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Optimization of electricity consumption in an industrial zone with a battery system: a case study of Ikitelli industrial zone in Turkey

Volume 8 Issue 4 - 2023

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Received: July 25, 2023 | **Published:** August 25, 2023

Abstract

Industrial power use is considerably high in Turkey. In the case of industrial zones, the three-time tariff is more economical for the owners. However, in industrial zones with considerably high energy consumption during peak hours, an alternative way is needed to reduce electricity costs. A battery-powered model was developed earlier in order to take advantage of the three-time tariff and to reduce the electric charge during peak hours. In this study, the aim was to reduce the power utility costs of industrial consumption and to mitigate CO_2 emissions for businesses with high electricity costs by using solar energy. A mixed-integer optimization model was constructed as a combination of solar panels and a battery system to minimize the peak-hour grid-connected energy consumption in industrial zones. Using the consumption data from 2018, a model was implemented for a case study in İkitelli Industrial Zone in terms of 24-h scheduling. Three different alternative energy combination scenarios were studied: a monofacial PV (photovoltaic) panel system with batteries, a bifacial PV panel system with batteries, and electricity received from the grid only at the night tariff. This study found that a combined method could minimize the grid usage during peak hours.

Keywords: clean energy, efficiency, renewable, energy, photovoltaic, solar

Introduction

The population growth and fast development of industries have expanded global energy requirements. The energy consumption of industries is very high worldwide. In 2018, the total industrial energy consumption was 157 EJ, which was 37% of the total energy use throughout the world. Total energy consumption rose by 0.8% in 2018 and 1.6% in 2017, and there was a total annual increase in energy consumption of 0.9% over the last nine years of the 2010-2018 period.[1]

The total worldwide primary energy resource usage in 2019 was 14,485.8 million tons of oil equivalent (Mtoe), and that of Turkey was 146.5 Mtoe for the same period.[2] Because of the global pandemic in 2020, the growth of energy consumption decreased by 4%, contrasting with the growth rate of 2% in the 2000-2018 period. Furthermore, there was a decrease of 0.8% in 2019.[3]

In the study of Koçak,[4] the estimated consumption for 2023 in Turkey is given as 218-million-ton equivalent petrol.[4] Figure 1 shows the distribution of primary energy consumption in 2019 on a sectoral basis. The industrial sector, as the largest energy-consuming sector, used one-third of the total final energy consumption. The total final energy consumption worldwide was 417,972,751 TJ, and in Turkey, it was 4,370,767 TJ. The total final industrial energy consumption globally was 120,978,863 TJ, whereas for Turkey it was 1,295,073 TJ.[5]

The primary energy source distribution of Turkey is seen in Figure 2. As in the global distribution, in Turkey, industry is the largest energy consumer, with 29% of the total final energy consumption, followed by transportation with 27%, and with both showing outstanding increases over the last ten-year period.[5]

Many industrial sectors including agriculture, manufacturing, finance, education, healthcare, sports, tourism, entertainment, and food were strongly affected by the Covid-19 pandemic. The full or partial lockdown periods applied in some developing countries reduced the energy demand. The rapid rising and falling of demand and consumption damaged the energy industries. For example, 19 energy production companies declared bankruptcy in the U.S.A. over the pandemic period. In the lockdown periods, the demand on electricity throughout industrialized countries dropped more than 10% in 2020 compared to 2019, which is seven times greater than the decline during the 2019 financial crisis.[6]

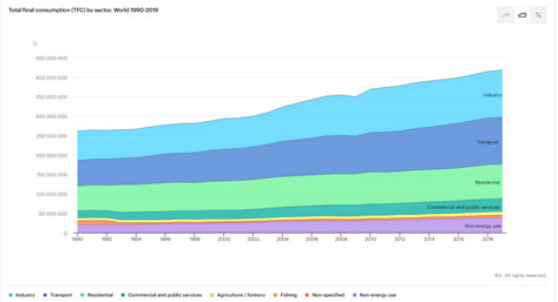


Figure 1 Distribution of primary energy consumption in 2019 on a sectoral basis.[5]

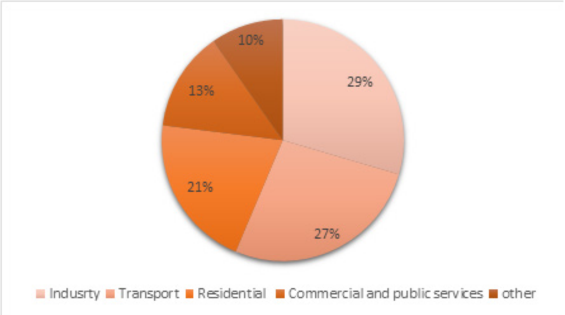


Figure 2 Primary energy source distribution of Turkey.[5]

Global industrial cutbacks caused by the reduction of activities during lockdowns amounted to 25%. The slowdown in consumer payments for manufactured items affected the natural gas demand of the Asian exporting companies.[7]

The year 2020 was highly affected by Covid-19, with the effects continuing to be seen in 2021 in terms of energy use and emissions. With the effort to return to past trends, after the 3.5% reduction in 2020, energy consumption was expected to rise by 4.1% in 2021.[8]

In 2020, electricity usage decreased by 1.1% globally. The first decrease was detected in 2019, contrasting with the continuous increase since 2009. China, which consumes 29% of global electricity, exhibited a fast recovery, with a 3.1% increase, compared to a 4.5% increase in 2019.[9]

