Mühendis ve Makina / Engineer and Machinery 65, 715, 268-306, 2024

Mühendis ve Makina / Engineer and Machinery
https://dergipark.org.tr/tr/pub/muhendismakina

OPTIMIZING RENEWABLE ENERGY INTEGRATION: A CASE STUDY OF STANDALONE PV-BATTERY SYSTEMS IN IZTECH CAMPUS

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Keywords

University Campus, off-grid system, solar energy, photovoltaic panel, battery

Abstract

In this research paper the feasibility of renewable-powered, self-sufficient university campuses was explored by conducting a technoeconomic analysis of standalone PV-Battery systems for the buildings of Izmir Institute of Technology (IZTECH) in Izmir, Turkey. Given the high energy demand and dependence on fossil-based grids by universities, integrating renewables becomes important for minimizing carbon footprints. In this study the campus's solar potential was focused and the techno-economic feasibility of grid-independent operations provided by PV-battery systems was evaluated. Four scenarios were investigated: (i) maximum PV installation for each building (MPVB), (ii) maximum PV installation for the entire campus (MPVC), (iii) necessary PV installation for self-sufficiency of each building (NPVB), and (iv) necessary PV installation for self-sufficiency of the whole campus (NPVC). The first two scenarios considered the maximum achievable rooftop PV installation while the latter two included additional PV installation to cover all electricity needs. For all scenarios both lead-acid and Li-ion batteries were considered. Mathematical models were developed using PVSol and TRNSYS software, and technoeconomic analysis was conducted using Levelized Cost of Energy (LCOE) and Net Present Value (NPV) methods. It was found that the NPVC scenario with lead-acid batteries is the most favorable, as it minimizes battery utilization by enabling more PV installation and facilitating energy transfer between buildings. Additionally, the research showed that off-grid PV-battery systems are economically less feasible compared to on-grid counterparts, primarily due to the high cost of batteries.

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doi : 10.46399/muhendismakina.1425616

YENİLENEBİLİR ENERJİ ENTEGRASYONUNUN OPTİMİZE EDİLMESİ: İYTE YERLEŞKESİNDEKİ BAĞIMSIZ PV-PİL SİSTEMLERİNE İLİŞKİN BİR ÖRNEK OLAY İNCELEMESİ

Anahtar Kelimeler

Üniversite Kampüsü, şebekeden bağımsız sistem, güneş enerjisi, fotovoltaik panel, pil

Öz

Bu araştırma makalesinde, İzmir, Türkiye'deki İzmir Yüksek Teknoloji Enstitüsü'nün (İYTE) binaları için bağımsız PV-Pil sistemlerinin teknoekonomik analizi yapılarak yenilenebilir enerjiyle çalışan, kendi kendine yeten üniversite kampüslerinin fizibilitesi araştırılmıştır. Yüksek enerji talebi ve üniversitelerin fosil bazlı şebekelere bağımlılığı göz önüne alındığında, yenilenebilir enerji kaynaklarının entegre edilmesi, karbon ayak izinin en aza indirilmesi açısından önem kazanmaktadır. Bu çalışmada kampüsün güneş enerjisi potansiyeline odaklanılmış ve PV-batarya sistemleri tarafından sağlanan şebekeden bağımsız operasyonların tekno-ekonomik fizibilitesi değerlendirilmiştir. Dört senaryo incelenmiştir: (i) her bina için maksimum PV kurulumu (MPVB), (ii) tüm kampüs için maksimum PV kurulumu (MPVC), (iii) her binanın kendi kendine yeterliliği için gerekli PV kurulumu (NPVB) ve (iv) tüm kampüsün kendi kendine yeterliliği (NPVC) için gerekli PV kurulumu. İlk iki senaryo, elde edilebilecek maksimum çatı üstü PV kurulumunu dikkate alırken, son iki senaryo, tüm elektrik ihtiyaçlarını karşılamak için ilave PV kurulumunu içeriyordu. Tüm senaryolar için hem kurşun-asit hem de Li-iyon piller dikkate alındı. PVSol ve TRNSYS yazılımları kullanılarak matematiksel modeller geliştirilmiş, Seviyelendirilmiş Enerji Maliyeti (LCOE) ve Net Bugünkü Değer (NPV) yöntemleri kullanılarak teknoekonomik analiz yapılmıştır. Kurşun-asit akülü NPVC senaryosunun, daha fazla PV kurulumuna olanak sağlayarak ve binalar arasında enerji transferini kolaylaştırarak akü kullanımını en aza indirdiği için en uygun senaryo olduğu bulunmuştur. Ek olarak araştırma, şebekeden bağımsız PV akü sistemlerinin, öncelikle akülerin yüksek maliyeti nedeniyle, şebekeye bağlı muadillerine kıyasla ekonomik olarak daha az uygulanabilir olduğunu göstermiştir.

Araştırma Makalesi			Research Article		
Başvuru Tarihi	:	25.01.2024	Submission Date	:	25.01.2024
Kabul Tarihi	:	15.03.2024	Accepted Date	:	15.03.2024

1. Introduction

Energy generation and management is an essential topic for sustainable development, due to its close link with economic growth, environmental protection, and social balance of countries (Dursun, 2012; Oymen, 2020). The main challenge in the current energy infrastructure is the excessive utilization of fossil fuels, which creates environmental burden due to the global warming effect of fossil fuel-derived gas emission and leads to socioeconomic instability for countries with insufficient reserves. To overcome this challenge, there is an urgent call for the transition from fossil fuels to renewable energy sources. 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 electricity generation of Turkey in 2020 is 306 TWh and the share of renewable energy sources in the total electricity generation is around 40% (TEİAŞ, 2020). 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 (TMMOB, 2023). 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 centers, restaurants, theatres, swimming pools, gyms, and recreational facilities (Dursun, 2012). 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 (Günerhan & Günerhan, 2016). Renewable energy resources with new practices for improving energy efficiency play a central role in covering these indicators (Sevilgen, 2008). To implement renewable energy technologies to university campuses, their technical and economic feasibilities need to be investigated, which has been addressed in literature several times. The related studies are summarized in the following parts.

Dursun (2012) investigated the feasibility of renewable energy systems containing photovoltaic array (PV) and fuel cell in comparison to diesel generator with and without grid connection for meeting the electricity need of Kirklareli University campus. In the fuel cell-containing system electrolyzers and hydrogen tanks were considered for energy storage during the mismatch between load and demand. Four different systems such as (i) stand-alone PV-diesel generator, (ii) grid connected PV, (iii) stand-alone PV-fuel cell, and (iv) grid connected PV-fuel cell were analyzed by using HOMER software. Authors determined optimum configurations for each case and found that the grid-connected systems are more cost-effective compared to the systems without grid connection. They also determined that the grid-PV system has the lowest levelized cost of electricity (LCOE) (0.256 $/kWh) and net present cost (NPC) ($82,000). The grid-connected PV-fuel cell hybrid system was found to have a slightly higher cost (0.294$/kWh) compared to the grid-connected PV system even if it has a higher renewable fraction.

The technical and economic feasibility of the replacement of diesel generator by PV-based renewable systems was also investigated by Chedid, Sawwas, & Fares (2020) for meeting energy demand of the American University in Beirut. Different from the previous study, authors considered PV in combination with battery energy storage systems (BESS). A heuristic genetic algorithm and a rules-based dynamic programming approaches were used for system sizing and ensuring optimal power flow. The research shows that implementing the hybrid system results in a remarkably low operational cost, as it nearly eliminates the need for diesel generators and significantly reduces grid energy consumption during peak hours. 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 conventional diesel generators (DG). 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. The feasibility of the PV-based renewable energy systems for university campus were also proved by other studies.

Wind turbine-containing renewable energy systems were also evaluated in terms of their energy generation potential and economic feasibility. Park & Kwon (2016) investigated the optimum energy system configuration by HOMER software for the Global Campus of Kyung-Hee University in South Korea. Authors evaluated 10 different energy system scenarios including PV, wind turbine, diesel generator, battery in on- and off-grid modes and found that on-grid scenarios are more feasible than off-grid scenarios. The simulation results show that the optimum energy system is the one containing PV, diesel generator and battery. NPC and COE values of the related system were calculated as 101,288,488 $ and 0.509 $/kWh, respectively. Authors determined that the hybrid PV-wind-battery system can be the renewable alternative of the related system with a very small increase in NPC and COE values (101,727,728$ and $0.511 $/kWh). Similar analysis was done by Khan et al. (2017) for a university campus in Abbottabad, Pakistan. Different from the previous one, they only consider off-grid systems and compare the economic performance of diesel generator and the hybrid PV-wind-battery systems. They found that the hybrid PV-wind-battery configuration has a significantly lower NPC (3,054,109$) and COE (0.258 $/kWh) values than diesel generator-based system.

