Master Thesis 2024-2025

An Analytical Study on the Design of Solar Power Plants for

Residential and Commercial Sector: Practical Implementation and Cost Analysis

ROY Jui

Master in Electrical Engineering
for smart grids and buildings

Louisiana Solar Energy Laboratory (LaSEL)

University of Louisiana at Lafayette, USA

Supervised by:
Terrence L. Chambers

School Tutor: **Fabien Sanchez**

President: **Vincent Debusschere**

STATEMENT ON ACADEMIC INTEGRITY

I hereby declare and confirm with my signature that the master thesis / dissertation is exclusively the result of my own autonomous work based on my research and literature published, which is seen in the notes and bibliography used.

I also declare that no part of the paper submitted has been made in an inappropriate way, whether by plagiarizing or infringing on any third person's copyright.

Student:

In ___Lafayette,____03/07/2025__ _____ROY Jui______
(city) (date) (signature)

Table of Contents

1. Abstract

2. Introduction

2.1 Background

2.2 Problem Statement

3. Objectives

3.1 Purpose of the Study

3.2 Objectives of the internship

4. Methods and Procedures

4.1 Fundamentals of a Solar Power Plant

4.2 Residential and Commercial Solar

4.3 Design of Residential and Commercial Solar

4.3.1 Site Survey

4.3.2 Preliminary System Sizing

4.3.3 String Sizing

4.3.4 Actual System Size

4.3.5 Electrical Integration

4.3.6 Mechanical Integration

4.4 Code Compliance and Design Standards

5. Results and System Performance Evaluation

5.1 Technical System Overview

5.2 Energy Yield Analysis

5.3 Economic Performance

6. Analysis

7. Discussion

8. Conclusion

9. References

1. Abstract

This report presents an analytical study on the design, implementation, and economic evaluation of solar photovoltaic (PV) systems in residential and commercial sectors. The internship was conducted at the Louisiana Solar Energy Laboratory (LaSEL), where real-world solar deployment conditions offered the opportunity to apply theoretical design knowledge to practical applications. Using national standards such as NEC and ASCE, and tools like PVWatts, ASHRAE data, and financial spreadsheets, three grid-tied PV systems were designed and evaluated: one commercial and two residential.

The process involved detailed site surveys, string sizing, electrical and mechanical integration, and code-compliant layouts. Economic performance was assessed using Levelized Cost of Energy (LCOE), payback period, and system offset percentages. Results showed that the commercial system achieved a lower LCOE ($0.123/kWh) due to economies of scale, while residential systems though smaller remained viable due to incentives like the ITC. A key limitation of this study was the exclusion of battery storage from system design, which limited the evaluation of self-consumption and backup capabilities.

The findings confirm that well-designed PV systems can offer strong energy savings, emission reductions, and long-term financial returns. The highlight points of this research work are designing the system using actual data, ensuring the regulatory standard and outlining future improvements.

2. Introduction

2.1 Background

Renewable energy refers to electricity generated from naturally replenished resources such as sunlight, wind, water, and geothermal heat. Unlike fossil fuels, which significantly increase greenhouse gas emissions and harm the environment, renewable energy sources are sustainable, clean, and becoming more and more affordable.

As climate change mitigation and energy security become global priorities, the demand for renewable energy has accelerated significantly in recent years.

According to the International Renewable Energy Agency (IRENA), global renewable energy capacity reached approximately 3,870 gigawatts (GW) by the end of 2023, marking a 13.4% increase from the previous year. In 2024 alone, the world added nearly 585 GW of new renewable capacity the largest annual increase in history with more than 92% of all newly installed electricity generation capacity coming from renewables. This upward trend reflects the growing economic feasibility of clean energy technologies, declining technology costs, and supportive policy frameworks worldwide.

Among all renewable energy technologies, solar photovoltaic (PV) systems have shown the highest growth rate. In 2024, solar PV alone contributed about 452 GW of the new renewable additions, representing 77% of global renewable capacity growth. This expansion is primarily driven by rapid cost declines in PV modules, increased efficiency, government incentives, and the flexibility of PV systems to be deployed in a wide range of settings from residential rooftops to utility-scale solar farms.

At the national level, China has emerged as the global leader in solar energy deployment, accounting for more than 60% of the newly added solar capacity in 2024. This includes large-scale utility plants as well as rapidly growing rooftop installations, supported by domestic manufacturing capacity and strong national policy support. In Europe, the European Union added over 70 GW of renewable capacity in 2024, with solar energy representing the largest share. Germany installed a record 18.8 GW of solar capacity in one year, and across the EU, solar electricity output increased by 32% in the first quarter of 2025 compared to the same period in 2024. Countries such as Spain, Poland, and the Netherlands also reported rapid solar adoption, driven by high electricity prices and favorable regulatory mechanisms.

In the United States, the solar sector added nearly 50 GW of new capacity in 2024, reflecting a 21% increase from 2023. This growth has been supported by declining system costs, long-term investment incentives under the Inflation Reduction Act (IRA), and growing consumer demand across both residential and commercial sectors. For the first time, solar energy surpassed wind and natural gas as the largest source of newly installed electricity generation capacity in the country.

The technical advantages of solar PV, along with its scalability and affordability, make it relevant in the worldwide energy shift. Solar systems can be effectively integrated with battery storage systems to increase grid reliability and stability. They also require minimal maintenance and can last for 20 to 30 years. Solar deployment also makes a substantial contribution to job creation, making it one of the clean energy workforce areas with the quickest rate of growth.

Although the share of residential and commercial solar in terms of total installed capacity is relatively small, these sectors are critically important due to the large number of individual users they serve. They offer significant opportunities for localized energy production, demand-side flexibility, and carbon emission reduction.

This report investigates the design methodology, practical implementation and economic analysis of the commercial and residential solar sector.

2.2 Problem Statement

Model Development: Developing a robust model is the foundation of solar PV system design both for the residential and commercial sectors. It helps to estimate system capacity, energy output, and component selection, supporting design layouts and proposals based on site and environmental conditions. The model integrates site-specific data including roof orientation, shading patterns, and historical energy consumption to ensure that the system meets user expectations and complies with design standards. It also supports preliminary financial estimates by projecting energy yield and guiding incentive calculations.