The goods and service industries consume various sources of energy including gas, oil, coal, and electricity for their production processes. However, in Turkey, the basic energy source used in all sectors is fossil fuels, and of the energy sources consumed by industry, one-third is electricity (Figure 3). A mix of oil, gas, coal, and electricity is consumed in industry and services. Although most of Turkey's energy demand is supplied by fossil fuels in all sectors, electricity has an important place as the third-largest energy source in Turkey.[10]

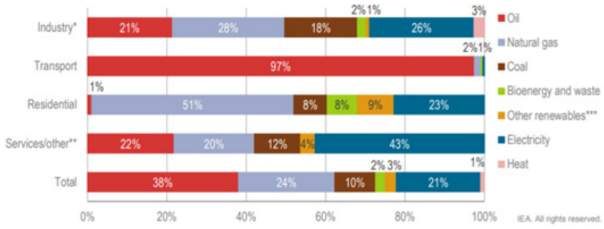


Figure 3 Total final consumption by source and sector in Turkey in 2018.[10]

Electricity is more efficient than fossil fuels in providing energy services and thus, its share of the final consumption indicates its contribution to the supply of useful energy. Because the demand for electricity increases as economic activities improve, improving the efficiency of electric consumption becomes very important. The effective consumption of electricity leads to a decrease in the total required supply capacity and reduces the costs and environmentally harmful carbon generation.[11]

In Turkey, electricity bills are calculated in single-time or three-time tariffs per kWh. In the single-time tariff, the price is the same for all hours during the day, whereas in the three-time tariff, varying prices are determined in order to reduce demand in the periods when energy demand is highest. Table 1 gives the electricity prices per kWh for 2018 taken from the Turkish Energy Market Regulatory Authority (EPDK) website. The one-time tariff electricity price is given as 0.464 Turkish Lira (TL) per kWh, whereas the three-time tariff per kWh is 0.462 TL for 06:00-17:00 in the morning, 0.707 TL for the peak hours of 17:00-22:00, and 0.288 TL for 22:00-06:00 at night.[4] The three-time tariff appears to be more advantageous for places with 24-h electricity consumption compared to the one-time tariff during day and night, but the cost paid for energy consumption at peak time intervals is high (Table 1).

Table 1 Commercial electricity unit costs for 2018[12]

Commercial electricity unit cost			
Commercial cost	**Morning**	**Peak**	**Night**
One-tariff	0.4642 TL		
Three-tariff	0.4622 TL	0.7065 TL	0.2883 TL

Among the places with high industrial energy consumption throughout the day are organized industrial zones. These special organized business units, referred to as "industrial zones", have good communication facilities, and work in a common area to develop new service and manufacturing processes in accordance with the cluster organization concept. These industrial zones are not only business development centers, but also act as factors affecting the sustainable improvement of their surroundings and the lifestyle.[12,13] Organized industrial zones are compatible with and complement each other through various sectoral productions. They are located in a comprehensively defined area in which, except for heavy industry and integrated facilities, small and/or medium-sized production areas and common structures with technical services are organized. The number of organized industrial zones in Turkey had reached 327 organized industrial zones in 80 cities by 2019.[14]

As a renewable resource, photovoltaic (PV) energy has an important share among the energy types consumed by industry. The spread of PV systems is accelerating as their costs are reduced. Another factor affecting their spread is the technological development of the PV generator operating systems toward increased efficiency, reliability, and power generation.[15] These PV systems can be classified according to their physical configuration as a single module, module strings, multiple string connections, and PV arrays in the form of parallel-connected strings.[16]

In this study, a mathematical model was developed to meet the energy demand at peak hours by using mixed-integer programming that considered the energy needs of industrial zones. The model was optimized between the energy charge provided by the battery system and the current peak-hourly rate. Three alternatives were identified to charge the battery system. The first and second were PV panels (monofacial and bifacial) that produced electricity in sunshine hours and stored it in the battery. The third system received electricity from the grid at cheaper night rates (22:00 - 6:00) and stored it. Minimization of costs for the alternative systems compared to the network system was determined according to the 2018 energy consumption of the İkitelli Organized Industrial Zone. A literature review was carried out regarding monofacial PV systems, bifacial PV systems, and battery systems. These systems were defined, properties revealed, and case studies examined.

Literature review

The multifunctional battery-structure composites are presented, modeled and examined to reduce the cost of electric vehicles (EVs).[17] Photovoltaics (PV) is the direct conversion of radiation to electricity. Photovoltaic systems contain cells that generate electricity from sunlight. There are layers of a semi-conductive material inside each cell. Light falling on the cell generates an electric field across the membranes, resulting in the flow of electricity. The light intensity determines the amount of electrical power produced by each cell. Solar cells based on semiconductors have been studied since 1960, and since that time, new technology has been developed for polycrystalline Si (poly-Si) and thin-film solar cells to minimize material costs and energy input while increasing production efficiency.[18] Thus, the unit cost of PV technology has been reduced to about one-third of where it stood five years ago, with ongoing technological development and productivity continuing to rise. These PV systems will undoubtedly continue to grow rapidly and ultimately become a major global supplier of energy. Research on solar photovoltaic energy is expected to enable the planet to generate about 345 GW by 2020 and 1081 GW by 2030.[19]

