MODELING AND ANALYSIS OF HEAT PUMP INTEGRATED PV-WIND SYSTEMS FOR A COMMERCIAL GREENHOUSE

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ABSTRACT

MODELING AND ANALYSIS OF HEAT PUMP INTEGRATED PV-WIND SYSTEMS FOR A COMMERCIAL GREENHOUSE

This thesis focuses on modeling and simulating renewable energy (RE) systems that include photovoltaic (PV) panels, wind turbines (WT), and air source heat pumps (HP) for meeting the heating load of a commercial greenhouse (GH) in the agricultural zone in Dikili. Five different energy systems scenarios, namely (i) PV-HP, (ii) PV-WT-HP, (iii) WT-PV-HP, (iv) WT-HP, and (v) only HP were considered. For all scenarios the mismatch between the load and the generation was covered by grid. The second and third scenarios differ from each other based on the number of PVs and WTs. The design of the greenhouse was made with SketchUp and TRNSYS software based on dimensions of the greenhouse. According to the weather data and greenhouse parameters, solar radiation calculations were made, and the greenhouse system was modeled by MATLAB software. The annual heating and cooling demands of the designed greenhouse and electricity generation by PVs and WTs were calculated on an hourly basis. The heating and cooling loads were found to be 5,922,015 and 11,014,446 kWh/year, respectively. Since the maximum power output by RE for the reserved area is not sufficient to meet the cooling load, the cooling process was excluded. Economic and environmental analyzes were made. The first scenario including 5,271 PV panels and 20 HPs was found to be the best scenario. Net Present Value (NPV), Levelized Cost of Energy (LCOE) and CO_2 savings of the related scenario were calculated as $547,440.40, 0.080146 $/kWh and 1,270.96 t.

Keywords: Greenhouse Heating and Cooling, Heat Pumps, Photovoltaics, Wind Turbine, Techno-Economic Analysis

ÖZET

TİCARİ BİR SERA İÇİN ISI POMPASI ENTEGRE PV-RÜZGAR SİSTEMLERİNİN MODELLENMESİ VE ANALİZİ

Bu tez, Dikili'deki bir tarım alanında bulunan ticari bir seranın ısıtma yükünü karşılamak için fotovoltaik paneller, rüzgar türbinleri ve hava kaynaklı ısı pompalarını içeren yenilenebilir enerji sistemlerinin modellenmesine ve simülasyonuna odaklanmaktadır. (i) Fotovoltaik panel-Isı pompası, (ii) Fotovoltaik panel-Rüzgar türbini-Isı pompası, (iii) Rüzgar türbini-Fotovoltaik panel-Isı pompası, (iv) Rüzgar türbini-Isı pompası ve (v) sadece Isı pompası, olmak üzere beş farklı enerji sistemi senaryosu dikkate alınmıştır. Tüm senaryolar için yük ve üretim arasındaki uyumsuzluk şebeke tarafından karşılanmıştır. İkinci ve üçüncü senaryolar, fotovoltaik panel ve rüzgar türbini sayısına bağlı olarak birbirinden farklılık gösterir. Seranın tasarımı, seranın boyutları baz alınarak SketchUp ve TRNSYS yazılımları ile yapılmıştır. Hava durumu verileri ve sera parametrelerine göre güneş ışınımı hesapları yapılmış ve MATLAB yazılımı ile sera sistemi modellenmiştir. Tasarlanan seranın yıllık ısıtma ve soğutma talepleri ile fotovoltaik paneller ve rüzgar türbinlerinden elektrik üretimi saatlik olarak hesaplanmıştır. Isıtma ve soğutma yükleri sırasıyla 5.922.015 ve 11.014.446 kWh/yıl olarak bulunmuştur. Ayrılmış alan için yenilenebilir enerji maksimum güç çıkışı soğutma yükünü karşılamak için yeterli olmadığından, soğutma işlemi hariç tutulmuştur. Ekonomik ve çevresel analizler yapılmıştır. 5.271 adet fotovoltaik panel ve 20 ısı pompası içeren birinci senaryo en iyi senaryo olarak bulundu. İlgili senaryonun Net Bugünkü Değeri, Seviyelendirilmiş Enerji Maliyeti ve CO_2 tasarrufu \$547.440,40, 0,080146 \$/kWh ve 1.270,96 ton olarak hesaplanmıştır.

Anahtar Kelimeler: Sera Isıtma ve Soğutma, Isı Pompaları, Fotovoltaik, Rüzgar Türbini, Tekno-Ekonomik Analiz

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CHAPTER 1

INTRODUCTION

The agricultural sector consumes a lot of energy for watering and fertilizing, drying vegetables and fruits, heating, cooling and lightning the greenhouses and providing proper environment for plants. Heating and cooling systems are the most energy consuming processes in greenhouses. Heating is often provided by burning fossil fuels or by utilizing electric heaters, which suffer from the excessive fossil fuel sourced-CO2 emission and low energy efficiency (Hassanien, Li, and Dong Lin 2016). Therefore, the inclusion of renewable energy and its effective utilization is crucial for green, profitable, and competitive areas agricultural sector.

1.1. Agriculture and the Role of Renewable Energy in the Greenhouse Industry

Since agriculture is directly related to the environment, many energy applications in this sector generally move towards renewable and sustainable sources which are environmentally friendly and clean. A sustainable agricultural system is one that makes good use of renewable resources. A system that is reliant on finite resources, such as fossil fuels, cannot be sustained indefinitely. Renewable energy sources such as solar, wind, geothermal, biological, or hydroelectric could be utilized in a sustainable system (Chel 2010).

Solar energy provides an option for many agricultural activities. Modern, well-designed, easy-to-maintain solar systems can deliver the energy required at a given location and time. These are technologies that have been tested and confirmed to be cost-effective and dependable over the world, and they are already increasing agricultural output globally. While solar collectors were used in heating applications, photovoltaic panels generally were used as electric energy providers in greenhouses by many researchers, resulting in a variety of capacities. On the other hand, other renewable energy sources and wind energy may also be utilized in agriculture. Small wind turbines can generate electricity that can be utilized directly or stored in batteries. These devices are extremely dependable in regions with sufficient constant wind. For many power demands on farms and ranches, the systems may be highly cost-effective and dependable (Chel 2010). However, besides generating electricity when it comes to the heating and cooling processes which consume a high amount of energy, additional energy sources were needed. Therefore, instead of using single energy sources, combined systems that use more than one energy source have become desired recently.

1.2. Literature Survey

Studies on the use of combined energy systems in agricultural greenhouses have generally focused on the design, construction, and dynamic modeling of solar and geothermal systems and most of them were conducted for Africa and Mediterranean regions. Awani et al. evaluated numerical model and simulated the coupling of heat pump system coupled with a ground horizontal heat exchanger and a flat plate solar collector associated to a glass greenhouse by using TRNSYS software, in the Centre of Energy Borj Cedria CRTEn in north of Tunisia. The goal in this research is to store hot water from the solar collector in the ground and for heating the soil and for use during the night and to calculate COP of the heat pump and determine its relation with solar collector (Awani et al. 2015). Mehrpooya et al. studied with combined solar collector and geothermal heat pump systems to meet heating load need for greenhouses in Tehran. They used 10 kW heat pump system and 3 solar collectors to meet 14.45 kW maximum heating load requirement and obtained total operational costs as $27,200 (Mehrpooya, Hemmatabady, and Ahmadi 2015). Yildirim and Bilir assessed a renewable energy system for the total energy need of a greenhouse. The annual heating, cooling, and lighting energy demand for a 150 m^2 greenhouse were calculated. Grid-connected 66 solar photovoltaic panels were chosen to assist a ground-source heat pump and generate adequate electricity for lighting. The annual photovoltaic electricity generation was calculated to be 21,510.4 kWh and it was observed that during the summer operating months, photovoltaic electricity generation can cover 33.2-67.2% of greenhouse demand

(Yildirim and Bilir 2017). Except from geothermal and ground-source applications, Hosseini-Fashami et al. investigated 3 different scenarios of a system without renewable energy sources, with PV and PV/T for the greenhouses to calculate energy production of these 3 systems and to optimize the life cycle assessment (LCA) (Hosseini-Fashami et al. 2019). The most proper system among them was selected as the scenario with PV. A different combined experimental system was set up by Esen and Yuksel in Elazig, Turkey to investigate greenhouse heating by biogas, solar and ground energy and resulted as utilization of biogas and ground source heat pump together is quite successful as greenhouse heating (Esen and Yuksel 2013). Apart from these combined applications, Ozgener investigated wind energy usage in heating a greenhouse with a 48.51 m^2 surface area, which is modeled as a small wind turbine (1.5 kW) system independently constructed in Solar Energy Institute of Ege University and a solar-assisted geothermal heat pump. According to the study, theoretically small wind turbine systems may meet 3.13% of the overall yearly electrical energy consumption of the modeled system (3,568 kWh). According to the results of the study, the modeled passive solar pre-heating techniques combined with geothermal heat pump systems and the small wind turbine system can be preferable to conventional space heating/cooling systems used in agriculture (Ozgener 2010). However, even though some small wind turbine applications were conducted, especially high-capacity wind turbine applications are still not common in the agriculture field.

Besides the lack of utilization for the combination of renewable energy system applications, there are also thermal and dynamic modeling open to development for greenhouse heating and cooling processes. Therefore, some researchers carried out their studies on this topic. Dalamagkidis et al. developed an algorithm that predicts ambient greenhouse air conditions for use in energy efficiency simulation and control scheme optimization using TRNSYS 15 software. Relative humidity, temperature, CO_2 concentration, and solar radiation are the climatic factors evaluated. The algorithm operates in two modes: the first models the greenhouse, while the second estimates heating, cooling, humidification or dehumidification, and CO_2 injection rates to maintain particular setpoints (Dalamagkidis, Saridakis, and Kolokotsa 2005). Ishigami et al. simulated a model using TRNSYS software to evaluate environmental controls in a tomato greenhouse while considering the local circumstances of East Asia. They chose and changed the ventilation-modeling components and computed the heat balance required to anticipate the indoor air temperature and humidity. For summer tomato production, a fog chilling module and an evapotranspiration module were incorporated. An experimental greenhouse with a fog chilling system was used to test the model. Based on hourly averaged values for solar radiation, outside air temperature, and relative humidity, the evapotranspiration module estimated evapotranspiration from the vegetative surface. The findings revealed that the simulated output for the inner air temperature was quite close to the observed values. As a result, it was indicated that when a dynamic plant development model is linked with the simulation model, it would be feasible to simulate climate management in a greenhouse (Ishigami et al. 2014). Ahamed et al. developed "CSGHEAT," a time-dependent heating simulation model, to estimate the supplementary heating needs for Chinese-style solar greenhouses. They determined the surface temperatures of the floor and north wall using the established inside temperatures by solving conventional differential heat balance equations. The model is relatively simple to use unlike other models since it does not require the input of measurable data such as solar radiation. The model allows for the short or long-term simulation of each heat source in the greenhouse. Therefore, it is useful tool for assisting with the energy-efficient design of Chinese-style solar greenhouses in any location (Ahamed, Guo, and Tanino 2018). Rasheed et al. studied a multi-span greenhouse building energy simulation model employing a transient system simulation tool to model greenhouse micro-environments. The proposed model was used to evaluate the influence of heating setpoint control, natural ventilation, and various thermal screens on a greenhouse's yearly and maximum heating loads (Rasheed et al. 2020). Choab et al. investigated important design aspects (shape, orientation, thickness of double glazing etc.) that influence the thermal behavior and heating and cooling energy requirements of a greenhouse in Morocco, also looked at the influence of evapotranspiration on greenhouse thermal behavior. The developed thermal model of the greenhouse is simulated using TRNSYS software. The model takes into consideration the plants' presence within the greenhouse by including heat and humidity gain into the greenhouse's heat and water balance via an evapotranspiration sub-model. One of the main findings was that as cover thickness increased, heating demand reduced and cooling demand rose significantly (Choab et al. 2021).

Literature studies show that heat transfer, natural ventilation, or heating and cooling calculations are made for greenhouses, especially for greenhouses with small areas and for the agriculture field (Blanchet, Pantaleo, and van Dam 2019; Shahbazi, Kouravand, and Hassan-Beygi 2019; Barakat, Ibrahim, and Elbaset 2020; Calise et al. 2020; Mohammadi et al. 2020). Most of the models were developed via TRNSYS software, and other less frequently used software in studies were EnergyPLAN and MATLAB. Some of these studies were planned to be carried out experimentally and some are simulation-based, mainly by solar and ground source heating systems. Besides these, a small part of the studies consisted of those using biomass applications or small wind turbines for greenhouses.

1.3. Motivation and Aim of the Thesis

This thesis focuses on extensive modeling and simulation of a renewable energy (RE) system that combines photovoltaic (PV) panels, wind turbines (WT), and air source heat pumps (HP) to meet the heating demand of a large commercial greenhouse (GH) in the agricultural zone in Dikili. The utilization of PV-wind turbine combination for meeting greenhouse energy requirement has been rarely addressed in the literature. Moreover, none of the literature studies include a detailed heat transfer analysis of a large glass greenhouse (about 25,000 m^2) considering factors such as solar radiation, ambient temperature and humidity. In this respect, the current study contributes to the related literature considerably.

The overall objective of the thesis is to design renewable energy systems for meeting the heating load of a greenhouse and evaluate their technical, economic and environmental performances. For this purpose, four different renewable energy systems were considered and analyzed in comparison to the only heat pump system. The considered energy system scenarios are:

1) PV-heat pump
2) PV-wind turbine-heat pump (1 wind turbine included)
3) Wind turbine-PV-heat pump (2 wind turbines included)
4) Wind turbine-heat pump

5) Only heat pump

Specific objectives of the thesis are (i) to develop a detailed heat transfer analysis of a large greenhouse, (ii) to determine PV and wind turbine power for the specified location, (iii) to determine the heating load and the cooling load of the greenhouse, (iv) to compare the economic and environmental performances of the proposed scenarios.

CHAPTER 2

SYSTEM DESCRIPTION

This thesis contains both the wind turbine and photovoltaic modules together and separately to meet the energy demand of a greenhouse in agricultural-based industrial zone in Dikili/Izmir. This TDIOSB (Specialized Organized Industrial Zone Based on Agriculture) in Dikili has 50 greenhouses within. According to the Agricultural-Based Specialized Organized Industrial Zone Regulation prepared by the Republic of Turkey Ministry of Agriculture and Forestry, there is a minimum lower limit of 25,000 m^2 regarding parcel sizes in TDIOSBs. The lower limit of the closed greenhouse area is determined as 20,000 m^2 (BCD Müşavirlik Mühendislik 2021b). When the planted TDIOSB area is evaluated in terms of the number of sunny days, glass-covered greenhouses are recommended, especially since the light required by the crops to be grown will be provided with the highest level of glass-covered greenhouses. However, it is envisaged to use plastic cover materials with maximum light transmittance instead of the glass covered greenhouse, since the Dikili TDIOSB area is a 2nd degree earthquake zone. Therefore, the technical features of an exemplary greenhouse model made in the Dikili TDIOSB area are generally planned to include a gothic arch roof with a polyethylene sheet, side walls with polycarbonate sheets and hot-dip galvanized steel interior construction material (BCD Müşavirlik Mühendislik 2021b).

2.1. Location

Izmir province of Turkey is located between 37º 45' and 39º 15' north latitudes and 26º 15' and 28º 20' east longitudes and its surface area is 12,012 km^2 (BCD Müşavirlik Mühendislik 2021b) Time zone of Izmir is GMT+03:00 (Greenwich Mean Time 2022).

Izmir has 30 districts in total. In this thesis, Dikili district, which is suitable for agriculture due to its geographical location and climatic characteristics, was chosen. Due to its location, the district was located on the Aegean Sea coast and across the Lesbos

Island. Neighboring districts are Ayvalik, Bergama and Aliaga. The local location of Dikili lies between 39º 03’ North Latitude and 26º 52’ East Longitude (BCD Müşavirlik Mühendislik 2021b).

This thesis focused on the first greenhouse placed in Dikili Agricultural Greenhouse Specialized Organized Industrial Zone (TDIOSB) shown in Figure 2.1. The selected greenhouse was accepted as it makes an angle of 0º with the North.

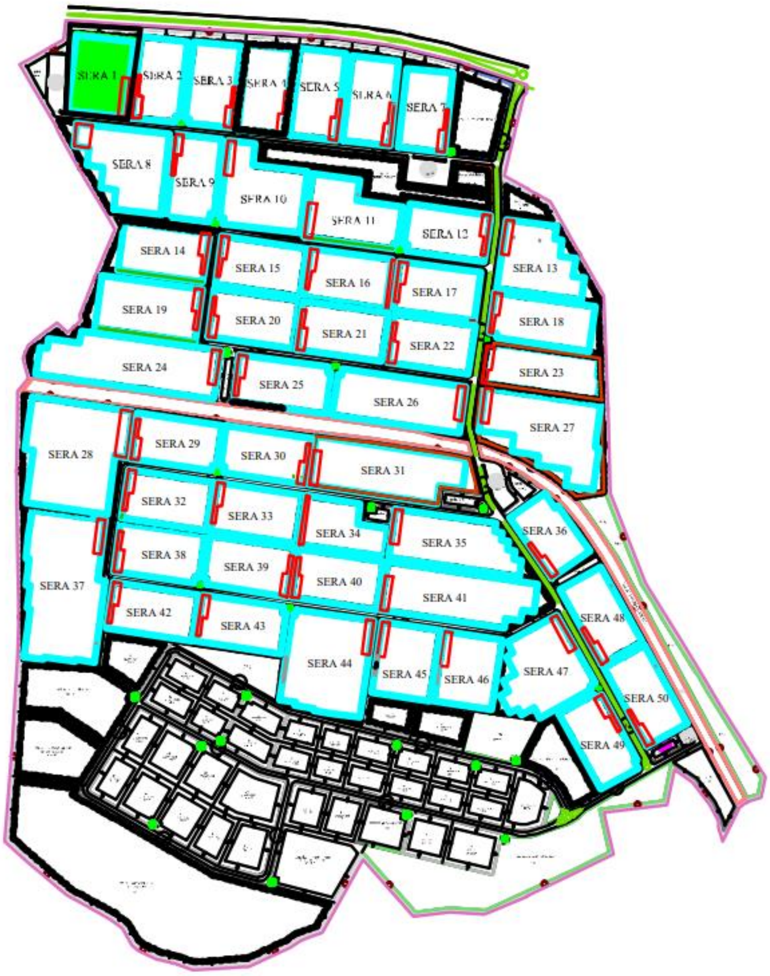


Figure 2.1. Dikili TDIOSB general area scheme
(BCD Müşavirlik Mühendislik 2021a)

Dikili TDIOSB reserved specific areas for the construction of photovoltaic panels and wind turbines, which are shown in Figure 2.2 and Figure 2.3, respectively. The land area for PVs is 169,541.71 m^2 There are two specific areas while areas reserved for wind turbines are29,893.63 m^2 and 28,939.46 m^2. The number of PV panels and wind turbines were determined based on the related land areas for all considered scenarios except for 4th scenario, where 3 wind turbines installation is proposed even if the related area for wind turbines allows the installation of 2 wind turbines.

