A DESIGN OF A SOLAR-POWERED VERTICAL FARM IN KHARTOUM, SUDAN

By

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A Thesis Submitted to the Faculty of the

THE DEPARTMENT OF BIOSYSTEMS ENGINEERING

In Partial Fulfillment of the Requirements For

The Degree Of

MASTER OF SCIENCE

In the Graduate College

THE UNIVERSITY OF ARIZONA

2022

THE UNIVERSITY OF ARIZONA
GRADUATE COLLEGE

As members of the Master's Committee, we certify that we have read the thesis prepared by Najwan Taha, titled A Design of a Solar-Powered Vertical Farm in Khartoum, Sudan and recommend that it be accepted as fulfilling the dissertation requirement for the Master's Degree.

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Final approval and acceptance of this thesis is contingent upon the candidate's submission of the final copies of the thesis to the Graduate College.

I hereby certify that I have read this thesis prepared under my direction and recommend that it be accepted as fulfilling the Master's requirement.

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ACKNOWLEDGEMENTS

I would like to thank Dr. Joel Cuello for his endless guidance in my research, helping develop my skills in reading, writing, imagining, drawing, making, and believing in every step I made throughout this research, forming my entire business acumen, and encouraging me to nurture my imagination. I would like to thank Dr. Kitt and Dr. Waller for their support, help, and kindness. Lastly, I would like to thank my favorite entomologist and lovely husband, Mozamel Elkurdi, for making everything happen.

DEDICATION

I dedicate this thesis to my respective parents, Taghreed and Tariq. My husband Muzammil, and my son Ahmed. For their unconditional love, support, and encouragement they offer me continuously throughout my journey. Without their existence, my life would not have been made possible.

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Abstract

Rising population, growing urbanization, diminishing fresh water supply, and climate change have been contributing to the planet's deteriorating stocks of arable land. Intensive crop production in urban areas through vertical farming is considered a promising solution to help meet the increased demand for food in cities using non-arable land and in a more local and

environmentally sustainable manner. In this study, we examined vertical farming as a potential solution to addressing the significant food insecurity in Sudan, Africa. Three types of vertical farms, each equipped with solar photovoltaics, were considered, namely: (1) warehouse vertical farm; (2) modular (shipping-container) vertical farm; and (3) greenhouse vertical farm. The specific objectives of the study were: (1) To design an appropriate embodiment for each of the three types of a vertical farm as powered by solar photovoltaics to meet the annual demand for 66,000 kg of Yellow Potato and 79,200 heads of Rocket Arugula by the local grocery store Al-Anfal Supermarket in Sudan's capital city of Khartoum; and (2) To assess the economic viability of each designed vertical farm embodiment as a business enterprise in Khartoum, Sudan. The conclusions of the study were as follows: (1) The greenhouse vertical farm was the most profitable case with a break-even period of 1.1 years and an estimated annual profit of $179,447; (2) The warehouse vertical farm was the second most profitable case with a break-even period of 1.3 years and an estimated annual profit of $166,924; (3) The modular shipping-container vertical farm was the last place with an estimated annual profit of $164,691 and breakeven point of 1.3 years; and, (4) Although requiring significant capital and operational investments, the foregoing three embodiments of vertical farming, powered by solar photovoltaics, to meet the annual demands for 66,000 kg of Yellow Potato and 79,200 heads of Rocket Arugula by the local grocery store Al-Anfal Supermarket in Sudan's capital city of Khartoum, demonstrated reasonable promise for economic profitability.

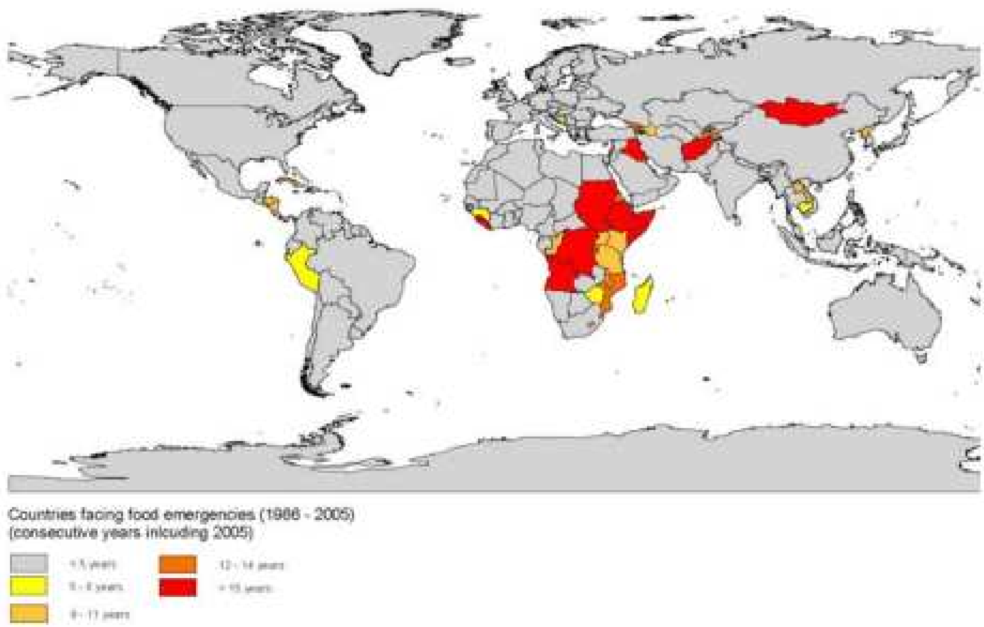
Chapter 1. Introduction

1.1 Explanation of the Problem and Objectives

The long-term depletion of agricultural land per capita is a major worldwide issue. According to the United Nations Food and Agriculture Organization (FAO) statistics, predicted growth in arable land per person is expected to fall to one-third of what it was in 1970 by 2050 (FAO, 2016). Climate change, the expanding geographic range of drylands, and the loss of freshwater resources are all expected to accelerate this deterioration (Fedoroff, 2015). Declining fisheries (resulting in a heavier food load on land-based goods), expanding urbanization, rising agribusiness expenses, and rapidly increasing population are all important risks to the future availability of arable land. As this takes place and as the world population continues to grow exponentially, fundamental changes are predicted to occur in the upcoming 50 years accompanied by higher demand for food (Banerjee & Adenaeuer, 2014). Human population is predicted to reach 9.7 billion in the year 2050, and this figure will increase to approximately 11.2 billion by 2100 (UN population report, 2019). As this occurs, it is estimated that urban areas will increase gradually by 55% to 68% as people move from rural to urban areas, translating into about 2.5 billion people predicted to move to urban areas. Thus, cities will be hosting about 80% of the population (D. D. Despommier, 2010; Islam & Siwar, 2012). As a result, there will be high pressure for agriculture to meet the high demand of food while at the same time there is a retracting of agricultural lands caused by the swift expansion of urban areas. Thus, farmland issues with the population increasing will lead to insecurity in food supply.

Moreover, more than 50 million people are believed to live in places affected by chronic crises that have persisted five years or more (Commission of the European Communities, 2006).

Some of these crises have been going on for years, others for decades, with varying degrees of intensity and impacts on food insecurity. In such a context, a protracted food crisis may be defined as "the persistent uncertainties in people's access to food due to a range of interacting demand- and supply-side factors" (Flores et al., 2005). Certainly, the key features of most protracted crises, in addition to the loss of human lives due to conflicts, are the increasing levels of food insecurity and hunger. As shown in Figure 1, five countries in Africa, including Sudan, have declared food emergencies during 15 or more of the years since 1986 (Alinovi et al., 2007).



Source: (*GIEWS - Global Information and Early Warning System on Food and Agriculture | Food and Agriculture Organization of the United Nations*, n.d.)

Figure 1. Protracted Food Emergencies in Africa

After decades of civil strife and going with political instability, millions of Sudanese people continue to experience severe and chronic food insecurity because of human-caused and periodic natural catastrophes (floods, droughts, outbreaks of livestock illnesses). As the agriculture sector have also been affected considering the agriculture supplies food and a livelihood for between 60% and 80% of Sudan's working-age population, the sector's importance to economic recovery and the establishment of long-term peace cannot be neglected (Mahgoub, 2014). The situation has been worsened throughout the years, the food prices elevated, and the economic conditions deteriorated caused prominent levels of danger in Sudan, along with the ongoing violence, flooding, resultant population displacement, disrupted trade, markets, and cultivation activities have increase food insecurity and humanitarian needs (USAID.gov, 2021). According to the country's Humanitarian Response Plan (HRP) approximately 9.3 million people need humanitarian assistance in 2020 (USAID.gov, 2021). Furthermore, 1.9 million people have been moved across Sudan due to conflict and instability and about 1.1 million refugees Sudan have been housed, with over 823,000 South Sudanese, many of whom are vulnerable to food insecurity (USAID.gov, 2021). Therefore, Sudan had to import food products and vegetables to satisfy the food demand. In 2018, Sudan imported food products from around the world spending US$873 million and imported vegetables by around US$2.2 million (WITS, 2022).

Due to food insecurity and growing food demand is Sudan, there is a need for using more arable land for farming as well as intensifying farming efforts that would affect Sudan’s agriculture. Vertical farms are being designed and implemented as a technological advance that may be able to satisfy this need (D. Despommier, 2013). Achieving food security and ending hunger by 2030 are the sustainable development goals set by the United Nations in 2015. Therefore, the growth of urban agriculture such as vertical farming is encouraged to meet a nation’s food demand (UN, 2017).

Vertical farming is the urban farming of a wide variety of crops, inside a building in a city or urban center, in which floors are designed to accommodate certain crops using certain type of technique. Vertical farms become a solution because it enables food production in an efficient and sustainable manner by saving water and energy, enhancing the economy, reducing pollution, supplying employment opportunities, and providing wider access to healthier food. Although the concept of growing food in cities is not new, dedicating an entire building/skyscraper to cultivating produce is a new idea. Among these factors, the general aim of this study was to examined vertical farming as a potential solution to addressing the significant food insecurity in Sudan, Africa. Three types of vertical farm, each equipped with solar photovoltaics, were designed, namely: (1) warehouse vertical farm; (2) modular (shipping-container) vertical farm; and (3) greenhouse vertical farm. Each vertical farm was designed to grow two crops -- Yellow Potato and Rocket Arugula – to meet the annual demands for the two crops by a local grocery store located in Sudan’s capital city of Khartoum. This study is specifically aimed to: (1) Design a proper embodiment for each of the three types of vertical farm as powered by solar photovoltaics to meet the annual demand of two crops by the local grocery store; and (2) Assess the economic viability of each designed vertical farm embodiment as a business enterprise in Khartoum, Sudan.

1.2 Background

1.2.1 Vertical Farming

Vertical Farming (VF) is an agricultural-based technique for food production typically in warehouses, resulting in the rapid expansion as well as arranged production by controlling climate factors and nutrient solutions to crops using innovative techniques and practices (Banerjee & Adenaeuer, 2014; D. Despommier, 2011; D. Despommier, 2010). According to

Perez's research (2014), VF combines engineering and biological sciences, and it has wide applicability in social and environmental issues. (Mendez Perez, 2014). Vertical farms come in several different forms, ranging from two-level or tower systems to massive warehouses that have several floors. However, all vertical farms use one of three soil-free nutrient delivery systems: hydroponic, aeroponic, or aquaponic (Birkby, 2016). These three growing systems are described in the following manner:

1. Hydroponics. Hydroponics is the most common growth technology used in vertical farms; it includes growing plants in nutrient solutions without the need of soil. The plant roots are immersed in the nutrient solution, which is constantly checked and cycled to support the proper chemical composition. Figure 2 shows a diagram for a hydroponic system.