Biomass including renewable energy systems are the other option to meet the energy demand of university campuses. The feasibility of the hybrid grid-connected Wind/PV/ Biomass power system from the techno-economic and environmental point of view was analyzed by Aykut & Terzi (2020) for Marmara University Goztepe campus. HOMER software was used for the sizing and optimization of 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 NPC and COE was found as the grid-connected wind/ biomass hybrid energy system with the power utilization of 1,000-kW from the grid, 1,000 kW from the biomass generator, and 1,500 kW from the wind turbine. The NPC and LCOE values of the related system were determined as $5,612,501 and $0.067/kW, respectively. In another study conducted by Sava et al. (2017) biogas generator was considered in combination with PV and battery. Authors tried to determine the optimum standalone system configuration for the Bucharest "Regie" campus of Politehnica University and found that the optimum design is the hybrid system with a 50 kW PV module, a 50-kW converter, 1 kW storage batteries and a 110-kW biogas generator. The hybrid system generates approximately 60% of the energy from biomass, 25% of the energy from PV panels, and 15% from the grid. The proposed hybrid system has enabled cluster buildings to achieve a nearly zero building concept.

Fossil-fuel powered combined heat and power (CHP) along with renewable options was also considered in the literature for university campuses. Fernando, Gupta, Özveren, & Linn (2018) studied the optimum configuration of a hybrid power system including PV, wind, and CHP and its economic performance for the Abertay University Campus library building in Dundee Scotland. The best scenario was found to be the grid-connected hybrid system with 70 kW PV array including a converter and 500 kW CHP plant. NPC and COE values of the related system were calculated as 338,241 $ and 0.032 $/kWh, respectively. Authors also determined that the hybrid PV-wind-CHP system is not a feasible option due to high operation and maintenance costs.

The literature studies show that several on-grid and off-grid renewable energy systems were analyzed in terms of their technical and economic performance for meeting energy demand of university campuses. In some of them, non-renewable energy generation components were also included to observe the system economic performance comparatively. In almost all cases, grid-connected systems were found to be more economically feasible than off-grid systems due to the relatively high cost of energy storage systems. However, off-grid systems are still the attractive option for remote locations and for the areas suffering from grid instabilities and they are important to minimize the energy loss due to transmission and distribution. In addition, national grids mainly depend on fossil fuel-sourced energy, which prevents on-grid systems from being sustainable and green. Since the IZTECH campus has suffered from regular power cuts and instabilities and a sustainable and green campus is desired, off-grid renewable energy systems were considered in the current study. This helps to evaluate the cost of energy for a self-sufficient campus and to develop improvement suggestions for future planning. Among renewable alternatives PV was selected as a power source for our off-grid system since PV seems to be the best option in terms of system economy due to their relatively low initial investment and operational and maintenance costs based the literature studies explained above. Considering the related literature studies, the novelty of this study is as follows:

(i) The PV-battery combination required for meeting energy needs of individual campus buildings and the whole campus were analyzed separately and the effect of energy transfer between buildings on the system economic performance was evaluated.

(ii) Two different battery options, namely lead acid and Li-ion batteries, were considered for detailed analysis of various off-grid scenarios.

(iii) The optimum system configuration depends on the locations, load profile and grid prices, which makes the technoeconomic analysis of a standalone energy system for the IZTECH campus a unique case, which was not studied before.

In this study, standalone PV-battery systems were designed to meet the electricity needs of the IZTECH campus buildings. Four different renewable energy scenarios were considered, and systems were modeled for each scenario by using PV*SOL and TRNSYS software. 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. The annual hourly electrical load was taken from the electricity supplier and the power output of PV modules was calculated based on the fixed tilt angle of modules by using real meteorological data for the campus location. The number of PV modules was determined to meet the annual electricity demand of the campus buildings while the capacity and number of batteries were determined in a way that the total accessible battery capacity covers the maximum cumulative energy deficiency in a year. This study contributes to determining PV-sourced energy generation capacity of each building and to understanding the importance of energetically interconnected buildings.

2. Description of Campus, Load Profile and Solar Potential

2.1 IZTECH Campus Layout and Building

Izmir Institute of Technology University (IZTECH) is in Izmir/Urla-Gulbahce region. Its coordinates are latitude 38° 19´ 13” N and longitude 26° 38´ 11” E (Fig.1). The total campus area is 132,000 . IZTECH consists of 3 faculties, one graduate school, one school of foreign languages and several administrative units. There are in total 30 buildings on the campus, which are listed in Table 1 with their total roof areas and type. The total roof area is not the usable area for PV installation due to the shading and blockage caused by other structures on the roofs (e.g., chimney outlets, column protrusions) depending on shapes and slopes of roofs. For this reason, suitable areas for installation were determined by using PV*SOL software and they are listed in Table 1. As seen from the Table 1, the total available area for PV installation is 23,199.

Figure 1. The satellite view of IZTECH Campus

Table 1. The total roof areas, the available roof areas for PV installation, and the roof types of IZTECH Campus Buildings

	Roof area (m^2)	**Suitable area for PV (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	23,199	-

2.2 Load Profile

The electricity requirement of the campus is currently met by the grid, which also mostly covers the cooling and heating load. In this study, the electricity load of the whole campus was taken from the Electricity Distribution Company (Gediz Elektrik A.S.) for the year of 2019 on an hourly basis. This year was specifically chosen to exclude the effect of Corona breakdown. The hourly electricity load of the whole campus does not contain information about the share of each building in the total electricity consumption. Therefore, the hourly electricity consumption of each building was calculated by multiplying the fractional consumption of buildings (taken from the university based on the monthly data) with the hourly consumption of the whole campus. The monthly electricity consumption of the whole campus in 2019 is shown in Table 2 to indicate the change of electricity consumption throughout the year. As seen from the Table, the total electricity consumption of the campus is 5748.7 MWh and the lowest and highest electricity consumption were observed in January (623.3 MWh) and May (328.6 MWh), respectively.

Table 2. IZTECH Campus Monthly and Daily Average Electricity Consumption in 2019

IZTECH TOTAL	Total (MWh)	Daily Average (MWh)
January	623.3	8.37
February	495.5	7.37
March	535.4	7.19
April	457.7	6.35
May	328.6	4.41
June	513.1	7.12
July	562.9	7.56
August	464.4	6.10
September	437.1	6.07
October	366.6	4.92
November	399.0	5.54
December	565.1	7.59
TOTAL	5748.7	78.66

2.3 Solar Radiation

The solar radiation data of the IZTECH campus was taken from the PVGIS-SAR-

AH2 program. The solar data used in this study are hourly horizontal beam radiation ($G_{T,b}$), diffuse radiation ($G_{T,d}$) and ground reflected diffuse radiation ($G_{T,gnd}$). The monthly average values of these radiation along with total radiation incident on PV array (G_T) based on the optimum angle of incidence (See section 3.2) throughout the year are shown in Figure 2. As seen from the Figure the lowest and highest total radiation values incident on the PV array are 98.54 (kWh//mo), and 239.92 (kWh//mo), observed in December and July, respectively.

