HYBRID RENEWABLE ENERGY SYSTEMS DESIGN FOR GREEN CAMPUS-IZTECH

A Thesis submitted to
the Graduate School of Engineering and Sciences of
İzmir Institute of Technology
in Partial Fulfilment of the Requirements for the Degree of

MASTER OF SCIENCE

in Energy Engineering

by
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December 2022
İZMİR

ACKNOWLEDGMENTS

First, I would like to express my deepest gratitude to my advisor's Assist. Prof. Başar Çağlar and Prof. Emin Açıkkalp for their inspiring guidance, mentorship, and support. During this process, I completed this study with their proposed correct directions and enthusiasm for teaching. I am very grateful for their help.

I would like to thank my friends for their great patience along and support during this time.

Lastly, I would like to express my most tremendous significant appreciation to my mother Afet Ramazan, my father Hasan Zeki Ramazan, and my brother Kemal Doruk Ramazan for their endless love, great effort, support, belief, and encouragement throughout my life.

ABSTRACT

HYBRID RENEWABLE ENERGY SYSTEMS DESIGN FOR GREEN CAMPUS-IZTECH

This study focuses on evaluating of standalone PV and Wind systems integrated with energy storage technologies to meet the electricity needs of the Izmir Institute of Technology campus in Izmir. University campuses with their high energy demand are one of the most important application areas for renewable energy systems and it’s critical to determine the types of renewable energy technologies, their size, and techno-economic feasibility for possible future implementation. Solar and wind energy were chosen as renewable energy sources based on the location and renewable energy potential of the IZTECH Campus. Two different energy storage systems are proposed to prevent any loss of power supply in standalone mode: (i) Lead-acid battery and (ii) Electrolyzer, hydrogen storage tank, and hydrogen-powered generator. Models were developed using the dynamic library-based structure of the TRNSYS program. The hourly electrical load was generated based on monthly data taken from the electricity supplier and the power output of PV modules was calculated based on the fixed tilt angle based on real meteorological data for the campus location. The electricity demand and generation were analyzed hourly for one calendar year. The number of PV modules was determined to meet the annual electricity demand of the campus while the capacity and number of energy storage modules were determined based on the maximum accumulative energy deficiency in a year. The round-trip efficiencies and the depth of discharge for the battery and the hydrogen storage efficiency for the hydrogen-based storage option were considered in the analysis. Parameters were calculated for both systems and simulation analyzes were evaluated. An economic cost analysis was performed for each system. In addition, suggestions are made for possible system improvements.

ÖZET

YEŞİL KAMPÜS İÇİN HİBRİT YENİLENEBİLİR ENERJİ SİSTEMLERİ TASARIMI-IZTECH

Bu çalışma, İzmir Yüksek Teknoloji Enstitüsü yerleşkesinin elektrik ihtiyacını karşılamak için enerji depolama teknolojileri ile entegre edilmiş şebekeden bağımsız PV ve Rüzgâr sistemlerinin değerlendirilmesine odaklanmaktadır. Yüksek enerji talebi ile üniversite kampüsleri, yenilenebilir enerji sistemlerinin uygulanması için en kritik uygulama alanlarından biri olan üniversite kampüsleri, yenilenebilir enerji kaynakları ile bu sistemlerin performans değerlendirmesi için faydalı bir araç sağlamaktadır. Ana enerji üretim kaynağı güneş ve rüzgâr enerjisidir. Şebekeden bağımsız modda herhangi bir güç kaynağı kaybını önlemek için iki farklı enerji depolama sistemi önerilmektedir: (i) Kurşun-asit batarya ve (ii) Elektrolizör, hidrojen depolama tankı ve hidrojenle çalışan jeneratör. TRNSYS programının dinamik kütüphane tabanlı yapısı kullanılarak modeller geliştirilmiştir. Saatlik elektrik yükü, elektrik tedarikçisinden alınan aylık verilere göre oluşturulmuş ve PV modüllerinin güç çıkışı, kampüs konumu için gerçek meteorolojik verilere dayalı sabit eğim açısına göre hesaplanmıştır. Elektrik talebi ve üretimi bir takvim yılı için saatlik olarak analiz edilmiştir. PV modül sayısı yerleşkenin yıllık elektrik ihtiyacını karşılayacak şekilde belirlenirken, kapasite ve enerji depolama modül sayısı bir yıldaki maksimum kümülatif enerji açığına göre belirlendi. Analizde, batarya için gidiş-dönüş verimlilikleri ve deşarj derinliği ve hidrojen bazlı depolama seçeneği için hidrojen depolama verimliliği dikkate alındı. Her iki sistem için parametreler hesaplanmış ve simülasyon analizleri değerlendirilmiştir. Her sistem için ekonomik maliyet analizi yapılmıştır. Ayrıca olası sistem iyileştirmeleri için önerilerde bulunulmuştur.

TABLE OF CONTENTS

LIST OF FIGURES

Figure **Page**

LIST OF TABLES

LIST OF SYMBOLS

$\boldsymbol{\beta}$	Slope of PV array (°)
$\boldsymbol{\gamma}$	The azimuth angle of the inclined plane (°)
$\emptyset$	The latitude of the location
$\boldsymbol{\omega}$	Hour Angle (°)
$\boldsymbol{\delta}$	Declination Angle (°)
α	Obstacle angle (°)
$\boldsymbol{\eta_{PV}}$	Efficiency of a solar cell
$\boldsymbol{\eta_f}$	Faraday efficiency
$\boldsymbol{N_{cell}}$	Number of cells in series per stack
$\boldsymbol{\theta}$	Angle of incidence for solar radiation (°)
$\boldsymbol{\tau a}$	Module transmittance-absorptance product
$\boldsymbol{\tau a_{normal}}$	Module transmittance-absorptance product at normal incidence
$\boldsymbol{\rho}$	Air density coefficient (kg/m^3)
$\boldsymbol{A_{PV}}$	Solar Panel Area (m^2)
$\boldsymbol{A_R}$	The area swept by the turbine blade (m^2)
$\boldsymbol{AREA}$	Area of electrodes (m^2)
$\boldsymbol{C_p}$	The power coefficient for a wind turbine
$\boldsymbol{d}$	Module row distance (m)
$\boldsymbol{E_t}$	Electrical energy generated
$\boldsymbol{e_{qc}, e_{qd}}$	Open circuit voltages at full charge, extrapolated from V vs I curves on charge; discharge
$\boldsymbol{FF}$	Fill Factor
$\boldsymbol{H}$	Obstacle Height (m)
$\boldsymbol{H_d}$	Depth of discharge
$\boldsymbol{L}$	Distance between the obstacle (m)
$\boldsymbol{G}$	Indicates the radiation from the sun (W/m^2)
$\boldsymbol{G_T}$	Total radiation incident on PV array (W/m^2)
$\boldsymbol{G_{T,beam}}$	Beam component of incident radiation (W/m^2)
$\boldsymbol{G_{T,diff}}$	Diffuse component of incident radiation (W/m^2)

$G_{T,gnd}$	Ground-reflected component of incident radiation (W/m^2)
$G_{T,ref}$	Incident radiation at reference conditions (W/m^2)
g_c, g_d	Small-valued coefficients of H in voltage-current-state of charge formulas (W/m^2)
I	Current (A)
I_L	Module photocurrent
I_{ely}	Electrical current (electrolyzer load) (A)
$I_{density}$	Current Density(mA/cm^2)
I_G	Photovoltaic Diode
$I_{L,ref}$	Module photocurrent at reference conditions
I_0	Diode reverse saturation current
I_{sc}	Short-circuit current
I_{max}	Current at maximum power point along IV curve
$I_{zp,}K_{zp}$	Parameters used in calculating V_{zp}
I_t	Investment expenditures
IAM	Dimensionless incidence angle modifier
i	Discount rate
k	Boltzmann constant [J/K]
$m_{c,}m_d$	Cell-type parameters which determine the shapes of the I-V-Q characteristics
M_T	Operations and maintenance expenditures
n_d	Diode ideality factor
n	Days of the year
N_p	Number of modules in parallel in array
N_S	Dimensionless incidence angle modifier
P_{solar}	PV output power
P_{wind}	Wind output power
P_{max}	PV output power at maximum power point along IV curve
P_{cr}	Critical pressure
p	Pressure (Real gas)
r^*	Ohmic Resistance [Ωm^2]
s^*	Overvoltage on electrodes

$\boldsymbol{t}^{*}$	Overvoltage on electrodes
$\boldsymbol{a}^{*}$	Faraday Efficiency
$\boldsymbol{a}$	Intermodular forces of attraction
$\boldsymbol{b}$	The volume occupied by the gas molecules
$\boldsymbol{R}$	Universal gas constant
$\boldsymbol{R_t}$	Net cash flow
$\boldsymbol{q}$	Electron charge constant
$\boldsymbol{R_s}$	Module series resistance [Ω]
$\boldsymbol{R_{sh}}$	Module shunt resistance [Ω]
$\boldsymbol{r_{qc}, r_{qd}}$	Internal resistances at full charge when charging; discharging
$\boldsymbol{T_c}$	Module temperature [K]
$\boldsymbol{T_{ambient}}$	Ambient temperature (°)
$\boldsymbol{T_{gas}}$	The temperature of the gas
$\boldsymbol{T_{cr}}$	Critical temperature
$\boldsymbol{T_{ely}}$	Electrolyte temperature(°C)
$\boldsymbol{t}$	Time of cash flow
$\boldsymbol{t_s}$	Solar time in hours
$\boldsymbol{U_{Cell}}$	Overall cell voltage
$\boldsymbol{U_{rev}}$	Reversible cell voltage
$\boldsymbol{U_o}$	Wind Speed (m/s)
$\boldsymbol{V}$	Voltage
$\boldsymbol{V_{max}}$	Voltage at maximum power point along IV curve
$\boldsymbol{V_{OC}}$	Open-circuit voltage
$\boldsymbol{V_{zp}}$	Additional voltage term in Hyman model
$\boldsymbol{Vol}$	The volume of the storage tank (m^3)
$\boldsymbol{Q_m}$	Rated capacity of cell
$\boldsymbol{Q_{c,} Q_d}$	Capacity parameters on charge; discharge
$\boldsymbol{H(h)\_m}$	Irradiation on horizontal plane(kWh/m^2/mo)
$\boldsymbol{H(opt)\_m}$	Irradiation on optimally inclined plane(kWh/m^2/mo)
$\boldsymbol{H(i)\_m}$	Irradiation on plane at angle (kWh/m^2/mo)
$\boldsymbol{H(n)\_m}$	Monthly beam(direct) irradiation on a plane always normal to sun rays (kWh/m^2/mo)

$\boldsymbol{Kd}$	Ratio of diffuse to global irradiation (-)
$\boldsymbol{T2m}$	24-hour average of temperature (°C)
$\boldsymbol{X}$	Normalized Power
$\boldsymbol{P_{DEGS}}$	DEGS Electrical Power (W)
$\boldsymbol{P_{DEGS,rated}}$	DEGS rated Electrical Power (W)
$\boldsymbol{\eta_{el}}$	Electrical Efficiency
$\boldsymbol{\rho_{fuel}}$	Fuel Density (kg/m^3)
$\boldsymbol{\dot{V}}$	Fuel Volumetric Flowrate (m^3/s)
$\boldsymbol{LHV_{fuel}}$	Lower Heating Value of the fuel (J/kg)
$\boldsymbol{N_{DEGS}}$	Number of identical DEGS units
$\boldsymbol{P_{in}}$	Power entering the conditioner (W)
$\boldsymbol{P_{out}}$	Power losses of the conditioner (W)
$\boldsymbol{I_{out}}$	Output current (A)
$\boldsymbol{U_{out}}$	Output voltage (V)
$\boldsymbol{x}$	The volume of the storage tank(m^3)

LIST OF ABBREVIATIONS

GWh	Gigawatt Hour
Mtoe	Millions of tons equivalent oil
TWh	Terawatt Hour
MENR	Ministry of Energy and Natural Resources
TFEC	Total Final Energy Consumption
EIA	Energy Information Administration
TRNSYS	Transient Energy System Simulation Tool
GEPA	Solar Energy Potential Atlas
EMRA	Energy Market Regulatory Authority
MPPIB	Maximum PV Panel Installation for each Building
MPPIC	Maximum PV Panel Installation on Campus
NPPIB	Necessary PV Panel Installation for each Building
NPPIC	Necessary PV Panel Installation on Campus
IZTECH	Izmir Institute of Technology University
PVGIS	Photovoltaic Geographical Information
HVAC	Heating, ventilation, and air conditioning
DMI	General Directorate of State Meteorology
MPPT	Maximum Power Point Tracker
SAPS	Standalone Power Systems
LCOE	Levelized Cost of Energy
NPV	Net Present Value

CHAPTER 1

INTRODUCTION

Energy generation and management is an essential topic for sustainable development, due to its close link with the economic growth, environmental protection, and social balance of countries [1–3]. Energy consumption has increased rapidly due to the population growth and energy consumption per capita. The world population reached 7,674 billion in 2019 and it is expected to be 9 billion in 2040 [2,4]. This rapid increase leads to question the availability of primary energy sources, i.e., fossil fuels, in the future considering their current reserve and consumption rates. Based on the current estimates, oil reserves in the world will be exhausted in 40 years, natural gas reserves in 67 years, and coal reserves in 227 years [5]. In addition, the use of fossil fuels causes greenhouse gas emissions and creates environmental problems [6,7]. To meet the energy demands in the future and to reduce the use of fossil fuels for a cleaner and more liveable world, many developed countries have taken action to use renewable energy sources [8], which increases the interest in renewable energy sources. The main renewable energy sources are solar, wind, biomass, hydropower, geothermal, and tidal and wave energy.

Turkey is a one of the countries, which heavily depend on imported fossil fuels. The transition from fossil fuels to renewable energy is essential for Turkey to decrease its the dependence on imported energy and the resulting economic burden. The total energy generation of Turkey in 2020 is 306 GWh, 182 GWh of which comes from thermal power plants, 78 GWh from hydraulic power plants, and 45 GWh from wind, geothermal and solar power plants [9]. This indicates that the share of renewable energy sources in the total energy generation is around 45% in the current situation. Although the share of renewable is almost the same as the world average the renewable energy generation of Turkey is still a way below its potential, suggesting that renewable energy resources have not been effectively used yet [5]. In order to address this issue, the implementation of renewable technologies in different sectors should be accelerated.

Renewable energy technologies can be applied to different areas to meet energy demand, such as highly populated university campuses; shopping centres, restaurants, theatres, swimming pools, gyms, and recreational facilities [1]. In particular, the renewable energy integration into university campuses has received considerable attention due to the intention of making campuses sustainable and green. For a sustainable green campus several indicators have been proposed such as green campus layout and infrastructure, waste management, water management, and environmentally-friendly transportation opportunities [10]. Renewable energy resources with new practices for improving energy efficiency play a central role to cover these indicators [11]. For achieving green campus, the utilization of a single renewable source is not adequate, which makes hybrid energy systems more appealing. There are many application areas for hybrid energy systems in the world and in Turkey and R&D and academic studies have increased day by day. This topic will be covered in detail in CHAPTER 2 with examples from the literature.

1.1. Status of Energy

1.1.1. Status of Energy in the World and Turkey

According to 2019 data, the amount of primary energy used in the world is 14,410 Mtoe (million tons equivalent oil) [12]. The energy demand of the world is still main met by fossil fuels (oil: 32.99%, coal: 27.10%, and natural gas: 24.16%) even if their share has decreased recently due to the integration of renewable energy into the energy infrastructure (Figure 1 and 2). The share of renewable energy in total energy generation was 5% in 2019 and this share increased by 9.7% from 2019 to 2020. Fossil fuels are also dominant for electricity generation. The amount of electricity generated from primary energy sources was 26,936 TWh in 2019. The shares of coal, natural gas, and hydropower are 36.7%, 23.6%, and 15.7%, respectively, while the share of non-hydro renewable is 10.8%.

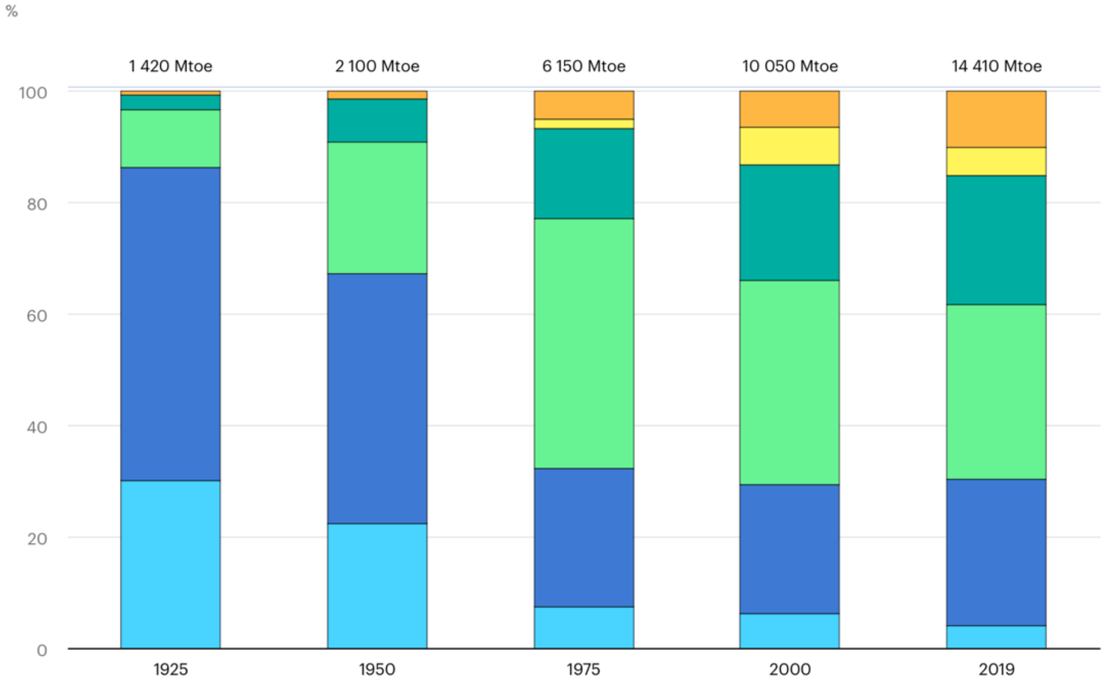

Figure 1. Global Primary Energy Demand by Fuel (1925-2019) [12]

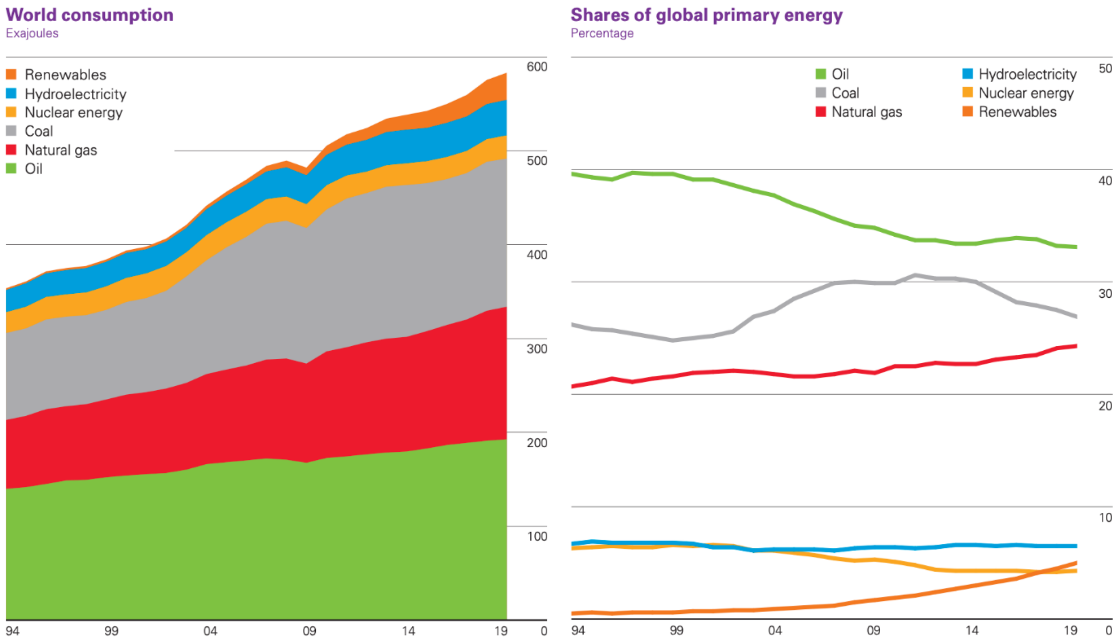

Figure 2. World Consumption and Shares of Global Primary Energy (2019) [13]

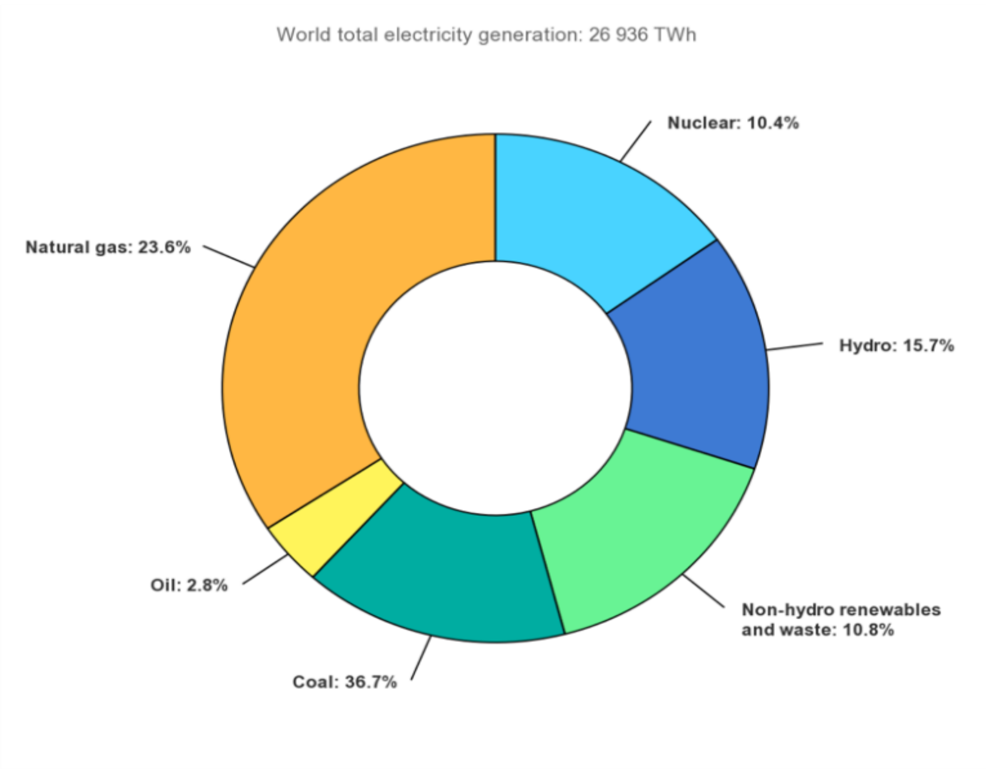

Figure 3. World Total Electricity Generation [14]

The similar energy scenario was also observed for Turkey. According to Ministry of Energy and Natural Resources (MENR) data, Turkey's total energy consumption in 2019 was given as 144.2 MToe. The energy generation by sources and their shares are 41 Mtoe by oil (28.61%), 40 Mtoe by coal (28.13%); 37 Mtoe by natural gas (25.74%), 9 Mtoe by geothermal (6.7%), 1,860 Mtoe by wind (1.29%), 1,620 Mtoe by solar (1.12%), 7,630 Mtoe by hydropower (5.29%) and 3,150 Mtoe by bioenergy, waste, and other resources (2.18%) [13,15,16].

1.1.2. Status of Renewable Energy in the World and Turkey

Renewable energy sources have gained an increasing importance due to the urgent need for the decarbonization of energy infrastructure, but the desired transition can only happen in the long term [17]. The current widely used renewable energy sources are hydraulic energy, geothermal energy, biomass energy, solar energy, and wind energy.

Hydrogen energy is also considered as a secondary renewable energy source and it is expected to gain more importance for the transportation of renewable energy [18,19]. The use of renewable energy sources increased by 3% in 2020 as the use of other fuels decreased. Similarly, the share of renewable energy sources in global electricity generation increased from 27% in 2019 to 29% in 2020.

The total energy generation and share of renewables in total final energy consumption are 11,700 Mtoe and 11.9%, respectively. The energy generation by renewable energy sources are 4,300 Mtoe by hydropower, 2 Mtoe by bioenergy, 2,500 Mtoe by geothermal, 1,400 Mtoe by wind, and 1,400 Mtoe by solar.

Renewable electricity generation in 2021 expanded by more than 8% to reach 8,300 TWh, the fastest annual growth since the 1970s. Solar and wind are expected to contribute to two-thirds of renewable energy growth and China contributed almost half of the global increase in renewable electricity in 2021, followed by the USA, European Union, and India (Figure 4) [20].

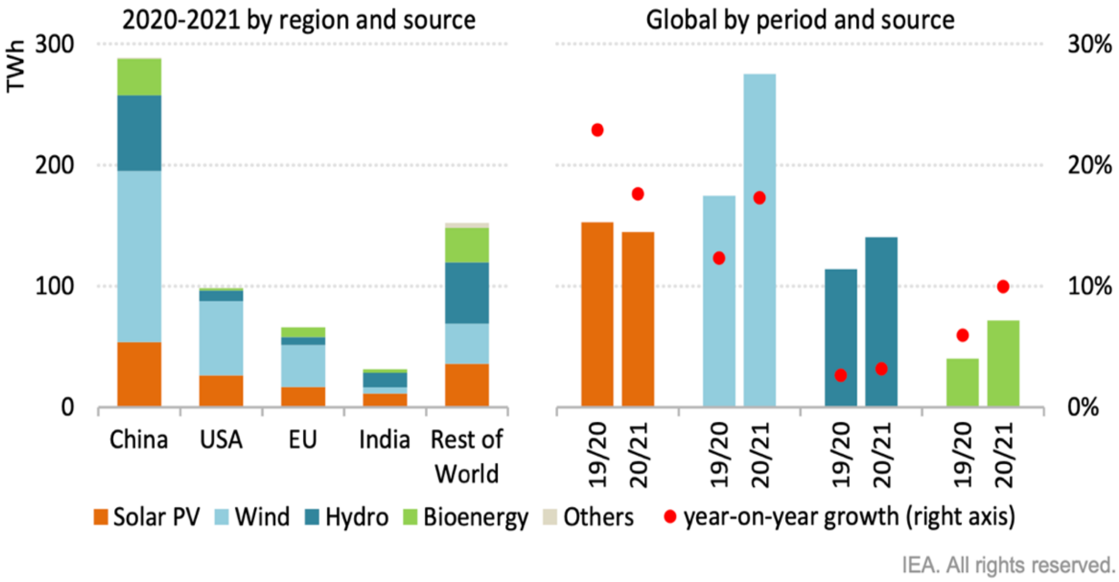

Figure 4. Renewable Electricity Generation [21]

In Turkey, renewable energy consumption in Turkey has increased dramatically in the last decade due to the capacity increase in hydro, wind, and solar energy, as seen in Figure 5 and 6. The renewable energy is mostly used for electricity generation (60% of total renewable energy) and the main contributions come from hydro, wind and solar

[22]. The renewable energy consumption rose 36% over the decade from 8,600 Mtoe in 2008 to 11,700 Mtoe in 2018. Renewable electricity has tripled since 2008 and its share in total electricity generation reached 44% in 2019. Also, both solar and geothermal energy used for heating has more than doubled in a decade, but growth appears to have stalled since 2015.

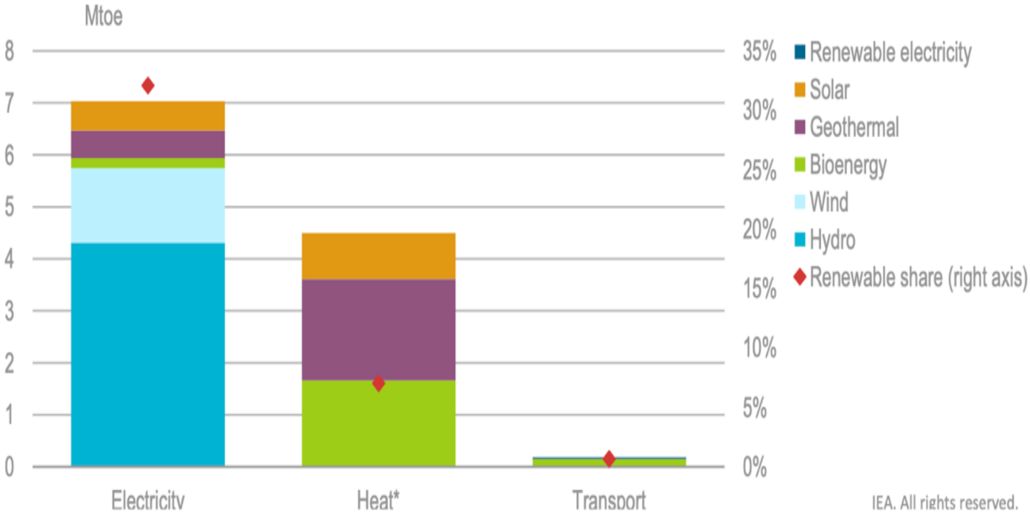

Figure 5. Renewable Energy in total final energy consumption (Turkey-2018) [23]

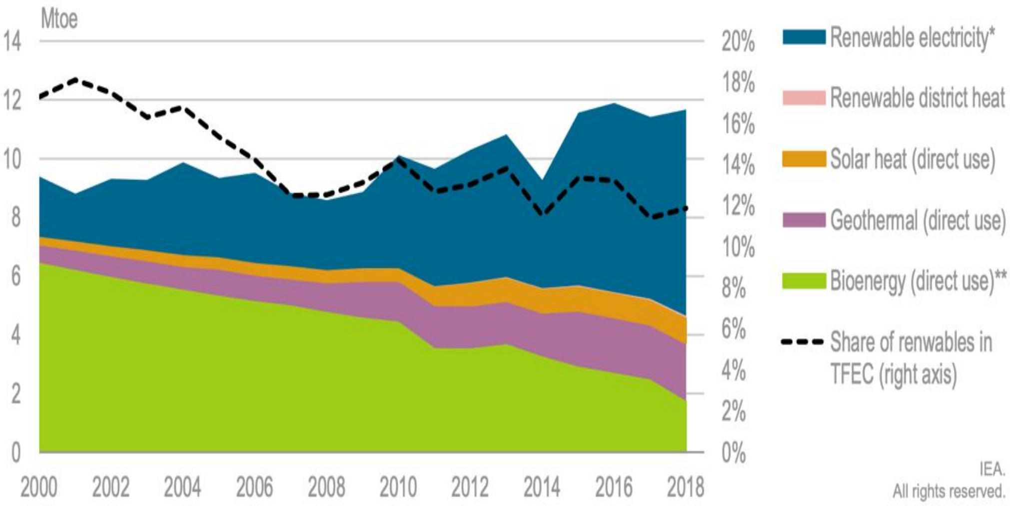

Figure 6. Renewable Energy in total final energy consumption (Turkey2000-18) [23]

Despite the growth in total renewable energy generation, the share of renewable energy sources in total consumption (11.9%) is relatively low compared to IEA member countries (Figure 7), suggesting that the renewable energy generation of Turkey needs to be increased further to reach the level seen in the developed countries.

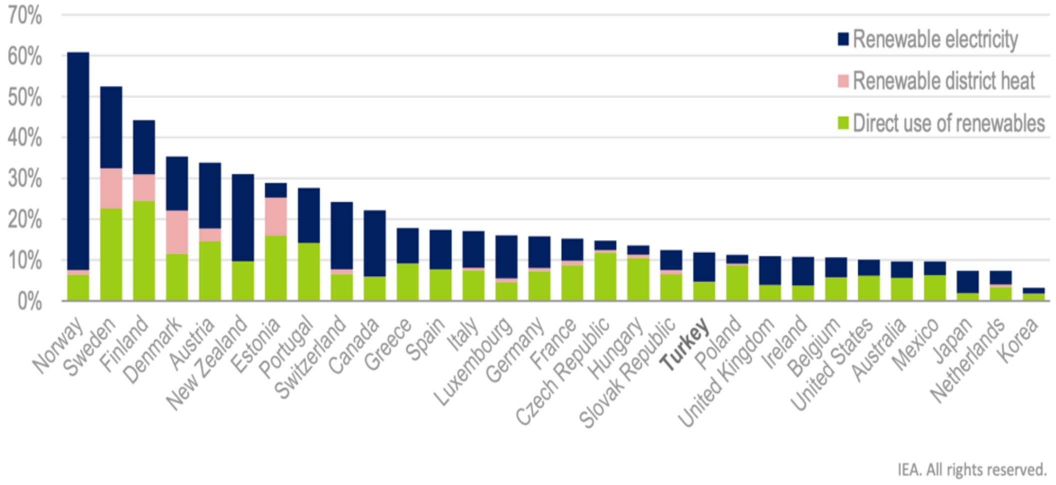

Figure 7. Renewable Energy as a share of total final energy consumption, (EIA member countries,2018) [23]

1.1.3. Standalone Hybrid Systems

Standalone hybrid energy systems are the systems that are not connected to the electricity grid and different renewable energy sources along with the energy storage units (e.g., batteries, electrolyzer, pump hydro storage, compressed air storage, etc.) are commonly included in this system due to the intermittent character of renewable energy sources. Standalone hybrid energy systems are especially preferred for remote and rural areas to avoid the installment of high-cost energy transfer lines. Since there is no grid connection, the system’s self-sufficiency is an important requirement. This can be achieved by energy storage units since renewable sources (e.g. wind, solar) don’t provide a continuous energy supply due to the variance in climatic conditions systems or mini-grids that can generate power with an external power input (renewable energy sources) and operate independently with additional equipment [24]. The other alternative is to use a generator, which can be operated to prevent any cut off when renewable energy is unavailable [25]. In this study a standalone hybrid PV-Wind system was considered for meeting the energy demand of IZTECH campus and its techno-economic feasibility was evaluated to assess the feasibility of a self-sufficient campus from energetic point of view.

1.2. Motivation and Scope of the Thesis

1.2.1. Motivation

In this study, a standalone renewable energy system was designed and evaluated for meeting energy needs of the campus buildings of the Izmir Institute of Technology. A wind turbine and PV modules were used for energy generation and lead acid batteries and electrolyzer-H_2 tank-generator combination was included to store the excess energy and release it in case of energy deficiency. The motivation of this study is to gain insight into about the feasibility of a renewable-powered self-sufficient university campus, which is not affected by grid instabilities and power cut-offs. This will help to understand the energy consumption profile of the campus, the renewable energy potential, the variance of accessible renewable energy in time, the total achievable renewable installed capacity, production-demand inequality, energy storage requirement and techno-economic performance. Even if the study is specific to the IZTECH campus, location, solar and wind energy and specific energy storage technologies, the approach, methodology and results will contribute to developing and applying similar analysis for another university campus as well as other application areas.

1.2.2. Objective and Approach

Solar The main objective of the thesis is to design a standalone renewable energy system for the IZTECH campus located in Gulbahce, Izmir and to assess the techno-economic feasibility of the related system. To achieve this objective 4 different scenarios were considered:

Scenario 1: PV, Lead Acid Battery, Power Controller

Scenario 2: PV, Electrolyzer, H_2 Tank, Generator, Power Controller

Scenario 3: Wind Turbine, Lead Acid Battery, Power Controller

Scenario 4: Wind Turbine, Electrolyzer, H_2 Tank, Generator, Power Controller

Specific objectives are to: (i) determine the maximum number of PV modules that can be built on the roof of each building on the campus and their power output; (ii) determine the number and capacity of batteries or the number, size, and capacity of electrolyzer-H_2 tank-generator system; (iii) determine the capacity and power output of wind turbine; (iv) evaluate technical and economic feasibilities of all scenarios.

To achieve these objectives, a detailed literature analysis was made (Chapter 2); the location and properties of campus buildings were specified, the annual electricity load profiles of the campus buildings were analyzed, and wind and solar energy potential were determined (Chapter 3); the number of PV modules were determined based on the available roof area and solar panel size by using the PV*SOL software, all systems components for all scenarios were modeled by TRNSYS and economic analysis was made (Chapter 4); the results were presented and discussed (Chapter 5) and main conclusions and future recommendations were explained at the end of the thesis.

CHAPTER 2

LITERATURE SURVEY

In this part, the literature studies on the design and analysis of renewable energy systems for meeting energy requirement of university campus working on-gird and off-gird mode are summarized. Aykut and Terzi carried out the feasibility study of the hybrid grid-connected Wind/PV/ Biomass power system in techno-economic and environmental terms for Marmara University Goztepe campus [7]. They have analyzed the energy demand of the campus and the technoeconomic feasibility of renewable energy systems. HOMER program was used for the sizing and optimization renewable energy systems and a sensitivity analysis was performed for wind speed and solar radiation. According to the simulation results, the energy system with minimum net present cost (NPC) and energy cost (COE) was found as the grid-connected wind/biomass system hybrid energy system consisting of a 1,000-kW grid, 1,000 kW biomass generator, and 1,500 kW wind turbine. The NPC and COE of the optimum system were determined as $5,612,501, and $0.067/kW, respectively.

In another study, Deng et al. designed an energy system for offices, laboratories, publicity offices, etc. in at Shanghai Jiao Tong University. They proposed an integrated and flexible energy system solution that includes three types of energy systems according to different indoor types and specific application demands [26]. Passive sustainable design is basically a good suggestion. A green energy system that combines renewable energy application technology, HVAC technology, and other building service technologies perfects the overall performance of the building. They discussed the properties and feasibility of typical parts of the energy system. They used DeST, EnergyPlus, and TRNSYS software to achieve energy savings rates and CO_2 emission reduction to evaluate the total efficiency of the energy system. The energy-saving rate of the entire energy system is approximately 57% during the summer and winter months, and they calculated that the entire energy input was reduced by 30% during the transition seasons. Renewable energy covers 78% of the total energy demand during the operation period and the CO_2 emission reduction is 24,500 tons per year. Authors also predicted that the reduction of CO_2 emissions over the future life cycle of the building could exceed 30 tons per year.

Chedid et al. designed an optimum distribution strategy for a microgrid at the American University in Beirut, which is characterized by reducing the use of diesel generators due to unreliable grids and increasing their reliability by using PV and Battery storage [27]. Chedid et al. used Matlab software; they did the optimum power flow analysis using DP over a 10-year period. The added optimum PV and BESS capacities remained only 3.5% of the DG energy share over the expected 10-year period in the original system. Chedid et al. found that their DGs were almost eliminated. The proposed PV-BESS system provided an average annual savings of $ 1,336 million, confirming the economic viability of the hybrid PV-BESS system compared to DGs operating under unreliable grids. They reduced the overall COE of the system from 13.7 ¢/kWh to 8.8 ¢/kWh in the first year and from 14.4 ¢/kWh to 10 ¢/kWh in the 10th year. Chedid and colleagues found that even though the entire PV-BESS system was financed by a 10-year bank loan, the payback period would be 6 years.