Citation: Yavuz K. Optimization of electricity consumption in an industrial zone with a battery system: a case study of Ikitelli industrial zone in Turkey. *MOJ Eco Environ Sci.* 2023;8(4):148–156. DOI: 10.15406/mojes.2023.08.00285

In order to reduce the cost of solar power generation, the main objective of the PV industry is to improve efficiency and increase production volume using low-cost materials for solar cells and modules. To increase the energy production in the unit area of solar systems, various solutions have been produced as a result of technological developments, such as increasing the efficiency of PV module systems, moving PV panels, etc. Another technology that has emerged in recent years is that of bifacial PV modules. All of these solutions deal with PV system $/W peak cost. Nevertheless, the ultimate goal of all solutions to cost management is to reduce the cost of solar power, i.e., $/kWh. As the efficiency of solar cells increases, more advanced manufacturing methods are needed to further improve efficiency. Consequently, the sophistication and cost of the devices often increase, resulting in lower returns.[20] For similar installation conditions, a power gain of 50 percent can be realized from bifacial modules compared to mono facial modules.[21]

Research on bifacial PV modules began in the 1960s. In 1966, the bifacial cell was first described by Hiroshi.[22] However, bifacial technology only began to receive appropriate attention from the PV community at the end of the 1970s. The status of bifacial PV cell research was presented at the first European Photovoltaic Solar Energy Conference, held in Luxembourg in 1977.[23] Bifacial PV technology work accelerated during the 1980s, when numerous scientific papers on high-efficiency, high-power-gain bifacial PV cells were published. Liang et al. (2018) stated that throughout the 1990s and early 2000s, cost-effective solutions were suggested and used for many specific applications such as noise barriers, shades, and fences.[24] In the 2010s, almost all major manufacturers of mono and polycrystalline silicon PV modules planned or began to market bifacial modules.[4] Many bifacial module plants have been installed to date. In the research conducted by the International Technology Roadmap for Photovoltaics (ITRPV), studies were carried out on how to place bifacial PV modules on the market and predictions were made for their future. According to ITRPV, by 2028, bifacial PV modules are expected to represent around 35 percent of the global share of the market.[25]

The bifacial panel has the potential to generate more energy per unit area due to the effect of reflected light (albedo) from the rear surface. In study investigating whether bifacial panels produce more energy per unit area with the effect of albedo, Cuveas et al.[21] reported that, using an appropriate concentration or reflector, both the front and rear surfaces of the bifacial panel could capture both direct and diffused sunlight.[21] A study by Solar World emphasized that bifacial panels produce extra energy in outdoor environments compared to standard mono-facial modules. Additionally, they declared that the frame of bifacial PV modules on glass/glass surfaces and glass/backsheet surfaces offered greater durability and reliability compared to the conventional bifacial PV module structures. They also stated that under the bifacial PV array of membranes, as an ideal surface for the albedo effect, white roofing was related to an increase in energy production and reflected about 80 percent of its light when it was new and unweathered.[26]

In many studies in the literature, the performance of bifacial panels has been compared to that of the older technology of monofacial panels. In their study, Van Aken et al.[27] collected data on monofacial and bifacial panels under the same external conditions and found differences in the gains on the back of the bifacial panels according to the time of day and month of the year.[27] The net gain produced on the rear side was quite symmetrical and exhibited very small gains at midday, whereas nearly constant gains were achieved when the sun reached negative angles relative to the plane of the module (Figure 4). On the other hand, they noted that the highest monthly gain in summer was due to the increased amount of sunlight at the latitude (52 ° 470 N) of the experimental location (Figure 5). The normalized difference of the bifacial and monofacial kWh/Wp as a function of the time of day (total energy production in kWh over the entire year) is shown in Figure 4 and the normalized monofacial kWh/Wp over the year (extrapolating for August and September) in Figure 5. These experiments were carried out at 52°470 N and 4°400 E at a low albedo location and 38 ° tilt.

Figure 4 Normalized difference of the bifacial and monofacial kWh/Wp as a function of the time of the day (total energy production in kWh over the entire year).[27]

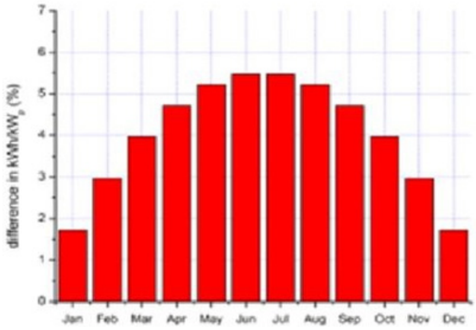


Figure 5 Normalized monofacial kWh/Wp over the year (extrapolating for August and September).[27]

Bifacial panels not only generate more energy per unit area, but also have advantages in terms of design varieties. Ooshaksaraei et al. performed various experiments on bifacial photovoltaic panels in terrestrial applications. According to this research, double surface absorption photovoltaic panels offer a wide range of applications, specifically as integrated building components that can produce energy (electricity) from outside walls, windows, open parking lots and rooftops.[28]