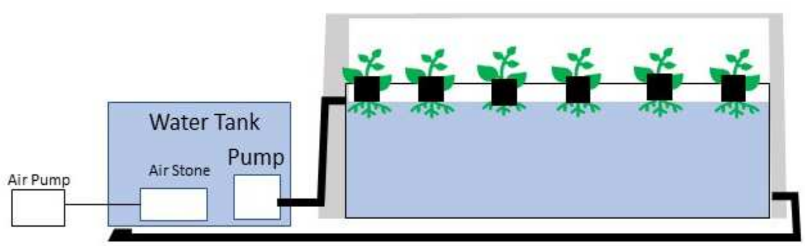


Figure 2. Hydroponic System

2. Aeroponics. The National Aeronautical and Space Administration (NASA) oversaw creating this ground-breaking indoor growth method. In the 1990s NASA invented the word "aeroponics" to describe growing plants in an air/mist environment with no soil and so little water because they were interested in discovering efficient ways to grow plants in space. Aeroponic systems are still a rarity in the field of vertical farming, but they are getting a lot of attention. Aeroponic systems use up to 90% less water than

open-field cultivation, making them the most efficient plant-growing technology for vertical farms. Aeroponic plants have also been discovered to absorb more minerals and vitamins, making them healthier and more nutritious (Birkby, 2016). Figure 3 shows a diagram for an aeroponic system.

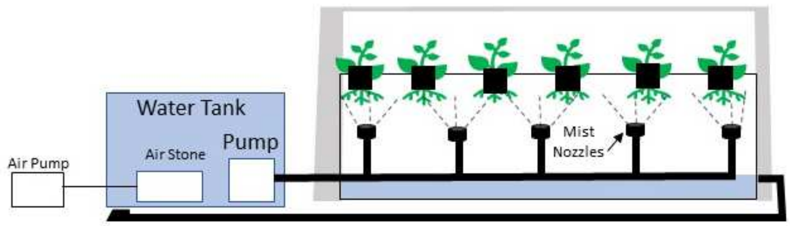


Figure 3. Aeroponic System

3. Aquaponics. An aquaponic system expands on the hydroponic system by incorporating plants and fish into one environment. Fish are raised in indoor ponds, creating nutrient-rich excrement that is used to feed the vertical farm's plants. The plants then filter and cleanse the wastewater before returning it to the fishponds. Although aquaponics is employed in small-scale vertical farming systems, most commercial vertical farming systems only produce a few fast-growing vegetable crops and do not have an aquaponics part. This reduces the complexity of economic and manufacturing challenges while increasing efficiency. New standardized aquaponic systems, on the other hand, may serve to increase the popularity of this closed-cycle system (Birkby, 2016). Figure 4 shows a diagram for an aquaponic system.

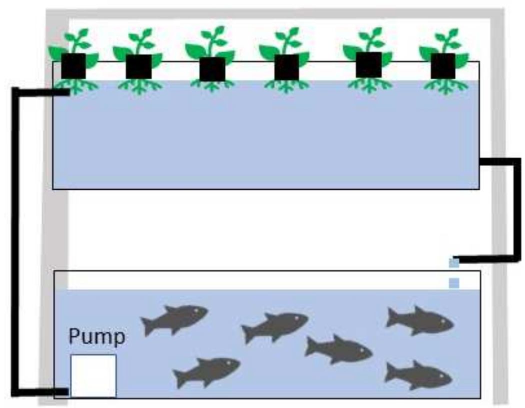


Figure 4. Aquaponic System

Vertical farming systems can be further classified by the type of structure that houses the system. Vertical farms in cities are often situated in new or abandoned (1) warehouses such as Chicago's "The Facility" vertical farm, which was built in an old pork-packing plant (Birkby, 2016), (2) greenhouses such as what BrightFarms has developed for the past eight years for growing fruits and vegetables in urban settings. Its goal has been in part to lower carbon footprint by lowering energy use in both the growing process and the transportation necessary to transport the produce to customers (Gibson, 2014), and (3) shipping-containers which make use of 20-foot or 40-foot shipping containers used to transport commodities throughout the world. Several firms are converting shipping containers into self-contained vertical farms (Birkby, 2016).

Most vertical farms employ extremely efficient Light-Emitting Diodes (LEDs), with customized bulbs that only use the red and blue light spectra, though white LEDs are now also becoming widely used. Reducing the emissions of light wavelengths can help save up to 15% on energy expenses. Even with these lighting cost savings, a self-contained vertical farm's overall power bill (and carbon footprint) can be large. Continued research and development of more efficient LEDs will aid in lowering lighting costs and carbon emissions in vertical farming operations (Birkby, 2016).

Producing sustainable food in urbanization has lately piqued the curiosity and consideration of several theoretical and practice disciplines (D. Despommier, 2013; Specht et al., 2014). Currently, vertical farms are mostly raising and supplying various sorts of products within cities, such as in China, Holland, South Korea, Japan, Canada, Italy, U.S., Singapore, United Arab Emirates, and England (Sivamani et al., 2013). Table.1 provides the specifics of the most effective vertical farms in various countries throughout the world, based on an assessment of VF viability for various environment locations based on their type and techniques. According to Table 1, the quantity, capacity, and scale of VF implementation and understanding are increasing. The distribution pattern of VF, on the other hand, reveals that the examination of VF feasibility for diverse climates or geographical places, as well as regional features, is rising exponentially. Seasonal changes will have no influence on the crops because they will be cultivated indoors using controlled environment agriculture techniques. VF are flourishing in several places throughout United States and China, each with its own unique features (Kalantari et al., 2018).

Table 1. Details of Some Vertical Farming Around in USA and China

No	Name	Location	Area	Year	Website
1	The Plant Vertical Farm	Chicago, Illinois, USA	100,000 sq.ft	2013	(*The Plant Vertical Farm*, 2020)
2	Vertical Harvest plans2	Jackson Wyoming, USA	4500 sq.ft	2012	(*Jackson*, n.d.)
3	AeroFarms	Newark, New Jersey, USA	20,000 sq.ft	2012	(*AeroFarms Home • The Vertical Farming,*

					Elevated Flavor Company, n.d.)
4	Green Sense Farms	Shenzhen, China	20,000 sq.ft	2016	(*Summary*, n.d.)
5	Plenty Unlimited	South San Francisco, CA, USA	95,000 sq.ft	2014	(*Plenty - Vertical Farming Company Summary*, n.d.)
6	Bowery Farming	Kearney, New Jersey, USA	Nd	2015	(*Bowery Opens Its Largest Indoor Farm In Baltimore*, n.d.)

Source:(Kalantari et al., 2018)

1.2.2 Vertical Farming Using Solar Energy

The incorporation of renewable energy sources (RE) such as solar and wind has been widely studied in a variety of works of literature to promote the sustainability of urban agriculture. One of the vertical farming system's flaws is its high energy use. In recent research, energy usage has been addressed by evaluating vertical farm components such as lighting and temperature regulation. Table 2 displays the most recent literature on the use of solar energy and energy consumption in urban agriculture. However, research on the application of solar PV systems to vertical farming is still in its preliminary stages. The available literature on the integration of solar PV to vertical farming only gives a model to prove its viability (Teo & Go, 2021).

Table 2. Summary of the Application of Solar PV and Energy Consumption in Urban Agriculture

No	Title	Key Findings	Performance Parameters	Year
1	Net-zero energy design and energy sharing potential of Retail - Greenhouse complex	Energy reduction in greenhouse-retail is achieved with energy efficiency measures.	Energy consumption of retail and greenhouse.	2019

	(Syed & Hachem, 2019)	Net-zero energy of the retail-greenhouse is achieved with solar PV integration.	Renewable energy generation and electricity management of the retail.	
2	Development of a simulation-based decision support workflow for the implementation of Building-Integrated Agriculture (BIA) in urban contexts (Benis et al., 2017)	Rooftop greenhouse and the top floor of vertical farming has the best overall performance.	Energy Use Intensity.	2017
3	A novel integrated framework to evaluate greenhouse energy demand and crop yield production (Golzar et al., 2018)	The energy loss is varied according to seasons and crops growth period.	Energy consumption.	2018
4	Vertical farming: Skyscraper sustainability? (Al-Chalabi, 2015)	The sustainability of vertical farm depends on the location and design.	Energy consumption.	2015

Source: (Teo & Go, 2021)

Vertical farming is an example of a century-long sustainable innovation. Because space is used more efficiently in the vertical farming technique, more crops are yielded as compared to conventional agriculture. Furthermore, because plants are grown in a confined and regulated environment, freshwater use is reduced by 70–95 percent. However, the vertical farming system's high energy consumption has always been a key disadvantage. Energy optimization of vertical farms using renewable energy generation, such as solar PV, has been advocated in many literatures to show its reliability.

1.2.3 Sudan

Sudan is in the Nile Basin, south of Egypt, near the center of the basin. The republic is in north-east Africa, with the given geographic coordinates: Longitudes 4° and 22° north, and longitudes 22° and 38° east, The country is traversed by the Blue Nile and White Nile rivers, which meet in the capital Khartoum to form the main Nile River, which flows north into the Mediterranean Sea (Mahgoub, 2014). Sudan is blessed with a plethora of natural resources. Indeed, the country's primary source of wealth is its natural resources. These include fertile land regions, abundant water from the Nile rivers and ground water, or other resources like cattle, gold, uranium, and other various minerals. However, Sudan's resources have not been used to date to deliver the country and its people the economic success that they so desperately need. On the contrary, many of today's national disputes are rooted in the management and distribution of these resources (Elmardi, 2018).

Agricultural Challenges in Sudan

Sudanese agriculture is divided into two primary farming systems. The major system is rainfed (both automated and traditional), accounting for more than 90% of all farmed land (21.2 million hectares in 2018), while the secondary system is irrigated (CBoS, 2018). Cropping, livestock, and forestry/fisheries are the three primary subsectors of the agricultural sector, each contributing 39, 60, and 1% of agricultural GDP in 2015/16, respectively (CBoS, 2016). This emphasizes the significance of livestock, which has been more vital in contributing to foreign exchange profits in recent years as oil exports have shrunk.

Agriculture employs 65 percent of the Sudanese people and is the major source of income for the country (CBS, 2009; World Bank Group, 2015). In 2011, it employed 47 percent of the labor force, including 41 percent of male workers and 63 percent of female workers. These proportions are significantly higher in rural regions. Agriculture accounts for 65 percent of overall rural employment, with male employees accounting for 59 percent and female workers accounting for 82 percent (AbuAgla et al., 2013). In 2012, 58 percent of rural families lived below the national poverty level of US $ 1.25 per day (AbuAgla et al., 2013), compared to 27 percent of urban households. As a result, the agriculture sector is critical for poverty reduction initiatives and any economic-wide measures.

Sudan's agriculture industry is running at less than its full productive capacity (World Bank Group, 2015). There are several reasons for low agricultural output. Traditional rainfed sectors face erratic rainfall and get minimal loans, research, and extension services, while governmental expenditures in basic infrastructure for rural and agricultural growth are often insignificant (World Bank Group, 2015). Low yields are caused by a lack of proper farm machinery, a lack of financing, the use of low yielding crop types with limited supply of better seeds, inadequate maintenance of irrigation canals, ineffective irrigation pumps, and poor agricultural techniques such as weed and insect management (FAO, 2018, 2019).