Dursun et al. investigated the possibilities of meeting the need for the load fed from the electricity grid used in the Kavaklı campus of Kırklareli University with solar energy and hydrogen fuel cell power generation system (electrolyzer/hydrogen tank/fuel cell) [1]. For this, Dursun et al. analyzed four independent and grid-connected hybrid systems using HOMER software. Dursun et al., achieved optimum configurations, fuel consumption and emission rates in the standalone PV-diesel hybrid system are 74% lower than the diesel system, except for a solar-powered power supplier. Similarly, the standalone PV-diesel hybrid system is considerably lower than the diesel system. Dursun et al., although the grid-connected photovoltaic (PV) hybrid system has the lowest COE and NPC, the grid-connected PV / fuel cell hybrid system has a slightly higher cost (0.294$/kWh) than the optimum. Dursun et al., strongly believed that this system could be chosen because it is a cleaner system, and its emissions are very low. According to Dursun et al. have the lowest COE (0.256 kWh^{-1}) and NPC ($82,000) of the grid-connected PV hybrid system. On the other hand, they found the grid-connected hybrid PV/fuel cell, a system with COE, cost slightly higher than the grid-connected PV hybrid system at 0.294 kWh^{-1} . They stated that this system is selectable because its renewable part is higher and gas emission rates are quite low.

Park et al., explored the potential of renewable energy generation facilities using HOMER software for the Global Campus of Kyung-Hee University in South Korea. Park et al., found that no research was conducted to simulate renewable energy generation facilities to respond to and reduce the current energy demand of educational institutions in South Korea [8]. 10 scenarios on and off the grid as PV-wind-diesel generator-battery generation systems were examined. The study has some limitations. Park et al., on-grid and off-grid scenarios 3 (a PV-diesel generator-based renewable energy generation system) were found to have the lowest initial capital, operating cost, total NPC, and COE. Also, since diesel generators are not generally seen as renewable energy sources, more applicability can be considered in grid-connected and off-grid scenarios 2. If the campus does not want to use wind turbines due to their potential noise, on-grid and off-grid scenarios can be the most suitable solutions without any location limitations. They used HOMER software to provide various energy sources and explore solutions. Calculate the renewable portion, cost of energy (COE), and total net present cost (NPC) of various scenarios for renewable energy generation systems. The simulation results show that the proposed systems achieve a COE in the range of \$0.509 to \$0.515 (on-grid) and \$0.525 to 0.531 (off-grid). Recommendations and limitations are discussed.

Faraja et al. designed a solar-powered air conditioning system by installing a solar photovoltaic panel system with operating parameters to generate enough electrical energy for the engineering building at Mutah University, to energize a cooling system, and to provide a cooler [28]. Also, Faraja et al. wanted to minimize electricity consumption from the local grid and contribute to reducing carbon dioxide emissions. The method used to calculate the cooling load value for classrooms and offices for the engineering building at Mutah University and to size the appropriate cooling system (CLTD) is the Cooling Load Temperature Difference method. Calculated cooling load analysis includes heat gain from radiation and transmission of solar energy, people, light, and ventilation. Faraja et al. found that the total cooling load of the building was 560 kW. The fill level has a significant effect on the cooling load value. Insulation of building walls and roofs will significantly reduce the cooling load. Faraja et al. showed that the use of PV panels is more economical than the energy from the grid for the first 10 years. Also, the payback period of the designed system has been analyzed as 5 years.

Ahmad et al., made the optimum dimensioning and analysis of the PV, Wind and Energy Storage Hybrid System for the microgrid of the Aligarh Muslim University campus [29]. Polygeneration based on grid-connected and off-grid topologies has been investigated. HOMER is used as a simulation and optimization tool to perform economic and feasibility analysis. Ahmad et al show that the total system cost under solar PV +

Battery (PV + B) mode is approximately INR 1,419.6 million. The total system cost under (Grid + Solar PV) G + PV mode is approximately 494.92 million, while 64.2% higher compared to the scenario (INR 864.2 million). They found it was 57.2% lower than in the scenario. A comparative study of the environmental and economic nature of the topology proposed by Ahmad et al. revealed that under the proposed topology, 3,636 * 106 kg CO_2, 1,578 * 104 kg SO_2, and 7.7 * 103 kg NOX would be reduced. Ahmad et al., based on the Net Available Cost (NPC), detailed analysis revealed that G + PV in grid-connected mode and PV + B in off-grid mode is the most suitable solution for micro-grid distribution in the AMU.

Fernando et al. studied the energy demand for the Abertay University Campus library building in Dundee Scotland, sustainable energy solutions, and the design of the optimum configuration of a hybrid power system [30]. The final optimum results have been obtained by analyzing the solar PV, wind, and CHP systems in detail. HOMER software was used for sensitivity analysis of sunlight, wind speed, CHP size, and fuel reward of the building area. Fernando et al. examined three simulation results. Since the sale of electricity to the national grid creates a cheaper option due to the feed-in tariff, NPC, and COE, a 70 kW PV array including a converter, 500 kW CHP plant, and grid-dependent system are the optimum solutions. HOMER software actively performs techno-economic analysis, considering two economic parameters: Net Present Cost (NPC) and Cost of Electricity (COE) of hybrid systems. Categorized simulation results the lowest COE is $0.032 per 1 kWh (with grid connection, 70 kW PV, converter, and CHP) and the worst outcome is $0.117.

Kekezoğlu et al. conducted a reliability analysis of hybrid energy systems for three different scenarios for Yıldız Technical University Davutpaşa Campus. The best results for reliability have been found if all renewable energy sources are used [31]. Kekezoğlu et al. concluded that stand-alone systems should be designed and sized to ensure maximum reliability during the planning phase. As a result, it has been proven that using different renewable energy sources together and choosing the right battery increases reliability.

Khan et al. evaluated a hybrid off-grid wind-photovoltaic system for a university campus in Abbottabad, Pakistan. Khan et al developed a tool to meet consumer demand by using a hybrid energy system with low cost and reduced CO_2 emissions, due to the high cost of electricity demand and traditional fossil fuel production causing increased carbon dioxide (CO_2) emissions [6]. HOMER has been used to assess campus energy demand through solar and wind electrification. Khan et al., the proposed design ensures optimum dimensioning and low energy generation costs. Khan et al. the analytical evaluation of the power generation system examines the load-shedding hours or the absence of power supply from the conventional power system. Khan et al analyzed four different configurations of the power system. Diesel-based, Photovoltaic (PV) based, wind-based, and wind and PV-based power generation systems. The Cost of Energy (COE) and Net Present Cost (NPC) indicated that the power generation system is essential. They used the Hybrid Optimization Model for Electric Renewable Energy Sources (HOMER) software. They analyzed COE and NPC. A configuration with reduced COE and NPC will be proposed for the University campus. The simulation results that the COE and NPC of the Wind-PV hybrid configuration are comparatively lower than other energy sources and show that this configuration can provide the required power at a low cost. The minimum COE from the result is 0.258.

Sava et al., POLITEHNICA University sought to determine the most appropriate standalone system configuration for the Bucharest "Regie" campus to achieve low energy bills that integrate renewable sources to generate energy that meets the load demand in the context of the European Commission's energy efficiency improvement requirements [32]. Sava et al., created the optimum design of the hybrid system from a 50 kW PV module and a 50-kW converter, 1 kW storage batteries and a 110-kW biogas generator. Sava et al. the aim was to reduce dependence on a single energy source. The proposed hybrid system enabled cluster buildings to achieve almost zero building concepts. Sava et al. presented a technical and economic analysis of a hybrid system based on renewable resources for a Campus for student clusters in Bucharest, Romania. The renewable system they designed consists of a micro wind turbine, solar modules, and a biomass power plant with battery storage. The hybrid system is designed to provide approximately 60% of the energy from biomass, 25% of the energy from PV panels, and 15% from the grid from early energy demand. The proposed hybrid system has enabled cluster buildings to achieve a nearly zero building concept. The analyzed economic coefficients, which determine a hierarchy of technical situations, indicated that there are net current costs and electricity costs.

Kalkan et al. investigated the technical and feasibility aspects of designing an off-grid PV system capable of generating excess electricity demand at the University of Southampton's Highfield Campus [33]. Using the irradiance data for Southampton, the power output of the entire system consisting of 5,016 panels was found to be 1,325 GWh, which corresponds to approximately 3.76% of the annual electricity needs of the campus. Kalkan et al., when they calculate the costs of the system, it shows that this system is worth investing in from the investor's point of view. The payback period is 5.6 years. According to Kalkan et al., the results are satisfactory in that the proposed designs are both technically and economically viable.

Mannah et al. have designed a solar and wind-based hybrid renewable system that presents calculations and evaluations to achieve an optimized design. Since hybrid system performance is mainly based on geographical and meteorological aspects, the study covers the Mediterranean region and especially Lebanon [34]. The simulation results appeared promising with a 33% reduction in the total cost of the system and a significant improvement in ROI.

Jyoti et al. presented the design of an optimized hybrid renewable energy system consisting of a photovoltaic, battery-powered wind generator and converter. The system was optimally simulated using the IHOGA (Improved Hybrid Optimization Genetic Algorithm) tool developed by the Department of Electrical Engineering at the University of Zaragoza, Spain [35]. Jyoti et al. also described the sensitivity analysis of the hybrid system, which helps to access the effect of uncertainty or change in the variable and find the optimal solution for the hybrid system. The optimum configuration of the hybrid PV-wind renewable energy system consists of three wind turbines with 1,326 PV panels parallel to 190 Wp rated power, 1,150 battery, and 72,477 W at 14m. They discussed the design and optimization of a hybrid renewable energy system, considering the impact of sensitivity variables such as global solar radiation, wind speed, and PV panel cost. A total of 20,504 cases were evaluated by Jyoti et al., IHOGA to determine the total net current cost. They found that the hybrid PV wind renewable energy system with the lowest net current cost equal to $2,756,065 and energy cost equal to $0.4/kWh is the optimum solution. This solution is considered the minimum. Sensitivity analysis helps the designer make accurate predictive planning for the future before the installation of the hybrid energy system.

Altun et al. investigated a PV/Wind hybrid power generation system using meteorological data from Bursa province [36]. They verified the reliability of the weather data when designing the renewable energy system. Altun et al. selected weather data from two specific years (2011, 2014) for dynamic simulations. The hybrid system they designed consists of PV panels and a wind turbine. Altun et al. showed that it is possible to produce enough electricity to meet the annual electricity needs of 450 households, which are considered a small district area, with a 1 MW PV + 2 MW wind turbine system. They found the levelized cost of energy to be between 0.413-0.568 $/kWh. Altun et al. found that the payback period of the system is around 20 years.

Nordin et al., using an iterative technique, compared the feasibility of a stand-alone photovoltaic system with a battery system and a stand-alone photovoltaic system with a battery-hydrogen generation system in Malaysian conditions [37]. From the levelized cost of energy (LCOE) analysis, they showed that the LCOE for SAPVBHPS was higher than for SAPVBS by replacing the dump load with a hydrogen generation system. Nordin et al. analyzed the impact of profit from the sale of hydrogen produced in SAPVBHPS. They did a break-even analysis of the payback period and return on investment analysis. To find the minimum hydrogen price required, they applied 25 years of profits from hydrogen sales to balance the installation cost and present value (worst-case scenario). By comparing the minimum hydrogen sales price to the standard hydrogen price, they proved that their proposed SAPVBHPS configuration is possible to be a profitable investment.

The energy produced from solar, and wind depends on the region's climate data. The fact that these resources are more efficient in specific locations is important in investigating the usage potential and measuring system performance. Simulating the energy performance of different sustainable hybrid energy systems such as electricity and hydrogen production on a campus basis using real climate data from PVGIS and comparing them with conventional energy systems are among the primary objectives of this thesis.

CHAPTER 3

DESCRIPTION OF IZTECH CAMPUS, LOAD PROFILE AND METEOROLOGICAL DATA

A standalone hybrid energy system including wind turbines and photovoltaic modules was used as the main power source, while a lead-acid battery and the combination of an electrolyzer, an H_2 storage tank and generators were used as energy storage units. To determine the proper size and number of units in the systems the location of the campus, buildings and their annual electricity load profile, and the solar and wind energy potential of the campus were evaluated.

3.1. IZTECH Campus, Building

Izmir Institute of Technology University is in Izmir/Urla-Gulbahce region. Its coordinates are latitude 38° 19´ 13" N and longitude 26° 38´ 11" E. The campus area is 132,000 m^2.

Figure 8. IZTECH University Google Earth View

Izmir Institute of Technology consists of 3 faculties, one graduate school, one school of foreign languages and several administrative units. Within the scope of this thesis, the electricity requirement of all buildings specified in the 2019 layout plan of the campus taken from the Construction Affairs Technical Department of IZTECH was analyzed. There are also newly constructed buildings on the campus, but these buildings were not included in this study due to the lack of information about these buildings. According to the layout plan, there are 30 buildings on the Campus. The names of the buildings and their size are shown in Table 1. The total roof areas of each building are also seen in Table 1 to gain insight into the areas available for possible PV installation. However, the total roof is not the usable roof area for PV installation due to the shading and blockage caused by other structures on roofs (e.g., chimney outlets, column protrusions) and shapes and slopes of roofs. For this reason, suitable areas for installation were determined by using PV*SOL software. The total roof area of 30 buildings on the IZTECH campus is 45,934 m^2 and the total suitable area for PV installation is 23,199 m^2.

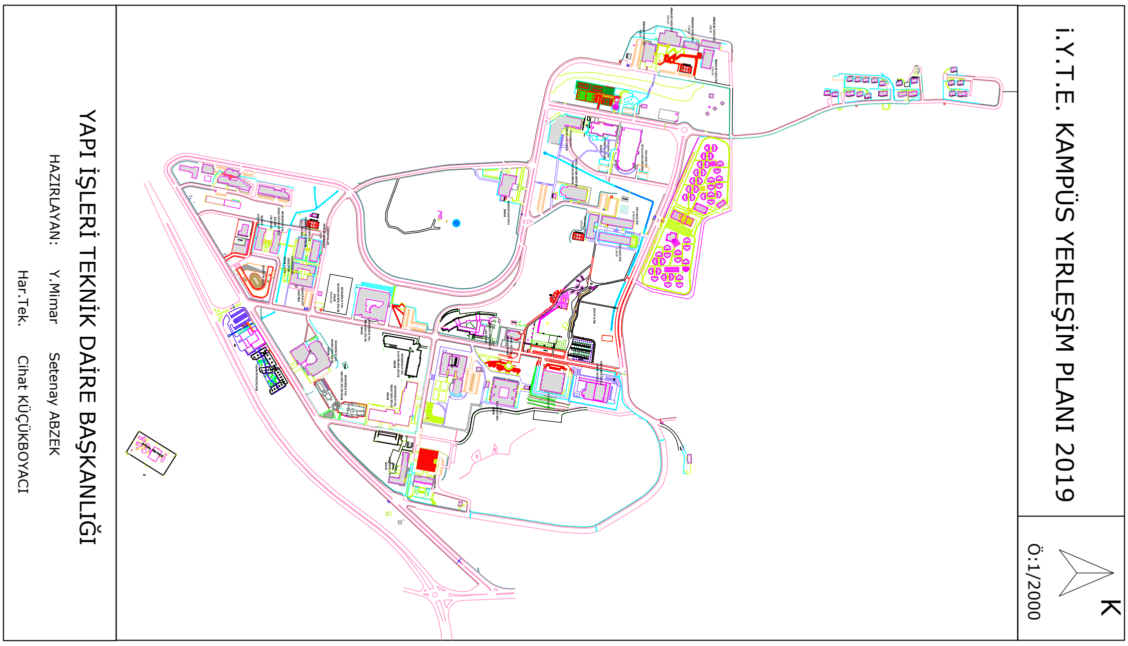

Figure 9. Situation Plan-IZTECH

Table 1. IZTECH Campus Building Total Roof Area, PV Roof, and Roof Type

	m^2	PV use m^2	Roof Type
General Culture Building	450.17	208.3	Flat
Recroate Building	456.69	278.6	Pitch
Head Of Department	1,315.97	753.1	Pitch
Faculty Of Science			
A Block	1,117.77	928.2	Pitch
B Block	1,172.97	1,045.70	Pitch
C Block	1,172.97	1,045.20	Pitch
Classroom Building	1,289.94	573.41	Flat
Physic Building	2,214.36	1,021.20	Flat
Mathematics Building	604.9	242.2	Flat
Biology Building	1,799.22	691.1	Flat
Foreign Language Building			
Foreign Language A Block	701.17	324.9	Flat
Foreign Language B Block	784.56	606.1	Flat
Administrate Building	1,118.65	633.8	Flat
Energy System Lab. Building	1,032.50	758.2	Pitch
Center Work	1,032.50	758.2	Pitch
Mechanical Engineering Building	2,162.34	1,005.60	Flat
Faculty of Architecture			
A Block	1,108.36	941.3	Pitch
B Block	1,278.94	1,072.70	Pitch
C Block	471.14	196	Flat
D Block	728.74	322.3	Pitch
E Block	1,141.09	628.6	Flat
Chemistry Eng. Building.	1,905.90	974.2	Flat
Computer Eng. Building	2,517.88	1,132.10	Flat
Library	2,211.49	1,049.50	Flat
Gym Center	2,775.29	1,354.80	Pitch
Pool	1,125.62	630.4	Flat
Café	1,653.16	606	Flat
Civil Engineering	5,206.74	400.2	Flat
Electric Electronic	2,185.84	1,124.20	Flat
Integrated Research Building	2,421.73	871.6	Flat
TOTAL	**45,934 m^2**	**23,199 m^2**	

3.2. Load Profile

Evaluation of energy requirements and the creation of a consumption model are very important parameters in power plant design. Most of the energy demand in universities consists of lighting and HVAC systems. Energy needs are currently met through different sources. Electricity is the most used source among them. The electricity consumption data of the campus are needed for system design and sizing. Information on electricity consumption data was first requested by IZTECH University and the monthly consumption data of each building for the years 2018-2019-2020 and 2021 (between January and April) were taken. The monthly consumption data of all buildings are listed in Table 2, which excludes the energy requirement for heating and cooling other than electricity-driven HVAC systems.

Table 2. IZTECH Campus Load Consumption (2019-2020-2021)

IZTECH TOTAL	2019 (kWh)	2020 (kWh)	2021 (kWh)
January	623,318	623,889	309,873
February	495,501	477,711	301,344
March	535,385	409,117	305,207
April	457,728	221,574	248,901
May	328,645	244,124	244,218
June	513,100	231,833	243,822
July	562,953	327,848	390,325
August	464,443	272,907	421,574
September	437,067	255,299	329,529
October	366,560	245,564	-
November	399,463	269,392	-
December	565,147	340,284	-

As seen from the Table 2, annual electricity consumption in 2019 is 5,749,310 kWh while this number decreases to 3,919,542 kWh in 2020 due to Corona breakdown. The same effect is also seen in 2021. Since Corona's breakdown affects the electricity consumption significantly, the year 2019 was chosen as the year of analysis to cover the electricity requirement of the campus properly.

The data taken from the university is monthly, but we intend is to make an hourly analysis to be sure that the required energy of each building for each hour is supplied without any break. For this reason, the hourly consumption data was requested and taken from the Electricity Distribution Company (Gediz Elektrik) of Izmir province. However, since these consumption data are read on a single meter, the electricity consumption data of each building is not available. To solve this problem, the fractional electricity consumption (in %) of each building based on the monthly data taken from the university were determined and the hourly consumptions of each building were calculated by multiplying the fractional consumption with the hourly consumption of the whole campus.

The hourly electricity consumption data of the campus in 2019 and the calculated monthly data are listed in Table 3. Based on the data, the annual electricity consumption of the campus was calculated as 9,580,236 kWh, which is higher than the electricity consumption of 30 buildings calculated from the data provided by the university. The difference between the two data was assigned to the electricity consumption of new buildings and buildings not counted in the calculation of electricity consumption of the university (e.g., dormitories). These consumptions were covered in the data from the electricity distribution company while they were not considered in the data provided by the university. Since the electricity consumption of 30 buildings was only considered in the current study, the electricity consumption of other buildings was not included.

Table 3. IZTECH Campus-GDZ Electricity Consumption (2019)

IZTECH TOTAL-GDZ ELECTRICITY CONSUMPTION	2019 (kWh)
January	1,034,492
February	567,598
March	812,804
April	687,852
May	702,418
June	908,874
July	1,115,155
August	945,328
September	753,474
October	577,551
November	594,427
December	880,261

3.3. Meteorological Data

3.3.1. Solar Data

Solar energy is a type of energy obtained from sunlight. Systems that produce electrical energy from the conversion of solar energy are called photovoltaic systems [38]. The component that provides electrical energy production in photovoltaic systems is the solar panel. Electrical energy is generated by the rays coming from the sun falling on the solar panel. The number of rays coming from the sun falling on the panel surface area varies as day, month, and year. The conversion of solar energy depends on several factors. Not all the power from the sun can be converted into electricity. Converted solar energy is affected by season, direction, surface slope, meteorological conditions, and geographic latitude [39].

Turkey is a country with high solar energy potential due to its geographical location. Turkey is in the sun belt between 36 - 42 north latitudes and 26-45 east longitudes. It has an important solar potential in terms of location. Turkey is in an advantageous position when compared to other countries. Turkey's solar potential is recorded by the General Directorate of State Meteorology (DMI). Table 4 shows Turkey's monthly average solar radiation values and sunshine duration [40].

Table 4. Turkey's Monthly Average Energy Potential [27]

Months	**Monthly-average solar radiation**		**Sunshine dur.**
	(kcal/cm^2-ay)	**(kWh/m^2-ay)**	**Hr/months**
January	4.45	51.75	103.0
February	5.44	63.27	115.0
March	8.31	96.65	165.0
April	10.51	122.23	197.0
May	13.23	153.86	273.0
June	14.51	168.75	325.0
July	15.08	175.38	365.0
August	13.62	158.40	343.0
September	10.60	123.28	280.0
October	7.73	89.90	214.0
November	5.23	60.82	157.0
December	4.03	46.87	103.0
Total	**112.74**	**1,311**	**2,640**
Average	**308.0 kcal/cm^2-day**	**3.6 kWh/m^2-day**	**7.2 h/day**

According to the data in Table 4, the average annual sunshine duration of Turkey is calculated as 2,640 hours (total 7.2 hours per day), and the average total radiation pressure is calculated as 1,311 kWh/m^{2}year (total daily 3.6 kWh/m^2). Solar energy potential has been calculated as 380 billion kWh/year [40,41].

Due to the topographic structure, the solar energy potential varies regionally. Accordingly, the highest solar energy potential is in the South-eastern Anatolia region, followed by the Mediterranean, Eastern Anatolia, Central Anatolia, Aegean, Marmara, and Black Sea regions, respectively. Turkey's Solar Energy Potential Atlas (GEPA) is shown in Figure 10 [42].

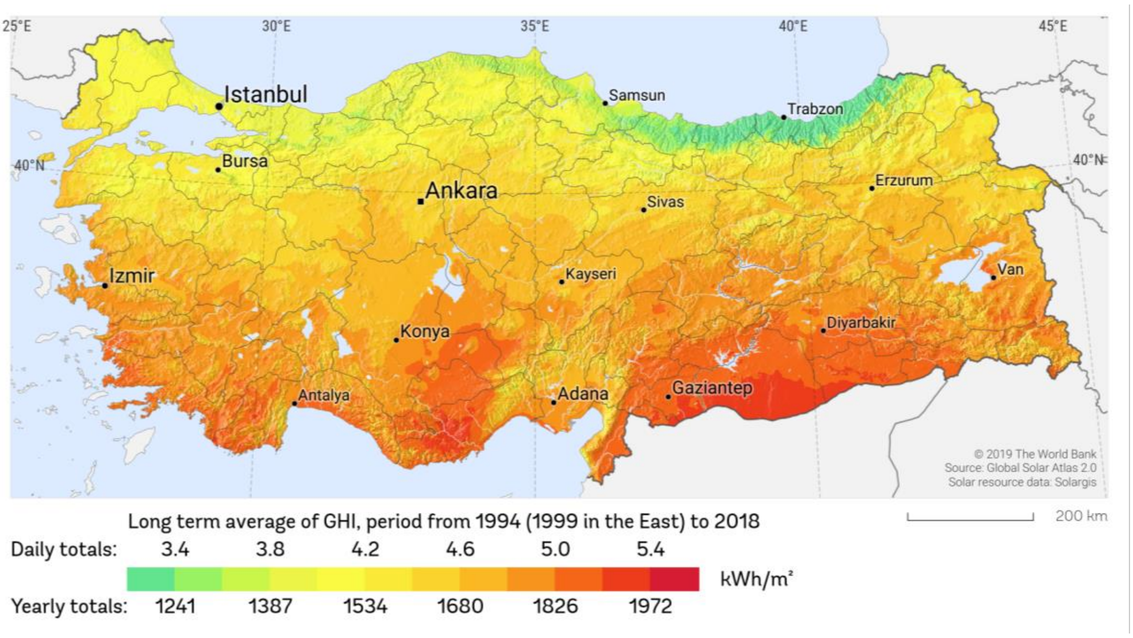

Figure 10. Daily and annual solar radiation value the horizontal plane in Turkey [43]

The study was obtained from the PVGIS-SARAH2 program since the IZTECH University campus does not have a meteorology station. The data used in the studied hourly; are horizontal radiation, radiation at the optimum slope, radiation in the plane, direct radiation, temperature, and wind speed data taken at the height of 10 m.

3.3.1.1. Meteorological Data and Solar Irradiance

The power produced by a photovoltaic panel system depends on the amount of radiation in the system and meteorological parameters [44]. Horizontal spherical radiation is the sum of direct, diffuse, and reflected solar radiation from the ground. Direct normal radiation is radiation that comes perpendicular to it without deflecting anywhere [45].

The solar source in terms of global irradiance at the IZTECH campus was taken from the radiation database – PVGIS-SARAH2 tab, which provides hourly data for 2020. Average monthly values were calculated. Total values are presented in Table 5 and a graph of values is in Figure 11.

Table 5. IZTECH Campus Solar Radiation (PVGIS)

Month	$H(h)\_m$	$H(opt)\_m$	$H(i)\_m$	$H(n)\_m$	Kd	$T2m$
January	82.86	139.52	146.06	135.3	0.37	9
February	94.69	133.52	137.12	117.94	0.41	10.3
March	136.36	166.48	167.74	142.12	0.41	12.4
April	183.96	197.98	195.46	178.23	0.35	14.5
May	214.41	208.72	202.5	198.68	0.34	19
June	225.56	206.07	197.58	225.49	0.3	22.7
July	254.93	239.92	230.99	283.37	0.22	26
August	224.86	234.55	229.97	250.7	0.24	25.9
September	175.32	208.74	209.17	202.81	0.29	24.3
October	117.49	157.99	161.27	135.55	0.4	20.3
November	92.31	151.6	158.23	148.56	0.33	14.3
December	60.42	98.54	102.94	85.91	0.49	12.6
Total	**1,863.17**	**2,143.63**	**2,139.03**	**2,104.66**	**-**	**-**

Here $\mathrm{H(h)\_m}$ is Irradiation on horizontal plane (kWh/m^2/mo), $\mathrm{H(opt)\_m}$ is Irradiation on optimally inclined plane (kWh/m^2/mo), $\mathrm{H(i)\_m}$ is Irradiation on plane at angle (kWh/m^2/mo), $\mathrm{H(n)\_m}$ is monthly beam(direct) irradiation on a plane always normal to sun rays (kWh/m^2/mo), Kd is ratio of diffuse to global irradiation (-), $T2m$ is 24-hour average of temperature in degree Celsius.

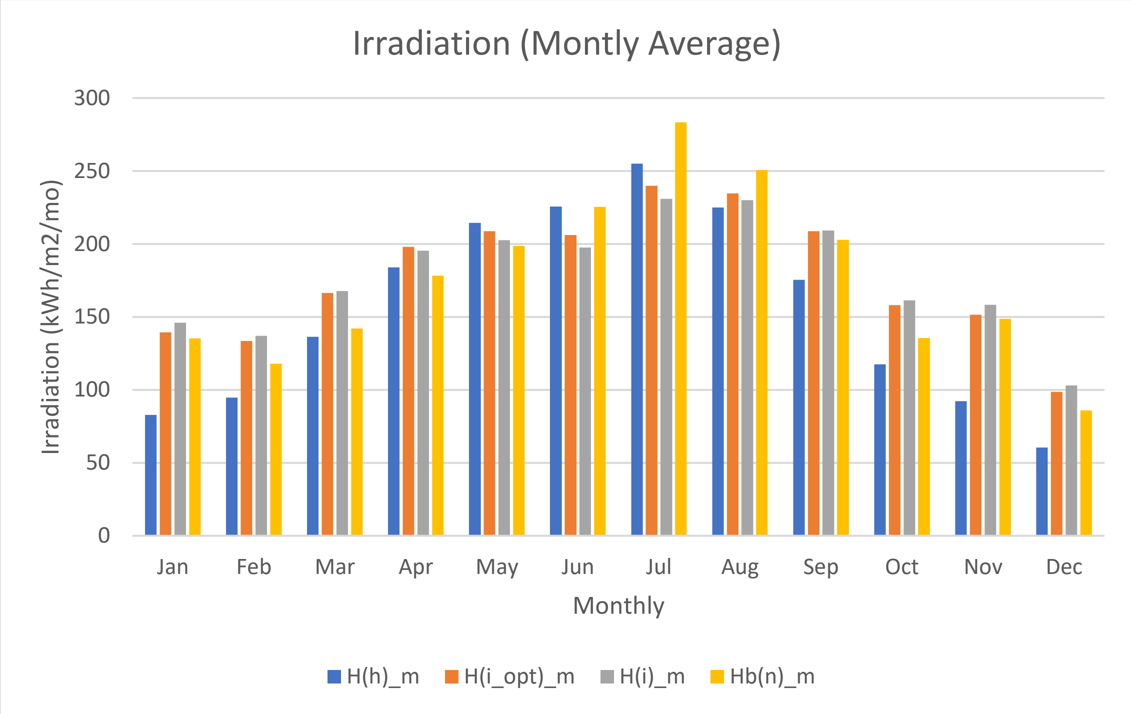

Figure 11. IZTECH Campus Irradiation Graphics (Monthly Average)

It is observed that the lowest solar radiation occurs in the winter months. December is the worst month to consider for optimal design. During December, solar radiation is seen as 60.42 kWh/m^2 in the horizontal plane and 98.54 kWh/m^2 in the optimally inclined plane. The irradiation appears to be higher in the optimally inclined plane. Inclination angle and azimuth angle are important parameters to know the orientation of the optimal inclined plane. Necessary parameter calculations are made in Section 4.3.

3.3.2. Wind Data

Wind Energy is one of the renewable energy types. Wind Energy is the result of the conversion of potential energy into kinetic energy under the influence of pressure forces [46]. Wind; it is a stable, reliable, and continuous source. It contains kinetic energy due to its structure. The amount of energy to be obtained from the wind varies depending on the speed of the wind. The kinetic energy in the moving air is converted into mechanical energy with the help of the blades rotating around an axis.

Wind energy is a clean energy source and its conversion to other types of energy is one of its advantages. In addition, its irregularity and low density are its disadvantages [47].

According to Figure 12 of March 2021, the installed wind energy in the world has reached 9.3 GW and 20% of this is within the borders of Izmir province [48]. In Turkey, it has been determined that the wind potential in the Aegean and Marmara regions is quite intense because of meteorological records and measurements. Generally, wind farms are in these regions. Figure 12 shows the average wind energy values of Turkey.

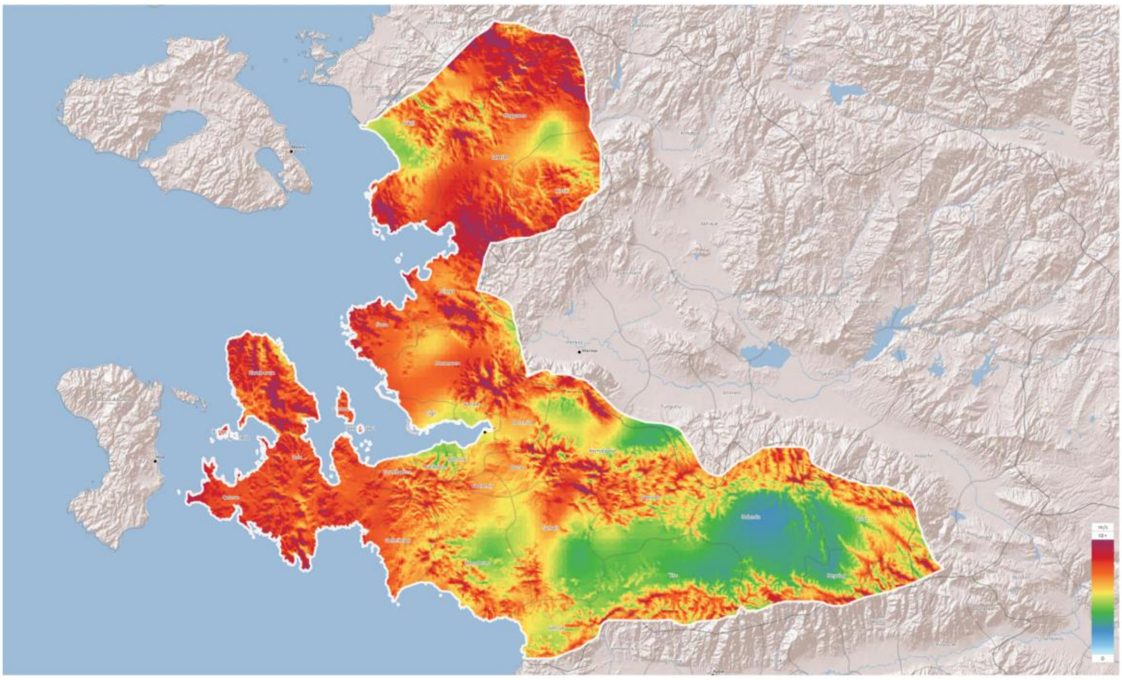

Figure 12. Average Wind Energy Values in Turkey [49]

Wind energy studies at IZTECH University started in the 2000s. There is a wind farm with a capacity of 15 MW located within the borders of IZTECH University (URLA RES). IZTECH University carries out studies for the use of domestic and renewable energy sources in electricity production, reducing carbon emissions and contributing to sustainable development, and for providing the electrical energy consumption of the campus partially from wind energy, as it is in a location with a high wind energy potential as a special purpose. In this context, performance measurements of small and medium-sized wind turbines that are planned to be installed are carried out. The wind data used in this thesis were taken from the measuring mast of IZTECH University. It is a reliable source because the data were obtained from IZTECH University. Wind measurement mast coordinates are 38.333194° latitude and 26.632639° longitude.

The hourly density variation of the wind speed of IZTECH University is shown in Figure 13. According to Figure 13, the highest average wind speed occurred in January.

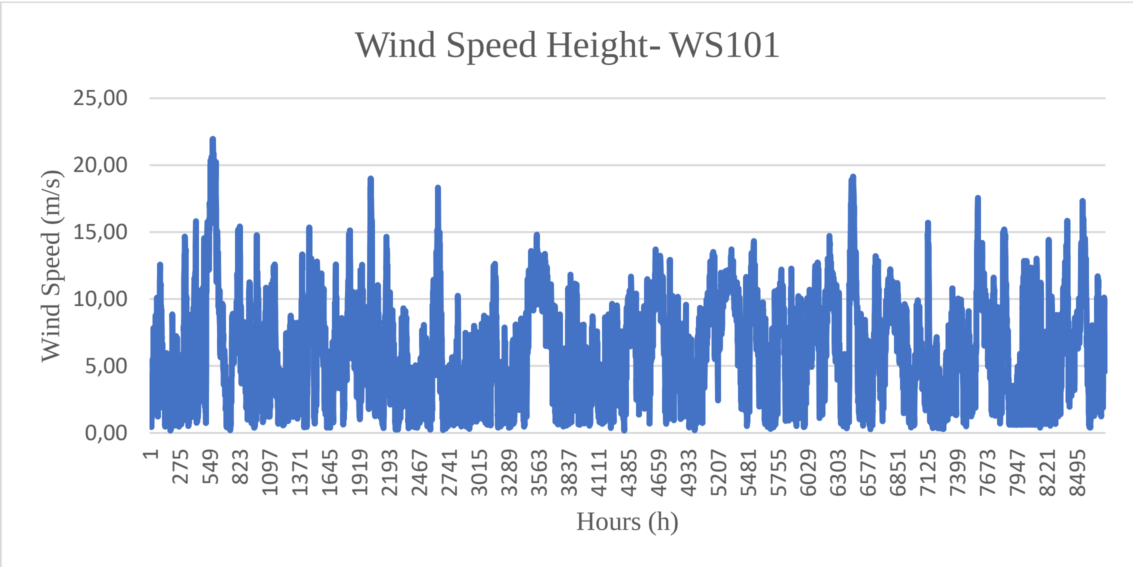

Figure 13. Yearly Wind Energy Speed Height-100m

CHAPTER 4

MODELING APPROACH

In this study, standalone renewable energy systems were designed to meet the electricity needs of the IZTECH campus buildings. Solar and wind energy systems were taken as power sources while batteries and the combination of electrolyzer, H_2 tank and generator were used to compensate for the production-consumption inequality arisen during days throughout the year. A specific location was selected for the wind turbine and the usable roof areas of buildings were evaluated for PV modules installation. Four different renewable energy scenarios were considered, and systems were modeled for each scenario by using PV*SOL and TRNSYS software. The former was used to determine the amount of PV modules, which can be installed on the roof of buildings and the latter was used to model all system components and to do dynamic analysis on an hourly basis for being sure that the required power is delivered without any power cut. Based on the system size (e.g., number of units) and capacity, the economic performance of each scenario was also evaluated by LCOE and NPV analysis.

In the following sections, the tools and methodology used for the design and performance evaluation of the standalone renewable energy systems are explained. In the first part, all assumptions used to model the PV module, wind turbine, battery, electrolyzer, H_2 tank and generator are listed and general information about modeling software is given. Then, the modeling approach used for the rooftop PV module and standalone renewable energy systems was explained. In the final part, the specification of each renewable energy scenario and their economic analysis were given.

4.1. Assumptions

- The year 2019 was used from the consumption data obtained. The data obtained by IYTE is compared to the total campus consumption data obtained from the GDZ Electricity Distribution Company.