Practical Implementation: Although designs and modeling tools offer a theoretical basis for the creation of PV systems, real-world execution frequently reveals unanticipated difficulties. The viability of an ideal design can be drastically changed by site-specific limitations including a small roof area, structural restrictions, shade from buildings or trees, and antiquated electrical infrastructure. Handling local permitting regulations, code compliance, and utility hookup standards also adds procedural complexity that may delay deployment or call for system modification. Because of these practical limits, we need a design strategy that is adaptable and based on what is known about the area, and that integrates engineering best practices with regulatory knowledge. In order to make sure that the system operates as it should and is safe, scalable, and favored by everyone, these issues need to be fixed.

Design: PV systems must meet complex design requirements, both electrically and mechanically, to ensure reliability, efficiency, and code compliance. On the electrical side, key challenges include string sizing under temperature extremes, DC/AC ratio selection, grounding, rapid shutdown, and voltage drop management. On the mechanical side, systems must be structurally sound under wind and snow loads, especially for varied roof types or topographies. Achieving an optimal system design demands following ASCE and NEC standards is a careful balance between technical specifications, environmental stresses, and material limitations—all while aligning with permitting and inspection criteria.

Economic Analysis: While the cost of solar technology continues to decline, financial viability remains a complex challenge, especially for small-scale systems. Economic performance is highly sensitive to local policies, including net metering structures, tax incentives, and state or utility-level rebates, which vary widely across regions and are subject to change over time. For example, full retail net metering may no longer be available in some states, while others may limit export compensation to avoided-cost rates or prohibit net export entirely. Tax credits like the federal ITC and local incentives can change with policy updates, directly impacting payback periods and project viability.

3. Objectives

3.1 Purpose of the Study

The primary objective of this research is to address the analytical and practical difficulties involved in creating cost-effective, code-compliant, and efficient solar PV systems for both home and commercial use. The project aims to integrate technical modeling, realistic site constraints, and financial performance evaluation to develop a cohesive design approach.

Objective 1: To develop and validate PV system design models that incorporate site-specific variables such as irradiance, shading, orientation, load demand, and available installation area.

Objective 2: To implement practical system layouts and sizing strategies that address real-world limitations—such as structural constraints, electrical service conditions, and permitting requirements—while ensuring compliance with applicable electrical and mechanical standards (e.g., NEC, ASCE), including considerations for voltage drop, inverter matching, string sizing, grounding, and structural loads.

Objective 3: To evaluate the economic feasibility of each system using metrics such as energy offset, Levelized Cost of Energy (LCOE), and simple payback period, while accounting for policy changes and local incentive structures.

3.2 Objectives of the Internship

The primary objective of the internship was to apply and expand theoretical knowledge of photovoltaic (PV) systems through hands-on experience in the design and implementation of solar power plants for both residential and commercial sectors. The internship aimed to bridge the gap between academic learning and industry practice by engaging in technical and analytical tasks that reflect real-world project workflows.

Key learning outcomes included developing site-specific system models, performing energy yield simulations, and optimizing system sizing based on environmental and structural conditions. Gaining experience in conducting site assessments, creating technical layouts, selecting appropriate components, and ensuring compliance with relevant electrical and mechanical design standards. In addition, the internship fostered practical understanding of regulatory processes such as permitting and interconnection, while also emphasizing economic analysis evaluating project feasibility through tools like LCOE calculations, payback period estimation, and incentive modeling. Overall, the experience aligns with the academic training while providing meaningful professional development in solar project design, performance evaluation, and techno-economic analysis.

4. Methods and Procedures

4.1 Fundamentals of a Solar Power Plant

A solar power plant is a large facility that converts solar radiation including light, heat, and ultraviolet rays into electricity. By primarily utilizing photovoltaic panels to harness sunlight, these plants produce electricity that can be used in homes, industries, and the grid. This method of generating clean energy is completely environmentally friendly, producing no pollutants, and represents one of the most effective renewable energy sources currently available. Due to the advantages of solar energy over fossil fuels, solar power plants play a crucial role in reducing carbon emissions and advancing the global shift to sustainable energy. They provide a dependable, eco-friendly solution that can be expanded to meet growing energy needs, thereby contributing to a more sustainable future.

Components of a Solar Power Plant:

A solar power plant is a symphony of various components working harmoniously to capture and convert sunray into usable electricity. The key components include:

- Solar Panels: The system's heart, converts the sunlight into electricity.
- Inverters: Convert the direct current (DC) generated by solar panels into alternating current (AC) for use.
- Mounting Systems: Structures that hold the solar panels in place, on rooftops, on the ground, or floating on water bodies.
- Battery Storage: Stores excess energy generated during the day for use during nighttime or cloudy days, enhancing the reliability of solar power.
- Racking: Supports and positions the solar panels.
- Electrical Components: Includes wiring, combiner boxes (Gather the output from multiple panels and safely connect it to the inverter.), charge controllers (Manage the flow of electricity to and from the batteries to prevent overcharging.), and transformers, all crucial for directing and managing the electricity flow.

Safety is highly prioritized in the solar sector to minimize the hazard. Several organizations actively work to establish and enforce safety standards in the solar industry, including the National Renewable Energy Laboratory (NREL), the Solar Energy Industries Association (SEIA), and the Occupational Safety and Health Administration (OSHA).

4.2 Residential and Commercial Solar

Residential Solar systems are photovoltaic (PV) installations specifically designed for individual homes, typically ranging from 3 kW to 10 kW in capacity. These systems use rooftop-mounted solar panels often monocrystalline for higher efficiency on limited roof space connected to string or microinverters that convert direct current (DC) into usable alternating current (AC). Most residential PV systems are grid-tied, synchronized with utility voltage and frequency, allowing homeowners to offset their energy consumption and export excess electricity to the grid under net metering agreements depending on the location. Other configurations include off-grid and hybrid systems, which incorporate battery storage to provide backup power during outages. These systems are generally optimized for south-facing exposure to maximize solar capture. In some regions, residential systems may also participate in community solar programs enabling households without suitable roof space to benefit from shared solar installations.