Environmental Challenges in Sudan

The Sudan's varying climate is clear. While the northern half of the nation has higher temperatures and uncommon or infrequent rainfalls, the southern section of the country, which is tropical, has very abundant and regular rainy seasons that may last six to nine months. Dust storms are widespread in the country's center and northern regions (Elmardi, 2018). The typical annual temperatures range from 26 to 32 degrees Celsius across the country. The rainfall patterns ecologically divide the country into five vegetation zones, from north to south: (1) desert with 0–75 mm of precipitation annually, (2) semi-desert with 75–300 mm, (3) low rainfall savannah on clay and sand with 300–800 mm, (4) high rainfall savannah with 800–

1500 mm, and (5) mountain vegetation with 300–1000 mm. Sudan, like many other African countries, is suffering from the effects of climate change. Agriculture, the country's main economic sector, has been and continues to be severely impacted. Several long-term severe droughts and near-annual floods have already had significant negative consequences on the people, cattle, and land (Elmardi, 2018).

1.2.4 Solar Power in Sudan

There are several forms of renewable energy that supply clean, environmentally beneficial energy. These include biomass (bioenergy), hydropower, solar, wind, and a variety of others. Many of these energies become practical options in a country like Sudan, which has enormous regions of arable land, an abundance of minerals, water, winds, and sunshine (Elmardi, 2018). Sudan's solar energy achievements so far in this appears to be quite low, with an average sunlight length of 10 hours per day. Most solar technology installations in the country are photovoltaic (PV), with a total installed capacity of around 2 MW (Rabah et al., 2016). The telecommunications industry (e.g., distant off-grid antennas and satellites) accounts for almost half of the installed ability. After that, the government recognized the importance of renewable energy, particularly solar energy, in tackling critical life concerns, particularly in rural areas (Elmardi, 2018). There are currently two major large-scale techniques of solar energy that convert sunlight into usable energy: solar thermal energy, which converts warmth to either thermal, heating usage, or electricity production; and photovoltaic (PV) energy, which converts radiant light quanta into electricity.

Simply stated, the solar thermal energy type of energy includes the reception of sunlight on a darkened surface, which then gets warmer. By passing either air or water across this warmed surface, the air or water may be warmed and then stored or transferred to wherever they are required to heat (Vanderhulst, P., et al., 1990). Solar thermal energy is divided into two categories: solar thermal non-electric, which includes agricultural drying, solar water heaters, solar air heaters, solar cooling systems, and solar cookers (Timilsina et al., 2011), and solar thermal electric, which uses heat to generate steam for electricity generation, also known as Concentrated Solar Power (CSP). There are now four types of CSP technologies on the market: Parabolic Trough, Fresnel Mirror, Power Tower, and Solar Dish Collector (Timilsina et al., 2011).

The solar photovoltaic energy described when sunlight reaches a solar cell, energy from the sun is converted to electrical power. As a result, an electric current is created, which, when many cells are connected in a panel, allows for the creation of enough current to run an electric pump, or charge a battery. There can be a wide range of photovoltaic applications depending on how the system is constructed and configured. These can range from large-scale energy generation in power plants to small-scale energy requirements for devices (Elmardi, 2018).

Natural Resources and Environment

Sudan has abundance of sunshine with an average duration ranging between 9 to 11 hours per day. Where most regions in the world exhibit annual average solar energy density ranging between 100 to 250 W/m2. Sudan solar energy density ranges between 436-639 W/m2 (Babiker, 2020). The map below (Figure. 5) reflects Sudan Global Horizontal Irradiation. It is quite indicative that both the northern and western regions acquire higher irradiance than the remaining areas of the country. The daily totals horizontal irradiation of Khartoum city which is between 6.2 kWh/m^2 to 6.4 kWh/m^2.

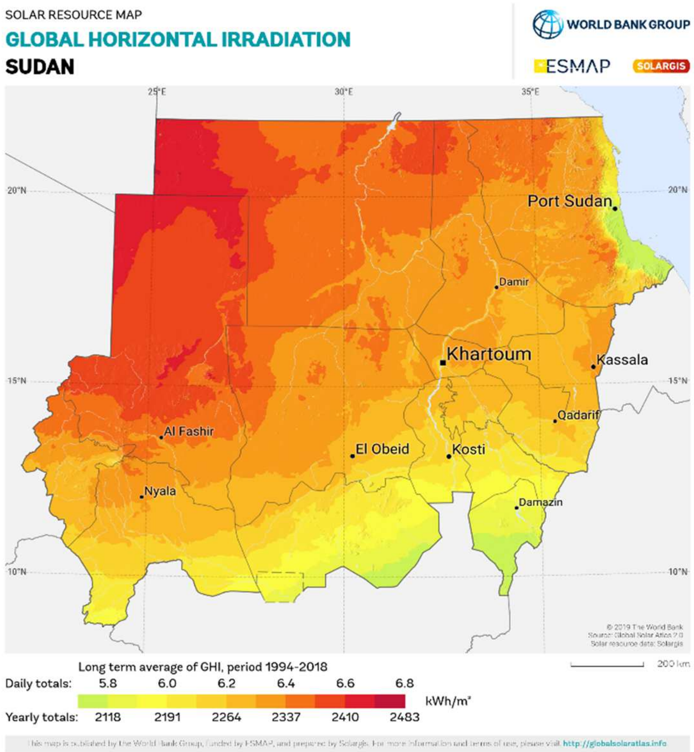


Figure 5. Sudan Global Horizontal Irradiation Map

Although, the overall radiance estimates are encouraging, it is important to note that Sudan, like many underdeveloped nations, suffers from air pollution. This has the potential to reduce the amount of solar energy reaching the earth's surface. According to a UNICEF air pollution assessment (*Pollution*, 2016), Sudan still lacked air quality rules and regulations as of 2016. Many causes contribute to the country's current levels of air pollution, which range from above moderate to high according to the particulate matter (PM)2.5 standard. Among the cases mentioned in the UNICEF study are: the country's lack of availability to non-solid fuels, as well as the absence of programs to encourage efficient cooking and heating stoves; the country lacks low sulfur fuels (550ppm) and advanced vehicle emission requirements; burning of agricultural and municipal trash is unregulated and widespread; and the inadequacy of air quality laws and regulations (*International Air Quality Standards - How Do They Compare?*, 2015). Sudan's high radiation intensity values are certainly an asset that may significantly improve the efficiency of any installed solar system; however, to get optimal results, pollution concerns must be addressed (Elmardi, 2018).

Chapter 2. Present Study

2.1 Summary

Vertical farming is the agricultural process in which crops are grown on top of each other, rather than in traditional, horizontal rows. Growing vertically allows for conservation of space, resulting in a higher crop yield per square meter of land used. Vertical farming requires high energy consumption in terms of operating its main components which are (1) climate control system, (2) lighting system, and (3) watering system. Using solar energy to power the farm can reduce the energy cost. The general aim of this study was to examine vertical farming as a potential solution to address the significant food insecurity in Sudan, Africa. Three types of vertical farm, each equipped with solar photovoltaics, were designed, namely: (1) warehouse vertical farm; (2) modular (shipping-container) vertical farm; and (3) greenhouse vertical farm. Each vertical farm was designed to grow two crops -- Yellow Potato and Rocket Arugula – to meet the annual demands of the two crops by a local grocery store located in Sudan's capital city of Khartoum. This study is specifically aimed to: (1) Design an appropriate embodiment for each of the three types of vertical farm as powered by solar photovoltaics to meet the annual demand for the two crops by the local grocery store; and (2) Assess the economic viability of each designed vertical farm embodiment as a business enterprise in Khartoum, Sudan.

2.2 Methods and Materials

A supermarket called Alanfal was selected to meet their vegetables demand. It is located at Al-Mashtal St, Khartoum, Sudan. The store is one of the most popular stores in the city. It has reasonable prices and a full range of groceries, home supplies, appliances, and a wide variety of vegetables and fruits. After contacting the store manager, it was determined that yellow potatoes and rocket arugula are the most popular in the store's sales and both are easy to grow and monitor. The two crops were thus selected to be grown in each farm. Alanfal supermarket in Khartoum sells about 79,200 heads of arugula per year and about 66,000 kilograms of potatoes per year.

The three nutrient groups of micronutrients, primary and secondary macronutrients were used to grow the crops hydroponically. The primary macronutrient used is the Nitrogen-Phosphorus-Potassium mix in the ratio of 7-9-5 for growing arugula and 20-20-20 N-P-K for growing potato. N-P-K presents three out of the six macronutrients needed for plant growth. The other three macronutrients consist of hydrogen, oxygen, and carbon, supplied by water and air. The secondary macronutrients required for the system are calcium nitrate and magnesium sulfate. The calcium nitrate needs to be added to the nutrient reservoir by itself, and the magnesium sulfate may be diluted with the nutrient mixture before adding them into the water tank. It was critical not to mix the calcium nitrate with the magnesium sulfate as they react quickly and form precipitates unavailable to the plants. The micronutrients are required in lesser amounts, and the elements in the micronutrients are found in the N-P-K mix solution. The micronutrients in the N-P-K mix consist of manganese, iron, nickel, copper, zinc, boron, chlorine, and molybdenum.

The same water system was used for the three types of vertical farms. Each arugula growing structure required 200 gallons of water per cycle. While each potato growing structure required 1200 gallons of water per cycle. This required a 1200 gallon per hour (GPH) pump to provide each growing structure with sufficient water. Each of the 18 growing structures in each vertical farm was equipped with a Pondmaster Magnetic Drive Utility pump (Appendix figure 1) at a unit cost of $159. (*Magnetically Driven Pump | Utility Pumps | The Pond Guy*, n.d.).

Each arugula growing layer and potato growing box has two MARS HYDRO LED Grow Lights (Appendix figure 2). Each light illuminates 9ft^2 (0.84m^2) of growing space, has an efficiency of 2.3μmol/J, and provides a full spectrum of infrared (IR), visible, and ultraviolet (UV) light (*Amazon.Com : MARS HYDRO TS-1000 Led Grow Light 3x3ft Coverage Upgraded Daisy Chain Dimmable Full Spectrum Grow Lamps for Indoor Plant LED Grow Hydroponic Growing Light with 354 LEDs Thermometer Hygrometer Timer : Patio, Lawn & Garden*, n.d.).

The air conditioning system was oversized by about 14% to allow for potential power surges. A 48,000 BTU AC (*48000 BTU Commercial Air Conditioner Heat Pump NSF 220V*, n.d.) was used for the warehouse VF. Evaporative coolers (2000 CFM) (*Slimline Window Evaporative Cooler 2000 CFM - Brisa WH2906*, n.d.) used for cooling the greenhouse VF and for shipping containers 12000 BTU and 15000 BTU AC units were used (*LG LSN120HXV2 12000 BTU Cooling / 12000 BTU | Build.Com*, n.d.) (*Daikin FTXS15LVJU 15,000 BTU Ductless Wall Mounted Air Handler*, n.d.).

2.3 Results and Discussion

2.3.1 Growing Systems

The warehouse VF had a total of 18 growing structures, two of them for growing arugula with six growing layers in each, and 16 growing structures for growing potatoes with three boxes (vertically stacked) in each structure with a total of 48 growing boxes in the farm. Figures 6 and 7 show the growing structure for potato and arugula, respectively.

For the greenhouse VF, there was a total of 12 growing structures (pyramid-shape) to benefit from the sunlight, eight pyramids for growing potatoes, each pyramid had six boxes, three boxes on each side, and four pyramids for growing arugula, each pyramid held 48 pipes, 24 on each side. Figures 9 and 10 show the pyramid growing structure for potato and arugula, respectively.

A total of nine shipping-containers were needed for the modular (shipping containers) VF, each shipping-container had two growing structures. The first shipping-container had two structures for growing arugula, while the rest of the eight shipping-containers, each had two growing structures for potatoes with a total of 16 growing structures.