Some parameters are important for the design of more efficient bifacial panels. Wanga et al.[29] established a bifacial module simulation model and focused on the albedo effect and the efficiency of bifacial modules in low-latitude locations. The energy gain of bifacial modules is highly site-dependent and is affected by the manner in which they are set up and installed. Bifacial modules generally work well in countries and regions at higher latitudes, as they perform better when sun elevation is at a low angle. In addition, a ground surface with high reflectivity is desirable as this is one of the key parameters for bifacial module electrical performance. A background surface with a high reflection coefficient gives a higher energy yield as this impacts the amount of reflected light. Moreover, a sufficient clearance distance in front of the module array should be considered.[29]

One of the biggest problems of solar panels is overheating, as this reduces efficiency. Guerrero-Lemus et al.[30] stated that with a lower working temperature of the cell, there is a corresponding increase in the maximum output.[30] There is decreased infrared absorption because of the lack of aluminum back metallization and the increased thermal insulation on the backside of the bifacial module, as opposed to the traditional backsheet laminate when a back glass is included. Bifacial PV modules can work at lower temperatures than monofacial modules, thus increasing maximum power output. Because of the combined effects of light irradiation on the front and rear of the module, the creation of a widely accepted standard for cell testing under synchronized front and rear lighting is needed. In addition, a greater understanding is needed of the nature of bifacial cell production in order to facilitate wider acceptance on the global solar market.

Energy storage systems have been advocated as a means of bridging renewable energy output gaps on a variety of time scales, and the use of batteries in combination with PV systems is expected to become a widely implemented solution for energy storage.[31] The advantages of connecting batteries to a photovoltaic network to form a photovoltaic battery system are numerous, including increased self-consumption of the output of photovoltaics, time-shifting grid import and export, and decreased peak electricity flows. Battery sizing is a vital part of the design phase of the PV-battery system, as its size affects the profitability of the battery. If the battery is too small, overhead costs will prevail and the capacity of the battery will not allow the excess PV energy to be stored and managed, thus limiting the achievable revenue. If its capacity is too large, however, the investment costs will be higher, but the use of the battery will decrease as all the savings or revenue opportunities are depleted.[32]

The two most important properties of a PV system are its efficiency and its reliability. In a grid-connected PV system, the energy gain and repayment period depend on these two characteristics.[33]

Adding battery energy storage to PV systems is an effective measure to reduce the discrepancy between electricity generation and load. Storage of battery energy accounts for a large share of the cost of PV systems. The latest comparative study showed that if battery aging is considered, lithium-ion batteries are more economical relative to lead-acid batteries and flow batteries.[34] A schematic of a PV- battery system is shown in Figure 6. It consists mainly of solar panels, battery systems, chargers, DC/DC converters, and inverters. Solar panel size and battery capacity are designed to meet load demand, environmental and economic conditions, etc. The solar panel transforms solar energy into electricity during daylight hours, which can be supplied to the loads and deposited for potential use in a battery system by resorting respectively to the inverter and DC/DC converter. Therefore, the excess electricity for grid-connected PV systems can also be fed to the grid. Both the battery management system and the load management system are integrated into the PV system to optimize energy storage and utilization.[35]

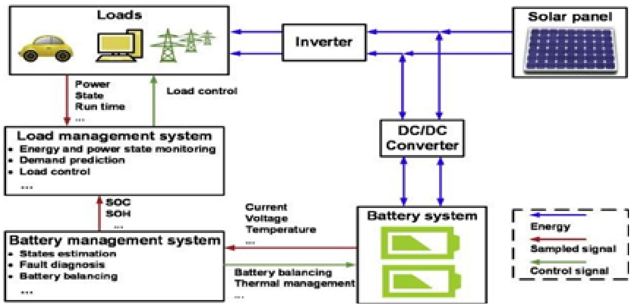


Figure 6 Schematic of a PV- battery system.[35]

The geographic information systems (GIS) with the support of multi-criteria decision-making (MCDM) techniques were employed in the study of Günen (2021) to determine the optimal areas for a solar photovoltaic power plant in Kayseri, Turkey. To find the solution, three main criteria and twelve subcriteria were given as determinants for the area. The MCDM, rank reciprocal, and analytic hierarchy process (AHP) techniques were employed to define the weights for the related criteria. The data obtained from 33 established solar PV power generators were used in the verification of the decision-making models. After ensuring that the stated criteria from the four MCDM techniques were met, efficient results were realized. Most of the existing plants complied with the results of the suitability map obtained from the GIS-based rank reciprocal method. The results obtained from the AHP were optimistic in nature since according to these results, no power plants were in poor regions. The inverse weights of the rank reciprocal technique gave optimal results indicating that the area of the established power plants was considered as the best area for new installations. Within the main criteria, the topographical and basic conditions had the highest weights. The infra- and superstructure characteristics with geomorphological and hydrological conditions had equal weights.[36]

Bhayo et al.[37] applied a proven evaluation methodology for a PV-battery power system using dumbed power for secondary applications such as water pumping.[37] The primary objective was to satisfy the rural housing unit demand of 3.2 kWh/day. By adjusting the number of PVs and the battery capacity, they determined the size of the PV-battery system. The levelized cost of energy was estimated at each configuration with the loss of power supply probability of 0. The number of PV panels was reported, depending on the day with the lowest solar irradiation. The required battery storage, indeed, depended on the actual number of hours needed by the battery to supply the load with electricity. The chosen size of the PV-battery system was 2.44 kWp of PVs and 3.55 kWh of installed battery capacity to meet the load demand of 3.2 kWh/day and to use the excess power for water pumping. The selected power system generated 9,807 kWh/day on average and provided 363 m^3/day water pumping. If the water was pumped to high capacity, hybrid PV-battery-hydro power could be used to generate extra hydropower.