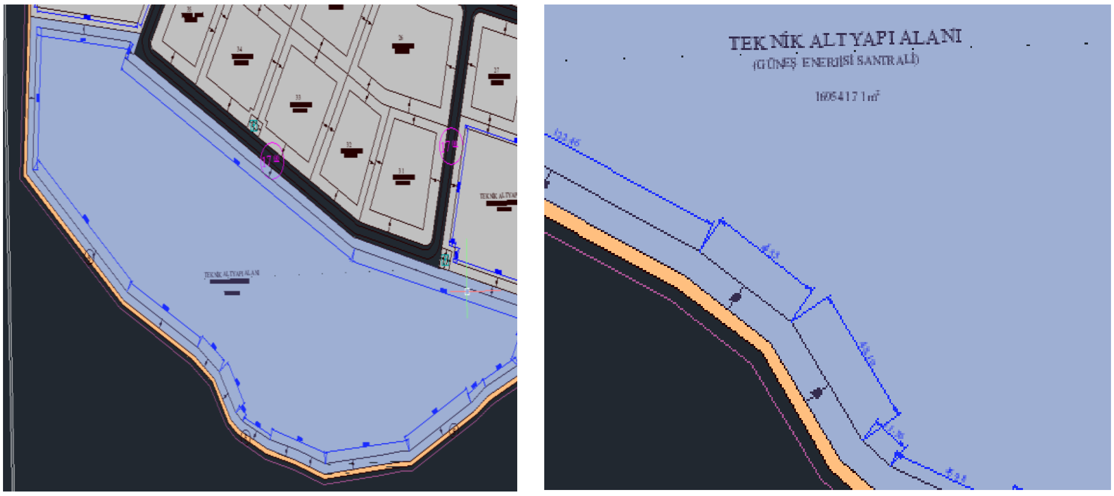


Figure 2.2. Construction area of photovoltaic panels
(BCD Müşavirlik Mühendislik 2021a)

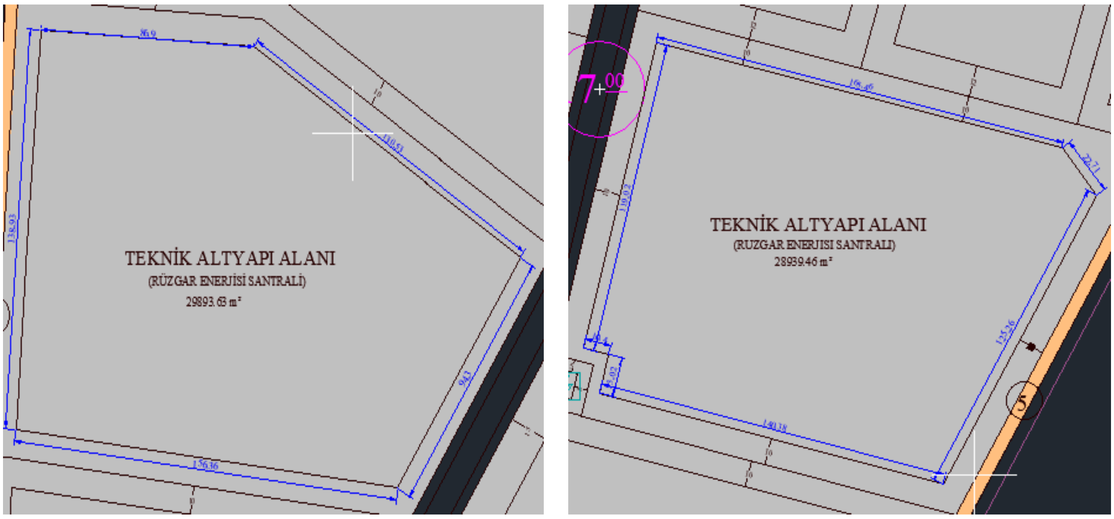


Figure 2.3. Construction area of wind turbines
(BCD Müşavirlik Mühendislik 2021a)

2.2. Base and Construction of the Greenhouse

In this thesis, the selected greenhouse has almost similar measurements to the greenhouse that already exists in Dikili TDIOSB, however as a difference the studied greenhouse is assumed to be a flat roof glass greenhouse. The cover material was selected as glass over plastic because glass has a long-life span and better light transmission characteristics compared to plastic. The glass laps between panes enable air to enter, whereas impermeable acrylic, polyethylene, and polycarbonate-structured sheet houses can result in excessive humidity and unwanted water drip on the plants if not adequately regulated (Goldammer 2019). The roof shape of the greenhouse was selected as a flat roof because, even though flat greenhouse roof designs are uncommon, they do offer advantages. The main advantage of a flat greenhouse roof is its low cost. Because there are no trusses, cost savings on structural, material, and installation expenses can be achieved. Retractable and folding roof designs may be quite useful when the exterior weather conditions are favorable. According to the University of Massachusetts Amherst, the ability to open the roof boosts the intensity of light and aids in controlling plant development and flowering. These designs also save money on power by eliminating the need for expensive cooling using fans (northern nester 2022). A study conducted by the Arizona Agricultural Experiment Station discovered that flat retractable greenhouse roofs offered significant advantages such as benefits from ventilation and additional lighting as needed (northern nester 2022).

As is seen in Figure 2.4 the already existing greenhouse was redesigned and demonstrated. The greenhouse has 15 sections (tunnels) for production outbuilding areas. The halves of 14th and 15th tunnels are used for outbuilding section while the remaining is used for production area. To simplify heat transfer analyzes the halves of 14th and 15th tunnels were considered as a one whole tunnel and the greenhouse design was done for 14 tunnels of the production area and 1 tunnel of the outbuilding area.

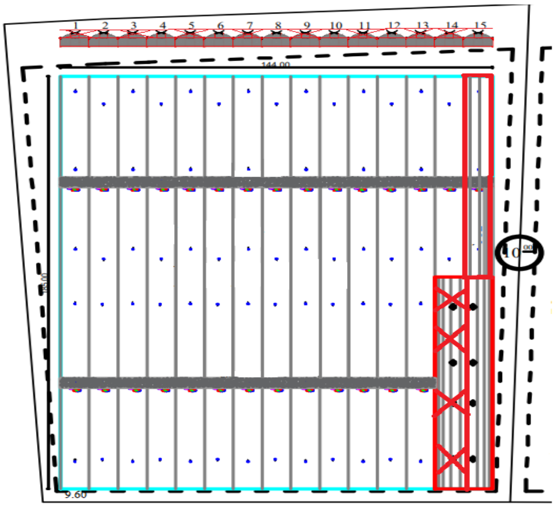


Figure 2.4. Edited base template of the selected greenhouse
(BCD Müşavirlik Mühendislik 2021c)

Technical specifications of the studied greenhouse were shown in Table 2.1. (DALSEM 2018; Morn Glass 2019), (BCD Müşavirlik Mühendislik 2021b). Since the size of glass on the walls has significant effect on heat transfer calculations, the glass area should be large. Therefore, the glass area was assumed as 95% of the wall area in this thesis (Vadiee 2013; Amin 2015; Mohammadi et al. 2020; Ozcan et al. 2021).

Table 2.1.Technical specifications of the studied greenhouse

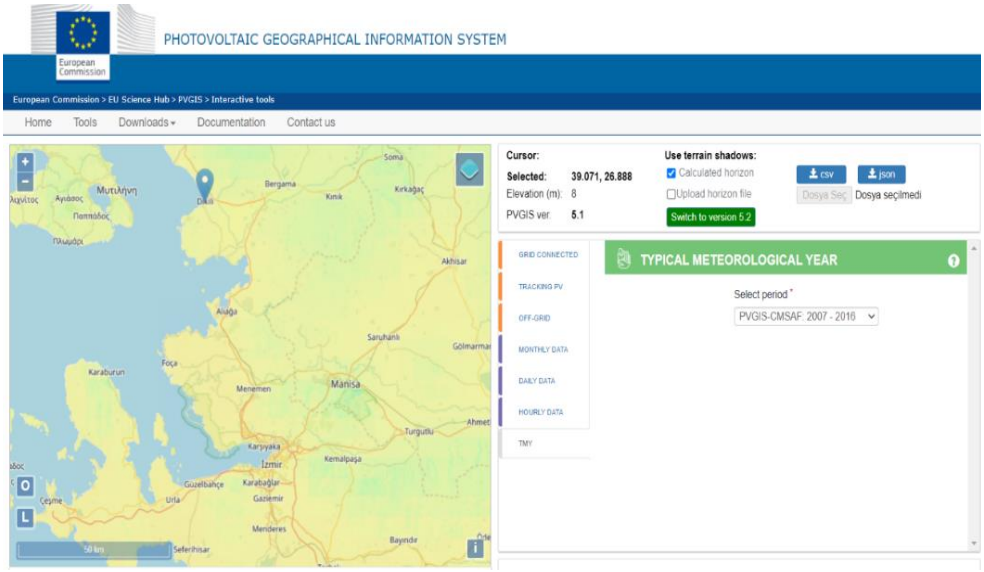
Crop	Tomatoes
Cover Material	Double Glazed Window Glass
Construction Material	Hot-dip Galvanized Steel, Concrete
Greenhouse Indoor Area	26,640 m^2
Production Area	24,816 m^2
Outbuilding Area	1,824 m^2
North Wall Area	720 m^2
South Wall Area	720 m^2
West Wall Area	925 m^2
East Wall Area	925 m^2
Lenght	185 m
Production Width	134.40 m
Outbuilding Width	9.60 m
Height	5 m
Ground Thickness	0.022 m
Glass Outwall Thickness	0.004 m
Glass Intwall Thickness	0.004 m
Glass Roof Thickness	0.004 m

2.3. Climate Data

According to the meteorological data of Dikili, the coldest month on average in the district is January and the hottest month is July. The annual average temperature is 17.9 °C. During the observation period until today, the lowest temperature was 8.6 °C in January and the highest temperature was 41.8 °C in July. Dikili district has a warm and temperate climate (BCD Müşavirlik Mühendislik 2021b).

In greenhouse project calculations, the wind load acts as pressure on the surfaces opposite to the wind direction and as suction force on other surfaces. The magnitude of this force depends on the wind speed, the size of the surface against the wind, and whether this surface is vertical or inclined. Other important points in greenhouse calculations are the ventilation and the air conditioning, openings must be adequate and well-distributed on the greenhouse surface, they must be well-closed and the heat loss must be kept at a minimum level (BCD Müşavirlik Mühendislik 2021b).

For this study, the weather data of Dikili for 8,760 hours were provided by PVGIS. As it is shown in Figure 2.5 PVGIS has created a typical meteorological year (TMY) with respect to the hourly weather data between 2007 and 2016. This weather data contains air temperature, relative humidity, global irradiance on the horizontal plane, beam/direct irradiance on a plane always normal to sun rays, diffuse irradiance on the horizontal plane, surface air pressure, total wind speed, and wind direction. These parameters were used for radiation incident calculations.



Cursor:
Selected: 39.071, 26.888
Elevation (m): 8
PVGIS ver: 5.1

Select period *: PVGIS-CMSAF: 2007 - 2016

Figure 2.5. Weather data of Dikili from PVGIS
(PVGIS 2022)

U-values of components of the greenhouse structure were determined by TRNSYS software (Klein 2017) for the heat transfer calculations and were listed in Table 2.2. Detailed radiation and heat transfer calculations and more were explained in the methodology section.

Table 2.2. Heat transfer coefficients of components of the greenhouse structure

Window U-value	2.36 W/m^2°C
Roof U-value	2.36 W/m^2°C
Ground U-value	3.383 W/m^2°C
Outwall U-value	2.907 W/m^2°C
Intwall U-value	2.36 W/m^2°C

2.4. Heat Pump

In this thesis, air to air heat pump was decided to be used. However, in the market, there is a lack of high-capacity air-source heat pumps. Despite this, with a detailed search approximately 250 kW capacity air source heat pump was found and selected for the system which will be designed. The chosen heat pump, shown in Figure 2.6, is called Multi V 5 ARUM900LTE5 and was produced by the LG brand.

Figure 2.6. LG Multi V 5 ARUM900LTE5 heat pump
(LG Electronics 2020)

Technical specifications of the chosen heat pump were listed in Table 2.3. from its datasheet. Since the studied greenhouse is approximately 25 daa, according to the heat loss and energy consumption calculation presented in the Methodology section, it was decided that to utilize 20 heat pumps for this greenhouse system.

Table 2.3. Heat pump technical specifications
(LG Electronics 2020)

Model Name	ARUM900LTE5
Cooling Capacity (Rated)	252 kW
Heating Capacity (Rated)	252 kW
Coefficient of Performance (COP) (Rated)	4.36
Refrigerant Name	R410A

2.5. PV Panel

In this section technical specifications of the PV system were explained. The Panasonic HIT N330 PV module was selected and was decided to be located horizontally in the area that is separated by Dikili TDIOSB. Panasonic N330 has monocrystalline-silicon cells shown in Figure 2.7 and has 19.7% efficiency as is seen in the technical specifications in Table 2.4.

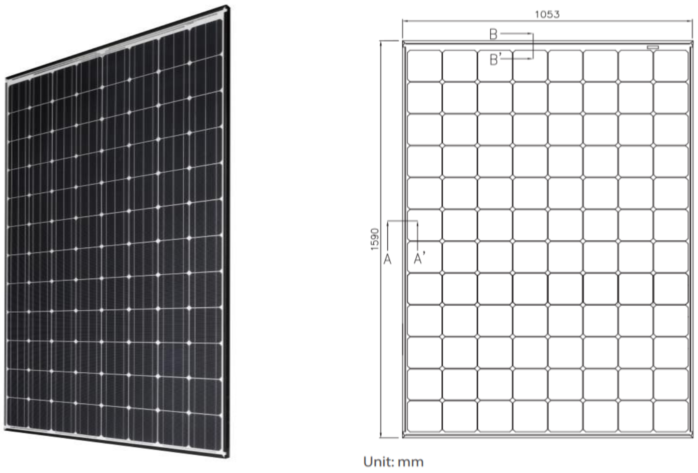


Figure 2.7. Panasonic HIT N330 PV module
(Panasonic 2018)

Table 2.4. PV module technical specifications
(Panasonic 2018)

Maximum Power	330 W
PV Module Efficiency	19.7%
Temperature Coefficient	-0.258% /°C
Reference Temperature	25 °C
Reference Global Radiation	1000 W/m^2
PV Module Area	1.67 m^2
PV Module Weight	19 kg

PV calculations which were presented in the Methodology section are made for 1 PV panel. Later, results were re-calculated for more PV panels according to the total electricity consumption of the heat pump, and scenarios were made. For the 1st scenario 5,271, for the 2nd scenario 2,648 and, for the 3rd scenario 26 PV panels were used.

2.6. Wind Turbine

Since the studied greenhouse has a large area and its consumption is high, a 1 MW capacity wind turbine was found suitable for the system. The EWT DW61 was chosen as wind turbine.

Electricity generation from the wind turbine in the Methodology section was made for 1 wind turbine with respect to the power curve shown in Figure 2.8, and according to Table 2.5. Later, results were re-arranged for different scenarios. For the 2nd scenario 1 wind turbine, and for the 3rd and 4th scenarios 2 and 3 wind turbines were utilized, respectively.

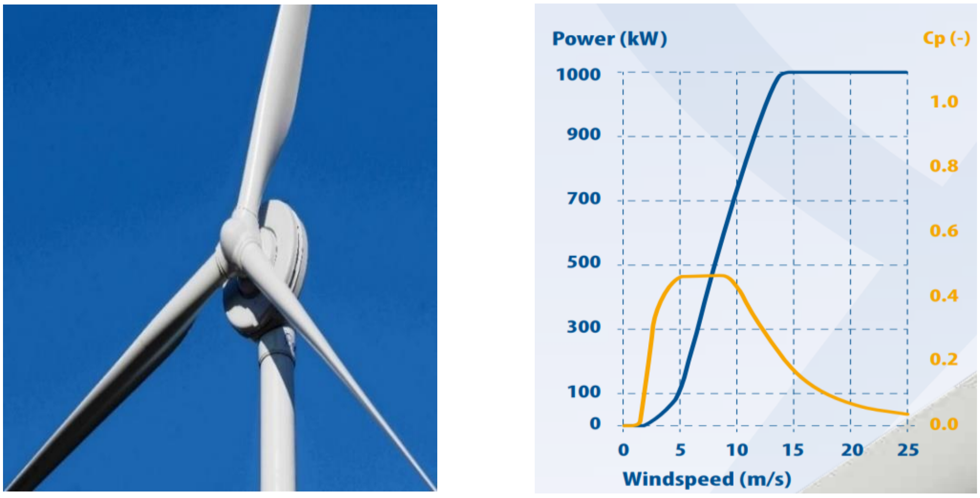


Figure 2.8. EWT DW 61 1 MW wind turbine and the power curve
(EWT 2018, 2023)

Table 2.5. EWT DW 61 1 MW wind turbine technical specifications
(EWT 2018)

Rotor Diameter	61 m
Rotor Speed Variable	8-29 rpm
Nominal Power Output	1000 kW
Hub Heights	69 m
Cut-in Wind Speed	3 m/s
Rated Wind Speed	14 m/s
Cut-out Wind Speed	25 m/s

The final form of the scenarios was listed in Table 2.6. In following sections, calculations of heating and cooling energy demand of the studied greenhouse, the consumption of heat pumps, electricity generation from PV and wind turbines, storage and grid decision, and economic and environmental analyzes were examined.

