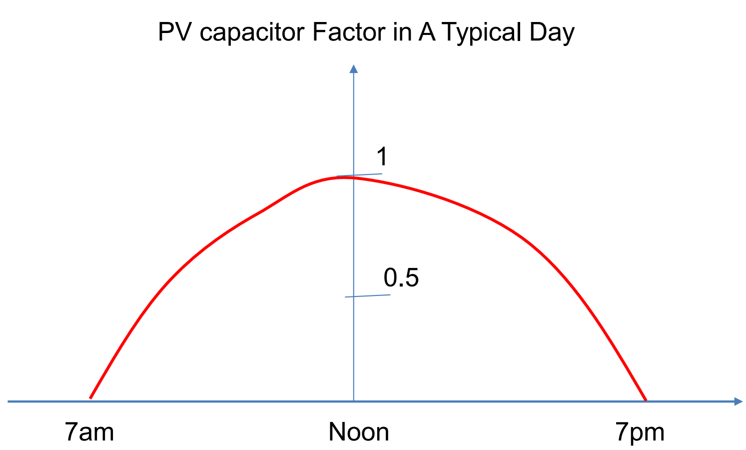


Figure 9: Capacity factor varies with the hour in a Clear Sky Day

## 3. Project Schedule and Deliverables

The following Project Timelines are Suggested (subject to minor changes)

| Time | Action and Deliverables |
|---|---|
| From now to 9/4 | Form the project team |
| From 9/5 to 10/23 | Complete about 50% of the tasks |
| 10/23 (Monday) | **Submit 1-2 pages mid-term report stating the completed or almost-completed tasks** |
| From 10/24 to 11/30 | Complete the remaining tasks<br>Writing report and preparing power point slides |
| On 12/4 | Final report due and oral presentation |