Merei et al.[38] presented conclusions on optimization regarding self-consumption and the degree of self-sufficiency for a supermarket in Aachen, Germany.[38] They optimized the use of a real load profile and solar radiation measurement data. Moreover, to raise self-consumption, different battery sizes with different battery system costs were investigated and analyzed for 2015 and 2025 scenarios. The results showed that the installation of a PV system could reduce electricity costs through the self-consumption of self-generated PV energy.

Laws et al.[39] portrayed a novel method for integrating a PV and battery energy storage system (BESS) resilience value into a techno-economic optimization model.[39] Including the resilience value when designing a cost-optimal PV and BESS generally increases the capacity of the system and in some cases makes a system economical when it previously was not. They found that for a large hotel, no device was economically priced without resilience; however, with a resilience value of $5317/h, a 363 kW and 60 kWh solar and BESS provided a net present value of $50,000.

When storage cycling is properly controlled, coupling energy storage to a photovoltaic (PV) system not only improves self-consumption, but also eliminates over-voltage problems. For whatever purpose the storage program is used, the primary concern of the owner is to maximize profits. Therefore, Ranaweera and Midtgard (2016) addressed an energy management system for a PV system coupled with battery energy storage that maximized the daily economic benefits.[40] At the same time, it curtailed the power injection to the grid in such a way that helped to mitigate over-voltage problems caused by reverse power flow. They proposed a time-dependent grid feed-in cap and they achieved the goal of a regular operating cost that included the cost of electricity. A battery was proposed to achieve this goal. Using dynamic programming, they solved a non-linear constrained problem of optimization and evaluated the economic benefits of charging the battery from the grid. Finally, they found that if batteries are charged from the PV system, there is a possibility for these devices to engage in load leveling. In order to be feasible, the peak-hour sellback demand for renewable energy should be higher than the off-peak utility power price.

In conclusion, monofacial PV, bifacial PV, and battery systems have been presented in numerous studies that investigated the reduction of electricity consumption and the enhancement of electricity systems. The literature review demonstrated the input of mathematical models that have been created and evaluated.

Methodology

For this study, initially, the problem was determined and then the literature review was completed. An appropriate project was created by taking advantage of previous studies. Scenarios were created to render the project adaptable to different situations. The mathematical model was completed according to these scenarios and a case study was applied using the electricity consumption data of İkitelli Organized Industrial Zone for 2018. These steps are shown in Figure 7 and more information will be given in section 5.

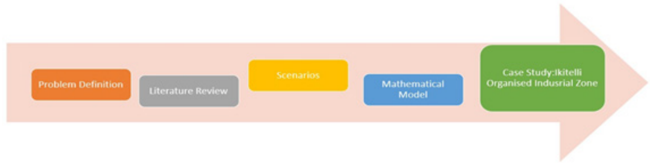


Figure 7 Flowchart of the study methodology.

To solve the site selection and warehousing problems a mixed-integer programming model was constructed. This model was also employed to find the answers for the collection place and extended investment in the selected site.[41]

In this study, the mixed-integer-programming model was used to minimize the energy received from the grid and to maximize the energy produced on the rooftops of industrial buildings using an alternative system.

A mixed-integer-programming problem is an integer-programming problem in which some of the variables are required to be integers. An example of the general structure of the mixed-integer model is:

$\max z = 3x_1 + 2x_2$; subject to: $x_1 + x_2 \leq 5$ $x_1, x_2 \geq 0$, x_1

Here, x_2 is not required to be an integer. There are two algorithmic principles that have proved successful in solving programs with integers: the branch-and-bound method and the cutting- plane method. Both are based on simple principles, but they are at the core of state-of -the-art programming technology and some mathematical sophistication is required for them to succeed.[42] The branch-and-bound method uses a "divide-and-conquer" approach to the idea of partial enumeration. The basic idea is to divide a bigger problem into a series of smaller issues and to solve those smaller issues in order to obtain information about the original problem. Typically, this is expressed through a tree of enumeration.[43] The model solution is simplified and is handled primarily by ignoring the condition of being an integer. The linear programming obtained by omitting the integer of all the variables or 0–1 constraints is called integer linear programming (LP) relaxation. The principle of the LP relaxation of an integer-programming problem plays a key role in the integrated programming solution.[42]

The result obtained by LP relaxation for the maximization problem is greater than or equal to that obtained by integer programming (Figure 8). In the minimization problem, the result is less than or equal to the integer modeling result.[44]

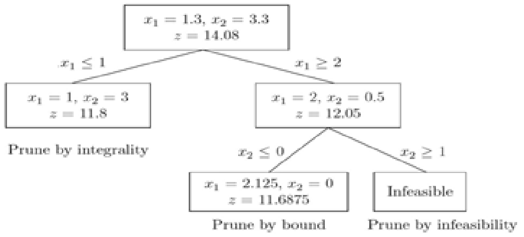


Figure 8 Example of a branch-and-bound tree algorithm.[44]