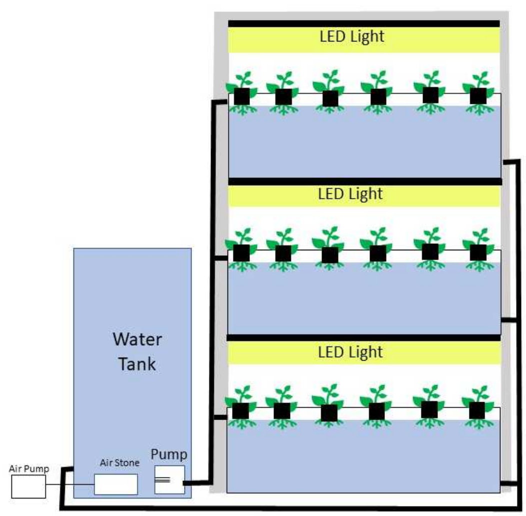


Figure 6. Potato Growing Structure

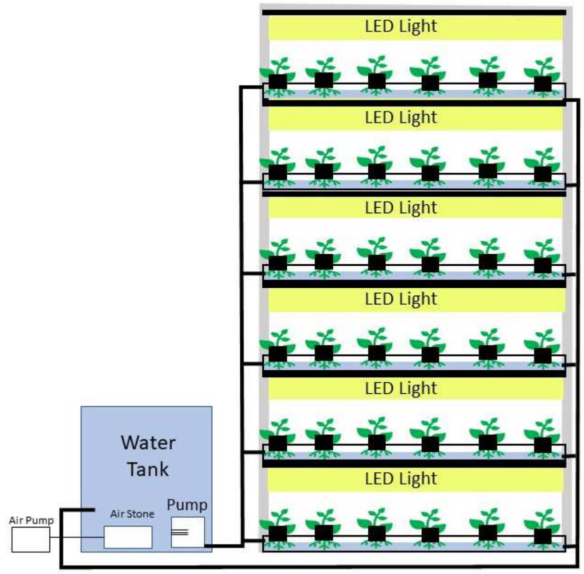


Figure 7. Arugula Growing Structure

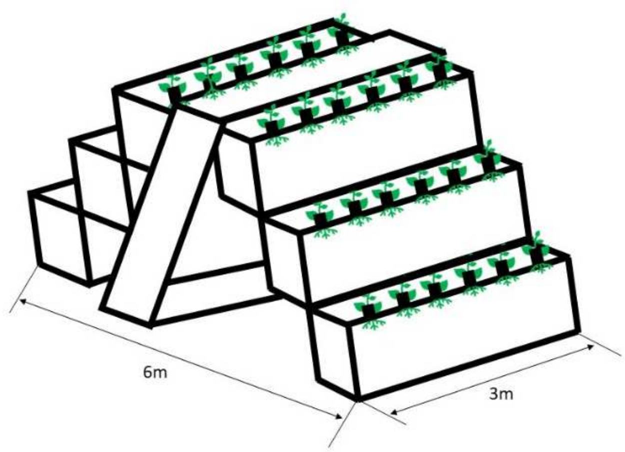


Figure 8. Potato Growing Pyramid-Structure

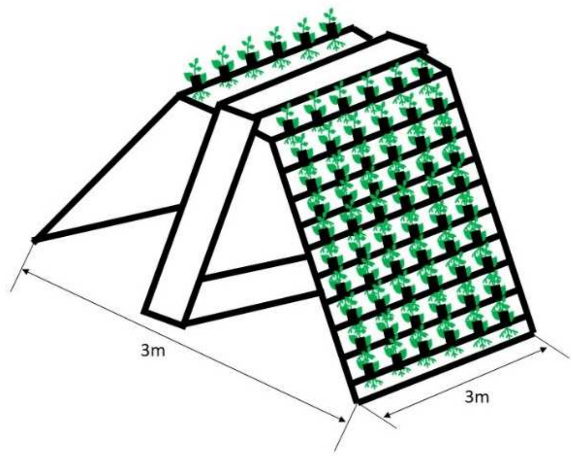


Figure 9. Arugula Growing Pyramid-Structure

2.3.2 Growing Requirements

Each arugula growing structure had its own 200-gallon water tank, and each potato growing structure had its own 1200-gallon water tank. The nutrient solution was treated to the appropriate pH and electrical conductivity required for arugula and potato to grow. The water supply for each growing structure was separated to make it easier to monitor the pH, and conductivity. It also allowed for protecting the other growing structures from contamination if a tank were to be compromised. Each arugula growing structure needed about 180 gallons of water per cycle (a month), while potato growing structure needed around 360 gallons of water every 10 weeks (about 2 and a half months), the water was recycled to reduce water consumption. About 2,160 gallons of water per growing was used to grow arugula in the entire operation, and 5,400 gallons of water per growing structure was used to grow potato in the entire operation.

The nutrient film technique (NFT) used allowed for low water and nutrient consumption and did not require a lot of growing media and allowed for efficient monitoring of the root quality and health (*The Nutrient Film Technique Explained*, 2016). The growing structures were made of both PVC and aluminum. Computer software is used to monitor the temperature and humidity to ensure optimal growing conditions. Furthermore, an air conditioning system provided the necessary cooling and ventilation for the enclosure. Given that the vertical farms placed in a hot city, they were subjected to heat exposure; therefore, an adequate air conditioning system was necessary.

2.3.3 Design Specifications

The total available area of the warehouse vertical farm was 336 square-meter with dimensions of 28 m long, 12 m wide and 2.65 m high. The shipping-container vertical farm was constructed with nine shipping containers. The dimensions of a single shipping-container were 12 m long, 2.35 m wide and 2.65 m high, with reference to Figure 2 in the appendix for a picture of a single shipping container. The warehouse was designed from metal and wood with a price of $166.50 per square meter for the warehouse vertical farm. A hoop greenhouse was designed with fiberglass for walls and roof, and concrete for flooring with a price of $111 per square meter. The hoop greenhouse was chosen because it is already used in Khartoum city and has been locally tried and tested.

The warehouse VF had 18 growing structures, each structure was 3 m long, 1 m wide, and 2.65 m high. Right to the entrance of the farm, there was a packaging station, three desks, storage cabinets, and a germination station, respectively. The packaging station was 2 m long, 1 m wide, and 1.4 m high, and was used for packaging all arugula and potatoes after harvesting. There were three desks, each 1 m long, 1 m wide, and 1.4 m high, all located to the right of the packaging station. One desk appointed with a label printer was used to print all the labels for packaging. Two of these desks equipped with computers were used as monitoring stations where laborers control and monitor the temperatures as needed. The storage cabinets were 1m to the left of the computer station, with dimensions of 8m long, 1m wide, and 2m high to store the nutrients and equipment. Lastly, the germination station was 1m to the left of the storage cabinets with a length of 6m long, 1m wide, and a height of 2m. The space between the germination station and the first row of the growing structures was 3m wide. Each growing structure is accompanied by a water tank, resulting in six growing structures and six water tanks per row. The harvesting racks are located 1m on the right of the sixth vertical farm with dimensions of 2m long, 1m wide, and 2.5m high. The harvesting racks served as a temporary home for the harvested produce. The spacing between the three rows of the growing structures was 2m wide. Figure 10 demonstrates a floor plan for the warehouse VF. Figures 6-8 in appendix show different inside views from the warehouse VF.

For the modular (shipping-container) VF, the 18 growing structures were equally distributed into nine shipping containers. Therefore, there were two growing structures, each being 3m long, 1m wide, and 2.65m high, in each shipping container. Right to the entrance of each shipping container, there was a germination station measuring 2m long and 1.4 wide, while right to the germination station there was a desk measuring 1m long and 1m wide. On the other side there were the two growing structures each equipped with its water tank. Figure 12 shows a floor plan for Modular (shipping-container) VF. In both warehouse VF and the modular VF, each arugula growing structure had 3m long tubes of 6.3cm diameter. Each layer had a 0.2m clearance for optimum growth. This enabled us to have a capacity of 79,200 heads. For growing potatoes, there were three PVC growing boxes in each of the 16-growing structures 0.5m high, 3m long, and 1m wide. The materials used to design the structures are PVC and aluminum. The use of aluminum is to establish a strong build, with the edges of the layers and the structure. While the tubes and the boxes made of PVC.

In the greenhouse VF, each of the 8-growing structures (pyramid structure) for growing potatoes was 6m long, 3m wide, and 2.6m high, on the other hand, each of the four growing structures for growing arugula was 4m long, 3m wide, and 2.65m high. Right at the entrance, there was the same layout for the warehouse VF. Except the space between the row of the germination station and the first row of the growing structures was 2m wide, and the space between the three rows of the growing structures was 2m wide. Figure 11 shows the floor plan for the greenhouse VF. Each arugula growing structure had 3m long tubes of 6.3cm diameter. For growing potatoes, there were six PVC growing boxes in each of the 8-growing structures with 0.5m high, 3m long, and 1m wide.

Considering the layouts mentioned above, three laborers can be present on each farm at a time. The space can accommodate more labors; however, for budget considerations, only three laborers were at first.