Figure 1: Examples of Residential Rooftop Solar PV Systems

From a financial perspective, residential installations tend to have a higher cost per watt than commercial systems due to smaller scale and site-specific design, but they benefit from a wide range of incentives including the federal Investment Tax Credit (ITC), local rebates, and state-level subsidies. The average payback period is seven to twelve years as a result of these financial supports and rising utility bills.
In addition to the financial benefit, household solar is essential for grassroots sustainabilit y promotion. It enables homeowners to reduce carbon emissions, increase property value, and contribute to a more resilient and decentralized energy system, especially as smart home technologies and energy storage become more mainstream.

Commercial Solar systems refer to photovoltaic (PV) arrays deployed on ground mount or on commercial buildings such as office parks, warehouses, factories, and other institutional or industrial facilities. These systems are typically much larger than

Figure 2: A 1.1 MW commercial solar power plant

residential arrays ranging from 30 kW to several megawatts and are commonly installed on flat rooftops, parking structures, or open land. Designed to operate during peak business hours when electricity demand is highest, they help reduce operational costs through both direct energy savings and demand charge reductions. System types include on-site grid-tied installations, solar carports, and community or shared solar farms. Technically, commercial PV systems utilize three-phase power configurations, centralized or large string inverters, and often require transformer upgrades and customized grid interconnection plans. Battery storage can be integrated for advanced functions such as peak shaving, backup power, and load shifting. Commercial solar projects are financially advantageous due to economies of scale, which lower the installation cost per watt. Companies can take advantage of a variety of financing options, such as equipment leasing, Power Purchase Agreements (PPAs), and tax breaks like the Modified Accelerated Cost Recovery System (MACRS) depreciation and the Investment Tax Credit (ITC). Typical payback periods range between 5 and 10 years. In addition to the economic advantages, commercial solar demonstrates corporate environmental responsibility, supports decarbonization goals, and creates clean energy jobs. Large-scale commercial deployments also improve grid resilience and facilitate broader renewable energy integration. As demonstrated in microgrid research at the University of Louisiana at Lafayette, commercial solar combined with storage plays a vital role in emergency preparedness and energy resiliency for critical infrastructure.

4.3 Design of Residential and Commercial Solar

4.3.1 Site Survey

A solar site survey is the first and crucial phase in planning a solar photovoltaic (PV). This survey carries a bunch of information on structural, electrical, environmental, and customer-specific data to evaluate the technical and financial feasibility of installing a system at a specific location. Additionally, to fulfill the customer's goal and chase the budget this stage ensures that the proposed system can be designed securely, effectively, and in accordance with applicable codes.

Figure 3: Site survey photographs, utility bill, and available area

The methodology begins with a general assessment of the property, including ownership status, customer energy goals, and future usage expectations. Site-specific information such as roof access, structure type, and surface condition is documented. Roof geometry such as tilt, orientation, and available surface area is measured using tools from Google Earth or PV Watts, or any other online tools available. The structural condition of the roof and support systems is inspected to determine load-bearing capacity and the need for reinforcement.

Solar access is evaluated using digital shading analysis tools, such as the Solmetric SunEye or Solar Pathfinder. These instruments allow for the identification of shading obstructions throughout the solar window and help assess the viability of different array locations. Environmental data is obtained using tools such as PVWATTS for estimating annual output per 1 kWdc according to the module & array type, system losses (%), tilt & azimuth, ASHRAE climate design databases for temperature parameters, and the ASCE Hazard Tool for site-specific wind speed and snow load data.

An inspection of the existing electrical infrastructure is performed to determine interconnection compatibility. The service panel's kind, size, and condition are all recorded, along with how it is grounded and bonded. Appropriate locations for system components including inverters, combiner boxes, and disconnect switches are selected to ensure safe access, ease of maintenance, and full compliance with electrical code requirements for spacing and clearance. Wiring routes are proposed based on proximity to the array, safety, and ease of installation.

Utility-related information is gathered to understand historical energy consumption patterns, effective energy cost, rate structures, and net metering policies. This data is used to estimate system capacity, economic performance, and customer payback.

All site observations and measurements are compiled into a comprehensive documentation package. This includes photographs, diagrams, field notes, and digital data outputs. The completed site survey provides a technically sound and regulatory-compliant basis for system design and serves as a critical input for sizing calculations, permitting, financial modeling, and installation planning.

4.3.2 Preliminary System Sizing

This preliminary sizing step represents making initial assumptions for the system which serves as a link between site survey data and final system design, supporting informed decisions about component selection, layout, and economic feasibility. The formulas and design approach used in this section as well as for whole the design are adapted from Photovoltaic Systems by Jim Dunlop (3rd Edition) and the Solar Electric Handbook: Photovoltaic Fundamentals and Applications by Solar Energy International, which both serve as foundational references for PV system engineering.

Starting with the calculation of the total energy used by the customer for one year, with the electricity bill, will permit the designer to dive into the next step to determine the desired energy from the system. Using data collected during the site survey, the available roof or ground area is analyzed to determine how many modules can fit based on module dimensions, tilt, spacing requirements, and code-compliant setbacks. The designer then calculates the maximum possible DC system size using industry-accepted values for module power density (W/m^2) and efficiency.

To estimate system performance, solar resource data specific to the project location is obtained using the PVWATTS tool from NREL. This tool provides the expected annual energy output per kilowatt of installed DC capacity (kWh/kWdc). The required system size to meet the desired offset is calculated by dividing the customer's annual energy consumption by the site-specific energy production factor. If the required size exceeds available space, trade-offs are considered between achievable offset, customer goals, and physical constraints.

Once the target DC system size is identified, the AC system size is determined using a suitable DC-to-AC ratio which guides inverter selection. Inverter output must align with the existing electrical service rating and comply with utility interconnection requirements.

The number of PV modules is then calculated by dividing the total DC system size by the rated wattage of a single module. The nominal installation area is checked against the measured available space from the site survey to ensure the system is physically feasible. Additional calculations may include expected annual energy output, system Performance Ratio (PR), and a preliminary estimate of cost per watt, all of which support early financial modeling.

Preliminary system sizing also plays a key role in determining incentive eligibility, interconnection category, and the economic return of the project. Since system capacity influences total installed cost, tax credit amount, and net metering classification, this step is essential for aligning the design with both technical feasibility and long-term financial performance.

Finally, preliminary system sizing provides the first quantitative snapshot of what a solar project can realistically achieve. A well-performed sizing assessment increases project confidence, reduces design revisions, and improves the likelihood of successful execution both technically and economically.