- In this thesis, heating and cooling consumption data are not considered while calculating.
- The area of the roofs of 30 buildings on the IYTE Campus was calculated using Google Earth.
- Suitable roof areas for PV Panel placement were calculated by PV*SOL.
- Optimum Panel angle changes every hour, month, or day. The annual average value of the optimum panel angle was taken.
- Trina solar Jinko Panel is calculated based on real meteorological data for the campus located at a fixed angle of inclination.
- The azimuth angles of the panels are located at 0 degrees - South. The panels are designed in the south direction on flat roofs. The design was carried out depending on the roof direction on pitched roofs.
- Since the installation will be done without trees or other obstacles on the roofs and high-rise buildings near the IYTE University campus, it is foreseen that there will be no external shading on the photovoltaic modules.
- The average roof height for pitched roofs is between 6-10 degrees [50,51].
- When calculating the number of lead-acid batteries, the appropriate derating factor range has been accepted from the literature. According to this study, it varies between 0.70 - 0.84 for a lead acid battery and 0.85 to 0.95 for a Li-ion battery. While making the calculations, the derating factor was accepted as 0.80 for the lead acid battery and 0.90 for the lithium-ion battery [52].
- There is no specific criterion in the selection of photovoltaic panels. The highly efficient Trina-solar Jinko panel used today was chosen. The photovoltaic panel is imported and sectoral preferred.
- In the selection of wind turbines, the Nordex N100/2500 model was chosen, which is large enough to meet the IZTECH consumption.
- Photovoltaic panel and wind turbine prices were obtained from the manufacturers.
- According to the consumption data obtained from GDZ Electricity Distribution, it is assumed that there are new buildings within the IZTECH university that did not exist before.
- Labor costs are considered an average value.

- Since the number of electrolyzers is insufficient in hydrogen scenarios, the minimum system is designed in TRNSYS software. It was found how many pieces of the same system are needed. Cost analyzes were calculated based on this.
- The currency used in the calculations is the dollar. The exchange rate from the Central Bank of Turkey has been accepted as 18.5 TL with an average value of 1 dollar [53].
- The interest rate is accepted as 4% [36], and the useful project life is determined as 25 years. The O&M escalation was accepted as 0.5%. According to the data obtained from the US 10-year bond rates, the expected annual escalation in electricity prices is taken as 4% [54]. Rebate/incentive benefits cannot be provided in a standalone renewable system design.
- The prices of the electrolyzer and hydrogen tanks are considered to be close to the real values in line with the sales prices on the websites and articles reviewed.

4.2. Modelling Software

There are numerous software programs available in the market for the calculation and simulation of PV, wind, battery, and hydrogen-based systems. Various programs were investigated for data extraction, simulation, and analysis. The selection was examined based on usability, desired output, and flexibility of software programs to achieve the required goal. In this direction, it is necessary to understand and learn the working principle of the selected software programs. Table 6 summarizes the software programs, the reason for selection, and the adaptation of meteorological data. The working principle of simulation software is explained in the following sections.

Table 6. List of Software programs for simulation and design

Software	Meteorological Database	Reason for selection	Website
PV*Sol Premium	Meteonorm 8.1 (1996-2015)	3D design capabilities were the selection criteria. It was used to determine panel layout and equipment numbers.	PV*SOL – Plan and design better pv systems with professional solar software | PV*SOL and PV*SOL premium (pvsol. software)
TNRSYS	User Format	The software used for modeling and simulation of renewable energy sources. It has dynamic modeling library.	Welcome | TRNSYS: Transient System Simulation Tool

4.2.1. PV*SOL Premium (2021)

PV*SOL software is a program used to design customized solar energy systems for users. It is a program that facilitates a complex task that requires the solar system to consider numerous factors, such as the overall climate and solar radiation, and the size and direction of the system. It is very important to perform 3D Shading Analysis for the designed systems. A real-world representation of the shading from objects surrounding the system plays a large role in calculating the exact system throughput. The advantages of PV*SOL software for solar energy system design are as follows [50];

- Determination of the number of modules and visualization of the module area using a photo.
- Automatic module assignment of any roofs with a 2D roof view.
- Planning of the PV system in a 3D environment [51].

From small roof systems to medium-scale systems on commercial rooftops and large solar parks - PV*SOL premium is a utility for design and simulation. Roof-mounted, small, angled roofs are used in large industrial areas or open land areas. Up to 7,500 mounted terrain modules or up to 10,000 roof modules can be visualized and calculated in 3D under the program. The 3D design is shading based on objects. It provides the highest reliability in terms of economic analysis.

All designs prepared in PV*SOL can be implemented as self-consumption calculation, battery storage design, or integrating electric vehicles. It has more than 1,900 PV modules, 5,500 inverters, 2,600 battery systems, and many other products such as electric vehicles and performance optimizers in its library. The library is updated periodically.

As an economic analysis, the current feed-in tariff is contained in the economic efficiency calculation database. Information on system costs provides a detailed economic analysis of the system for 20 years [50].

4.2.2. TRNSYS

One of the software programs used in this thesis is TRNSYS, which is a flexible simulation program that allows user to integrate their developed models [55]. TRNSYS is a software program used to model and simulate the performance and behaviour of engineered system designs as a function of time [56].

It is a software package that has been commercially available since 1975. The software program generates a graphical front-end (TRNSYS Simulation Studio) to create a simulation. An interface for TRNSYS multi-zoning (TRNBuild/Type56), a SketchUp plugin for creating a multi-site building envelope (TRNSYS3d), and manually editing TRNSYS input files and creating standalone TRNSYS-based applications (TRNEdit/TRNSED). TRNSYS adopts a modular, "black box" component approach to developing and solving simulations in-house. The outputs of one component are sent to the inputs of another component.

TRNSYS is a modular and dynamic simulation tool. TRNSYS uses the dynamic library-based structure of the program and general programming languages. It is possible to convert mathematical models created for energy systems consisting of different components into program components that can be simulated in this program [57]. Figure 14 shows an example TRNSYS system.

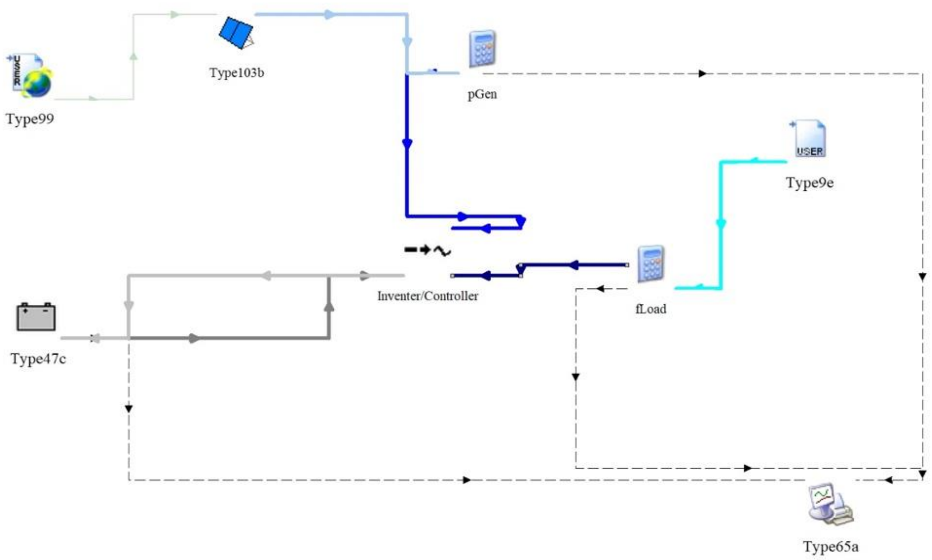

Figure 14. TRNSYS Modeling

TRNSYS software is used in all systems to design and simulate the performance of a hybrid system [58]. Component links described in the section are integrated via links.

The panel, inverter, and battery technical specifications shared by the manufacturers were embedded in the modules of the system.

Meteorological data defined as User Defined in TRNSYS software is selected from its location on the map. Data were obtained from PVGIS-SARAH2. The technical information of the photovoltaic panel is connected to the climate data as defined in the module. The number of panels obtained from the PV*SOL software and the optimum inverter power determined were defined by the TRNSYS software. System analysis was performed with the entered component values. Studies have been carried out with solar and wind energy as the main source, batteries, and hydrogen storage systems connected to these systems. The simulation was continued with TRNSYS to compare the results and determine the most suitable system design. In addition, there were different reasons for choosing TRNSYS software. These are as follows.

1. Using different renewable energy components,

2. Identification of data from external sources,

3. Inability to install more than 20 batteries in PV*SOL software.

4.3. Rooftop PV Module Design

One of the renewable energy sources chosen for this study is solar energy and the related technology for power generation from solar energy is photovoltaic panels. Since the aim is to meet the electricity needs of campus buildings, the best location to place PV modules is the roof of buildings. The design of the rooftop PV panel was made by the PV*SOL software, which requires an analysis of roof structures and meteorological data. The design of each building was made separately and for each installation the solar radiation data was taken from the METEONORM database. Rooftop panel system designs vary according to roof area and type. Roof types of buildings at the IZTECH campus are inclined and flat. In sloping roofs, elevation is given based on the slope of the roof by performing a 3-dimensional layout. The heights and roof slopes of IZTECH campus buildings were not known. Therefore, the average roof height for pitched roofs (between 6-10 degrees) was used in this study [59,60]. The orientation of the panels on pitched roofs varies depending on the building design. Figure 15 shows an example of a pitched roof panel installation.

Figure 15. Pitched Roof Panel Installation

In flat roofs, there are specific parameters when the 3D layout is done. These parameters are optimum tilt angle, azimuth angle, shading, and distance between panels. The solar radiation that a photovoltaic module can receive depends on the module's direction. The tilt angle and the azimuth angle are the factors that determine the orientation of the module. The determined angles should be optimized and determined so that the PV panels can reach the maximum value [44]. The explanations for the related parameters are given in the following parts.

Azimuth Angle: The azimuth angle is related to the distance of the solar panel from the equator line. If the location is in the northern hemisphere, the azimuth angle in the south direction is 0° and the azimuth angle in the west direction is 90°. If the location is in the southern hemisphere, the azimuth angle is 0° to the north. Within the scope of this thesis, since the location of IZTECH University is in the northern hemisphere and between 23 and 90 latitudes, the optimum azimuth angle is determined as the south direction according to the rule [45].

Optimum Tilt Angle: The angle between the photovoltaic panel surface and the horizontal surface is called the tilt angle. It should be known that for the high efficiency of the panel system, the sun's rays must come at a right angle to the panel surface. Under normal conditions, the optimum tilt angle varies daily and seasonally. Variable angle application is not very applicable in real life. For this reason, a fixed angle is determined by considering the annual electricity production of the panels and the latitude of the region where the system will be installed [45].

According to the formula given in Section 4.4.1, solar panel tilt angle, latitude [°] of the location of the panel, and declination angle [°] are used.

An inclination angle is needed for photovoltaic panel placement on IZTECH campus roofs. IZTECH location is given in Table 7 below.

Table 7. IZTECH Location

IZTECH	
Lat [°]	**Lon [°]**
38.33°	26.63°

The declination angle is known as the angle it makes with the equatorial plane of the earth concerning the direction of the sun's rays. Solar declination for any day of the year is maximum on 21 June: 23.5°, minimum on 21 December: -23.45°. Due to the sun's rays perpendicular to the equator, it takes the value of zero on March 20-September 23. Their calculations are given in Section 4.4.1.

Table 8. Declination Angle

Declination Angle (Degree)	
22 March	0°
21 June	23.45°
22 September	0°
22 December	-23.45°

The declination angle takes different values throughout the year. The declination values for each day of the year are given in Table 9.

Table 9. Yearly Declination Angle

Yearly Declination Angle												
	Jan.	**Feb.**	**March**	**April**	**May**	**June**	**July**	**August**	**Sep.**	**Oct.**	**Nov.**	**Dec.**
1	-23.012	-17.516	-8.294	4.017	14.901	22.040	23.120	17.913	7.725	-4.216	-15.363	-22.108
2	-22.931	-17.246	-7.915	4.414	15.210	22.174	23.050	17.650	7.342	-4.612	-15.666	-22.239
3	-22.843	-16.969	-7.534	4.810	15.515	22.302	22.972	17.382	6.958	-5.007	-15.964	-22.364
4	-22.748	-16.688	-7.150	5.204	15.816	22.424	22.887	17.108	6.571	-5.401	-16.257	-22.482
5	-22.647	-16.402	-6.765	5.597	16.111	22.538	22.796	16.830	6.183	-5.793	-16.546	-22.593
6	-22.538	-16.111	-6.377	5.988	16.402	22.647	22.698	16.546	5.793	-6.183	-16.830	-22.698
7	-22.424	-15.816	-5.988	6.377	16.688	22.748	22.593	16.257	5.401	-6.571	-17.108	-22.796
8	-22.302	-15.515	-5.597	6.765	16.969	22.843	22.482	15.964	5.007	-6.958	-17.382	-22.887
9	-22.174	-15.210	-5.204	7.150	17.246	22.931	22.364	15.666	4.612	-7.342	-17.650	-22.972
10	-22.040	-14.901	-4.810	7.534	17.516	23.012	22.239	15.363	4.216	-7.725	-17.913	-23.050
11	-21.898	-14.587	-4.414	7.915	17.782	23.086	22.108	15.056	3.818	-8.105	-18.171	-23.120
12	-21.751	-14.269	-4.017	8.294	18.043	23.153	21.970	14.744	3.419	-8.482	-18.423	-23.184
13	-21.597	-13.946	-3.619	8.670	18.298	23.214	21.825	14.428	3.019	-8.857	-18.670	-23.242
14	-21.436	-13.620	-3.219	9.044	18.548	23.268	21.675	14.108	2.618	-9.230	-18.912	-23.292
15	-21.269	-13.289	-2.819	9.415	18.792	23.314	21.517	13.784	2.217	-9.599	-19.148	-23.335
16	-21.096	-12.955	-2.418	9.783	19.031	23.354	21.354	13.455	1.815	-9.966	-19.378	-23.372
17	-20.917	-12.616	-2.016	10.149	19.264	23.387	21.184	13.122	1.412	-10.330	-19.602	-23.401
18	-20.731	-12.274	-1.613	10.511	19.491	23.413	21.007	12.786	1.009	-10.691	-19.821	-23.424
19	-20.540	-11.928	-1.210	10.870	19.713	23.432	20.825	12.446	0.605	-11.049	-20.034	-23.439
20	-20.342	-11.579	-0.807	11.226	19.928	23.445	20.636	12.102	0.202	-11.403	-20.241	-23.448
21	-20.138	-11.226	-0.404	11.579	20.138	23.450	20.442	11.754	-0.202	-11.754	-20.442	-23.450
22	-19.928	-10.870	0.000	11.928	20.342	23.448	20.241	11.403	-0.605	-12.102	-20.636	-23.445
23	-19.713	-10.511	0.404	12.274	20.540	23.439	20.034	11.049	-1.009	-12.446	-20.825	-23.432
24	-19.491	-10.149	0.807	12.616	20.731	23.424	19.821	10.691	-1.412	-12.786	-21.007	-23.413
25	-19.264	-9.783	1.210	12.955	20.917	23.401	19.602	10.330	-1.815	-13.122	-21.184	-23.387
26	-19.031	-9.415	1.613	13.289	21.096	23.372	19.378	9.966	-2.217	-13.455	-21.354	-23.354
27	-18.792	-9.044	2.016	13.620	21.269	23.335	19.148	9.599	-2.618	-13.784	-21.517	-23.314
28	-18.548	-8.670	2.418	13.946	21.436	23.292	18.912	9.230	-3.019	-14.108	-21.675	-23.268
29	-18.298		2.819	14.269	21.597	23.242	18.670	8.857	-3.419	-14.428	-21.825	-23.214
30	-18.043		3.219	14.587	21.751	23.184	18.423	8.482	-3.818	-14.744	-21.970	-23.153
31	-17.782		3.619		21.898		18.171	8.105		-15.056		-23.086

Table 10. Yearly Tilt Angle

Tilt Angle												
	Jan	**Feb.**	**March**	**April**	**May**	**June**	**July**	**August**	**Sep**	**October**	**Nov**	**Dec**
1	61.34	55.85	46.62	34.31	23.43	16.29	15.21	20.42	30.61	42.55	53.69	60.44
2	61.26	55.58	46.24	33.92	23.12	16.16	15.28	20.68	30.99	42.94	54.00	60.57
3	61.17	55.30	45.86	33.52	22.81	16.03	15.36	20.95	31.37	43.34	54.29	60.69
4	61.08	55.02	45.48	33.13	22.51	15.91	15.44	21.22	31.76	43.73	54.59	60.81
5	60.98	54.73	45.09	32.73	22.22	15.79	15.53	21.50	32.15	44.12	54.88	60.92
6	60.87	54.44	44.71	32.34	21.93	15.68	15.63	21.78	32.54	44.51	55.16	61.03
7	60.75	54.15	44.32	31.95	21.64	15.58	15.74	22.07	32.93	44.90	55.44	61.13
8	60.63	53.85	43.93	31.57	21.36	15.49	15.85	22.37	33.32	45.29	55.71	61.22
9	60.50	53.54	43.53	31.18	21.08	15.40	15.97	22.66	33.72	45.67	55.98	61.30
10	60.37	53.23	43.14	30.80	20.81	15.32	16.09	22.97	34.11	46.05	56.24	61.38
11	60.23	52.92	42.74	30.42	20.55	15.24	16.22	23.27	34.51	46.43	56.50	61.45
12	60.08	52.60	42.35	30.04	20.29	15.18	16.36	23.59	34.91	46.81	56.75	61.51
13	59.93	52.28	41.95	29.66	20.03	15.12	16.50	23.90	35.31	47.19	57.00	61.57
14	59.77	51.95	41.55	29.29	19.78	15.06	16.66	24.22	35.71	47.56	57.24	61.62
15	59.60	51.62	41.15	28.92	19.54	15.02	16.81	24.55	36.11	47.93	57.48	61.67
16	59.43	51.28	40.75	28.55	19.30	14.98	16.98	24.88	36.52	48.30	57.71	61.70
17	59.25	50.95	40.35	28.18	19.07	14.94	17.15	25.21	36.92	48.66	57.93	61.73
18	59.06	50.60	39.94	27.82	18.84	14.92	17.32	25.54	37.32	49.02	58.15	61.75
19	58.87	50.26	39.54	27.46	18.62	14.90	17.51	25.88	37.72	49.38	58.36	61.77
20	58.67	49.91	39.14	27.10	18.40	14.89	17.69	26.23	38.13	49.73	58.57	61.78
21	58.47	49.56	38.73	26.75	18.19	14.88	17.89	26.58	38.53	50.08	58.77	61.78
22	58.26	4920	38.33	26.40	17.99	14.88	18.09	26.93	38.94	50.43	58.97	61.77
23	58.04	48.84	37.93	26.06	17.79	14.89	18.30	27.28	39.34	50.78	59.15	61.76
24	57.82	48.48	37.52	25.71	17.60	14.91	18.51	27.64	39.74	51.12	59.34	61.74
25	57.59	48.11	37.12	25.38	17.41	14.93	18.73	28.00	40.14	51.45	59.51	61.72
26	57.36	47.74	36.72	25.04	17.23	14.96	18.95	28.36	40.55	51.78	59.68	61.68
27	57.12	47.37	36.31	24.71	17.06	14.99	19.18	28.73	40.95	52.11	59.85	61.64
28	56.88	47.00	35.91	24.38	16.89	15.04	19.42	29.10	41.35	52.44	60.00	61.60
29	56.63		35.51	24.06	16.73	15.09	19.66	29.47	41.75	52.76	60.16	61.54
30	56.37		35.11	23.74	16.58	15.15	19.91	29.85	42.15	53.07	60.30	61.48
31	56.11		34.71		16.43		20.16	30.23		53.39		61.42
Ave.	**59.18**	**51.66**	**40.72**	**28.84**	**19.52**	**15.25**	**17.23**	**25.03**	**36.34**	**48.18**	**57.38**	**61.43**
Opt. Tilt Angle = 38.4°												

Declination values are deduced from the latitude of the location where the photovoltaic panel will be installed. There is the required solar panel tilt angle for each day of the year. Table 10 gives the solar panel tilt angles for each day of the year.

Since the inclination angle cannot change every day in the photovoltaic panel installation, monthly average values are found. According to the annual average of the monthly average values, the inclination angle of the solar panel was calculated as 38.4 degrees [61].

Shading: In photovoltaic system designs, even a tiny amount of shadow cast on the panels can significantly reduce the output current. For this reason, it is essential to choose as much shadow-free area as possible for the photovoltaic panel system design to be installed.

The shadow falls on the photovoltaic panel systems installed on the building, shown in Figure 16, due to an obstacle calculated as follows [62].

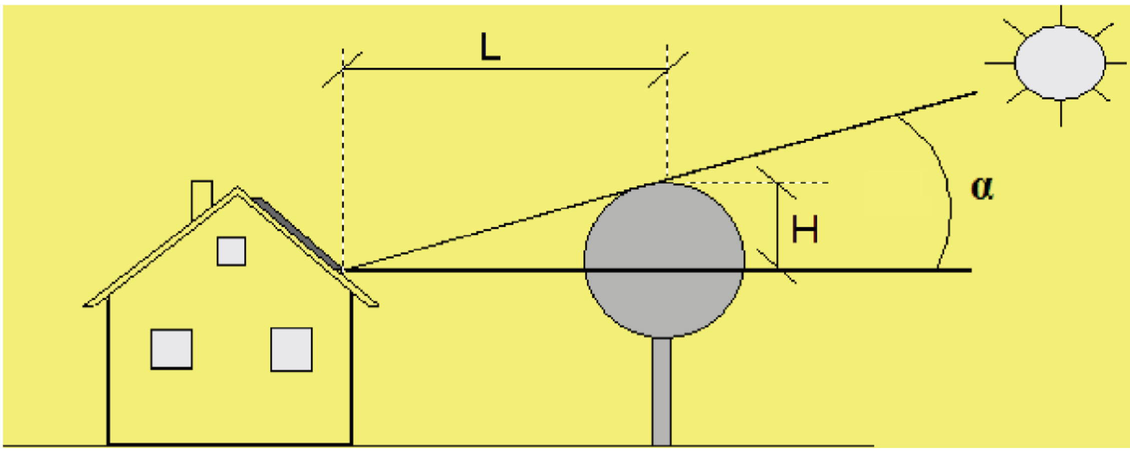

Figure 16. Obstacle Calculation [62]

$$L > \frac{H}{\tan\alpha} \tag{1}$$

If the distance (L) between the obstacle and the module is greater than the value of H/tanα, shadow formation will not occur due to the obstruction.

It is foreseen that there will be no external shading on the photovoltaic modules since the installation will be on the rooftops near the IZTECH University campus and high-rise buildings without trees or other obstacles.

Distance Between Panels: The distance between modules should be considered in photovoltaic systems installed on flat roofs. Shadows on the solar panels reduce the efficiency of that panel array and sometimes cause it to be completely disabled. In the placement of the modules, the incoming sun rays should not be interrupted by the previous module. The day when the sun's rays are most oblique in Turkey is December 21, the shortest day of the year.

It will help to determine the ideal inter-row spacing to understand and analyze the shadowing between strings, which is one of the sensitive parameters in the installation for IZTECH University.

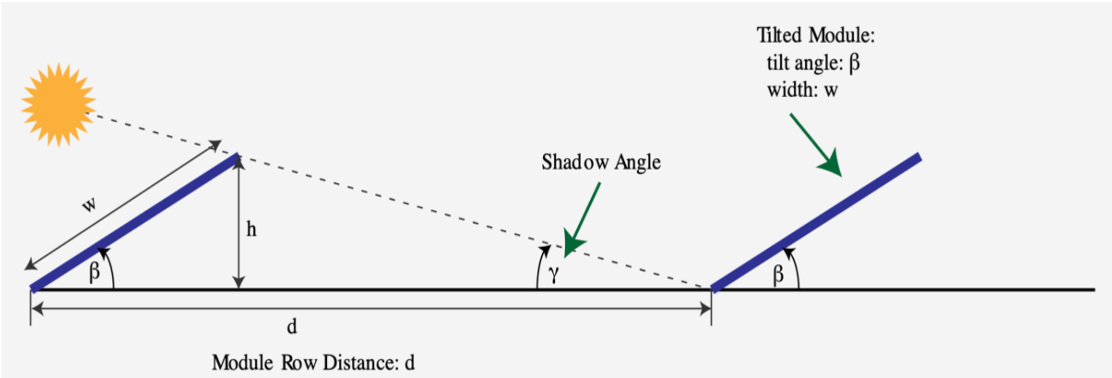

Figure 17. Distance calculation between two modules [63]

The width distance (d) between successive panel rows is approximately three times the panel slope (β). The distance between the two modules is calculated as follows.

$$d = w * \left(\frac{\sin\beta}{\tan\gamma} + \cos\beta\right) \tag{2}$$

The module array spacing for the IZTECH campus was found to be 2.75 meters. This value is entered in the photovoltaic panel layout for buildings with flat roofs designed with the PV*SOL program. Control was achieved by performing shading analysis.

The system design was made by entering the calculated parameters into the PV*SOL program. Figure 18 shows an exemplary flat roof panel setup installed.

Figure 18. Flat Roof Panel Installation

While designing the system, suitable roof areas where the panel system will be installed were selected. Panel Trina solar Jinko has 525 Wp power and its inverter model has been chosen as Huawei with different abilities. 3D panels were placed on the roof. Panel model, number, and connections with inverter were made. Other power models of Huawei inverters have been used commercially. The number of inverters connected to the photovoltaic system installation is calculated automatically in the program itself. A shading analysis of rooftop panel systems was made. Pitched roofs were installed in the direction of the building, and the panel systems on flat roofs were installed in the south direction. In general, the maximum number of photovoltaic panels that can be used for all buildings was determined by the PV*SOL program based on the parameters explained above and climate data. The information obtained in PV*SOL was also used in TRNSYS modeling, where four different standalone renewable energy systems were simulated.

Table 11. Constant Parameters PV System

PV System	
Calculate Optimum Tilt	38.4°
Calculate Azimuth Angle	0° (Slope Roof)
Model Of Module Used	Jinko 545 Wp
Model Of Inverter Used	Huawei
Model Of Battery Used	Sunlight RES OPzV

4.4. Standalone Renewable Energy System Design

Four different standalone renewable energy systems were considered in this study. The components of these systems, namely the PV module, wind turbine, lead-acid battery, elctrolyzer, H_2 tank, generator, and inverter, were mathematically modeled and all system scenarios were analyzed dynamically in TRNSYS. The explanation of each component modeling and the system modeling for four different scenarios are explained in the following sections.

4.4.1. Type 103: Simple Photovoltaic System Modeling

Type103 is a simplified model of a photovoltaic (PV) array. This component is appropriate for modeling the electrical performance of mono and polycrystalline photovoltaic (PV) panels [64]. The TYPE 103b photovoltaic (PV) array used in TRNSYS modeling is linked to the Weather data TYPE99. These connections affect parameters and data inputs. The parameter table is given in Appendix A.

The received data has parameters according to the working principles of photovoltaic (PV) arrays. These parameters are usually derived from the catalogue values of photovoltaic (PV) arrays. Section 4.5.1. gives the parameters of the TYPE103b.

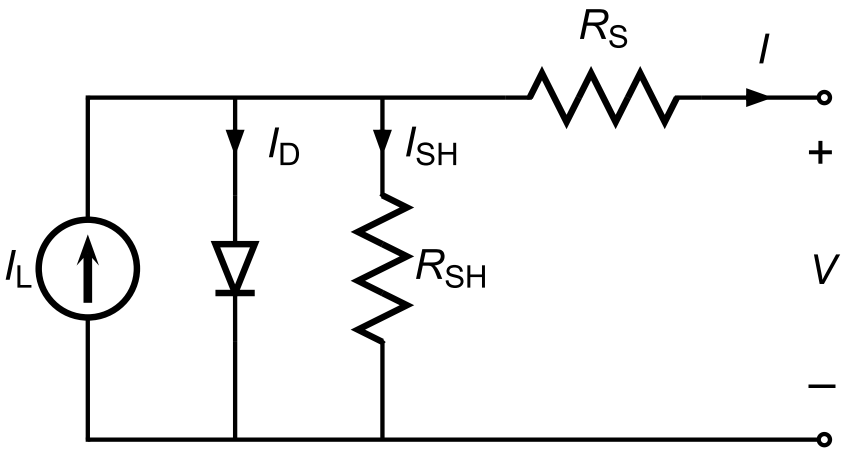

Figure 19. The equivalent circuit of a solar cell [65]

The electrical equivalent of PV cells in Figure 19 is given. This circuit consists of a DC current source, diode, and resistor. The power of the PV module depends on solar radiation, and the IV properties of the diode depend on the temperature.

In general, the power calculation of the PV module is as follows.

$$P_{solar} = \mathrm{I} \times \mathrm{V}. \tag{3}$$

Where I is the output current of the PV cell; V is the output voltage of the PV cell. The output current of the photovoltaic cell is calculated as follows.

$$\mathrm{I} = \mathrm{I_L} - \mathrm{I_0}\left[\exp\left(\frac{\mathrm{q}}{\gamma \mathrm{k} \mathrm{T_C}}(\mathrm{V} + \mathrm{IR_s}) - 1\right)\right] - \left(\frac{\mathrm{V} + \mathrm{IR_s}}{\mathrm{R_{sh}}}\right) \tag{4}$$

When $\mathrm{R_{sh}}$=∞ open circuit in the cell equivalent circuit, the PV cell current is as follows.

$$\mathrm{I} = \mathrm{I_L} - \mathrm{I_0}\left[\exp\left(\frac{\mathrm{q}}{\gamma \mathrm{k} \mathrm{T_C}}(\mathrm{V} + \mathrm{IR_s}) - 1\right)\right] \tag{5}$$

Here k is Boltzmann constant $(1.380622 \times 10^{-23}\ \mathrm{J/°K})$, q is electron charge $(1.6021917 \times 10^{-19}$ C). R_s is the module series resistance, and R_{sh} is the module shunt resistance. R_s and γ are constants, I_L is photocurrent, I_0 is diode reverse saturation current, and T_c is PV cell temperature. The photocurrent $I_L$depends linearly on incident radiation:

$$I_L = I_{L,ref} \frac{G_T}{G_{T,ref}} \quad (6)$$

where G_T is incident radiation, $G_{T,ref}$ is incident radiation at reference conditions (a radiant value of 1000 (W/m^2) and a wind speed of 1 (m/s). The cell temperature is calculated as follows:

$$T_c = T_{ambient} + \frac{T_{nom} - 25}{1.0} \times G_T \quad (7)$$

where $T_{ambient}$ is defined as the ambient temperature (25°C). The voltage of the PV cell can be calculated by rearranging the Eqn 5. as follows:

$$V = \frac{\gamma k T_C}{q} \ln\left(\frac{I_L + I_0 + I}{I_0}\right) - IR_s \quad (8)$$

Based on the equation shown above and the number of serial and parallel PV cells (Np, Ns), the output power of the photovoltaic (PV) panel can be calculated as follows:

$$P = \left[N_p I_L - N_p I_0 \left[\exp\left(\frac{q}{\gamma k T_C} \left(\frac{V}{N_s} + \frac{IR_s}{N_p} \right) - 1 \right) \right] \right] \times \left[\frac{\gamma k T_C}{q} \ln\left(\frac{I_L + I_0 + I + N_p}{I_0} \right) - IR_s \right] \quad (9)$$

The voltage induced in a photovoltaic (PV) cell is proportional to the intensity of light incident on the cell surface. If a load is connected to the PV cell output terminals, a current flow through the load.

The angle of incidence for the beam component of solar radiation is output directly from the TRNSYS weather components. However, weather components typically do not calculate effective incidence angles for the radiated and ground-reflected radiation components. To determine the solar angles and position of the photovoltaic panel, it is necessary to know the relations between horizontal and inclined planes.

The intensity of solar radiation coming from outside the Earth's atmosphere is 1.370 W/m^2. However, it varies between 0-1.100 W/m^2 on earth [37]. Different angles occur between the sun's rays falling on the earth and the surfaces on which they fall. Sun angles are used to see the changing position of the sun from time to time and its changing movements in a day.

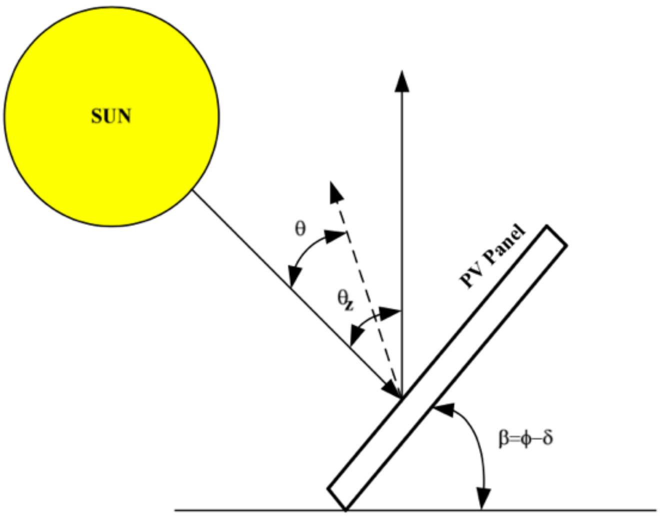

Figure 20. Incidence Tilt Angle [66]

The angle of incidence (θ) is the angle between the radiation rays falling directly on the surface and the normal to that surface. The angle of incidence is used in the design of solar energy systems. The angle of incidence and the angle of inclination are shown in Figure 20. The angle of incidence is calculated as:

$$\theta = \cos^{-1}[\cos(\delta)\cos(\omega)\cos(\phi) + \sin(\delta)\sin(\omega)] \quad (10)$$

First, the fixed angles for the direction and position of the inclined plane are:

β is the inclination of the plane concerning the horizontal, $0^{\circ} \leq \beta \leq 180^{\circ}$. This angle faces south in the Northern Hemisphere and north in the Southern Hemisphere.

When the photovoltaic panel to be placed in the selected location is adjusted to a single daily angle and rotated around the horizontal east-west axis, the inclination angle of the surface will be fixed for each day. It is calculated as follows.

$$\beta = \phi - \delta \quad (11)$$

γ, the azimuth angle of the inclined plane, zero relatives to south, west positive, $-180^{\circ} \leq \gamma \leq 180^{\circ}$.

ϕ, the latitude of the location, north positive, $-90^{\circ} \leq \phi \leq 90^{\circ}$. Latitude and longitude angles are used to describe any location on the earth's surface. Turkey is located at $36^{\circ} - 42^{\circ}$north latitudes and $26^{\circ} - 45^{\circ}$ east longitudes. The rotation of the sun varies with different latitudes and longitudes.

Second, the time-varying angles that define the position of the Sun relative to the celestial sphere and the Earth are as follows.

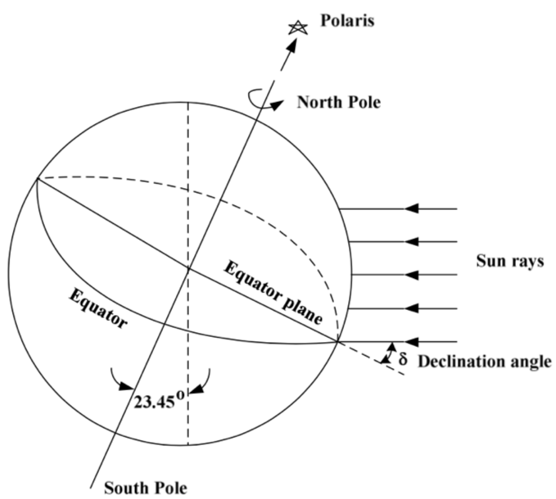

Figure 21. Declination Angle [66]

δ occurs between the sun's rays and the equatorial plane. The tilt angle of 23.45 degrees is formed between the earth's rotation angle and the orbital plane. North is positive, $-23.45^{\circ} \leq \delta \leq 23.45^{\circ}$.

n represents the days of the year and January 1 is considered the start.

$$\delta = 23.45\left[360 \times \frac{(284 + n)}{365}\right] \tag{12}$$

ω, hour angle, is the angle between the longitude of the sun's rays and the longitude of its location. Negative before noon, zero at noon, positive in the afternoon, $-180^{\circ} \leq \omega \leq 180^{\circ}$. Deviation makes a complete cycle in a year.

The hour angle from solar time is calculated as:

$$\omega = 15\left(\frac{t_s}{60} - 12\right) \tag{13}$$

where t_s is the solar time in hours.

As I just mentioned, in TRNSYS modeling, weather output data typically cannot calculate effective incidence angles for radiated and ground-reflected radiation components. And for that, there is the "angle of incidence modifier" routine. This form of calculation proceeds based on the slope of the module and the incidence angle and intensity of each radiation component (direct, diffuse, and ground-reflected). For calculation, τa was assumed to have a value of 0.95 at normal incidence.

Before using Equation 6. to determine the photocurrent, the radiation incident on the PV is multiplied by τa to account for reflective losses. The equation used for the angle of incidence modifier is as follows [64];

$$\mathrm{IAM} = 1 - 1.1098\mathrm{x}10^{-4}\theta - 6.267\mathrm{x}10^{-6}\theta^2 + 6.583\mathrm{x}10^{-7}\theta^3 - 1.427\mathrm{x}10^{-8}\theta^4 \tag{14}$$

where;

$$\mathrm{IAM} = \frac{\tau a}{\tau a_{\mathrm{normal}}} \tag{15}$$

The θ seen is the angle of incidence in degrees. θ = 0 means coming from a normal angle.