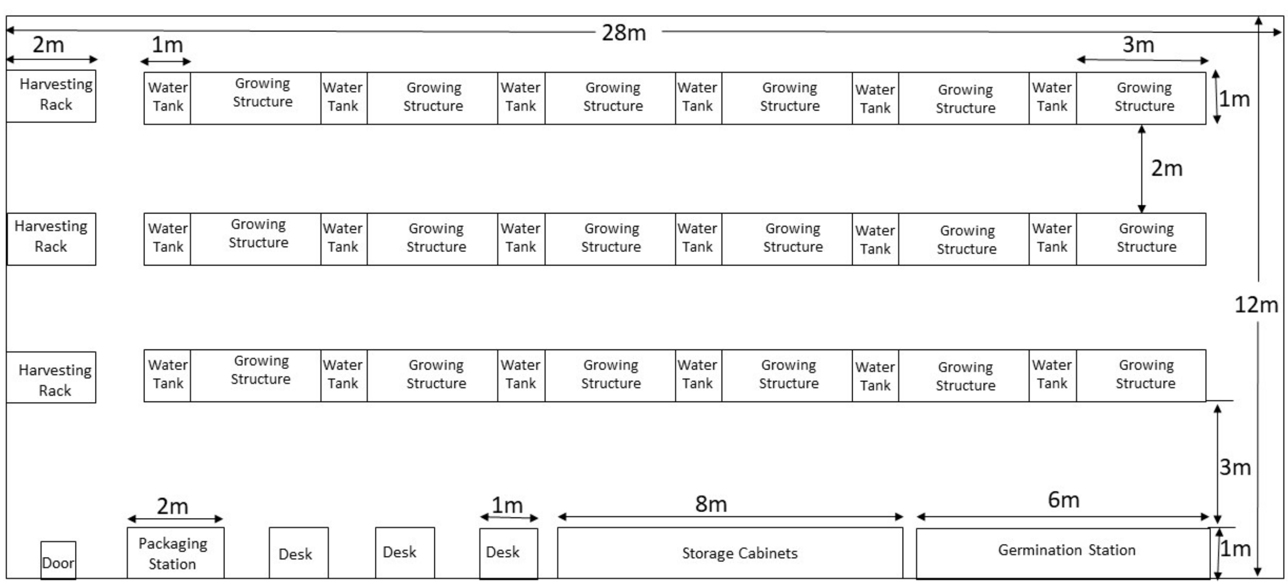


Figure 10. Floor Plan for Warehouse VF

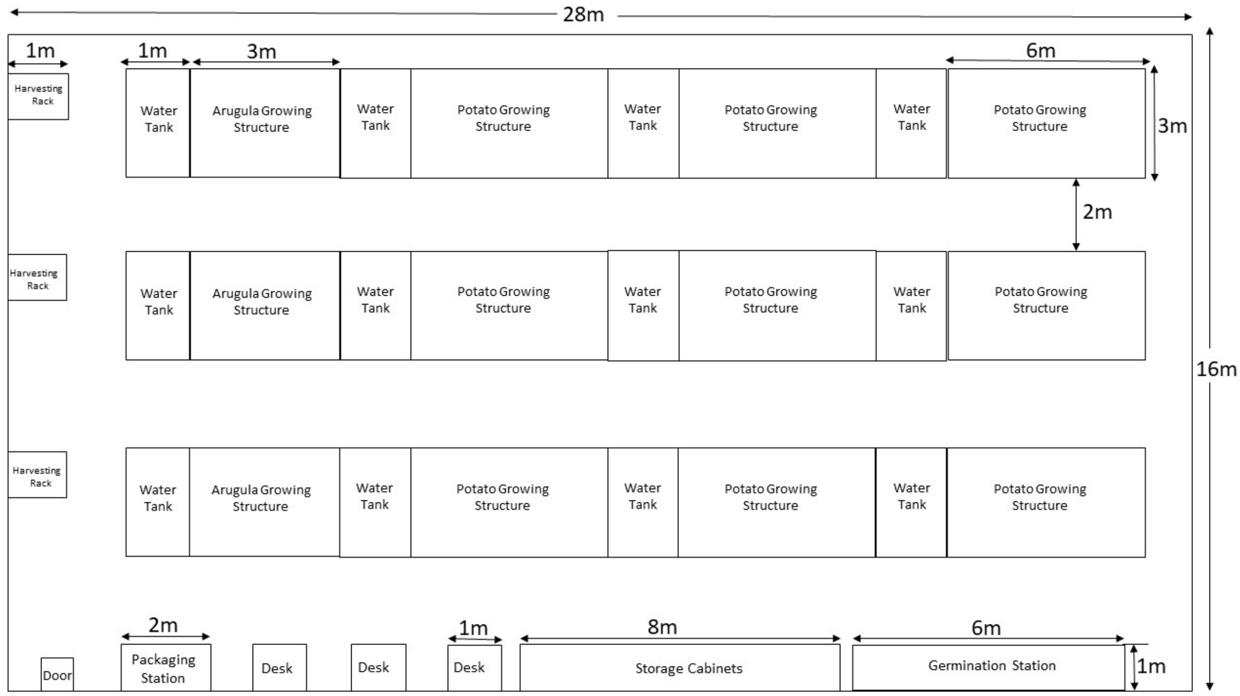


Figure 11. Floor Plan for Greenhouse VF

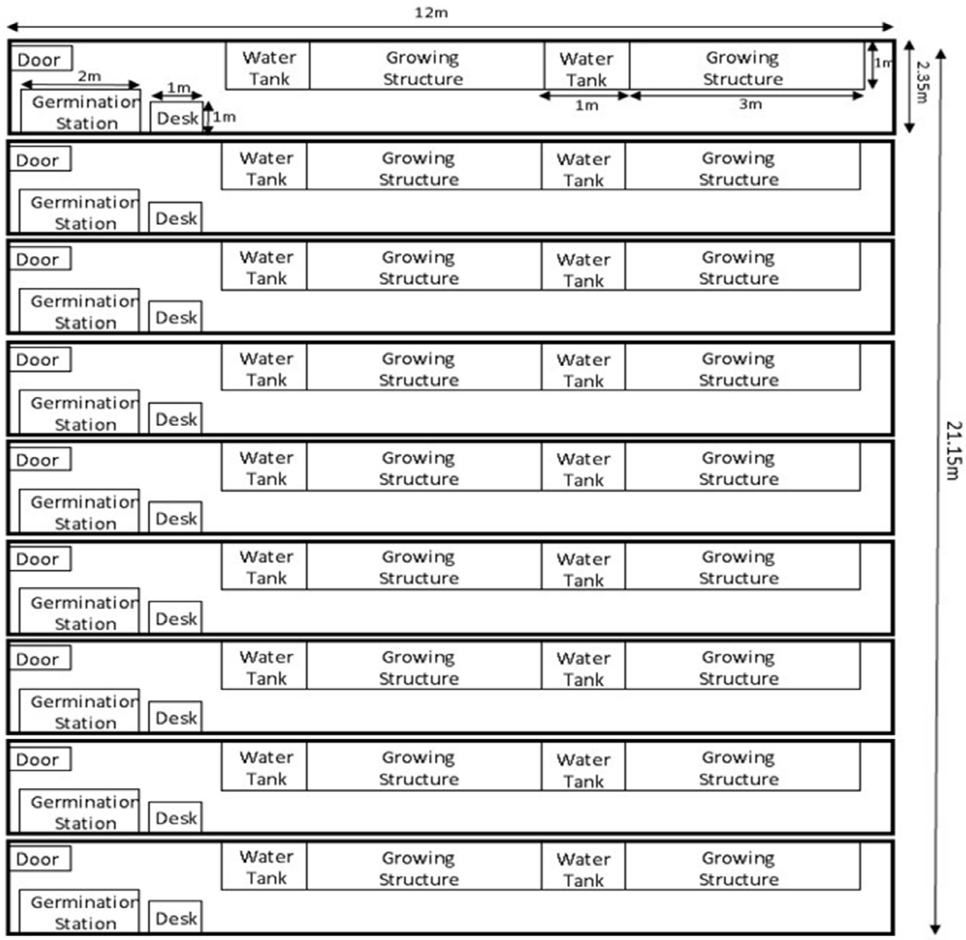


Figure 12. Floor Plan for Shipping-Containers VF

2.3.4 Operational Flow

For growing arugula, the entire growth period from the seedlings to the plant leaves lasts about five weeks, with the germination period lasting for a week and the harvesting period lasting for four weeks. Oasis horticube trays have been used for germination, where one tray contains 276 holes, and 2 seeds will be placed into each hole for optimum growth. A total of 287 trays will be used per year. Necessary specifications required for optimal growth consist of a temperature range from 50-75°F with an ideal temperature of 65°F. In terms of lighting, 12-17 mol/m²/day

(*MechaTronix - Typical PPFD and DLI Values per Crop*, n.d.) and 12-18 hours required daily. Additionally, the pH should range from 6-7.5.

The entire growth period for growing potatoes from the seedlings to the harvesting lasts about 12 weeks (about 3 months), with a germination period lasting for two weeks and the harvesting period lasting for approximately 10 weeks (about 2 and a half months). Horticube in net cups will be used for germination and be placed in a tray. One seed of potato will be placed per net cup, which results in 5760 net cups for each vertical farm. Necessary specifications required for optimal growth consist of a temperature range from 65-75°F. In terms of lighting, 15-40 mol/m²/day (*MechaTronix - Typical PPFD and DLI Values per Crop*, n.d.) and 10-12 hours required daily. Additionally, the pH should range from 5.8 – 6.2 (*Potato Seed Germination, Temperature, Time, Process | Gardening Tips*, 2020)

2.3.5 Germination & Harvesting Schedule

For growing arugula, the design is to have a one-time initial week to germinate batch one and then by the end of each cycle (last week or week 4) the germination of the next batch will start. Each batch will be harvested at the beginning of the next cycle. Table 3 below illustrates the germination and harvesting arugula schedule.

For growing potatoes, each farm consisted of 16 growing structures and in terms of having easier germination and harvesting process, the 16-growing structure of potatoes will be split into two groups, group A which consists of the first eight growing structure, and group B for the second 8 structures. Note that the potato will be harvested 5 times per year, therefore, there will be 5 batches with growth period of 12 weeks (the first 2 weeks for germination included). To begin, there will be a one-time 2 weeks to begin the germination process for group 1A. After two weeks the germination process for group 1B will start (week 1,2 in table 4) at the beginning of the plan. In the last two weeks (week 9,10) the germination process for the next batch will begin. (Same process for the initial two weeks). Group 1A will be harvested at the beginning of the cycle, while group 1B will be harvested in the following two weeks. Every 10 weeks a batch will be to harvest one batch. With a total of 5 harvested batches per year. Additionally, the germination process for the following weeks batch will start after every harvest. Table 4 below illustrates the germination and harvesting potato schedule.

Table 3. Germination and Harvesting Arugula Schedule

	Week 1	Week 2	Week 3	Week 4
First Batch				Germination 2nd batch
Second Batch	Harvesting 1st batch			Germination 3rd batch
Third Batch	Harvesting 2nd batch			Germination 4th batch
Fourth Batch	Harvesting 3rd batch			Germination 5th batch
Fifth Batch	Harvesting 4th batch			Germination 6th batch
Sixth Batch	Harvesting 5th batch			Germination 7th batch
Seventh batch	Harvesting 6th batch			Germination 8th batch
Eighth batch	Harvesting 7th batch			Germination 9th batch
Nineth batch	Harvesting 8th batch			Germination 10th batch

Tenth batch	Harvesting 9th batch			Germination 11th batch
Eleventh batch	Harvesting 10th batch			Germination 12th batch
Twelfth batch	Harvesting 11th batch			Germination 1st batch

Table 4. Germination and Harvesting Potato Schedule

	Week 1,2	Week 3,4	Week 5,6	Week 7,8	Week 9,10
Batch 1	Germination Batch 1B				Germination batch 2A
Batch 2	Germination batch 2B Harvesting batch 1A	Harvesting batch 1B			Germination batch 3A
Batch 3	Germination batch 3B Harvesting batch 2A	Harvesting batch 2B			Germination batch 4A
Batch 4	Germination batch 4B Harvesting batch 3A	Harvesting batch 3B			Germination batch 5A
Batch 5	Germination batch 5B Harvesting batch 4A	Harvesting batch 4B			Germination batch 1A

2.3.6 Power Usage and Cost

Water System

The water system for the warehouse and shipping containers vertical farms will be the same.

Each arugula growing structure of 6 layers require 200 gallons of water per cycle. While each potato growing structure requires 1200 gallon of water per cycle. This require a 1200-gallon per hour (GPH) pump to provide each growing structure with sufficient water. Each of the 18 growing structures in each vertical farm was equipped with a Pondmaster Magnetic Drive Utility pump at a unit cost of $159 (*Magnetically Driven Pump | Utility Pumps | The Pond Guy*, n.d.). These pumps have a maximum draw power of 110W and was in operation 24 hours a day. The energy and power calculations for each warehouse VF and shipping- containers VF for the water system are shown in table 5. For greenhouse vertical farm, there were 12 growing structures, each required 1 pump (same pump used for warehouse and shipping containers VFs). The energy and power calculations for the water system in greenhouse vertical farm shown in table 6.

Table 5. Energy and Power Calculations for each Warehouse and Shipping-Containers VFs Water System

Category	**value**
Max draw power per pump (kW)	0.11
Number of pumps	18
Max draw power of the system (kW)	1.98
Hours of operation	24
Hours of operation (nighttime)	14
kWHr per day	47.52
kWHr per day (nighttime)	27.72
kWHr per year	17,344.80
kWHr per year (nighttime)	10,117.80

Table 6. Energy and Power Calculations for Greenhouse VF Water System

Category	**Value**
Max draw power per pump (kW)	0.11
Number of pumps	12
Max draw power of the system (kW)	1.32
Hours of operation	24
Hours of operation (nighttime)	14
kWHr per day	31.68
kWHr per day (nighttime)	18.48
kWHr per year	11,563.20
kWHr per year (nighttime)	6,745.20

Lighting System

The lights for growing arugula will be operated between 12-18 hours per day depending on plant needs, as the lights for growing potato will be operated between 10-12 hours per day. The lights have a predicted lifespan of more than 50,000 hours (about 5 and a half years) of operation. This translates into a lifespan of about 7.6 years if operated 18 hours per day. Each potato growing box and arugula growing layer required 2 MARS HYDRO LED Grow Lights (*Amazon.Com : MARS HYDRO TS-1000 Led Grow Light 3x3ft Coverage Upgraded Daisy Chain Dimmable Full Spectrum Grow Lamps for Indoor Plant LED Grow Hydroponic Growing Light with 354 LEDs Thermometer Hygrometer Timer : Patio, Lawn & Garden*, n.d.). The germination station will additionally use 6 lights. Each light has a maximum draw power of 150W and will be in operation for a maximum of 18 hours per day. Tables 7 and 8 show each lighting system calculations for warehouse and shipping containers vertical farms. For the greenhouse VF the light source was the sun, and no lights were required for any of the growing structures except for the germination station as 6 lights were required as shown in table 9.