Table 2.6. Scenarios of heating and renewable energy system for the studied greenhouse

Scenarios	**System**	**Number of heat pumps**	**Number of PV panels**	**Number of wind turbines**	**Grid on/off**
1st	Heat pump + PV	20	5,271	-	On
2nd	Heat pump + PV + Wind turbine	20	2,648	1	On
3rd	Heat pump + PV + Wind turbine	20	26	2	On
4th	Heat pump + Wind turbine	20	-	3	On
5th	Heat pump	20	-	-	On

CHAPTER 3

METHODOLOGY

In this section, simulation tools (SketchUp, TRNSYS and MATLAB), mathematical references and the overall methodology used for the detailed heat transfer model of the selected greenhouse, the simulation of PV-wind-heat pump system and the economic and environmental analyzes of the system.

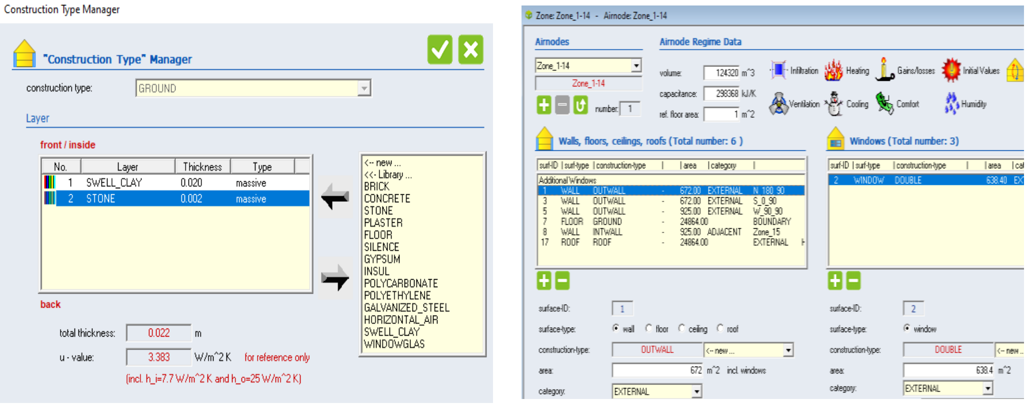
3.1. Software

The shape, external design, materials, and glasses of the greenhouse were made via SketchUp (Trimble 2017) and TRNSYS (Klein 2017) software. According to greenhouse design from TRNSYS software and solar radiation, ambient temperature, and weather data of Dikili provided by PVGIS (PVGIS 2022), inlet temperature values of the greenhouse and temperature changes due to time were, created by MATLAB (The MathWorks Inc. 2016) software. Hourly, monthly, and yearly heat pump utilization and consumption, electricity generation from photovoltaic panels and wind turbines were made by MATLAB software. Economic and environmental analyzes were made by EXCEL (Microsoft Corporation 2019).

3.1.1. SketchUp and TRNSYS

Measurement of the greenhouse and materials used in construction were defined in TRNSYS software and the 3D design of the greenhouse was made in SketchUp software.

Measurements of the greenhouse walls and materials used in the construction were selected via TRNSYS software and were presented in Figure 3.1.



Construction Type Manager

"Construction Type" Manager

construction type: GROUND

Layer

front / inside

No.	Layer	Thickness	Type
1	SWELL_CLAY	0.020	massive
2	STONE	0.002	massive

back

total thickness: 0.022 m

u - value: 3.383 W/m^2 K for reference only

(incl. h_i=7.7 W/m^2 K and h_o=25 W/m^2 K)

Zone: Zone_1-14 - Airnode: Zone_1-14

Airnodes

Zone_1-14

Zone_1-14

number: 1

Airnode Regime Data

volume: 124320 m^3

capacitance: 298368 kJ/K

ref. floor area: 1 m^2

Walls, floors, ceilings, roofs (Total number: 6)

Additional Windows

surf-ID	surf-type	construction-type		area	category	
1	WALL	OUTWALL	-	672.00	EXTERNAL	N_180_90
3	WALL	OUTWALL	-	672.00	EXTERNAL	S_0_90
5	WALL	OUTWALL	-	925.00	EXTERNAL	W_90_90
7	FLOOR	GROUND	-	24864.00		BOUNDARY
8	WALL	INTWALL	-	925.00	ADJACENT	Zone_15
17	ROOF	ROOF	-	24864.00		EXTERNAL

surface-ID: 1

surface-type: ● wall ○ floor ○ ceiling ○ roof

construction-type: OUTWALL <-- new ...

area: 672 m^2 incl. windows

category: EXTERNAL

Windows (Total number: 3)

surf-ID	surf-type	construction-type		area	ca
2	WINDOW	DOUBLE		638.40	EX

surface-ID: 2

surface-type: ● window

construction-type: DOUBLE <-- new ...

area: 638.4 m^2

category: EXTERNAL

Figure 3.1. The construction library and building zones in TRNSYS

3D design of the selected greenhouse for flat glass roof in SketchUp from front and left corner were demonstrated in Figure 3.2.

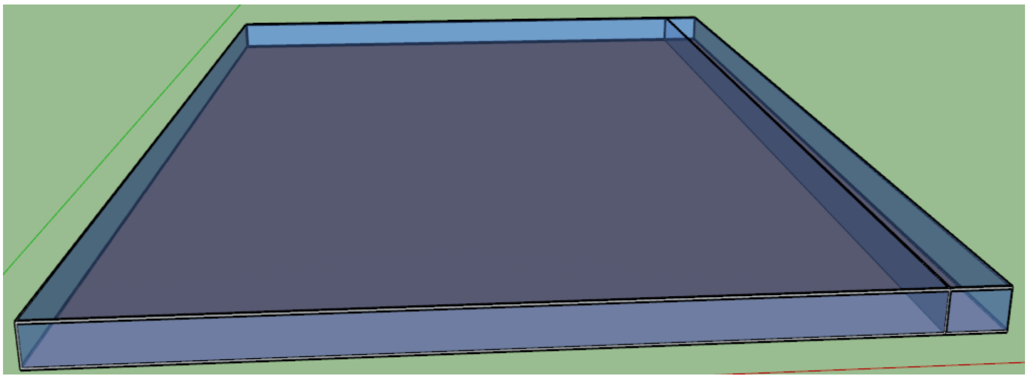


Figure 3.2. 3D design of the selected greenhouse for flat glass roof in SketchUp (front view)

3D design of the selected greenhouse for flat glass roof in SketchUp from top and bottom view were shown in Figure 3.3.

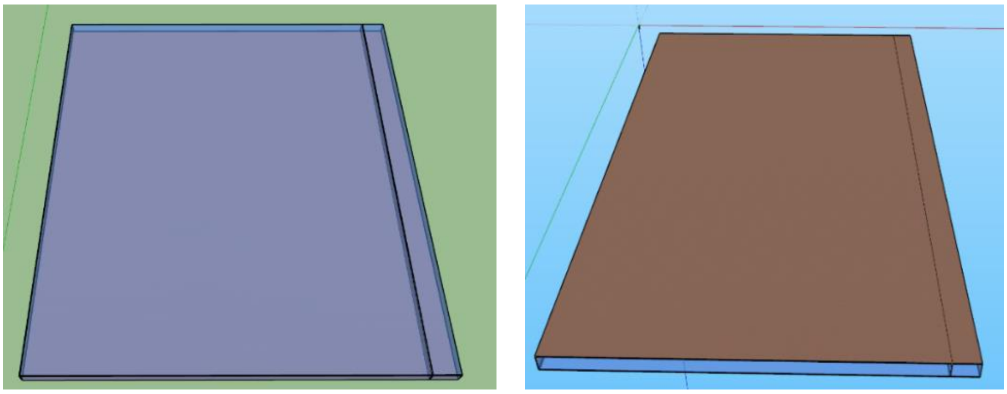


Figure 3.3. 3D design of the selected greenhouse for flat glass roof in SketchUp (top and bottom view)

3.1.2. MATLAB

Solar radiation due to walls facing different directions, temperature changes inside the greenhouse, heating and cooling demand of the greenhouse, the capacity of the air source heat pump, electrical consumption of the heat pump and electricity generation from photovoltaic panels and wind turbines were calculated via MATLAB software.

3.2. Technical Analysis

In this section solar radiation calculations from (Kalogirou 2012)(Duffie and Beckman 2013) Rasheed et al., 2020; Özcan et al., 2021) used in this thesis were presented step by step.

The declination angle δ,

$$\delta = 23.45 \sin\left(360 \frac{284+n}{365}\right) \tag{3.1}$$

n= The day of the year

The hour angle ω,

$$\omega = (t_s - 12hr) \times 15°/hr \tag{3.2}$$

t_s= The solar time (hr) where, solar time is hours of the day from 1 to 24.

The zenith angle θ_z,

$$\cos\theta_z = \cos\phi\cos\delta\cos\omega + \sin\phi\sin\delta \tag{3.3}$$

The solar altitude angle a_s,

$$\sin a_s = \cos\phi\cos\delta\cos\omega + \sin\phi\sin\delta \tag{3.4}$$

ϕ = Latitude (39.07°)

The solar azimuth angle γ,

$$\sin\gamma = \frac{\cos\delta\sin\omega}{\cos a_s} \tag{3.5}$$

The angle of incidence θ,

$$\begin{aligned}\cos\theta = {} & \sin\delta\sin\phi\cos\beta - \sin\delta\cos\phi\sin\beta\cos\gamma \\ & + \cos\delta\cos\phi\cos\beta\cos\omega \\ & + \cos\delta\sin\phi\sin\beta\cos\gamma\cos\omega \\ & + \cos\delta\sin\beta\sin\gamma\sin\omega\end{aligned} \tag{3.6}$$

β= The slope of the surface (β=90° for vertical)

The beam radiation R_b, the ratio of beam radiation on the tilted surface to beam radiation on the horizontal surface,

$$R_b = \frac{\cos\theta}{\cos\theta_z} \tag{3.7}$$

Hourly radiation incident of the tilted surface I_T (W/m^2),

$$I_T = (I_G - I_d)R_b + I_d\left(\frac{1+\cos\beta}{2}\right) + I_G\rho_g\left(\frac{1-\cos\beta}{2}\right) \tag{3.8}$$

ρ_g= Ground reflection coefficient (was taken as 0.2)

I_G= Global radiation (W/m^2)

I_d= Diffuse radiation (W/m^2)

Heating and heat loss calculation and other parameters that were used in this thesis were presented in accordance with the American Society of Agricultural Engineers Standard for Heating, Cooling and Ventilation of Greenhouses ANSI - ASAE EP 406.4 in following steps (ASAE 1998; Weather Edge Inc. 2000; NASA Earth Observatory 2009; Duffie and Beckman 2013; Berkeley University of California 2022; CarnotCycle 2023),

Absolute humidity ratio W in g/m^3,

$$W = \frac{6.112 \times e^{\left[\frac{17.67 \times T}{T+243.5}\right]} \times rh \times 2.1674}{273.15 + T} \tag{3.9}$$

rh= Relative humidity

The total heat loss value (Q_T) in this greenhouse is equal to the sum of the heat transfer value from the greenhouse by convection (Q_{con}), radiation (Q_{rad}) and the heat transfer value (Q_{inf}) that occurs because of infiltration.

$$Q_T = Q_{con} + Q_{rad} + Q_{inf} \tag{3.10}$$

Heating and heat loss determination by convection Q_{con},

$$Q_{con} = U \times A \times \Delta T \tag{3.11}$$

U= Heat transfer coefficient of each material (W/m^2°C)

A= Area of the greenhouse cover (wall, ground, window etc.) (m^2)

ΔT= Temperature difference between ambient and greenhouse indoor (°C)

Heating and heat loss determination by radiation Q_{rad},

$$Q_{rad} = A \times I_T \times \tau \tag{3.12}$$

τ= Window standard solar transmittance & atmosphere absorption (0.86 × 0.28)

For each direction, radiation incidents I_T and areas A of the greenhouse surfaces (walls, roof etc.) facing that direction were taken as a basis.

Heating and heat loss determination by infiltration Q_{inf},

$$Q_{inf} = \rho_{air} V N \times \left[C_{pair} \Delta T + h_{fg}(W_i - W_o)\right] \tag{3.13}$$

ρ_{air}= Density of the air (1.225 kg/m^3) (Cengel and Boles 2015)
V= Volume of the greenhouse (m^3)
N= Infiltration rate ($2.8 \times 10^{-4}\ s^{-1}$)
C_{pair}= Specific heat of the inside air (1.006 kJ/kg°C) (Cengel and Boles 2015)
h_{fg}= Latent heat of vaporization of water at greenhouse indoor temperature (2450 kJ/kg at 20 °C, enthalpy values of water and steam can be obtain at the same temperature or directly from table and graph values (Cengel and Boles 2015))
W_i= Humidity ratio of the greenhouse indoor air (kg$_{\text{water}}$/kg$_{\text{air}}$)
W_o= Humidity ratio of the outside air (kg$_{\text{water}}$/kg$_{\text{air}}$)

All heat values (Q) presented in previous steps were converted into kW and all heat values (Q), power values (P) and work values (W) used in kW in forward calculations (Cengel and Boles 2015).

3.2.1. Heat Pump Work

Considering the greenhouse effect resulting from solar radiation, it was determined that there is no need for heating and cooling in the greenhouse if the daily average temperature values are between 18°C - 22°C (Ata 2015; Pavani 2020; Icoz 2022) which is the proper temperature range for tomatoes. The heat pump capacity was determined based on this range. The heat pump was designed to turn on/off on an hourly basis when the temperature is out of the range. The initial and set temperatures were assumed as 20°C. When the greenhouse indoor temperature (T_{gh}) is lower than 18 °C, the heating process is activated when the greenhouse indoor temperature is higher than 22 °C the cooling process is activated. Both the heating and cooling processes were assumed to operate at full power. The power load of the heat pump for the heating (Q_{hph}) and cooling (Q_{hpc}) was calculated as follows:

T_{gh}< 18 °C;

$$T_{gh} = \int_{t=ti}^{t=tf} \left(\frac{Q_{con} + Q_{rad} + Q_{inf} + Q_{hph}}{V\rho_{air}C_{pair}} \right) dt \tag{3.14}$$

ti=0, tf=8760

T_{gh}> 22 °C;

$$T_{gh} = \int_{t=ti}^{t=tf} \left(\frac{Q_{con} + Q_{rad} + Q_{inf} - Q_{hpc}}{V\rho_{air}C_{pair}} \right) dt \tag{3.15}$$

The heat pump capacity was determined as 5,000 kW due to the energy demand of the greenhouse. Since the selected heat pump has approximately 250 kW capacity (LG Electronics 2020), 20 heat pumps were used in this greenhouse.

The heat pump work (the compressor work) W_{hpcomp},

$$W_{hpcomp} = \int_{t=ti}^{t=tf} \frac{\left(Q_{hph} + Q_{hpc}\right)}{COP_{hp}} dt \tag{3.16}$$

COP_{hp}= Coefficient of performance of the selected heat pump (4.36 was taken from the technical specification sheet)

After calculating the hourly heating and cooling demands of the designed greenhouse for one year and selecting the proper heat pump, due to the high cooling load, it was decided that the cooling process was not taken into account. The reason of this was explained in Results and Discussion section. Therefore, the consumption of the heat pump was taken into account for the period of 7 months (October-April) which needed heating.

3.2.2. Electricity Generation from the PV Panel

In this section equations for calculations of photovoltaics were used from (Duffie and Beckman 2013), (Dubey, Sarvaiya, and Seshadri 2013) and (Özcan et al. 2021). For the PV panel selection, Panasonic N330 PV module was selected to be used in PV system for the designed greenhouse (Panasonic 2018).

Cell temperature T_c,

$$T_c = T_a + k \times I_h \tag{3.17}$$

where, T_a is the ambient temperature for each hour and k is the ventilation coefficient, taken as 0.2 (Özcan et al. 2021). Hourly global radiation values on the horizontal plane I_h (W/m^2) were used from PVGIS (PVGIS 2022).

Hourly PV efficiency η_i,

$$\eta_i = \eta_{mp,ref} \times \left(1 - \mu_{mp}\left(T_c - T_{ref}\right) + \delta ln\left(\frac{I_h}{G_{ref}}\right)\right) \tag{3.18}$$

$\eta_{mp,ref}$ = PV panel efficiency (19.7% (Panasonic 2018))

μ_{mp} = The temperature coefficient of maximum power point efficiency (was taken as 0.00258 for 25 °C from (Skoplaki and Palyvos 2009), (Panasonic 2018) and (Özcan et al. 2021))

δ= Solar radiation coefficient (was taken as 0.052 from (Skoplaki and Palyvos 2009; Dubey, Sarvaiya, and Seshadri 2013; Özcan et al. 2021))

T_{ref}= The reference temperature (25 °C) (Panasonic 2018)

G_{ref}= The reference global radiation (1000 W/m^2) (Panasonic 2018)

Hourly PV electricity generation E_i,

$$E_i = \eta_i \times n_{pv} \times A_{pv} \times I_h \tag{3.19}$$

η_{PV} = The number of PV panel

A_{PV} = Area of PV panel (1.67 m^2 was taken from Panasonic N330 PV module datasheet (Panasonic 2018))

3.2.3. Electricity Generation from the Wind Turbine

In this section equations for calculations of wind power were used from (Manwell 2009; Letcher 2017). For the wind turbine selection, EWT DW 61 1 MW was selected to be used in wind turbine system for the designed greenhouse (EWT 2018).