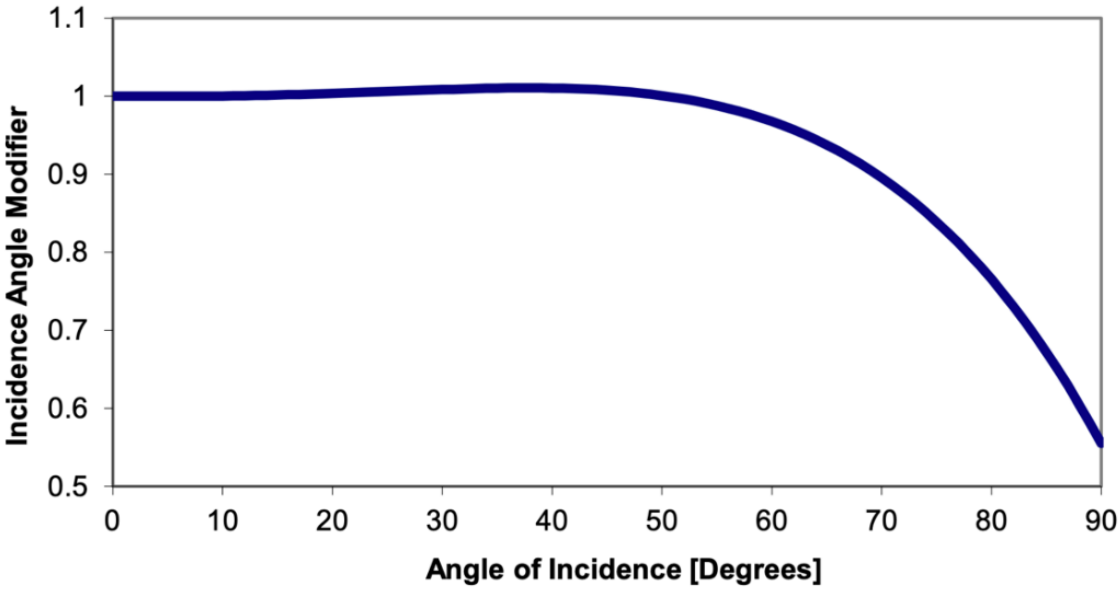

Figure 22. The Angle of Incidence [64]

Two additional relations are used to calculate the effective angle of incidence for the beam component of solar radiation. These are as follows [64];

$$\theta_{eff,diff} = 59.567 - 9.123x10^{-2}\beta - 5.424x10^{-4}\beta^2 + 3.216x10^{-5}\beta^3 - 1.7x10^{-7}\beta^4 \quad (16)$$

$$\theta_{eff,gnd} = 90.032 - 6.615x10^{-1}\beta - 4.796x10^{-3}\beta^2 + 1.543x10^{-5}\beta^3 - 2.000x10^{-}\beta^4 \quad (17)$$

$$G_{T,eff} = \tau a_{normal}\left(G_{T,beam}IAM_{beam} + G_{T,diff}IAM_{diff} + G_{T,gnd}IAM_{gnd}\right) \quad (18)$$

It may be used in one of two modes depending on how the first parameter (MPPT mode) is set. When the MPPT mode parameter is set to 0, the PV array is assumed to be directly connected to a load voltage and/or to a battery such that the array and the load operating voltages are equal, and the operating voltage will be taken as an input to the PV model.

When the MPPT mode parameter is set to 1 then the array is assumed to be connected to its load through a maximum power point tracker such that the array and the load will operate at independent voltages. In this case, the load voltage is not needed as an input.

An iterative search routine finds the current (I_{mp}) and voltage (V_{mp}) at the point of maximum power along the IV curve.

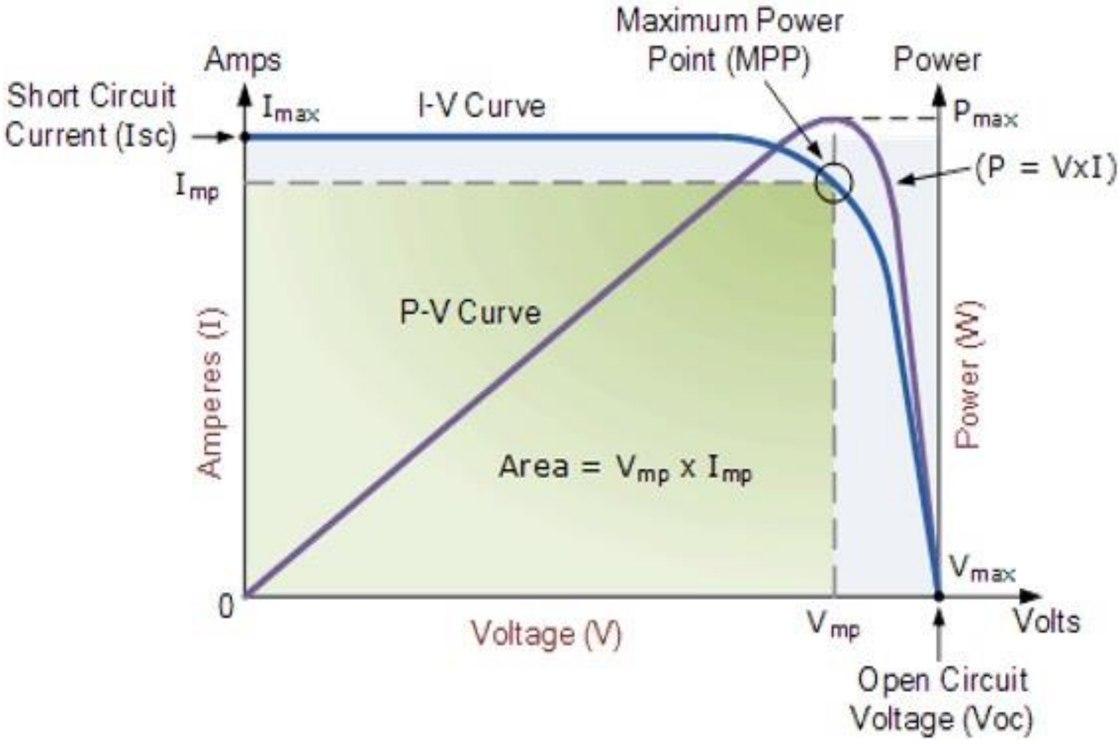

Figure 23. I-V Curve Graphs

The product of each point, current, and voltage on the I-V graph gives the output power of the system. For power to be at its maximum value, V and I must be maximum.

$$P_{max} = V_{max} \times I_{max} \tag{19}$$

The maximum output power P_{max} is at the elbow point of the current-voltage characteristic. The maximum output power of the photovoltaic battery is proportional to the change in current and voltage. This change depends on the temperature and sunlight falling on the photovoltaic battery. Current and voltage parameters must be kept constant to ensure maximum power.

The model uses the following equations from the equivalent circuit model to predict the current-voltage characteristics of a single module. This circuit consists of a DC source, diode, and resistor.

$$P_{max} = V_{max} \times I_{max} = V_{oc} \times I_{sc} \times FF \tag{20}$$

The open-circuit voltage (V_{OC}) to the measured voltage when the resistance between the terminals of the diode is infinite. The short-circuit current (I_{sc}) to the measured current when the resistance between the terminals of the diode is infinite. FF is called the fill factor.

$$\eta_{PV} = \frac{V_{oc} \times I_{sc} \times FF}{I_G} \tag{21}$$

When finding the efficiency (η_{PV}) of a solar cell, is calculated by the ratio of the power taken from the diode to the intensity of the light falling on the photovoltaic diode (I_G). Based on these calculations, the power output from the photovoltaic panel,

$$P_{max} = A_{PV} \times I_G \times \eta_{PV} \tag{22}$$

η_{PV} is the location where the solar panels are placed, the temperature of the surface, the transmission losses, the temperature of the environment, etc. It is the total efficiency of the system that includes the factors.

4.4.2. Type 90: Wind Turbine Modeling

The TRNSYS Type 90 model is a wind energy conversion system (WECS). A wind turbine converts the kinetic energy of the moving air into useful work. The Type 90 model calculates the power output of the WECS based on the power versus wind speed characteristics. Wind turbine energy production can be explained by the power equation derived from the kinetic energy equation. However, the efficiency of the turbine components must be considered to obtain the ultimate power output. The wind turbine power output equation depends on 3 main factors: rotor diameter, air density, and wind speed. In TRNSYS, calculations are modeled for the effect of air density changes and wind speed increase with height. Since not all the wind coming to the turbine blades can be converted into mechanical power in the rotor, a change in power occurs depending on the value difference between the inlet and outlet speeds. The power output of a wind turbine is defined as thrust times speed.

The value of the coefficient multiplied by the rotor area and the power in the wind gives the power output of the wind turbine as follows.

$$P_{wind} = \frac{1}{2}\rho A_R U_0^3 C_p \tag{23}$$

where ρ is the air density (1.225 kg/m^3), A_R is the area swept, U_0 is the wind speeds. C_p is gives an expression for the power factor as a function of the axial induction factor.

While calculating the TRNSYS software, the data from the turbine manufacturer was used. The power curve formed because of these data was solved with the TRNSYS software curve fitting equation. With the data entered from different heights, the TRNSYS software performed the calculations on the equation.

In calculations, the Cp value varies according to the speed. It is necessary to know the speed at rotor height.

4.4.3. Type 47c: Simple Lead Acid Battery Modeling

A lead-acid battery model shows how the state of charge of the battery changes over time, depending on the rate of charge or discharge. In system design, Mode 3 was used to better model behaviour at low charge and discharge currents. This model applies some modifications to the Shepherd equations proposed by Hyman. The input of the battery into the model in Mode 3 is its charging or discharging power. Lead acid battery parameters are given in Section 4.7. This model works with Type48 Regulator/Inverter, which regulates the power and does the related AC/DC conversion.

In the Type 47 model, if the battery status reaches 0% charge and continues to discharge, it will not generate an error and the simulation will continue. This assumes an auxiliary power source it can draw to keep the battery charged. In this case, the user sees how much auxiliary power is required. The same is true when the battery reaches 100% SOC and continues to charge. Lead acid battery inputs and derivatives are given in Section 4.5.3.

Type 47 model works based on the Shepherd formula, which was originally designed to describe the discharge of a battery, but it can also apply to battery charging with different parameters. The Shepherd formula at discharge ($I < 0$) is:

$$V = e_{qd} - g_d H + I r_{qd}\left(1 + \frac{m_d H}{\frac{Q_d}{Q_m} - H}\right) \tag{24}$$

and on charge ($I > 0$):

$$V = e_{qc} - g_c H + I r_{qc}\left(1 + \frac{m_c H}{\frac{Q_c}{Q_m} - H}\right) \tag{25}$$

where e_{qd} and e_{qc} are open circuit voltage at full charge and discharge, H is the depth of discharge, g_d is battery coefficient, r_{qd} is internal resistance at full charge, md and mc are cell type parameters, Q_d and Q_c are capacity parameters on charge/discharge and Q_m is rated capacity of the cell.

The Shepherd formula loses precision at low voltage. In order to overcome this precision loss, Hyman added an additional voltage term (V_{zp}) to the Shepherd formula as follows [64];

$$V = V_{oc} - V_{zp} - g_c H + I r_{qc} \left(1 + \frac{m_c H}{\frac{Q_c}{Q_m} - H} \right) \quad (26)$$

where V_{zp} is the correction voltage term and V_{oc} is open circuit voltage at full charge and they can be calculated as follows:

$$V_{zp} = \frac{1}{k_{zp}} \ln \left(\frac{|I|}{I_{zp}} + 1 \right) \quad (27)$$

$$V_{oc} = \frac{1}{2} (e_{qd} + e_{qc}) \quad (28)$$

In this study, the Hyman formula (Eqn. 25) was used to model the V-I relationship and the corresponding state of the charge of the battery. The calculation was made on a single cell and the total power, voltage, and the current was determined by multiplying the number of cells in series and/or parallel. The parameter table is given in Appendix C.

4.4.4. Type 105a: Mini Grid Controller

For stand-alone power systems, the Type 105a is the control mechanism for systems consisting of renewable energy sources, an electrolyzer, a hydrogen storage unit, and a diesel generator. The controller's action works to calculate a power setpoint for the controlled components. It provides integrated operation of all systems as a controller for solar panels, wind turbines, batteries, diesel generators, electrolyzers, and hydrogen tanks [64].

4.4.5. Type 175a: Power Conditioning

Type175 is a mathematical model for a power conditioning unit. The model is based on empirical efficiency curves for electric converters (DC/DC) or inverters (DC/AC or AC/DC). The type can operate in either of two modes. In mode 1 it is assumed that the current input power is known. The corresponding output power is calculated. In mode 2 it is assumed that the required output power is known. The corresponding input power is calculated. Power conditioners are tools that can convert DC power to AC power and/or vice versa. These devices operate as DC/DC converters. In Independent Power Systems (SAPS), which consist of both DC power generating and DC power consuming components, DC/DC converters are sometimes used to transfer DC power from one voltage to another.

In a SAPS based on a renewable energy source such as solar or wind power, the input power of the system is constantly changing. The output characteristics of a PV panel array, wind turbine, or other energy source have peak power points that depend on sunlight and cell temperature, wind speeds, respectively. To use the full capacity of the input power supply, it is necessary to use a maximum power point monitor (MPPT).

System losses occur depending on the electric current passing through the systems. The power loss is calculated as follows [64].

$$\mathrm{P_{loss}} = \mathrm{P_{in}} - \mathrm{P_{out}} \tag{29}$$

The electrical efficiency of the power conditioner is calculated as follows.

$$\eta_{el} = \frac{\mathrm{P_{out}}}{\mathrm{P_{in}}} \tag{30}$$

Current output:

$$I_{out} = \frac{P_{out}}{U_{out}} \tag{31}$$

4.4.6. Type 160a: Electrolyzer

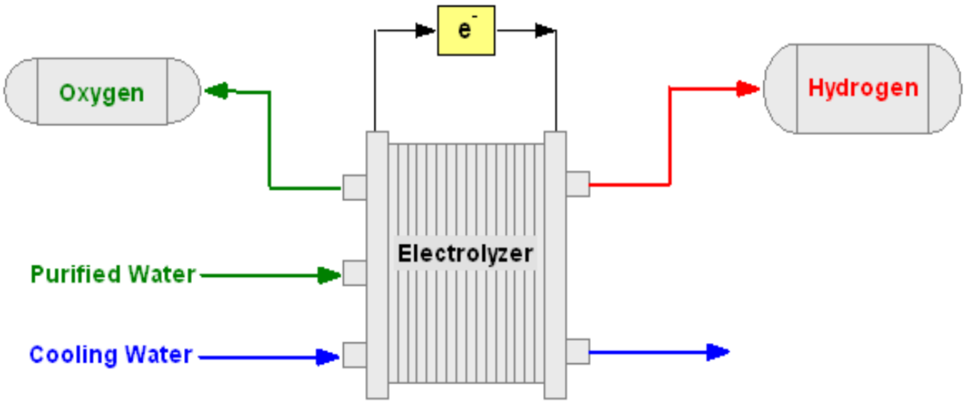

Figure 24. Electrolyzer Working Principle [64]

Water is separated into hydrogen and oxygen by passing a DC electric current between two electrodes separated by an aqueous electrolyte with strong ionic conductivity. The parameter table is given in Appendix D. The reaction formula for the decomposition of water [37,64]:

$$H_2O(I) + \text{Electric Energy} \rightarrow H_2(g) + {}^1/_2\, O_2 \tag{32}$$

Electrochemical Model: The subcomponent model is used based on purely theoretical laws of thermodynamics, heat transfer, and electrochemical empirical expression. This includes a thermal model. A temperature-dependent current-voltage equation is used. This equation is designed for the high-end alkaline electrolyzer. The characteristic equation of the electrolyzer is given as follows.

$$U_{cell} = U_{rev} r^* \frac{I_{ely}}{AREA} + s^* \left(\frac{I_{ely}}{AREA} + 1\right) \quad (33)$$

With:

$$r^* = r_1 + r_2 T_{ely} \quad (34)$$

$$s^* = s_1 + s_2 T_{ely} + s_2 {T_{ely}}^2 \quad (35)$$

$$t^* = t_1 + \frac{t_2}{T_{ely}} + \frac{t_3}{{T_{ely}}^3} \quad (36)$$

Where, s^* and $t^*$are parameters for overvoltage on electrodes and r^*, for resistance of electrolyte. T is electrolyte temperature (°C) and AREA, is electrode area (m^2).

The typical I-V curve for alkaline electrolyzer at different operating temperatures is seen in Figure 24 indicating that the electrolyzer current increases with voltage and temperature. The I-V relationship determines how much power is required to produce a unit of hydrogen gas. However, this equation excludes the effect of parasitic current caused by gas leakage throughout the membrane and any side reactions occurring simultaneously. This lowers the hydrogen production rate per power consumed. To include this effect, the Faradaic efficiency needs to be determined.

According to Faraday's law, the hydrogen production rate in an electrolyzer cell is directly proportional to the transfer rate of electrons at the electrodes. However, this relation fails when there is a parasitic current due to gas leakage and side reactions, i.e., either the product gas or electrons are wasted. To cover this effect, the Faradaic efficiency was introduced, which is defined as the ratio between the actual and theoretical maximum amount of hydrogen produced in the electrolyzer [64,67,68]. In TRNSYS, the Faradaic efficiency and the hydrogen production rate were calculated by using the following equations [64].

$$\eta_f = \left[\frac{I_{density}^2}{a_1 + I_{density}^2}\right].a_2 \qquad (37)$$

where, $I_{density}$ is the current density of the cell, and a_1, a_2 are unitless fitting parameters.

$$\dot{n}_{H_2} = \eta_f . N_{cells} . \frac{I_{ely}}{\eta_d . F} \qquad (38)$$

where, $\dot{n}_{H_2}$ is the hydrogen production rate, η_f is the faraday efficiency, N_{cells} is the number of series, η_d is the moles of electrons per mole of water, and F is the Faraday constant.

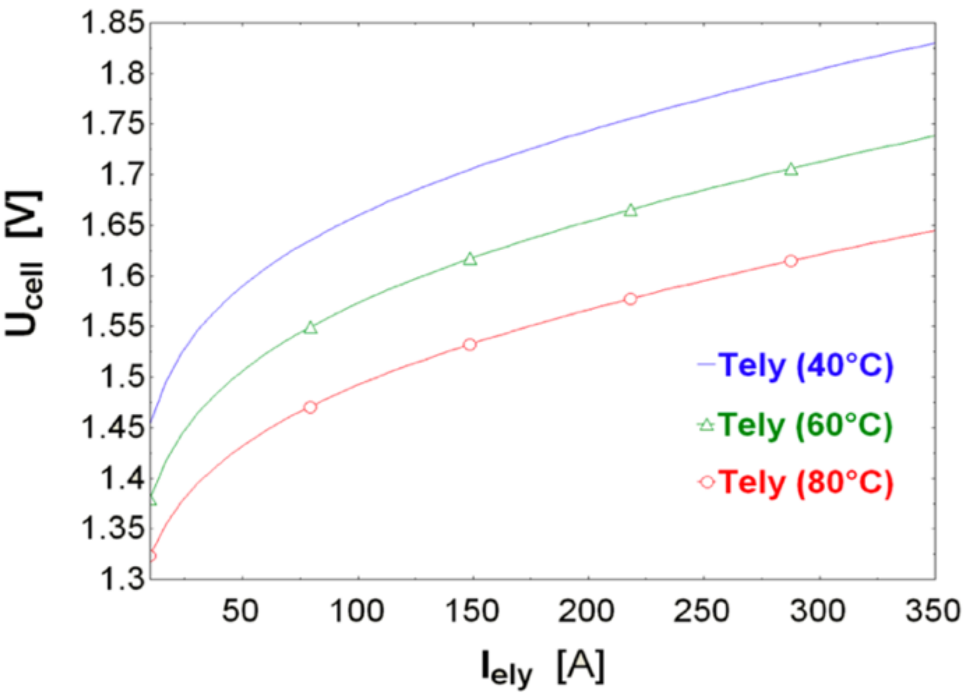

Figure 25. Electrolyzer-Cell Voltage/Current Graphs [64]

4.4.7. Type 164: Compressed gas storage

The Type164 model calculates the pressure in a storage tank according to the van der Waals equation of state for real gases. The pressure p of the real gas is calculated as [64,67]:

$$p = \frac{n.R.T_{gas}}{Vol - n.b} - a.\frac{n^2}{Vol^2} \tag{39}$$

where n represents the number of moles of gas, R is the universal gas constant, Vol is the volume of the storage tank, and T_{gas} is the temperature of the gas. The second term (containing the constant a) describes the intermolecular forces of attraction, and b describes the volume occupied by the gas molecules.

In the van der Waals equation, a and b are defined as:

$$a = \frac{27R^2T_{cr}^2}{64p_{cr}} \tag{40}$$

$$b = \frac{RT_{cr}}{8p_{cr}} \tag{41}$$

where T_{cr} and p_{cr} are the critical temperature and pressure of the substance, respectively. Calculates the hydrogen in the tank according to the mass. If the pressure is above the specified level, excess hydrogen is discharged. The parameter table is given in Appendix E.

4.4.8. Type 120: Internal Combustion Engine/ Generator

Type 120 is a mathematical model for a diesel engine generator (DEGs). The DEGs model is based on the empirical relationship for differential fuel consumption expressed as a function of electrical power output. Within the scope of the DEGs model, both electricity and fuel efficiency calculations are made. This model can simulate the same DEGS models in its content.

The model includes 5 different DEGS fuel models. In this study, natural gas or hydrogen (H^2) was chosen as a liquid fuel [64]:

The normalized power is defined as:

$$X = \frac{P_{DEGS}}{P_{DEGS,rated}} \quad (42)$$

The electrical efficiency is:

$$\eta_{el} = \frac{P_{DEGS}}{\rho_{fuel}\dot{V}_{fuel}LVH_{fuel}} \quad (43)$$

The total power output is:

$$P_{total} = N_{DEGs}P_{DEGs} \quad (44)$$

4.5. System Size Selection

Some equipment is used in the systems designed for the IZTECH campus. The selection criteria and models of the equipment used are given below.

4.5.1. Determination of the Type and Number PV Panel

The choice of photovoltaic panels to be installed on the roof of the buildings in the IZTECH University Campus has been chosen among the panels that are used today and display high efficiency and performance indicators.

Within the scope of this thesis, a photovoltaic panel with Jinko Tiger Pro 525 Wp features was selected. It has a monocrystalline structure. The catalogue information of the monocrystalline module is shown in Figure 26.

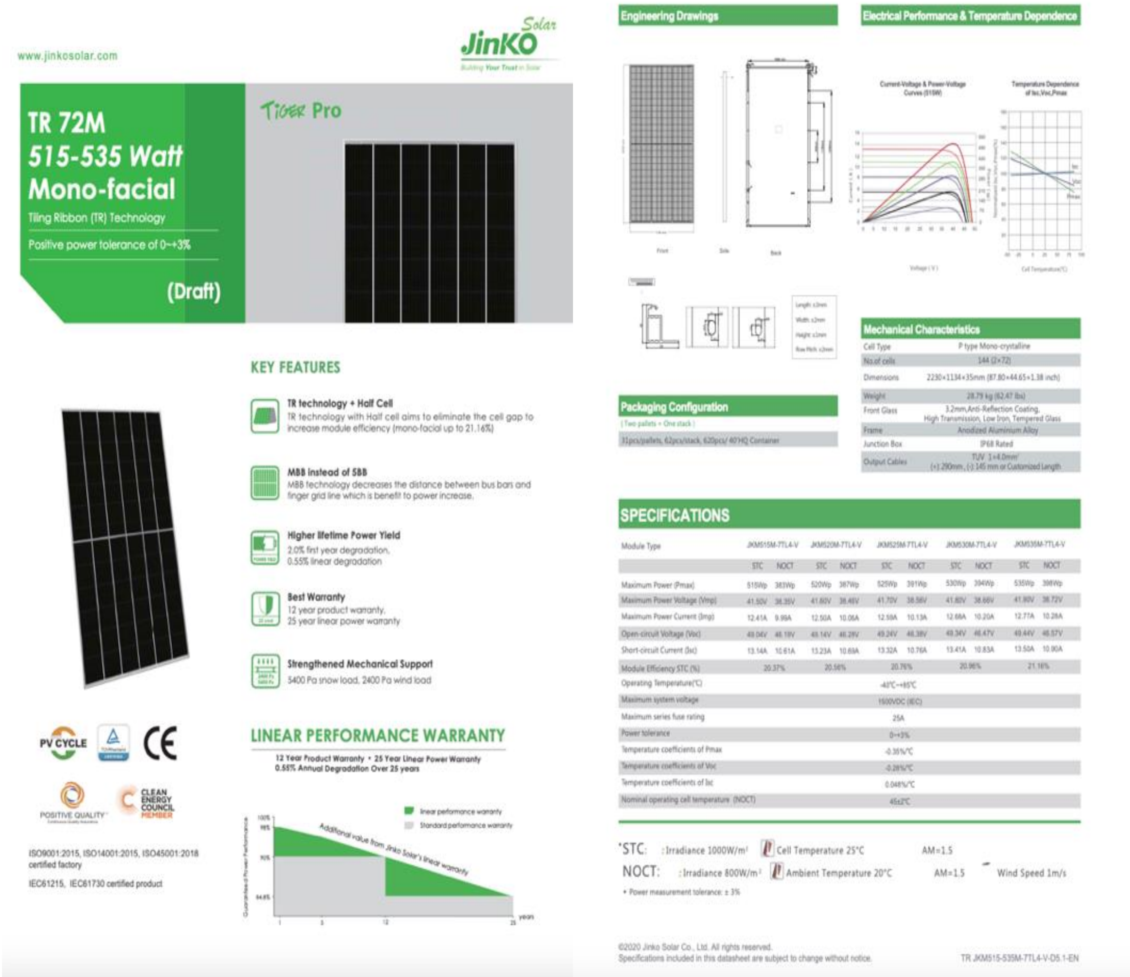

Figure 26. Jinko 525 Wp Panel Datasheet [69]

4.5.1.1. Determination of the Number PV Panel

In TRNSYS 18, solar radiation data is used from a different database. There is a User-Defined file in TRNSYS 18 software. An online meteorological database PVGIS was used for this study.

Table 12. Meteorological Databases used and their characteristics

Database	Meteorological Database	Reason for selection	Website
PVGIS	Europe, Africa parts of Asia and America	Satellite-based dollar radiation data	http://ec.europa.eu/jrc/en/pvgis

Since the buildings are in different locations within the campus, it is necessary to understand the relationship between location and solar radiation. Climate data were obtained for each location in the campus by the PVGIS program. The received data were loaded to TRNSYS 18 software. The annual electricity production of each building for 1 PV module was calculated (Table 13) based on the equations in Section 4.4.1. The highest production rate is seen in the General Culture Building and the radiation rates vary slightly concerning location on the campus. By using this information, the amount of power generation for each building was calculated based on the location of the buildings. Then, the number of PV panels required for each building was determined by dividing the annual electricity need of the building and the amount of electricity produced by a single PV panel.

Table 13. Annual Production for 1 Panel

Campus Building	kWh
General Culture Building	447.20
Rectorate Building	446.70
Head Of Department	446.70
Faculty Of Science	
A Block	444.70
B Block	444.83
C Block	444.83
Classroom Building	444.58
Physic Building	443.42
Mathematics Building	443.66
Biology Building	443.66
Foreign Language Building	
Foreign Language A Block	445.57
Foreign Language B Block	445.57
Administrate Building	445.57
Energy System Lab. Building	445.23
Center Work	445.23
Mechanical Engineering Building	446.54
Faculty of Architecture	
A Block	437.20
B Block	437.20
C Block	437.20
D Block	437.20
E Block	437.20
Chemistry Eng. Building.	446.16
Computer Eng. Building	446.33
Library	446.33
Gym Center	446.37
Pool	446.33
Café	446.52
Civil Engineering	446.23
Electric Electronic	446.14
Average	**444.15**

4.5.2. Determination of the Type and Number Wind Turbine Capacity

The conversion of kinetic energy in Wind Energy into mechanical energy is done by the components [47]. The general components of the wind turbine are as follows.

- Tower,
- Wings,
- Gearbox,

It consists of a generator and electrical-electronic elements.

Wind turbines are classified according to various criteria. The criteria to be considered while making this classification can be classified according to the position of the wing axis on the ground.

Within the scope of this thesis, it has progressed with a horizontal axis wind turbine. The rotation axes of horizontal axis wind turbines are parallel to the wind direction and their blades are perpendicular to the wind direction. Horizontal-axis wind turbines are generally designed to receive the wind from the front [38].

A few of the obtained information on different turbine brands are presented in Table 14 below.

Table 14. Wind Turbine Models

Turbine Type	**Manufacturer**	**Name**	**Nominal Power (MW)**	**Rotor Diameter (m)**	**Rotor Area (m^2)**	**Hub Height (m)**
MM92/ 2050	Senvion/REpower	MM92	2.05	93	6.719	68,5;80,0;100,0
N100/ 2500	Nordex		2.5	100	7.853	75;85;100
V80/ 2000	Vestas	V80-2.0 MW	2.0	80	5.026	60;67;78;80;100
VS112/ 2500	Vensys	VENSYS100 2.5MW	2.5	100	7.853	100;

The test measuring mast in the IZTECH University Campus affects the selection of the wind turbine to be used. The selection of the wind turbine model was made by considering that the annual power generation of the selected turbine covers the annual electricity need of the campus. The wind turbine model considered in the current study is Nordex-N100/2500 for the IZTECH University Campus. The evaluated wind turbine has a nominal capacity of 2.5 MW, a hub height of 75-100 m, a rotor diameter of 100 m, a turn-on wind speed of 3.0 m/s, a cut-out wind speed of 20.0 m/s, and a nominal wind speed of 12 m/s. Horizontal axis wind turbine was selected. The wind turbine will be installed within the IZTECH campus. The turbine specifications in Figure 27 are given.

FACTS AND FIGURES.

	N100/2500
Rotor	
Number of rotor blades	3
Rotor speed	9.6 – 14.9 rpm
Rotor diameter	100 m
Swept area	7,854 m²
Power regulation	Pitch
Cut-in wind speed	3 m/s
Cut-out wind speed	20 m/s
Rated power	From 13 m/s
Survival wind speed	52.5 m/s
Pitch regulation	Individual rotor blade pitch
Weight	Approx. 56,500 kg
Rotor blades	
Length	48.7 m
Material	GRP
Weight	Approx. 9,800 kg
Gearbox	
Type	Planetary/spur gear or differential gearbox
Gear ratio	1:77.4 (50 Hz)/1:92.9 (60 Hz)
Generator	
Power	2,500 kW
Voltage	660 V
Type	Double-fed asynchronous generator with partial frequency converter
Frequency	50 or 60 Hz

	N100/2500
Yaw system	
Bearing	Ball bearing
Brake	Hydraulic disc brake
Drive	Asynchronous motors with integrated brakes
Speed	Approx. 0,4 deg/s
Control system	
Type	PLC, Remote Field Controller (RFC)
Grid connection	Via IGBT converter
Scope of monitoring	Remote monitoring of over 300 different parameters, e.g. temperature, hydraulic pressure, pitch parameters, wind speed and direction
Recording	Production data, event lists with filter function, long and short-term trends
Visualisation	Panel PC in control cabinet and Web-based access possible from any PC, adapter for laptop at the bottom of tower or in nacelle
Brakes	
Primary	Rotor blade pitch
Secondary	Hydraulic disc brake
Tower	
Type	Modular, tubular steel tower
Hub height	100 m, certificate DIBt 2, IEC 3a

POWER CURVE N100/2500

Wind speed [m/s]	Power [kW]	Power coefficient Cp
4	50	0,162
5	221	0,368
6	431	0,415
7	720	0,436
8	1102	0,447
9	1575	0,449
10	2019	0,420
11	2304	0,360
12	2458	0,296
13	2500	0,237
14	2500	0,189
15	2500	0,154
16	2500	0,127
17	2500	0,106
18	2500	0,089
19	2500	0,076
20	2500	0,065

Rounded values based on aerodynamic calculations from 06/08, subject to change.

Figure 27. Nordex N100/2500 Turbine Datasheet [70]

Power curves are given in Figure 28. These curves are obtained from wind turbine manufacturers and show the amount of power that can be obtained for different wind speeds.

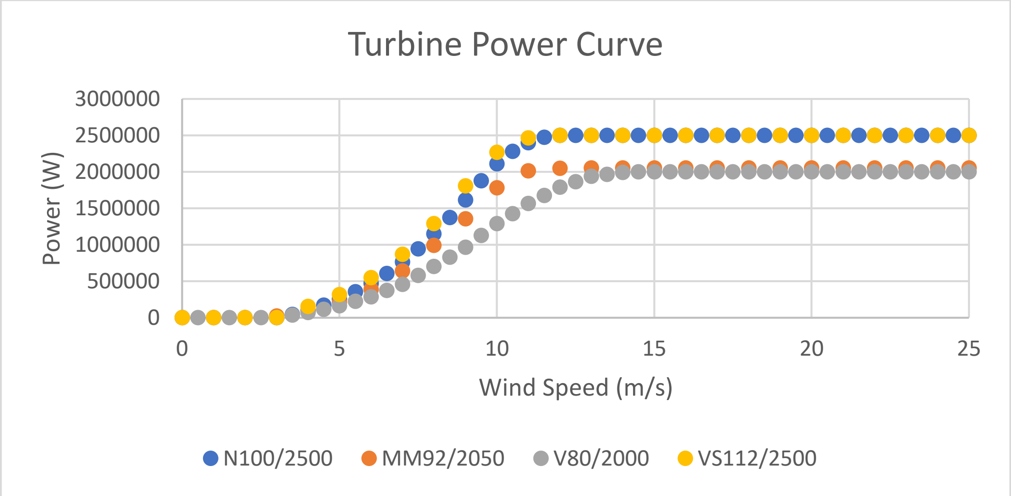

Figure 28. Turbines Power Curve

Turbine Power Data: The wind data to be used in wind energy calculations were recorded for an average of 10 minutes. The obtained data were converted into 10-minute averages and hourly data. Hourly data are entered into the climate data in TRNSYS. The system design for wind energy is based on real data. The determined TRNSYS parameters are as follows.

- Height above sea level is 52 m. The determined parameters are as follows.
- The wind data in the weather data file is measured from 100 meters of tower height.
- The wind turbine to be selected with a power of 2.5 MW has been accepted as the hub height varying between 100 m according to the manufacturer.

Table 15, other parameter data is available in an external file.

Table 15. Wind Turbine-TRNSYS External File

Turbine Rated Conditions	
Rotor Height (Rotor_Ht)	60 m
Rotor Diameter (Rotor_Di)	100 m
Sensor Height (Sensor_Ht)	101.0 m
Rated turbine power output (Pwr_Ratd)	2.5 MW
Rated Wind Speed (Spd_Ratd)	15.00 m/s
Number of Rotors Fields	26

4.5.3. Inverter Selection

The inverter is of great importance in systems created with renewable energy sources. An inverter is a device that converts direct current to alternating current. It converts DC energy obtained from photovoltaic panel systems to AC energy. It balances the AC power from wind turbines. Inverters can be of different sizes and configurations. The inverter is in the role of connecting renewable energy systems. When enough renewable energy is available to both meet the load and charge the battery, it is thanks to the inverters that the battery reaches its lower and upper limits.

Huawei was chosen as the inverter brand in the hybrid energy system design. Within the scope of the campus, each system has different installed powers. Therefore, inverters with different powers have been selected. Huawei-branded inverters and their powers are given in Table 16. Depending on these inverter models and MPPT inputs, the series-parallel connections of the panels are determined.

Table 16. Huawei Inverter Models [58]

Inverter Model	Power (Watt)
Huawei Inverter SUN200-12KTL	12,000
Huawei Inverter SUN200-17KTL	17,000
Huawei Inverter SUN200-30KTL	30,000
Huawei Inverter SUN200-33KTL	33,000
Huawei Inverter SUN200-36KTL	36,000
Huawei Inverter SUN200-40KTL	40,000
Huawei Inverter SUN200-50KTL	50,000
Huawei Inverter SUN200-105KTL	105,000
Huawei Inverter SUN200-110KTL	110,000
Huawei Inverter SUN200-185KTL	185,000

4.5.4. Battery Selection

A battery is used to store the electrical energy obtained from renewable energy sources and use it at the required hours. It is an important component in standalone hybrid system designs. There is a lead acid battery model in TRNSYS software. In this thesis, the SUNLIGHT RES OPzV-2V 26 RES POzV 4535 model lead acid battery has been selected. The catalogue values of the battery are given in Figure 29.

	RES OPzV model	Rated Capacity (Ah) at 20°C (68°F)					Dimensions mm (in)				Weight kg (lb)	Internal Resistance (mOhm)	Short Circuit Current (A)
		C240 1.85 Vpc	C120 1.85 Vpc	C48 1.80 Vpc	C24 1.80 Vpc	C12 1.80 Vpc	Length	Width	$Height_1$	$Height_2$			
Cells	2V 2 RES OPzV 145	150	145	141	129	116	103 (4.06)	206 (8.11)	354 (13.94)	382 (15.04)	13.6 (30.0)	1.650	1240
	2V 3 RES OPzV 215	225	218	211	194	174	103 (4.06)	206 (8.11)	354 (13.94)	382 (15.04)	15.7 (34.6)	1.110	1840
	2V 4 RES OPzV 290	301	290	281	258	232	103 (4.06)	206 (8.11)	354 (13.94)	382 (15.04)	18.3 (40.3)	0.830	2460
	2V 5 RES OPzV 360	376	363	352	323	290	124 (4.88)	206 (8.11)	354 (13.94)	382 (15.04)	21.8 (48.1)	0.670	3040
	2V 6 RES OPzV 435	452	435	423	388	347	145 (5.71)	206 (8.11)	354 (13.94)	382 (15.04)	26.4 (58.2)	0.565	3620
	2V 5 RES OPzV 535	561	536	517	472	420	124 (4.88)	206 (8.11)	471 (18.54)	499 (19.65)	30.0 (66.1)	0.570	3580
	2V 6 RES OPzV 640	675	644	622	567	504	145 (5.71)	206 (8.11)	471 (18.54)	499 (19.65)	35.3 (77.8)	0.485	4200
	2V 7 RES OPzV 750	789	753	727	662	588	166 (6.54)	206 (8.11)	471 (18.54)	499 (19.65)	40.8 (89.9)	0.430	4740
	2V 5 RES OPzV 780	822	781	744	674	597	145 (5.71)	206 (8.11)	643 (25.31)	671 (26.42)	43.8 (96.6)	0.530	3850
	2V 6 RES OPzV 935	986	937	892	809	716	145 (5.71)	206 (8.11)	643 (25.31)	671 (26.42)	48.2 (106.3)	0.445	4600
	2V 7 RES OPzV 1090	1147	1091	1039	942	835	191 (7.52)	210 (8.27)	644 (25.35)	672 (26.46)	61.2 (134.9)	0.365	5600
	2V 8 RES OPzV 1245	1311	1247	1187	1077	954	191 (7.52)	210 (8.27)	644 (25.35)	672 (26.46)	65.5 (144.4)	0.325	6300
	2V 9 RES OPZV 1400	1477	1404	1337	1212	1074	233 (9.17)	210 (8.27)	646 (25.43)	674 (26.54)	75.9 (167.3)	0.295	6900
	2V 10 RES OPzV 1560	1641	1560	1485	1347	1193	233 (9.17)	210 (8.27)	646 (25.43)	674 (26.54)	80.4 (177.3)	0.265	7700
	2V 11 RES OPzV 1720	1811	1720	1637	1483	1313	275 (10.83)	210 (8.27)	645 (25.39)	673 (26.50)	90.8 (200.2)	0.245	8350
	2V 12 RES OPzV 1875	1976	1877	1786	1618	1432	275 (10.83)	210 (8.27)	645 (25.39)	673 (26.50)	95.1 (209.7)	0.225	9050
	2V 11 RES OPzV 1940	2029	1943	1879	1722	1538	275 (10.83)	210 (8.27)	796 (31.34)	824 (32.44)	105.0 (231.5)	0.230	8850
	2V 12 RES OPzV 2120	2214	2120	2050	1878	1678	275 (10.83)	210 (8.27)	796 (31.34)	824 (32.44)	110.1 (242.7)	0.210	9700
	2V 14 RES OPzV 2470	2580	2471	2390	2190	1957	399 (15.71)	214 (8.43)	771 (30.35)	799 (31.46)	146.0 (321.9)	0.180	11350
	2V 15 RES OPzV 2645	2764	2647	2561	2346	2097	399 (15.71)	214 (8.43)	771 (30.35)	799 (31.46)	151.0 (332.9)	0.167	12200
	2V 16 RES OPzV 2820	2949	2824	2731	2503	2237	399 (15.71)	214 (8.43)	771 (30.35)	799 (31.46)	156.1 (344.1)	0.157	13000
	2V 18 RES OPzV 3170	3310	3171	3071	2814	2516	487 (19.17)	212 (8.35)	769 (30.28)	797 (31.38)	185.2 (408.3)	0.137	14900
	2V 20 RES OPzV 3520	3678	3523	3412	3127	2796	487 (19.17)	212 (8.35)	769 (30.28)	797 (31.38)	195.3 (430.6)	0.123	16600
	2V 22 RES OPzV 3890	4068	3894	3764	3447	3077	576 (22.68)	212 (8.35)	771 (30.35)	799 (31.46)	221.2 (487.7)	0.115	17750
	2V 24 RES OPzV 4245	4438	4248	4106	3760	3357	576 (22.68)	212 (8.35)	771 (30.35)	799 (31.46)	231.4 (510.1)	0.108	18900
	2V 26 RES OPzV 4535	4747	4536	4405	4026	3586	576 (22.68)	212 (8.35)	771 (30.35)	799 (31.46)	241.5 (532.4)	0.103	19800
Blocks	6V 4 RES OPzV 250	263	253	250	233	212	272 (10.71)	205 (8.07)	332 (13.07)	372 (14.65)	55.2 (121.7)	2.70	2270
	6V 5 RES OPzV 315	330	317	313	292	265	380 (14.96)	205 (8.07)	332 (13.07)	372 (14.65)	62.8 (138.5)	2.22	2760
	6V 6 RES OPzV 380	397	381	377	350	318	380 (14.96)	205 (8.07)	332 (13.07)	372 (14.65)	69.0 (152.1)	1.89	3240
	12V 1 RES OPzV 65	65	63	62	58	52	272 (10.71)	205 (8.07)	332 (13.07)	372 (14.65)	43.8 (96.6)	19.01	640
	12V 2 RES OPzV 125	130	125	124	115	105	272 (10.71)	205 (8.07)	332 (13.07)	372 (14.65)	50.5 (111.3)	9.50	1290
	12V 3 RES OPzV 185	196	188	186	173	158	380 (14.96)	205 (8.07)	332 (13.07)	372 (14.65)	73.3 (161.6)	6.80	1800

Figure 29. Sunlight RES OPzV Battery Datasheet [71]

There is no lithium-ion battery model in TRNSYS software. As the future projection of the study, the values of Lithium-ion batteries, which are widely used today, were found. The Huawei Smart String ESS Battery Pack model lithium-ion battery was selected in this study. The catalogue values of the battery are given in Figure 30.