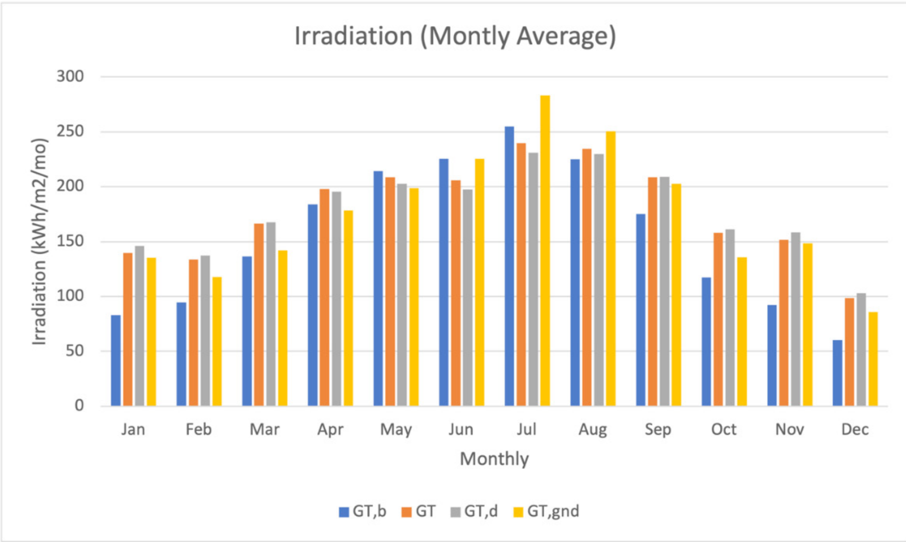

Figure 2. The Monthly Averaged Solar Radiations On The Campus

3. Modeling Approach

Four different PV-battery combinations were analyzed as standalone renewable energy systems for meeting electricity requirement of IZTECH campus buildings explained in Section 2.1. The investigated scenarios are (i) maximum PV panel installation for each building (MPVB), (ii) maximum PV panel installation for the whole campus (MPVC), (iii) necessary PV installation for each building (NPVB), and (iv) necessary PV installation for the whole campus (NPVC). For the first two scenarios (MPVB, MPVC) the maximum amount PV installation was determined based on the available roof area of each building while for the last two scenarios (NPVB, NPVC) additional PV installations on free land areas in the campus were considered to cover the total electricity demand of the campus building. In scenario 1 (MPVB) and scenario 3 (NPVB) each building in the campus was taken as a separate unit and the analysis was made based on no energy transfer between buildings. On the other hand, in the second (MPVC) and fourth (NPVC) scenarios buildings were evaluated as interconnected so that the excess energy produced in one building can transfer to the other, which suffers from energy deficiency.

For all scenarios the components of these systems, namely the PV module, lead-acid battery, and inverter, were mathematically modeled and all system scenarios were analyzed dynamically in TRNSYS (Klein et al., 2018). The maximum allowable PV installation on the rooftop area of each building was determined by PV-Sol software while the number of batteries required was determined based on the maximum cumulative energy deficiency in a year, i.e., the total accessible battery capacity covers the whole energy deficiency in a year. To access the economic feasibility of the related systems, Levelized Cost of Energy (LCOE) and Net Present Value (NPV) methods were used. The approaches used for mathematical modelling of system components by TRNSYS and PV-Sol software and for the economic analysis were explained in the following sections.

3.1 TRNSYS Modeling

The considered standalone energy systems consist of photovoltaic panel, lead acid battery and regulator-inverter. The mathematical references of each unit are available in the TRNSYS software. The main expressions used to model the system were shown in the following parts.

3.1.1. Simple Photovoltaic System Modeling

For mathematical modelling of PV array Type 103 in TRNSYS software was used considering that the PV array operates at maximum power point condition. This model is based on the four-parameter equivalent circuit (John & Beckham, 1991) consisting of a direct current (DC) source, diode, and resistor (Figure 3). According to this model, the power of the PV array was calculated by the following equation (Klein et al., 2018):

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

where N_p is the number of PV module in parallel, N_s is the number of PV module in series, q is electron charge (1.6x10-19 C), k is the Boltzman constant (1.38x10-23 J/K), γ is PV curve-fitting parameter, I is the module current, V is the module voltage, I_L is the module photocurrent and is the diode reverse saturation current.

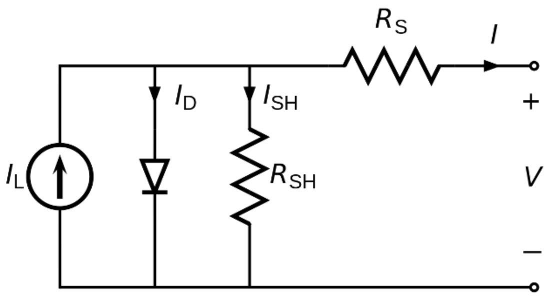

Figure 3. The Equivalent Circuit Of A Solar Cell *(John & Beckham, 1991)*

The I-V relation of the PV module changes with solar radiation and cell temperature. The photocurrent is affected by the solar radiation while the diode saturation current is influenced by the cell temperature. The photocurrent changes linearly with on the incident solar radiation as follows:

$$I_L = I_{L,ref}\frac{G_T}{G_{T,ref}} \tag{2}$$

where is the module photocurrent at the reference conditions (25°C, 1000 W/m^2), is incident radiation on the PV module, is incident radiation at reference conditions (1000 W/m^2). The incident radiation on the PV module was determined by the following formula:

$$G_{T,eff} = \tau\alpha_{normal}\left(G_{T,b}IAM_b + G_{T,d}IAM_d + G_{T,gnd}IAM_{gnd}\right) \tag{3}$$

where $\tau\alpha_{normal}$ is the transmittance-absorptance product at normal incidence (0.95), G_T and IAM are solar radiation and angle incidence modifiers for the beam, diffuse and ground reflected radiation. IAM values were calculated by using relation taken from King et al. (Keelialafreniere, 2018) as follows:

$$IAM = 1 - 1.1098x10^{-4}\theta - 6.267x10^{-6}\theta^2 + 6.583x10^{-7}\theta^3 - 1.427x10^{-8}\theta^4 \tag{4}$$

where θ is the angle of incidence, which was calculated as:

$$\theta = cos^{-1}\begin{bmatrix} sin\,\delta\,sin\,\phi\,cos\,\beta - sin\,\delta\,cos\,\phi\,sin\,\beta\,cos\,\gamma + cos\,\delta\,cos\,\phi\,cos\,\beta\,cos\,\omega \\ + cos\,\delta\,sin\,\phi\,sin\,\beta\,cos\,\gamma\,cos\,\omega + cos\,\delta\,sin\,\beta\,sin\,\gamma\,sin\,\omega \end{bmatrix} \tag{5}$$

where δ is the solar declination angle, ω is the hour angle, φ is the latitude and β is the slope of the module (the angle between the photovoltaic panel surface and the horizontal surface). The effective angle of incidence for diffuse and ground reflected radiation were calculated as:

$$\theta_{eff,d} = 59.567 - 9.123x10^{-2}\beta - 5.424x10^{-4}\beta^2 + 3.216x10^{-5}\beta^3 - 1.7x10^{-7}\beta^4 \quad (6)$$

$$\theta_{eff,gnd} = 90.032 - 6.615x10^{-1}\beta - 4.796x10^{-3}\beta^2 + 1.543x10^{-5}\beta^3 - 2.000x10^{-}\beta^4 \quad (7)$$

The cell temperature affects the power output of the PV module negatively. This effect was modelled by the following equation:

$$I_o = I_{o,ref}x(\frac{T_c}{T_{c,ref}})^3 \quad (8)$$

is the diode reverse saturation current at reference conditions, T_c is the module temperature and $T_{c,ref}$ is the module temperature at reference condition (25°C). The cell temperature depends on incident radiation (G_T), the ambient temperature (taken from climate data), the module efficiency (η_c), the transmittance-absorptance product ($\tau\alpha$), the normal operating cell temperature ($T_{c,NOCT}$), the ambient temperature ($T_{a,NOCT}$=20°C) and solar radiation ($G_{T',NOCT}$=800 W/m^2) at normal operating conditions.

In order to calculate the power output of a PV module by the four-parameter equivalent circuit model, the four module constants ($I_{L,ref}$, $I_{0,ref}$, R_s and γ) that cannot be determined by physical measurements were calculated by the Newton method based the open curcuit potential (V_{oc}), the short curcuit current (I_{sc}), the current at maximum power point (I_{mpp}), the voltage at maximum power point (V_{mpp}), temperature coefficient of I_{sc} and V_{oc} taken from manufacturer's technical sheets. In this study, Jinko Tiger Pro 525 Wp PV panel was selected, and the related parameters of the PV panel are listed in Table 3.