Available wind power P_w,

$$P_w = \frac{1}{2}\rho_{air} A_s {U_w}^3 \tag{3.20}$$

ρ_{air}= Density of the air (1.225 kg/m^3)
A_s= Area swept by the rotor (m^2)
U_w= Air velocity (m/s)

The power law representation of a basic model for the wind speed profile,

$$U(z) = U(z_r)\left(\frac{z}{z_r}\right)^a \tag{3.21}$$

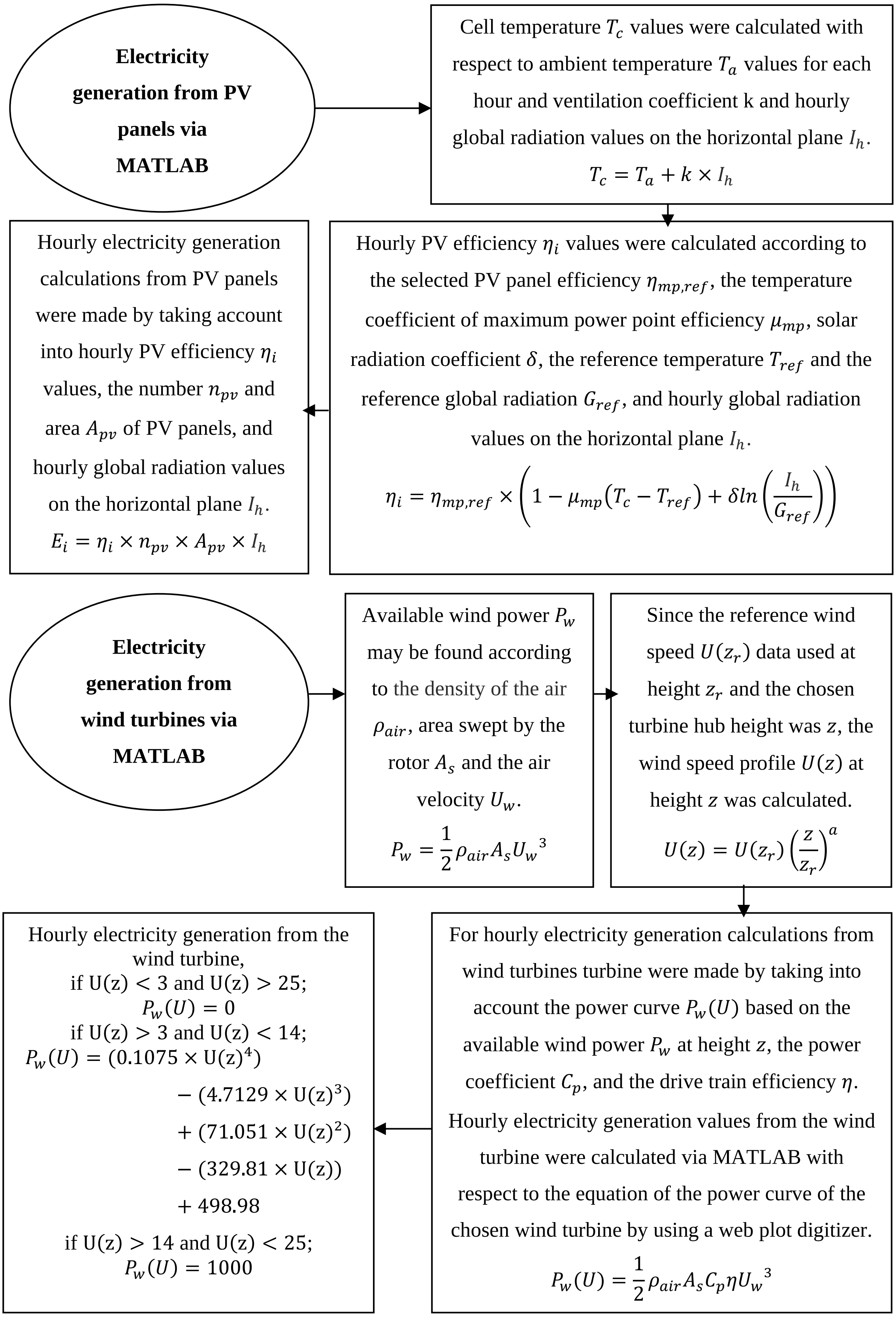
where $U(z)$ represents the wind speed at height z, $U(z_r)$ represents the reference wind speed at height z_r, and a represents the power law exponent. Early research on this topic revealed that under certain conditions, a=1/7, demonstrating a link between wind profiles and flow through flat plates. The wind speed data from PVGIS (PVGIS 2022) is for 10 m, so using the above correlation, since the chosen turbine hub height is 69 m the approximate value of the wind speed at 69 m height was calculated.

The turbine power curve $P_w(U)$ based on the available wind power P_w, the power coefficient C_p, and the drive train efficiency η,

$$P_w(U) = \frac{1}{2}\rho_{air} A_s C_p \eta {U_w}^3 \tag{3.22}$$

Electricity generation from the wind turbine was made for 1 wind turbine with respect to the power curve shown in Figure 2.8. by using a web plot digitizer (Ankit Rohatgi 2022), and according to Table 2.5 in System Description Section 2.6. While the power correlations and power curve in Figure 2.8 were taken into account when the wind speed was between 3 and 14 m/s, 1000 kW power generation was taken into account when the wind speed was between 14 and 25 m/s. Also, it was assumed that the turbine does not operate when the wind speed is less than 3 m/s and greater than 25 m/s.

In Figure 3.4 the summary of electricity generation calculations from PV panels and wind turbines via MATLAB software was demonstrated as a flow chart.



Electricity generation from PV panels via MATLAB

Cell temperature T_c values were calculated with respect to ambient temperature T_a values for each hour and ventilation coefficient k and hourly global radiation values on the horizontal plane I_h.

$$T_c = T_a + k \times I_h$$

Hourly PV efficiency η_i values were calculated according to the selected PV panel efficiency $\eta_{mp,ref}$, the temperature coefficient of maximum power point efficiency μ_{mp}, solar radiation coefficient δ, the reference temperature T_{ref} and the reference global radiation G_{ref}, and hourly global radiation values on the horizontal plane I_h.

$$\eta_i = \eta_{mp,ref} \times \left(1 - \mu_{mp}\left(T_c - T_{ref}\right) + \delta ln\left(\frac{I_h}{G_{ref}}\right)\right)$$

Hourly electricity generation calculations from PV panels were made by taking account into hourly PV efficiency η_i values, the number n_{pv} and area A_{pv} of PV panels, and hourly global radiation values on the horizontal plane I_h.

$$E_i = \eta_i \times n_{pv} \times A_{pv} \times I_h$$

Electricity generation from wind turbines via MATLAB

Available wind power P_w may be found according to the density of the air ρ_{air}, area swept by the rotor A_s and the air velocity U_w.

$$P_w = \frac{1}{2}\rho_{air} A_s {U_w}^3$$

Since the reference wind speed $U(z_r)$ data used at height z_r and the chosen turbine hub height was z, the wind speed profile $U(z)$ at height z was calculated.

$$U(z) = U(z_r)\left(\frac{z}{z_r}\right)^a$$

For hourly electricity generation calculations from wind turbines turbine were made by taking into account the power curve $P_w(U)$ based on the available wind power P_w at height z, the power coefficient C_p, and the drive train efficiency η. Hourly electricity generation values from the wind turbine were calculated via MATLAB with respect to the equation of the power curve of the chosen wind turbine by using a web plot digitizer.

$$P_w(U) = \frac{1}{2}\rho_{air} A_s C_p \eta {U_w}^3$$

Hourly electricity generation from the wind turbine,

if $\mathrm{U(z)} < 3$ and $\mathrm{U(z)} > 25$;

$$P_w(U) = 0$$

if $\mathrm{U(z)} > 3$ and $\mathrm{U(z)} < 14$;

$$P_w(U) = (0.1075 \times \mathrm{U(z)}^4) - (4.7129 \times \mathrm{U(z)}^3) + (71.051 \times \mathrm{U(z)}^2) - (329.81 \times \mathrm{U(z)}) + 498.98$$

if $\mathrm{U(z)} > 14$ and $\mathrm{U(z)} < 25$;

$$P_w(U) = 1000$$

Figure 3.4. Flow chart of electricity generation from PV panels and wind turbines

After calculating hourly electricity generation from photovoltaic panels and wind turbines for 12 months, the mismatch between the load and generation was determined and grid connection and energy storage options were evaluated.

3.2.4. Grid and Storage

In this section, according to the amount of surplus electricity generation for a storage system, the calculation of the capacity of a battery was explained.

Since the 1st scenario containing 5,271 PV panels was observed to be the most optimal one, storage calculations were made with respect to this scenario. To determine the required capacity value for the battery, the hourly electrical consumption of the heat pump for the heating process and the total electricity generation from PV panels during one year period were compared and the maximum cumulative difference between consumption and production was calculated. The maximum cumulative energy difference was found to be 1,648,302 kWh. Based on the related energy storage requirement and available large scale battery options, the number of required batteries were calculated. Considering the price of batteries, the energy storage by batteries was found to be not economically feasible. Therefore, the energy storage by batteries was not included in the current study and for all scenarios the system was evaluated as grid-connected to prevent the energy mismatch. For a feasible energy storage options, batteries with large energy storage capacity (e.g., 1000 MW) and low price should be realized (ET Energy World 2021; Ampyr Energy 2022; Energy Storage News 2023; Outlook 2023).

3.3. Economic Analysis

Many parameters must be considered when interpreting an investment's economic analysis. This analysis used a 25-year actual study using 2022 pricing. Since the life span of photovoltaic panels and wind turbines is 25-year (Forbes 2022a; TWI 2022), the financial analysis of this study will be conducted throughout this time period.

In Turkey, corporate tax is applied gradually over the company's total yearly gross earnings. The general corporate tax in Turkey is 20% (Dentons 2022; PWC Worldwide Tax Summaries Online 2022), therefore in this study, this value was used.

MARR (Minimum Attractive Rate of Return): By investing in a project, an investor intends to earn a minimum rate of return. In other words, it is the minimum rate of return needed to cover an investment's costs. MARR may also be used as a large ratio to account for the high level of risk that investments might pose. As a result, the MARR value of 5% (Icoz 2022) will be used in the calculations to show that the return on the deployment of the utilization of photovoltaic systems and wind turbines for meeting the greenhouse energy demands is a high investment.

Working Capital: Working capital refers to assets such as stocks and trade receivables that are required for an investment to begin its daily operations after realizing investments in fixed assets such as the production facility. To get working capital annual expenses were divided by the operational turnover coefficient. If the activity turnover time for greenhouses is accepted as 2 months (Icoz 2022), the activity turnover coefficient will be assumed to be 6 in the study since it is computed by dividing the number of months in a year by the activity turnover period (Icoz 2022). The working capital for both areas was estimated in the financial analysis by dividing the yearly expenditure for that year by 6. The average value of working capital was used in the 25-year financial study.

Fixed Capital: Fixed capital investment refers to the capital necessary to construct all essential buildings, and purchase and install all required machinery and equipment for a system. The fixed capital investment may be calculated by subtracting additional outlays such as working capital from the total investment.

Depreciation Cost (DC): Depreciation is the expenditure share that may be exhibited in scenarios such as the wear or obsolescence of assets acquired for usage by businesses. The depreciation share of each piece of equipment may be different. However, in this study, the depreciation share of the system was taken common and for a 25-year period.

Net Present Value (NPV): It is the difference between the present value of cash inflows and the present value of cash outflows from an investment (Investopedia 2022b). It is used in financial analysis to determine if an investment is profitable or not by converting each of the investment's costs and income over time to its present value at a risk-adjusted interest rate.

$$NPV = \sum_{t=1}^{T} \frac{C_t}{(1+i)^t} - C_0 \tag{3.23}$$

C_t= Net cash inflow during the period t
C_0= Total initial investment costs
i= Required return or discount rate
t= The number of time periods

IRR (The Internal Rate of Return): The internal rate of return is the rate of return that results in a net present value of zero (Investopedia 2022a). The project will have a positive net present value if the internal rate of return is greater than the Minimum Attractive Rate of Return. By comparing the IRR with the MARR, one may determine whether or not the investment is feasible. If the IRR is more than the MARR, the investment is feasible; if it is less than that, the investment is not feasible for that time.

$$0 = NPV = \sum_{t=1}^{T} \frac{C_t}{(1+IRR)^t} - C_0 \tag{3.24}$$

LCOE (Levelized Cost of Energy): The cost of generating electricity for a specific system is known as the levelized cost of energy. It is an economic analysis of the cost of an energy generating process over its entire lifespan, including initial investment, operations and maintenance, capital costs, and so on (CFI 2022).

$$LCOE = \frac{NPV\ of\ Total\ Costs\ Over\ Lifetime}{NPV\ of\ Electrical\ Energy\ Produced\ Over\ Lifetime} \tag{3.25}$$

Assumptions:

MS Excel was used to undertake revenue and cost analysis of systems for a 25-year period with 2022 prices by taking into account of parameters explained above. For other values which are required for the estimation of cash flow and cost analysis, some acceptations were made (for price calculations, values were taken according to €1=₺19.9 and $1=₺18.60 currency exchange (The Central Bank of the Republic of Turkey 2022)):

- Electricity purchase price and electricity sale price were taken $0.288 per kWh and $0.017 per kWh, respectively (Devlet Destekli 2022; EPDK 2022; Leblebicioglu 2022). Production surplus and shortage electricity needs were made based on monthly offset (Solarist 2022), then electricity purchase and sale prices were calculated for the yearly periods and presented as annual electricity cost or income. In the further calculations, the values of 2020, which are more advantageous electricity purchase-sale values than 2022, were taken to make a comparison with a year 2022. Therefore, the purchase price of electricity was taken as $0.0315 per kWh and the sale price of electricity was taken as $0.029 per kWh (Power Enerji 2020).
- Since 2500 tomato seedlings can fit in 1 daa, it was accepted to use approximately 62,000 tomato seedlings on the 24.8 daa greenhouse production area in this study (Tarım Dünyası 2022). Within the literature research, it has been reached that tomato seedlings grown in a greenhouse can yield 10-20 kg tomatoes on average, but additionally, it has been found that a maximum of 55 kg tomatoes can be obtained from seedlings under optimum conditions. For this reason, without a heating system in the greenhouse (under base conditions), it was accepted that one tomato seedling can yield 10 kg. On the other hand, in this study, since there will be a heating system providing a system close to optimum conditions for tomatoes, it was accepted that one tomato seedling can yield 55 kg. Therefore economic calculations were made by taking the 45 kg difference into account for additional contribution values (Pena 2005; Sabah Newspaper 2013; Tarım TV 2022; Tarım Dünyası 2022; Petektar Tohumculuk 2023).
- The production of tomatoes was accepted as 6 months (March-August), for this reason, tomato selling prices were taken for these months (Ata 2015; Pavani 2020). Since tomato selling prices may be differ from month to month, prices were

taken between \$0.2688 and \$0.4301 approximately (Izmir Büyükşehir Belediyesi 2022).

- The installation cost of 250 kW capacity air source heat pump installation cost was determined as \$6,500 per heat pump and since 20 heat pumps are required for the studied greenhouses total heat pump installation cost was \$130,000 (Alibaba 2022; Forbes 2022b). Additionally, the annual Operation and Maintenance (O&M) cost was taken as \$75 per heat pump (Forbes 2022b) and \$1,500 for 20 heat pumps.
- The price of one Panasonic 330 W PV panel is about \$340-341 (around \$1,033/W) (Atakale Elektrik 2022). The prices of other installation equipment such as inverter, cabling, transformer, etc., and the rest cost (labor and transport) for one 330 W PV installation is about \$212. Since in the 1st scenario 5,271, in the 2nd scenario 2,648, and, in the 3rd scenario 26 PV panels were used, prices were adjusted to these scenarios. The fixed O&M cost of a PV panel was reported as \$21/kW according to NREL (NREL 2022). Therefore, in this study, the O&M cost was taken as \$7 per PV panel.
- While the price of one EWT DW61 1 MW wind turbine installation cost was about \$1,512,097 (Renewables First 2022a), the O&M cost of the same turbine was reported at about \$54,435 (Renewables First 2022b).

In cash flow estimation, the above assumptions were taken into account and initial investments and annual costs of five scenarios were presented in Table 3.1.

Table 3.1. Cost summary of all scenarios

Scenarios	**1st**	**2nd**	**3rd**	**4th**	**5th**
HP Installation Cost	$130,000	$130,000	$130,000	$130,000	$130,000
PV System Installation Cost	$2,913,274.9	$1,463,684.9	$14,371.53	-	-
WT Installation Cost	-	$1,512,097	$3,024,194	$4,536,291	-
Working Capital	$114,519.09	$115,535.46	$116,547.58	$106,522.74	$146,121.56
Total Initial Investment	**$3,157,793.98**	**$3,221,317.36**	**$3,285,113.11**	**$4,772,813.74**	**$276,121.56**
Annual Electricity Cost	$648,717.55	$618,741.78	$588,733.51	$474,331.43	$875,229.36
O&M Cost of HP	$1,500	$1,500	$1,500	$1,500	$1,500
O&M Cost of PV System	$36,897	$18,536	$182	-	-
O&M Cost of WT	-	$54,435	$108,870	$163,305	-
Total Annual Cost	**$687,114.55**	**$693,212.78**	**$699,285.51**	**$639,136.43**	**$876,729.36**

3.4. Environmental Analysis

There are several reasons why people prefer solar and wind energy systems in the world, and one of the finest ways is to contribute to a healthier environment. Furthermore, because solar and wind energy systems do not require water to function, they do not contribute to the consumption of water resources. Also, unlike fossil fuels, it does not emit as many pollutants into the atmosphere, such as carbon dioxide, methane, and nitrous oxide, and it does not produce air pollution or health concerns. The calculations of carbon dioxide emissions from coal, natural gas, and other energy sources that are prevented as a result of the installation of PV panels and wind turbines are made according to Figure 3.5 and the shares of resources in electricity generation.