4.3.3 String Sizing

In the solar PV design process, string sizing is the point at which actual system calculations start. This stage involves configuring the array according to the chosen PV module and inverter, making sure that voltage, current, and layout constraints are satisfied safely and effectively, following the completion of the site survey and preliminary system size.

All the PV modules and inverters were selected from CED Greentech, a reputable solar equipment distributor. Product datasheets provided key electrical specifications such as open-circuit voltage (Voc), short-circuit current (Isc), maximum power point voltage (Vmp), and temperature coefficients, along with inverter voltage limits and MPPT input ranges. These specifications served as the basis for determining safe and optimal string configurations.

Temperature correction factors were applied using site-specific environmental data, particularly the ASHRAE extreme minimum and high design temperatures. The lowest temperature was used to calculate the adjusted Voc and ensure the string voltage remained within the inverter's maximum DC input limit. Conversely, the highest temperature was used to confirm that the string voltage would stay above the inverter's MPPT minimum, even under hot conditions.

Figure 4: PV module, inverter, and spec sheet.

Once the safe voltage window was established, the maximum and minimum number of modules per string were calculated. In order to maximize system efficiency, the final value selected usually indicates the maximum number of modules that stayed within voltage limitations. To ensure safe operation, the matching string current was then compared to the inverter's MPPT current rating.

The number of parallel strings was determined based on the system's total power requirement and inverter input capacity. Based on the dimensions and usable space documented during the site survey, the array layout is optimized to accommodate the total number of modules calculated during string sizing. The mounting orientation landscape or portrait is selected based on roof or ground dimensions, shading, and structural preferences, directly influencing the number of rows, columns, and overall system configuration. This process resulted in a complete set of system characteristics, including the number of modules per string, number of strings, total module count, maximum voltage and current, array layout (rows and columns), and physical dimensions of the array.

4.3.4 Actual System Size

The actual system size is the finalized, buildable PV configuration that translates preliminary assumptions into precise design values based on real components, site constraints, and verified calculations.

The process begins by applying the exact specifications of the selected module and inverter to finalize the number of modules per string, total string count, and overall DC and AC system capacities. Unlike preliminary estimates, these values reflect actual module ratings under Standard Test Conditions (STC) and site-adjusted conditions, using temperature correction factors and voltage compliance checks to ensure both performance and safety.

In addition to electrical finalization, all confirmed values—including actual DC and AC system sizes, annual energy production, and percentage of site energy offset—are used to calculate economic and financial performance. Electrical parameters such as the DC/AC ratio, string current limits, inverter loading, and conductor sizing are finalized in accordance with NEC standards and manufacturer specifications. Protection devices, voltage drop thresholds, and utility interconnection compatibility are also validated to ensure long-term system safety and efficiency.

This finalized configuration informs all downstream financial modeling. Key metrics such as total installed cost, tax incentives, annual energy savings, simple payback period, life cycle cost (LCC), and Levelized Cost of Energy (LCOE) are calculated. Financing variables including interest rate, loan term, down payment, and annual payments are also considered to evaluate return on investment and long-term project viability.

Ultimately, the actual system size marks the point where design becomes implementation-ready. It serves as the foundation for utility interconnection, cost estimation, detailed construction drawings, bills of materials, and permits. The system is prepared for purchase and installation since its technical accuracy and financial feasibility have been verified.

4.3.5 Electrical Integration

Electrical integration is a critical step that connects all parts of the photovoltaic (PV) system into a safe, functional, and code-compliant design. It involves selecting and sizing all electrical components, routing wiring correctly, and ensuring compliance with the National Electrical Code (NEC), especially Articles 690 and 705. Every component from rapid shutdown devices to conductors is chosen based on its compatibility with the system's voltage, current, and layout.

To meet NEC safety standards, a module-level rapid shutdown device was selected to ensure that the voltage within the array boundary drops quickly in the event of an emergency. A junction box is used to transition wiring from the modules to conduitenclosed circuits, while a DC disconnect switch allows safe isolation of the solar array from the inverter. Since the system used a small number of strings, a DC combiner box was not required. On the AC side, an inverter feeds power to the utility through an AC disconnect, which is often required by the utility company to provide a safe service shutoff point.

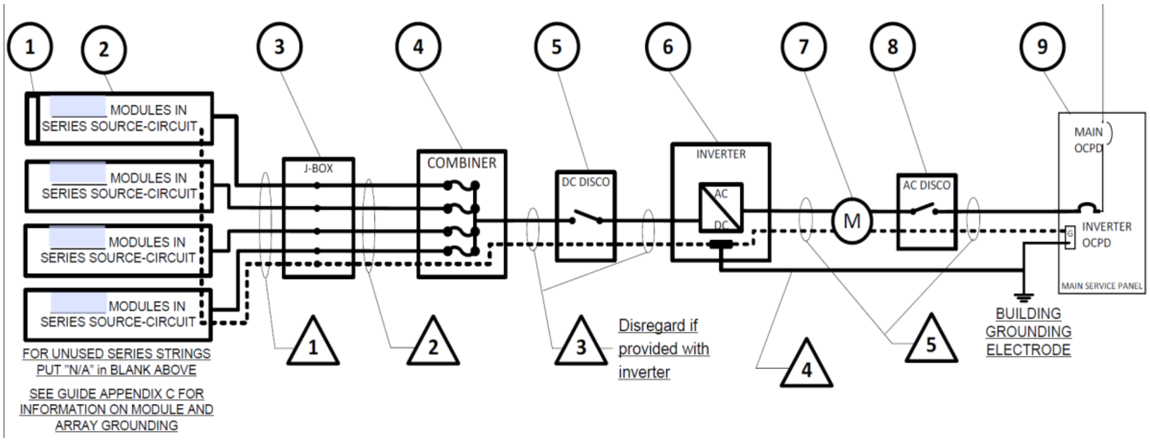

Figure 5: Standard electrical diagram.

Each circuit such as PV source circuits, inverter output circuits, and grounding was designed using corrected temperature and conduit factors. Conductors were sized based on current-carrying requirements, terminal ratings, and allowable voltage drop. Overcurrent protection devices were selected to prevent damage from short circuits or overloads, and grounding conductors were specified to ensure all exposed metal parts are safely bonded.