Table 3. Technical Parameters of the PV Panel (Jinko Tiger Pro 525 Wp)

Parameters	Values
V_{oc}	49.42 V
I_{sc}	13.63 A
V_{mpp}	40.80 V
I_{mpp}	12.87 A
α_{Isc}	0.032 A/K
α_{Voc}	-0.28 V/K

3.1.2 Simple Lead Acid Battery Modeling

For the modelling of lead acid battery Type47 module was used in TRNSYS software, which determines how the state of charge of the battery changes over time depending on the rate of charge or discharge. The model works based on the Shepherd formula (Keelialafreniere, 2018), which relates the battery current and voltage to battery state of charge. The I-V relation was determined by Shepherd formula at discharge mode (I < 0) (Eqn 9) and charge mode (I > 0) (Eqn 10) as follows:

$$V = e_{qd} - g_d H + I r_{qd}\left(1 + \frac{m_d H}{\frac{Q_d}{Q_m} - H}\right) \tag{9}$$

$$V = e_{qc} - g_c H + I r_{qc}\left(1 + \frac{m_c H}{\frac{Q_c}{Q_m} - H}\right) \tag{10}$$

where and are open circuit voltage at full charge and discharge, H is the depth of discharge, and gc are battery coefficients, and internal resistances at full discharge and charge, m_d and m_c are cell type parameters, and are capacity parameters for discharge and charge and is rated capacity of the cell (Keelialafreniere, 2018). Power was given as input in this model, which works with Type 48 regulator-inverter used to regulate the power and to provide AC/DC conversion. The power withdrawal and release were calculated by multiplying the power of a single unit with the number of units in series and parallel. The input parameters of the model such as cell energy capacity, charging efficiency, the maximum charging and discharging current, the maximum charging voltage and discharge cutoff voltage are listed in Table 4, which were determined based on the selected battery for this study (SUNLIGHT RES OPzV-2V 26 RES POzV 4535). Li-ion battery was not modelled in TRNSYS, but it was included in the study to determine the effect of the battery type on the number of batteries required and the economic performance of the considered scenarios. The number of Li-ion batteries used in the system was calculated based on the battery capacity given at the same C-rate (i.e., discharge rate) with the lead acid battery and the battery charging efficiency (Table 3). In addition, the economic performance of the Li-ion containing scenarios was evaluated considering the lifetime of Li-ion battery, which is also shown in Table 3. The selection of battery models for both lead-acid and Li-ion batteries was made based on the availability of large capacity batteries in the market.

Table 4. Technical Parameters of Batteries

Parameters	Lead Acid (Sunlight RES 4535)	Li-Ion (Huawei Luna2000)
C_{10}	3996 Ah	320 Ah
V_{nom}	2 V	51.2 V
E	7.99 kWh	16.38 kWh
η_{ch}	90%	99.0%
$I_{max,ch}$	424.8 A	320 A
$I_{max,dis}$	-424.8 A	-320 A
V_{max}	2.45 V	3.50 V
V_c	1.80 V	2.70 V
Lifetime	2500 cycle (at 60% DOD)	3600 cycle (100% DOD)

3.1.3 Regulator-Inverter Modeling

Type 48 regulator-inverter model in TRNSYS software was used for power regulation and AC/DC conversion. This model simply regulates the power between the load, PV array and batteries and does the related power conversion. For the energy analysis campus buildings inverters with different powers were selected since each building has a different installed power capacity. The selected inverters and their powers are seen in Table 5. Depending on these inverter models and MPPT inputs, the series-parallel connections of the panels were determined.

Table 5. The Selected Inverters and Their Power Values

Inverter Model	Power (W)
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

3.2 PVSOL Modeling

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 design varies according to roof area and type. The 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 (Bilgili & Dağtekin, 2019; Atılgan, 2019). The orientation of the panels on pitched roofs varies depending on the building design. Figure 4 shows an example of a pitched roof panel installation.

Figure 4. Pitched Roof Panel Installation

In flat roofs, there are specific parameters when the 3D layout is done. These parameters are panel slope, azimuth angle, shading, and distance between panels. The solar radiation that a photovoltaic module can receive depends on the module's direction. The panel slope and the azimuth angle are the factors that determine the orientation of the module (Prakash, 2020). Since IZTECH campus building locates in the northern hemisphere, they were taken as pointing to the south, so the azimuth angle was taken as 0° while the optimum panel slope was determined as 38.4° based on the annual average solar radiation and directions (Yıldız, 2017). This angle was used in the TRNSYS modelling of PV modules.

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 system design to be installed. The shadow falls on the photovoltaic panel systems installed on the building due to an obstacle calculated as follows (PVSOL, 2023):

$$L > \frac{H}{tan\,\alpha} \tag{11}$$

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. Since the installation was considered on the rooftops of the campus buildings and there are no high-rise buildings, trees, or any other obstacles near to the buildings, the external shading on the photovoltaic modules were excluded. The only shadow effect can be seen due to the successive panel alignment. To prevent this effect, the optimum inter-row spacing needs to be determined. The safe distance between the two modules was calculated as follows:

$$d = w * (\frac{sin\,\beta}{tan\,\gamma} + cos\,\beta) \tag{12}$$

where w is the panel length, γ is the shadow angle and β is the panel slope. Based on the formula and solar data, the optimum inter row spacing was calculated as 2.75 m.

The PV array design was made by entering the calculated parameters into the PV*SOL program and the maximum allowable rooftop PV panel was determined for each building. Figure 5 shows an exemplary flat roof panel setup installed.

Figure 5. Flat Roof PV Panel Installation by PV-Sol Software

3.3 Economic Analysis

Economic feasibility is the main concern for the realization of renewable energy systems. In this study, the economic performance of all PV-battery scenarios was evaluated by Levelized Cost of Energy (LCOE) and Net Present Value (NPV) analysis.

3.3.1 Levelized Cost of Energy (LCOE)

The levelized cost of energy (LCOE) indicates the average cost per kWh of electricity produced by the system during the system lifetime. LCOE was calculated as follows:

$$LCOE = \frac{\sum_{t=0}^{n} \frac{I_t + M_t + Re_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+i)^t}} \tag{13}$$

where t is the number of time period, is the investment cost in the year t, is the operations and maintenance cost (O&M Cost) in the year t, Re_t is the replacement cost in the year t, is the electrical energy generated in the year t, is the interest rate, n is the expected lifetime of the system (Park C. S., 2016). The initial investment cost, operation and maintenance costs and lifetime for each component of the PV-battery system are shown in Table 6. The interest rate was taken as 5% (İçöz, 2022). The analysis was made for the system's lifetime of 25 years.

3.3.2 Net Present Value (NPV)

Net Present Value (NPV) analysis shows the difference between the present value of cash inflow and outflow, and it is an indication for the profitability of the project in the system lifetime. NPV value of systems were calculated by the following formula (Altun, 2021; Saray, 2019; Acakpovi, Adjei, Nwulu, & Asabere, 2020; Gokcol & Dursun, 2013):

$$NPV(i,N) = \sum_{t=1}^{N} \frac{R_t}{(1+i)^t} - R_0 \tag{14}$$

where is the net cash flow, R_0 is the total initial investment cost, is the interest rate, t is the time of cash flow, and N is the project lifetime (Park C. S., 2016). The net cash flow was determined by taking the difference between the annual money saved due to self-electricity generation and the annual O&M Cost while the total investment cost was calculated based on costs of components listed in Table 6. The installation cost of 25,000$/MW was also included in the calculation of total investment cost for all scenarios. The electricity price was taken 0.153 $/kWh in 2019. The analysis was made for the system's lifetime of 25 years and the replacement costs of batteries were also included in the analysis for related years.

Table 6. Investment Cost, O&M Cost, Replacement Cost, Lifetime of the PV-battery system components

Equipment	**Investment Cost**	**O&M Cost**	**Replacement Cost**	**Lifetime**
Jinko 525Wp PV Panel	180$	- 0 for 1st-5th years (warranty period) - 0,5% of the initial investment cost for 5th-10th years - 1% of the initial investment cost for 10th-25th years (Girgin, 2011; Ozcan, 2009)	100%	25 years

Huawei Inverter	2.000-3.300$ for 12-50 kW, 5.600-6.700$ for 100-185 kW (Europe Solar Store, 2023)	- 0 for 1st-5th years (warranty period) - 0,5% of the initial investment cost for 5th-10th years - 1% of the initial investment cost for 10th-25th years (Girgin, 2011; Ozcan, 2009)	100%	25 years
Sunlight RES 4535 Lead Acid Battery 7.99 kWh	1,044$ (Sunlight RES OpzV, 2023)	20 $/kW.year (NREL, 2023)	100%	7 years
Huawei Luna2000 Li-ion Battery 16.38 kWh	5,766$ (MG Solar Shop, 2023)	10$/kW.year (NREL, 2023)	100%	10 years

4. Result and Discussions

Four off-grid renewable energy scenarios were evaluated to meet the electricity consumption of the faculty buildings in the IZTECH Campus. For each scenario, the annual electricity consumption of each building and the annual electricity generation by PV array were determined on an hourly basis and the number of required batteries to cover the mismatch between the load and generation were calculated. The dynamic simulation was made by TRNSYS to confirm that a continuous power supply is sustained throughout the year. Based on the number of PV panels and batteries, LCOE and NPV analysis were made, and economic performances of systems were evaluated comparatively.

