

Implementation of Solar Driven Vertical Farming in Manila, Philippines

Amida Akpan, Jade Malendez, Jakobi Davis, Jasmine Mustafa, Teresa Crisantos-Prudencio

Table of Contents

Abstract.....	3
Scope of the Problem.....	3
Proposed Solution.....	5
Implementation in Manila.....	7
Criteria for Selecting Sites in Urban Areas.....	7
Advantages of Manila’s Tropical Climate for Solar Energy.....	9
Pilot Project Description.....	9
Expected Outcomes and Scalability.....	11
Initial Outcomes of the Pilot Farm.....	11
Scalability of Solar-Driven Vertical Farms.....	12
Technical Analysis.....	12
Solar Energy Integration.....	14
Efficiency and Productivity Metrics.....	15
Crop Yield Comparison.....	15
Resource Efficiency.....	15
Economic Feasibility.....	16
Conclusion.....	19
References.....	20
Appendix A: Source Code Graphs and Calculations for Economic Feasibility.....	22

Abstract

This report presents a novel approach to addressing food insecurity and energy challenges in urban environments through the implementation of solar-driven vertical farming, with a specific focus on Manila, Philippines. Manila, a densely populated city, faces critical issues of limited agricultural land, high energy demands, and food supply chain vulnerabilities. The proposed solution integrates renewable energy, specifically solar power, with advanced vertical farming technologies to create a scalable, sustainable model for urban agriculture. Key features of the project include the use of a 6 kW rooftop solar array to power energy-intensive hydroponic systems, enabling year-round crop production with minimal resource consumption. The hydroponic setup optimizes water usage, achieving up to 90% reductions compared to traditional farming, and delivers crop yields 20 to 25 times higher per square meter. The solar integration ensures a reliable and renewable energy source, reducing dependency on fossil fuels and lowering greenhouse gas emissions. Surplus energy generated can be sold back to the grid, enhancing economic feasibility. The economic analysis highlights the project's viability, with a competitive levelized cost of energy (LCOE) calculated at \$0.0528 per kWh. This cost underscores the financial sustainability of the model, making it comparable to or more affordable than traditional energy sources, while providing additional revenue streams through produce sales and grid energy feedback. This initiative not only addresses food and energy security but also provides a replicable framework for sustainable urban development. By leveraging Manila's tropical climate and urban infrastructure, solar-driven vertical farming has the potential to transform urban landscapes, improve resource efficiency, and enhance the resilience of cities across Southeast Asia.

Scope of the Problem

Manila, the capital city of the Philippines, faces significant challenges in urban food production and food insecurity. According to a United Nations report, nearly 51 million Filipinos experienced moderate or severe food insecurity between 2020 and 2022, the highest number in Southeast Asia (1). This alarming statistic highlights the urgent need for innovative solutions to address food scarcity in densely populated urban areas like Manila.

The high population density in Manila exacerbates the issue of food insecurity. With limited space for traditional farming, the city struggles to produce enough food to meet the needs of its residents. Urbanization has led to longer and more complex food supply chains, increasing the vulnerability of food systems to external shocks such as climate change and economic disruptions (2). As a result, many urban dwellers must rely on food sources outside their local production, further straining the food supply and increasing the risk of food insecurity.

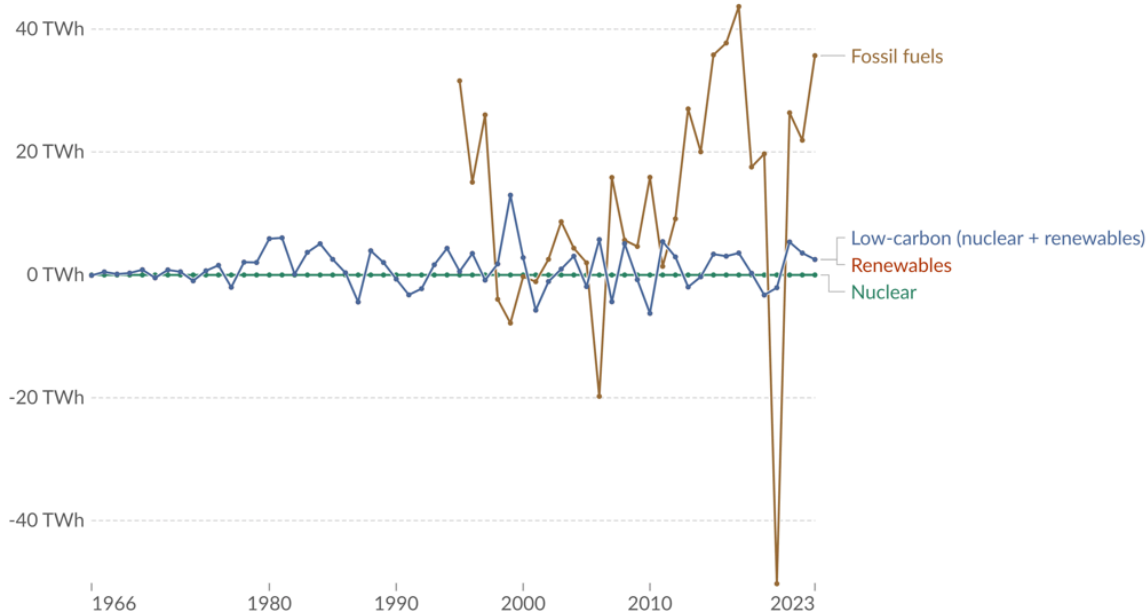
The COVID-19 pandemic has further weakened food security in urban poor communities in Manila. The pandemic disrupted food supply chains, reduced incomes, and increased the number of people facing hunger (3). Families living in informal settlements, who already had limited access to regular livelihoods, were disproportionately affected. This situation underscores the need for resilient and sustainable food production systems that can withstand such shocks and ensure a stable food supply for urban populations.

In addition to food insecurity, Manila faces significant energy challenges. The city's tropical climate, with average high temperatures never dropping below 30°C, results in high energy consumption for cooling (4). This demand places a substantial burden on the energy infrastructure, leading to frequent shortages and high energy costs for residents and businesses.

Year-to-year change in primary energy consumption from fossil fuels vs. low-carbon energy, Philippines, 1966 to 2023

Our World
in Data

Annual change in primary energy¹ consumption in one year, relative to the previous year. Energy is measured in terawatt-hours², using the substitution method³.



Data source: Energy Institute - Statistical Review of World Energy (2024)

OurWorldinData.org/energy | CC BY

Figure 1: Illustrating the lack of renewables in the Philippines energy mix (6).

The Philippine government has recognized the importance of addressing energy needs and has implemented policies to promote renewable energy and energy efficiency. The Renewable Energy Act aims to increase the share of renewable energy in the country's energy mix, while the Energy Efficiency and Conservation Law encourages the adoption of energy-saving practices (5). Despite these efforts, the rapid urbanization and economic growth in Manila continue to drive up energy demand, necessitating further innovative solutions to ensure a sustainable energy supply.

Integrating renewable energy sources, such as solar power, into urban infrastructure can help address these energy challenges. Solar energy is particularly suitable for Manila due to its consistent sunlight throughout the year (5). By harnessing solar power, urban areas can reduce their reliance on non-renewable energy sources, lower energy costs, and contribute to a more sustainable and resilient energy system.