Voltage drop was calculated for both DC and AC circuits to maintain system efficiency and avoid shutdown due to voltage rise. The utility interconnection was designed using the NEC 120% rule to determine the allowable size of the backfed breaker in the main service panel. These calculations help confirm that the inverter output does not exceed panel limits and that the system can operate safely under normal and extreme conditions.

All equipment selections, wire sizing, protection devices, and voltage drop and utility interconnection calculations were documented in detail in the project spreadsheet. This ensures transparency, compliance, and a reliable electrical design ready for construction and inspection.

4.3.6 Mechanical Integration

Mechanical integration focuses on the physical structure that supports the solar PV system. It ensures that the array is securely mounted to the building and is capable of withstanding local wind, snow, and other structural loads, and complies with national structural codes, particularly ASCE 7 and the International Building Code (IBC).

The process begins with selecting a racking system that is compatible with the module type and roof structure. In this project, the racking was selected based on manufacturer specifications for strength, spacing, and compatibility with the site's roof slope and material. The total rail length was calculated from the number of modules and their orientation. The weight of the array, including modules and rails, was also computed to ensure it remains within roof capacity limits. Wind and snow loads were determined using the simplified ASCE 7 method, which considers factors such as building height, roof type, exposure category, and local wind speeds. Using pressure coefficients, the downward and uplift forces on the array were calculated.

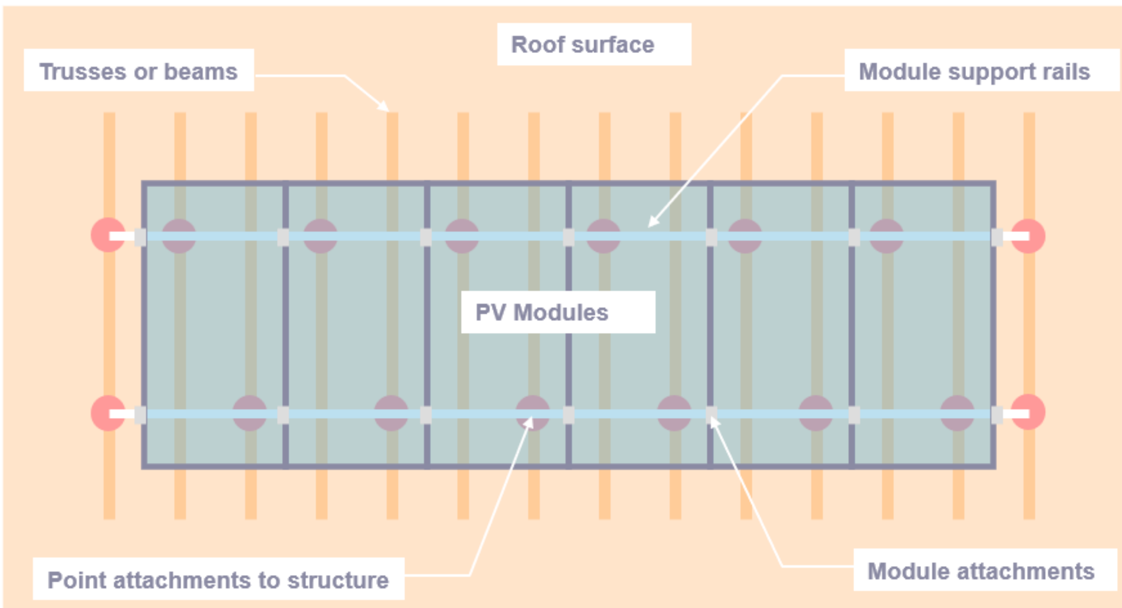

Figure 6: Structural layout of a rooftop PV system

To resist these forces, we determined how many structural attachment points were required. Each attachment point was designed to anchor securely into the underlying structure, such as rafters or trusses, using lag screws. The allowable withdrawal strength of the screws was calculated based on wood type, screw size, and embedment depth. From this, the minimum number of attachment points needed to resist uplift was calculated and evenly distributed across the array. Spacing between attachment points was then compared to the racking manufacturer's guidelines to confirm compliance. Additionally, the total distributed weight on the roof was calculated in pounds per square foot to verify it remained below the limit for residential roofs. The load calculations, racking layout, rail spans, and attachment spacing were all validated to ensure the array can resist both downward and uplift pressures safely. All hardware used rails, fasteners, clamps was selected to match environmental conditions and ensure corrosion resistance.

4.4 Code Compliance and Design Standards

Figure 7: Compliance standards followed for PV system design and installation.

To ensure the safe, efficient, and legally compliant deployment of residential and commercial solar PV systems, all aspects of system design and installation were carried out in strict accordance with national and international codes and standards. Electrical system design followed the National Electrical Code (NEC), with primary focus on Article 690 for photovoltaic systems, and supporting articles including 705 (interconnections), 250 (grounding and bonding), 310 (conductor sizing), and 110 (general requirements). All conductors, overcurrent protection devices (OCPDs), grounding systems, and disconnects were selected and sized based on these NEC guidelines to ensure proper current handling, thermal and mechanical safety, voltage drop limits, and protection under normal and fault conditions.

Structural and mechanical components were designed in accordance with ASCE 7 and local building codes, incorporating wind and snow load calculations, exposure categories, topographic factors, and allowable stress design. Load combinations were analyzed using simplified procedures from ASCE 7 to determine uplift and downward forces, which guided the selection and placement of racking systems and attachment hardware. Compliance with surface roughness categories, occupancy types, and design pressures ensured the array's structural integrity under extreme weather conditions.

All major equipment including PV modules, inverters, and racking systems—was selected based on third-party certifications from Nationally Recognized Testing Laboratories (NRTLs). These products meet international standards such as IEC 61215 for PV module performance and durability, and IEEE 1547/1741 for grid-interactive inverter functionality and safety.

The system design package prepared for permitting and interconnection includes all required documentation: detailed electrical and mechanical drawings, a one-line diagram, system specifications, grounding and bonding methods, warning placards, and verification of rapid shutdown capability in compliance with NEC 2017 requirements. This code-compliant framework makes the system more reliable, safe and streamlines approval by Authorities Having Jurisdiction (AHJs) and utility partners.