Smart String ESS
Battery Pack & Smart Rack Controller

Battery Pack	
General	
Cell Material	LFP
Pack Configuration	16S 1P
Rated Voltage	51.2 V
Nominal Capacity	320 Ah / 16.38 kWh
Supported Charge & Discharge Rate	≤ 1 C
Weight	≤ 140 kg
Dimensions (W x H x D)	442 x 308 x 660 mm
Operating Voltage Range	43.2 V ~ 56.4 V

Figure 30. Huawei Smart String ESS Battery Pack [72]

4.6. A Standalone Renewable Energy System Scenarios

For the IZTECH Campus, 4 different standalone renewable energy scenarios were considered. PV array or wind turbine were used as a power source while lead-acid battery or the combination of electrolyzer-H_2 tank-generator were used as a storage unit. The technical specifications of the equipment used are given in Section 4.5. The modeling of renewable energy systems was done by using the TRNSYS program. In addition, the results in the case of Li-ion battery applications have been investigated.

4.6.1. Scenario 1: PV, Lead Acid Battery, Power Controller

The main source of the standalone energy system designed in the first scenario is Solar Energy. Due to the location of İzmir Institute of Technology, solar radiation is high. Appropriate roof areas of the faculties were used for system designs. In section 3.1, suitable roof areas identified by the PV*SOL program were examined. Photovoltaic panels placed on suitable roof areas produce electrical energy with maximum efficiency. The system structure, the electrical energy produced, is stored in the battery if the building meets the load demand. The stored energy is designed to meet the electricity need when solar energy is not active.

The grid-independent photovoltaic panel and battery system setup was examined in 4 different sub-scenarios and the most suitable option was determined.

4.6.1.1. Sub-scenario 1. Maximum PV Panel Installation for each Building (MPPIB)

In this installation, the maximum photovoltaic panel installation on the roofs of IZTECH buildings was designed, and the number of batteries was calculated and examined to meet the self-consumption of each connected building.

4.6.1.2. Sub-scenario 2. Maximum PV Panel Installation on Campus (MPPIC)

In this installation, maximum photovoltaic panel installation was designed on the roofs of IZTECH buildings, and the number of batteries was calculated and examined to meet the consumption of the entire campus.

4.6.1.3. Sub-scenario 3. Necessary PV Panel Installation for each Building (NPPIB)

In this installation, the necessary photovoltaic panel installation was designed depending on the consumption of IZTECH buildings, and the number of batteries was calculated and examined to meet the self-consumption of each building.

4.6.1.4. Sub-scenario 4. Necessary PV Panel Installation on Campus (NPPIC)

In this installation, the necessary photovoltaic panel installation was designed depending on the consumption of IZTECH buildings, and the number of batteries was calculated and examined to meet the consumption of the entire campus.

4.6.2. Scenario 2: PV, Electrolyzer, H_2 Tank, Generator, Power Controller

The main objective of the second scenario was designed to model the typical annual operation of a hydrogen energy storage system powered by a PV array. Determining its size is very important for the performance of the system. System designs were modeled using TRNSYS software. The main elements of this scenario are PV Panel, diesel generator, electrolyzer, and hydrogen tank. Power conversions between systems are done by the controller [19]. IZTECH decides to operate solar energy and hydrogen tank parameters depending on the power demand of the university. If the electrical energy produced from photovoltaic panels is higher than the load demand, it is transferred to the electrolyzer. The electrolyzer begins to produce hydrogen. When hydrogen reaches the maximum pressure limit entered in the tank, hydrogen production stops. The excess power produced is thrown out [68].

If the electrical energy produced from photovoltaic panels is less than the load demand, it is converted into hydrogen electricity by the diesel generator. The stored hydrogen is converted back into electrical energy with the help of DEGs and the load demand is met.

4.6.3. Scenario 3: Wind turbine, Lead Acid Battery, Power Controller

The main source of the standalone energy system designed in the third scenario is Wind Energy. If the energy produced from the wind turbine is more than the electricity load demand, the excess energy produced is stored in the battery system. The excess energy stored is used when wind energy is not produced or when there are network failures. When wind energy is not produced, or when it cannot meet the electrical load, the energy stored in the battery is activated. After reaching the minimum charge level, its discharge is stopped. It stops charging when it reaches the maximum charge level.

4.6.4. Scenario 4: Wind Turbine, Electrolyzer, H_2 Tank, Generator, Power Controller

Designed in the fourth scenario, is designed to model the typical annual operation of an off-grid hydrogen energy storage system powered by a wind turbine. Determining its size is very important for the performance of the system. The main elements of this scenario are a wind turbine, diesel generator, electrolyzer, and hydrogen tank. Power conversions between systems are done by the controller [19]. IZTECH decides to run wind energy and hydrogen tank parameters depending on the power demand of the university. If the electrical energy produced from the wind turbine is higher than the load demand, it is transferred to the electrolyzer. The electrolyzer begins to produce hydrogen. When hydrogen reaches the maximum pressure limit entered in the tank, hydrogen production stops. The excess power produced is thrown out.

If the electrical energy produced from the wind turbine is less than the load demand, it is converted into hydrogen electricity by the diesel generator. The stored hydrogen is converted back into electrical energy with the help of DEGs and the load demand is met [68].

4.7. Economic Analysis

One of the important issues to be evaluated while designing a standalone hybrid energy system is the profitability of the project. If the project is implemented, income and expenses need to be calculated and evaluated. In addition, the depreciation period calculation is performed. After a certain period, it is decided whether the project will be realized or not by applying economic analysis methods to the projects that are planned to generate income. At the same time, economic analysis methods are used to select and support the more appropriate projects [73].

Investment cost and project income are important for the financial calculation of standalone hybrid energy systems. System costs depend on many factors. These; system configuration, equipment options, labor cost, and financing cost. Within the scope of this thesis, although the same brand materials and equipment were used, designs were made with different system powers. The roof types, areas, and load demand of the buildings in the IZTECH campus area are different. The main items that make up the cost in hybrid system installations are as follows, photovoltaic panel, wind turbine, inverter, battery, diesel generator electrolyzer, and hydrogen tank. Section 5.5., for each scenario designed for the IZTECH campus, an economic cost analysis was made.

LCOE (Levelized Cost of Energy): Levelized energy cost is the cost of energy investments, starting from the establishment of the projects, after their implementation, and after the start of production. It is the unit energy cost calculated by considering the It is a very important criterion in determining whether to progress in a project or to compare different energy-producing projects. Levelized energy cost is one of the main parameters that express the production costs of electricity generation facilities. The following formula is used to calculate LCOE.

The levelized cost of energy (LCOE) is the ratio of the annual cost of the system to the electrical energy the system produces annually:

$$LCOE = \frac{Sum\ of\ Costs\ Over\ Lifetime}{Sum\ of\ Electrical\ Energy\ Produced\ Over\ Lifetime} \tag{45}$$

$$= \frac{\sum_{t=1}^{n} \frac{I_t + M_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+i)^t}}$$

where t is the time of cash flow, I_t is the investment expenditures in the year t, M_t is the operations and maintenance expenditures in the year t, E_t is the electrical energy generated in the year t, i is the interest rate, n is the expected lifetime of system or power station [74].

Net Present Value: The cash flows of the project to be invested are valued according to the time value of money. NPV is the present value of the initial and operating costs over the life of the system. It can also be considered as the life cycle cost of the system. Net present value calculation is done to analyze the profitability of the planned project. The net present value of the project is the difference between the sum of the present values of the project's revenues over the years and the sum of the net present values of the costs over the years. Calculations are made using the appropriate discount rate. If the net present value is positive, the projects are viable, if it is negative, the project is not viable. The following formula is used to calculate NPV [45,73,75,76].

$$NPV(i, N) = \sum_{t=0}^{N} \frac{R_t}{(1+i)^t} \tag{46}$$

where R_t is the net cash flow, i is the interest rate, t is the time of cash flow,and N is the project life [77].

The capital recovery factor is used to calculate the annualized project cost for a given time period and can be calculated as follows:

$$CRF(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{47}$$

CRF is the capital recovery factor. The interest rate i is accepted as 4%, and the useful project life N is determined as 25 years [36].

Electrical Mechanical Cost: These are the initial construction costs of the plant and major maintenance work that require electrical and mechanical equipment beyond typical operating costs. Since the IZTECH campus area consists of 30 buildings, calculations should be made on a building basis.

Annual Energy Cost Saving: Electricity prices in Turkey are announced on the EMRA website at regular intervals (on average every 3 months) with the decision of the EMRA board of directors. The electricity price forecast for 2023 is calculated as 440 TL/MW [78]. Since the system designed for the IZTECH campus is independent of the grid, the generated electricity will be used directly.

$$\begin{aligned} &Annual\ Energy\ Cost\ Saving \\ &\quad = Electricity\ Price\ (\$/kWh) * Production(kWh) \end{aligned} \tag{48}$$

$$\begin{aligned} &Annual\ Energy\ Cost\ Saving \\ &\quad = 0.23783\ (\$/kWh) * Production(kWh) \end{aligned}$$

Annual Operating cost:

Maintenance costs must be considered for each year. The maintenance cost calculation is as follows. Operation and maintenance costs vary depending on the difficulty of implementing equipment maintenance in the system to be installed [79].

To financially evaluate the results of the designed systems, an economic analysis is made in section 5.3. The cost of renewable energy systems is a major concern. In the sizing steps, the best configuration is selected by choosing the configuration with the lowest LCOE. Levelized cost of energy (LCOE) and net present value (NPV) are calculated for standalone hybrid systems.

CHAPTER 5

RESULT AND DISCUSSION

This thesis focuses on the Hybrid System design and Green Campus study within the scope of Izmir Institute of Technology University in Turkey. It is aimed to meet the electricity consumption of the faculty buildings in the IZTECH Campus with renewable energy sources. This study used TRNSYS software to simulate an independent hybrid renewable energy system consisting of solar and wind energy as the primary source, battery, electrolyzer, and diesel generator system as a backup source. Hybrid system designs are examined as PV/Battery, Wind/Battery, PV/Electrolyzer/H_2 Storage/Generator, and Wind/Electrolyser/H_2 Storage/Generator. These systems are designed and optimized to meet the electrical load demand of IZTECH University. The same load profiles were used for the simulated system. Hourly, daily, and annual performance evaluations and component costs of these systems are estimated and analyzed. Optimized system goals include minimizing LCOE and reducing residual power generation and unmet electrical power. System models are created as realistically as possible. Each system design is handled separately. Suggestions for performance improvements are presented.

In this study, hybrid energy systems are designed to operate independently of the grid. Dimensioning of hybrid system designs is very important. Otherwise, problems such as power outages occur due to being independent of the network. The technical and economic performances of the energy system applications of hybrid systems were examined. Different storage types were used in the scenarios examined. The annual energy balances of the systems should be considered. Depending on this, optimal results are obtained with different configurations. The analysis results obtained by performing modeling studies using the TRNSYS program for hybrid energy systems, the details of which are given in the previous sections, are presented within the scope of this section. The results were evaluated separately for each system.

5.1. Scenario 1. PV/Battery System

The main source of the hybrid energy system designed in the first scenario is Solar Energy. Roof areas of the faculties of Izmir Institute of Technology University, which have high solar radiation, were used. We have given suitable roof areas in Section 3.1. If the electrical energy produced by the photovoltaic panels placed on the appropriate roof areas meets the building consumption, the residual energy is stored by the battery. The stored energy is intended to meet the electricity consumption need during the hours when solar energy is not active.

5.1.1. Maximum PV Panel Installation for each Building (MPPIB)

In this part of the study, the maximum number of PV panels installation each building (MPPIB) roof was found. PV*SOL software has been studied for each building roof from the design. The number of photovoltaic panels varies for each building. Accordingly, system capacities vary between 40 kWp and 360 kWp. The parameters of the buildings for which the system is designed are given in Section 4.5.

Considering each building, according to Table 17, a total of 9,108 panels and 522,406 lead acid batteries were used. A battery model other than a lead acid battery cannot be used in the TRNSYS software. If a different battery model is desired to be used within the scope of this study, it is foreseen that 202,705 Li-ions will be used. The electrical energy produced by the photovoltaic panel is 4,319,266 kWh. It has been observed that the IZTECH campus does not fully meet the yearly consumption. Cost and economic analysis are done in Section 5.5.1.1.

In Table 17 below, the photovoltaic PV panel, the number of batteries, installed power, and production-consumption output determined for each building are given.

Table 17. Maximum PV Installation for Each Building Optimization (MPPIB)

		Load	Panel	Lead-Acid B.	Li-ion B.	kWp	PV Output
		kWh	Quantity	Quantity	Quantity	kWp	kWh
GENERAL CULTURE BUILDING		23,726	80	427	249	42	35,776
RECTORATE		201,956	104	20,772	12,036	54.6	48,919
HEAD OF DEPARTMENT		177,610	288	6,804	3,301	151.2	135,639
FACULTY OF SCIENCE	A BLOCK	164,160	352	3,748	2,010	184.8	165,781
	B BLOCK	254,621	360	8,961	6,691	189	169,549
	C BLOCK	125,761	440	1,602	662	231	207,226
	CLASSROOM B.	40,347	222	430	62	116.55	104,555
	PHYSICS BUILD.	300,278	396	23,600	8,948	207.9	186,504
	MATHS BUILD	79,101	88	6,519	2,962	46.2	41,445
	BIOLOGY BUILD	712,077	260	272,353	46,376	136.5	122,452
FOREIGN BUILDING	F. ADMINISTRATE	42,077	204	300	60	107.1	96,078
	F. A BLOCK	14,983	128	102	16	67.2	60,284
	F. B BLOCK	259,020	462	11,000	3,258	242.55	217,587
	F. ENERGY S.E.	29,132	288	20	2	151.2	135,639
	CENTERAL W.	26,161	288	15	4	151.2	135,639
MECHANICAL ENG.		494,200	396	32,410	24,200	207.9	186,504
FACULTY OF ARCHITECTURE	A BLOCK	117,039	360	2,730	712	189	169,549
	B BLOCK	90,866	420	1,980	208	220.5	197,897
	C BLOCK	17,016	76	11	8	39.9	35,794
	D BLOCK	245	130	8	2	68.25	61,226
	E BLOCK	734	204	80	6	107.1	96,078
CHEMISTRY ENG		646,107	336	51,386	38,372	176.4	158,245
COMPUTER ENG		169,789	416	3,420	1,816	218.4	203,458
LIBRARY		387,551	405	16,134	13,812	212.625	211,936
GYM CENTER		110,291	684	2,094	1,564	359.1	322,142
POOL		200,229	204	11,195	8,192	107.1	96,078
CAFE		84,136	228	2,170	344	119.7	110,207
CIVIL ENG		209,107	540	3,950	2,708	283.5	254,323
ELECTRIC ELECTRONIC ENG		134,412	416	4,005	3,420	218.4	195,923
INTEGRATED RESEARCH		420,069	333	34,180	20,704	174.825	156,833
TOTAL		**5,532,801**	**9,108**	**522,406**	**202,705**	**4,781.7**	**4,319,266**

The battery storage TRNSYS system design for each building is given in Figure 31.

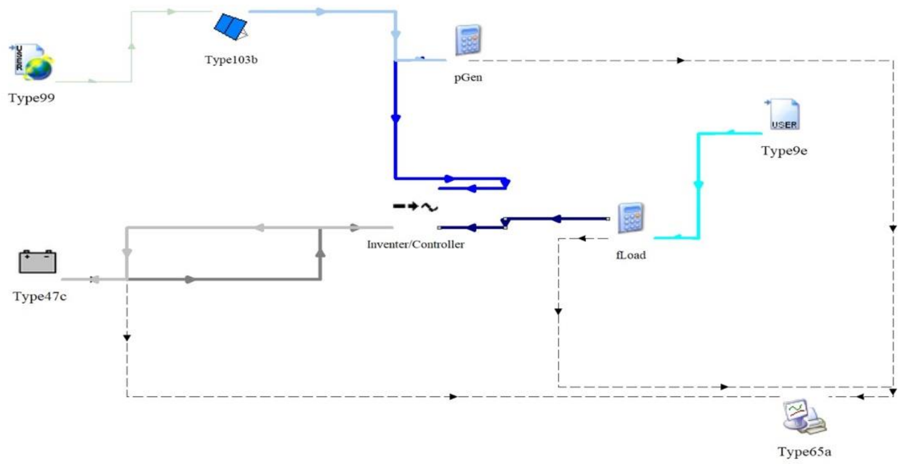

Figure 31. Standalone PV/Battery TRNSYS System (MPPIB)

The system design given in Figure 31 was made separately for 30 buildings. While the number of PV modules was determined to meet the annual electricity need of the campus, the number of capacity and energy storage modules was determined according to the maximum cumulative energy deficit in a year. The required number of batteries was calculated by using the technical characteristics of the battery.

5.1.2. Maximum PV Panel Installation on Campus (MPPIC)

Some of the university buildings for which system analysis is performed can afford themselves depending on their consumption. Depending on the consumption, 19 buildings are self-supporting with solar energy generation and batteries. Battery usage is a problem due to the lack of roof area suitability of other buildings, excess consumption, and low solar energy.

It is also available in buildings whose consumption is less than production. Overproduction in these buildings is stored in the battery. It has been observed that it is not used due to low consumption. After the battery is full, the energy is wasted as it will not allow further charging. For this reason, when the maximum PV panel installation on campus (MPPIC), is considered as a whole, fewer batteries will be used because of the integrated operation of the systems. Considering these data, a system analysis was made for the entire campus.

Table 18. Maximum PV Installation for Campus Optimization (MPPIC)

	Load	Panel	Lead Acid Battery	Li-ion Battery	kWp	PV Output
	kWh	Quantity	Quantity	Quantity	kWp	kWh
MPPIC	5,687,670	9,108	226,200	107,482	4,781.7	4,321,136

The systems designed for each building have been combined into a single system. In this way, the system appears to be more efficient. The reason for this is that buildings with high electricity production and no consumption are integrated into other buildings. Due to the increase in the consumption coverage ratio, the required number of batteries has decreased. Considering the for each building, according to Table 18, a total of 9,108 panels and 226,200 lead acid batteries were used. If a different battery model is desired to be used within the scope of this study, it is foreseen that 107,482 Li-ions will be used. The electrical energy produced by the photovoltaic panel is 4,321,136 kWh. Cost and economic analysis are done in Section 5.5.1.2.

5.1.3. Necessary PV Panel Installation for each Building (NPPIB)

In this scenario, the number of panels and batteries required for each building is calculated. In scenario 1 and scenario 2, it was observed that the number of batteries was very high due to the insufficient number of panels. The necessary PV panel installation for each building (NPPIB) is made according to the building's consumption. Since the system works independently from the grid, in addition to building consumption, inverter and battery load are considered. In Table 19 below, the photovoltaic PV panel, the number of batteries, installed power, and production-consumption output determined for each building are given.

Table 19. Necessary PV Installation for each Building (NPPIB)

		Load	Panel	Lead-Acid B.	Li-ion B.	kWp	PV Output
		kWh	Quantity	Quantity	Quantity	kWp	kWh
GENERAL CULTURE BUILDING		23,726	454	82	26	238.5	203,030
RECTORATE		201,956	4,984	912	304	2,616.6	2,344,358
HEAD OF DEPARTMENT		177,610	3,696	676	224	1,940.4	1,740,700
FACULTY OF SCIENCE	**A BLOCK**	164,160	2,898	528	174	1,521.45	1,364,867
	B BLOCK	254,621	4,844	884	292	2,543.1	2,281,371
	C BLOCK	125,761	2,352	430	158	1,234.8	1,107,718
	CLASSROOM B.	40,347	800	146	48	420	376,775
	PHYSICS BUILD.	300,278	5,616	1,024	336	2,948.4	2,644,959
	MATHS BUILD	79,101	15,488	2,826	932	8,131.2	730,943
	BIOLOGY BUILD	712,077	1,552	284	94	814.8	7,294,360
FOREIGN BUILDING	**F. ADMINISTRATE**	42,077	714	130	44	374.85	336,272
	F. A BLOCK	14,983	350	64	21	183.75	164,839
	F. B BLOCK	259,020	4,104	750	246	2,154.6	1,932,855
	F. ENERGY S.E.	29,132	558	100	32	292.95	262,800
	CENTERAL W.	26,161	594	108	36	311.85	279,755
MECHANICAL ENG.		494,200	11,136	2,028	666	5,846.4	5,224,705
FACULTY OF ARCHITECTURE	**A BLOCK**	117,039	2,112	386	128	1,108.8	994,686
	B BLOCK	90,866	1,824	334	110	957.6	859,047
	C BLOCK	17,016	624	114	38	327.6	293,884
	D BLOCK	245	32	6	2	16.8	15,071
	E BLOCK	734	472	86	28	247.8	222,297
CHEMISTRY ENG		646,107	12,960	2,358	772	6,804	6,103,752
COMPUTER ENG		169,789	3,200	582	190	1,680	1,507,099
LIBRARY		387,551	7,790	1,426	474	4,089.75	3,668,845
GYM CENTER		110,291	4,074	745	248	2,138.85	1,918,726
POOL		200,229	4,656	850	280	2,444.4	2,192,829
CAFE		84,136	1,344	244	80	705.6	632,982
CIVIL ENG		209,107	4,092	745	245	2,148.3	1,927,203
ELECTRIC ELECTRONIC ENG		134,412	3,740	682	225	1,963.5	1,761,422
INTEGRATED RESEARCH		420,069	7,280	1,325	434	3,822	3,428,651
TOTAL		**5,532,801**	**114,340**	**20,855**	**6,887**	**60,028.5**	**53,086,589**

Consumption values analyzed hourly were calculated daily. Based on the daily consumption demands, the system designed to meet the worst day was made. The number of photovoltaic panels, lead acid batteries and li-ion batteries required to meet the consumption of the IZTECH campus building has been calculated in Table 19. With the calculated values, each building must meet its consumption. Additional installation is required for the IZTECH campus to meet the total consumption. As a result of the additional installation, the electrical energy produced will increase. Since the IZTECH campus area has a large land area, it is suitable for additional installation. Eligibility has been confirmed by university officials.

Calculated panel numbers were entered into TRNSYS software. Photovoltaic Panel production outputs are recorded. To supply the entire campus building consumption, a total of 114,340 panels and 20,855 batteries were used, according to Table 19. If a different battery model is desired to be used within the scope of this study, it is foreseen that 6,887 Li-ions will be used. The electrical energy produced by the photovoltaic panel is 53,086,589 kWh. It has been observed that IZTECH meets the campus consumption annually. Cost and economic analysis are done in Section 5.1.1.3.

5.1.4. Necessary PV Panel Installation on Campus (NPPIC)

The necessary PV panel installation for the entire campus (NPPIC) has been made. The required number of panels and batteries has been combined into a single system for the campus. Considering these data, a system analysis was made for the entire campus. The battery storage TRNSYS system design on campus is given in Figure 32.

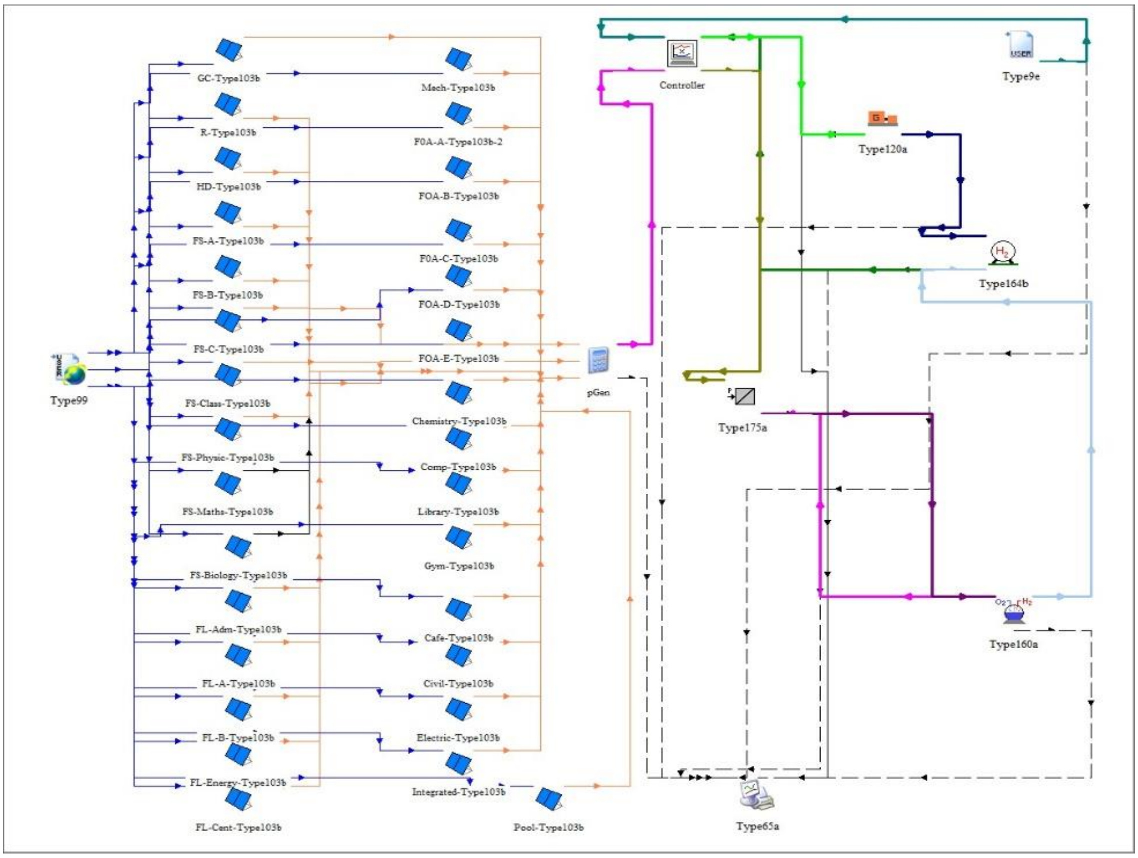

Figure 32. Standalone PV/Battery TRNSYS System (NPPIC)

Table 20. Necessary PV Installation for Campus (NPPIC)

	Load	Panel	Lead Acid Battery	Li-ion Battery	kWp	PV Output
	kWh	Quantity	Quantity	Quantity	kWp	kWh
NPPIC	5,687,670	114,340	3,790	2,009	60,028.5	53,850,540

According to the results obtained, system design parameters were determined to meet the consumption of the entire campus. Considering the values calculated in Table 20. It is seen that it is the most suitable system. The total electrical power produced by the photovoltaic panel is 53,850,540 kWh. It is almost the same as the total power output from the standalone system calculated in section 5.1.3. As a result of the increase in production and integrated work with all campus buildings, the minimum number of batteries has been achieved. It can meet the total consumption of the campus with fewer batteries. Simulations and analyzes of these systems gave better results than other studies.

The annual electricity need of IZTECH campus is 5,687,670 kWh. No matter how high the energy produced by the sun is, it is not enough to meet the annual consumption requirement for a stand-alone system without the use of batteries. Since the PV/Battery is a standalone system, it is supported by a battery during the hours when there is no sun. The number of batteries to be used has been calculated as 114,340. If a different battery model is desired to be used within the scope of this study, it is foreseen that 2,009 Li-ions will be used. Annual PV/Battery simulation outputs are given in Figure 33. The battery is activated when there is no energy production from the photovoltaic panel. Seasonal consumption changes affect the number of ingredients. Figure 33 shows that the demand for batteries is high in winter. The high load demand in the winter months affects the number of batteries. The negative drop (grey area) seen in Figure 33 is the battery usage. It reaches 0 when the battery is not in use. When the battery starts to charge, it goes positive.

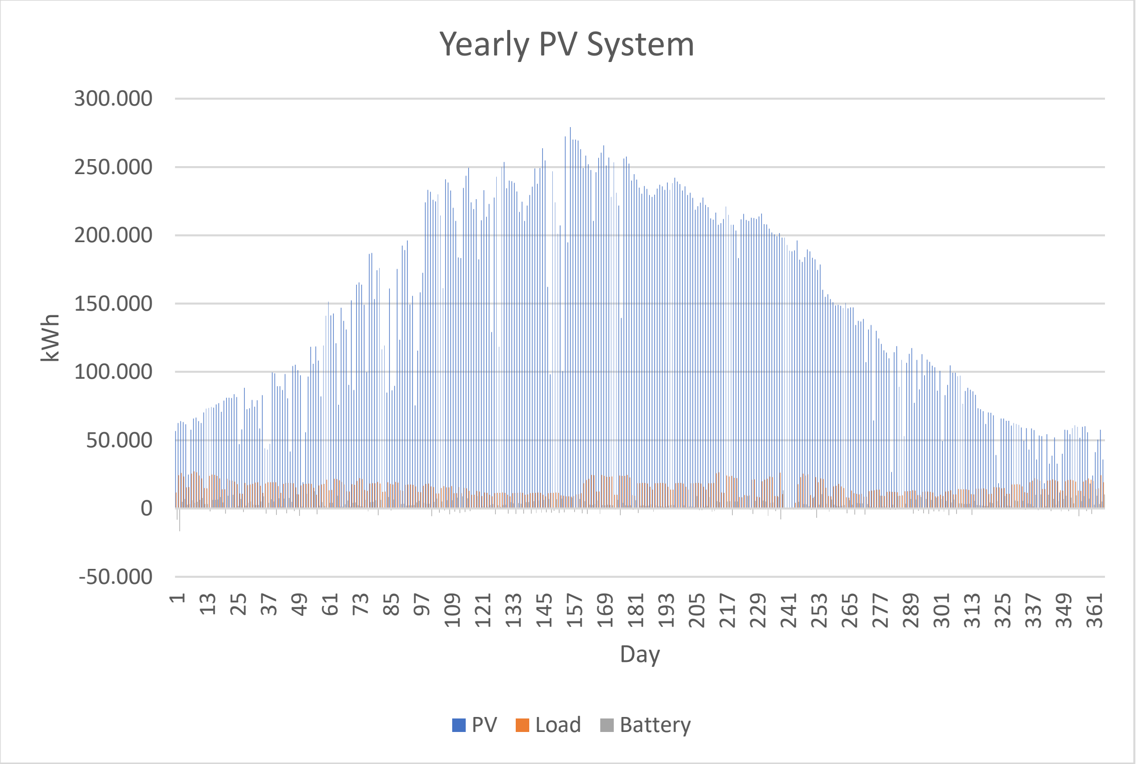

Figure 33. Yearly PV/Battery System (NPPIC)

The maximum consumption and minimum PV panel production days of on campus throughout the year are examined in Figure 34 and Figure 35.

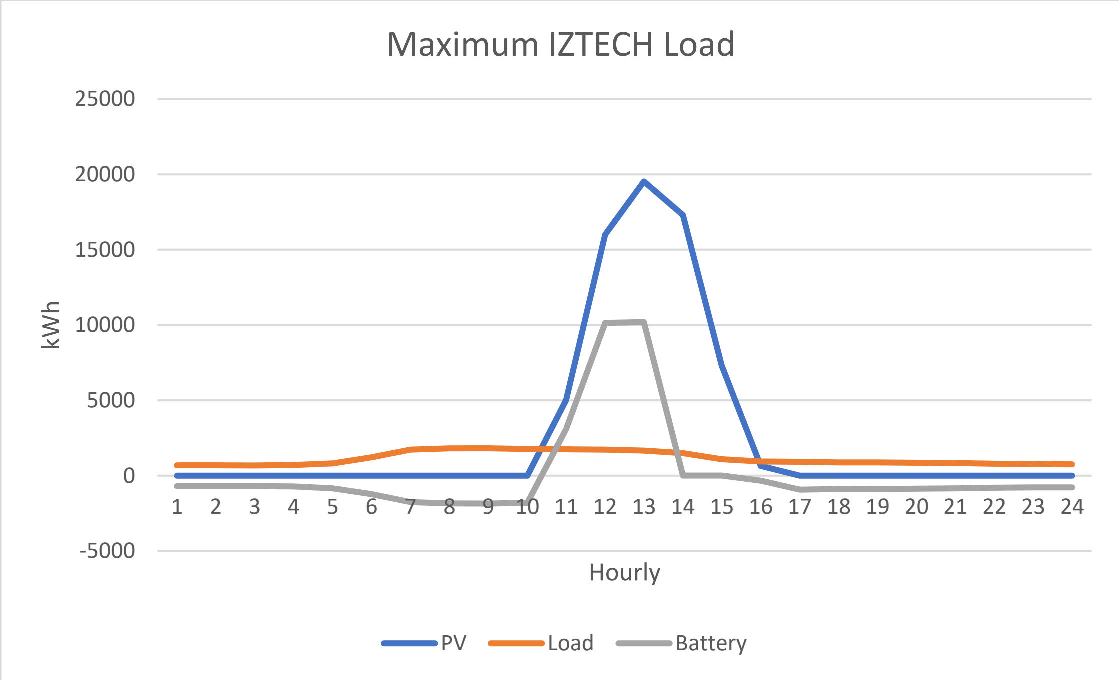

Figure 34. Maximum Load Demand Fulfillment

The maximum load request was made on 8 January 2019. The consumption with the highest load demand is 27,207 kWh. The power produced from the photovoltaic panel is 65,839 kWh. Consumption was met during non-sun hours using lead acid batteries. With the power generated by the photovoltaic panel in the designed system, the load demand of the worst day was met as seen in Figure 34. The remaining energy during sunny hours is stored by the battery. The average solar energy production during the day is 2,743 kWh. The average load demand during the day is 1,133 kWh. According to Figure 34, the load demand was met from the sun between 10:00 and 16:00. After the consumption is met, the batteries are charged. In the remaining hours, the consumption is covered by the battery.

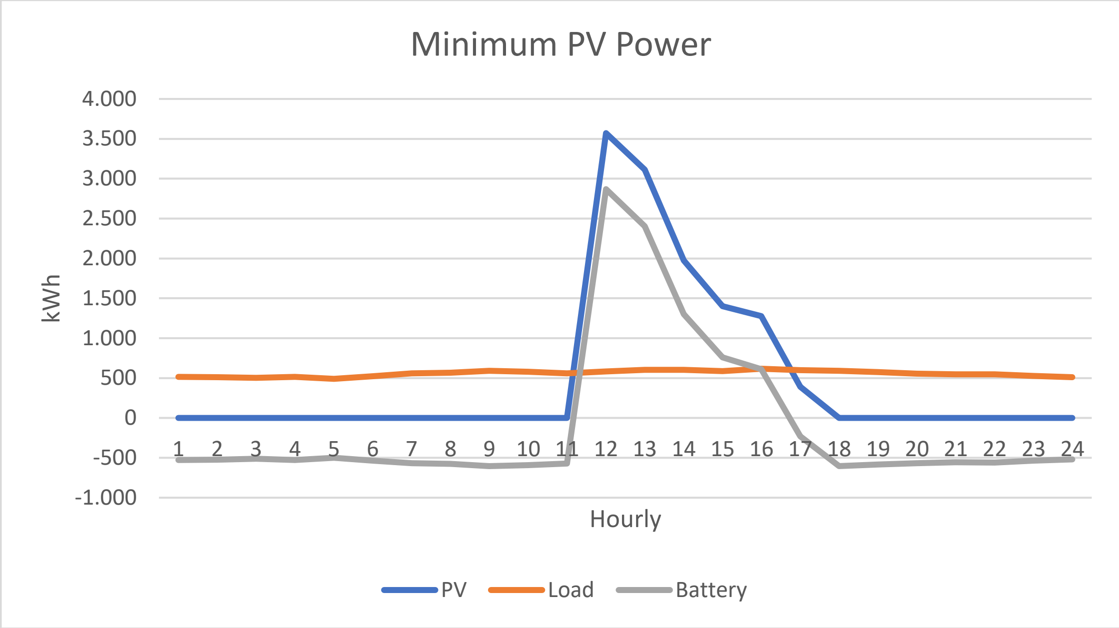

Figure 35. Daily Minimum PV/Battery System

On 14 December 2019, the least solar energy production was realized. On a day when solar production is low, the total production is 11,728 kWh. The total load demand is 13,357 kWh. Until the sunshine hours started, the load demand was met by the battery. Solar energy was obtained on a limited basis between 11:00 and 17:00. Despite this, it is seen that the load demand is met from the battery thanks to the previously stored energy.