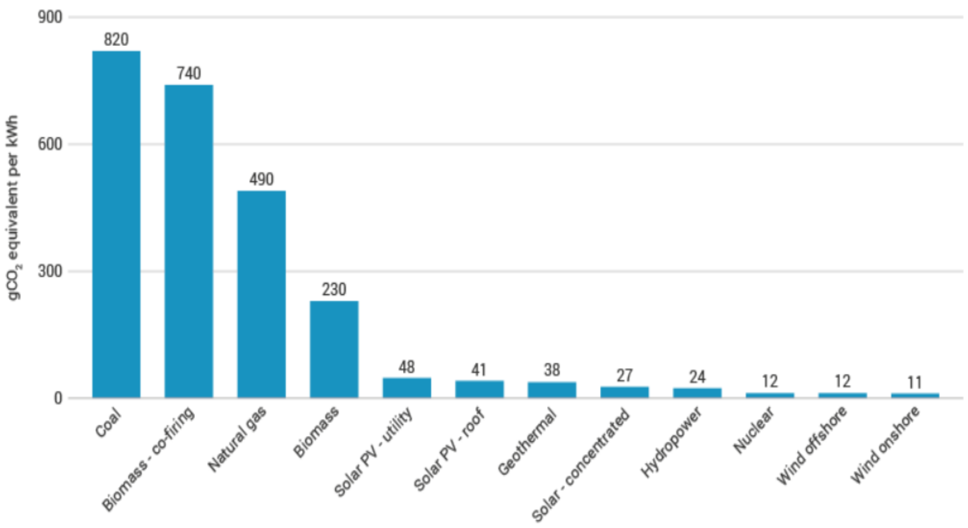


Figure 3.5. Average life-cycle CO_2 equivalent emissions
(World Nuclear Association 2022)

The shares of resources in electricity generation in 2022 were recorded as (Republic of Türkiye Ministry of Energy and Natural Resources 2022):

- Coal: 34.6%,
- Natural gas: 22.2%,
- Hydropower: 20.6%,
- Wind: 10.8%,
- Solar: 4.7%,
- Geothermal: 3.3%,
- Other sources: 3.7%.

While calculating CO_2 emissions originating from the renewable energy system in the scenarios were calculated by multiplying the average life-cycle CO_2 equivalent emissions of the PV and the wind turbine according to the electricity generation amount obtained from the PV and wind turbines. Then if the amount of electricity required for heat consumption would be met by the grid, not from the renewable energy systems in the scenarios, CO_2 emissions were calculated by multiplying the electricity coming from the grid by the shares of resources in electricity generation. Finally, to find the savings, the CO_2 emissions from if the electricity was produced with a renewable energy system were found by subtracting from the CO_2 emissions if the electricity was supplied from the grid.

CHAPTER 4

RESULTS AND DISCUSSION

This section presents and discusses the results of all technical, economic, and environmental calculations for five scenarios. The technical analysis made via MATLAB software was described by considering the calculations and methods in the MATLAB section. The economic and environmental analyzes made via EXCEL were examined taking into account assumptions and acceptances in the Economic Analysis and coefficients and percentiles in the Environmental Analysis sections, respectively.

As mentioned in the Methodology section, the exterior installation characteristics of the greenhouse studied, from the external wall dimensions to the material thickness and u-values, were first defined from the TRNSYS software to the MATLAB software. Afterwards, the climate data of Dikili, which was downloaded from PVGIS to calculate the heating and cooling needs of the greenhouse for a year in MATLAB software, were also defined in the MATLAB software and the radiation calculations specified in the methodology section were made respectively. Every calculation described in this section has been made over the MATLAB software, up to the economic and environmental consequences.

The heat gain and loss calculations made with the outside of the greenhouse, that is, convection and radiation, heat transfers, and humidity-related infiltration, were made by taking into account the solar radiation values falling on each surface of the greenhouse, reflection, and transmission coefficients. In this way, the indoor temperature of the greenhouse, which was determined as a 20°C set temperature, was accepted as the initial temperature and hourly indoor temperature values of the greenhouse were calculated by including the outside temperature and heat loss gain values. The new indoor temperature values were calculated to try to keep the indoor temperature of the greenhouse between 18°C-22°C, a heat pump capacity value was determined that can meet how much power is required to be heated and cooled within this temperature range. According to these calculations, the total heating load was found to be 5,922,015 kWh and the total cooling load was found as 11,014,446 kWh in one year period. The average heating load and the average cooling load were calculated as 1,419.8 and 3,408.9 kW, respectively. Additionally, the average heating load per greenhouse area square meter was 53.66 W/m^2 and the average cooling load per greenhouse area square meter was 128.83 W/m^2. Since, the cooling load was higher than the heating load, the average cooling load was used to determine the heat pump capacity. Therefore, the heat pump capacity was determined as 5,000 kW. The total electricity consumption of the heat pump for heating and cooling the greenhouse for one year is 5,583,716 kWh. Since including the cooling load in analyzes to determine the total electricity consumption of the heat pump was found as very high compared to the reserved land area mentioned in System Description section for the maximum PV and wind turbine installation, the cooling process was excluded from analyzes. Therefore, the heating load of the greenhouse was taken as a basis and the electricity consumption value depending on this load which was found as 3,038,991 kWh was used in all analyzes.

The hourly indoor temperature of the greenhouse which depends on the outside temperature and radiation values when there is no heat pump also the 18°C-22°C limit, which is the temperature range desired to be kept in the presence of a heat pump, and the new indoor temperature values of the greenhouse, which is heated and cooled in order to approach these temperature values in the presence of a heat pump, were shown in Figure 4.1.

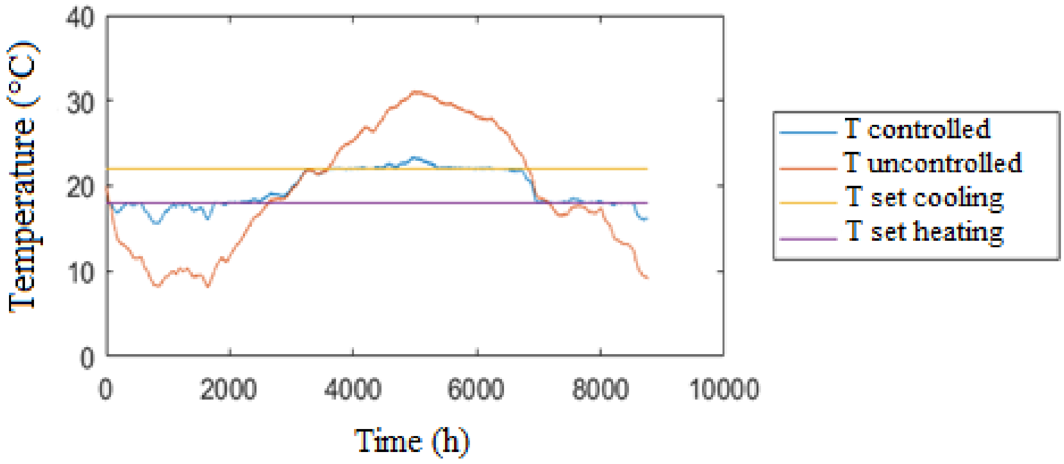


Figure 4.1. Hourly temperature changes in the greenhouse

According to these calculations, when the hourly indoor temperature values of the greenhouse without heat pump are brought to be closest to the 18°C-22°C limit in the presence of a heat pump, the required capacity of the heat pump to heat and cool the inside of the greenhouse was determined as 5,000 kW. After the air source heat pumps in the market were investigated, a high capacity 252 kW heat pump of the LG brand, which was also mentioned in the system description, was chosen. Accordingly, the number of heat pump required to meet heating and cooling load of the greenhouse (about 25,000 m^2) was found to be 20.

In Figure 4.2, the required full capacity power values of the heat pump while heating and cooling the greenhouse hourly according to the temperatures in Figure 4.1 were shown for a one-year period.

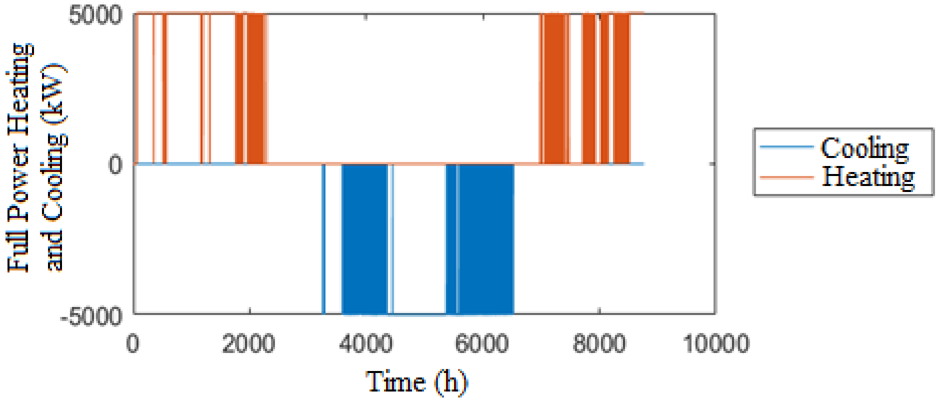


Figure 4.2. Hourly heating and cooling by heat pumps for one year period

While it is a fact that the 5,000 kW heat pump will consume a lot of electricity, the hourly electricity requirement of the compressor which is the electricity consuming equipment of the heat pump, was calculated for a one-year period and given in Figure 4.3. According to the COP values of the heat pump for heating the power consumption (the compressor work) of the 5,000 kW heat pump was calculated as 1,146.789 kW assuming that it always operates at full capacity.

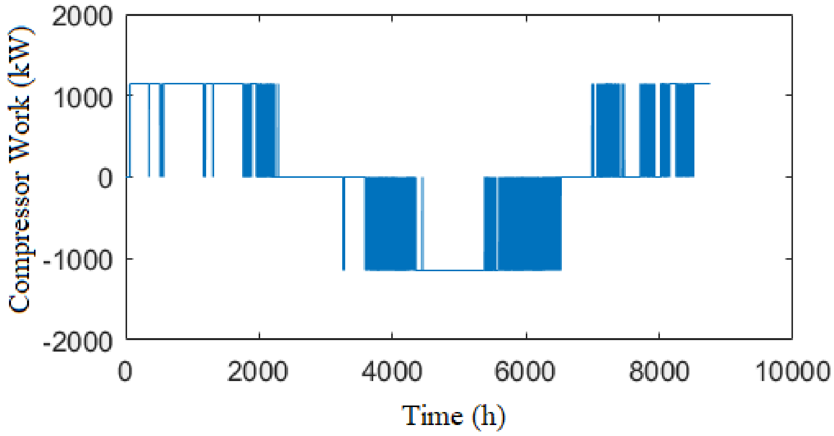


Figure 4.3. Hourly compressor work of heat pumps

The total electricity consumption for heating the greenhouse for one year is 3,038,991 kWh. In order to meet this energy, Panasonic 330 W solar panel and EWT 1 MW wind turbine were selected and they were used in different scenarios to meet the consumption value. Hourly electricity generation values of 330 W solar panels and 1 MW wind turbines within a one-year period were calculated according to the formulas in the methodology and shown in Figure 4.4 and Figure 4.5, respectively.

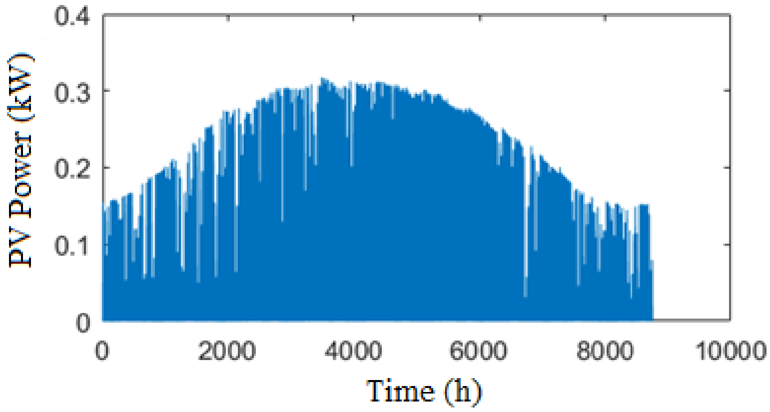


Figure 4.4. Hourly electricity generation from the 330 W photovoltaic panel

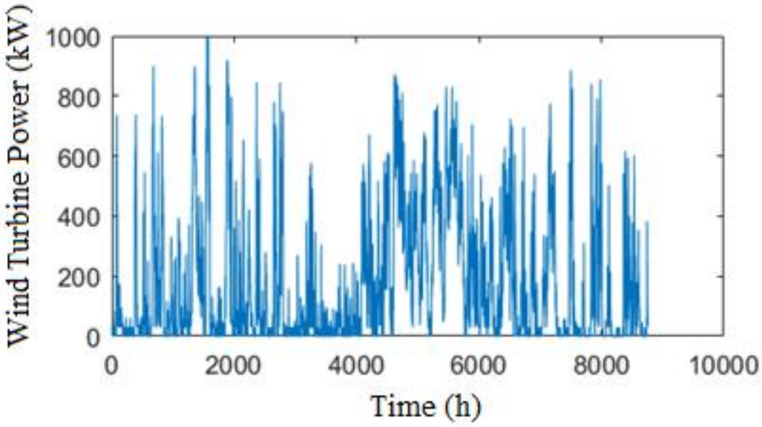


Figure 4.5. Hourly electricity generation from the 1 MW wind turbine

In Table 4.1, five different scenarios and how many solar panels and wind turbines are used in these scenarios were shown to meet the electricity consumption value required for the heat pump to heat the greenhouse according to the scenarios.

Table 4.1. Annual electricity consumption and generation in all scenarios

Scenarios	**System**	**Electricity Consumption of HPs (kWh)**	**Electricity Generation from PVs (kWh)**	**Electricity Generation from WTs (kWh)**	**Total Electricity Generation (kWh)**
1st	20 HPs 5271 PVs	3,038,991	3,039,468.077	-	3,039,468.077
2nd	20 HPs 2648 PVs 1 WT		1,526,942.035	1,512,119.942	3,039,061.977
3rd	20 HPs 26 PVs 2 WTs		14,992.633	3,024,239.884	3,039,232.517
4th	20 HPs 3 WTs		-	4,536,359.826	4,536,359.826
5th	20 HPs		-	-	-

In Table 4.2, total initial investments, annual expenditures, and tax-related annual incomes of all five scenarios were shown.

As seen in Table 4.2. the annual electricity generation is higher than in other scenarios since 3 wind turbines were used in the 4th scenario therefore, the annual income is higher than in the other scenarios. However, since the installation costs of wind turbines are high and wind turbines were used a lot in the 4th scenario, the total initial cost was much higher than in other scenarios. On the other hand, the 1st scenario has the second-highest annual income. It can be concluded from Table 4.2 that the scenario where wind turbines and solar panels are used together could be the best scenario if the wind turbine installation cost was reduced.

Table 4.2. Total annual cost and annual income of all scenarios

Scenarios	**1st**	**2nd**	**3rd**	**4th**	**5th**
Total Initial Investment	**$3,157,793.98**	**$3,221,317.36**	**$3,285,113.11**	**$4,772,813.74**	**$276,121.56**
Annual Electricity Purchase	$648,717.55	$618,741.78	$588,733.51	$474,331.43	$875,229.36
Annual Total O&M Cost	$38,397	$74,471	$110,552	$164,805	$1,500
Fixed Capital Investment	$3,043,274.09	$3,105,781.90	$3,168,565.53	$4,666,291	$130,000
Working Capital	$114,519.09	$115,535.46	$116,547.58	$106,522.74	$146,121.56
Annual Depreciation Cost	$121,730.99	$124,231.27	$126,742.62	$186,651.64	$5,199.99
Annual Electricity Sale	$38,300.47	$35,994.71	$33,696.83	$51,865.64	-
Annual Tomato Sale	$950,000	$950,000	$950,000	$950,000	$950,000
Revenues	$988,300.47	$985,994.71	$983,696.83	$1,001,865.63	$950,000
Taxable Income	$179,454.93	$168,550.65	$157,668.69	$176,077.57	$68,070.64
Tax Payment	$35,890.98	$33,710.13	$31,533.74	$35,215.51	$13,614.13
After Tax Annual Income	**$265,294.94**	**$259,071.79**	**$252,877.58**	**$327,513.69**	**$59,656.51**

When it is looked at in Table 4.3, it is seen that since the IRR of the 4th scenario was lower than the MARR value and the NPV of the 4th scenario was negative, the 4th scenario was not feasible and acceptable. On the other hand, the 1st and 5th scenarios' breakeven periods are less than other scenarios, which means that the investment balance of these scenarios turns positive in earlier years than others. As a result, when the 1st and 5th scenarios are compared, the 1st scenario is better than the 5th and other scenarios, because it has the highest NPV, a high total income value, and a good breakeven period.