Proposed Solution

Vertical farming

Traditional farming utilizes vast amounts of land and water and depends on natural sunlight. According to the UN Food and Agriculture organization 44% of habitable land is used for agriculture. (1) This is almost half of the Earth's habitable land. Utilizing this amount of land for agriculture will be hard to maintain as our world's population continues to grow. Not only does traditional farming depend on vast amounts of land but also on a lot of water. According to the UN's World Water Development Report 70% of freshwater is used for agriculture. (2) However, 40% of the water used is underutilized. (2) In traditional farming sprinklers are used to water crops. These sprinklers do not water specific crops but rather cover entire areas. This is oftentimes wasteful as less water could be used if crops were specifically targeted. Water is also lost to evaporation, runoff, and it being lost in transit.(2) Runoff coming from farms is filled with pesticides, fertilizers, and manure that are harmful to aquatic life and to our drinking water supplies. (3)

Vertical Farming can address a lot of the problems that come with traditional farming. Vertical farming can maximize land utilization, produce more food per unit area, and operate year-round, ensuring a stable supply of fresh produce (4) Additionally, these farms can reduce transportation costs, wastage, and emissions by bringing food production closer to consumers. (4) Vertical farming is an innovative approach to agriculture that involves growing crops in vertically stacked layers, often integrated into other structures like buildings or shipping containers. This method maximizes land use efficiency and is particularly suited for urban environments where space is at a premium. Vertical farms can operate year-round, independent of seasonal changes, and can be located close to consumers, reducing transportation costs and emissions (5). Since vertical farming has controlled conditions there can be higher crop yields and even faster growing cycles.

Recent advancements in vertical farming technology include the use of LED lighting, automated climate control systems, and advanced hydroponic and aeroponic systems (6). These technologies enable precise control over growing conditions, leading to higher yields and better quality produce. Studies have shown that vertical farming can significantly reduce water usage compared to traditional farming methods, making it a more sustainable option for urban agriculture (6)

Design of Solar-Driven Vertical Farms

One of the biggest concerns of vertical farms as they stand now is their massive electricity use. They require a lot of electricity as they utilize a lot of LED lamps, HVAC systems, and water filtration systems. Reports have found that vertical farms have a significantly higher average energy use at 38.8 kWh per kg of produce compared to traditional greenhouses, which average 5.4 kWh per kg. (7)

The integration of solar panels allows these farms to harness renewable energy, which can power the farm's operations, including lighting, climate control, and water circulation systems. This dual-purpose use of space and resources makes solar-driven vertical farms particularly suitable for densely populated urban areas like Manila, where land is scarce and energy demands are high.

Solar panels are designed to capture a wide spectrum of light. (8) Thus even if there are cloudy days where there is not a lot of sunlight enough electricity can be generated to power the vertical farm. There are also methods of storing solar energy that may be generated in excess in case there are times where not enough electricity is produced. This is especially important as peak energy output is during daylight hours, however there should be enough energy to keep the farms running at night.

Down below is a diagram of how solar panels could be integrated into a vertical farm.

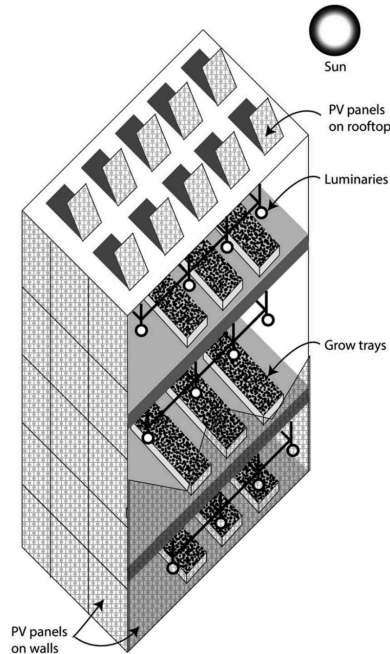


Figure 2: Schematic diagram of a vertical farm (9)

Benefits of Solar-Driven Vertical Farms

Solar panels can be installed on rooftops or integrated into the structure of vertical farms to provide a reliable source of clean energy. This energy can be used to power all the necessary components of vertical farming, reducing the reliance on fossil fuels and lowering greenhouse gas emissions.

Studies have shown that the integration of renewable energy into urban farming systems can improve their economic viability by reducing energy costs and increasing the overall efficiency of the farming operations. For example, rooftop greenhouses that utilize solar energy have been found to optimize land use, increase water use efficiency, and reduce the energy consumption of both the greenhouse and the host building (10). Since solar panels are well integrated into these vertical farms they are taking up the least amount of space possible. This allows for more space for crops to be grown. This symbiotic relationship between urban farming and renewable energy not only enhances the sustainability of food production but also contributes to the overall resilience of urban infrastructure (10).

Vertical farms can produce more crops than traditional farms on average. This is essential when we think about fighting food insecurity. Roughly 470 tons of produce is harvested per acre of land in a vertical farm. (5) A major reason why so much can be grown per acre is because space is efficiently used in

vertical farms. For example, the amount of strawberries that can be grown in one acre of vertical farming land would require 30 acres of traditional farming land. (5) Multiple different crops can be grown at the same time in a vertical farm in comparison to traditional farming. (5) In traditional farming only one crop can be grown at a time in every field. This is not true for vertical farming as different crops can be grown on each floor. This will allow communities to have access to more produce. In vertical farms crops can be grown year round regardless of whether they are “in season” or not since the conditions inside of the farm are controlled.

Not only does vertical farming help with crop production but also helps reduce the amount of water used in the process. Vertical farming can reduce the amount of water used by 95%. (5) Wastewater of the host building can be recycled to be used in the farm as well. Harmful runoff can also be prevented as these farms will be in buildings where it will be harder for water to seep out. In addition since vertical farms do not take as much space they can be implemented in more urban areas. This will result in produce not having to be transported far. This will bring this expense down and make some produce more cost friendly.

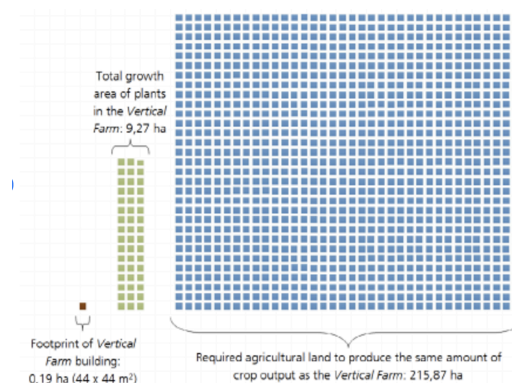


Figure 3: Illustrating difference of land required in traditional farming vs vertical farming (11)

Implementation in Manila

Site Selection and Suitability for Solar-Driven Vertical Farms

Location selection is crucial for the successful implementation of solar-driven vertical farms in urban areas. In a dense and dynamic city like Manila, site suitability depends on factors such as sunlight availability, infrastructure compatibility, and potential community impact. Identifying optimal sites ensures efficient resource utilization, maximizes energy generation, and supports sustainable food production, addressing both urban food insecurity and energy needs.

Criteria for Selecting Sites in Urban Areas

Manila's dense urban environment and tropical climate create both opportunities and challenges for implementing solar energy systems integrated with vertical farming. Ideal sites for these systems include low-rise and high-rise buildings with sufficient structural support and unobstructed exposure to sunlight. Rooftops or walls that receive at least six hours of direct sunlight daily are essential for

maximizing energy output. Proximity to water sources and urban infrastructure further ensures efficient operation and ease of maintenance. Prioritizing high energy-consuming buildings, such as commercial complexes, optimizes renewable energy utilization, while focusing on areas with high levels of food insecurity and energy costs enhances the project's social and economic benefits.

Manila's high solar irradiance, averaging 5.5 kWh/m²/day, enables solar panels to operate with exceptional efficiency and cost-effectiveness. Minimal seasonal variation ensures a reliable and consistent energy supply, critical for powering vertical farming operations such as lighting, water pumps, and climate control systems. This dependable energy generation underscores the suitability of Manila's climate for integrating solar power into sustainable urban agriculture systems.