5. Results and System Performance Evaluation

5.1 Technical System Overview

This study evaluated three photovoltaic (PV) systems deployed across distinct sites representing both commercial and residential sectors: MLK Centre (commercial), and Sarah Molbert and Tara B. Nice (residential). Each system was designed to match specific site conditions and energy usage profiles while ensuring technical compliance with NEC standards and economic feasibility. The MLK Centre system, mounted on a flat roof, is the largest installation, with a DC capacity of 34.56 kWdc and AC output of 30 kWac, yielding a DC/AC ratio of 1.15. It comprises 72 modules and is projected to produce approximately 45,300 kWh annually, covering 63% of the building's electricity needs. The residential systems, installed on gable roofs, are significantly smaller in scale, with DC sizes of 2.4 kWdc (Sarah Molbert) and 4.56 kWdc (Tara B. Nice), respectively. They each utilize fewer modules 6 and 12 and produce between 3,600 to 6,800 kWh annually, offsetting 34% to 46% of household consumption.

Project Name	MLK Centre	Sarah Molbert	Tara B. Nice	
Type	Commercial	Residential	Residential	
Mounting type	Flat roof	Gable roof	Gable roof	
Azimuth	189	170	170	
Actual DC Size	34.56	2.4	4.56	kWdc
Actual AC Size	30	2	3.84	kWac
DC/AC Ratio	1.15	1.2	1.19	
Expected Annual Production (kWh)	45300	3607	6854	kWh
Total number of modules	72	6	12	
Percent of Annual Usage	63	46	34	%
LCOE	0.123	0.161	0.141	$/kWh
Simple Payback	13.5	9.3	12.8	years
Total DC Voltage Drop	0.34	1.38	0.73	%
Total AC Voltage Drop	0.03	0.05	0.08	%

Figure 8: Technical and Economic Comparison of all the Systems

The systems' performance is further characterized by key metrics such as Levelized Cost of Energy (LCOE), ranging from $0.123/kWh for the commercial system to $0.161/kWh for the smaller residential array. This reflects economies of scale and site-specific installation efficiencies. Voltage drop levels both DC and AC were maintained within acceptable limits, ensuring minimal electrical losses and compliance with design standards. All three systems exhibit effective energy generation and integration, with simple payback periods between 9 and 13.5 years depending on system size and usage offset.

5.2 Energy Yield Analysis

By evaluating each PV system's yearly output according to design parameters including azimuth, roof type, and DC/AC ratio, the energy yield analysis shows how well solar irradiation is transformed into electrical power.

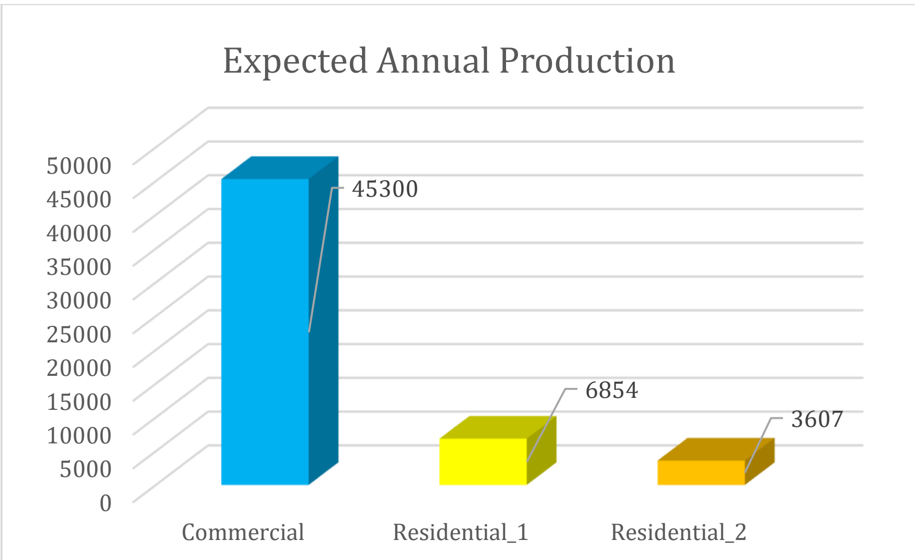

Figure 9: Expected Annual Energy Output by System Type

With a yearly energy yield of about 45,300 kWh, the MLK Center demonstrated the highest energy yield of any commercial system. This performance is a direct result of its larger array size (34.56 kWdc), optimized flat-roof layout, and favorable azimuth orientation of 189°, which allows for consistent solar exposure throughout the day. The resulting energy yield per installed kilowatt is indicative of efficient system utilization, aided by minimal DC (0.34%) and AC (0.03%) voltage drops.

The residential systems, Sarah Molbert and Tara B. Nice, produced 3,607 kWh and 6,854 kWh annually, respectively. Despite their smaller scale, these systems demonstrate solid performance for gable-roof installations, with azimuths of 170° aligning close to optimal south-facing orientation. Their DC/AC ratios (1.2 and 1.19), which facilitate inverter efficiency and energy harvesting without severe clipping losses, are noteworthy since they fall within suggested design standards. Higher percentages of voltage drop, like 1.38% DC in the Sarah Molbert system, may, nevertheless, marginally lower net production, highlighting the necessity of properly sized and arranged conductors in smaller installations.

Across all systems, the energy yield reflects alignment with expected production estimates derived from preliminary modeling tools such as PVWatts or equivalent simulation software. The results validate the technical assumptions made during the design phase and confirm that the systems are capable of delivering consistent, long-term energy output in accordance with site conditions and usage profiles.

5.3 Economic Performance

The economic performance of the three PV systems is evaluated using key financial metrics such as LCOE, offset percentage, and payback period to assess overall cost-effectiveness and return on investment.