Accordingly, the comparison of cost and economic analysis depending on the number of equipment will be made in Section 5.5.1.4.

Additional installation can be accomplished through the land area or roof overhaul. After this study, it needs to be worked on in terms of cost.

5.2. Scenario 2: PV/Electrolyzer/H_2 Storage/Generator

The main objective of the second scenario was designed to model the typical annual operation of a hydrogen energy storage system powered by a PV array. System determining its size is very important for the performance of the system. System designs were modeled using TRNSYS software. The main elements of this scenario are PV Panel, diesel generator, electrolyzer, and hydrogen tank. Power conversions between systems are done by the controller [19]. IZTECH decides to operate solar energy and hydrogen tank parameters depending on the power demand of the university. If the electrical energy produced from photovoltaic panels is higher than the load demand, it is transferred to the electrolyzer. The electrolyzer begins to produce hydrogen. When hydrogen reaches the maximum pressure limit entered in the tank, hydrogen production stops. The excess power produced is thrown out [80].

If the electrical energy produced from photovoltaic panels is less than the load demand, it is converted into hydrogen electricity by the diesel generator. The stored hydrogen is converted back into electrical energy with the help of DEGs and the load demand is met. The TRNSYS design of the electrolyzer/hydrogen tank system is given in Figure 36.

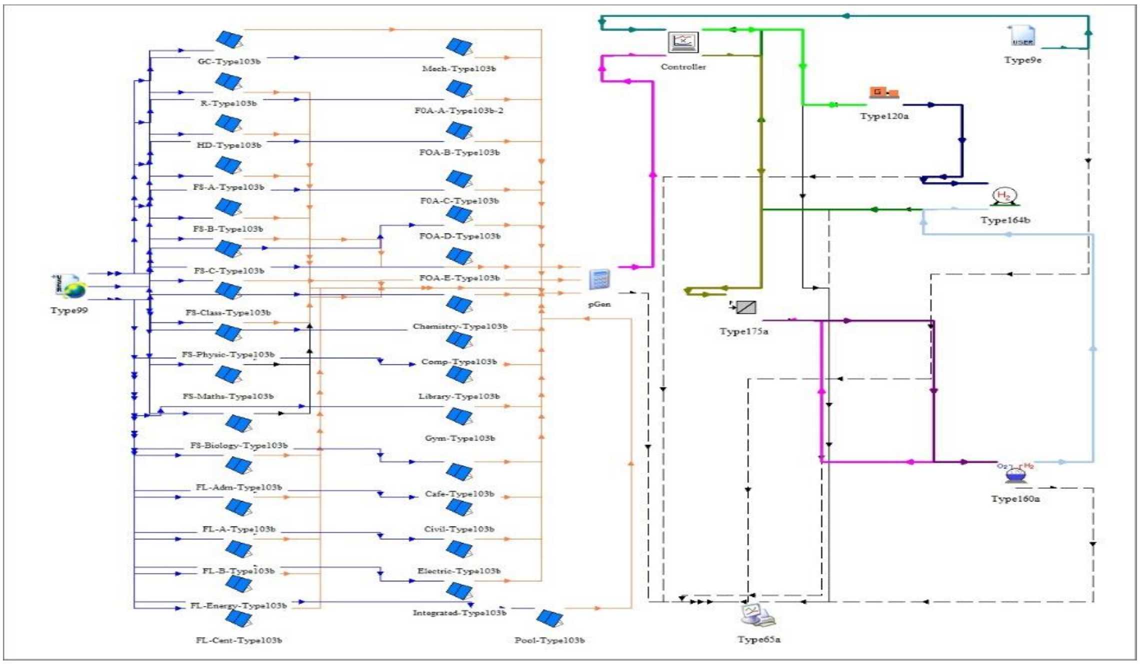

Figure 36. Standalone PV/Electrolyzer/H_2 Storage/Generator TRNSYS System

The system created with TRNSYS software cannot be designed to meet the electricity consumption of the entire campus. Enough electrolyzer numbers cannot be entered in the TRNSYS software. The program does not allow this. For this reason, the minimum operating parameters of the system were found. The energy requirement required to ensure consumption has been determined. Photovoltaic panel parameter obtained from the manufacturer's catalogue was used. For other components, the system was used as default. The designed system parameters are given in Table 21.

Table 21. PV/Electrolyzer/H_2 Storage/Generator TRNSYS System Parameters

System Parameters	**Value**
Fotovoltaic Panel (TYPE 103)	
Module short-circuit current at reference conditions	13.63. A
Module open-circuit voltage at reference conditions	49.42 V
Reference cell temperature	25 C
Reference insolation	1000 W/m^2
Module voltage at max power point and reference conditions	40.80 V
Module current at max power point and reference conditions	12.87 A
Temperature coefficient of Isc (ref. cond)	0.032 A/K
Temperature coefficient of Voc (ref. cond.)	-0.28 V/K
Power Conditioning (TYPE 175a)	
Nominal Power	500.000 W
Controller (TYPE 105a)	
DEGs Rated	300.000 W
Electrolyzer idling power	120.000 W
Rated electrolyzer cell power	600.000 W
Upper limit on H2 storage(electrolzer)	90%
Lower limit on H2 storage(electrolzer)	80%
Alkaline Electrolyser (TYPE 160a)	
Electrode Area	0.25 m^2
Number of cells is series	190
Number of stacks in parallel	2
Compressed Gas Storage (TYPE 164)	
Tank Volume	100 m^3
Maximum Pressure	300 bar

Table 22. PV/Electrolyzer/H_2 Storage/Generator Installation on Campus

	Load	Panel	Electrolyzer	Hydrogen production	Diesel Gen.	PV Output
	kWh	Quantity	Quantity	m^3/hr	Quantity	kWh
PV/HYDROGEN	5,687,670	12,581	380	393,224.3	16	5,926,197

According to Table 22, 12,581 solar panels, 380 electrolyzers, and a 300 bar 100 m^3 hydrogen tank were used in the system established for the campus. Annual solar production is 5,926,197 kWh. This system design has been established with the minimum number of electrolyzers. The amount of kg that the electrolyzer sent to hydrogen per hour and the number of kWh converted with DEGs at the required times were calculated. The DEGs yield was calculated as 0.40. It can use 40% of hydrogen per kg.

The amount of energy produced per kg of hydrogen was found. Accordingly, 305 clustered units must be installed from the same system. The hydrogen production rate in the designed system was found to be 393,224.3 m^3/hr. The conversion of hydrogen gas is 0.082. 32,244.4 kg of hydrogen was produced. Cost and economic analysis are done in Section 5.5.2.

The annual electricity need of the IZTECH campus is 5,687,670 kWh. In this study, the amount of electrolyzer and hydrogen tank that can meet the hourly energy need of the IZTECH University campus has been calculated. The amount of electrolyzer to be used is 115,900 and the amount of hydrogen tank is 305. Annual simulation based on minimum calculated component counts is given in Figure 37.

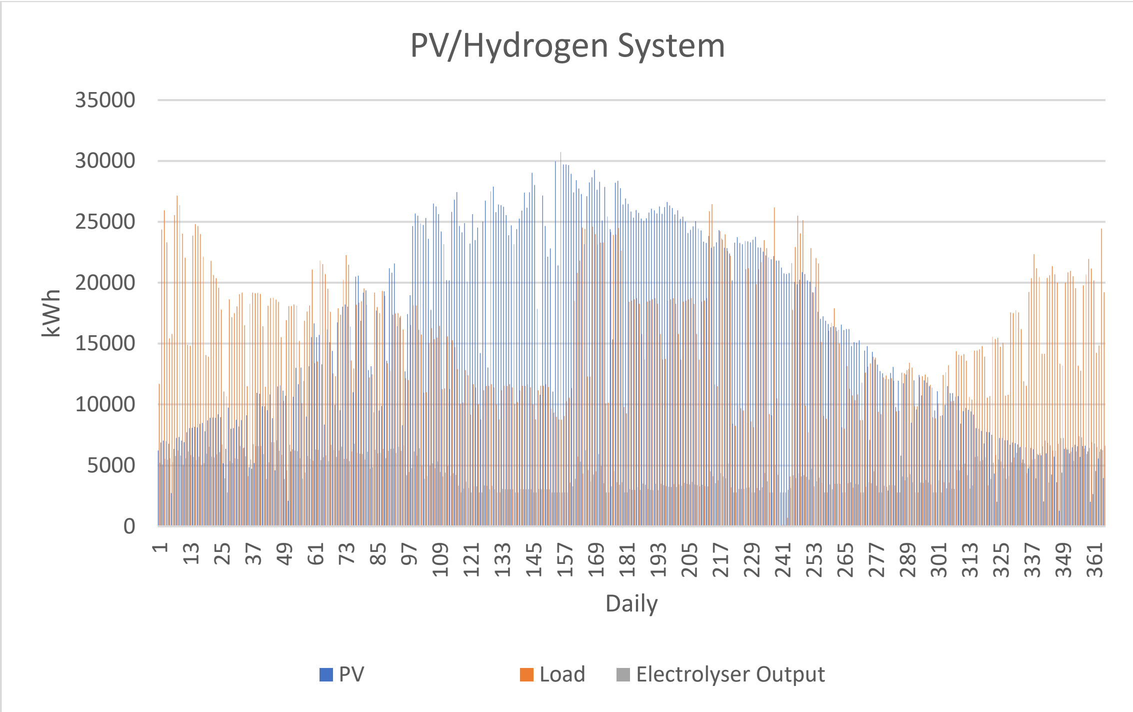

Figure 37. PV/Hydrogen System Simulation

The storage of the energy obtained from the electrolyzer in the hydrogen tank is shown in Figure 38.

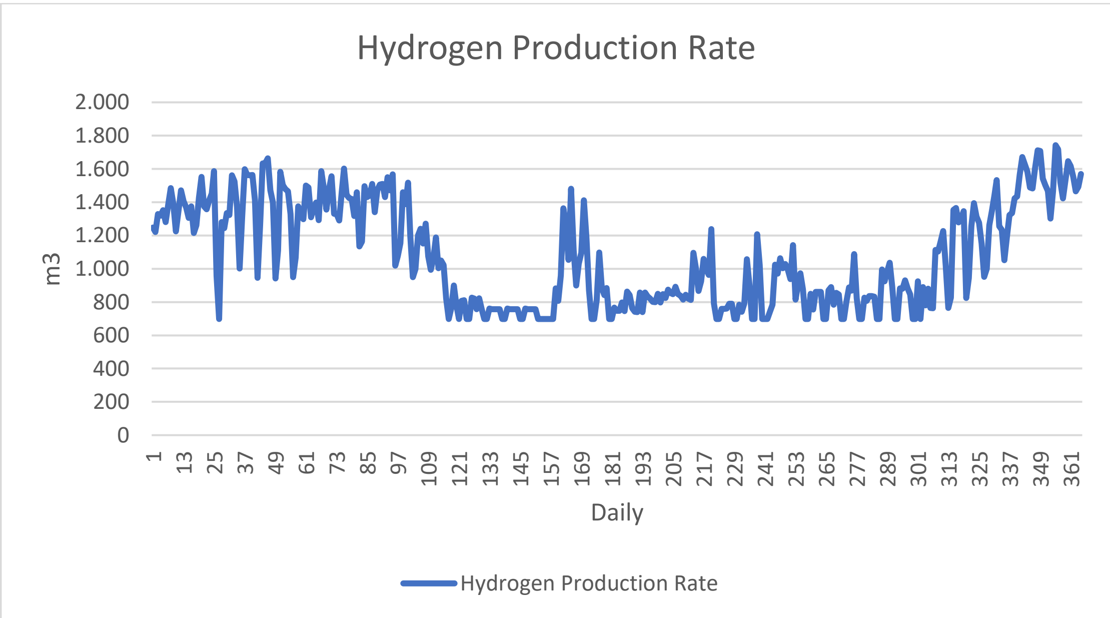

Figure 38. Hydrogen Production Rate-PV System

5.3. Scenario 3: Wind Turbine/Battery

The main source of the hybrid energy system designed in the third scenario is Wind Energy. If the energy produced by the Wind Turbine is more than the electrical load, the excess energy produced is stored in the battery system. The residual energy is stored and used when wind energy is not available. The stored energy comes into play when there is no wind energy, or the electricity load is not met. After reaching the minimum state of charge, its discharge is stopped. The TRNSYS design of the battery storage system is given in Figure 39.

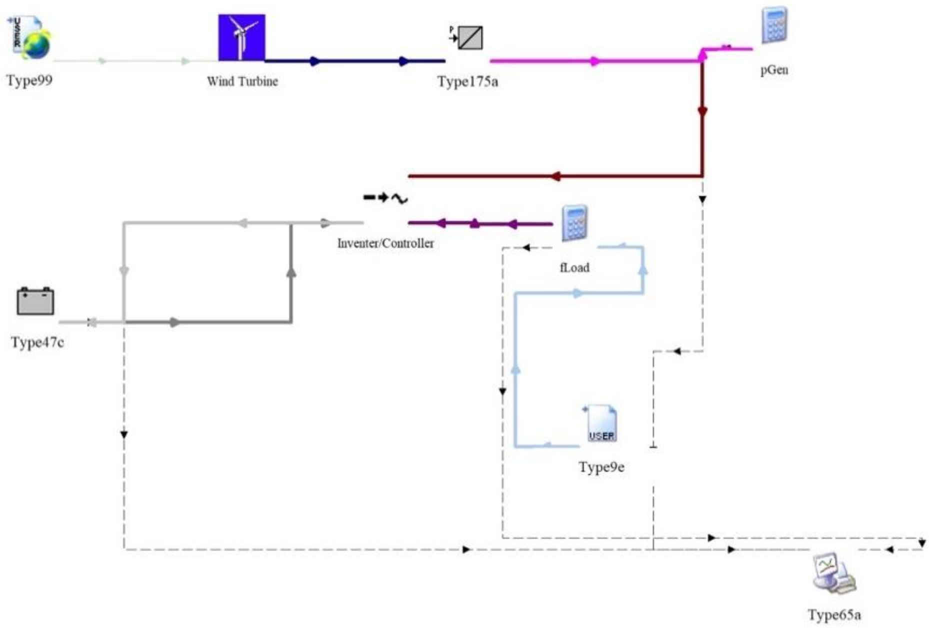

Figure 39. Wind Turbine/Battery TRNSYS System Modeling

The system created with the wind turbine is designed to supply the electricity consumption of the whole campus. The energy produced by the wind turbine is converted into electrical energy by the converter and inverter. The selected turbine supplies the annual energy needs of the campus. On an hourly basis, a battery storage system is needed during windless hours. The hourly power outputs produced are compared with the consumption values. Hours, when wind energy could not meet the consumption, were collected cumulatively. The energy requirement required to supply the consumption has been determined. Battery parameters obtained from manufacturers' catalogues were used. The number of batteries required for the determined energy need has been found. The parameters of the TRNSYS models are given in Table 23.

Table 23. Wind/Battery TRNSYS Design Parameters

System Parameters	**Value**
Wind Turbine (TYPE 90)	
Capacity	2.5 MW
Site Elevation	52 m
Data Collection Height	100 m
Hub Height	75-100 m
Turbine Number	1
Inverter/Controller (Type48)	
Regulator Efficiency	0.97
Inverter Efficiency	0.98
High limit on fractional state of charge (FSOC)	0.8%
Low limit on FSOC	0.2%
Charge to discharge limit on FSOC	0.2%
Inverter output power capacity	500.000 W
Battery (TYPE47c)	
Cell Energy Capacity	4747 Ah
Cells in parallel	44.200
Cell in series	1
Max. Current per cell charging	424.8 A
Max. current per cell discharging	-424.8 A

Nordex N100/2500 was chosen among the turbine brands given in Section 4.5.2. Within the scope of this thesis, the Vestas V80/2000 model was first tested and found to be inadequate. Turbine model selection criteria were selected based on IZTECH wind measurement data height. Nordex N100/2500 hub height is 75, 85, and 100 meters. It agrees with the obtained data. Turbine data is imported into TRNSYS with an external file. The simulation was analyzed accordingly.

System parameters were determined for the battery storage system. The parameters were determined according to the selected commercial battery specifications. System parameters are given in Table 24. Depending on these parameters, if the state of charge reaches 80%, it stops charging the battery. If there is excess energy produced, it cannot be used. To 20% during discharge, the system stops discharging the battery.

Wind power generation and IZTECH campus consumption were compared. In the hours when there is no wind, the consumption must be covered by the battery. For this, after the campus consumption is fulfilled, the residual energy is stored by the battery.

In Table 24, the number of batteries and production-consumption output is given for IZTECH Campus.

Table 24. Wind Turbine Installation for Campus

	Load	Wind Turbine	Lead Acid Battery	Li-ion Battery	Wind Output
	kWh	Quantity	Quantity	Quantity	kWh
Wind/Battery	5,687,670	1	18,543	11,077	7,651,335

According to Table 24, 1 wind turbine and 18,543 batteries were used in the system established for the campus. If a different battery model is desired to be used within the scope of this study, it is foreseen that 11,077 Li-ions will be used. Annual wind energy production is 7,651,335 kWh. Cost and economic analysis is done in Section 5.5.3.

Wind energy is one of the most efficient renewable energy sources. Turkey is an efficient country in terms of wind energy. In the study, wind data of the IZTECH campus measured at 52, 72, and 100 m altitudes at 10-minute intervals for 1 year were reached. One wind turbine with a power of 2.5 MW was selected from the obtained turbine brands and data. The wind turbine chosen is Nordex N100/2500.

In this study, the number of wind turbines and batteries that can meet the hourly energy need of the IZTECH University campus has been calculated. The annual simulation based on the computed component numbers is given in Figure 40.

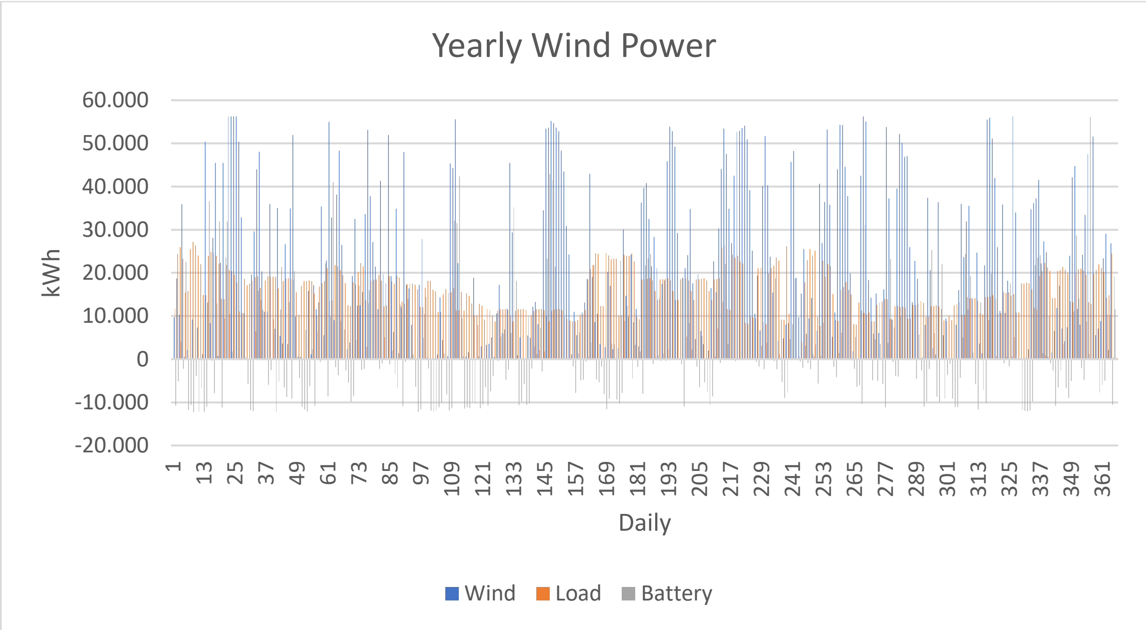

Figure 40. Yearly Wind/Battery System

The negative drop (grey area) is seen in Figure 40 is the battery usage. It reaches 0 when the battery is not in use. When the battery starts to charge, it goes positive. The annual electricity need of the IZTECH campus is 5,687,670 kWh. The energy produced by the turbine is 7,651,335 kWh. It is not enough to meet the annual consumption needs. Since it is a wind/battery standalone system the required number of batteries is calculated as 18,543 during the hours when there is no wind. As seen in Figure 40, the battery is activated when there is no energy production from the wind.

To support that the campus meets the electricity consumption all year, the maximum and minimum days of wind generation are determined in Figure 41 and Figure 42.

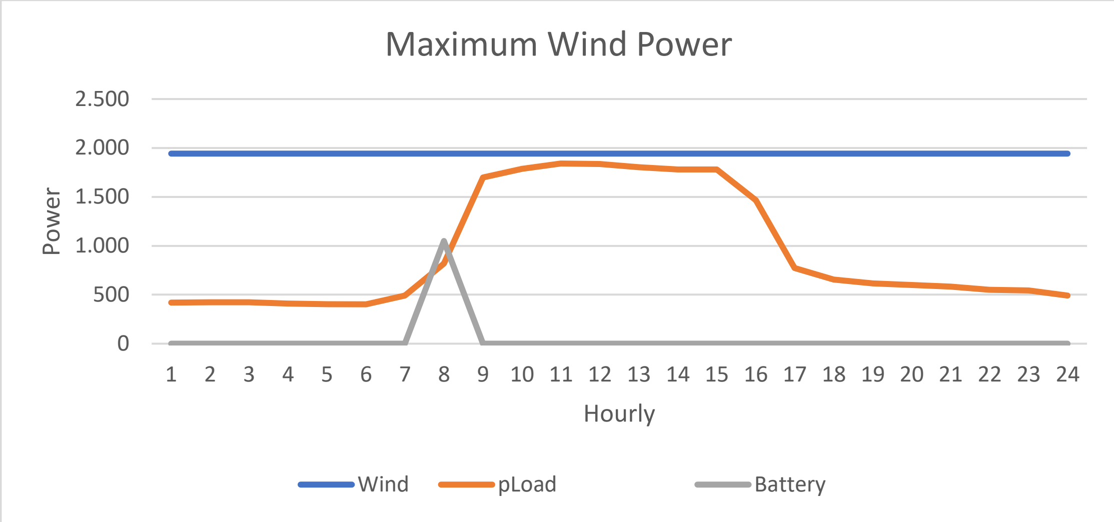

Figure 41. Daily Maximum Wind/Battery System

It has been observed that the maximum wind generation is not a single day. According to turbine specifications, after a certain speed, the wind is cut off to prevent damage to the turbine. Among the days with maximum wind generation, the day with the highest load consumption was selected. Maximum wind generation was determined as of 6 August 2019. Average wind generation during the day 1,942.11 kWh. The load demand during the day is 22,600 kWh. According to Figure 41, the load demand is met by wind energy all day. After the consumption is met, the battery is charged from 7:00 to 8:00. It is seen that the battery is not used after it is fully charged.

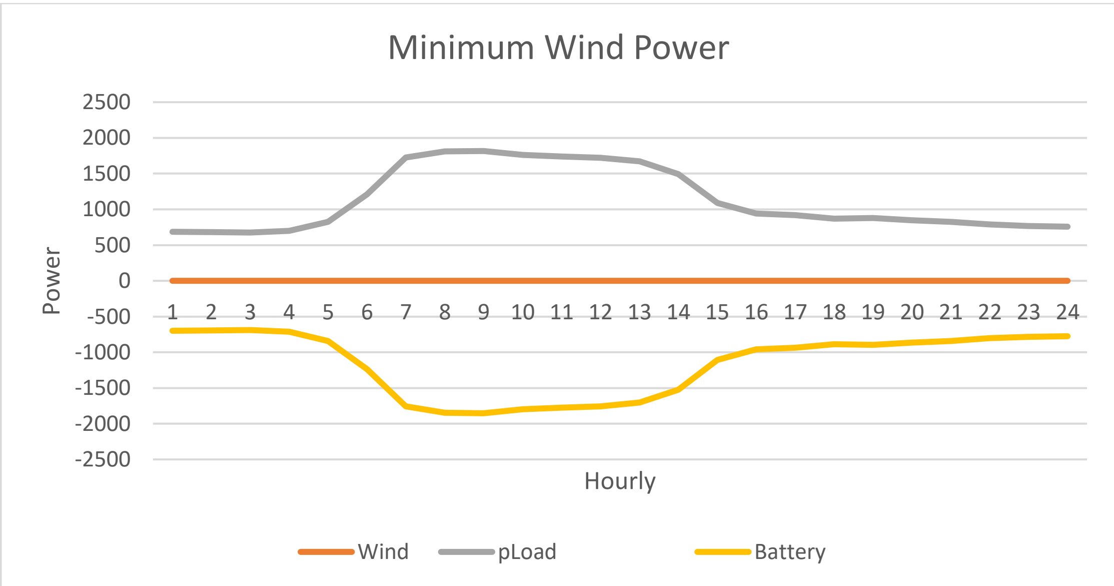

Figure 42. Daily Minimum Wind/Battery System

Likewise, days without wind generation are not a single day. Among the days when there is no wind generation, the day with the highest load consumption was selected. The selected day is 6 January 2019. The selected load demand is the day of the year with the highest consumption. There is no wind generation during the day. It is seen that the load consumption is met by the battery.

5.4. Scenario 4: Wind Turbine/Electrolyzer/H_2 Storage/Generator

The main source of the hybrid energy system designed in the fourth scenario is Wind Energy. It is designed to model the typical annual operation of a hydrogen storage system supporting the selected wind turbine. TRNSYS software was used for modeling. The main components of this scenario are a wind turbine, diesel generator, electrolyzer, and hydrogen tank. IZTECH decides to run it in solar energy and hydrogen tank parameters according to the electricity needs of the university. If the energy produced by the wind turbine is more than the electrical load, it is transferred to the electrolyzer. Residual energy is stored in the hydrogen tank and used when wind power is not available. When there is no wind power or the electricity load is not met, the stored energy is converted into hydrogen electricity by the diesel generator. The stored hydrogen is converted back into electrical energy with the help of DEGs and the load demand is met. The TRNSYS design of the electrolyzer/hydrogen tank system is given in Figure 43.

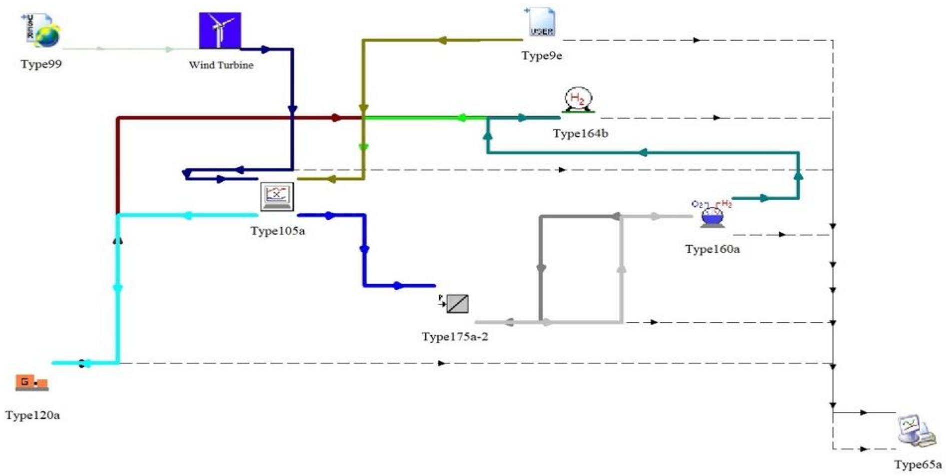

Figure 43. Standalone Wind/Hydrogen TRNSYS System

The wind turbine/electrolyzer/hydrogen tank/generator system design created with TRNSYS software cannot be designed to meet the electricity consumption of the entire campus. Enough electrolyzer numbers cannot be entered in the TRNSYS software. The program does not allow this. For this reason, the minimum operating parameters of the designed wind system were found. The energy requirement required to ensure consumption has been determined. Wind turbine parameters obtained from the manufacturer's catalogue were used. For other components, the system is left as default. The designed system parameters are given in Table 25.

Table 25. Wind/Hydrogen TRNSYS Parameters

System Parameters	**Value**
Wind Turbine (TYPE 90)	
Capacity	2.5 MW
Site Elevation	52 m
Data Collection Height	100 m
Hub Height	75-100 m
Turbine Number	1
Power Conditioning (TYPE 175a)	
Nominal Power	13.000.000 W
Controller (TYPE 105a)	
DEGs Rated	300.000 W
Electrolyzer idling power	120.000 W
Rated electrolyzer cell power	600.000 W
Upper limit on H2 storage(electrolzer)	90%
Lower limit on H2 storage(electrolzer)	80%
Alkaline Electrolyser (TYPE 160a)	
Electrode Area	0.25 m^2
Number of cells is series	172
Number of stacks in parallel	2
Compressed Gas Storage (TYPE 164)	
Tank Volume	100 m^3
Maximum Pressure	300 bar

According to Table 25, 1 wind turbine and 344 electrolyzers, and 1 hydrogen tank of 300 bar 100 m^3 were used in the system established for the campus. Annual wind generation is 7,651,335 kWh. This system design has been established with the minimum number of electrolyzers. The amount of kg that the electrolyzer sent to hydrogen per hour and the number of kWh converted with DEGs at the required times were calculated. The DEGs yield was calculated as 0.40. It can use 40% of hydrogen per kg.

The amount of energy produced per kg of hydrogen was found. Accordingly, 315 clustered units must be installed from the same system. Cost and economic analysis are done in Section 5.5.4.

The annual electricity need of the IZTECH campus is 5,687,670 kWh. In this study, the amount of electrolyzer and hydrogen tank that can meet the hourly energy need of the IYTE University campus has been calculated. The amount of electrolyzer to be used is 108,306 and the amount of hydrogen tank is 315. Annual simulation based on minimum calculated component counts is given in Figure 44.

Table 26. Wind/Electrolyzer/H_2 Storage/Generator Installation on Campus

	Load	**Wind Turbine**	**Electrolyzer**	**Hydrogen production**	**Diesel Gen.**	**Wind Output**
	kWh	**Quantity**	**Quantity**	**m^3/hr**	**Quantity**	**kWh**
Wind/HYDROGEN	5,687,670	1	344	326,499.78	16	7,651,335

The hydrogen production rate in the designed system was found to be 326,499.78 m^3/hr. The conversion of hydrogen gas is 0.082. 109,932.7 kg of hydrogen was produced.

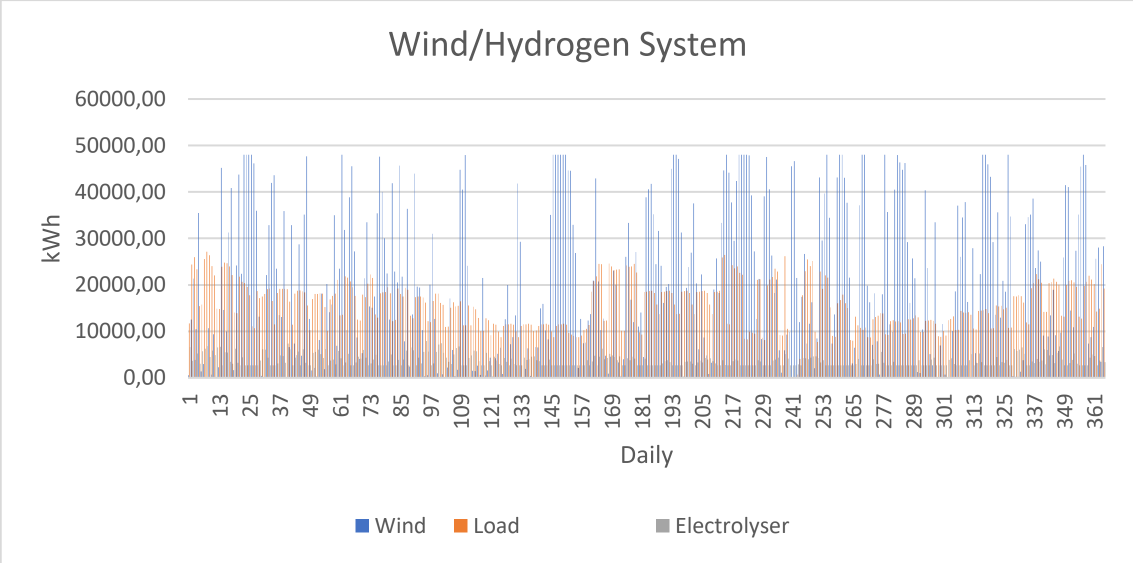

Figure 44. Wind/Hydrogen System Simulation

The storage of the energy obtained from the electrolyzer in the hydrogen tank is shown in Figure 45.

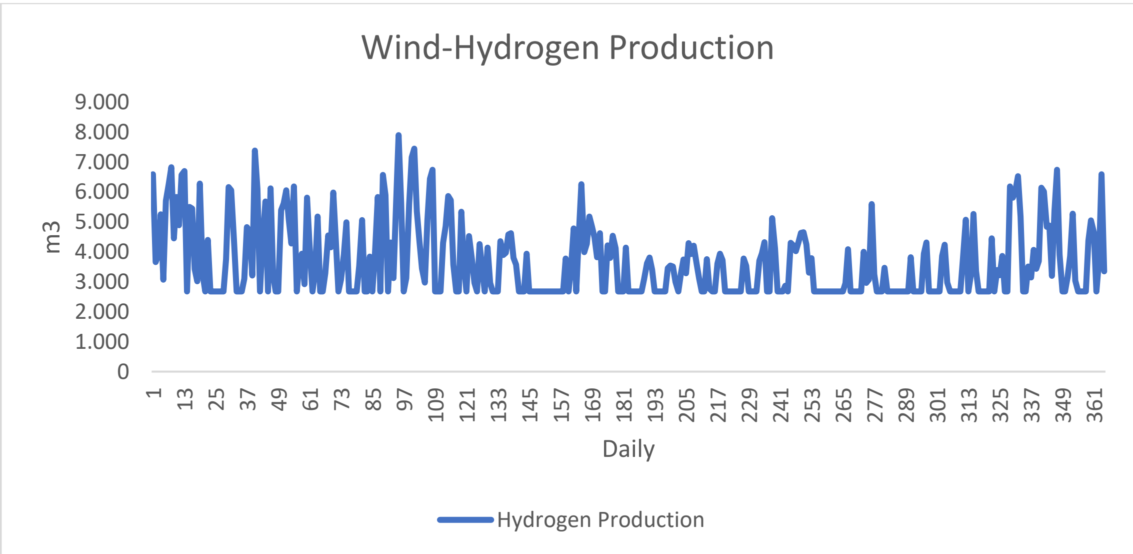

Figure 45. Wind-Hydrogen Production

5.5. Economic Analysis

In this section, economic analysis outputs are given for designed for the IZTECH campus. The currency used in calculations is dollars. The exchange rate from the Central Bank of Turkey has been accepted as 18.5 TL. The interest rate is accepted as 4%, and the useful project life is determined as 25 years. The O&M escalation was accepted as 5%. According to the data obtained from the US 10-year bond rates, the expected annual escalation in electricity prices is taken as 4% [54]. Rebate/incentive benefits cannot be provided in a standalone renewable system design. The parameters used in the economic analysis are given in Table 27.

Table 27. Economic Costs

Equipment	Equipment Cost	O&M Cost	Replacement Cost	Project Life
PV Panel	241.5$	1%-5% of the initial investment cost annually [81].	100%	25 years
Wind Turbine	2,800,000$ [82]	43$/kW/year [82]	80%	25 years
Inverter	It varies by product [83].	0.5% of the initial investment cost annually [36].	100%	25 years
Lead Acid Battery	1,044$ [84]	5$/kW/year [85]	100%	12 years
Li-ion Battery	7,076$ [84]	10$/kW/year [85]	100%	12 years
Electrolyzer	6,375$	17$/kW/year [86]	100%	20 years
Hydrogen Tank	10,000$ [36]	0.5% of the initial investment cost annually.	100%	25 years
Diesel Generator	25,400$ [87]	0.16$/kWh	100%	10 years

5.5.1. PV/Battery System Economic Analysis

When the basic elements that make up the investment cost related to solar energy-battery systems are listed, the engineering and project development costs for site selection and installation, solar panels, battery and equipment costs, field and construction work costs, financing expenses, operating expenses, and unexpected expenses are listed. Panels and batteries constitute the largest part of the cost in photovoltaic system scenarios. Today, there are many panel brands and types. According to the information received from the suppliers, the prices vary depending on the product variety. With the development of technology, panel powers exceeding 600 Wp are available. It should be known that when the panel power increases, the panel dimensions increase at a certain rate. Panel selection should be chosen according to roof suitability.

Trina solar-Jinko 525 Wp photovoltaic panel was chosen for the photovoltaic systems used in this thesis. The number of panels in each building differs in photovoltaic system designs.

In Table 28, the total costs of the systems using photovoltaic panels are calculated based on the unit price obtained under market conditions [33]. The unit price of TR-72M 515–535-Watt Monocrystalline panel by the manufacturing company Trina Solar is $0.46 [69]. If this system is installed, it is thought that it will work with an outside company. Photovoltaic panels are pre-purchased and stocked. As a surveillance tax for imported panel arrivals, 20$ per kilogram and the addition of 18% VAT are not included in the calculation.

Hybrid stand-alone power systems are expected to have a large share in the total cost of their batteries. A Sunlight - RES OPzV model battery with a power of 2 V, 4747 Ah, and 9.494 kWh was used in the system designs and simulations [71]. As the selection criterion, the Huawei Smart String ESS Battery Pack model was used with a 51.2 V, 320 ah 16.38 kWh Li-ion battery [88]. The estimated life of the battery is 10 years. Cabling costs are taken as average. Since the IZTECH campus area consists of 30 buildings, calculations must be made based on each building. Labor costs are considered as an average value.

System costs do not matter much in photovoltaic system installations. The annual maintenance cost after the warranty period given by the manufacturers covers a certain percentage of the capital cost [33,89]. An economic analysis was carried out to financially evaluate the results of the designed systems; an economic analysis is made in section 5.3. The cost of renewable energy systems is a major concern. In the sizing steps, the best configuration is selected by choosing the configuration with the lowest LCOE. Levelized cost of energy (LCOE), and net present value (NPV) are calculated for standalone hybrid systems.

5.5.1.1. Maximum PV Panel Installation for Each Building Economic Analysis (MPPIB)

The economic analysis results for each building with maximum photovoltaic panel placement are as follows.