When considering the establishment of solar-driven vertical farms in urban environments, several critical factors must be evaluated to ensure efficiency and sustainability. The following criteria are fundamental in identifying optimal locations:

Space Availability: Urban areas are typically constrained by limited land available for traditional farming. However, underutilized spaces such as rooftops, vacant lots, and abandoned buildings present an ideal opportunity for vertical farming. These spaces are highly suitable because vertical farming employs multi-layered systems, maximizing limited space and making it perfect for densely packed cities like Manila, where land is scarce.

Solar Exposure: Solar-driven vertical farms rely heavily on solar energy to power their operations. Therefore, selecting a site with high solar exposure is crucial for the farm's energy efficiency. Locations receiving high levels of solar irradiance ensure adequate energy generation to operate LED grow lights, irrigation systems, and other essential technologies. Maximizing solar energy is key to reducing reliance on external electricity grids, contributing to the farm's sustainability.

Proximity to Markets

Urban areas with high population densities offer significant advantages for urban agriculture. Proximity to markets is crucial for reducing transportation costs and food miles, which helps in delivering fresher produce. Being located near consumers allows farms to address local food demand, contributing to regional food security and reducing the environmental impact associated with long-distance food transportation.

Infrastructure Accessibility

A reliable water supply, access to electricity (either through solar panels or backup power), and proximity to transportation networks are vital infrastructure considerations. Vertical farms require substantial water and energy resources, making it essential to be close to reliable utilities and transport routes for both supply and distribution.

Zoning and Regulations

Compliance with local zoning laws, building codes, and urban agricultural policies is essential to avoid legal challenges. Urban agricultural projects must navigate land-use restrictions and construction codes, ensuring the site is suitable for vertical farming operations. Adherence to these regulations helps mitigate delays and legal obstacles during the project development phase.

Advantages of Manila's Tropical Climate for Solar Energy

Manila, the capital city of the Philippines, is uniquely positioned to benefit from solar-driven vertical farms due to its tropical climate, which offers several distinct advantages for solar energy generation. These advantages include:

High Solar Irradiance

Manila enjoys high levels of solar irradiance, with an average of 3.2–6.5 kWh/m²/day. This makes the city an ideal location for solar power installations. High solar irradiance ensures that solar panels can generate significant amounts of energy, providing the necessary power to run a vertical farm's operations.

Year-Round Sunlight

Unlike regions with seasonal changes, Manila experiences consistent daylight hours throughout the year. This consistent exposure to sunlight allows for stable solar energy production, even during cloudy or rainy days, albeit at reduced efficiency. The year-round sunlight is essential for maintaining a reliable power supply for solar-driven vertical farms.

Urban Density

Manila's dense population, with over 1.7 million residents, is a significant advantage for urban agriculture. With a large urban population, there is a continuous demand for fresh, locally grown produce. By locating solar-driven vertical farms in or near densely populated areas, the farm can minimize the distance between production and consumption, reducing transportation costs and providing a steady market for the farm's produce.

Disadvantages of Manila's Tropical Climate for Solar Energy

Seasonal Variation (Monsoons)

Manila experiences distinct seasonal variations, characterized by a dry season from January to April and a rainy season from May to December (3). The dry season is relatively hot and dry, with temperatures peaking in April and May. In contrast, the rainy season, particularly from June to October, brings heavy rainfall and high humidity, often accompanied by typhoons. These seasonal changes can significantly impact the performance of solar photovoltaic (PV) systems. During the rainy season, reduced sunlight due

to cloud cover and frequent rain can decrease the efficiency and energy output of solar panels. Additionally, severe weather conditions, such as typhoons, can cause physical damage to the solar infrastructure, leading to potential disruptions in energy production. Therefore, when implementing solar-driven vertical farming systems in Manila, it is crucial to consider these seasonal variations to ensure consistent and reliable energy supply throughout the year.

Pilot Project Description

The pilot project integrating solar energy with vertical farming in Manila is expected to deliver transformative outcomes across energy, food security, and economic dimensions. By utilizing solar power, the project will significantly reduce dependence on fossil fuels, offsetting building energy needs and contributing to a cleaner urban energy landscape. This shift not only addresses the city's high energy demand but also reduces greenhouse gas emissions, aligning with global sustainability goals. Additionally, the production of fresh, locally grown produce will enhance food security by minimizing reliance on imported goods, cutting transportation costs, and lowering carbon emissions associated with food logistics.

Economic feasibility is another crucial benefit anticipated from the pilot project. The integration of renewable energy and urban agriculture is designed to demonstrate tangible cost savings through improved energy efficiency. Revenue generated from the sale of fresh produce and the potential to feed surplus solar energy back into the grid further supports the project's financial viability. These outcomes provide a scalable model that could be replicated across other urban areas, showcasing the economic, environmental, and social benefits of solar-driven vertical farming in addressing the dual challenges of food insecurity and energy sustainability.

Design Features

Solar Panels

A 6 kW rooftop solar array would be installed to provide the necessary power for the vertical farm's operations. This array would power LED grow lights, water pumps, and automated climate control systems.

Hydroponic Systems

The farm would utilize hydroponic systems with multi-layered growth chambers, optimizing water and nutrient usage. This design allows for the efficient cultivation of leafy greens and herbs in a compact urban space. The Hydroponic Farming System will have the dimensions of 12.192m x 2.438m x 2.896m (Volume = 86.08 m³).

Water Recycling

A closed-loop irrigation system would be implemented to minimize water waste and maximize the efficiency of water usage throughout the farm.

Digital Monitoring

Internet of Things (IoT)-based sensors would be employed to monitor and optimize key environmental factors such as temperature, humidity, and nutrient levels. This technology ensures that the farm operates at peak efficiency.

Location

This economic analysis will focus on the Low-Rise and High-Rise Condominiums in Manila. This will allow the most amount of lives to benefit from the vertical integrated farming system, helping to provide food and energy for all the families living in these buildings. In order to conduct the analysis, further definition of the space of feasible implementation is needed.

Expected Outcomes and Scalability

The pilot project for integrating solar energy with vertical farming in Manila leverages the city's unique urban environment and tropical climate to address pressing energy and food security challenges. Ideal sites include low-rise and high-rise buildings with sufficient structural support, unshaded rooftops or walls receiving at least six hours of direct sunlight daily, and proximity to urban infrastructure for efficient operation. These locations, particularly in areas with high energy demand and food insecurity, maximize both environmental and social benefits. Manila's climate, offering high solar irradiance averaging 5.5 kWh/m²/day and minimal seasonal variation, ensures efficient and steady energy production critical for vertical farming operations such as lighting, water pumps, and climate control systems. The pilot project, utilizing a 6 kW solar array on selected buildings, includes rooftop photovoltaic panels, hydroponic systems for growing high-demand crops like leafy greens, and smart monitoring technology for resource optimization.

This initiative is expected to deliver significant outcomes, including reduced reliance on fossil fuels through renewable energy use, enhanced food security via locally grown produce with lower transportation costs, and improved economic feasibility through energy efficiency and revenue from produce sales and energy feedback to the grid. Scalability is a key feature, with potential for expanding to other urban buildings in Manila and licensing the model to similar cities across Southeast Asia. By integrating cutting-edge solar and agricultural technologies, this project not only demonstrates immediate environmental and economic benefits but also provides a replicable model for sustainable urban development, engaging stakeholders to drive long-term impact.

Initial Outcomes of the Pilot Farm

The proposed solar-driven hydroponic pilot farm in Manila is expected to deliver transformative outcomes in agricultural productivity, energy efficiency, and cost management. One of the most significant advantages is the anticipated high yield, with the farm projected to produce 20 to 25 times more crops per square meter than traditional farming methods. This dramatic increase is made possible by the farm's vertical design and advanced growing techniques, which maximize the use of limited urban space while ensuring optimal growing conditions for crops.