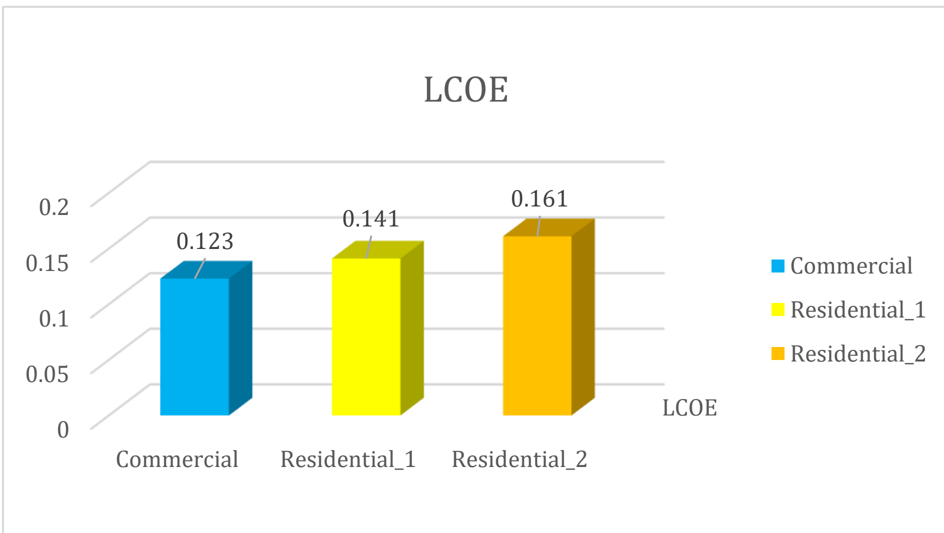

Figure 10: LCOE by System Type: Commercial vs. Residential PV

The MLK Centre commercial system demonstrated the most favorable economic profile, with an LCOE of $0.123/kWh and a simple payback period of approximately 13.5 years. Despite a higher upfront capital investment due to its scale, the larger system benefits from economies of scale, reduced installation cost per watt, and better utilization of equipment and labor. Covering 63% of the facility’s annual electricity usage, the system significantly reduces long-term utility expenses while contributing to sustainability targets and grid resilience.

In contrast, the residential systems Sarah Molbert and Tara B. Nice exhibited higher LCOEs of $0.161/kWh and $0.141/kWh, respectively. These values are typical of small-scale rooftop installations where fixed costs (e.g., permitting, labor, and soft costs) have a greater per-watt impact. Nevertheless, both systems remain economically viable due to long-term energy savings and the availability of financial incentives such as net metering and the federal Investment Tax Credit (ITC). Their simple payback periods, 9.3 years for Sarah Molbert and 12.8 years for Tara B. Nice, reflect the balance between system scale, energy offset levels, and site-specific cost factors. Notably, the computed LCOEs for these systems are higher than the retail rate in Louisiana, although utility energy costs are among the lowest in the United States. This highlights the challenge of achieving short payback purely from cost savings in low-rate regions and underscores the importance of non-financial drivers such as energy independence and sustainability.

6. Analysis

By analyzing key financial metrics such as the Levelized Cost of Energy (LCOE), system offset percentage, and simple payback period, the economic performance of the installed solar PV systems was assessed. Different cost dynamics impacted by scale, design complexity, and incentive eligibility are revealed by comparing residential and commercial systems.

Because of its bigger system size and the economies of scale that lowered the cost per installed watt, the commercial installation at the MLK Centre showed superior economic efficiency. The system is a cost-effective investment for long-term energy savings and operational expense reduction because of these benefits, which translate into a lower LCOE and a reasonable payback period. In contrast, the residential systems, while smaller in capacity, exhibited higher LCOE values due to fixed costs like permitting, labor, and soft costs that are spread over fewer kilowatts. While the LCOE for all systems ranged from $0.123/kWh to $0.161/kWh, these values are higher than the current average utility electricity rate in Louisiana. This is mainly due to Louisiana's low electricity rates, which reduce short-term savings, but solar remains a viable investment when considering long-term benefits and incentives. However, the availability of residential financial incentives—such as the federal Investment Tax Credit (ITC), local net metering policies, and utility rebates—helped improve their economic viability.

The report also highlights how local regulatory limitations can significantly affect solar project profitability. Project viability and return on investment may be significantly impacted by modifications to tax incentive programs, interconnection regulations, and net metering schemes. Therefore, ongoing policy monitoring and adaptable financial modeling are necessary to sustain favorable investment outcomes.

7. Discussion

This internship project provided a multifaceted perspective on the practical and theoretical aspects of solar PV system deployment for both residential and commercial applications. While the design methodology followed standardized approaches using NEC and ASCE guidelines, real-world implementation presented site-specific challenges such as roof orientation, shading, structural load capacity, and interconnection limitations, particularly for residential systems. One key limitation of this study is that it did not incorporate energy storage systems in the design phase. As a result, the analysis could not evaluate the impact of batteries on load shifting, backup power, or overall self-consumption, which are becoming increasingly relevant in modern PV applications. Economic modeling also had to accommodate evolving incentive policies and assumptions on utility rates and tax credits, which could significantly impact financial viability over time. More advanced simulation platforms like PVSyst could enhance future system accuracy, especially under variable weather conditions, although PVWatts and spreadsheet-based tools provided sufficient preliminary estimates. The future goal is to integrate energy storage, real-time monitoring, and adaptive control, which can significantly enhance system resilience and functionality, reaffirming that the battery system does not exist in this design, that successful PV deployment relies on thoughtful engineering, site-specific adaptation, economic viability, and strict adherence to codes and safety standards.

8. Conclusion

This internship evolved with challenges and solutions in solar PV deployment from the bottom of practical implementation to the integration of design standards and economic modeling. It was a contemplation of valuable insight into how scale, site conditions, and regulatory factors influence both technical and financial outcomes. The commercial systems took advantage of economies of scale, while the residential systems showed how important good design and incentives are. Each installation met its performance goals even without energy storage in the design, which highlights how crucial careful engineering and following codes can be. The research underlined the need for adapting designs to specific sites and considering sustainability, reinforcing our understanding of how to design photovoltaic (PV) systems from start to finish. Adding storage and smart energy controls in the future will be key to improving energy independence, resilience, and the overall value of future designs.