Table 7. **Energy and Power Calculation for Lighting System for Growing Arugula in each of the Warehouse and Shipping container VF**

Category	Value
Power consumption for each light kW	0.15
Number of lights needed per layer	2
Number of layers per growing structure	6
Number of growing structures	2
Number of lights needed for germination station	6
Total number of lights needed	30
Total power consumption of the system kW	4.5
Hours of operation per day	18
Hours of operation (nighttime)	8
kWHr per day	81
kWHr per day (nighttime)	36
kWHr per year	29,565.00
kWHr per year (nighttime)	13,140.00

Table 8. Energy and Power Calculation for Lighting System for Growing Potato in each of the Warehouse and Shipping Container VF

Category	Value
Power consumption for each light kW	0.15
Number of lights needed per box	2
Number of boxes per one growing structure	3
Number of growing structures	16
Total number of lights needed	96
Total power consumption of the system kW	14.4
Hours of operation per day	12
Hours of operation (nighttime)	2
kWHr per day	172.8
kWHr per day (nighttime)	28.8
kWHr per year	63,072
kWHr per year (nighttime)	10,512.00

Table 9. Energy and Power Calculation for Lighting System for Greenhouse VF

Category	Value
Power consumption for each light kW	0.15
Number of lights needed for germination station	6
Number of lights	6
Total power consumption of the system kW	0.9
Hours of operation	8
kWHr per day	7.2
kWHr per year	2,628

Climate Control System

The AC system was oversized by about 14% to allow for potential power surges. 48,000 BTU AC (*48000 BTU Commercial Air Conditioner Heat Pump NSF 220V*, n.d.) used for the warehouse VF. Evaporative coolers (2000 CFM) (*Slimline Window Evaporative Cooler 2000 CFM - Brisa WH2906*, n.d.) used for cooling the greenhouse VF and for shipping containers VF 12000 BTU and 15000 BTU AC units were used (*LG LSN120HXV2 12000 BTU Cooling / 12000 BTU | Build.Com*, n.d.) (*Daikin FTXS15LVJU 15,000 BTU Ductless Wall Mounted Air Handler*, n.d.). Tables 10 and 11 show the energy and power calculations for the climate control system for warehouse and greenhouse, respectively. While table 12 shows the power calculation for the climate control system for the first shipping container, as it was for growing arugula, and it required more BTUs for AC units than the potato needed to maintain appropriate growing temperature. Table 13 shows the calculations for the rest of each of the 8 shipping containers which are for growing potatoes.

Table 10. Energy and Power Calculations for Warehouse VF Climate Control System

Category	Value
BTU needed for W of light	3.41
Total lighting system power demand (W)	18900
Total BTU needed	64,449
BTU per AC unit	48000
AC units needed	2
Total power consumption of system (kWh)	19
Hours of operation	24
Hours of operation (nighttime)	14
kWHr per day	453.6
kWHr per day (nighttime)	264.6
kWHr per year	165,564
kWHr per year (nighttime)	96,579

Table 11. Energy and Power Calculations for Greenhouse VF Climate Control System

Category	Value
BTU needed for W of light	3.41
Total lighting system power demand (W)	900
Total BTU needed from lights	3069
Total BTU needed from sunlight	87148.7
Total BTU needed	90217.7
CFM	3007.3
AC units needed	2

kWh per AC unit	0.115
Total power consumption of system (kWh)	0.23
Hours of operation	24
Hours of operation (nighttime)	14
kWHr per day	5.5
kWHr per day (nighttime)	3.2
kWHr per year	2014.8
kWHr per year (nighttime)	1175.3

Table 12. Energy and Power Calculations for the First Shipping-Container VF Climate Control System

Category	Value
BTU needed for W of light	3.41
Total lighting system power demand (W)	3900
Total BTU needed	13,299
BTU per AC unit	12000
AC units needed	2
Total power consumption of system (kWh)	4
Hours of operation	24
Hours of operation (nighttime)	14
kWHr per day	93.6
kWHr per day (nighttime)	54.6
kWHr per year	34164
kWHr per year (nighttime)	19929

Table 13. Energy and Power Calculations for each of the 8 Shipping-Container VF Climate Control System

Category	Value
BTU needed for W of light	3.41
Total lighting system power demand (W)	2100
Total BTU needed	7,161
BTU per AC unit	15000
AC units needed	1
Total power consumption of system (kWh)	2
Hours of operation	24
Hours of operation (nighttime)	14
kWHr per day	50.4
kWHr per day (nighttime)	29.4
kWHr per year	18396
kWHr per year (nighttime)	10731

2.3.7 Photovoltaics System Usage and Cost

The photovoltaics systems for the three types of vertical farms provided 100% of the farm's annual energy demand at the daytime which reduced the energy consumption per day. The solar panels used were Panasonic 330W Mono (*Panasonic SC330 330w Mono Solar Panel*, n.d.) (see appendix figure 9 for picture of single panel). Every 25 solar panels required one Fronius 8.2kW inverter to convert the direct current (DC) power produced by the solar panels to the alternating current (AC) power used by the vertical farm equipment (Sunwatts) (*Fronius*

Primo 8.2-1 TL 8.2kW Inverter, n.d.) (see appendix figure 10 for picture of the inverter). The inverters have a conversion efficiency of 97%, meaning that 3% of generated power is lost during the process of converting the generated DC to consumable AC. Number of solar panels were estimated to cover the energy demand at the daytime including the 3% loss. At night and during other times when the solar power system is insufficient to power the vertical farm, the energy was purchased from the Sudanese Electricity Distribution Company (SEDC) grid at the price of $0.056 per kWh.

Panels should face the south in Khartoum as Sudan is above the equator, meaning it is part of the northern hemisphere. The latitude of Khartoum, Sudan is 15.5° N, so tilt angle for summer/winter were calculated as:

Solar panels angle in summer = 15.5° – 15° = 0.5°

Solar panels angle in winter = 15.5° + 15° = 30.5°

Warehouse Photovoltaics System

The total number of Panasonic 330W Mono solar panels required to produce energy during the time for the warehouse VF was 98, as shown in the below diagram, figure 14 shows the layout of the photovoltaics system for warehouse VF. The annual energy calculations for 100% solar powered for warehouse VF are shown in table 14. The total capital cost for the solar power system was $36,111, meaning this system would pay for itself in energy savings in almost 5.6 years. The expected lifetime of the solar power system is 25 years (*Panasonic SC330 330w Mono Solar Panel*, n.d.), resulting in estimated lifetime energy savings of $2,870,268.75.

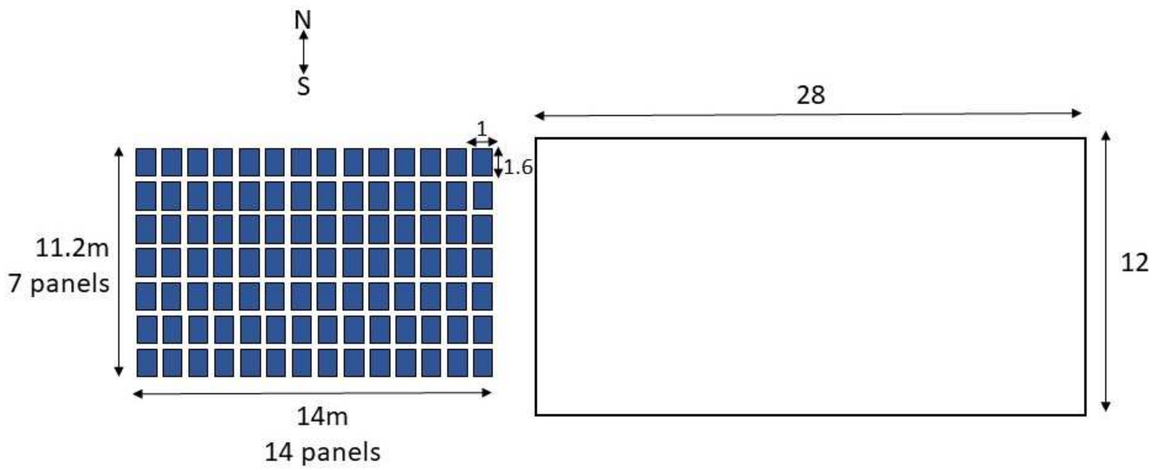


Figure 13. Photovoltaic System for Warehouse VF.

Table 14. Warehouse VF Annual Energy Calculations -100% Solar Powered

Total energy consumed (kWh)	275545.8
Total energy consumption (daytime)	114810.75
kW per solar panel	0.33
Number of panels needed	98
Solar Energy produced (kWh)	114810.75
Energy purchase rate ($/kWh)	0.056
Annual energy consumption cost ($)	6429.4
Cost of panels and inverters	36111.04
Years of operation to pay for system with energy savings	5.6

Greenhouse Photovoltaics System

The total number of Panasonic 330W Mono solar panels needed to produce energy at the daytime for the warehouse VF was 6 as shown in figure 15. The annual energy calculations for

100% solar-powered greenhouse VF are shown in table 15. The total capital cost for the solar power system was $5,742, meaning this system would pay for itself in energy savings in almost 14.6 years. The expected lifetime of the solar power system is 25 years, resulting in estimated lifetime energy savings of $9,837.5.

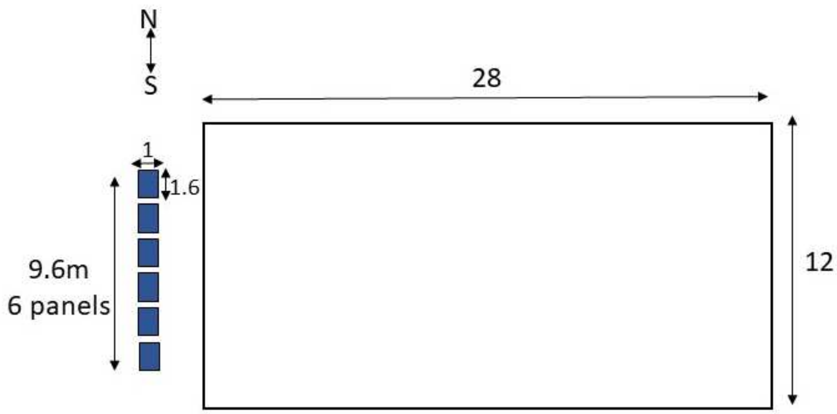


Figure 14. Photovoltaic System for Greenhouse VF.