Energy independence is another critical outcome of the pilot project. Solar panels integrated into the system are expected to meet up to 90% of the farm's energy requirements, significantly reducing

reliance on external power sources. Any surplus energy generated can be sold back to the grid, not only offsetting costs but also contributing to the local energy supply and promoting renewable energy adoption in the city.

In addition to increased productivity and energy efficiency, the pilot farm will achieve substantial cost reductions. By utilizing solar energy, recycling water, and employing optimized nutrient delivery systems, the farm minimizes expenses related to electricity, water, fertilizer, and transportation. These efficiencies make the project economically viable while demonstrating the potential for sustainable urban agriculture to address food and energy challenges in densely populated cities like Manila. This pilot farm serves as a scalable model for future urban farming initiatives, combining environmental sustainability with practical economic benefits.

Scalability of Solar-Driven Vertical Farms

The scalability of solar-driven vertical farms offers a promising vision for addressing urban food and energy challenges in Manila and beyond. Following the pilot project's success, similar farms could be established on rooftops across the city, utilizing underutilized spaces on malls, office buildings, and residential complexes. This urban expansion would capitalize on Manila's dense infrastructure and tropical climate, creating a network of productive and sustainable urban farms. Strategic site selection will ensure that these locations maximize sunlight exposure and proximity to urban resources, further enhancing their feasibility and impact.

The adaptability of this model extends beyond Manila, with potential applications in other tropical cities across Southeast Asia. High levels of solar irradiance throughout the region make solar energy a reliable and efficient power source, enabling the replication of these systems in cities facing similar challenges of food insecurity and urban density. Furthermore, large-scale implementation of solar-driven vertical farms could have a significant economic impact, generating employment opportunities in both the agricultural and renewable energy sectors. By supporting local food systems, reducing reliance on imports, and promoting urban sustainability goals, these farms can contribute to long-term environmental and economic resilience. The success of the pilot project in Manila could serve as a catalyst for transforming urban landscapes throughout the region, demonstrating the viability of integrating renewable energy and innovative agriculture into modern cities.

Technical Analysis

Defining The System

This economic analysis will focus on the Low-Rise and High-Rise Condominiums in Manila. This will allow the most amount of lives to benefit from the vertical integrated farming system, helping to provide food and energy for all the families living in these buildings. In order to conduct the analysis, further definition of the space of feasible implementation is needed.

Low-rise buildings are defined as structures with fewer than 12 stories, and are prevalent in Manila, especially in residential areas. According to urban development studies and housing reports, there are approximately 12,000 low-rise residential buildings in Metro Manila (1)(2). Low-rise buildings have an average rooftop size of 111 square meters. High-rise buildings, defined as buildings with 12 or more

stories, have seen significant growth in Manila over the past few decades. As of recent data, there are approximately 215 high-rise buildings in Metro Manila that are 150 meters or taller (3). High Rise buildings have approximately 372 square meters of average rooftop size. This analysis will assume that only 70% of the rooftop space is usable for vertical farming applications. Therefore, the available space for implementation is as follows:

$$A_{LowRise} = (111 \text{ m}^2) * (.70) = 77.7 \text{ m}^2$$

$$A_{HighRise} = (372 \text{ m}^2) * (.70) = 260.4 \text{ m}^2$$

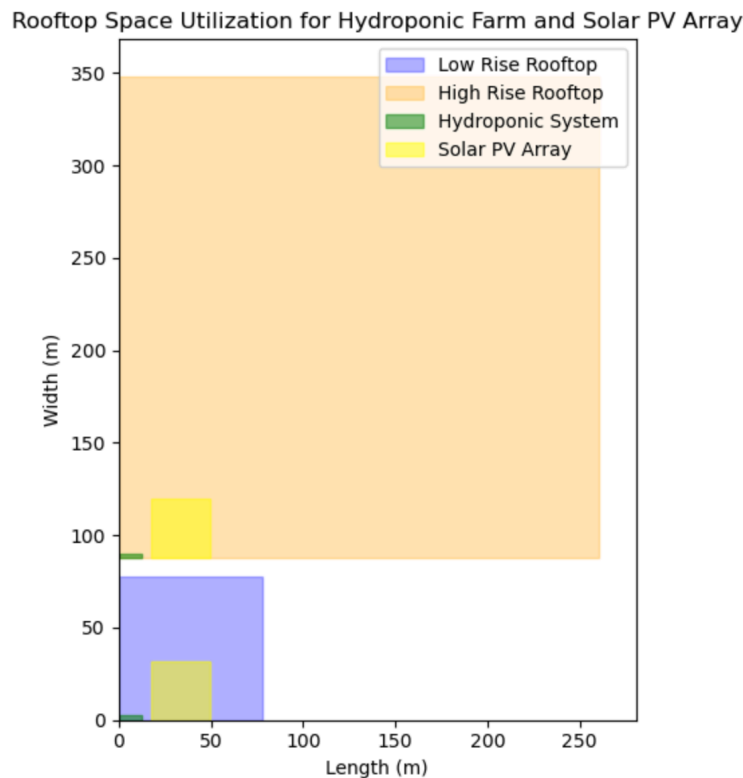


Figure 5: Demonstrates the minimal space required to house the proposed Agro Voltaic system.

This graph is particularly impressive because it visually demonstrates that the space required to house both the hydroponic farm and the solar PV array is not overly burdensome. The hydroponic system, with its compact dimensions, and the solar array, efficiently arranged, occupy only a portion of the available rooftop space on both low-rise and high-rise buildings. This leaves ample room for other uses, such as recreational areas, gardens, or additional infrastructure. Moreover, there is a large potential for scalability of these systems. By highlighting that these systems can coexist with other rooftop functions, the graph underscores the versatility and practicality of integrating sustainable food and energy production into urban environments. This approach enhances the utility of rooftop spaces without monopolizing them, making it a valuable addition rather than a restrictive solution.

Hydroponic Systems in Urban Farming

Hydroponics is a soil-free farming method that grows plants in nutrient-rich water solutions, making it particularly suited for space-constrained urban environments like Manila. These systems consist of the following components:

- **Growth Medium:** Materials such as perlite or coconut coir that support plant roots without soil.
- **Nutrient Solution Delivery:** Recirculated water enriched with nutrients to nourish plants efficiently.
- **Grow Lights:** Energy-efficient LEDs to provide supplemental light in shaded urban areas.
- **Environmental Controls:** Automated systems to regulate temperature, humidity, and nutrient levels for optimal plant growth.

Hydroponic systems are highly productive, using up to 90% less water than traditional farming while producing 20–25 times more crops per square meter. They are ideal for growing high-demand crops like leafy greens and herbs, which are well-suited for local markets.

Solar Energy Integration

Solar energy enhances the sustainability of hydroponic systems by providing a renewable energy source for their operation. In Manila, solar panels can harness the city's average irradiance of 5.5 kWh/m²/day to power essential system components, including grow lights, water pumps, and climate control mechanisms.

Energy Storage and Grid Interaction:

Energy storage and grid interaction play a vital role in the proposed solar-driven hydroponic project in Manila, ensuring reliable and efficient energy use. Battery systems are integrated to provide a continuous power supply during periods of low sunlight, such as nighttime or cloudy days, maintaining the consistent operation of hydroponic systems. Additionally, any surplus energy generated by the solar panels can be fed back into the local grid, not only supporting the city's energy infrastructure but also creating an additional revenue stream for the project. This dual approach enhances the sustainability and economic viability of the system while contributing to Manila's renewable energy goals.