In order to apply a branch boundary algorithm, first, one of the variables that is desired to be an integer is selected. Thus, when $x_1 = 3.5$, if the system has the best value, the $x_1 \leq 3$ and $x_1 \geq 3$ constraints are added to the model. If x_1 reaches an integer value in the new boundaries, the integer values of the other variables are searched. In the branch-and-bound method, the tightness of the upper bound is important for the pruning of the enumeration tree. Tighter upper limits can be determined using the cutting-plane approach to the subproblems. This leads to the branch-and-cut method, which is currently the most efficient way to solve integer programs. It is obtained by introducing a cutting-plane step prior to the branching in the branch-and-bound algorithm step.[45]

The branch-and-cut approach refers to algorithms that use a cutting-plane procedure to reinforce the lower boundaries at each node within a branch-and-bound search routine. Therefore, the large subset of constraints used is appropriate for each search tree node, and this property is exploited (Figure 9).[46]

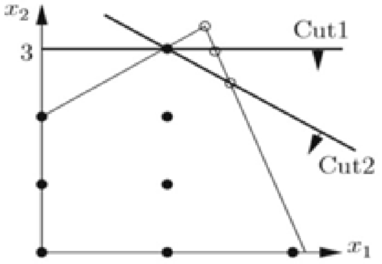


Figure 9 Cutting-plane algorithm.[46]

The number of decision variables is high in large-scale issues, and the number of iterations to be repeated in order to reach the solution is high. Branch-cut algorithms using branch-boundary algorithms and cutting-plane algorithms are applied in such cases.[47]

As a result of the study, a model was designed to minimize the energy intake from the network and to maximize the energy production in the unit of the rooftop bifacial PV. The general structure, inputs, and outputs of the model to be created were determined. In large-capacity PV power plants, the grid connection needs to be in a line linked with wind power plants at the distribution or transferring phase.[15]

This study identified three different strategies to fill the battery system. The first strategy was to charge the batteries during the night schedule and store the energy. The second alternative was to produce energy during the hours it could be generated from solar rays with the monofacial PV system and store it in the batteries. The last strategy was to produce energy during the hours it could be generated from solar rays with the bifacial PV system and store it. The last alternative was specifically created for industrial areas with restricted panel space. After selecting one of these alternatives, an optimization model was created using the alternative and the existing network systems to minimize the cost and produce a supply equal to the demand. The structure of the model is illustrated in Figure 10.

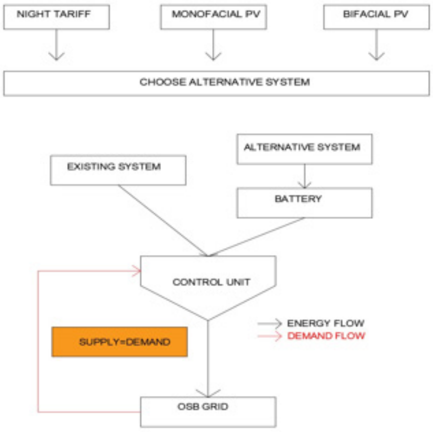


Figure 10 Flowchart of the proposed model.

Mathematical model

Certain assumptions were made before constructing the mathematical model:

a. If the energy produced by the PV system is stored only in the battery and used at peak hours, the excess amount used during the daytime will not be taken into consideration.

b. In the system where the energy received from the grid is stored in the battery, battery storage will be carried out during the hours under the night tariff.

c. There will be 24/7 power consumption in the industrial zone.

d. There will be no space constraints for the PV system or battery.

e. The average albedo value will be equal for all fields.

$$Min\ z = \sum_{t=1}^{365} \left\{ \left(f_{pig}(t) + f_{aes}(t) + f_{bat}(t) \right) \right\} \tag{1}$$

$f_{pig}(t)$ = Peak time interval grid cost

$f_{aes}(t)$ = Alternative energy system cost

$f_{bat}(t)$ = Battery system cost

$E_{ch}(t)$: Total energy charged in battery

$E_{dis}(t)$: Total energy discharged from battery

$E_{pig}(t)$: Total energy received from the grid at peak time interval

$E_{aes}(t)$: Energy taken from the alternative energy system

$D(t)$: Total Energy Demand (at t time)

$Cpg(t)$: Unit cost of energy taken at peak hour from grid (at t time)

Com: Operation and maintenance unit cost of the battery

$Cbat$: Battery unit cost

$Bcap$: Battery capacity

$SoC(t)$: Battery minimum charge

$Dcrit(t)$: Critical load amount

Ugm: Minimum energy taken from the grid in 1 h

Demand constraint:

$$E_{pig}(t) + E_{dis}(t) \geq D(t), \forall t \tag{2}$$

Alternative system energy constraint:

$$E_{ase}(t) \leq \max E_{ase}(t), \forall t \tag{3}$$

Battery capacity constraint:

$$SoC(t) \leq Bcap, \forall t \tag{4}$$

Minimum battery charge rate:

$$SoC(t) \leq Dcrit(t), \forall t \tag{5}$$

Limit of purchase:

$$E_{pig}(t) \leq Ugm, \forall t \tag{6}$$

$I \ldots \in \{0,1\}$

Alternative system constraints:

$$Impv(t) + Ibpv(t) + Ing(t) \leq 1, \forall t \tag{7}$$

Battery constraints:

$$Ich(t) + Idis(t) \leq 1, \forall t \tag{8}$$

Battery grid constraint:

$$Istd(t) + Istb(t) \leq 1, \forall t \tag{9}$$

Battery-grid constraint:

$$Idis(t) + Ipg(t) \leq 1, \forall t \tag{10}$$

I_{mvp}: Whether or not the battery is charged by the monofacial PV panel

I_{bvp}: Whether or not the battery is charged by the bifacial PV panel

I_{ng}: Whether or not the battery is charged with electricity taken at the night tariff