Table 4.3. Comparison of net present value

Scenarios	**1st**	**2nd**	**3rd**	**4th**	**5th**
MARR 5%					
IRR	7%	6.21%	5.74%	4.60%	21.34%
Total Initial Investment ($)	3,157,793.98	3,221,317.36	3,285,113.11	4,772,813.74	276,121.56
Investment	Acceptable	Acceptable	Acceptable	Not Acceptable	Acceptable
NPV (MARR) ($)	**547,440.40**	395,908.19	244,521.62	-188,310.34	521,523.94
Breakeven Period	19th year	20th year	22nd year	-	6th year

LCOE values were given in Table 4.4, where it is seen that scenario 1 has the lowest LCOE value. A low LCOE is a good thing because the LCOE value is the ratio of the expenditures of the systems that produce electricity to the amount of electricity generation. The low LCOE value of the 1st scenario also makes the 1st scenario preferable, since the expenditure is low and the amount of electricity generation is high.

Table 4.4. Comparison of levelized cost of electricity

Scenarios	**1st**	**2nd**	**3rd**	**4th**	**5th**
NPV of Production (kWh)	42,838,094.59	42,832,371.04	42,834,774.62	63,935,203.92	-
NPV of Expenditures ($)	3,433,299.16	4,004,231.13	4,575,538.37	6,837,902.62	-
LCOE ($/kWh)	**0.080146**	0.093486	0.106818	0.106950	-

Since the 1st scenario was determined to have the most optimal conditions according to the comparisons of the scenarios in the tables above, some parameters of this scenario were changed in further evaluations, and the current 2022 situation and the modified parameterized states were compared. These parameters are taken as the change due to the use of electricity sales and purchase values of 2020 and the change in sales depending on the amount of product yielded by tomato seedlings. Since there was not much change in electricity purchase and sale prices in 2021, the values in 2020 were examined for change. In addition, if the tomato seedling, which normally yields 55 kg in the current scenario, yielded 45 kg, the scenario was examined.

As is seen in Table 4.5, since the sale price of electricity to the government in 2020 was higher than the price in 2022, the NPV of the system has increased and the breakeven period has decreased from the 19th to the 17th year.

Table 4.5. Comparison of 1st scenario according to electricity sale prices in years 2020 and 2022

Scenarios	**1st (2022)**	**1st (2020)**
Annual Electricity Sale ($)	38,300.47	65,336.10
NPV (MARR) ($)	547,440.40	852,271.32
Breakeven Period	19th year	17th year

In Table 4.6, since the purchase price of electricity from the government in 2020 was much cheaper than in 2022, the NPV in 2020 has increased considerably and the breakeven period has been reduced to the 5th year.

Table 4.6. Comparison of 1st scenario according to electricity purchase prices in years 2020 and 2022

Scenarios	**1st (2022)**	**1st (2020)**
Annual Electricity Purchase ($)	648,717.55	70,953.48
NPV (MARR) ($)	547,440.40	7,197,407.36
Breakeven Period	19th year	5th year

In Table 4.7, both parameters changed in Table 4.5 and Table 4.6 were applied, that is when the electricity purchase and sale price in 2020 was taken into account at the same time. It was seen that the NPV is quite high and the breakeven period is in the 5th year. This means that if the system was built today with electricity prices in 2020, it would be a very profitable system.

Table 4.7. Comparison of 1st scenario according to electricity prices in years 2020 and 2022

Scenarios	**1st (2022)**	**1st (2020)**
Annual Electricity Purchase ($)	648,717.55	70,953.48
Annual Electricity Sale ($)	38,300.47	65,336.10
NPV (MARR) ($)	547,440.40	7,502,238.27
Breakeven Period	19th year	5th year

In Table 4.8, the revenue from the tomato related to the product obtained from the tomato seedling was evaluated. If a seedling gave 45 kg of tomatoes instead of 55 kg, the system would have suffered an economic loss as seen in Table 4.8. It showed that this system not only gains from electricity but also plays a major role in the production of tomatoes in the system's profit.

Table 4.8. Comparison of 1st scenario according to the production of tomato

Scenarios	**1st (55 kg)**	**1st (45kg)**
Annual Tomato Sale ($)	950,000	738,889
NPV (MARR) ($)	547,440.40	-1,832,870.24
Breakeven Period	19th year	-

As a result of changing the different parameters above, when the effects of the variables on NPV are examined and compared, it was seen that NPV increased significantly, especially in the case of a decrease in the purchase price of electricity. Apart from these variables, another variable that was thought to seriously affect the profitability of the system is the initial investment of the system. Since the values that increase the initial investment for these scenarios can be considered as PV panel prices or the installation cost of wind turbines, the effect of their changes was examined. Since the 1st scenario, where only PV panels are used, is the most profitable scenario, comparisons were made over it. Moreover, since the value that will most affect the initial investment of this scenario is the price of the PV panel, this parameter was changed and its effect on NPV was investigated and its sensitivity to NPV was examined.

Sensitivity analysis is a risk analysis approach that measures the extent that the NPV changes depending on changes in the main variables that comprise the project's net present value (Icoz 2022). Also, sensitivity analysis is a technique used in this context to discover and assess potential hazards in project efficiency. Rather than determining the risk value, it is also utilized to quantify the effects of factors on NPV. The effect of changes in investment based on various assumptions surrounding the most likely value of a basic variable, which is considered while holding other variables constant, is investigated. The technique is then repeated for the remaining variables. When the variables below and above the fundamental variable are altered at different rates, new NPVs are calculated as long as the other variables stay constant (Icoz 2022).

As mentioned earlier, the PV panel price used in scenarios was 1.033 ($/W) in this study. In Table 4.9, the dollar prices per watt of the PV panels were changed and the effect on the NPV was examined.

As seen in Table 4.9, when PV panel prices decrease, NPV increases considerably, which is an indication that the scenarios examined will yield serious profits in case the PV panel equipment costs and installation costs in the scenarios and the costs of wind turbines decrease.

Table 4.9. Sensitivity of NPV to PV panel price

PV Panel Price ($/W)	**NPV (MARR) ($)**
0.033	2,089,852.35
0.283	1,704,025.71
0.533	1,318,199.07
0.783	932,372.43
1.033	**547,440.40**
1.283	160,719.15
1.533	-225,107.49
1.783	-610,934.13
2.033	-996,760.77

In Figure 4.6, the sensitivity analysis graph of NPV and PV panel price was made. The steeper NPV curve and the bigger change in NPV mean that the project's profitability is more sensitive to that variable. When it is looked at Figure 4.6, a slight adjustment in the PV panel price resulted in significant changes in the project's profitability. As a result, it was foreseen that there is a risk factor in 1.533 ($/W) and the following and that the investment will begin to lose its economic appeal.

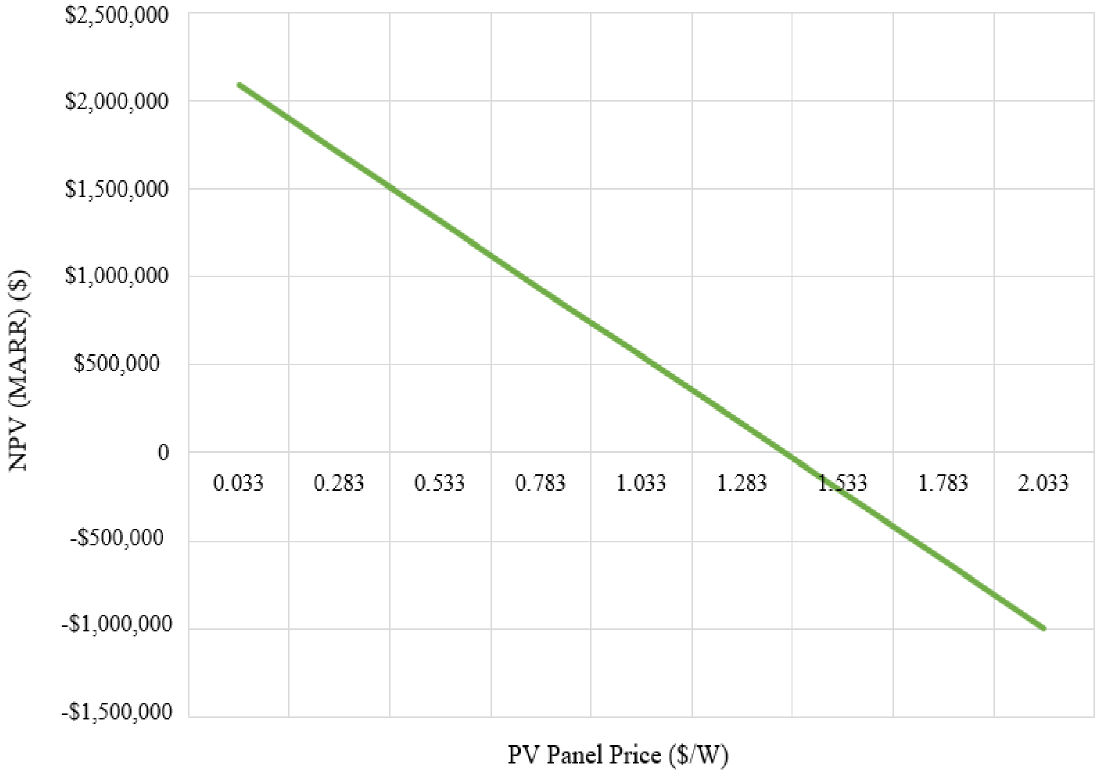


Figure 4.6. Sensitivity analysis of NPV and PV panel price

In Table 4.10, CO_2 emissions from the renewable energy system life-cycle and grid were presented. Also, how many tons of CO_2 emissions are prevented based on the utilization of renewable energy systems in scenarios were shown in Table 4.10.

The highest CO_2 emission prevention was seen in the 4th scenario with 2,064.73 t savings since the electricity production was at the highest in that scenario. Also, as seen in Table 4.10 CO_2 savings in other scenarios with the utilization of wind turbines are also high, because the average life-cycle CO_2 equivalent emissions of wind turbines are lower than PV's. Since the average life-cycle CO_2 equivalent emissions of PV panels are higher, the prevention of CO_2 emissions has been slightly less compared to other scenarios. Therefore, in the 1st scenario, 1,270.96 t CO_2 saving was observed. Lastly, since the 5th scenario was the only scenario where there was no electricity production, no CO_2 saving was observed.

Table 4.10. CO_2 emissions and savings

Scenarios	**1st**	**2nd**	**3rd**	**4th**	**5th**
CO_2 Emissions from the RE System Life-Cycle (g)	145,894,467.7	89,926,537.1	33,986,285.1	49,899,958.1	-
CO_2 Emissions from the Grid (g)					
Coal	862,357,883	862,242,664	862,291,050	1,287,056,010	862,222,526
Natural gas	499,323,816	499,257,102	499,285,118	745,233,192.2	499,245,441
Hydropower	15,027,130	15,025,122.4	15,025,965.6	22,427,762.98	15,024,771.5
Wind	3,610,888.1	3,610,405.63	3,610,608.23	5,389,195.47	3,610,321.31
Solar	6,857,039.9	6,856,123.82	6,856,508.56	10,234,027.77	6,855,963.69
Geothermal	3,811,492.9	3,810,983.72	3,811,197.58	5,688,595.22	3,810,894.71
Other sources	25,865,873	25,862,417.4	25,863,868.7	38,604,422.12	25,861,813.4
Total Emission from the Grid (g)	1,416,854,1	1,416,664,82	1,416,744,31	2,114,633,206	1,416,631,73
Savings (t)	**1,270.96**	**1,326.74**	**1,382.76**	**2,064.73**	-

CHAPTER 5

CONCLUSIONS

In this study, the indoor temperature of an approximately 25,000 m^2 area commercial greenhouse in the agricultural zone of Dikili and its annual heating and cooling needs were calculated on a hourly basis, depending on the external materials, the U-values of the materials, weather data, and solar radiation. Then the capacity of the heat pump required to meet the energy demand was determined, and the electrical load of this heat pump was calculated. Afterwards, to meet this electrical load of the heat pump, the number of PV panels and wind turbines were calculated for 4 different scenarios based on the power output of PV and wind turbine at the specified location. The renewable-free grid connected system was also considered as a comparison. Economic and environmental performances of systems in different scenarios were analyzed and the best scenario was determined accordingly. Improvement suggestions were also made on the best scenario for future implementation of renewable-powered greenhouse applications.

The innovative aspects of the study are the inclusion of a detailed heat transfer of a large glass greenhouse with a flat roof and an area of approximately 25,000 m^2 and the detailed technical, economic, and environmental analyzes of systems, photovoltaic panels, wind turbines, and large-capacity air source heat pumps containing systems and the utilization of combination of software such as TRNSYS, SketchUp, and MATLAB.

The heating and cooling demand of the greenhouse was determined by considering all processes resulting in the heat gain and the loss of the studied greenhouse (convection and radiation heat transfers, humidity-related infiltration, the solar radiation on each surface of the greenhouse, reflection, and transmission). In this manner, the greenhouse's indoor temperature, which was determined as a 20°C set temperature, was accepted as the initial temperature, and the greenhouse's hourly indoor temperature values were computed by incorporating the outside temperature and heat loss gain data. To try to keep the greenhouse's indoor temperature between 18°C and 22°C, a heat pump capacity was found in a way that the heat pump can meet the required heating and cooling within this temperature range. The required capacity of the heat pump to heat and cool the inside of the greenhouse was determined as 5,000 kW. To obtain this much capacity heat pump, 20 heat pumps with a capacity of 250 kW for each were used in each scenario. Since the cooling demand was found to be high compared to the power generation from PV and wind turbines for the reserved land area and the location, the colling of the greenhouse was excluded from the study, i.e., only greenhouse heating was considered.

Electricity generation calculations for meeting the electricity consumption of heat pumps were made on a 330 W PV panel and a 1 MW wind turbine, and they were used in different amounts according to the different scenarios. The 1st scenario consisted of only 5,271 PV panels and 20 heat pumps, the 2nd consisted of 2,648 PV panels, 1 wind turbine, and 20 heat pumps, the 3rd consisted of 26 PV panels, 2 wind turbines, and 20 heat pumps, the 4th consisted of 3 wind turbines and 20 heat pumps, Finally, the 5th scenario consisted of only 20 heat pumps. All these systems were connected to the grid without a storage system and monthly offset was based on electricity generation consumption amounts.

The total electrical consumption in the heat pump system required for the one-year heating of the greenhouse was 3,038,991 kWh. According to the numerical results, the total electricity generation in the 1st scenario was 3,039,468.077 kWh, in the 2nd scenario was 3,039,061.977 kWh, in the 3rd scenario was 3,039,232.517 kWh, in the 4th scenario was 4,536,359.826 kWh. In the 5th scenario, since there were not any renewable energy systems there was electricity generation.

Even though the annual electricity generation, the annual income of the 4th scenario, and CO_2 savings are higher than in the other scenarios, since the installation costs of wind turbines are high and wind turbines were used a lot in the 4th scenario, the total initial cost is much higher than in other scenarios. Also, since the NPV of the 4th scenario was negative, it was not acceptable. Therefore, even though the 1st scenario has slightly fewer CO_2 savings (1,270.96 t) than in scenarios the 2nd and the 3rd since the 1st scenario had the second-highest annual income could be accepted as the best-case scenario. However, if the installation cost of the wind turbine is reduced in the market, the scenario where wind turbines and solar panels were used together may be the best scenario.

Among the scenarios with renewable energy systems, the high amount of electricity generation in the 1st scenario and the economic breakeven point which was in the 19th year showed that it is better than the others. In addition, it became clear that the 1st scenario with the highest NPV of $547,440.40 and the lowest LCOE of 0.080146 $/kWh was accepted as the best scenario among the five scenarios.

Since the 1st scenario was determined to have the most optimal conditions, some parameters of this scenario were electricity purchase and sale prices in 2020, production of tomato amount, and PV panel prices were changed for evaluation. Moreover, the current 2022 situation and these modified parameterized states were compared. After comparisons by changing parameters to increase the NPV of the 1st scenario and lower the breakeven point, following observations were made:

- When the electricity purchase prices of 2022 and 2020 were compared, it was observed that NPV value increased approximately 13.14 times in case of an approximately 88.8% decrease in the 2022 electricity purchase price. Also, drastic fall in breakeven was observed.
- When the electricity sale prices of 2022 and 2020 were compared, it was observed that there was an increase of approximately 55.6% in the NPV value in case of an approximately 70.5% increase in the 2022 electricity sale price. Additionally, a little drop in breakeven point was observed.
- By decreasing the electricity purchase price and increasing the electricity sale price at the same time there was significant increase in NPV and there was sharp decrease in breakeven point.
- In case of under less than 55 kg tomato production per plant, NPV negative throughout the system life time.
- Since the change in PV panel price affects initial cost of the system, by decreasing PV panel price there was also a dramatic of rise in NPV.
- By increasing PV panel price to 1.533 ($/W) and above, it was observed that there was a risk factor in the investment, and it started to lose its economic attraction.

The main conclusions drawn from all findings are that renewable energy systems can provide profit for heating operations in large-scale commercial greenhouses, even though the electricity purchase price in 2022 is very high and the electricity selling price is extremely low. However, it takes too many years to return to positive in the investment balance. For this reason, the suggestions made to make these systems more profitable and reduce the breakeven points are as follows:

- If the government makes the electricity purchase prices more affordable as in previous years and increases the renewable-sourced electricity sale prices, the renewable energy investment for greenhouses will more profitable.
- Since the prices of wind turbines and solar panels are still relatively high, research and development can be done to reduce these prices, for example domestic productions can be promoted.
- Since the amount of tomato production contributes greatly to the revenue of the greenhouse, studies can be carried out to increase production rate and capacity per plant.

Finally, in addition to the features that distinguish this study from other studies mentioned at the beginning, its additional contribution to the literature will be as follows:

With the change in the regulation no 31755 (Republic of Türkiye Ministry of Environment Urbanization and Climate Change 2022b) prepared by the Republic of Türkiye Ministry of Environment, Urbanization and Climate Change (Republic of Türkiye Ministry of Environment Urbanization and Climate Change 2022a), the transition to the concept of Near Zero Energy Buildings, which provides a certain part of the energy used from renewable energy sources, is made compulsory gradually. Accordingly, as of January 2023, it will be mandatory for all buildings with a total construction area of more than 5,000 m^2 in a parcel to meet at least 5% of their energy from renewable energy sources such as PV panels, wind turbines and heat pumps.