Table 28. The maximum number of PV panels installation each building (MPPIB)

	PV Panel	Inverter	Lead Acid Battery	Electrical-Mechanical
Quantity	9,108	194	522,046	-
Price ($)	241.5$	-	1,044$	-
Total ($)	2,199,582$	656,089$	545,016,024$	100,000$
Capital Cost ($)	547,971,695$			

As seen in Table 28, the battery cost is higher than the photovoltaic panel cost. This increases the system cost considerably. In cost distribution, the photovoltaic panel has 0.4%, Inverter 0.1%, and the lead acid battery 99.4%. The remaining 0.1% includes the cost of electrical-mechanical tools and installation.

The amount of savings obtained from the electricity produced is as follows.

$$Annual\ Energy\ Cost\ Saving = 0.23783\ (\$/kWh\ ) * 4{,}319{,}266(kWh)$$

$$Annual\ Energy\ Cost\ Saving = 1{,}027{,}251\$$$

Table 29. MPPIB-O&M and Replacement Cost

	PV Panel	Inverter	Lead Acid Battery
O&M	21,995.82$	3,280.445$	24,781,524$
Replacement Cost	-	-	545,016,024$
Total ($)	21,995.82$	3,280.445$	569,797,548$
Overall Cost ($)	569,822,824$		

Annual O&M and replacement costs are calculated in Table 29. During this period, the replacement cost of the battery will be added at the end of 12 years. Electricity prices will vary for 25 years. Using the calculations in Section 4.7, the levelized cost of energy 24.27$/kWh is calculated as the capital recovery factor, net present value of 1,535,594,713 $ It was seen that the MPPIB system was not cost-effective. Calculations tables are given in Appendix F.

5.5.1.2. Maximum PV Panel Installation on Campus Economic Analysis (MPPIC)

The economic analysis results for the entire campus where the maximum photovoltaic panel placement is made are as follows.

Table 30. The maximum PV panel installation on campus (MPPIC)

	PV Panel	Inverter	Lead Acid Battery	Electrical-Mechanical
Quantity	9,108	91	226,200	-
Price ($)	241.5$	5,555$	1,044$	-
Total ($)	2,199,582$	505,505$	236,152,800$	100,000$
Capital Cost($)	238,957,887$			

As seen in Table 30, the highest cost in the system is the photovoltaic panel cost. In the cost distribution, photovoltaic panel has 0.9%, Inverter 0.2%, lead acid battery 98.82%. The remaining 0.7% includes the cost of electrical-mechanical tools and installation.

$$Annual\ Energy\ Cost\ Saving = 0.23783\ (\$/kWh\,) * 4{,}321{,}136(kWh)$$

$$Annual\ Energy\ Cost\ Saving = 1{,}027{,}696\$$$

Table 31. MPPIC-O&M and Replacement Cost

	PV Panel	Inverter	Lead Acid Battery
O&M	21,995.82$	2,527.52$	10,737,714$
Replacement Cost	-	-	236,152,800$
Total ($)	21,995.82$	2,527.52$	246,890,514$
Overall Cost ($)	246,915,037$		

Annual maintenance, repair, and electricity costs have been calculated. During this period, the maintenance-repair cost of the battery will be added at the end of 12 years. Electricity prices will vary for 25 years. Using the calculations in Section 4.7, the levelized cost of energy 10.07$/kWh is calculated as the capital recovery factor, net present value of 624,797,780 $. It was seen that the MPPIC system was not cost-effective. Calculations tables are given in Appendix G.

5.5.1.3. Necessary PV Panel Installation for Each Building Economic Analysis (NPPIB)

The economic analysis results for each building where the required necessary PV/Battery for each building placement is made are as follows.

Table 32. The necessary PV panel installation for each building (NPPIB)

	PV Panel	**Inverter**	**Lead Acid Battery**	**Electrical-Mechanical**
Quantity	114,340	379	20,855	-
Price ($)	241.5$	-	1,044$	-
Total ($)	27,613,110$	2,648,376$	21,772,620$	260,000$
Capital Cost ($)	52,294,106$			

As seen in Table 32, the highest cost in the system is the photovoltaic panel cost. In the cost distribution, the photovoltaic panel has 52.8%, inverter 5.06%, and the lead acid battery 41.63%. The remaining 0.49% includes electrical-mechanical equipment and assembly costs.

$$Annual\ Energy\ Cost\ Saving = 0.23783(\$/kWh\ ) * 55{,}086{,}589(kWh)$$

$$Annual\ Energy\ Cost\ Saving = 12{,}625{,}583\$$$

Table 33. NPPIB-O&M and Replacement Cost

	PV Panel	Inverter	Lead Acid Battery
O&M	1,380,656$	13,241.8$	989,986.8$
Replacement Cost	-	-	21,762,607$
Total ($)	1,380,656$	13,241.8$	22,762,607$
Overall Cost ($)	24,156,504$		

Annual maintenance, repair, and electricity costs have been calculated. During this period, the maintenance-repair cost of the battery will be added at the end of 12 years. Electricity prices will vary for 25 years. Using the calculations in Section 4.7, the levelized cost of energy 0.12$/kWh is calculated as the capital recovery factor, net present value of 183,685,909 $. Calculations tables are given in Appendix H.

5.5.1.4. Necessary PV Panel Installation on Campus Economic Analysis (NPPIC)

The economic analysis results for the entire campus where the required necessary PV/Battery on campus placement is made are as follows.

Table 34. The necessary PV-Lead Acid installation for the entire campus (NPPIC-Lead Acid)

	PV Panel	Inverter	Lead Acid Battery	Electrical-Mechanical
Quantity	114,340	325	3,790	-
Price ($)	241.5$	5,555$	1,044$	-
Total ($)	27,613,110$	1,805,375$	3,956,760$	260.000$
Capital Cost ($)	33,635,245$			

As seen in Table 34, the highest cost in the system is the photovoltaic panel cost. In the cost distribution, the photovoltaic panel has 82%, the inverter 5.3%, and the lead acid battery 11.76%. The remaining 0.94% includes electrical-mechanical equipment and assembly costs.

$$Annual\ Energy\ Cost\ Saving = 0.23783\ (\$/kWh\ ) * 55{,}086{,}589((kWh)$$

$$Annual\ Energy\ Cost\ Saving = 12{,}625{,}583\$$$

Table 35. NPPIC-O&M and Replacement Cost

	PV Panel	Inverter	Lead Acid Battery
O&M	1,380,656$	9,027$	179,911.3$
Replacement Cost	-	-	3,956,760$
Total ($)	1,380,656$	9,027$	4,136,671$
Overall Cost ($)	5,526,354$		

Annual maintenance, repair, and electricity costs have been calculated. During this period, the maintenance-repair cost of the battery will be added at the end of 12 years. Electricity prices will vary for 25 years. Using the calculations in Section 4.7, the levelized cost of energy 0.07$/kWh is calculated as the capital recovery factor, net present value of 213,813,990 $. Calculations tables are given in Appendix I.

If Li-ion battery is used as a new technology battery within the scope of this study, the economic analysis results are as follows.

Table 36. The necessary PV-Li-ion installation for the entire campus (NPPIC-Li-ion)

	PV Panel	**Inverter**	**Li-ion Battery**	**Electrical-Mechanical**
Quantity	114,340	325	2,009	-
Price ($)	241.5$	7,202.52$	7,076$	-
Total ($)	27,613,110$	2,340,819$	14,215,684$	260,000$
Capital Cost ($)	44,429,613$			

$$Annual\ Energy\ Cost\ Saving = 0.23783\ (\$/kWh\ ) *\ 55{,}850{,}540(((kWh)$$

$$Annual\ Energy\ Cost\ Saving = 12{,}807{,}274\$$$

Table 37. Li-ion-O&M and Replacement Cost

	PV Panel	**Inverter**	**Li-ion Battery**
O&M	1,380,656$	11,704.09$	95,367$
Replacement Cost	-	-	14,215,684$
Total ($)	1,380,656$	11,704.09$	14,311,051$
Overall Cost ($)	15,703,411$		

Annual maintenance, repair, and electricity costs have been calculated. During this period, the maintenance-repair cost of the battery will be added at the end of 12 years. Electricity prices will vary for 25 years. Using the calculations in Section 4.7, the levelized cost of energy 0.09$/kWh is calculated as the capital recovery factor, net present value of 203,226,749 $. In case of using Li-ion battery, levelized cost of energy cost and net present value costs increase. Calculations tables are given in Appendix J.

5.5.2. PV/Electrolyzer/H_2 Storage/Generator Economic Analysis

The economic analysis results for the entire campus where the required PV/Hydrogen system placement is made are as follows.

Table 38. The necessary PV panel-Hydrogen installation for the entire campus

	PV Panel	Electrolyzer	Hydrogen Tank	Diesel Generator	Electrical-Mechanical
Quantity	12,581	115.900	305	16	-
Price ($)	241.5$	6,375$	10,000$	25,400$	-
Total ($)	3,038,312$	738,862,500$	3,050,000$	406,400$	320,000$
Capital Cost ($)	745,677,212$				

As seen in Table 38, the highest cost in the system is the electrolyzer. In the cost distribution, the photovoltaic panel has 0.4%, the electrolyzer 99.08%, the hydrogen tank 0.4% and diesel generator has less %.

$$Annual\ Energy\ Cost\ Saving = 0.23783\ (\$/kWh) * 5{,}977{,}396 (kWh)$$

$$Annual\ Energy\ Cost\ Saving = 1{,}421{,}604\$$$

Table 39. PV-Electrolyzer O&M and Replacement Cost

	PV Panel	Electrolyzer	Hydrogen Tank	Diesel Generator
O&M	30,383.11$	13,792,100$	152,500$	8,192$
Replacement Cost	-	-	-	406,400$
Total ($)	30,383.11$	13,792,100$	152,500$	406,408$
Overall Cost ($)	14,381,391$			

Annual maintenance, repair, and electricity costs have been calculated. Electricity prices will vary for 25 years. Using the calculations in Section 4.7, the levelized cost of energy 10,97$/kWh is calculated as the capital recovery factor, net present value of 944,508,736 $. Calculations tables are given in Appendix K.

5.5.3. Wind/Battery System Economic Analysis

When performing a cost analysis for a wind turbine installation, the initial costs are divided into annual costs, production, taxes, and depreciation. In this study, most of the cost in the systems installed with the wind turbine is the wind turbine. Before the investment is made, the cost of establishing and operating a wind power plant is largely determined. Approximately 80% of the cost of electricity generation from wind energy consists of superstructure expenditures, and a large part of the investment cost occurs in the first years of the investment [73]. The expenses incurred after the wind turbine installation are maintenance expenses. After the wind turbine installation starts operating, maintenance throughout its economic life is important for the uninterrupted production of wind power plants. Maintenance costs include wind turbine components and transformers used during the transmission of energy, power poles, and transmission lines.

In wind energy investment, financial analyzes such as net energy production, turbine cost, and construction cost are made, and if the investment is found profitable, the installation phase is started. The installation of wind power plants is increasing day by day. With the development of technology, turbine heights are increasing. Prices vary from suppliers depending on turbine brand, model, and power.

In this thesis, Nordex, N100/2500 model wind turbine will be used. The selected wind turbine has a power of 2.5 MW. 1 wind turbine was used according to the consumption of the IZTECH campus. It is stated that in 2019, a 2.5-megawatt turbine produced $153.300 at 35% capacity, $219.000 at 50% capacity, and $284.700 at 65% capacity [90].

Electrical Mechanical: The calculation of the initial cost includes site preparation and the cost of the wind turbine. Site preparation the area where the turbine will be installed must be able to withstand heavy equipment loads.

The cost of the selected wind turbine in Table 40 has been calculated based on the unit price obtained under market conditions. The unit price per MW of the wind turbine by the manufacturing company Nordex is $1.100/kWh. Turbine cost increases with turbine size. The project life of turbine installations is between 20-25 years. Since the land area belongs to IZTECH University, there will be no land cost.

Sunlight - RES OPzV model lead acid battery with 2 V, 4747 Ah, and 9.494 kWh power was selected for wind system designs and simulations. As the selection criterion, the Huawei Smart String ESS Battery Pack model was used with a 51.2 V, 320 ah 16.38 kWh Li-ion battery. The estimated life of the battery is 12 years. Cabling costs are taken as average. Since the IZTECH campus area consists of 30 buildings, calculations must be made based on each building. The labor cost is accepted as $15.000.

Once a wind turbine is purchased and built, there will be maintenance costs. The annual maintenance cost of the wind turbine covers a certain percentage of the capital cost. Annual maintenance costs are fixed. In this study, the annual maintenance and repair value of the wind turbine was accepted as 43$/kW/year. Maintenance costs must be considered for each year.

The economic analysis results for the IZTECH campus, where the wind turbine is installed, are as follows.

Table 40. Wind Turbine-Lead Acid Installation Total Cost

	Wind Turbine	**Inverter**	**Lead Acid Battery**	**Electrical-Mechanical**
Quantity	1	125	18,543	-
Price ($)	2,800,000$	5,555$	1,044$	-
Total ($)	2,800,000$	694,375$	19,358,892$	300,000$
Capital Cost ($)	23,153,267$			

As can be seen in Table 40, most of the total cost is the lead acid battery cost. In the cost distribution, the wind turbine has 12,09%, inverter 3%, lead acid battery 83,61%. The remaining 1,3% includes the cost of electrical-mechanical tools and installation.

$$Annual\ Energy\ Cost\ Saving = 0.23783\ (\$/kWh\,) * 7{,}651{,}335(kWh)$$

$$Annual\ Energy\ Cost\ Saving = 1{,}819{,}717\$$$

Table 41. Wind Turbine O&M and Replacement Cost

	Wind Turbine	**Inverter**	**Lead Acid Battery**
O&M	75,000$	3,471.87$	31,320$
Replacement Cost	-	-	19,358,892$
Total ($)	75,000$	3,471.87$	19,390,212$
Overall Cost ($)	19,468,684$		

Annual maintenance, repair, and electricity costs have been calculated. During this period, the maintenance-repair cost of the battery will be added at the end of 12 years. Electricity prices will vary for 25 years. Using the calculations in Section 4.7, the levelized cost of energy 0.21$/kWh is calculated as the capital recovery factor, net present value of 12,783,739 $. Calculations tables are given in Appendix L.

If Li-ion battery is used as a new technology battery within the scope of this study, the economic analysis results are as follows.

Table 42. Wind Turbine-Li-ion Installation Total Cost

	Wind Turbine	**Inverter**	**Li-ion Battery**	**Electrical-Mechanical**
Quantity	1	125	11,077	-
Price ($)	2,800,000$	7,202.52$	7,076$	-
Total ($)	2,800,000$	900,315$	78,380,852$	300,000$
Overall ($)	82,175,227$			

As seen in Table 42, the highest cost in the system is the wind turbine cost. In the cost distribution, the wind turbine has 3.4%, the inverter 1%, and the li-ion battery 95.24%. The remaining 0.36% includes electrical-mechanical equipment and assembly costs.

$$Annual\ Energy\ Cost\ Saving = 0.23783\ (\$/kWh\ ) * 7{,}651{,}335(kWh)$$

$$Annual\ Energy\ Cost\ Saving = 1{,}819{,}717\$$$

Table 43. Wind Turbine -Li-ion O&M and Replacement Cost

	Wind Turbine	**Inverter**	**Lead Acid Battery**
O&M	75,000$	4,501.57$	212,280$
Replacement Cost	-	-	78,380,852$
Total ($)	75,000$	4,501.57$	78,593,132$
Overall Cost ($)	78,672,634$		

Annual maintenance, repair, and electricity costs have been calculated. During this period, the maintenance-repair cost of the battery will be added at the end of 12 years. Electricity prices will vary for 25 years. Using the calculations in Section 4.7, the levelized cost of energy 1.1$/kWh is calculated as the capital recovery factor, net present value of 86,463,079 $. Calculations tables are given in Appendix M.

5.5.4. Wind/Electrolyzer/H_2 Storage/Generator Economic Analysis

The economic analysis results for the IZTECH campus, where the wind turbine/hydrogen system is installed, are as follows.

Table 44. Wind Turbine-Hydrogen Installation Total Cost

	Wind Turbine	**Electrolyzer**	**Hydrogen Tank**	**Diesel Generator**	**Electrical-Mechanical**
Quantity	1	108,306	315	16	-
Price ($)	2,800,000$	6,375$	10.000$	25,400$	-
Total ($)	2,800,000$	690,450,750$	3,150,000$	406,400$	320.000$
Capital Cost ($)	697,127,150$				

As seen in Table 44, the highest cost in the system is the electrolyzer. In the cost distribution, the photovoltaic panel has 0.4%, the electrolyzer 99.04%, the hydrogen tank 0.45% and diesel generator has less %. The remaining 1% includes electrical-mechanical equipment and assembly costs.

$$Annual\ Energy\ Cost\ Saving = 0.23783\ (\$/kWh\ ) * 7{,}651{,}335(kWh)$$

$$Annual\ Energy\ Cost\ Saving = 1{,}819{,}717\$$$

Table 45. Wind Turbine -Hydrogen O&M and Replacement Cost

	Wind Turbine	Electrolyzer	Hydrogen Tank	Diesel Generator
O&M	75,000$	12,888,414$	157,500$	8,192$
Replacement Cost	-	-	-	406,400$
Total ($)	75,000$	12,888,414$	157,500$	406,408$
Overall Cost ($)	13,527,322$			

Annual maintenance, repair, and electricity costs have been calculated. Electricity prices will vary for 25 years. Using the calculations in Section 4.7, the levelized cost of energy 8,02$/kWh is calculated as the capital recovery factor, net present value of 873,054,130 $. Calculations tables are given in Appendix N.

The NPV and LCOE results of the techno-economic analysis of the systems are given in Table 46.

Table 46. NPV and LCOE Results

Scenarios	Sub-scenarios	NPV	LCOE
PV/Battery	**MPPIB**	1,535,594,713$	24.27$/kWh
	MPPIC	624,797,780$	10.07$/kWh
	NPPIB	183,685,909$	0.12$/kWh
	NPPIC	213,813,990$	0.07$/kWh
PV/Electrolyzer/ Hydrogen Tank/Generator	-	944,508,736$	10.97$/kWh
Wind Battery	-	12,783,739$	0.21$/kWh
Wind/Electrolyzer/. Hydrogen Tank/Generator	-	873,054,130$	8.02$/kWh

Levelized cost of energy recommended system configurations for each system individually PV/Battery (NPPIC), WT/Battery, PV/Hydrogen and WT/Hydrogen $0.07/kWh, $0.21/kWh, $10.97/ kWh and 8.02$/kWh. PV/Battery system is seen as the most suitable system in terms of levelized cost of energy (Table 46).

Net present values for PV/Battery (NPPIC), WT/Battery, PV/Hydrogen, and WT/Hydrogen are $213,813,990, $12,783,739, $944,508,736, and $873,054,130, respectively. According to net present values, PV/Battery system is seen as the most suitable system. Alternatively, a WT/Battery system can be used.

CHAPTER 6

CONCLUSION

In this study we have examined the use of standalone photovoltaic (PV) and wind systems combined with energy storage solutions to satisfy the energy needs of the Izmir Institute of Technology campus. Solar and wind energy were selected as the renewable energy sources due to the favorable location and energy potential of the IZTECH Campus. Two different energy storage systems are proposed to ensure a continuous power supply during standalone mode: (1) lead-acid battery and (2) electrolyzer, hydrogen storage tank, and hydrogen-powered generator. Based on the selection of energy conversion and storage devices, 4 different scenarios were proposed, and their techno-economic feasibilities were evaluated. The proposed scenarios are as follows:

Scenario 1: PV, Lead Acid Battery, Power Controller

Scenario 2: PV, Electrolyzer, H_2tank, Generator, Power Controller

Scenario 3: Wind Turbine, Lead Acid Battery, Power Controller

Scenario 4: Wind Turbine, Electrolyzer, H_2 Tank, Generator, Power Controller

For the first scenario, 4 different sub-scenarios were considered: (i) MPPIB, (ii) MPPIC, (iii) NPPIB, and (iv) NPPIC. In order to determine the equipment capacities and the number of the designed systems, the campus location, buildings, their annual electrical load profiles, and the solar and wind energy potential of the campus were analyzed. The maximum number of PV modules that can be installed on the roof of each building on the campus and their power output was calculated by the PV*SOL software while the dynamic system modelling was made by using TRNSYS software.

The results obtained in the photovoltaic PV/Battery scenario and its sub-scenarios are as follows:

- **MPPIB:** Photovoltaic panel system placed on the maximum available roof area for each building. In the MPPIB system, 9,108 panels, 194 inverters with different powers, and 522,046 lead acid batteries were used. In the case of using Li-ion batteries, the number of batteries is 202,705. The total investment cost of the system is \$547,971,695. LCOE and NPV values were calculated as 24.27\$/kWh and 1,535,594,713\$, respectively.

- **MPPIC:** Photovoltaic panel system for the entire campus, placed on the maximum available roof area. In the MPPIC system, 9,108 panels, 91 inverters, and 226,200 batteries were used. In the case of using Li-ion batteries, the number of batteries is 107,482. The total investment cost of the system is \$238,957,887. LCOE and NPV values were calculated as 10.07\$/kWh and 624,797,780\$, respectively.
- **NPPIB:** For each building, the required number of photovoltaic panels has been calculated. In the NPPIB system, 114,340 panels, 379 inverters with different powers, and 20,885 batteries were used. In the case of using Li-ion batteries, the number of batteries is 6,887. The total investment cost of the system is \$52,294,106. LCOE and NPV values were calculated as 0.12\$/kWh and 183,685,909\$, respectively.
- **NPPIC:** For the entire campus, the required number of photovoltaic panels has been calculated. In the NPPIC system, 114,340 panels, 325 inverters, and 3,790 lead-acid batteries are used. In the case of using a Li-ion battery, the number of batteries is 2009. The total investment cost of the system is \$33,635,245. LCOE and NPV values were calculated as 0.07\$/kWh and 213,813,990\$, respectively.

The results obtained in the Photovoltaic Panel/Electrolyzer/Hydrogen Tank/Generator scenario are as follows.

- Since the number of electrolyzers is not sufficient to meet the system consumption by TRNSYS software, system analysis has been made as aggregated multiples of the minimum scenario. 12,581 solar panels, 380 electrolyzers, 16 generators, and a 300 bar 100 m^3 hydrogen tanks were used in the system established for the campus.
- PV/Hydrogen system, 32,244.4 kg of hydrogen was produced and used annually.
- The number of electrolyzer and hydrogen tanks required to meet the hourly energy needs of the IZTECH University campus are 115,900 and 305, respectively.
- LCOE and NPV values were calculated as 10.97\$/kWh and 944,508,736\$, respectively.

The parameter analysis and results used in the Wind Turbine/Lead Acid Battery scenario are as follows.

- For the IZTECH campus, 1 wind turbine of 2.5 MW, 18,543 lead acid batteries, 11,077 li-ion batteries were used. Annual energy generation by wind turbine is 7,651,335 kWh.
- LCOE and NPV values were calculated as 0.21$/kWh and 12,783,739$, respectively.

The results obtained in Wind Turbine/Electrolyzer/Hydrogen Tank/Generator scenario are as follows.

- Since the number of electrolyzers was not sufficient to meet the system consumption of the TRNSYS software, system analysis was performed as combined multiples of the minimum scenario. In the system established for the campus, 1 wind turbine, 108,306 electrolyzers, 16 generators and 300 bar 100 m^3 hydrogen tanks were used.
- Wind/Hydrogen system, 109,932.7 kg of hydrogen was produced and used anuually.
- LCOE and NPV values were calculated as 8.02$/kWh and 873,054,130$, respectively.

The comparison of the designed system scenarios is as follows:

- Levelized costs of energy of battery storage systems are lower than that of hydrogen storage systems.
- Levelized costs of energy system recommended system configurations for each system individually PV/Battery (NPPIC), WT/Battery, PV/Hydrogen and WT/Hydrogen $0.07/kWh, $0.21/kWh, $10.97/ kWh and 8.02$/kWh. PV/Battery system was chosen as the most suitable system in terms of levelized costs of energy.
- Net present values for PV/Battery (NPPIC), WT/Battery, PV/Hydrogen, and WT/Hydrogen are $213,813,990, $12,783,739, $944,508,736 and $873,054,130, respectively. According to the net present values, the PV/Battery system was chosen as the most suitable system. Alternatively, the WT/Battery system can be used.
- Considering the net present value, it is more reasonable to prefer WT/Battery system as cost. In the future perspective, it would be more appropriate to advance the PV/Battery system step by step.

- Based on the thesis results, off-grid hybrid energy systems was found to be not economically feasible compared to traditional power generation systems. This is manly caused by high initial investment costs of off-grid hybrid energy systems.
  The following suggestions are made for similar studies to be done in the future:
- The climatic data of the designed systems should be reliable. Wind and solar energy potential can differ even in different locations within the same region. It does not differ much in the current study. In general, it is recommended to use long-term measured climate data in system designs.
- Roof revisions or additional installation planning should be done in the designed systems. With equity capital, large energy system installations can be accomplished in several parts.
- Control strategies in energy storage systems should be chosen according to load demand changes. Consumption values in campus buildings have a highly variable structure. Automatic control devices should be used. In this way, the electrical load demand is met in a more reasonable way. Power outages can be avoided.
- Selection of system components and sizing of the system should be done in detail. Since many components are used in the multi-structured campus area, integrated systems should be selected according to the system requirements.
- According to the results of the thesis, detailed feasibility studies of the systems should be carried out in future studies at the IZTECH campus.

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APPENDICES

APPENDIX A

Simple Photovoltaic Panel

PARAMETERS			
1	MPPT mode	[-]	When MPPT mode is set to 1, this parameter causes the PV to operate at its maximum power point rather than at a load voltage specified among the components inputs.
2	Module short-circuit current at reference conditions	[A]	The short circuit current reported on the manufacturer's spec sheet. Reference conditions are typically 1000 W/m2 (incident solar radiation) and 25C (module temperature)
3	Module open-circuit voltage at reference conditions	[V]	The open circuit voltage reported on the manufacturer's spec sheet. Reference conditions are typically 1000 W/m2 (incident solar radiation) and 25C (module temperature)
4	Reference cell temperature	[C]	The cell temperature at which the manufacturer reports open circuit voltage and short circuit current. This value is typically 25C
5	Reference insolation	[W/m^2]	The solar radiation level at which the manufacturer reports open circuit voltage and short circuit current. This value is typically 1000 W/m2.
6	Module voltage at max power point and reference conditions	[V]	Maximum power point voltage, the selected module is entered in the technical data sheet. Reference conditions are typically 1000 W/m2 (incident solar radiation) and 25C (module temperature).
7	Module current at max power point and reference conditions	[A]	Maximum power point current, the selected module is entered in the technical data sheet. Reference conditions are typically 1000 W/m2 (incident solar radiation) and 25C (module temperature).
8	Temperature coefficient of Isc (ref. cond)	[A/K]	In technical coument, it explains how the temperature affects the short circuit current of the module under reference conditions. The short circuit current typically increases with increasing ambient temperature.
9	Temperature coefficient of Voc (ref. cond.)	[V/K]	In the white paper, it explains how temperature affects the open circuit voltage of the module at referance conditions. The open circuit voltage typically decreases with increasing ambient temperature.
10	Number of cells wired in series	[-]	It refers to the number of individual cells connected in series within a module.
11	Module temperature at NOCT	[C]	It refers to the cell temperature of the module under nominal operating cell temperature (NOCT) conditions.
12	Module area	[m^2]	The active area of the module.
13	Number of modules in series	[-]	The number of modules wired in series within the PV array. Series wiring increases the array's total voltage.
14	Number of modules in parallel	[-]	The number of modules wired in parallel within the PV array. Parallel wiring increases the array's total current.

INPUTS			
1	Ambient temperature	[C]	Ambient temperature
2	Beam radiation	[kJ/hr. m^2]	The amount of beam solar radiation incident on the array.
3	Sky diffuse radiation	[kJ/hr. m^2]	The amount of sky diffuse solar incident on the array.
4	Ground reflected diffuse radiation	[kJ/hr. m^2]	The amount of ground reflected diffuse radiation incident on the surface of the array.
5	Array slope	Direction	[Degrees]
6	Incidence angle of beam radiation	[Degrees]	The angle between the normal to the array plane and the line between the sun and the surface of the array.
If MPPT mode (parameter 1) = 0			
7	Load voltage	[V]	The voltage of the electrical load imposed on the PV array. This voltage will determine the PV array's operating point on its I-V curve.
8	Flag for convergence promotion	[-]	Because a PV's I-V curve is so flat near the short circuit current and so vertical near the open circuit voltage, it can be very difficult to solve when the load voltage depends on the PV performance and the PV performance depends on the load voltage. This Type contains an internal solver to assist in the solution. Setting this input flag to "1" activates that algorithm. The algorithm is unnecessary if the PV is assumed to be attached to a maximum power point tracker.

APPENDIX B

Wind Turbine

INPUTS			
1	Control signal	[C]	The control signal for the wind turbine. CTRL = 0: WECS is OFF, CTRL = 1: WECS is ON and providing power.
2	Wind Speed	[m/s]	The uncorrected wind speed measured at the site at the data collection height specified as one of the parameters to this model. Note that "uncorrected" in this case means that the wind speed being provided to this component should NOT include any correction for site wind shear. If the wind speed has already been corrected for site shear effects, then the site shear exponent should be set to 0.
3	Ambient temperature	[C]	Ambient temperature
4	Site shear exponent	[kJ/hr.m^2]	Site wind shear exponent is a dimensionless measure of the wind speed at a particular height above the ground as compared to the free stream wind speed that was measured at a data collection site. The shear exponent is the value “a” in the formula: v / vo = (h / ho) ^a Some typical values are: -0.06 = inverted profile, 0.00 = neutral profile, 0.06 = open water, 0.10 = short grasses, 0.14 = 1/7-profile-common, 0.18 = low vegetation, 0.22 = forests, 0.26 = obstructed flows, 0.30 = rare
5	Barometric Pressure	[Pa]	Barometric (atmospheric) pressure

PARAMETERS			
1	Site elevation	[m]	The height of the site above sea level.
2	Data collection height	[m]	The height above site ground level at which the wind data was collected.
3	Hub height	[m]	Hub height of WECS, as installed on site
4	Turbine power loss	[% (base 100)]	The percentage of turbine output power that is lost due to inefficacies and transmission.
5	Number of turbines	[-]	Number of exactly similar turbines
6	Module voltage at max power Logical unit of file containing power curve datapoint and reference conditions	[-]	The integer identifier (logical unit number) associated with the data file containing additional WECS parameters.

APPENDIX C

Lead Acid Battery

PARAMETERS			
1	Mode	[-]	Mode 3 corresponds to the Hyman modified Shepherd equations. In modes 2 and 3 power is given as input.
2	Cell energy capacity	[Wh]	The rated energy capacity of each cell. The battery capacity is obtained by multiplying the cell capacity by the number of cells in series and by the number of cells in parallel.
3	Cells in parallel	[-]	The number of cells connected in parallel in the battery.
4	Cells in series	[-]	The number of cells in series in the battery.
5	Charging efficiency	[0..1]	The charging efficiency is typically higher when the battery is at a low state of charge (<=85%) but can drop below 50% for when the battery is at a high state of charge (SOC higher than 90%). This model, however, assumes that the charging efficiency is independent of battery state of charge.
If Mode (parameter 1) = 2, 3, 4, or 5			
6	Maximum current per cell charging	[A]	The maximum allowable battery cell charging current.
7	Maximum current per cell discharging	[A]	The maximum allowable battery cell discharging current.
8	Maximum charge voltage per cell	[V]	The maximum voltage allowed for each cell while charging. Do not use values greater than 2.8V.
9	Discharge cutoff voltage	[V]	The discharge cutoff voltage is the cell voltage below which battery discharge will be automatically shut off.

INPUTS			
If Mode (parameter 1) = 1,2 or 3			
1	Power to or from battery	[kJ/hr]	The power used to charge the battery has a positive sign while the power drawn from the battery by the load is negative.

DERIVATIVES			
1	State of charge	[Wh]	The initial state of charge of one cell of the battery. This value should use the same units as parameter 2 [Wh]. The value is given for one cell. The initial SOC of the battery is obtained by multiplying this value by the number of cells.

APPENDIX D

Electrolyzer

PARAMETERS			
1	Temperature mode	[-]	Temperature mode. In TMODE=1, T is given as input 7. In TMODE=2, T is calculated based on a simple quasi-static thermal model. In TMODE=3, T is calculated based on a complex lumped capacitance thermal model.
2	Electrode area	[m^2]	Area of electrode
3	Number of cells is series	[-]	Number of cells in series per stack
4	Number of stacks in parallel	[-]	Number of stacks in parallel per unit [mA/cm2] Maximum allowable current density per stack [C] Maximum allowable operating temperature [V] Minimum allowable cell voltage
5	Maximum allowable current density	[mA/cm^2]	Maximum allowable current density per stack
6	Maximum allowable operating temperature	[C]	Maximum allowable operating temperature
7	Minimum allowable cell voltage	[V]	Minimum allowable cell voltage
8	Minimum allowable cell voltage	[K/W]	Thermal resistance. NOTE: this value is ignored in TMODE 1. It is only needed when using one of the two thermal models (TMODE=2 or 3)
9	Thermal time constant	[hr]	Thermal time constant, TAU_T = C_T * R_T (See manual for further information onequation)
10	Electrolyzer type	[-]	The identification number of the electrolyzer listed in external file
11	Logical Unit for data file	[-]	Logical unit for external file with electrolyzer parameters

INPUTS			
1	Electrolyzer control signal	[-]	Electrolyzer operating switch. 0=OFF, 1=ON
2	Electrolyzer current	[A]	Current through single electrolyzer stack
3	Electrolyzer pressure	[bar]	Electrolyzer pressure. Constant pressure is assumed. The main equations in the model are based on a constant pressure.
4	Electrolyzer environment temperature	[C]	Ambient (or room) temperature
5	Cooling water inlet temperature	[C]	Temperature of inlet cooling water
6	Cooling water flow rate	[m^3/hr]	Volumetric flow rate of cooling water
7	Electrolyzer operating temperature	[C]	Temperature of electrolyzer. In TMODES 2 and 3, this input gives the electrolyzer's initial temperature.

OUTPUTS			
3	Electrolyzer power	[W]	Total power drawn by electrolyzer
4	Hydrogen production rate	[m^3/hr]	The volumetric rate at which hydrogen gas is produced by the electrolyzer
5	Oxygen production rate	[m^3/hr]	The volumetric rate at which oxygen gas is produced by the electrolyzer.

APPENDIX E

Compressed Gas Storage

PARAMETERS			
1	Pressure mode	[-]	Pressure mode (1=ideal gas, 2=real gas)
2	Maximum allowable pressure	[bar]	Maximum allowable pressure
3	Tank volume	[m^3]	Actual volume of pressure tank
4	Molar weight of gas	[kg/mol]	Molar weight of gas
If Pressure Mode (parameter 1) =2			
6	Gas critical temperature	[C]	Critical temperature of gas
7	Gas critical pressure	[-]	Critical pressure of gas

INPUTS			
1	Volumetric flow rate of gas entering the tank	[m^3/hr]	Inlet gas flow rate
2	Volumetric flow rate of gas leaving the tank	[m^3/hr]	Outlet gas flow rate
3	Gas temperature	[C]	Temperature of gas
4	Initial pressure level	[C]	Initial pressure level. This value is normalized 0: completely empty. 1: completely full (pressure will in this case be set to the maximum allowable tank pressure that is specified as a parameter to this model.