4.1 Electricity Load Profile of the Campus

The total annual electricity consumption and the hourly load profile of each building in the campus were analyzed to determine the scale of PV and battery systems. The annual electricity consumption of each building was determined based on the electricity consumption of the whole campus and the share of buildings in total electricity consumption (see section 2.2) and listed in Table 7. As seen from the table the annual electricity consumption of buildings varies between 3.08 and 719.387 MWh. The level of consumption is high for the buildings housing a high population and requiring strict air-conditioning control. To observe the change in electricity consumption of buildings throughout the year the daily electricity consumption of each building in the campus was also determined. The daily load profiles of buildings have almost the same trend. Therefore, the load profile of each building was not shown separately here, but the load profile of the whole campus is presented instead to indicate the level of change. Figure 6 shows the daily consumption of the whole campus starting from 1st January to 31st December. As seen from the Figure, the daily load is between 8000-17000 kWh due to the mild climate conditions of spring and autumn seasons while it varies between 12000-27000 kWh and 10000-27000 kWh for winter and summer seasons, respectively. The load observed in spring and autumn seasons is mainly related to lighting and electrical equipment whereas the additional consumption observed in winter and summer seasons is caused by electricity-driven HVAC systems. The total electricity load in summer is higher than that in winter since part of heating requirements in winter is met by fossil fuel powered heating systems. Figure 6 also shows that there is an exceptional power outage (i.e., zero load) for a certain period (ca. 4 days) at the beginning of September. This is related to the planned maintenance-repair work done by the relevant distribution company.

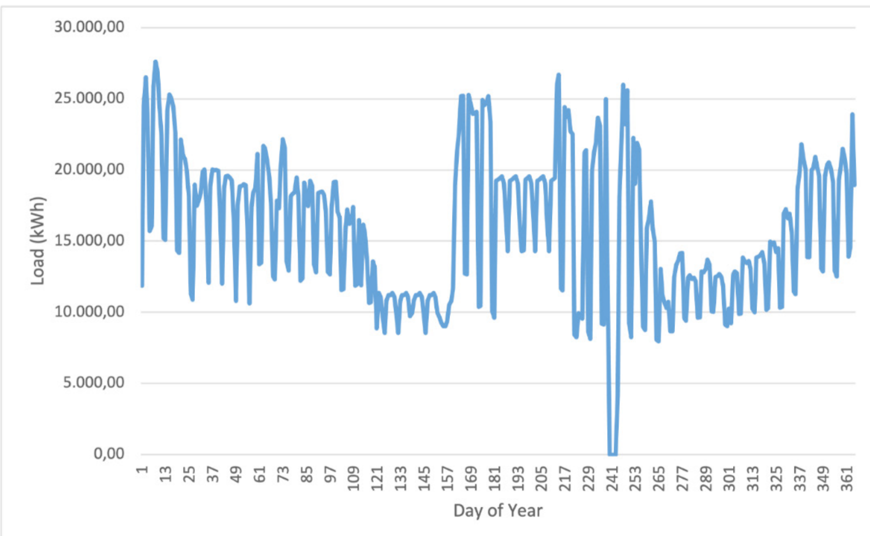

Figure 6. Daily load profile of the IZTECH Campus throughout the year

The hourly load profile of the campus for the day with a peak load was also analyzed. Figure 7 shows hourly load profile of the whole campus for the day (8th

January) with the highest daily consumption (27,207 kWh). The figure indicates that the hourly electricity consumption increases at the working hours from the base load to the daily maximum and drops to the base load at the end of the working day.

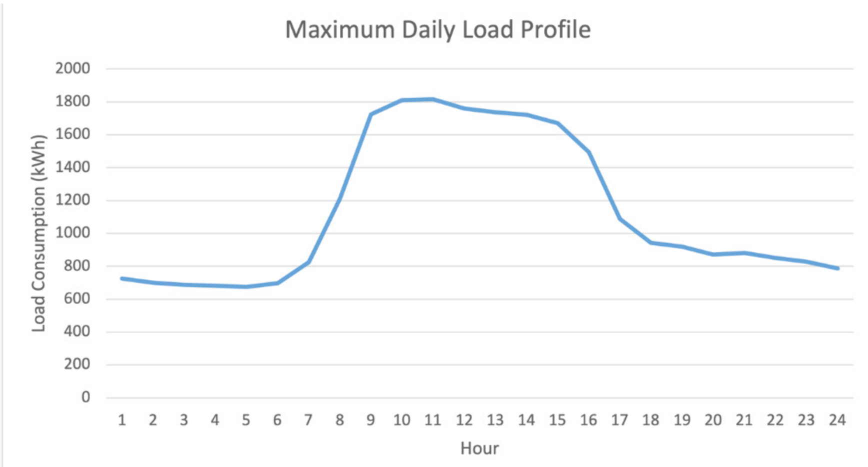

Figure 7. The Hourly Load Profile of the IZTECH Campus for the Day With A Peak Load (8^{th} January)

4.2 Determination of Numbers of PV Panels And Battery

For the MPVB and MPVC scenarios, the maximum amount of PV panels that can be installed on the roof of each building was calculated by PV-SOL software. The results are shown in Table 7 and Table 8 along with total annual electricity generation by PV panels, electricity consumption and coverage ratios. The coverage ratio indicates what percentage of electricity is met by PV panels. As seen from Table 6, the coverage ratio is less than 100% for some buildings while it is above 100% for some of them. The coverage ratio of <100% indicates that some of the buildings don't have sufficient roof area for PV installation to cover their annual electricity consumptions. For buildings with a coverage ratio of >100%, batteries were considered to prevent the daily and seasonal mismatch between the load and generation and the number of batteries were determined based on the maximum cumulative energy deficiency in a year (Table 7). On the other hand, for buildings with a coverage ratio <100% the number of batteries were determined to compensate the electricity deficiency throughout the year to sustain off-grid system design. Due to this reason, the number of batteries for buildings with a coverage ratio <100% were found to be significantly higher than those for self-sufficient buildings. The calculations were made for both lead-acid and Li-ion batteries for all buildings. The number of Li-ion batteries were found to be less than the number lead-acid batteries as expected due to higher energy storage capacity and depth of discharge of Li-ion batteries (see Table 4). The results show that the total number of PV panels installed on the available rooftop area of each building is 9108 and the total amount of energy produced by those PV panels is 4,319,266 kWh annually. This corresponds to the coverage ratio of 75%, which leads to the significant amount of battery utilization (N_{PbA}: 522,406, $N_{Li\text{-}ion}$: 202,705) to compensate for the energy deficiency. To reduce the number of batteries, buildings can be energetically connected or an additional area other than rooftop can be used for more PV installation, which are discussed in the following parts.