On the other hand, if the greenhouse is a glass-enclosed structure with thick and high pillars on a concrete perimeter wall, with a gable roof, that is, a greenhouse with a high cost, then the Zoning Law (Tarım Hukuku Derneği 2020) is referred to and the structures in accordance with the definition specified in 5th clause of the law are determined in the same way as specified in 20th clause of the law. It is understood that it will become a building (Tarım Hukuku Derneği 2020).

For this reason, since the large-scale greenhouse in this study will be counted as a building, this thesis will take its place as a pioneering study in the literature according to the law on the necessity of using renewable energy systems and heat pumps for buildings.

From the future perspective, it may be studied on these topics:

- In this study, when the average heating demand of one greenhouse for a year period was found to be 1,419.8 kW, the whole plant which contains 50 greenhouses may be calculated as 70,990 kW linearly. However, detailed calculations for the whole plant should be made in the future.
- The average heating load per greenhouse area square meter was calculated as 53.66 W/m^2 to preserve optimum conditions for tomato production. Therefore, this study can be conducted for other vegetable species productions, and comparisons with this study can be made.
- Since this study used the air source heat pump, the same study can be made for the geothermal heat pump. The cost of a geothermal heat pump is generally higher than an air source heat pump in the markets, but since the COP value is higher, it can meet the heating power more easily, hence detailed technical and economic analyzes should be made and compared.

REFERENCES

Ahamed, Md Shamim, Huiqing Guo, and Karen Tanino. 2018. “Development of a Thermal Model for Simulation of Supplemental Heating Requirements in Chinese-Style Solar Greenhouses.” *Computers and Electronics in Agriculture* 150 (May): 235–44. https://doi.org/10.1016/j.compag.2018.04.025.

Alibaba. 2022. “250kw Air Source Heat Pump.” 2022. https://www.alibaba.com/product-detail/250kw-Air-source-heat-pump-Air_1700006297574.html.

Amin, Majdi Talal. 2015. “Dynamic Modeling and Verification of an Energy-Efficient Greenhouse With an Aquaponic System Using TRNSYS.” University of Dayton.

Ampyr Energy. 2022. “AMPYR and Shell Energy to Jointly Develop, Own and Operate a 500 MW / 1,000 MWh Battery Energy Storage System in Wellington, New South Wales.” 2022. https://www.ampyrenergy.com/2022/10/13/ampyr-and-shell-energy-to-jointly-develop-own-and-operate-a-500-mw-1000-mwh-battery-energy-storage-system-in-wellington-new-south-wales/.

Ankit Rohatgi. 2022. “Web Plot Digitizer.” 2022. https://apps.automeris.io/wpd/.

ASAE. 1998. “Heating, Ventilating, and Cooling Greenhouses(EP406.3).” *ASAE Standards*, 222.

Ata, Atilla. 2015. “Örtüaltı Domates Yetiştiriciliği.” *T.C. Gıda Tarım ve Hayvancılık Bakanlığı*.

Atakale Elektrik. 2022. “Panasonic 330W.” 2022. https://www.atakale.com.tr/index.php?route=product/product&product_id=96.

Awani, S., R. Chargui, S. Kooli, A. Farhat, and A. Guizani. 2015. “Performance of the Coupling of the Flat Plate Collector and a Heat Pump System Associated with a Vertical Heat Exchanger for Heating of the Two Types of Greenhouses System.” *Energy Conversion and Management* 103: 266–75. https://doi.org/10.1016/j.enconman.2015.06.032.

Barakat, Shimaa, Haitham Ibrahim, and Adel A. Elbaset. 2020. “Multi-Objective Optimization of Grid-Connected PV-Wind Hybrid System Considering Reliability, Cost, and Environmental Aspects.” *Sustainable Cities and Society* 60 (December 2019): 102178. https://doi.org/10.1016/j.scs.2020.102178.

BCD Müşavirlik Mühendislik. 2021a. “Genel_Yerlesim_Planı_1000_20.09.2021.Pdf.”

———. 2021b. “İzmir Dikili Tarıma Dayalı İhtisas Sera Organize Sanayi Bölgesi Detaylı Teknik Rapor.”

———. 2021c. “Sera 1 Tip.”

Berkeley University of California. 2022. “Absorption / Reflection of Sunlight.” 2022. https://ugc.berkeley.edu/background-content/reflection-absorption-sunlight/.

Blanchet, Carolina Alvarez C., Antonio M. Pantaleo, and Koen H. van Dam. 2019. “A Process Systems Engineering Approach to Designing a Solar/Biomass Hybrid Energy System for Dairy Farms in Argentina.” *Computer Aided Chemical Engineering* 46: 1609–14. https://doi.org/10.1016/B978-0-12-818634-3.50269-1.

Calise, Francesco, Francesco Liberato Cappiello, Massimo Dentice d’Accadia, and Maria Vicidomini. 2020. “Dynamic Modelling and Thermoeconomic Analysis of Micro Wind Turbines and Building Integrated Photovoltaic Panels.” *Renewable Energy* 160: 633–52. https://doi.org/10.1016/j.renene.2020.06.075.

CarnotCycle. 2023. “Absolute Humidity.” 2023.

https://carnotcycle.wordpress.com/2012/08/04/how-to-convert-relative-humidity-to-absolute-humidity/.

Cengel, Yunus A., and Michael A. Boles. 2015. *Thermodynamics : An Engineering Approach, 8th Edition*. McGraw-Hill Higher Education. https://doi.org/10.1080/15348430701826941.

CFI. 2022. "Levelized Cost of Energy (LCOE)." 2022. https://corporatefinanceinstitute.com/resources/valuation/levelized-cost-of-energy-lcoe/.

Chel, Kaushik. 2010. "Renewable Energy for Sustainable Agriculture To Cite This Version : Review Article." *Agronomy for Sustainable Development* 31 (1): 91–118.

Choab, Noureddine, Amine Allouhi, Anas El Maakoul, Tarik Kousksou, Said Saadeddine, and Abdelmajid Jamil. 2021. "Effect of Greenhouse Design Parameters on the Heating and Cooling Requirement of Greenhouses in Moroccan Climatic Conditions." *IEEE Access* 9: 2986–3003. https://doi.org/10.1109/ACCESS.2020.3047851.

Dalamagkidis, K, G Saridakis, and D Kolokotsa. 2005. "Development of Simulation Algorithms for Control Scheme Optimization in Greenhouses," no. January 2005: 1–7.

DALSEM. 2018. "Uygun Türde Cam Düzenlemesi Düşük Maliyetle Optimum Verim Sağlamaya Yardımcı Olur." 2018. https://www.dalsem.com/tr/SERA-CAMLARI#:~:text=Seralarda kullanılan standart cam 4,olarak %90 ışık geçirgenliğine sahiptir.

Dentons. 2022. "Global Tax Guide to Doing Business in Turkey." 2022. https://www.dentons.com/en/services-and-solutions/global-tax-guide-to-doing-business-in/turkey#:~:text=The general corporate income tax,rate was increased to 23%25.

Devlet Destekli. 2022. "Devlet Elektrik Alım Fiyatı." 2022. https://www.devletdestekli.com/devlete-elektrik-satmak-alim-fiyati/#devlet-elektrik-satis-fiyati-2022.

Dubey, Swapnil, Jatin Narotam Sarvaiya, and Bharath Seshadri. 2013. "Temperature Dependent Photovoltaic (PV) Efficiency and Its Effect on PV Production in the World - A Review." *Energy Procedia* 33: 311–21. https://doi.org/10.1016/j.egypro.2013.05.072.

Duffie, John A, and William A Beckman. 2013. *Solar Engineering of Thermal Processes, 4th Edition. John Wiley & Sons, Inc.* https://doi.org/10.1016/0142-694x(82)90016-3.

Energy Storage News. 2023. "Winner of SECI's 1,000MWh Pilot Energy Storage Tender in India given Green Light to Proceed." 2023. https://www.energy-storage.news/winner-of-secis-1000mwh-pilot-energy-storage-tender-in-india-given-green-light-to-proceed/.

EPDK. 2022. "Elektrik Faturalarına Esas Tarife Tabloları." 2022. https://www.epdk.gov.tr/Detay/Icerik/3-1327/elektrik-faturalarina-esas-tarife-tablolari.

Esen, Mehmet, and Tahsin Yuksel. 2013. "Experimental Evaluation of Using Various Renewable Energy Sources for Heating a Greenhouse." *Energy and Buildings* 65: 340–51. https://doi.org/10.1016/j.enbuild.2013.06.018.

ET Energy World. 2021. "SECI to Float Tender for 1,000 MW Battery Energy Storage

System.” 2021. https://energy.economictimes.indiatimes.com/news/power/seci-to-float-tender-for-1000-mw-battery-energy-storage-system/87450248?redirect=1.

EWT. 2018. “Direct Drive Wind Turbines DW611MW.”

———. 2023. “EWT.” 2023. https://ewtdirectwind.com/.

Forbes. 2022a. “How Long Do Solar Panels Last?” 2022. https://www.forbes.com/home-improvement/solar/how-long-do-solar-panels-last/.

———. 2022b. “How Much Does Heat Pump Maintenance, Service And Repair Cost?” 2022. https://www.forbes.com/home-improvement/hvac/heat-pump-maintenance-service-cost/#:~:text=The cost of heat pump,from around %24150 to %241%2C950.

Goldammer, Ted. 2019. *Greenhouse Management A Guide to Operations and Technology*. *Apex Publishers*. https://doi.org/10.1016/0002-1571(80)90046-1.

Greenwich Mean Time. 2022. “GreenwichMeanTime.Com.” 2022. https://greenwichmeantime.com/time/turkey/izmir/.

Hassanien, Reda Hassanien Emam, Ming Li, and Wei Dong Lin. 2016. “Advanced Applications of Solar Energy in Agricultural Greenhouses.” *Renewable and Sustainable Energy Reviews* 54: 989–1001. https://doi.org/10.1016/j.rser.2015.10.095.

Hosseini-Fashami, Fatemeh, Ali Motevali, Ashkan Nabavi-Pelesaraei, Seyyed Jafar Hashemi, and Kwok wing Chau. 2019. “Energy-Life Cycle Assessment on Applying Solar Technologies for Greenhouse Strawberry Production.” *Renewable and Sustainable Energy Reviews* 116 (August): 109411. https://doi.org/10.1016/j.rser.2019.109411.

Icoz, Didem. 2022. “Design and Techno-Economic Analysis of a Smart Solar Greenhouse.” Izmir Institute of Technology.

Investopedia. 2022a. “IRR.” 2022. https://www.investopedia.com/terms/i/irr.asp.

———. 2022b. “NPV.” 2022. https://www.investopedia.com/terms/n/npv.asp#toc-npv-vs-internal-rate-of-return-irr.

Ishigami, Y., E. Goto, M. Watanabe, T. Takahashi, and L. Okushima. 2014. “Development of a Simulation Model to Evaluate Environmental Controls in a Tomato Greenhouse.” *Acta Horticulturae* 1037: 93–98. https://doi.org/10.17660/ActaHortic.2014.1037.7.

Izmir Büyükşehir Belediyesi. 2022. “Sebze/Meyve Hal Fiyatları.” 2022. https://eislem.izmir.bel.tr/tr/HalFiyatlari/20?date=2022-06-02&tip=1&aranacak=domates.

Kalogirou, S. A. 2012. *Solar Thermal Systems: Components and Applications - Introduction*. *Comprehensive Renewable Energy*. Vol. 3. Elsevier Ltd. https://doi.org/10.1016/B978-0-08-087872-0.00301-2.

Klein, S.A. 2017. “TRNSYS 18: A Transient System Simulation Program.” Madison, USA: Solar Energy Laboratory, University of Wisconsin. http://sel.me.wisc.edu/trnsys.

Leblebicioglu, Emre. 2022. “Elektrik Birim Fiyatları 2022 [Vergili ve Vergisiz Fiyatlar].” 2022. https://muhendistan.com/elektrik-birim-fiyatlari-2022/.

Letcher, Trevor M. 2017. *Wind Energy Engineering: A Handbook for Onshore and Offshore Wind Turbines*. *Elsevier Inc.*

LG Electronics. 2020. “LG MULTI V5.”

Manwell, J. F. 2009. *Wind Energy Explained Theory, Design and Application 2nd Edition*. *John Wiley & Sons Ltd.*

Mehrpooya, Mehdi, Hoofar Hemmatabady, and Mohammad H. Ahmadi. 2015. “Optimization of Performance of Combined Solar Collector-Geothermal Heat Pump Systems to Supply Thermal Load Needed for Heating Greenhouses.” *Energy Conversion and Management* 97: 382–92. https://doi.org/10.1016/j.enconman.2015.03.073.

Microsoft Corporation. 2019. “EXCEL.” https://office.microsoft.com/excel.

Mohammadi, Saleh, Amir Hosein Afkari Sayyah, Ali Mohammad Nikbakht, and Esmail Khalife. 2020. “Modeling and Design a Special Type of Passive Solar Greenhouse in Cold Climate by Trnsys.” *Tarim Bilimleri Dergisi* 26 (4): 488–98. https://doi.org/10.15832/ankutbd.502073.

Morn Glass. 2019. “Greenhouse Glass Types.” 2019. https://www.mornglass.com/greenhouse-glass-types.html.

NASA Earth Observatory. 2009. “Earth’s Energy Budget.” 2009. https://earthobservatory.nasa.gov/features/EnergyBalance/page4.php#:~:text=The atmosphere absorbs 23 percent,cooling happens in the atmosphere.

northern nester. 2022. “Can A Greenhouse Have A Flat Roof? Garden Tips 2022.” 2022. https://northernnester.com/can-a-greenhouse-have-a-flat-roof/.

NREL. 2022. “Utility-Scale PV.” 2022. https://atb.nrel.gov/electricity/2022/utility-scale_pv.

Outlook. 2023. “JSW Energy Arm Bags Two Battery Energy Storage System Projects From SECI.” 2023. https://www.outlookindia.com/business/jsw-energy-arm-bags-two-battery-energy-storage-system-projects-from-seci-news-254856.

Ozcan, Huseyin Gunhan, Szabolcs Varga, Huseyin Gunerhan, and Arif Hepbasli. 2021. “Numerical Simulation and Parametric Study of Various Operational Factors Affecting a PV-Battery-Air Conditioner System under Prevailing European Weather Conditions.” *Sustainable Cities and Society* 67 (August 2020): 102754. https://doi.org/10.1016/j.scs.2021.102754.

Özcan, Zeynep, Miray Gülgün, Ecem Şen, Nezir Yağız Çam, and Levent Bilir. 2021. “Cooling Channel Effect on Photovoltaic Panel Energy Generation.” *Solar Energy* 230 (September): 943–53. https://doi.org/10.1016/j.solener.2021.10.086.

Ozgener, Onder. 2010. “Use of Solar Assisted Geothermal Heat Pump and Small Wind Turbine Systems for Heating Agricultural and Residential Buildings.” *Energy* 35 (1): 262–68. https://doi.org/10.1016/j.energy.2009.09.018.

Panasonic. 2018. “Photovoltaic Module HIT ® N330 / N325 Resulting in Higher Energy Output than Conventional Panels . Our Competitive Advantages.”

Pavani, Kommana. 2020. “Cultivation Technology of Tomato in Greenhouse.” *Protected Cultivation and Smart Agriculture*, no. December. https://doi.org/10.30954/ndp-pcsa.2020.12.

Pena, Jose G. 2005. “Greenhouse Vegetable Production Economic Considerations, Marketing, and Financing.” 2005. https://aggie-hort.tamu.edu/greenhouse/hydroponics/economics.html#:~:text=A south central U.S. wide,entering the greenhouse tomato industry.

Petektar Tohumculuk. 2023. “Tohum Ar-Ge.” 2023. https://petektar.com/tohum-ar-ge-calismalari/.

Power Enerji. 2020. “Devlete Elektrik Satış Fiyatı 2020.” 2020. https://www.powerenerji.com/devlete-elektrik-satis-fiyati-2020.html#:~:text=1 kW başına elektrik birim,edildiğinde 0%2C7511 kuruş olmaktadır.

PVGIS. 2022. “Photovoltaic Geographical Information System.” EU Science Hub - European Commission. 2022. http://re.jrc.ec.europa.eu/pvg_download/map_index.html%0Ahttps://re.jrc.ec.europa.eu/pvg_tools/en/%0Ahttps://re.jrc.ec.europa.eu/pvg_tools/es/#PVP%0Ahttps://ec.europa.eu/jrc/en/pvgis.

PWC Worldwide Tax Summaries Online. 2022. “Corporate - Taxes on Corporate Income.” 2022. https://taxsummaries.pwc.com/turkey/corporate/taxes-on-corporate-income.

Rasheed, Adnan, Cheul Soon Kwak, Wook Ho Na, Jong Won Lee, Hyeon Tae Kim, and Hyun Woo Lee. 2020. “Development of a Building Energy Simulation Model for Control of Multi-Span Greenhouse Microclimate.” *Agronomy* 10 (9). https://doi.org/10.3390/agronomy10091236.

Renewables First. 2022a. “How Much Does a Wind Turbine Cost?” 2022. https://www.renewablesfirst.co.uk/windpower/windpower-learning-centre/how-much-does-a-wind-turbine-cost/.

———. 2022b. “What Is the Cost to Operate Wind Turbines ?” 2022. https://www.renewablesfirst.co.uk/windpower/windpower-learning-centre/how-much-does-a-wind-turbine-cost-to-operate/.

Republic of Türkiye Ministry of Energy and Natural Resources. 2022. “The Shares of Resources in Electricity Generation.” 2022. https://enerji.gov.tr/infobank-energy-electricity.

Republic of Türkiye Ministry of Environment Urbanization and Climate Change. 2022a. “Mevzuat Bilgi Sistemi.” 2022. https://mevzuat.csb.gov.tr/#!/.