I_{ch}: Whether or not the battery is charged

I_{dis}: Whether or not the battery is discharged

Discharged battery constraint:

$$E_{dis} \leq M * Idis \tag{11}$$

Charged battery constraint:

$$Ech \leq M * Ich \tag{12}$$

$$f_{pig}(t) = E_{pig}(t) * C_{pig}, \forall t \tag{13}$$

$$f_{aes}(t) = E_{aes}(t) * C_{aes}, \forall t \tag{14}$$

$$f_{bat}(t) = E_{dis}(t) * C_{dis}, \forall t \tag{15}$$

Case study: application in Ikitelli organized industrial zone

İkitelli Organized Industrial Zone (Figure 11), with a total area of 700 ha, is among the largest organized industrial zone in Turkey, as are the Eskisehir and Adana Organized Industrial Zones. Approximately 600 ha of this area are devoted to small industrial domains and the remaining 100 ha to roads and communal areas. Currently, 9849 enterprises operate in a total of 24,313 active companies. The average occupancy rate is around 86%.[48]

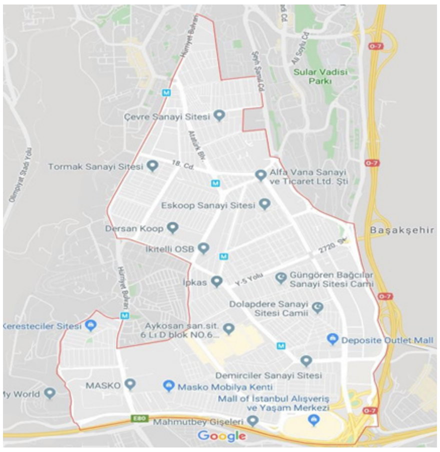


Figure 11 Map of İkitelli Organized Industrial Zone.[49]

The monthly and daily electricity consumption data for İkitelli Organized Industrial Zone in 2018 are given below (Figure 12) (Figure 13).

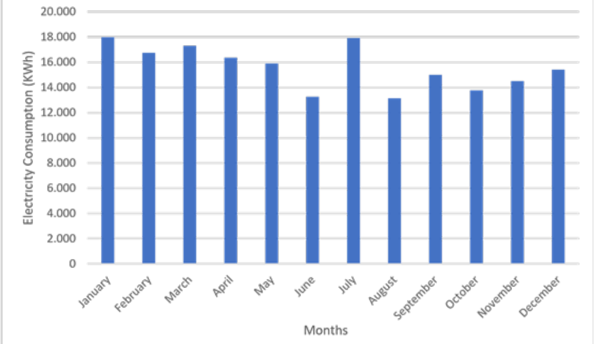


Figure 12 Monthly electricity consumption of İkitelli Organized Industrial Zone for 2018.

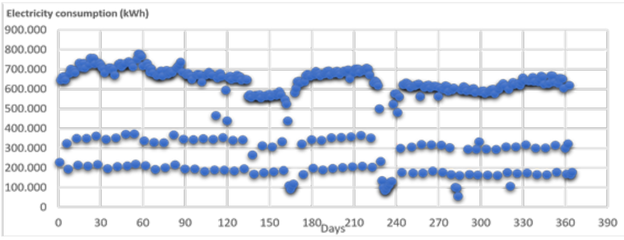
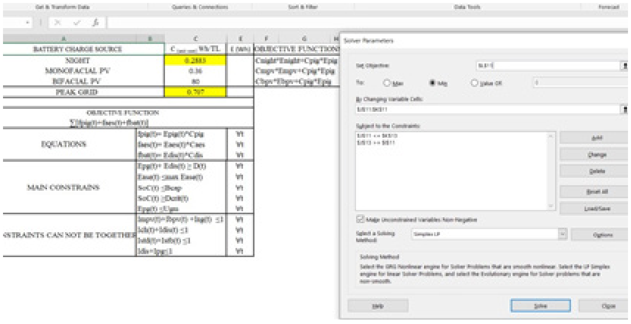


Figure 13 Distribution of daily electricity consumption for İkitelli Organized Industrial Zone in 2018.

Three strategies for the İkitelli Organized Industrial Zone were implemented for 365 days of electricity demand. Panel life was taken as 20 years and battery life was assumed as five years. The costs were calculated for the night tariff as 0.2883 TL/Wh, for the monofacial PV panel as 0.36 TL/Wh ($0.32 = 0.36 TL), for the bifacial PV panel as 0.41 TL/Wh ($0.36 = 0.41 TL), and for the battery as 4520 TL/kWh.

When optimization was performed with mixed-integer programming (Figure 14), the 2018 cost for electricity obtained at the night tariff was the lowest. The optimized bifacial and monofacial panels were found to be costlier.