A 6 kW solar array, as proposed for the pilot project, is sufficient to power small-scale hydroponic farms integrated into urban buildings, such as low-rise and high-rise structures.

Efficiency and Productivity

The integration of hydroponics and solar energy offers numerous efficiency and productivity benefits, making it a sustainable solution for urban food production. Controlled environments in hydroponic systems ensure consistently high crop yields, independent of seasonal changes, while significantly reducing water and energy consumption compared to traditional farming methods. Additionally, this innovative combination minimizes the carbon footprint of food production by cutting transportation emissions and reducing reliance on fossil fuels, creating a more environmentally friendly approach to addressing food and energy challenges in urban areas.

By integrating hydroponic farming with solar energy, the project provides an innovative and scalable solution to Manila's food insecurity and energy challenges. Hydroponics and aquaponics are both soil-free farming methods that allow crops to grow in a controlled, water-based environment. These systems are particularly well-suited for urban areas like Manila, where space is limited and traditional farming methods are not feasible. This model, focused on efficient resource use and renewable energy, not only addresses urban sustainability needs but also sets a replicable precedent for other cities facing similar issues. Scaling these systems can contribute significantly to local food production, energy resilience, and environmental conservation.

Efficiency and Productivity Metrics

The integration of hydroponics with solar energy provides significant efficiency and productivity advantages, particularly suited for urban environments like Manila. These metrics include higher crop yields, optimized resource usage, and reduced environmental impact, which collectively contribute to the project's sustainability and scalability.

Crop Yield Comparison

Hydroponic systems enable controlled environments that optimize plant growth, leading to significantly higher yields compared to traditional farming. This is due to precise nutrient delivery, controlled climate conditions, and year-round production capability.

The following chart illustrates crop yield comparisons between traditional farming, hydroponics, and aquaponics:

Farming Method	Yield per Square Meter	Water Usage
Traditional Farming	1x	High
Hydroponics	20-25x	Very Low
Aquaponics	30-40x (fish + plants)	Very Low

Hydroponics can achieve up to 25 times the yield of traditional soil-based farming due to its space-efficient design and ability to grow multiple crops vertically. This is crucial for a densely populated city like Manila, where land availability is a major constraint.

Resource Efficiency

Hydroponic systems are designed to use resources more efficiently, making them ideal for urban environments where water and energy resources may be limited. Solar energy integration further enhances this efficiency.

Hydroponic systems reduce water usage by up to 90% compared to traditional farming methods through closed-loop irrigation. Solar energy integration eliminates dependency on fossil fuels, further reducing environmental impact and operational costs.

The project significantly reduces the carbon footprint of food production by cutting transportation emissions and energy reliance on fossil fuels. The combination of local food production and renewable energy ensures a sustainable approach to urban agriculture, reducing the overall environmental impact.

Economic Feasibility

Capital Cost

The initial capital cost for the project includes the expenses associated with both the solar PV system and the hydroponic farm. The solar PV system, with a capacity of 6 kW, incurs a cost of \$3,400 per kW, resulting in a total expenditure of \$20,400. Additionally, the hydroponic system requires an investment of \$640. Consequently, the combined initial capital cost for the entire setup amounts to \$21,040. This investment is crucial for establishing the infrastructure necessary to meet the energy demands of the hydroponic farm and to ensure the system's operational efficiency from the outset.

In order to solidify capital costs, the overall production of the solar system must be forecasted. For this, PVWatts was employed to provide the necessary forecasts with parameters fed to the engine by our team.

SYSTEM INFO

Modify the inputs below to run the simulation.

DC System Size (kW): 6

Module Type: Standard

Array Type: Fixed (open rack)

System Losses (%): 14.08

Tilt (deg): 15

Azimuth (deg): 180

Rooftop Size Estimator

Click below to estimate the system size from your roof area on a map. (optional)

Figure 6: PVWatts inputs for proposed solar array system (21).

A 6 kW DC system is used to meet the 15 kWh daily energy consumption required by the hydroponics system. This system employs fixed (open rack) array bearings to simplify installation and minimize potential maintenance issues for residents. The design assumes 14.08% system losses, based on global averages, and incorporates a 15° tilt, appropriate for Manila's latitude of 14.6° N. The azimuth is set due south (180°), as solar panels in the northern hemisphere should face the equator to maximize efficiency. This setup ensures that the hydroponic system operates effectively while maintaining ease of use and reliability for urban environments.

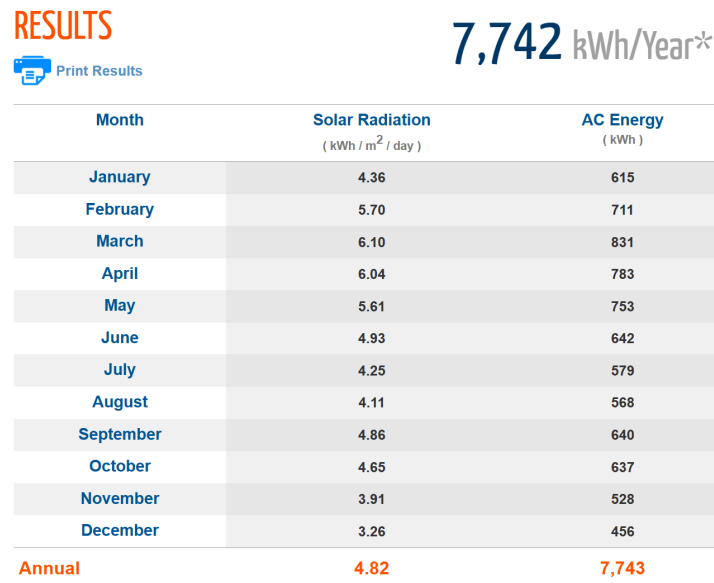


Figure 7: PVWatts predicted monthly output based on aforementioned input parameters (21).

The predicted monthly outputs generated by PVWatts provide a detailed estimate of the solar energy production for each month, considering the aforementioned solar panel factors. Therefore, the capacity factor of this PV system is 14.74%. These outputs and capacity factor are crucial for calculating the Levelized Cost of Energy (LCOE), as they directly influence the total energy production over the system's lifetime. By averaging the monthly outputs, we can determine the annual energy production, which is then used to calculate the LCOE.

Investment Lifetime

The investment lifetime of the project is projected to be 25 years. This duration is chosen to reflect the typical operational lifespan of solar PV systems and hydroponic setups, ensuring that the infrastructure remains functional and efficient over a significant period. The discount rate applied to this investment is 4.2%, which is consistent with the prevailing interest rates offered by Philippine banks. This rate is used to calculate the present value of future costs and revenues, providing a comprehensive understanding of the project's long-term financial viability.

Cost and Revenue

The annual operating cost for the project encompasses maintenance expenses for both the solar PV system and the hydroponic farm. These costs are estimated to be \$21 per year. This figure includes routine maintenance activities necessary to ensure the optimal performance of the systems and to prevent any potential operational disruptions. The total annual costs also account for the depreciation of the initial capital investment over the 25-year lifespan, resulting in an annualized cost of \$1,641.60. This comprehensive approach to calculating operating costs ensures that all expenses are accounted for, providing a realistic estimate of the ongoing financial requirements of the project. To combat the operating costs, the solar PV operator will have the ability to sell excess energy back to the grid.