Table 7. The Number of PV Panels and Batteries, The Annual Electricity Consumption and Generation for the MPVB Scenario

NPVB		# of Panel	# of Lead-Acid B.	# of Li-ion B.	# of additional PV Panels	Area required for additional PV installation (m²)	PV Output
		Quantity	Quantity	Quantity	Quantity	Area	kWh
GENERAL CULTURE BUILDING		54	530	293	-26	-	24,149
RECTORATE		448	2,19	1,167	344	910	210,729
HEAD OF DEPARTMENT		400	4,5	1,02	112	300	188,387
FACULTY OF SCIENCE	A BLOCK	376	3,658	1,848	24	60	177,084
	B BLOCK	576	4,38	1,618	216	560	271,278
	C BLOCK	287	2,45	1,142	-153	-	135,168
	CLASSROOM B.	90	860	517	-132	-	42,387
	PHYSICS BUILD.	676	4,926	2,25	280	730	318,375
	MATHS BUILD	187	1,32	714	99	226	88,071
	BIOLOGY BUILD	1.605	13,221	4,686	1.345	3,500	755,904
FOREIGN BUILDING	F. ADMINISTRATE	96	830	374	-108	-	45,213
	F. A BLOCK	34	540	212	-94	-	16,013
	F. B BLOCK	582	6,17	1,892	120	320	274,104
	F. ENERGY S.E.	66	800	158	-222	-	31,084
	CENTERAL W.	60	466	348	-228	-	28,258
MECHANICAL ENG.		1.120	7,651	5,712	724	1,880	527,485
FACULTY OF ARCHITECT URE	A BLOCK	273	3,555	1,146	-87	-	128,574
	B BLOCK	208	3,254	744	-212	-	97,961
	C BLOCK	39	87	64	-37	-	18,368
	D BLOCK	4	20	6	-126	-	1,884
	E BLOCK	64	640	220	-140	-	30,142
CHEMISTRY ENG		1.456	11,9	5,996	1.120	2,900	685,73
COMPUTER ENG		385	3,76	2,084	-31	-	181,323
LIBRARY		882	6,826	5,098	477	1,250	415,394
GYM CENTER		252	3,923	2,928	-432	-	118,684
POOL		456	4,33	1,568	252	670	214,762
CAFE		188	2,58	514	-40	-	88,542
CIVIL ENG		470	4,274	3,164	-70	-	221,355
ELECTRIC ELECTRONIC ENG		302	4,01	3,424	-114	-	195,923
INTEGRATED RESEARCH		945	8	4,358	612	1,580	445,065
TOTAL		12,581	111,651	55,265	3,473	14,886	5,977.396

Table 8. The Number of PV Panels and Batteries, The Annual Electricity Consumption and Generation for the MPVC Scenario

	Load (kWh)	Number of Panel	Number of Lead Acid Battery	Number of Li-ion Battery	PV Output (kWh)	Coverage Ratio (%)
MPVC	5,748,700	9,108	226,200	107,482	4,321,136	75.16

The MPVB scenario takes each building as a single unit and excludes energy transfer between the buildings. This leads to the utilization of a significant number of batteries. To prevent this situation and to observe how much improvement can be obtained in the number of batteries, the same analysis was made for MPVC scenario, which takes buildings as energetically interconnected. The results in Table 8 show that the number of batteries decreases almost 2-fold (N_{PbA}: 226,200, $N_{Li\text{-}ion}$: 107,482) indicating that a significant cost saving can be obtained by this strategy as seen in Section 4.3.

MPVB and MPVC scenarios show that the available roof areas for PV installation are not adequate to meet the total annual electricity consumption of the campus. This leads to excessive battery utilization and poor economic performance considering the high cost of batteries in the current market. In this respect NPVB and NPVC scenarios were also evaluated to determine the effect of additional PV installation on the required number of battery and on the system economy for each building and the whole campus, respectively. For the NPVB scenario, Table 9 shows the amount PV panels required to cover the annual electricity consumption of each building, the additional number of PV compared to the MPVB scenario, and the land area required for the installation of these additional PV panels. As seen from the Table, the total additional PV panels for the whole campus and the required land area 3,473 and 14,886 , respectively. With the installation of these PV panels the required number of batteries decreases by ca. 4 to 5-fold compared to the MPVB scenario, which provides significant cost savings. When buildings are considered to transfer energy between each other (NPVC scenario), further improvements were obtained, i.e., the number of batteries drops to 56,180 and 38,981 for lead-acid and Li-ion batteries, respectively (Table 10).

Table 9. The Number of PV Panels And Batteries, the Additional PV Panels, and the Corresponding Land Area for the NPVB Scenario

NPVB		# of Panel	# of Lead-Acid B.	# of Li-ion B.	# of additional PV Panels	Area required for additional PV installation (m^2)	PV Output
		Quantity	Quantity	Quantity	Quantity	Area	kWh
GENERAL CULTURE BUILDING		54	530	293	-26	-	24,149
RECTORATE		448	2,19	1,167	344	910	210,729
HEAD OF DEPARTMENT		400	4,5	1,02	112	300	188,387
FACULTY OF SCIENCE	A BLOCK	376	3,658	1,848	24	60	177,084
	B BLOCK	576	4,38	1,618	216	560	271,278
	C BLOCK	287	2,45	1,142	-153	-	135,168
	CLASSROOM B.	90	860	517	-132	-	42,387
	PHYSICS BUILD.	676	4,926	2,25	280	730	318,375
	MATHS BUILD	187	1,32	714	99	226	88,071
	BIOLOGY BUILD	1.605	13,221	4,686	1.345	3,500	755,904
FOREIGN BUILDING	F. ADMINISTRATE	96	830	374	-108	-	45,213
	F. A BLOCK	34	540	212	-94	-	16,013
	F. B BLOCK	582	6,17	1,892	120	320	274,104
	F. ENERGY S.E.	66	800	158	-222	-	31,084
	CENTERAL W.	60	466	348	-228	-	28,258
MECHANICAL ENG.		1.120	7,651	5,712	724	1,880	527,485
FACULTY OF ARCHITECTURE	A BLOCK	273	3,555	1,146	-87	-	128,574
	B BLOCK	208	3,254	744	-212	-	97,961
	C BLOCK	39	87	64	-37	-	18,368
	D BLOCK	4	20	6	-126	-	1,884
	E BLOCK	64	640	220	-140	-	30,142
CHEMISTRY ENG		1.456	11,9	5,996	1.120	2,900	685,73
COMPUTER ENG		385	3,76	2,084	-31	-	181,323
LIBRARY		882	6,826	5,098	477	1,250	415,394
GYM CENTER		252	3,923	2,928	-432	-	118,684
POOL		456	4,33	1,568	252	670	214,762
CAFE		188	2,58	514	-40	-	88,542
CIVIL ENG		470	4,274	3,164	-70	-	221,355
ELECTRIC ELECTRONIC ENG		302	4,01	3,424	-114	-	195,923
INTEGRATED RESEARCH		945	8	4,358	612	1,580	445,065
TOTAL		**12,581**	**111,651**	**55,265**	**3,473**	**14,886**	**5,977.396**

Table 10. The number of PV panels and batteries, the additional PV panels, and the corresponding land area for the NPVC scenario

	Panel	Number of Lead Acid Battery	Number ofLi-ion Battery	Number of additional PV Panels	Area required for additonal PV installation (m^2)	PV Output (kWh)
NPVC	12,581	56,180	38,981	3,473	14,886	5,977.396

For all scenarios the dynamic system simulation was made on TRSNYS and the continuous power supply by PV-battery combination was controlled throughout the year. Figure 8 shows the change of electricity demand, electricity generation and battery utilization in time throughout the year for the best scenario (NPVC). Figure clearly indicates that the battery charge/discharge properly compensates the mismatch between the load and electricity generation by PV array and does not allow any power cut.

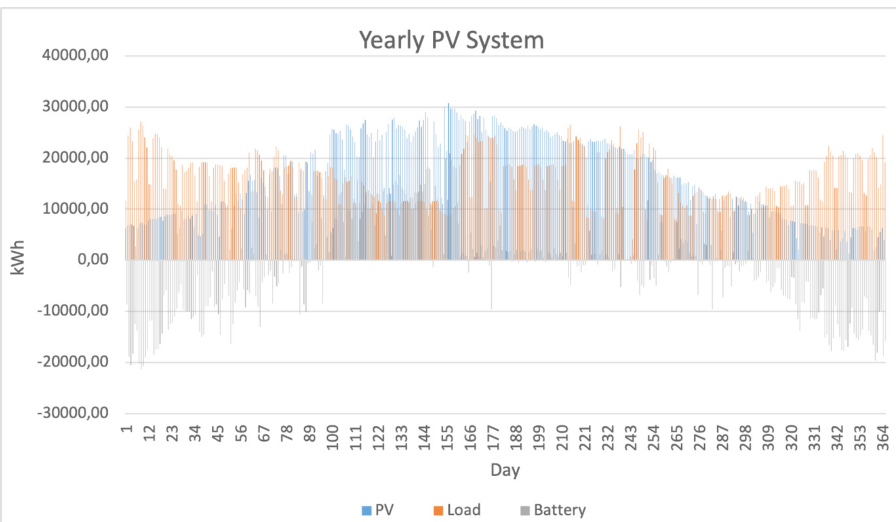

Figure 8. The Daily Change Of Electricity Demand, Electricity Generation And Battery Utilization for the NPVC Scenario