Table 15. Greenhouse VF Annual Energy Calculations -100% Solar Powered

Total energy consumed (kWh)	16,863.00
Total energy consumption (daytime)	7026.3
kW per solar panel	0.33
Number of panels needed	6
Solar Energy produced (kWh)	7026.3
Energy purchase rate ($/kWh)	0.056
Annual energy consumption cost ($)	393.5
Cost of panels and inverters	5,742
Years of operation to pay for system with energy savings	14.6

Shipping-Containers Photovoltaics System

The total number of Panasonic 330W Mono solar panels required to produce energy at the daytime for the warehouse VF was 110, as shown in figure 16. The annual energy calculations for 100% solar-powered are shown in table 16. The total capital cost for the solar power system is $41,755, meaning this system would pay for itself in energy savings in almost 6 years. The expected lifetime of the solar power system is 25 years, resulting in estimated lifetime energy savings of $173,765.

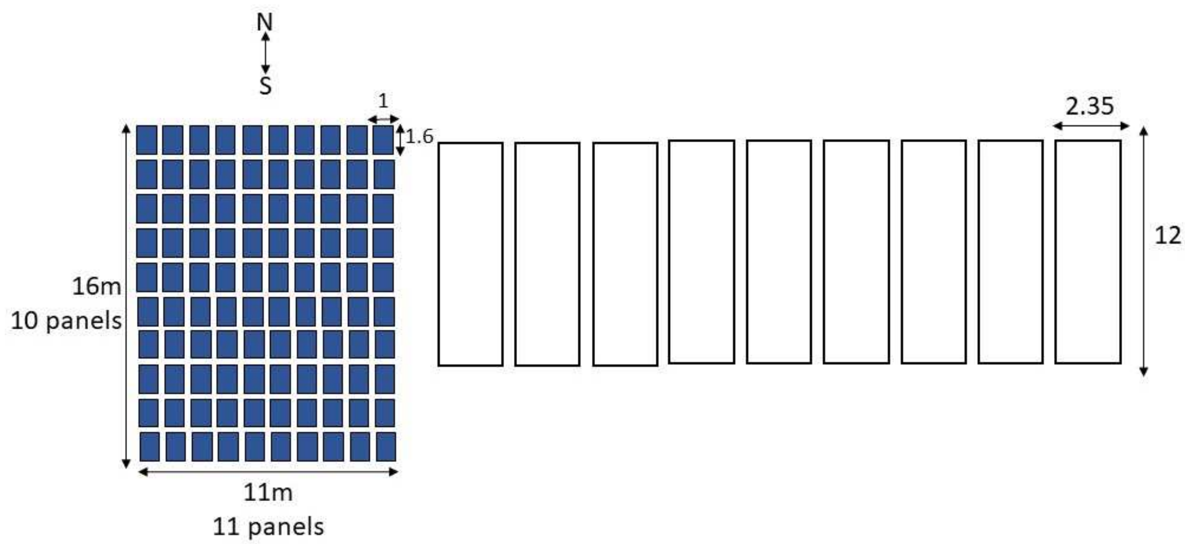


Figure 15. Photovoltaic System for Shipping-Containers VF.

Table 16. Shipping-Containers VF Annual Energy Calculations -100% Solar Powered

Total energy consumed (kWh)	297883.8
Total energy consumption (daytime)	124118.25
kW per solar panel	0.33
Number of panels needed	110
Solar Energy produced (kWh)	128520.15
Energy purchase rate ($/kWh)	0.056

Annual energy consumption cost ($)	6950.6
Cost of panels and inverters	41755.00
Years of operation to pay for system with energy savings	6.0

Budget Overview

The budget is split into two parts: the capital costs and operational costs. The capital costs included the land price, structure building costs, in addition to insulation in warehouse VF and shipping-container VF, and the photovoltaic system components (solar panels and inverters). The operational costs included labor costs, water and energy consumption costs, and growing supplies.

Warehouse VF Budget Overview

Capital Costs

The total capital cost for the warehouse VF is $261,275. The highest cost was the land purchasing cost, which is $168,000, followed by the cost for the warehouse building of $55,944. The third most expensive item was for the 98 solar panels and inverter of $27,244.00 and $8,148, respectively. Table 17 shows the breakdown of the capital cost for Warehouse VF.

Table 17. Capital Costs for Warehouse VF

Capital Costs	**Unit Price**	**Units Required**	**Total Cost**
Solar Panels	$278	98	$27,244.00
Inverter	$2,037	4	$8,148.00
Warehouse Building /1m^2	$166.50	336	$55,944.00
Germination station	$649	1	$1,298.00
Insulation 1.2mx38m	$161	8	$1,290.00

Land price/m^2	$500	336	$168,000.00
			$261,275.00

Operational Costs

The supply costs included the supplies for growing both crops depending on their different growing requirements. The total annual energy consumption was for the energy purchased during the night and any other time the solar panels would not be able to supply energy, which was $7,300. The total operational cost for warehouse VF was $116,875.88 since the labor cost was $6 per hour and 3 workers were needed to operate the farm. The highest cost in the operational cost was the labor cost which was $37,440. Table 18 shows the total operational costs including all items used with the quantity and price of each of them.

Table 18. Total Annual Operational Cost for Warehouse VF

Category	Unit price	Quantity needed	Total Cost
Oasis Horticube trays	$5.00	287	$1,434.78
Seeds (1028)	$2.00	1620	$3,240.00
7-9-5 NPK for growing arugula	$23.98	7	$159.87
Calcium Nitrate	$49.99	2	$99.98
Magnesium Sulfate	$32.95	2	$65.90
Water /1m^3 (for growing potato)	$0.80	1440	$1,152.00
Clone Collars	$0.28	4080	$1,142.40
Plastic net cups	$0.25	4080	$1,020.00
Seeds	$0.08	16320	$1,224.00
20-20-20 NPK for growing potato	$23.98	19	$463.61
Water/1m^3 (for growing arugula)	$0.80	37.44	$29.95
Lighting	$139.00	120	$16,680.00
Racks	$252.99	3	$758.97

Water pump	$159	18	$2,862.00
EC Meter	$14.97	18	$269.46
pH Meter	$99	18	$1,782.00
Water tank (for arugula)	$133	2	$265.90
Category	**Unit price**	**Quantity needed**	**Total Cost**
Water tank (for potato)	$1,246	16	$19,936.00
Computer/Laptop	$1,000	2	$2,000.00
Storage Cabinet	$329	6	$1,974.00
Air Conditioner	$2,990	2	$5,980.00
Ladder	$119	3	$357.00
PVC	$13.99	500	$6,995.00
Aluminum (dollar per pound)	$0.60		$1,050.00
Chair	$14.97	4	$59.88
Plastic box	$12	48	$576.00
Air Stone	$14.99	18	$269.82
Air pump	$15.99	18	$287.82
Labor			$37,440
Total Energy Consumption Cost			$7,300
			$116,875.88

Greenhouse VF Budget Overview

Capital Costs

The total capital cost for the greenhouse VF was $211,690. The highest cost was the land purchasing cost, which is $168,000, followed by the cost for warehouse building of $37,296. Table 19 shows the breakdown of the capital cost for Greenhouse VF.

Operational Costs

The supplies costs included the supplies for growing both crops depending on their different growing requirements. The total energy consumption was for the energy purchased during the night and any other time the solar panels would not be able to provide energy $7,300. The total annual operational cost for warehouse VF was $104,352.88 since the labor cost was $6 per hour and 3 workers were needed to operate the farm. The highest cost in the operational cost was the labor cost which was $37,440. Table 20 shows the total operational costs including all items used with the quantity and price of each of them.

Table 19. Capital Costs for Greenhouse VF

Capital Costs	Unit Price	Units Required	Total Cost
Solar Panels	$278	6	$1,671.82
Inverter	$2,037	2	$4,074.00
Greenhouse Building / 1m2	$111.00	336	$37,296.00
Germination station	$649	1	$649.00
Land price/m2	$500	336	$168,000.00
			$211,690.82

Table 20. Total Annual Operational Cost for Greenhouse VF

Category	Unit price	Quantity needed	Total Cost
Oasis Horticube trays	$5.00	287	$1,434.78
Seeds (1028)	$2.00	1620	$3,240.00
7-9-5 NPK for growing arugula	$23.98	7	$159.87
Calcium Nitrate	$49.99	2	$99.98
Magnesium Sulfate	$32.95	2	$65.90
Water /1m3 (for growing potato)	$0.80	1440	$1,152.00
Clone Collars	$0.28	4080	$1,142.40
Plastic net cups	$0.25	4080	$1,020.00
Seeds	$0.08	16320	$1,224.00
20-20-20 NPK for growing potato	$23.98	19	$463.61

Water/1m^3 (for growing arugula)	$0.80	37.44	$29.95
Lighting	$139.00	6	$834.00
Shelves for Harvested Produce	$252.99	3	$758.97
Category	**Unit price**	**Quantity needed**	**Total Cost**
Water pump	$159	18	$2,862.00
EC Meter	$14.97	18	$269.46
pH Meter	$99	18	$1,782.00
Water tank	$133	2	$265.90
Water tank (for potato)	$1,246	16	$19,936.00
Computer/Laptop	$1,000	2	$2,000.00
Storage Cabinet	$329	6	$1,974.00
Evaporative Cooler	$649	2	$1,298.00
Ladder	$119	3	$357.00
PVC	$13.99	1000	$13,990.00
Aluminum (dollar per pound)	0.60		$2,060.00
Chair	$14.97	4	$59.88
Plastic box	$12	48	$576.00
Air Stone	$14.99	18	$269.82
Air pump	$15.99	18	$287.82
Labor			$37,440
Total Energy Consumption Cost			$7,300
			$104,352.88

Shipping-Containers VF Budget Overview

Capital Costs

The total capital cost for the Shipping Containers VF is $252,426. The highest cost was the land purchasing cost, which is $168,000, followed by the cost for the warehouse building of $39,600. The third most expensive item was for the 98 solar panels and inverter, costing

$30,580 and $10,185, respectively. Table 21 shows the breakdown of the capital cost for the Shipping-Containers VF.

Table 21. Capital Costs for Shipping-Containers VF

Capital Costs	Unit Price	Quantity Needed	Total Cost
Solar Panels	$278	110	$30,580.00
Inverter	$2,037	5	$10,185.00
Cost of shipping container	$4,400	9	$39,600.00
Germination station	$290	9	$2,610.00
Insulation 1.2mx38m	$161	9	$1,451.25
Land price/m^2	$500	336	$168,000.00
			$252,426.25

Operational Cost

The operational costs included the supplies for growing both crops depending on their different growing requirements. The total annual energy consumption was for the energy purchased during the night and any other time the solar panels would not be able to provide energy, which was $5,502. The total operational cost for the modular (shipping-container) VF was $119,108.72 since the labor cost was $6 per hour and 3 workers were needed to operate the farm. The highest cost in the operational cost was the labor cost for $37,440. Table 22 shows the total operational costs including all items used with the quantity and price for each.

Table 22. Total Annual Operational Costs for Shipping-Containers VF

Category	Unit price	Quantity needed	Total Cost
Oasis Horticube trays	$5.00	287	$1,434.78
Seeds (1028)	$2.00	1620	$3,240.00
Dyna-Gro 7-9-5 NPK Solution	$23.98	7	$159.87

Calcium Nitrate	$49.99	2	$99.98
Magnesium Sulfate	$32.95	2	$65.90
Category	**Unit price**	**Quantity needed**	**Total Cost**
Water /1m3 (for growing potato)	$0.80	1440	$1,152.00
Clone Collars	$0.28	4080	$1,142.40
Plastic net cups	$0.25	4080	$1,020.00
Seeds	$0.08	16320	$1,224.00
Southern Ag 20-20-20 Soluble Fertilizer	$23.98	19	$463.61
Water/1m^3 (for growing arugula)	$0.80	37.44	$29.95
Lighting	$139.00	96	$13,344.00
Water pump	$159	18	$2,862.00
EC Meter	$14.97	18	$269.46
pH Meter	$99	18	$1,782.00
water tank	$133	2	$265.90
water tank (for potato)	$1,246	16	$19,936.00
Computer/Laptop	$1,000	3	$3,000.00
Air Conditioner (12000BTU)	$319	2	$638.00
Air Conditioner (15000BTU)	$443	8	$3,544.00
PVC	$13.99	500	$6,995.00
Aluminum (dollar per pound)	$0.60		$1,050.00
Chair	$14.97	9	$134.73
Plastic box	$12	48	$576.00
Air Stone	$14.99	18	$269.82
Air pump	$15.99	18	$287.82
Labor			$37,440
Total Energy Consumption Cost			$16,681
			$119,108.72

The annual production for each VF was 66,000 kg of potatoes and 79,200 heads of arugula as shown in Table 23, which equaled the annual demand by the Al-Anfal supermarket.