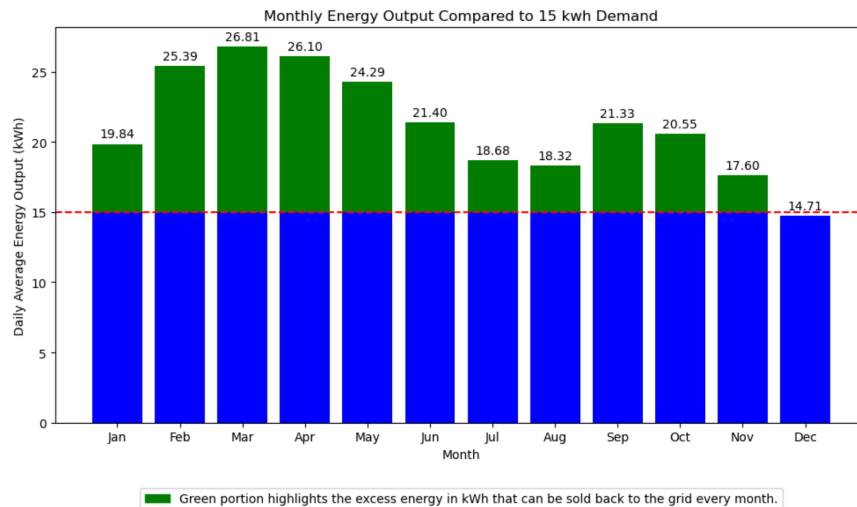


Figure 8: Graphical Representation of the excess energy sold back to the grid each month.

In addition to the revenue from excess energy, the value of the hydroponics annual yield will work to offset the operating costs. The value of food produced per year by the hydroponic farm has been calculated by determining the market price of staple fruits and vegetables in the Philippines, which is \$11.85 per kilogram (20). Hydroponic farms in tropical climates typically achieve an average of 8 harvests per year, with each harvest yielding approximately 13 kilograms (20). Using these figures, we estimated the annual revenue from the hydroponic farm yields to be \$1,232. This revenue was then subtracted from the total annual costs, thereby reducing the overall cost of energy production and providing a more accurate assessment of the project's economic feasibility.

Levelized Cost of Energy

The Levelized Cost of Energy (LCOE) is a critical metric for assessing the economic feasibility of the project. It represents the cost per kilowatt-hour (kWh) of energy produced, factoring in both the initial capital investment and the ongoing operating costs.

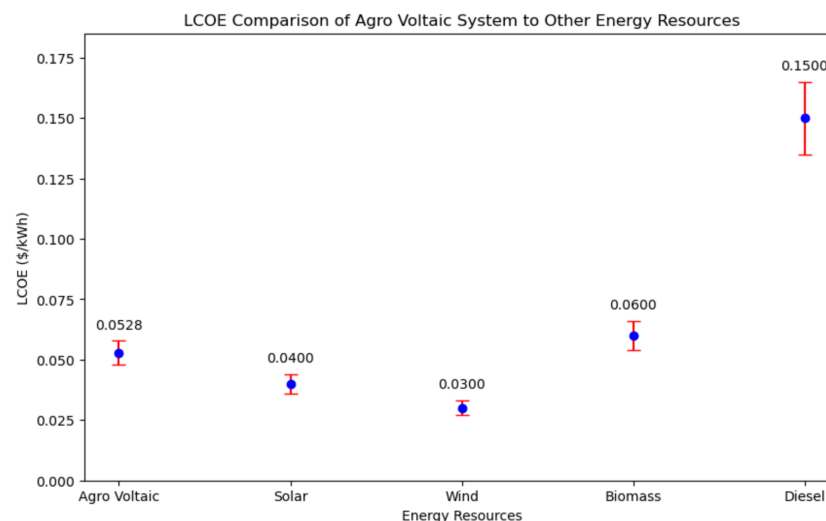


Figure 9: Illustrating the competitive LCOE of Agro Voltatics to other energy resources at this time.

The total annual energy production is calculated to be 7,743 kWh, based on the predicted monthly outputs generated by PVWatts. The annual revenue from the hydroponic farm yields, estimated at \$1,232.40, is subtracted from the total annual costs to determine the net cost of energy production. The resulting LCOE is approximately \$0.0528 per kWh. This competitive LCOE indicates that the project is economically viable and can be favorably compared to other energy systems currently available on the market. The data for sources other than solar in Figure 9, such as wind, biomass, and diesel, were obtained from external studies rather than calculated independently. Specifically, the LCOE values for these energy sources were sourced from Lazard's comprehensive annual reports on the LCOE for various generation technologies (22). By integrating the revenue from hydroponic yields into the LCOE calculation, the analysis provides a comprehensive assessment of the project's financial performance, ensuring its sustainability and cost-effectiveness.

Conclusion

In this report we provide an overview of the food insecurity and energy challenges in urban environments like Manila in order to present a feasible and sustainable approach to mitigating these issues through solar-driven vertical farms. By integrating renewable energy with advanced agricultural technologies such as hydroponics and aquaponics, these systems maximize urban space usage, increase crop yields, and reduce reliance on traditional energy and farming methods.

The proposed solution offers numerous benefits, including a stable supply of fresh produce, reduced greenhouse gas emissions, and lower operational costs through the use of renewable energy and resource efficient farming practices. Manila's tropical climate facilitates this approach as it ensures year round solar energy availability and the abundance of underutilized urban spaces suitable for vertical farming. Solar driven vertical farms have significant potential for expansion into other urban areas across Southeast Asia and beyond, especially in regions facing similar challenges. Large scale implementation could transform urban landscapes, create jobs in both agriculture and renewable energy sectors, and contribute to broader sustainability goals.

The proposed agro-voltaic system demonstrates economic feasibility and attractiveness, particularly when considering the externality of community health benefits measured by the annual production capacity of the hydroponic farm (in kilograms). Future steps for this analysis should include evaluating the impact of scaling the system, such as increasing the size of the hydroponics and solar arrays, and assessing market penetration. These factors could potentially improve the Levelized Cost of Energy (LCOE), as observed with many technologies in the energy sector. Additionally, further research should focus on optimizing the energy usage of the hydroponic system itself. As energy consumption decreases, the investment's attractiveness and overall economic viability will increase.

The LCOE model used in this study assumes a consistent, year-round output from the solar photovoltaic (PV) system. However, this assumption does not account for the significant seasonal variations experienced in Manila, where the rainy season from May to December, particularly from June to October, can greatly affect solar energy production. Reduced sunlight due to cloud cover and frequent rain during these months can decrease the efficiency and overall energy output of the solar panels.

To enhance the accuracy and reliability of the economic feasibility analysis, a valuable next step would be to study the system using a model that incorporates seasonal variations. This would provide a more realistic assessment of the solar PV system's performance and its impact on the overall feasibility of

the agro-voltaic system. By understanding and planning for these seasonal fluctuations, we can better optimize the design and operation of the system to ensure consistent and reliable energy supply throughout the year.

To further refine and scale this solution, additional research is needed in several areas. Optimizing the integration of renewable energy systems with vertical farms, exploring more efficient hydroponic and aquaponic techniques, and assessing the economic and social impacts of such systems on urban communities are all next steps. With continued development and strategic investment, solar-driven vertical farms could play a pivotal role in shaping the future of sustainable urban agriculture.