4.3 Economic Analysis

The economic feasibility of off-grid scenarios was evaluated by LCOE and NPV analyses. The initial investment costs were calculated based on the number of

PV panels, battery and inverter calculated in Section 3.2 and cost items shown in Table 6. The cost details of the investment cost for all scenarios are shown in Table 11 and 12. According to the related cost items and yearly expenses including O&M cost and replacement cost, LCOE and NPV values were determined and listed in Table 13 and 14 for lead-acid battery and Li-ion battery, respectively. The results show that the highest NPV and the lowest LCOE values were obtained for the NPVC scenario where the lowest number of batteries is employed. Since the total battery cost accounts for almost 99% of total investment cost and batteries needs to be replaced in the project lifetime, scenarios with a higher number of batteries yield lower NPV and higher LCOE values and any reduction in battery number results in a significant improvement in the system economy. This suggests that the battery utilization needs to be minimized for improving the economic viability of the system, which can be achieved by increasing the number of PV and by allowing energy transfer between campus buildings. The effect of the former is clearly seen in the comparison of MPVB and NPVB or MPVC and NPVC scenarios, i.e., a ca. 40% increase in the number of PV results in a 4-7-fold decrease in the LCOE value. A significant reduction in the number of batteries and the corresponding improvement in LCOE values was also obtained by energy transfer between campus buildings. This effect results in a 1.5-2.5-fold decrease in the LCOE value indicating the importance of energetically interconnected buildings.

Table 11. Cost and Percentage Values for all Lead Acid Batteries Including Scenarios

	Initial Investment				
	Cost Item	Quantity	Price ($/unit)	Price ($)	%
MPVB-Lead Acid	PV Panel	9,108	180	$1,639,440	0.30
	Pb-acid battery	522,406	1,044	$545,391,864	99.63
	Inverter	89	-	$305,481	0.06
	Infrastructure	-	-	$100,000	0.02
		Total		$547,436,785	100

	Cost Item	Quantity	Price ($/ unit)	Price ($)	%
MPVC-Lead Acid	PV Panel	9,108	180	$1,639,440	0.69
	Pb-acid battery	226,200	1,044	$236,152,800	99.19
	Inverter	26	7,402	$192,452	0.08
	Infrastructure	-	-	$100,000	0.04
	Total			$238,084,692	100
	Cost Item	Quantity	Price ($/ unit)	Price ($)	%
NPVB-Lead Acid	PV Panel	12,581	180	$2,264,580	1.90
	Pb-acid battery	111,651	1.044	$116,563,644	97.66
	Inverter	379	-	$263,506	0,22
	Infrastructure	-	-	$260,000	0,22
	Total			$119,351,730	100
	Cost Item	Quantity	Price ($/ unit)	Price ($)	%
NPVC-Lead Acid	PV Panel	12,581	180	$2,264,580	3.69
	Pb-acid battery	56,180	1,044	$58,651,920	95.46
	Inverter	35	7,402	$263,506	0.43
	Infrastructure	-	-	$260,000	0.42
	Total			$61,440,006	100
	Cost Item	Quantity	Price ($/ unit)	Price ($)	%
MB-Lead Acid	PV Panel	114,340	180	$20,581,200	75.66
	Pb-acid battery	3,790	1,044	$3,956,760	14.54
	Inverter	325	7,402	$2,405,650	8.84
	Infrastructure	-	-	$260,000	0.96
	Total			$27,203,610	100

Table 12. Cost and Percentage Values for All Li-Ion Batteries Including Scenarios

Initial Investment					
	Cost Item	Quantity	Price ($/ unit)	Price ($)	%
MPVB-Li-ion	PV Panel	9,108	180	$1,639,440	0.14
	Pb-acid battery	202,705	5,766	$1,168,797,030	99.80
	Inverter	194	-	$656,089	0.06
	Infrastructure	-	-	$100,000	0.01
	Total			$1,171,192,559	100
	Cost Item	Quantity	Price ($/ unit)	Price ($)	%
MPVC-Li-ion	PV Panel	9,108	180	$1,639,440	0.26
	Pb-acid battery	107,482	5,766	$619,741,212	99.69
	Inverter	26	7,402	$192,452	0.03
	Infrastructure	-	-	$100,000	0.02
	Total			$621,673,104	100
	Cost Item	Quantity	Price ($/ unit)	Price ($)	%
NPVB-Li-ion	PV Panel	12,581	180	$2,264,580	0.70
	Pb-acid battery	55,265	5,766	$318,657,990	99.12
	Inverter	62	-	$316,686	0.10
	Infrastructure	-	-	$260,000	0.08
	Total			$321,499,256	100

	Cost Item	Quantity	Price ($/unit)	Price ($)	%
NPVC-Li-ion	PV Panel	12,581	180	$2,264,580	0.99
	Pb-acid battery	38,981	5,766	$224,764,446	97.85
	Inverter	325	7,402	$2,405,650	1.05
	Infrastructure	-	-	$260,000	0.11
	Total			$229,694,676	100
	Cost Item	Quantity	Price ($/unit)	Price ($)	%
MB-Li-ion	PV Panel	114,340	180	$20,581,200	59.09
	Pb-acid battery	2,009	5,766	$11,583,894	33.26
	Inverter	325	7,402	$2,405,650	6.91
	Infrastructure	-	-	$260,000	0.75
	Total			$34,830,744	100

Table 13. LCOE and NPV Values For All Lead-Acid Battery Including Scenarios (interest rate=%5)

Scenario	Quantity of Panel	Quantity of Lead-Acid B.	NPV ($)	LCOE ($/kWh)
MPVB	9,108	522,406	-1,146,214,817.20	19.3
MPVC	9,108	226,200	-489,590,710.92	8.4
NPVB	12,581	111,651	-231,322,607.67	3.0
NPVC	12,581	56,180	-108,380,325.16	1.5
MB	114,340	3,790	138,814,908.59	0.044

Table 14. LCOE and NPV Values for All Li-Ion Battery Including Scenarios. (interest rate=%5)

Scenario	Quantity of Panel	Quantity of Li-ion Battery	NPV ($)	LCOE ($/kWh)
MPVB	9,108	202,705	-1,804,518,099.77	30.4
MPVC	9,108	107,482	-951,037,639.58	16.1
NPVB	12,581	55,265	-484,966,477.54	6.0
NPVC	12,581	38,981	-335,278,616.50	4.3
MB	114,340	2,009	129,218,972.21	0.057

For each scenario the economic performance of two battery options were also evaluated separately to determine the effect of battery selection on the LCOE and NPV values. The comparison between Table 13 and 14 clearly shows that the utilization of lead-acid battery is economically more favorable than that of Li-ion battery for the considered scenarios. This is attributed to the high cost of Li-ion battery that is 3-fold higher than that of lead-acid battery per kWh. Even if Li-ion battery has a higher energy capacity, depth of discharge and lifetime, the high cost of Li-ion battery makes itself unfavorable for the considered system size.

Economic analyses show that all considered scenarios yield negative NPV values suggesting that the total investment cannot be restored within the project lifetime. This is mainly associated with the high cost of batteries in the market. To make the related system economically feasible, the number of batteries needs to be minimized. Based on these findings, a new scenario called minimum battery (MB) scenario was also considered and its economic feasibility was evaluated. In the MB scenario, campus buildings were taken as energetically connected and the number of batteries was decreased to the limit where the off-grid system was still maintained with a minimum number of batteries. The required numbers of lead-acid and Li-ion batteries for the related scenario are 3790 and 2009, respectively (Table 13 and 14). This significant reduction in the battery numbers is related to excessive PV utilization (114,340 PV panels) and the resulting electricity generation (53,850,540 kWh/year), which allows to prevent power deficiency even in wintertime where solar radiation is relatively low due to the overlap between the period of PV-sourced electricity generation and consumption (Figure 7). NPV and LCOE values for the MB scenario were calculated as 138,814,908.59$ and 0.044$/kWh for lead-acid battery and 129,218,972.21$ and 0.057$/kWh for Li-ion battery. Even if NPV values of the MB scenario are positive and LCOE values are close to those reported in the literature for on-grid renewable energy system designed for university campus, the excessive electricity generation (ca. 10-fold higher than the consumption) makes this scenario unfeasible.