———. 2022b. “Resmi Gazete.” https://www.resmigazete.gov.tr/eskiler/2022/02/20220219-2.htm.

Sabah Newspaper. 2013. “7 Metre Boyunda Domates Ağacı.” 2013. https://www.sabah.com.tr/yasam/7-metre-boyunda-domates-agaci-2415996.

Shahbazi, Reza, Shahriar Kouravand, and Reza Hassan-Beygi. 2019. “Analysis of Wind Turbine Usage in Greenhouses: Wind Resource Assessment, Distributed Generation of Electricity and Environmental Protection.” *Energy Sources, Part A: Recovery, Utilization and Environmental Effects* 00 (00): 1–21. https://doi.org/10.1080/15567036.2019.1677810.

Skoplaki, E., and J. A. Palyvos. 2009. “On the Temperature Dependence of Photovoltaic Module Electrical Performance: A Review of Efficiency/Power Correlations.” *Solar Energy* 83 (5): 614–24. https://doi.org/10.1016/j.solener.2008.10.008.

Solarist. 2022. “Lisanssız Elektrik Üreticilerine Ödenecek Mahsuplaşma Bedeli Için Kademeli Tarife Esas Alınacak.” 2022. https://www.solar.ist/lisanssiz-elektrik-ureticilerine-odenecek-mahsuplasma-bedeli-icin-kademeli-tarife-esas-alinacak/.

Tarım Dünyası. 2022. “Bir Dekar Domates Üretimi Için Giderler.” 2022. https://www.tarimdunyasi.net/2022/02/02/serada-uretim-maliyeti-yuzde-138-artti/.

Tarım Hukuku Derneği. 2020. “Mevzuatımızda Seraların Hukuki Niteliği.” 2020. https://www.tarimhukuku.org/mevzuatimizda-seralarin-hukuki-niteligi/.

Tarım TV. 2022. “1 Domates Fidesi Kaç Kilo Verir.” https://tarimtv.gen.tr/1-domates-fidesi-kaç-kilo-verir/.

The Central Bank of the Republic of Turkey. 2022. “CBRT Exchange Rates.” 2022. https://www.tcmb.gov.tr/wps/wcm/connect/en/tcmb+en.

The MathWorks Inc. 2016. “MATLAB.” Natick, Massachusetts, USA.

https://www.mathworks.com.

Trimble. 2017. “SketchUp Make 2017.” Westminster, Colorado, USA.

TWI. 2022. “How Long Do Wind Turbines Last?” 2022. https://www.twi-global.com/technical-knowledge/faqs/how-long-do-wind-turbines-last#:~:text=A good quality%2C modern wind,correct maintenance procedures being followed.

Vadiee, Amir. 2013. “Energy Management in Large Scale Solar Buildings : The Closed Greenhouse Concept.”

Weather Edge Inc. 2000. “Atmospheric Absorption.” 2000. https://www.everythingweather.com/atmospheric-radiation/absorption.shtml.

World Nuclear Association. 2022. “Carbon Dioxide Emissions From Electricity.” 2022. https://www.world-nuclear.org/information-library/energy-and-the-environment/carbon-dioxide-emissions-from-electricity.aspx.

Yildirim, Nurdan, and Levent Bilir. 2017. “Evaluation of a Hybrid System for a Nearly Zero Energy Greenhouse.” *Energy Conversion and Management* 148 (September): 1278–90. https://doi.org/10.1016/j.enconman.2017.06.068.

APPENDIX A

MATLAB CODE

```
clc;
clear all;
close all;
%Dikili Greenhouse model%
%Dikili weather cond.%
TA=xlsread('Ta');%Air temperature(degree celcius)%
GH=xlsread('G_h');%Global iraddiance on the horizontal plane (W/m2)%
GBN=xlsread('Gb_n');%Beam/direct irradiance on a plane always normal to sunrays (W/m2)%
GDH=xlsread('Gd_h');%Diffuse irradiance on the horizontal plane (W/m2)%
IR=xlsread('IR_h');%Surface infrared(thermal) irradiance on a horizon
RH=xlsread('Rh');%Relative humidity(%)%
WD=xlsread('Wd');%10m wind direction (0=N,90=E) degree%
Ws=xlsread('Ws');%10m total wind speed(m/s)%
SP=xlsread('Sp');%Surface air pressure(Pa)%
%Greenhouse area%
GA= 26640; %m^2%
%production area%
PA= 24816; %m^2%
%outbuilding area%
OA= 1824; %m^2%
%roof
R=26640; %m^2%
%roof window area
RA= 26640*0.95;
%Ceiling height is 5m
H= 5; %m%
% Gas volume of the green house
V=H*GA;
%Length%
L= 185; %m%
%Width is 144m (production+outbuilding)%
W_p= 134.4; %m%
W_o= 9.60; %m%
%Outwall contains galvanized steel, concrete and glass%
%Production side Outwall area North and South%
WA1_NS= 672; %m^2% +48=720 %95 --> 684
window1_NS= 638.40; %m^2%
WA1_WE= 925; %m^2%
window1_W= 878.75; %m^2%
```

```
%Outbuilding side Outwall area North and South%
WA2_NS= 48; %m^2%
window2_NS= 45.60; %m^2%
WA2_WE= 925; %m^2%
window2_WE= 878.75; %m^2%
Total_WA=(window1_NS*2)+(window2_WE*2)+RA; %total window area
%wall areas
WN=720;
WS=720;
WW=925; %46.25 m^ outwall
WE=925;
Uw= 2.36;%W/m^2K window u-value 4-5mm
Ug= 3.383; %W/m^2K ground u-value
Xg= 0.022; %m ground thickness
Uow= 2.907; %W/m^2K outwall u-value 4x
Xow= 0.004; %m outwall thickness
Uiw= 2.36; %W/m^2K intwall u-value 1x
Xiw= 0.004; %m intwall thickness
Ur= 2.36; %W/m^2K roof window u-value
Xr= 0.004; %m roof thickness
U_A=(GA*Ug)+((Uow*(46.25*2))+(Uw*(878.75*2)))+((Uow*(36*2))+(Uw*(684*2))
)+(Uiw*925)+(Ur*GA);
U_A_hour=U_A*3600;
rho_air = 1.225 ; % kg/m3
Cp_air = 1.006; %kj/kgK
Beta= 90;%slope of the surface vertical
groundref = 0.2;
phi=39.07; %latitude
%VERTICAL
for n=1:365
    dec(n)=23.45*(sind(360*((284+n)/365))); %solar declination
    for j=1:24
        i=(((n-1)*24)+j);
         omega(i)=(j-12)*15; %hour angle
          sin_a= (sind(phi)*sind(dec(n)))+(cosd(phi)*cosd(dec(n))*cosd(omega(i)));
       a= asind(sin_a);%solar altitude
       KK(n,j)=a;
       sin_z= (cosd(dec(n))*sind(omega(i)))/cosd(a);
       z= asind(sin_z);%solar azimuth
%        z=z*pi/180;
       MM(n,j)=z;
if z==0
      R_bs(i)= ((sind(phi)*sind(dec(n))*cosd(Beta))-
(cosd(phi)*sind(dec(n))*sind(Beta)*cosd(z))+(cosd(phi)*cosd(dec(n))*cosd(omega(i))*
cosd(Beta))+(sind(phi)*cosd(dec(n))*cosd(omega(i))*sind(Beta)*cosd(z))+(cosd(dec(n)
)*sind(omega(i))*sind(Beta)*sind(z)))/((cosd(phi)*cosd(dec(n))*cosd(omega(i)))+(sind
(phi)*sind(dec(n))));
```

```
I_Ts(i)= ((GH(i)-GDH(i))*R_bs(i)) +
(GDH(i)*((1+cosd(Beta))/2))+(GH(i)*groundref*((1-cosd(Beta))/2));
      R_bn(i)= ((sind(phi)*sind(dec(n))*cosd(Beta))-
(cosd(phi)*sind(dec(n))*sind(Beta)*cosd(z))+(cosd(phi)*cosd(dec(n))*cosd(omega(i))*
cosd(Beta))+(sind(phi)*cosd(dec(n))*cosd(omega(i))*sind(Beta)*cosd(z))+(cosd(dec(n)
)*sind(omega(i))*sind(Beta)*sind(z)))/((cosd(phi)*cosd(dec(n))*cosd(omega(i)))+(sind
(phi)*sind(dec(n))));
I_Tn(i)= ((GH(i)-GDH(i))*R_bn(i)) +
(GDH(i)*((1+cosd(Beta))/2))+(GH(i)*groundref*((1-cosd(Beta))/2));
    I_Tw(i)=0;
    I_Te(i)=0;
    R_be(i)=0;
    R_bw(i)=0;
elseif z>0 && z<=90 %west
    R_bw(i)= ((sind(phi)*sind(dec(n))*cosd(Beta))-
(cosd(phi)*sind(dec(n))*sind(Beta)*cosd(z))+(cosd(phi)*cosd(dec(n))*cosd(omega(i))*
cosd(Beta))+(sind(phi)*cosd(dec(n))*cosd(omega(i))*sind(Beta)*cosd(z))+(cosd(dec(n)
)*sind(omega(i))*sind(Beta)*sind(z)))/((cosd(phi)*cosd(dec(n))*cosd(omega(i)))+(sind
(phi)*sind(dec(n))));
I_Tw(i)= ((GH(i)-GDH(i))*R_bw(i)) +
(GDH(i)*((1+cosd(Beta))/2))+(GH(i)*groundref*((1-cosd(Beta))/2));
        R_be(i)=0;
elseif z<0  %east
    R_be(i)= ((sind(phi)*sind(dec(n))*cosd(Beta))-
(cosd(phi)*sind(dec(n))*sind(Beta)*cosd(z))+(cosd(phi)*cosd(dec(n))*cosd(omega(i))*
cosd(Beta))+(sind(phi)*cosd(dec(n))*cosd(omega(i))*sind(Beta)*cosd(z))+(cosd(dec(n)
)*sind(omega(i))*sind(Beta)*sind(z)))/((cosd(phi)*cosd(dec(n))*cosd(omega(i)))+(sind
(phi)*sind(dec(n))));
I_Te(i)= ((GH(i)-GDH(i))*R_be(i)) +
(GDH(i)*((1+cosd(Beta))/2))+(GH(i)*groundref*((1-cosd(Beta))/2));
R_bw(i)=0;
R_be(1926)=0;
I_Te(1926)=0;
else
 I_Ts(i)=0;
 I_Tn(i)=0;
 I_Tw(i)=0;
 I_Te(i)=0;
end
    end
end
 tau=0.86*0.2; % std solar transmittance window& atmosphere absorption
 N_i=2.8*10e-4; %infiltration rate for good maintenance
 T_cont=20; %initial greenhouse temperature with heat pump
 T_unc=20; %initial greenhouse temperature without heat pump
 hfg=2450; % kj/kg heat of evaporation at 20 degree celcius used as fixed value for the
following calculation
```

```
 Q_HP=5000; %selected HP kW (ct demand avg 3000kW),
 COP_rated= 4.36;
 p=0.02;
 eff_mpref= 0.197;
 T_ref= 25;
 G_ref= 1000;
 n_pv=1;
 A_pv=1.67;
 Rotor_d=61/2; %m
 A_wt=(Rotor_d^2)*pi %m2
  m=0; n=0;
  %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%ITERATION STARTS%%%%%%%%%%%%%%%%%%%%%%%%%%
for k=1:8760 % hours
Wi(k,1)=((6.112*exp((17.67*T_cont)/(243.5+T_cont))*RH(k,1)*2.1674)/(273.15+T_cont))*1e-3/rho_air; %indoor absolute humadity at HP case
Wo(k,1)=((6.112*exp((17.67*TA(k,1))/(243.5+TA(k,1)))*RH(k,1)*2.1674)/(273.15+TA(k,1)))*1e-3/rho_air; %outdoor absolute humadity at HP case
Wi_unc(k,1)=((6.112*exp((17.67*T_unc)/(243.5+T_unc))*RH(k,1)*2.1674)/(273.15+T_unc))*1e-3/rho_air; %indoor absolute humadity at without HP
Wo_unc(k,1)=((6.112*exp((17.67*TA(k,1))/(243.5+TA(k,1)))*RH(k,1)*2.1674)/(273.15+TA(k,1)))*1e-3/rho_air; %outdoor absolute humadity at without HP
  %instant heat flows
  Q_d(k)= (U_A*(TA(k)-T_cont))*1e-3; %heat transfer by lost or gain from environment (convection) with HP
  Q_flow(k)=(V*N_i)*rho_air*Cp_air*(TA(k)-T_cont)+hfg*(Wi(k,1)-Wo(k,1)); %forced convection due to air circulation with HP
Q_r(k)=(((RA*GH(k))+(WN*I_Tn(k))+(WS*I_Ts(k))+(WW*I_Tw(k))+(WE*I_Te(k))))*tau*1e-3; %radiation
  Q_d_unc(k)= (U_A*(-T_unc+TA(k)))*1e-3; %heat transfer by lost or gain from environment (convection) without HP
  Q_flow_unc(k)=(V*N_i)*rho_air*Cp_air*(TA(k)-T_unc)+hfg*(Wi_unc(k,1)-Wo_unc(k,1)); %forced convection due to air circulation without HP
%Mathematical filter in order to avoid nan-values
  R_nan=isnan(Q_r(k));
if R_nan==1
Q_r(k)=0;
else
Q_r(k)=Q_r(k);
end
if Q_r(k)<0
Q_r(k)=0;
else
Q_r(k)=Q_r(k);
end
%HP on/off control because it is not continuous but 1h discrete data base mode
%on/off control is set as: when greenhouse temperature <18C full power
```

```
%heating, when greenhouse temperature >22C full power cooling
%18<T_cont<22 HP is off
if T_cont<18
T_cont=T_cont+(Q_d(k)+Q_flow(k)+Q_r(k)+Q_HP)/(V*rho_air*Cp_air);
%Greenhouse temperature monitoring by heating
Q_ht(k)=Q_HP; % Heating full power
Q_ct(k)=0;
elseif T_cont>22
T_cont=T_cont+(Q_d(k)+Q_flow(k)+Q_r(k)-Q_HP)/(V*rho_air*Cp_air);
%Greenhouse temperature monitoring by cooling
Q_ct(k)=-Q_HP; % Cooling full power
Q_ht(k)=0;
else
T_cont=T_cont+(Q_d(k)+Q_flow(k)+Q_r(k))/(V*rho_air*Cp_air); %Greenhouse
temperature monitoring 18<T_cont<22
Q_ct(k)=0;
Q_ht(k)=0;
end
W_compcal(k)=(Q_ht(k)+Q_ct(k))/COP_rated;
W_compcal_h(k)=Q_ht(k)/COP_rated;
%PV ELECTRICITY GENERATION
 T_c(k)= TA(k)+(p*GH(k)); %horizontal radiation
        if GH(k)<10
            eff_h(k)=0;
        else
            eff_h(k)= eff_mpref*((1-(0.00258*(T_c(k)-
T_ref)))+(0.052*log((GH(k)/G_ref))));
        end
        elec_gen(k)= (eff_h(k)*n_pv*A_pv*GH(k))*1e-3;
%WIND TURBINE ELECTRICITY GENERATION
U(k)=((69/10)^0.143)*Ws(k); %hellman corelation u1/u2=(z1/z2)^n n=1/7 (0.143)
if U(k)<3 && U(k)>25
   P_w(k)=0;
elseif U(k)>3 && U(k)<14
P_w(k)=(0.1075*U(k)^4)-(4.7129*U(k)^3)+(71.051*U(k)^2)-(329.81*U(k))+498.98;
elseif U(k)>14 && U(k)<25
P_w(k)= 1000;
end
%Energy demand demonstration
if T_unc<18
    m=m+1;
Q_ht_demand(k)=abs(Q_d_unc(k))+abs(Q_flow_unc(k))-abs(Q_r(k));
Q_ct_demand(k)=0;
elseif T_unc>22
    n=n+1;
Q_ct_demand(k)=abs(Q_d_unc(k))+abs(Q_flow_unc(k))+abs(Q_r(k));
Q_ht_demand(k)=0;
```

```
end
T_unc=T_unc+(Q_d_unc(k)+Q_flow_unc(k)+Q_r(k))/(V*rho_air*Cp_air);
%Greenhouse temperature monitoring without HP
T_green(k)=T_cont;
T_green_unc(k)=T_unc;
T_set_c(k)=22;
T_set_h(k)=18;
end
Q_ht_demand_avg=(sum(Q_ht_demand)/m)
Q_ct_demand_avg=(sum(Q_ct_demand)/n)
Q_ht_demand_sum=sum(Q_ht_demand)
Q_ct_demand_sum=sum(Q_ct_demand)
%RESULTS DISPLAY
subplot(3,3,1)
plot([1:8760],Q_ct) %HP cooling
hold on
plot([1:8760],Q_ht) %HP heating
xlabel('Time,h'),ylabel('Heat pump work,kW')
legend('HP cooling','HP heating')
subplot(3,3,2)
plot([1:8760],T_green)
hold on
plot([1:8760],T_green_unc)
hold on
plot([1:8760],T_set_c)
hold on
plot([1:8760],T_set_h)
xlabel('Time,h'),ylabel('Temperature,C')
legend('T green controlled','T green uncontrolled','T set c','T set h')
subplot(3,3,3)
plot([1:8760],W_compcal)
xlabel('Time,h'),ylabel('Compressor work,kW')
hold on
subplot(3,3,4)
plot([1:8760],elec_gen)
xlabel('Time,h'),ylabel('PV electricity generation,kW')
hold on
subplot(3,3,5)
plot([1:8760],GH)
xlabel('Time,h'),ylabel('Horizontal raditation,W/m2')
hold on
subplot(3,3,6)
plot([1:8760],P_w)
xlabel('Time,h'),ylabel('Wind turbine electricity generation,kW')
hold on
```