References

1. Ritchie, H., & Roser, M. (n.d.). Global land for agriculture. Our World in Data. Retrieved from [https://ourworldindata.org/global-land-for-agriculture#:~:text=Almost%20half%20\(44%25\)%20of,land%20is%20used%20for%20agriculture.](https://ourworldindata.org/global-land-for-agriculture#:~:text=Almost%20half%20(44%25)%20of,land%20is%20used%20for%20agriculture.)
2. HTT. (n.d.). Water usage in the agricultural industry. Retrieved from <https://htt.io/water-usage-in-the-agricultural-industry/>
3. U.S. Environmental Protection Agency. (n.d.). Nonpoint source: Agriculture. Retrieved from <https://www.epa.gov/nps/nonpoint-source-agriculture#:~:text=Pesticide%20runoff%20to%20streams%20can,might%20occur%20as%20a%20result.>
4. Asia Farming. (n.d.). The rise of vertical farming in the Philippines: A review and analysis for cost and benefits. Retrieved from <https://www.asiafarming.com/the-rise-of-vertical-farming-in-the-philippines-a-review-and-analysis-for-cost-and-benefits>
5. Kalantari, F., Tahir, O. M., Joni, R. A., & Fatemi, E. (2017). Opportunities and challenges in sustainability of vertical farming: A review. *Journal of Landscape Ecology*, 11(1), 35–60. <https://doi.org/10.1515/jlecol-2017-0003>
6. Drottberger, A., Zhang, Y., Yong, J. W. H., & Dubois, M.-C. (2023). Urban farming with rooftop greenhouses: A systematic literature review. *Renewable and Sustainable Energy Reviews*, 188, 113884. <https://doi.org/10.1016/j.rser.2023.113884>
7. Agritecture. (2022, June 10). Vertical farms have the vision, but do they have the energy? Retrieved from <https://www.agritecture.com/blog/2022/6/10/vertical-farms-have-the-vision-but-do-they-have-the-energy>
8. Eden Green. (n.d.). Renewable energy & vertical farming. Retrieved from <https://www.edengreen.com/blog-collection/renewable-energy-vertical-farming>
9. Rehman, N. U. (August 23, 2021). "Vertical Farms With Integrated Solar Photovoltaics." *ASME. J. Sol. Energy Eng.* February 2022; 144(1): 011007. <https://doi.org/10.1115/1.4052055>
10. Thomaier, S., Specht, K., Henckel, D., Dierich, A., Siebert, R., Freisinger, U. B., & Sawicka, M. (2015). Farming in and on urban buildings: Present practice and specific novelties of zero-acreage farming (ZFarming). *Renewable Agriculture and Food Systems*, 30(1), 43–54. <https://doi.org/10.1017/S1742170514000143>
11. Bioregenerative Life Support Systems for Space to Vertical Farming on Earth – The 100% Spin-off - Scientific Figure on ResearchGate. Available from: https://www.researchgate.net/figure/ertical-Farm-compared-to-Traditional-Agriculture-The-increases-in-yield-of-the-VF-is-the_fig5_263747164 [accessed 8 Dec 2024]
12. Food Bank Philippines. (n.d.). Nearly 51M Filipinos face food insecurity: UN report. Retrieved from <https://foodbank.org.ph/nearly-51m-filipinos-face-food-insecurity-un-report/>
13. BusinessWorld. (2023, July 14). Nearly 51M Filipinos face food insecurity: UN report. Retrieved from <https://www.bworldonline.com/top-stories/2023/07/14/534036/nearly-51m-filipinos-face-food-insecurity-un-report/>
14. Inquirer.net. (2020, October 5). Pandemic weakens food security in urban poor communities. Retrieved from

- <https://newsinfo.inquirer.net/1341286/pandemic-weakens-food-security-in-urban-poor-communities>
15. ICLEI. (n.d.). How two cities in Metro Manila are accelerating energy efficiency. Retrieved from <https://talkofthecities.iclei.org/how-two-cities-in-metro-manila-are-accelerating-energy-efficiency/>
 16. Asia Pacific Energy Research Centre. (n.d.). Philippines energy demand and supply outlook 5th edition. Retrieved from https://aperc.or.jp/reports/outlook/5th/volume2/EDSO5_V2_Philippines.pdf
 17. Ritchie, H., & Roser, M. (n.d.). Philippines: Energy country profile. Our World in Data. Retrieved from <https://ourworldindata.org/energy/country/philippines>
 18. Reach Alliance. (2023, November). Philippines final report. Retrieved from <https://reachalliance.org/wp-content/uploads/2023/11/Philippines-Final.pdf>
 19. Yoorekka. (2018, June 29). Condo building types in the Philippines and the advantages of each. Retrieved from <https://yoorekka.com/magazine/metro-manila/2018/06/29/condo-building-types-in-the-philippines-and-the-advantages-of-each>
 20. Statista. (n.d.). Number of completed condo units in Metro Manila, Philippines. Retrieved from <https://www.statista.com/statistics/1264933/philippines-completed-condo-units-in-metro-manila/>
 21. National Renewable Energy Laboratory. (n.d.). PVWatts calculator. Retrieved from <https://pvwatts.nrel.gov/>
 22. Lazard. (2023). Levelized cost of energy+. Retrieved from <https://www.lazard.com/research-insights/2023-levelized-cost-of-energyplus/>

Appendix A: Source Code Graphs and Calculations for Economic Feasibility

Introduction

This appendix contains the source code used for the Levelized Cost of Energy (LCOE) calculation and the graphs presented in the Economic Feasibility section of the paper. The code is written in Python and includes functions for calculating the LCOE based on various parameters. The graphs illustrate key data points and results from the economic analysis.

A.1 Source Code for LCOE Calculation

```
# Constants
investment_lifetime_years = 25
discount_rate = 0.042

# Costs
solar_system_cost_per_kw = 3400 # USD per kW
solar_system_capacity_kw = 6 # kW
hydroponic_system_cost = 640 # USD
annual_maintenance_cost = 800 # USD

# Energy production
energy_output_per_month = [615, 711, 831, 783, 753, 642, 579, 568, 640, 637, 528, 456] # kWh per month
days_in_month = [31, 28, 31, 30, 31, 30, 31, 31, 30, 31, 30, 31]
daily_energy_needed = 15 # kWh per day

# Hydroponic farm yields
price_per_kg = 11.85 # USD per kg
yield_per_harvest = 13 # kg
harvests_per_year = 8

# Calculate daily average energy output for each month
daily_average_energy_output = [energy_output_per_month[i] / days_in_month[i]
    for i in range(12)]

# Calculate extra energy sold back to the grid for each month
extra_energy_sold_per_month = [(daily_average_energy_output[i] -
    daily_energy_needed) * days_in_month[i] for i in range(12)]

# Calculate total annual energy production (kWh)
total_annual_energy_production = sum(extra_energy_sold_per_month)

# Calculate annual revenue from hydroponic farm yields (USD)
annual_revenue_from_yields = price_per_kg * yield_per_harvest *
    harvests_per_year

# Calculate total initial cost (USD)
```

```

total_solar_system_cost = solar_system_cost_per_kw * solar_system_capacity_kw
total_initial_cost = total_solar_system_cost + hydroponic_system_cost

# Calculate total annual costs (USD) and total annual production
total_annual_costs = annual_maintenance_cost + (total_initial_cost /
    ↪investment_lifetime_years)
total_annual_production = sum(energy_output_per_month)
# Calculate LCOE (USD per kWh)
lcoe = (total_annual_costs - annual_revenue_from_yields) /
    ↪total_annual_production

# Print results
print(f"Total annual energy production (kWh): {total_annual_production}")
print(f"Annual revenue from hydroponic farm yields (USD):
    ↪{annual_revenue_from_yields}")
print(f"Total initial cost (USD): {total_initial_cost}")
print(f"Total annual costs (USD): {total_annual_costs}")
print(f"Levelized Cost of Energy (LCOE) including hydroponic system (USD per
    ↪kWh): {lcoe:.4f}")

```

Total annual energy production (kWh): 7743

Annual revenue from hydroponic farm yields (USD): 1232.3999999999999

Total initial cost (USD): 21040

Total annual costs (USD): 1641.6

Levelized Cost of Energy (LCOE) including hydroponic system (USD per kWh):