To assess the relative economic performance of off-grid systems in comparison to on-grid systems, LCOE values of the NPVC scenario in off-grid and on-grid mode were compared. As seen from Table 15, the LCOE value of the on-grid system is 0.04$/kWh, which is >3 times less than the lead-acid battery containing off-grid system. This indicates that off-grid systems are economically less feasible than on-grid systems for IZTECH campus. This is mainly related to the high cost of batteries. To make off-grid system compete with on-grid system, the prices of lead-acid and Li-ion batteries needs to be decreased by more than 50 and 100 folds, respectively, or their lifetime must increase significantly, which depends on R&D activities in the coming decades.

Table 15. LCOE and NPV Calculated For All Scenarios NPVC - On Grid

Scenario	Quantity of Panel	NPV	LCOE
NPVC-ON	12,581	2,987,268.97$	0.04$/kWh

For all calculation explained above the interest rate was taken as 5%, which has shown significant variations for Turkey recently. To address this issue, the effect of interest rate on LCOE values for MB and NPVC scenarios was also investigated for various interest rates considering both lead acid and Li-ion batteries as energy storage units. As shown from Figure 9, the interest rate has a significant effect on LCOE values for both scenarios, i.e., more than 2-fold reduction was observed when the rate decreases from 12% to 1%. For the NPVC scenario the minimum LCOE value (3.3 $/kWh) obtained for 1% interest rate is still way above the LCOE value of the on-grid scenario while for the MB scenario the LCOE value goes below the value obtained for the on-grid scenario when the interest rate is below 4%. This suggests that the NPVC scenario can not compete with the on-grid scenario even at very low interest rate whereas the MB scenario can be more favorable compared to the on-grid scenario based on the interest rate.

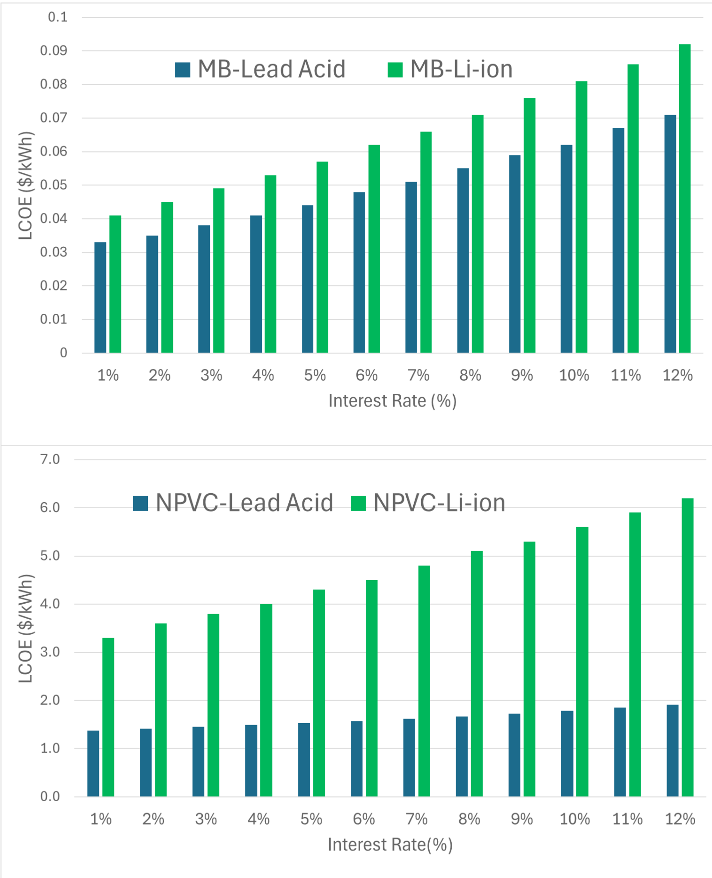

Figure 9. LCOE Values At Different Interest Rates for MB (left panel) and NPVC (right panel) Scenarios Considering Both Lead Acid and Li-Ion Batteries As Energy Storage Units

5.Conclusions

Technoeconomic analyses of standalone PV-Battery systems were conducted for the campus buildings of Izmir Institute of Technology (IZTECH) located in Izmir, Turkey. This study aims to assess the viability of self-sustaining university campuses powered by renewable sources. Given the advantageous solar radiation potential at the campus location, photovoltaic (PV) technology emerged as a suitable renewable option and its integration with battery technologies was evaluated to explore the technoeconomic feasibility of grid-independent campus. Four different off-grid scenarios were evaluated: (i) maximum PV installation for each building of the campus (MPVB), (ii) maximum PV installation on the whole campus (MPVC), (iii) necessary PV installation for self-sufficiency of each building of the campus (NPVB), and (iv) necessary PV installation for self-sufficiency of the whole campus (NPVC). In all scenarios, two types of batteries were considered: lead-acid and Li-ion batteries. Main conclusions are as follows:

- The NPVC scenario showed the highest NPV and the lowest LCOE values due to the significant reduction in battery utilization compared to other scenarios by enabling higher PV installation and facilitating energy transfer between buildings.
- Lead-acid battery-containing scenarios were found to be more economically feasible compared to Li-ion battery-containing scenarios.
- Off-grid renewable energy systems are less economically viable than on-grid counterparts due to the high price of batteries.
- Battery prices need to be reduced significantly or their lifetime must be improved drastically to make off-grid system feasible.

6. Declaration of Competing Interest

The work described in this paper has been neither copyrighted, classified, published, nor is being considered for publication in any other journals. The authors declare that this study adhered to research and publication ethics. There is no conflict of interest among the authors.

Acknowledgements

This research was not financially supported by any funding agencies in the public, commercial, or not-for-profit sectors. The authors gratefully acknowledge Dr. Hüseyin Günhan Özcan from Bahcesehir University Energy Systems Engineering Department for the support in TRNSYS modelling.

List Of Symbols

β	Slope of PV array (°)
γ	The azimuth angle of the inclined plane (°)
θ	The latitude of the location
ω	Hour Angle (°)
δ	Declination Angle (°)
α	Obstacle angle (°)
θ	Angle of incidence for solar radiation (°)
$\theta_{eff,diff}$	Diffuse of incidence for solar radiation (°)

θ_{gnd}	Ground-reflected of incidence for solar radiation (°)
$\tau\alpha_{normal}$	Module transmittance-absorptance product at normal incidence
η_{ch}	Efficiency
C	Capacity (Ah)
d	Module row distance (m)
E	Power (kWh)
E_t	Electrical energy generated
e_{qc}, e_{qd}	Open circuit voltages at full charge, extrapolated from V vs I curves on charge; discharge
H	Obstacle Height (m)
H_d	Depth of discharge
L	Distance between the obstacle (m)
G_T	Total radiation incident on PV array (W/m^2)
$G_{T,beam}$	Beam component of incident radiation (W/m^2)
$G_{T,diff}$	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
$I_{L,ref}$	Module photocurrent at reference conditions
I_0	Diode reverse saturation current
$I_{0,ref}$	Diode reverse saturation current at reference conditions
I_{sc}	Short-circuit current
I_{max}	Current at maximum power point along IV curve
$I_{max,ch}$	Maximum Battery Charge (A)
I_t	Investment expenditures
I_{AM}	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 character-

istics

M_T	Operations and maintenance expenditures
N	Project Lifetime
N_p	Number of modules in parallel in array
N_S	Dimensionless incidence angle modifier
P	PV output power
R_0	Total Initial Investment Cost
Re_t	Net cash flow
R_s	Module series resistance [Ω]
r_{qc}, r_{qd}	Internal resistances at full charge when charging; discharging
T_c	Module temperature [K]
$T_{c,ref}$	Module temperature at reference condition (25°C)
t	Time of cash flow
w	Panel Length (m)
V	Voltage
V_c	
V_{max}	Voltage at maximum power point along IV curve
V_{OC}	Open-circuit voltage
V_{nom}	Nominal Voltage
q	Electron Charge (1.6x10-19 C)
Q_m	Rated capacity of cell
Q_c, Q_d	Capacity parameters on charge; discharge

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