9. References

1. Jim Dunlop, Photovoltaic Systems (3rd ed.). (2012). American Technical Publishers.
2. *Solar Electric Handbook: Photovoltaic Fundamentals and Applications*, (2nd ed). (2017). Solar Energy International.
3. International Energy Agency. (2024, October). IEA. https://www.iea.org/reports/renewables-2024
4. SEIA. (2025, June 26). *Home – SEIA*. https://seia.org/
5. *ASCE Hazard Tool*. (n.d.). https://ascehazardtool.org/
6. Record Growth in Renewables, but Progress Needs to be Equitable. (2024, March 27). https://www.irena.org/News/pressreleases/2024/Mar/Record-Growth-in-Renewables-but-Progress-Needs-to-be-Equitable
7. *China's solar capacity installations grew rapidly in 2024*. (2025, April 22). U.S. Energy Information Administration. https://www.eia.gov/todayinenergy/detail.php?id=65064
8. *EU expects to add record renewable capacity in 2025, industry sees headwinds*. (2015, April 10). https://www.renewableinstitute.org/significant-renewable-energy-expansion-expected-for-europe-in-2025/
9. Greentech Renewables. (n.d.). *Going beyond supply*. https://www.greentechrenewables.com/
10. SEIA. (2025a, March 11). *REPORT: Solar adds more new capacity to the grid in 2024 than any energy technology in the past two decades – SEIA*. https://seia.org/news/report-solar-adds-more-new-capacity-to-the-grid-in-2024-than-any-energy-technology-in-the-past-two-decades/
11. *Wind and solar overtake coal power for first time in U.S*. (2025, March 12). Wall Street Journal. https://www.wsj.com/articles/wind-and-solar-overtake-coal-power-for-the-first-time-in-the-u-a52e9d8f?gaa_at=eafs&gaa_n=ASWzDAj4wlKznZbzZXZVecChBYAFPl6eTzATC8TUq8oFTpNUwl06JhGuwjTdHQvDJqk%3D&gaa_ts=6867983b&gaa_sig=KGefloXIP32azuEA4e_96Un5ksISf_Y_KCmYWLJanDP3mvDbTWZ1J_7Xc1rABphw7G5NPx9bQptRavfSaR0mOw%3D%3D
12. *PVWatts - NREL*. (n.d.). https://pvwatts.nrel.gov/pvwatts.php
13. *NFPA 70 (NEC) Code Development*. (n.d.). https://www.nfpa.org/codes-and-standards/nfpa-70-standard-development/70
14. https://unirac.com/. (2022, April 10). UNIRAC: World-Class Solar Mounting Products and Services. https://unirac.com/

Appendix

- *Module Power Density (Wdc/m2) = (Module Output in Wdc)/(Module Area in m2)*
- *Largest Possible DC System Size (kWdc) = (Available roof area for array)(Module Power Density)/1000*
- *Necessary DC System Size (kWdc) = (Desired Percent of Annual Electricity Offset)(Annual Energy Use)/(PVWATTS annual output per 1 kWdc)*
- *Nominal AC System Size (kWac) = (DC System Size)/(Assumed DC/AC Ratio)*
- *Nominal Surface Area Needed (m2) = (DC System Size)/(Module Power Density)*
- *Nominal Number of Modules = (DC System Size in kWdc)(1000 Wdc/ kWdc)/(Assumed Module Pmp in Wdc)*
- *Expected Annual Production (kWh/year) = [(Nominal Number of Modules)(Assumed Module Pmp in W)/1000 W/kW](PVWATTS annual output per 1 kWdc)*
- *Estimated Installed Cost ($) = (Assumed Installed Cost in $/kWdc)(Nominal Number of Modules)(Assumed Module Pmp in W)*
- *Total Tax Credits and Rebates ($) = (Estimated Installed Cost)(Eligible Federal Tax Credit% + Eligible State Tax Credit% + Rebates%)*
- *Net Installed Cost ($) = Estimated Installed Cost -Total Tax Credits and Rebates*
- *Annual Energy Savings ($/year) = (Expected Annual Production in kWh/year)(Effective Energy Cost in $/kWh)*
- *Simple Payback Period (Years) = (Net Installed Cost in $)/(Annual Energy Savings ($/year)*
- *Present value,* $PV = \frac{FV}{(1+i)^t}$
- $P_{ann} = S\left[\frac{i}{1-(1+i)^{-t}}\right]$
  - $LCOE\left(\frac{\$}{kWh}\right) = \left[\frac{What\ the\ energy\ costs\ over\ lifetime}{How\ much\ energy\ you\ get\ over\ lifetime}\right]$
  - $LCOE = \left[\frac{(TCC)(FCR) + FOC}{AEP}\right] + VOC$
  - $SPP = \frac{initial\ cost}{annual\ savings}$
- *Temperature-corrected maximum module*

Voc = Voc x [100% + ((Tmin - Tstc) x TkVoc)]

- *Maximum of modules in series≤ Maximum inverter voltage/Maximum module Voc*
- *Temperature-corrected minimum module*

  Vmp = Vmp x [100% + ((Tadd+ Tmax - Tstc) x TkPmp)]
- *Max String Current = Module Isc * 1.25*
- *Max String STC Power (kW) = (Module Pmp in W)(Number of Modules per String)/1000 W/kW*
- *Max System Voltage = Max Vmp * Number of Modules per String*
- *Max Parallel Strings = (Max Inverter STC Power) / (Max String STC Power)*
- *Max Parallel Strings Series Fusing = ((Maximum Series Fuse Rating) / (Max String Current)) + 1*
- *Total Number of Modules = Number of Modules per String * Number of Parallel Strings*
- *PV source circuit current = Module Isc x 1.25*
- *PV output circuit current = Parallel source circuits x Module Isc x 1.25*
- *Ampacity Under Conditions of Use = (Max String Current) / (Conditions of Use Factors)*
- *Required Backfed Breaker Size = 1.25 * Inverter Max Output Current (for continuous use)*
- *Allowable Backfed Breaker Size = (1.2)(Service Panel Main Lug Rating) – (Main Breaker Rating)*
- *DC and split phase AC,* $V_{drop\%} = \frac{0.2*D*I*R}{V_{circuit}}$
- *Wind pressure,* $P_{net} = \lambda \times K_{zt} \times I \times P_{net30}$

Self-assessment:

” Returning for the second internship at the same place feels like a long-awaited homecoming, where the surroundings offer a sense of belonging and comfort, and the path ahead unfolds effortlessly. There’s something remarkable about being in an environment that feels so right, where every task brings a sense of purpose. From the moment this journey began in France, it has blossomed into a daily growth that continues to unfold. To be part of this lab is nothing short of an honor, where every corner sparks a desire to learn more and make a real difference in the world, pushing us all closer to a future of sustainability.”

03/07/2025

ROY jui