0.0528

A.2 Source Code for Monthly Energy Output Compared to 15 kwh Demand Graph

```

import matplotlib.pyplot as plt
import matplotlib.patches as mpatches

# Data for the chart
months = ["Jan", "Feb", "Mar", "Apr", "May", "Jun", "Jul", "Aug", "Sep", "Oct",
    ↪"Nov", "Dec"]
energy_output_per_month = [615, 711, 831, 783, 753, 642, 579, 568, 640, 637,
    ↪528, 456] # kWh per month
daily_energy_needed = 15 # kWh per day
days_in_month = [31, 28, 31, 30, 31, 30, 31, 31, 30, 31, 30, 31]

# Calculate daily average energy output for each month
daily_average_energy_output = [energy_output_per_month[i] / days_in_month[i]
    ↪for i in range(12)]

# Calculate the amount above the needed 15 kWh
extra_energy_per_day = [daily_average_energy_output[i] - daily_energy_needed
    ↪for i in range(12)]

# Create the chart

```

```

fig, ax = plt.subplots(figsize=(10, 6))

# Plot the daily average energy output
bars = ax.bar(months, daily_average_energy_output, color='blue', label='Daily Average Energy Output')

# Highlight the amount above the needed 15 kWh in green
for i in range(12):
    if extra_energy_per_day[i] > 0:
        ax.bar(months[i], extra_energy_per_day[i], bottom=daily_energy_needed, color='green')

# Add labels and title
ax.set_xlabel('Month')
ax.set_ylabel('Daily Average Energy Output (kWh)')
ax.set_title('Monthly Energy Output Compared to 15 kWh Demand')
ax.axhline(y=daily_energy_needed, color='red', linestyle='--', label='Energy Needed (15 kWh/day)')
ax.legend()

# Add value labels on top of the bars
for bar in bars:
    height = bar.get_height()
    ax.annotate(f'{height:.2f}',
                xy=(bar.get_x() + bar.get_width() / 2, height),
                xytext=(0, 3), # 3 points vertical offset
                textcoords="offset points",
                ha='center', va='bottom')

# Add custom legend and place it underneath the graph
green_patch = mpatches.Patch(color='green', label='Green portion highlights the excess energy in kWh that can be sold back to the grid every month.')
ax.legend(handles=[green_patch], loc='upper center', bbox_to_anchor=(0.5, -0.15), ncol=1)

# Show the chart
plt.tight_layout()
plt.show()

```

A.3 Source Code for Rooftop Utilization Graph

```
import matplotlib.pyplot as plt
import matplotlib.patches as mpatches

# Constants
hydroponic_system_length = 12.192 # meters
hydroponic_system_width = 2.438 # meters
hydroponic_system_area = hydroponic_system_length * hydroponic_system_width #  $m^2$ 
low_rise_rooftop_area = 77.7 #  $m^2$ 
high_rise_rooftop_area = 260.4 #  $m^2$ 

# Estimate the area required for the 6kW solar array
# Assuming an average solar panel size of 1.6m x 1m and each panel is 300W
solar_panel_area = 1.6 * 1 #  $m^2$  per panel
number_of_panels = 6000 / 300 # 6kW system with 300W panels
total_solar_array_area = solar_panel_area * number_of_panels #  $m^2$ 

# Create the graph
fig, ax = plt.subplots(figsize=(10, 6))

# Plot the low rise rooftop
low_rise_rect = plt.Rectangle((0, 0), low_rise_rooftop_area,  $low\_rise\_rooftop\_area$ , color='blue', alpha=0.3, label='Low Rise Rooftop')
ax.add_patch(low_rise_rect)
```

```

# Plot the high rise rooftop
high_rise_rect = plt.Rectangle((0, low_rise_rooftop_area + 10),
    ↪high_rise_rooftop_area, high_rise_rooftop_area, color='orange', alpha=0.3,
    ↪label='High Rise Rooftop')
ax.add_patch(high_rise_rect)

# Plot the hydroponic system on both rooftops
hydroponic_rect_low = plt.Rectangle((0, 0), hydroponic_system_length,
    ↪hydroponic_system_width, color='green', alpha=0.5, label='Hydroponic System')
ax.add_patch(hydroponic_rect_low)

hydroponic_rect_high = plt.Rectangle((0, low_rise_rooftop_area + 10),
    ↪hydroponic_system_length, hydroponic_system_width, color='green', alpha=0.5)
ax.add_patch(hydroponic_rect_high)

# Plot the solar PV array on both rooftops
solar_array_rect_low = plt.Rectangle((hydroponic_system_length + 5, 0),
    ↪total_solar_array_area, total_solar_array_area, color='yellow', alpha=0.5,
    ↪label='Solar PV Array')
ax.add_patch(solar_array_rect_low)

solar_array_rect_high = plt.Rectangle((hydroponic_system_length + 5,
    ↪low_rise_rooftop_area + 10), total_solar_array_area, total_solar_array_area,
    ↪color='yellow', alpha=0.5)
ax.add_patch(solar_array_rect_high)

# Add labels and title
ax.set_xlabel('Length (m)')
ax.set_ylabel('Width (m)')
ax.set_title('Rooftop Space Utilization for Hydroponic Farm and Solar PV Array')
ax.legend(loc='upper right')

# Set limits and aspect ratio
ax.set_xlim(0, max(low_rise_rooftop_area, high_rise_rooftop_area) + 20)
ax.set_ylim(0, high_rise_rooftop_area + low_rise_rooftop_area + 30)
ax.set_aspect('equal')

# Show the graph
plt.tight_layout()
plt.show()

```

A.4 Source Code for LCOE Comparison Graph

```

import matplotlib.pyplot as plt
import numpy as np

# Define the LCOE values for different energy resources in $/kWh
lcoe_agro_voltaic = 0.0528
lcoe_solar = 0.04 # Example value
lcoe_wind = 0.03 # Example value
lcoe_biomass = 0.06 # Example value
lcoe_diesel = 0.15 # Example value

# Define the error values (standard deviation) for each energy resource
error_agro_voltaic = 0.005
error_solar = 0.004

```

```

error_wind = 0.003
error_biomass = 0.006
error_diesel = 0.015

# Create a dictionary to store the LCOE values and their errors
lcoe_values = {
    "Agro Voltaic": (lcoe_agro_voltaic, error_agro_voltaic),
    "Solar": (lcoe_solar, error_solar),
    "Wind": (lcoe_wind, error_wind),
    "Biomass": (lcoe_biomass, error_biomass),
    "Diesel": (lcoe_diesel, error_diesel)
}

# Create lists for the resources, their LCOE values, and errors
resources = list(lcoe_values.keys())
lcoe = [value[0] for value in lcoe_values.values()]
errors = [value[1] for value in lcoe_values.values()]

# Create a scatter plot with error bars
plt.figure(figsize=(10, 6))
plt.errorbar(resources, lcoe, yerr=errors, fmt='o', color='blue', ecolor='red',
             capsize=5)
plt.xlabel('Energy Resources')
plt.ylabel('LCOE ($/kWh)')
plt.title('LCOE Comparison of Agro Voltaic System to Other Energy Resources')
plt.ylim(0, max(lcoe) + max(errors) + 0.02)

# Add the LCOE values next to the points
for i in range(len(resources)):
    plt.text(i, lcoe[i] + errors[i] + 0.005, f'{lcoe[i]:.4f}', ha='center')

# Save the plot as an image file
plt.savefig('lcoe_comparison_errorBars.png')

# Show the plot
plt.show()

```

Conclusion

The source code and graphs provided in this appendix support the economic feasibility analysis of the proposed solar-driven vertical farming system. They illustrate the calculations and data visualizations that underpin the conclusions drawn in the paper.