OUTPUTS			
2	Gas pressure	[bar]	Pressure of gas in tank
3	Pressure level	[-]	Pressure level in tank

APPENDIX F

Maximum PV Panel Installation for each Building (MPPIB)

Year	Production (kWh)	NPV Production (kWh)	Direct Purchase Cost ($)	O&M Cost ($)	NPV O&M Cost ($)	Replacement Cost($)	NPV Replacement Cost	PPA Escalator (%)	PPA Rate ($/kWh)	PPA Cost ($)	NPV PPA ($)
0			$ 547.971.695					-			
1	4.319.266	4.153.140		$ 24.806.800	$ 23.852.692	-	-		$ 0,2378	$ 1.027.251	$ 987.741
2	4.297.670	3.973.437		$ 26.047.140	$ 24.082.045	-	-	4%	$ 0,2473	$ 1.062.999	$ 982.803
3	4.276.181	3.801.510		$ 27.349.497	$ 24.313.603	-	-	4%	$ 0,2572	$ 1.099.992	$ 977.889
4	4.254.800	3.637.021		$ 28.716.972	$ 24.547.388	-	-	4%	$ 0,2675	$ 1.138.271	$ 972.999
5	4.233.526	3.479.650		$ 30.152.820	$ 24.783.420	-	-	4%	$ 0,2782	$ 1.177.883	$ 968.134
6	4.212.359	3.329.088		$ 31.660.461	$ 25.021.722	-	-	4%	$ 0,2894	$ 1.218.874	$ 963.294
7	4.191.297	3.185.041		$ 33.243.484	$ 25.262.316	-	-	4%	$ 0,3009	$ 1.261.290	$ 958.477
8	4.170.341	3.047.227		$ 34.905.659	$ 25.505.223	-	-	4%	$ 0,3130	$ 1.305.183	$ 953.685
9	4.149.489	2.915.376		$ 36.650.942	$ 25.750.465	-	-	4%	$ 0,3255	$ 1.350.604	$ 948.916
10	4.128.741	2.789.230		$ 38.483.489	$ 25.998.066	-	-	4%	$ 0,3385	$ 1.397.605	$ 944.172
11	4.108.098	2.668.542		$ 40.407.663	$ 26.248.047	-	-	4%	$ 0,3520	$ 1.446.241	$ 939.451
12	4.087.557	2.553.076		$ 42.428.046	$ 26.500.432	$ 545.016.024	$ 340.415.400	4%	$ 0,3661	$ 1.496.571	$ 934.754
13	4.067.119	2.442.607		$ 44.549.448	$ 26.755.244	-	-	4%	$ 0,3808	$ 1.548.651	$ 930.080
14	4.046.784	2.336.917		$ 46.776.921	$ 27.012.506	-	-	4%	$ 0,3960	$ 1.602.544	$ 925.429
15	4.026.550	2.235.800		$ 49.115.767	$ 27.272.242	-	-	4%	$ 0,4118	$ 1.658.313	$ 920.802
16	4.006.417	2.139.059		$ 51.571.555	$ 27.534.475	-	-	4%	$ 0,4283	$ 1.716.022	$ 916.198
17	3.986.385	2.046.503		$ 54.150.133	$ 27.799.230	-	-	4%	$ 0,4455	$ 1.775.740	$ 911.617
18	3.966.453	1.957.953		$ 56.857.640	$ 28.066.530	-	-	4%	$ 0,4633	$ 1.837.535	$ 907.059
19	3.946.621	1.873.234		$ 59.700.522	$ 28.336.400	-	-	4%	$ 0,4818	$ 1.901.482	$ 902.524
20	3.926.888	1.792.180		$ 62.685.548	$ 28.608.866	-	-	4%	$ 0,5011	$ 1.967.653	$ 898.011
21	3.907.253	1.714.634		$ 65.819.825	$ 28.883.951	-	-	4%	$ 0,5211	$ 2.036.128	$ 893.521
22	3.887.717	1.640.443		$ 69.110.816	$ 29.161.681	-	-	4%	$ 0,5420	$ 2.106.985	$ 889.054
23	3.868.278	1.569.462		$ 72.566.357	$ 29.442.082	-	-	4%	$ 0,5636	$ 2.180.308	$ 884.608
24	3.848.937	1.501.553		$ 76.194.675	$ 29.725.179	-	-	4%	$ 0,5862	$ 2.256.183	$ 880.185
25	3.829.692	1.436.582		$ 80.004.409	$ 30.010.998	-	-	4%	$ 0,6096	$ 2.334.698	$ 875.784
Total	**101.744.420**	**64.219.266**	**$ 547.971.695**	**$ 1.183.956.589**	**$ 670.474.805**	**$ 545.016.024**	**$ 340.415.400**			**$ 39.905.006**	**$ 23.267.188**

Direct Purchase	
20 Year	$ 19,00794
25 Year	$ 24,27405
NPV	
Direct Purchase	
25 Year	$ (1.535.594.713)

APPENDIX G

Maximum PV Panel Installation on Campus (MPPIC)

Year	Production (kWh)	NPV Production (kWh)	Direct Purchase Cost ($)	O&M Cost ($)	NPV O&M Cost ($)	Replacement Cost($)	NPV Replacement Cost	PPA Escalator (%)	PPA Rate ($/kWh)	PPA Cost ($)	NPV PPA ($)
0			$ 238.957.887					-			
1	4.321.136	4.154.938		$ 10.762.237	$ 10.348.305	-	-		$ 0,2378	$ 1.027.696	$ 988.169
2	4.299.530	3.975.157		$ 11.300.349	$ 10.447.808	-	-	4%	$ 0,2473	$ 1.063.460	$ 983.228
3	4.278.033	3.803.155		$ 11.865.367	$ 10.548.268	-	-	4%	$ 0,2572	$ 1.100.468	$ 978.312
4	4.256.643	3.638.596		$ 12.458.635	$ 10.649.693	-	-	4%	$ 0,2675	$ 1.138.764	$ 973.420
5	4.235.359	3.481.157		$ 13.081.567	$ 10.752.094	-	-	4%	$ 0,2782	$ 1.178.393	$ 968.553
6	4.214.182	3.330.530		$ 13.735.645	$ 10.855.480	-	-	4%	$ 0,2894	$ 1.219.401	$ 963.711
7	4.193.112	3.186.420		$ 14.422.427	$ 10.959.859	-	-	4%	$ 0,3009	$ 1.261.837	$ 958.892
8	4.172.146	3.048.546		$ 15.143.549	$ 11.065.243	-	-	4%	$ 0,3130	$ 1.305.748	$ 954.098
9	4.151.285	2.916.638		$ 15.900.726	$ 11.171.639	-	-	4%	$ 0,3255	$ 1.351.188	$ 949.327
10	4.130.529	2.790.437		$ 16.695.762	$ 11.279.059	-	-	4%	$ 0,3385	$ 1.398.210	$ 944.580
11	4.109.876	2.669.697		$ 17.530.551	$ 11.387.511	-	-	4%	$ 0,3520	$ 1.446.868	$ 939.858
12	4.089.327	2.554.181		$ 18.407.078	$ 11.497.007	$236.152.800	$ 117.360.707	4%	$ 0,3661	$ 1.497.219	$ 935.158
13	4.068.880	2.443.664		$ 19.327.432	$ 11.607.555	-	-	4%	$ 0,3808	$ 1.549.322	$ 930.482
14	4.048.536	2.337.929		$ 20.293.804	$ 11.719.166	-	-	4%	$ 0,3960	$ 1.603.238	$ 925.830
15	4.028.293	2.236.768		$ 21.308.494	$ 11.831.850	-	-	4%	$ 0,4118	$ 1.659.031	$ 921.201
16	4.008.152	2.139.985		$ 22.373.918	$ 11.945.618	-	-	4%	$ 0,4283	$ 1.716.765	$ 916.595
17	3.988.111	2.047.389		$ 23.492.614	$ 12.060.480	-	-	4%	$ 0,4455	$ 1.776.509	$ 912.012
18	3.968.170	1.958.800		$ 24.667.245	$ 12.176.446	-	-	4%	$ 0,4633	$ 1.838.331	$ 907.452
19	3.948.329	1.874.045		$ 25.900.607	$ 12.293.527	-	-	4%	$ 0,4818	$ 1.902.305	$ 902.915
20	3.928.588	1.792.956		$ 27.195.638	$ 12.411.734	-	-	4%	$ 0,5011	$ 1.968.505	$ 898.400
21	3.908.945	1.715.376		$ 28.555.420	$ 12.531.078	-	-	4%	$ 0,5211	$ 2.037.009	$ 893.908
22	3.889.400	1.641.153		$ 29.983.191	$ 12.651.569	-	-	4%	$ 0,5420	$ 2.107.897	$ 889.439
23	3.869.953	1.570.142		$ 31.482.350	$ 12.773.218	-	-	4%	$ 0,5636	$ 2.181.252	$ 884.991
24	3.850.603	1.502.203		$ 33.056.468	$ 12.896.038	-	-	4%	$ 0,5862	$ 2.257.159	$ 880.566
25	3.831.350	1.437.204		$ 34.709.291	$ 13.020.038	-	-	4%	$ 0,6096	$ 2.335.709	$ 876.164
Total	**101.788.470**	**64.247.069**	**$ 238.957.887**	**$ 513.650.365**	**$ 290.880.284**	**$236.152.800**	**$ 117.360.707**			**$ 39.922.283**	**$ 22.401.098**

Direct Purchase	
20 Year	$ 8,26460
25 Year	$ 10,07359
NPV	
Direct Purchase	
25 Year	$ (624.797.780)

APPENDIX H

Necessary PV Panel Installation for each Building (NPPIB)

Year	Production (kWh)	NPV Production (kWh)	Direct Purchase Cost ($)	O&M Cost ($)	NPV O&M Cost ($)	Replacement Cost($)	NPV Replacement Cost	PPA Escalator (%)	PPA Rate ($/kWh)	PPA Cost ($)	NPV PPA ($)
0			$ 52.294.106					-			
1	53.086.589	51.044.797		$ 2.383.884	$ 2.292.196	-	-		$ 0,2378	$ 12.625.583	$ 12.139.984
2	52.821.156	48.836.128		$ 2.395.804	$ 2.215.055	-	-	4%	$ 0,2473	$ 13.064.954	$ 12.079.284
3	52.557.050	46.723.026		$ 2.407.783	$ 2.140.510	-	-	4%	$ 0,2572	$ 13.519.614	$ 12.018.888
4	52.294.265	44.701.357		$ 2.419.822	$ 2.068.474	-	-	4%	$ 0,2675	$ 13.990.097	$ 11.958.793
5	52.032.794	42.767.164		$ 2.431.921	$ 1.998.862	-	-	4%	$ 0,2782	$ 14.476.952	$ 11.898.999
6	51.772.630	40.916.661		$ 2.444.080	$ 1.931.592	-	-	4%	$ 0,2894	$ 14.980.750	$ 11.839.504
7	51.513.767	39.146.229		$ 2.456.301	$ 1.866.587	-	-	4%	$ 0,3009	$ 15.502.080	$ 11.780.307
8	51.256.198	37.452.402		$ 2.468.582	$ 1.803.769	-	-	4%	$ 0,3130	$ 16.041.553	$ 11.721.405
9	50.999.917	35.831.865		$ 2.480.925	$ 1.743.065	-	-	4%	$ 0,3255	$ 16.599.799	$ 11.662.798
10	50.744.917	34.281.448		$ 2.493.330	$ 1.684.404	-	-	4%	$ 0,3385	$ 17.177.472	$ 11.604.484
11	50.491.193	32.798.116		$ 2.505.796	$ 1.627.718	-	-	4%	$ 0,3520	$ 17.775.248	$ 11.546.462
12	50.238.737	31.378.967		$ 2.518.325	$ 1.572.939	$ 21.772.620	$ 10.820.325	4%	$ 0,3661	$ 18.393.826	$ 11.488.730
13	49.987.543	30.021.223		$ 2.530.917	$ 1.520.003	-	-	4%	$ 0,3808	$ 19.033.931	$ 11.431.286
14	49.737.605	28.722.228		$ 2.543.572	$ 1.468.849	-	-	4%	$ 0,3960	$ 19.696.312	$ 11.374.129
15	49.488.917	27.479.439		$ 2.556.289	$ 1.419.417	-	-	4%	$ 0,4118	$ 20.381.744	$ 11.317.259
16	49.241.473	26.290.425		$ 2.569.071	$ 1.371.648	-	-	4%	$ 0,4283	$ 21.091.028	$ 11.260.673
17	48.995.265	25.152.858		$ 2.581.916	$ 1.325.487	-	-	4%	$ 0,4455	$ 21.824.996	$ 11.204.369
18	48.750.289	24.064.514		$ 2.594.826	$ 1.280.879	-	-	4%	$ 0,4633	$ 22.584.506	$ 11.148.347
19	48.506.537	23.023.261		$ 2.607.800	$ 1.237.772	-	-	4%	$ 0,4818	$ 23.370.447	$ 11.092.606
20	48.264.005	22.027.062		$ 2.620.839	$ 1.196.117	-	-	4%	$ 0,5011	$ 24.183.738	$ 11.037.143
21	48.022.685	21.073.968		$ 2.633.943	$ 1.155.863	-	-	4%	$ 0,5211	$ 25.025.333	$ 10.981.957
22	47.782.571	20.162.113		$ 2.647.113	$ 1.116.964	-	-	4%	$ 0,5420	$ 25.896.214	$ 10.927.047
23	47.543.658	19.289.714		$ 2.660.348	$ 1.079.373	-	-	4%	$ 0,5636	$ 26.797.402	$ 10.872.412
24	47.305.940	18.455.063		$ 2.673.650	$ 1.043.048	-	-	4%	$ 0,5862	$ 27.729.952	$ 10.818.050
25	47.069.410	17.656.527		$ 2.687.018	$ 1.007.946	-	-	4%	$ 0,6096	$ 28.694.954	$ 10.763.960
Total	**1.250.505.111**	**789.296.553**	**$ 52.294.106**	**$ 63.313.855**	**$ 39.168.535**	**$ 21.772.620**	**$ 10.820.325**			**$ 490.458.486**	**$ 285.968.876**

LCOE Outputs*	
Direct Purchase	
20 Year	$ 0,12425
25 Year	$ 0,12959
NPV	
Direct Purchase	
25 Year	$ 183.685.909

APPENDIX I

Necessary PV-Lead Acid Installation on Campus (NPPIC)

Year	Production (kWh)	NPV Production (kWh)	Direct Purchase Cost ($)	O&M Cost ($)	NPV O&M Cost ($)	Replacement Cost($)	NPV Replacement Cost	PPA Escalator (%)	PPA Rate ($/kWh)	PPA Cost ($)	NPV PPA ($)
0			$ 33.635.245					-			
1	53.086.589	51.044.797		$ 1.569.594	$ 1.509.225	-	-		$ 0,2378	$ 12.625.583	$ 12.139.984
2	52.821.156	48.836.128		$ 1.577.442	$ 1.458.433	-	-	4%	$ 0,2473	$ 13.064.954	$ 12.079.284
3	52.557.050	46.723.026		$ 1.585.329	$ 1.409.352	-	-	4%	$ 0,2572	$ 13.519.614	$ 12.018.888
4	52.294.265	44.701.357		$ 1.593.256	$ 1.361.921	-	-	4%	$ 0,2675	$ 13.990.097	$ 11.958.793
5	52.032.794	42.767.164		$ 1.601.222	$ 1.316.088	-	-	4%	$ 0,2782	$ 14.476.952	$ 11.898.999
6	51.772.630	40.916.661		$ 1.609.228	$ 1.271.796	-	-	4%	$ 0,2894	$ 14.980.750	$ 11.839.504
7	51.513.767	39.146.229		$ 1.617.274	$ 1.228.995	-	-	4%	$ 0,3009	$ 15.502.080	$ 11.780.307
8	51.256.198	37.452.402		$ 1.625.360	$ 1.187.635	-	-	4%	$ 0,3130	$ 16.041.553	$ 11.721.405
9	50.999.917	35.831.865		$ 1.633.487	$ 1.147.666	-	-	4%	$ 0,3255	$ 16.599.799	$ 11.662.798
10	50.744.917	34.281.448		$ 1.641.655	$ 1.109.043	-	-	4%	$ 0,3385	$ 17.177.472	$ 11.604.484
11	50.491.193	32.798.116		$ 1.649.863	$ 1.071.720	-	-	4%	$ 0,3520	$ 17.775.248	$ 11.546.462
12	50.238.737	31.378.967		$ 1.658.112	$ 1.035.652	$ 3.956.760	$ 1.966.389	4%	$ 0,3661	$ 18.393.826	$ 11.488.730
13	49.987.543	30.021.223		$ 1.666.403	$ 1.000.798	-	-	4%	$ 0,3808	$ 19.033.931	$ 11.431.286
14	49.737.605	28.722.228		$ 1.674.735	$ 967.118	-	-	4%	$ 0,3960	$ 19.696.312	$ 11.374.129
15	49.488.917	27.479.439		$ 1.683.108	$ 934.570	-	-	4%	$ 0,4118	$ 20.381.744	$ 11.317.259
16	49.241.473	26.290.425		$ 1.691.524	$ 903.119	-	-	4%	$ 0,4283	$ 21.091.028	$ 11.260.673
17	48.995.265	25.152.858		$ 1.699.982	$ 872.725	-	-	4%	$ 0,4455	$ 21.824.996	$ 11.204.369
18	48.750.289	24.064.514		$ 1.708.482	$ 843.355	-	-	4%	$ 0,4633	$ 22.584.506	$ 11.148.347
19	48.506.537	23.023.261		$ 1.717.024	$ 814.972	-	-	4%	$ 0,4818	$ 23.370.447	$ 11.092.606
20	48.264.005	22.027.062		$ 1.725.609	$ 787.545	-	-	4%	$ 0,5011	$ 24.183.738	$ 11.037.143
21	48.022.685	21.073.968		$ 1.734.237	$ 761.042	-	-	4%	$ 0,5211	$ 25.025.333	$ 10.981.957
22	47.782.571	20.162.113		$ 1.742.908	$ 735.430	-	-	4%	$ 0,5420	$ 25.896.214	$ 10.927.047
23	47.543.658	19.289.714		$ 1.751.623	$ 710.680	-	-	4%	$ 0,5636	$ 26.797.402	$ 10.872.412
24	47.305.940	18.455.063		$ 1.760.381	$ 686.762	-	-	4%	$ 0,5862	$ 27.729.952	$ 10.818.050
25	47.069.410	17.656.527		$ 1.769.183	$ 663.650	-	-	4%	$ 0,6096	$ 28.694.954	$ 10.763.960
Total	**1.250.505.111**	**789.296.553**	**$ 33.635.245**	**$ 41.687.020**	**$ 25.789.292**	**$ 3.956.760**	**$ 1.966.389**			**$ 490.458.486**	**$ 275.204.916**

Direct Purchase	
20 Year	$ 0,08349
25 Year	$ 0,07778
NPV	
Direct Purchase	
25 Year	$ 213.813.990

APPENDIX J

Necessary PV-Li-ion Installation on Campus (NPPIC)

Year	Production (kWh)	NPV Production (kWh)	Direct Purchase Cost ($)	O&M Cost ($)	NPV O&M Cost ($)	Replacement Cost($)	NPV Replacement Cost	PPA Escalator (%)	PPA Rate ($/kWh)	PPA Cost ($)	NPV PPA ($)
0			$ 44.429.613					-			
1	53.850.540	51.779.365		$ 1.487.727	$ 1.430.507	-	-		$ 0,2378	$ 12.807.274	$ 12.314.686
2	53.581.287	49.538.912		$ 1.495.165	$ 1.382.365	-	-	4%	$ 0,2473	$ 13.252.967	$ 12.253.113
3	53.313.381	47.395.401		$ 1.502.641	$ 1.335.843	-	-	4%	$ 0,2572	$ 13.714.170	$ 12.191.847
4	53.046.814	45.344.639		$ 1.510.155	$ 1.290.886	-	-	4%	$ 0,2675	$ 14.191.423	$ 12.130.888
5	52.781.580	43.382.611		$ 1.517.705	$ 1.247.443	-	-	4%	$ 0,2782	$ 14.685.285	$ 12.070.234
6	52.517.672	41.505.479		$ 1.525.294	$ 1.205.462	-	-	4%	$ 0,2894	$ 15.196.333	$ 12.009.883
7	52.255.084	39.709.569		$ 1.532.920	$ 1.164.893	-	-	4%	$ 0,3009	$ 15.725.165	$ 11.949.833
8	51.993.808	37.991.366		$ 1.540.585	$ 1.125.690	-	-	4%	$ 0,3130	$ 16.272.401	$ 11.890.084
9	51.733.839	36.347.509		$ 1.548.288	$ 1.087.806	-	-	4%	$ 0,3255	$ 16.838.681	$ 11.830.634
10	51.475.170	34.774.780		$ 1.556.029	$ 1.051.198	-	-	4%	$ 0,3385	$ 17.424.667	$ 11.771.480
11	51.217.794	33.270.102		$ 1.563.809	$ 1.015.821	-	-	4%	$ 0,3520	$ 18.031.045	$ 11.712.623
12	50.961.705	31.830.531		$ 1.571.628	$ 981.634	$ 14.215.684	$ 7.064.759	4%	$ 0,3661	$ 18.658.525	$ 11.654.060
13	50.706.897	30.453.248		$ 1.579.487	$ 948.599	-	-	4%	$ 0,3808	$ 19.307.842	$ 11.595.790
14	50.453.362	29.135.559		$ 1.587.384	$ 916.675	-	-	4%	$ 0,3960	$ 19.979.755	$ 11.537.811
15	50.201.095	27.874.886		$ 1.595.321	$ 885.825	-	-	4%	$ 0,4118	$ 20.675.051	$ 11.480.122
16	49.950.090	26.668.761		$ 1.603.298	$ 856.014	-	-	4%	$ 0,4283	$ 21.394.542	$ 11.422.721
17	49.700.339	25.514.825		$ 1.611.314	$ 827.206	-	-	4%	$ 0,4455	$ 22.139.072	$ 11.365.607
18	49.451.838	24.410.818		$ 1.619.371	$ 799.367	-	-	4%	$ 0,4633	$ 22.909.512	$ 11.308.779
19	49.204.579	23.354.580		$ 1.627.467	$ 772.465	-	-	4%	$ 0,4818	$ 23.706.763	$ 11.252.235
20	48.958.556	22.344.046		$ 1.635.605	$ 746.469	-	-	4%	$ 0,5011	$ 24.531.758	$ 11.195.974
21	48.713.763	21.377.236		$ 1.643.783	$ 721.347	-	-	4%	$ 0,5211	$ 25.385.464	$ 11.139.994
22	48.470.194	20.452.259		$ 1.652.002	$ 697.071	-	-	4%	$ 0,5420	$ 26.268.878	$ 11.084.294
23	48.227.843	19.567.306		$ 1.660.262	$ 673.612	-	-	4%	$ 0,5636	$ 27.183.035	$ 11.028.873
24	47.986.704	18.720.644		$ 1.668.563	$ 650.942	-	-	4%	$ 0,5862	$ 28.129.004	$ 10.973.729
25	47.746.770	17.910.616		$ 1.676.906	$ 629.036	-	-	4%	$ 0,6096	$ 29.107.894	$ 10.918.860
Total	**1.268.500.704**	**800.655.051**	**$ 44.429.613**	**$ 39.512.708**	**$ 24.444.174**	**$ 14.215.684**	**$ 7.064.759**			**$ 497.516.507**	**$ 279.165.296**

Direct Purchase	
20 Year	$ 0,10328
25 Year	$ 0,09485
NPV	
Direct Purchase	
25 Year	$ 203.226.749

APPENDIX K

PV/Electrolyzer/Hydrogen Installation on Campus

Year	Production (kWh)	NPV Production (kWh)	Direct Purchase Cost ($)	O&M Cost ($)	NPV O&M Cost ($)	Replacement Cost($)	NPV Replacement Cost	PPA Escalator (%)	PPA Rate ($/kWh)	PPA Cost ($)	NPV PPA ($)
0			$ 745.677.212					-			
1	5.977.396	5.747.496		$ 13.974.991	$ 13.437.492	-	-		$ 0,2378	$ 1.421.604	$ 1.366.927
2	5.947.509	5.498.806		$ 14.044.866	$ 12.985.268	-	-	4%	$ 0,2473	$ 1.471.076	$ 1.360.092
3	5.917.771	5.260.877		$ 14.115.091	$ 12.548.264	-	-	4%	$ 0,2572	$ 1.522.269	$ 1.353.292
4	5.888.183	5.033.243		$ 14.185.666	$ 12.125.967	-	-	4%	$ 0,2675	$ 1.575.244	$ 1.346.525
5	5.858.742	4.815.459		$ 14.256.594	$ 11.717.881	-	-	4%	$ 0,2782	$ 1.630.063	$ 1.339.793
6	5.829.448	4.607.097		$ 14.327.877	$ 11.323.530	-	-	4%	$ 0,2894	$ 1.686.789	$ 1.333.094
7	5.800.301	4.407.752		$ 14.399.517	$ 10.942.449	-	-	4%	$ 0,3009	$ 1.745.489	$ 1.326.428
8	5.771.299	4.217.032		$ 14.471.514	$ 10.574.194	-	-	4%	$ 0,3130	$ 1.806.232	$ 1.319.796
9	5.742.443	4.034.564		$ 14.543.872	$ 10.218.331	-	-	4%	$ 0,3255	$ 1.869.089	$ 1.313.197
10	5.713.731	3.859.992		$ 14.616.591	$ 9.874.445	$ 406.400	$ 201.968	4%	$ 0,3385	$ 1.934.133	$ 1.306.631
11	5.685.162	3.692.973		$ 14.689.674	$ 9.542.132	-	-	4%	$ 0,3520	$ 2.001.441	$ 1.300.098
12	5.656.736	3.533.181		$ 14.763.123	$ 9.221.003	-	-	4%	$ 0,3661	$ 2.071.091	$ 1.293.598
13	5.628.452	3.380.303		$ 14.836.938	$ 8.910.681	-	-	4%	$ 0,3808	$ 2.143.165	$ 1.287.130
14	5.600.310	3.234.040		$ 14.911.123	$ 8.610.802	-	-	4%	$ 0,3960	$ 2.217.748	$ 1.280.694
15	5.572.309	3.094.105		$ 14.985.678	$ 8.321.015	-	-	4%	$ 0,4118	$ 2.294.925	$ 1.274.291
16	5.544.447	2.960.226		$ 15.060.607	$ 8.040.981	-	-	4%	$ 0,4283	$ 2.374.789	$ 1.267.919
17	5.516.725	2.832.139		$ 15.135.910	$ 7.770.371	-	-	4%	$ 0,4455	$ 2.457.431	$ 1.261.579
18	5.489.141	2.709.594		$ 15.211.589	$ 7.508.868	-	-	4%	$ 0,4633	$ 2.542.950	$ 1.255.272
19	5.461.695	2.592.352		$ 15.287.647	$ 7.256.166	-	-	4%	$ 0,4818	$ 2.631.445	$ 1.248.995
20	5.434.387	2.480.183		$ 15.364.086	$ 7.011.968	-	-	4%	$ 0,5011	$ 2.723.019	$ 1.242.750
21	5.407.215	2.372.868		$ 15.440.906	$ 6.775.988	-	-	4%	$ 0,5211	$ 2.817.780	$ 1.236.536
22	5.380.179	2.270.196		$ 15.518.111	$ 6.547.950	-	-	4%	$ 0,5420	$ 2.915.839	$ 1.230.354
23	5.353.278	2.171.966		$ 15.595.701	$ 6.327.587	-	-	4%	$ 0,5636	$ 3.017.310	$ 1.224.202
24	5.326.512	2.077.987		$ 15.673.680	$ 6.114.639	-	-	4%	$ 0,5862	$ 3.122.312	$ 1.218.081
25	5.299.879	1.988.074		$ 15.752.048	$ 5.908.858	-	-	4%	$ 0,6096	$ 3.230.969	$ 1.211.991
Total	**140.803.250**	**88.872.503**	**$ 745.677.212**	**$ 371.163.401**	**$ 229.616.832**	**$ 406.400**	**$ 201.968**			**$ 55.224.203**	**$ 30.987.276**

LCOE Outputs*	
Direct Purchase	
20 Year	$ 12,10160
25 Year	$ 10,97635
NPV	
Direct Purchase	
25 Year	$ (944.508.736)

APPENDIX L

Wind Turbine-Lead Acid Installation on Campus

Year	Production (kWh)	NPV Production (kWh)	Direct Purchase Cost ($)	O&M Cost ($)	NPV O&M Cost ($)	Replacement Cost($)	NPV Replacement Cost	PPA Escalator (%)	PPA Rate ($/kWh)	PPA Cost ($)	NPV PPA ($)
0			$ 23.153.267					-			
1	7.651.335	7.357.053		$ 109.792	$ 105.569	-	-		$ 0,2378	$ 1.819.717	$ 1.749.728
2	7.613.078	7.038.719		$ 110.341	$ 102.016	-	-	4%	$ 0,2473	$ 1.883.043	$ 1.740.979
3	7.575.013	6.734.159		$ 110.893	$ 98.583	-	-	4%	$ 0,2572	$ 1.948.573	$ 1.732.274
4	7.537.138	6.442.777		$ 111.447	$ 95.265	-	-	4%	$ 0,2675	$ 2.016.383	$ 1.723.613
5	7.499.452	6.164.003		$ 112.004	$ 92.059	-	-	4%	$ 0,2782	$ 2.086.554	$ 1.714.995
6	7.461.955	5.897.291		$ 112.564	$ 88.961	-	-	4%	$ 0,2894	$ 2.159.166	$ 1.706.420
7	7.424.645	5.642.120		$ 113.127	$ 85.967	-	-	4%	$ 0,3009	$ 2.234.305	$ 1.697.888
8	7.387.522	5.397.990		$ 113.693	$ 83.074	-	-	4%	$ 0,3130	$ 2.312.058	$ 1.689.398
9	7.350.584	5.164.423		$ 114.261	$ 80.278	-	-	4%	$ 0,3255	$ 2.392.518	$ 1.680.951
10	7.313.831	4.940.962		$ 114.832	$ 77.577	-	-	4%	$ 0,3385	$ 2.475.778	$ 1.672.547
11	7.277.262	4.727.171		$ 115.407	$ 74.966	-	-	4%	$ 0,3520	$ 2.561.935	$ 1.664.184
12	7.240.876	4.522.630		$ 115.984	$ 72.443	$ 3.871.778	$ 1.924.155	4%	$ 0,3661	$ 2.651.090	$ 1.655.863
13	7.204.672	4.326.939		$ 116.564	$ 70.005	-	-	4%	$ 0,3808	$ 2.743.348	$ 1.647.584
14	7.168.648	4.139.716		$ 117.146	$ 67.649	-	-	4%	$ 0,3960	$ 2.838.816	$ 1.639.346
15	7.132.805	3.960.593		$ 117.732	$ 65.372	-	-	4%	$ 0,4118	$ 2.937.607	$ 1.631.149
16	7.097.141	3.789.222		$ 118.321	$ 63.172	-	-	4%	$ 0,4283	$ 3.039.836	$ 1.622.993
17	7.061.655	3.625.265		$ 118.912	$ 61.046	-	-	4%	$ 0,4455	$ 3.145.622	$ 1.614.878
18	7.026.347	3.468.402		$ 119.507	$ 58.992	-	-	4%	$ 0,4633	$ 3.255.090	$ 1.606.804
19	6.991.215	3.318.327		$ 120.105	$ 57.007	-	-	4%	$ 0,4818	$ 3.368.367	$ 1.598.770
20	6.956.259	3.174.746		$ 120.705	$ 55.088	-	-	4%	$ 0,5011	$ 3.485.586	$ 1.590.776
21	6.921.478	3.037.377		$ 121.309	$ 53.234	-	-	4%	$ 0,5211	$ 3.606.885	$ 1.582.822
22	6.886.870	2.905.952		$ 121.915	$ 51.443	-	-	4%	$ 0,5420	$ 3.732.404	$ 1.574.908
23	6.852.436	2.780.214		$ 122.525	$ 49.711	-	-	4%	$ 0,5636	$ 3.862.292	$ 1.567.034
24	6.818.174	2.659.916		$ 123.137	$ 48.039	-	-	4%	$ 0,5862	$ 3.996.700	$ 1.559.198
25	6.784.083	2.544.824		$ 123.753	$ 46.422	-	-	4%	$ 0,6096	$ 4.135.785	$ 1.551.402
Total	**180.234.475**	**113.760.791**	**$ 23.153.267**	**$ 2.915.975**	**$ 1.803.941**	**$ 3.871.778**	**$ 1.924.155**			**$ 70.689.458**	**$ 39.665.103**

LCOE Outputs*	
Direct Purchase	
20 Year	$ 0,24750
25 Year	$ 0,21938
NPV	
Direct Purchase	
25 Year	$ 12.783.739

APPENDIX M

Wind Turbine-Li-ion Installation on Campus

Year	Production (kWh)	NPV Production (kWh)	Direct Purchase Cost ($)	O&M Cost ($)	NPV O&M Cost ($)	Replacement Cost($)	NPV Replacement Cost	PPA Escalator (%)	PPA Rate ($/kWh)	PPA Cost ($)	NPV PPA ($)
0			$ 82.381.167					-			
1	7.651.335	7.357.053		$ 291.782	$ 280.559	-	-		$ 0,2378	$ 1.819.717	$ 1.749.728
2	7.613.078	7.038.719		$ 293.240	$ 271.117	-	-	4%	$ 0,2473	$ 1.883.043	$ 1.740.979
3	7.575.013	6.734.159		$ 294.707	$ 261.993	-	-	4%	$ 0,2572	$ 1.948.573	$ 1.732.274
4	7.537.138	6.442.777		$ 296.180	$ 253.176	-	-	4%	$ 0,2675	$ 2.016.383	$ 1.723.613
5	7.499.452	6.164.003		$ 297.661	$ 244.656	-	-	4%	$ 0,2782	$ 2.086.554	$ 1.714.995
6	7.461.955	5.897.291		$ 299.149	$ 236.422	-	-	4%	$ 0,2894	$ 2.159.166	$ 1.706.420
7	7.424.645	5.642.120		$ 300.645	$ 228.466	-	-	4%	$ 0,3009	$ 2.234.305	$ 1.697.888
8	7.387.522	5.397.990		$ 302.148	$ 220.777	-	-	4%	$ 0,3130	$ 2.312.058	$ 1.689.398
9	7.350.584	5.164.423		$ 303.659	$ 213.347	-	-	4%	$ 0,3255	$ 2.392.518	$ 1.680.951
10	7.313.831	4.940.962		$ 305.177	$ 206.167	-	-	4%	$ 0,3385	$ 2.475.778	$ 1.672.547
11	7.277.262	4.727.171		$ 306.703	$ 199.229	-	-	4%	$ 0,3520	$ 2.561.935	$ 1.664.184
12	7.240.876	4.522.630		$ 308.237	$ 192.524	$ 78.380.852	$ 38.952.882	4%	$ 0,3661	$ 2.651.090	$ 1.655.863
13	7.204.672	4.326.939		$ 309.778	$ 186.045	-	-	4%	$ 0,3808	$ 2.743.348	$ 1.647.584
14	7.168.648	4.139.716		$ 311.327	$ 179.784	-	-	4%	$ 0,3960	$ 2.838.816	$ 1.639.346
15	7.132.805	3.960.593		$ 312.884	$ 173.733	-	-	4%	$ 0,4118	$ 2.937.607	$ 1.631.149
16	7.097.141	3.789.222		$ 314.448	$ 167.886	-	-	4%	$ 0,4283	$ 3.039.836	$ 1.622.993
17	7.061.655	3.625.265		$ 316.020	$ 162.236	-	-	4%	$ 0,4455	$ 3.145.622	$ 1.614.878
18	7.026.347	3.468.402		$ 317.600	$ 156.776	-	-	4%	$ 0,4633	$ 3.255.090	$ 1.606.804
19	6.991.215	3.318.327		$ 319.188	$ 151.500	-	-	4%	$ 0,4818	$ 3.368.367	$ 1.598.770
20	6.956.259	3.174.746		$ 320.784	$ 146.402	-	-	4%	$ 0,5011	$ 3.485.586	$ 1.590.776
21	6.921.478	3.037.377		$ 322.388	$ 141.475	-	-	4%	$ 0,5211	$ 3.606.885	$ 1.582.822
22	6.886.870	2.905.952		$ 324.000	$ 136.714	-	-	4%	$ 0,5420	$ 3.732.404	$ 1.574.908
23	6.852.436	2.780.214		$ 325.620	$ 132.113	-	-	4%	$ 0,5636	$ 3.862.292	$ 1.567.034
24	6.818.174	2.659.916		$ 327.248	$ 127.667	-	-	4%	$ 0,5862	$ 3.996.700	$ 1.559.198
25	6.784.083	2.544.824		$ 328.884	$ 123.370	-	-	4%	$ 0,6096	$ 4.135.785	$ 1.551.402
Total	**180.234.475**	**113.760.791**	**$ 82.381.167**	**$ 7.749.460**	**$ 4.794.133**	**$ 78.380.852**	**$ 38.952.882**			**$ 70.689.458**	**$ 39.665.103**

Direct Purchase	
20 Year	$ 1,25677
25 Year	$ 1,10871
NPV	
Direct Purchase	
25 Year	$ (86.463.079)

APPENDIX N

Wind/Electrolyzer/Hydrogen Installation on Campus

Year	Production (kWh)	NPV Production (kWh)	Direct Purchase Cost ($)	O&M Cost ($)	NPV O&M Cost ($)	Replacement Cost($)	NPV Replacement Cost	PPA Escalator (%)	PPA Rate ($/kWh)	PPA Cost ($)	NPV PPA ($)
0			$ 697.127.150					-			
1	7.651.335	7.357.053		$ 13.120.922	$ 12.616.271	-	-		$ 0,2378	$ 1.819.717	$ 1.749.728
2	7.613.078	7.038.719		$ 13.186.527	$ 12.191.685	-	-	4%	$ 0,2473	$ 1.883.043	$ 1.740.979
3	7.575.013	6.734.159		$ 13.252.459	$ 11.781.388	-	-	4%	$ 0,2572	$ 1.948.573	$ 1.732.274
4	7.537.138	6.442.777		$ 13.318.722	$ 11.384.899	-	-	4%	$ 0,2675	$ 2.016.383	$ 1.723.613
5	7.499.452	6.164.003		$ 13.385.315	$ 11.001.754	-	-	4%	$ 0,2782	$ 2.086.554	$ 1.714.995
6	7.461.955	5.897.291		$ 13.452.242	$ 10.631.502	-	-	4%	$ 0,2894	$ 2.159.166	$ 1.706.420
7	7.424.645	5.642.120		$ 13.519.503	$ 10.273.711	-	-	4%	$ 0,3009	$ 2.234.305	$ 1.697.888
8	7.387.522	5.397.990		$ 13.587.101	$ 9.927.961	-	-	4%	$ 0,3130	$ 2.312.058	$ 1.689.398
9	7.350.584	5.164.423		$ 13.655.036	$ 9.593.847	-	-	4%	$ 0,3255	$ 2.392.518	$ 1.680.951
10	7.313.831	4.940.962		$ 13.723.311	$ 9.270.977	$ 16.256	$ 8.079	4%	$ 0,3385	$ 2.475.778	$ 1.672.547
11	7.277.262	4.727.171		$ 13.791.928	$ 8.958.973	-	-	4%	$ 0,3520	$ 2.561.935	$ 1.664.184
12	7.240.876	4.522.630		$ 13.860.888	$ 8.657.469	-	-	4%	$ 0,3661	$ 2.651.090	$ 1.655.863
13	7.204.672	4.326.939		$ 13.930.192	$ 8.366.112	-	-	4%	$ 0,3808	$ 2.743.348	$ 1.647.584
14	7.168.648	4.139.716		$ 13.999.843	$ 8.084.560	-	-	4%	$ 0,3960	$ 2.838.816	$ 1.639.346
15	7.132.805	3.960.593		$ 14.069.842	$ 7.812.484	-	-	4%	$ 0,4118	$ 2.937.607	$ 1.631.149
16	7.097.141	3.789.222		$ 14.140.191	$ 7.549.564	-	-	4%	$ 0,4283	$ 3.039.836	$ 1.622.993
17	7.061.655	3.625.265		$ 14.210.892	$ 7.295.492	-	-	4%	$ 0,4455	$ 3.145.622	$ 1.614.878
18	7.026.347	3.468.402		$ 14.281.947	$ 7.049.971	-	-	4%	$ 0,4633	$ 3.255.090	$ 1.606.804
19	6.991.215	3.318.327		$ 14.353.357	$ 6.812.712	-	-	4%	$ 0,4818	$ 3.368.367	$ 1.598.770
20	6.956.259	3.174.746		$ 14.425.123	$ 6.583.438	-	-	4%	$ 0,5011	$ 3.485.586	$ 1.590.776
21	6.921.478	3.037.377		$ 14.497.249	$ 6.361.880	-	-	4%	$ 0,5211	$ 3.606.885	$ 1.582.822
22	6.886.870	2.905.952		$ 14.569.735	$ 6.147.778	-	-	4%	$ 0,5420	$ 3.732.404	$ 1.574.908
23	6.852.436	2.780.214		$ 14.642.584	$ 5.940.882	-	-	4%	$ 0,5636	$ 3.862.292	$ 1.567.034
24	6.818.174	2.659.916		$ 14.715.797	$ 5.740.948	-	-	4%	$ 0,5862	$ 3.996.700	$ 1.559.198
25	6.784.083	2.544.824		$ 14.789.376	$ 5.547.743	-	-	4%	$ 0,6096	$ 4.135.785	$ 1.551.402
Total	**180.234.475**	**113.760.791**	**$ 697.127.150**	**$ 348.480.082**	**$ 215.584.004**	**$ 16.256**	**$ 8.079**			**$ 70.689.458**	**$ 39.665.103**

LCOE Outputs*	
Direct Purchase	
20 Year	$ 8,84461
25 Year	$ 8,02314
NPV	
Direct Purchase	
25 Year	$ (873.054.130)