Table 23. The Whole Price for Crops and Total Revenue.

	Potatoes (1kg)	Arugula (head)
Unit whole price	$2.5	$1.5
Total production	66,000	79,200
	$165,000	$118,800
Total revenue		$283,800

The years to break-even for the warehouse VF and the shipping container VF was 1.3 years, while for the greenhouse VF was 1.1 years. The time to break-even is remarkably similar for the three designs, but the greenhouse design is the fastest to break-even as it required only six solar panels to meet its energy demand – in contrast to 98 for the warehouse VF and 110 for the shipping-container VF -- which resulted in a lower capital cost compared to other VFs. Also, the greenhouse VF is the most profitable case as it required less supplies utilization (lighting and cooling) and it had lower annual energy consumption costs, which made it the most profitable design after the break-even point with an estimated annual profit of $179,447. The warehouse VF is the second most profitable design after break-even with an estimated annual profit of $166,924. The modular (shipping-container) VF was in third place with an estimated annual profit after break-even of $164,691 as shown below in Table 24.

Table 24. Comparison of The Feasibility of the Three Types of Vertical Farms

	WAREHOUSE VF	GREENHOUSE VF	SHIPP CONT VF
Total capital cost	$261,275	$211,691	$252,426
Total operational cost	$116,876	$104,353	$119,109

Total cost	$378,151	$316,044	$371,535
Years to break even	1.3	1.1	1.3
Annual profit	$166,924	$179,447	$164,691

2.4 Conclusions and Recommendations

The conclusions of the study were as follows:

(1) The greenhouse vertical farm was the most profitable case with a break-even period of 1.1 years and an estimated annual profit of $179,447;

(2) The warehouse vertical farm was the second most profitable case with a break-even period of 1.3 years and an estimated annual profit of $166,924;

(3) The modular shipping-container vertical farm was the last place with an estimated annual profit of $164,691 and breakeven point of 1.3 years; and,

(4) Although requiring significant capital and operational investments, the foregoing three embodiments of vertical farming, powered by solar photovoltaics, to meet the annual demands for 66,000 kg of Yellow Potato and 79,200 heads of Rocket Arugula by the local grocery store Al-Anfal Supermarket in Sudan's capital city of Khartoum demonstrated reasonable promise for economic profitability.

For further improvements, additional investments can be made to employ data analytics to optimize environmental control and energy expenditure relative to crop productivity and quality. Automation tools may also be considered to reduce labor costs. Also, battery storage systems for excess daylight solar power may be used to supply power during the night. These offer potential to increase crop productivity and quality as well as profit.

Appendix

Figure 1. Pondmaster 110W 1200GPH Magnetic Drive Utility Pump

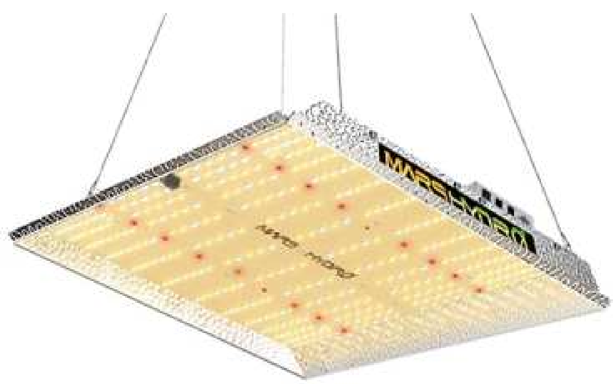


Figure 2. MARS HYDRO TS 1000W LED Grow Light

Figure 3. Pioneer 48,000 BTU Air Conditioner with Heat Pump

Figure 4. Slimline Window Evaporative Cooler 2000 CFM - Brisa WH2906

Figure 5. Single Shipping Container

Figure 6. Inside View of the Warehouse VF

Figure 7. Inside View of the Warehouse VF

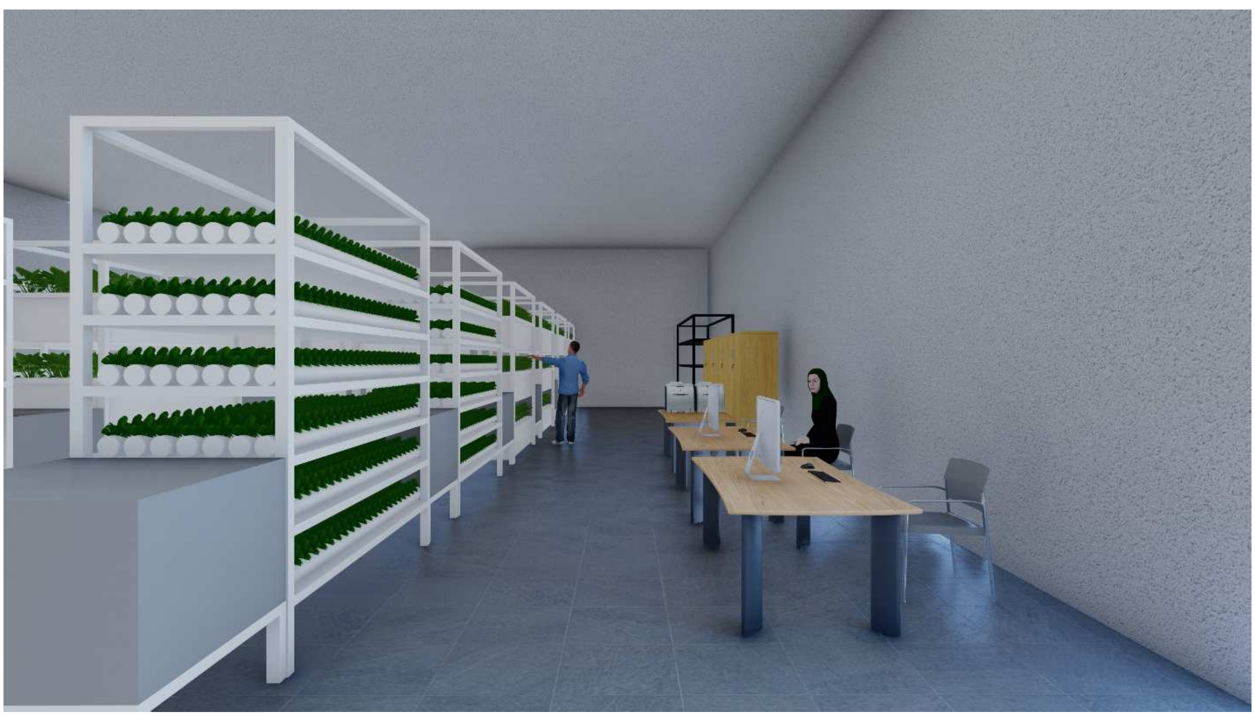


Figure 8. Inside View of the Warehouse VF

Figure 9. External View for the Warehouse Vertical Farm

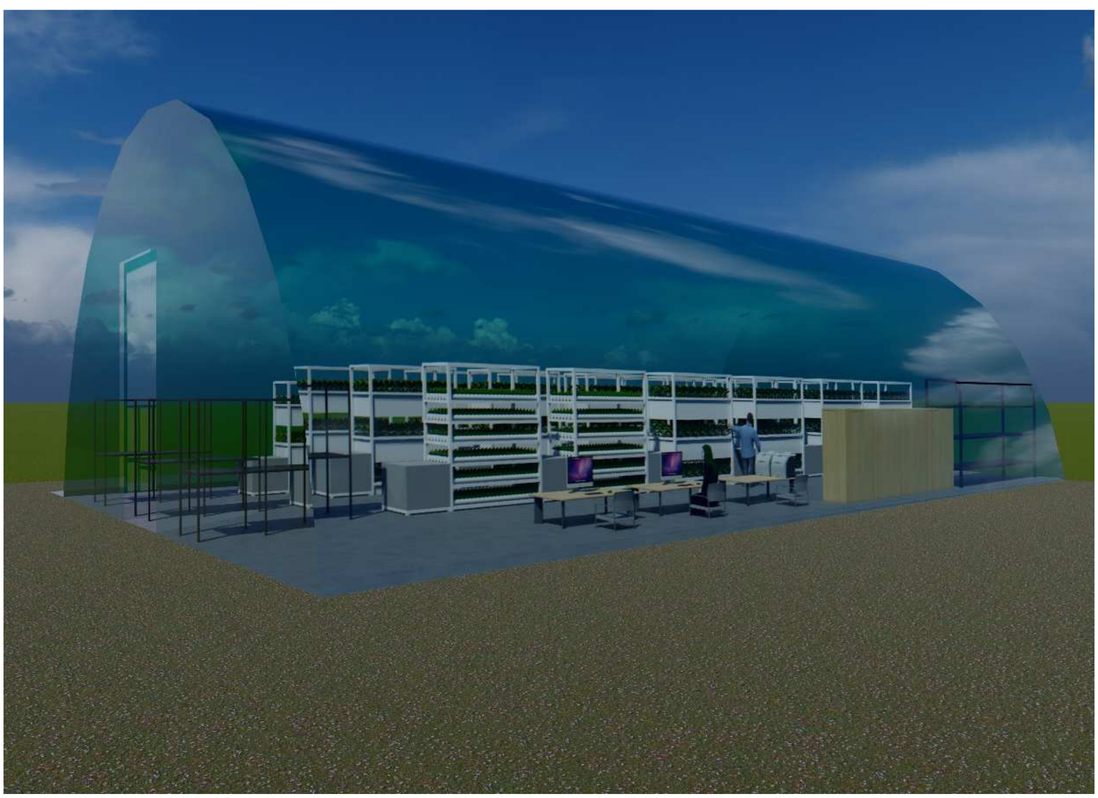


Figure 10. External view for the Greenhouse Vertical Farm

Figure 11. Panasonic 330W Mono Solar Panel

Figure 12. Fronius 8.2kW Inverter

Figure 13. 48 in. x 125 ft. Double Reflective Insulation Radiant Barrier

Table 1. Labor Cost Calculation

Number of working hours per day	8
Days per week	5
Weeks per year	52
Hours per year	2080
Rate per hour	$6
Labor cost per year	$12,480
Labor cost per month	$1,040
Number of labors needed per VF	2
Annual cost for 6 labors per year	$24,960

Table 2. Potato Annual Production

Plastic Net Cup Per Box	120
Number of Boxes Per growing Structure	3
Number of Growing Structure Per VF	16
Total Number of Net Cups Required	5760
Number of Plants Per VF	5760
Kg of Potato Per Plant	2.3
Total kg of Potato for VF Per One Harvesting	13248
Number of Harvesting Per Year	5
Total kg of Potato for one VF Per Year	66240

Table 3. Arugula Annual Production

Number of Holes Per Tray	276
Number of Trays for VF (per year)	287
Number of Trays per 1 Harvesting	24
Number of Harvesting Per Year	12
Total Heads of Arugula for One VF Per Year	79200

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