BATTERY CHARGE SOURCE	C (ncl..) Wh/TL		OBJECTIVE FUNCTION
NIGHT	0.2883		Cnight*Enight+Cpig*Epig
MONOFACIAL PV	0.36		Cmpv*Empv+Cpig*Epig
BIFACIAL PV	80		Cbpv*Ebpv+Cpig*Epig
PEAK GRID	0.797		

OBJECTIVE FUNCTION

EQUATIONS	fpig(t)= Epig(t)*Cpig fses(t)= Eses(t)*Cses fbat(t)= Edis(t)*Cdis	∀t ∀t ∀t
MAIN CONSTRAINS	Epg(t)+ Edis(t) ≥ D(t) Eses(t) ≤max Eses(t) SoC(t) ≤Bcap SoC(t) ≥Dcrit(t) Epg(t) ≤Ugm	∀t ∀t ∀t ∀t ∀t
NSTRAINTS CAN NOT BE TOGETHER	Impv(t)+Ibpv(t) +Ipg(t) ≤1 Ich(t)+Idis(t) ≤1 Ich(t)+Idis(t) ≤1 Idis+Ipg≤1	∀t ∀t ∀t ∀t

Figure 14 Optimization using Excel Solver.

It can be concluded that the monofacial PV system (Figure 15) and the bifacial PV system (Figure 16) are not profitable since the daily base costs are cheaper. In Figure 17, the night tariff is seen as more profitable than the base tariff.[49]

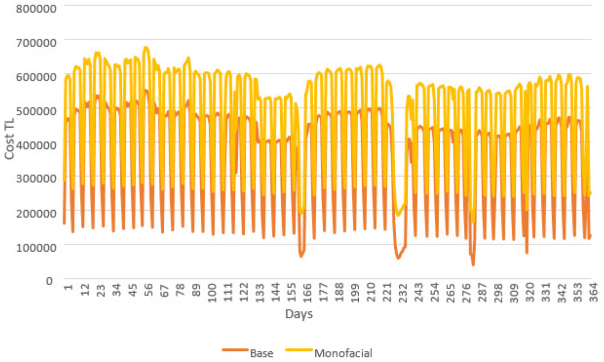


Figure 15 Cost optimization between peak grid tariff (base) and monofacial PV system.

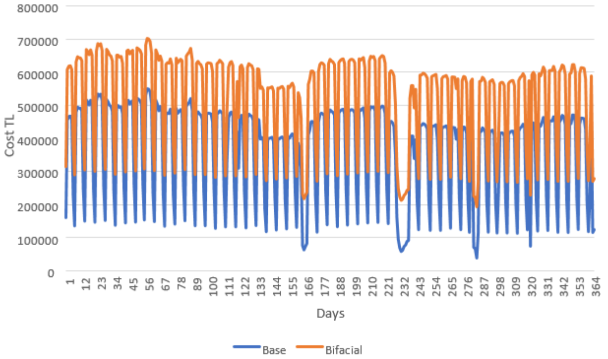


Figure 16 Cost optimization between peak grid tariff (base) and bifacial PV system.

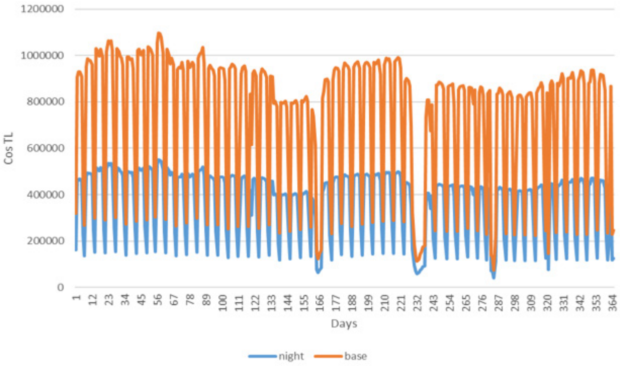


Figure 17 Cost optimization between peak grid tariff (base) and night tariff.

Citation: Yavuz K. Optimization of electricity consumption in an industrial zone with a battery system: a case study of Ikitelli industrial zone in Turkey. *MOJ Eco Environ Sci.* 2023;8(4):148–156. DOI: 10.15406/mojes.2023.08.00285

Conclusion

To combat excessive global and local industrial energy consumption, this study was organized with the aim of optimizing this consumption and reducing it in industrial zones in Turkey. A battery-powered model was developed in order to take advantage of the three-time tariff and to reduce the electricity charge during peak hours.

Three different energy source strategies were developed to support the battery system. The first strategy was to take electrical energy at the night tariff and store it in the battery, the second was to charge the battery with the monofavial PV system, and the third was to charge the battery with the bifacial PV system. The final strategy took into account the areal disadvantage of organized industrial zones.

A suitable low-cost region was chosen as the battery energy source for the systems supporting the battery with electrical energy. Afterwards, an optimization study was carried out to minimize the cost of the electrical energy taken from the grid at peak hours at the current system rate, considering battery and installation costs.

Mixed-integer programming was selected for the optimization model. Initially, certain assumptions were made and constraints were established. This model was tested using İkitelli Organized Industrial Zone as a case study. The electricity demand of the region in 2018 was taken into consideration when creating the study model. Analyses of the results showed that, when electricity was taken at the night tariff and stored in the battery, the cost was reduced by 1,916,250 TL annually. However, the annual energy cost was increased by 45,387,750 TL and 55,899,750 TL with the monofacial and bifacial PV panel systems, respectively. However, the use of solar energy reduces CO_2 emissions. At the same time, considering the decrease in panel costs after the first year, the system was predicted to be economically advantageous in the following years.

Acknowledgments

None.

Funding

None.

Conflicts of interest

Author declares that there is no conflict of interest.

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