World Academy of Science, Engineering and Technology
International Journal of Electrical and Computer Engineering
Vol:18, No:6, 2024

Minimizing Grid Reliance: A Power Model Approach for Peak Hour Demand Based on Hybrid Solar Systems

Almutasim Billa A. Alanazi, Hal S. Tharp

***Abstract*—**Electrical energy demands have increased due to population growth and the variety of new electrical load technologies. This increase demand has nearly doubled during peak hours. Consequently, that necessitates the construction of new power plant infrastructures, which is a costly approach due to the expense of construction building, future preservation like maintenance, and environmental impact. As an alternative approach, most electrical utilities increase the price of electrical usage during peak hours, encouraging consumers to use less electricity during peak periods under Time-Of-Use programs, which may not be universally suitable for all consumers. Furthermore, in some areas, the excessive demand and the lack of supply cause an electrical outage, posing considerable stress and challenges to electrical utilities and consumers. However, control systems, artificial intelligence (AI), and renewable energy (RE), when effectively integrated, provide new solutions to mitigate excessive demand during peak hours. This paper presents a power model that reduces the reliance on the power grid during peak hours by utilizing a hybrid solar system connected to a residential house with a power management controller, that prioritizes the power drives between Photovoltaic (PV) production, battery backup, and the utility electrical grid. As a result, dependence on utility grid was from 3% to 18% during peak hours, improving energy stability safely and efficiently for electrical utilities, consumers, and communities, providing a viable alternative to conventional approaches such as Time-Of-Use programs.

***Keywords*—**Artificial intelligence, AI, control system, photovoltaic, PV, renewable energy.

I. Introduction

THE increasing global demand for electrical energy, due to population growth and new electrical load technologies, presents significant challenges to traditional power infrastructures. This surge in demand, particularly evident during peak hours, could necessitate the construction of new power plant infrastructures, a financially burdensome approach due to construction costs and future maintenance expenses. As well it poses environmental concerns since power plants are significant contributors to greenhouse gas pollution [1].

Furthermore, energy prices have risen worldwide, notably in the United States of America (USA). As of February 2023, the average residential electricity rate in the USA stands at approximately 23 cents per kilowatt-hour (kWh). Table I illustrates how electricity prices increased in 2023 compared to the previous year, 2022, for various states [2]. In response to escalating costs and the strain on the grid, some electrical providers have introduced innovative pricing strategies, such as Time-Of-Use Pricing Plans. These plans offer higher "on-peak" rates during peak demand, incentivizing customers to shift their usage to "off-peak" hours. Fig. 1 [3] visually elucidates this concept, highlighting the potential benefits of load shifting in alleviating strain on electrical power plants during peak periods. However, Time-Of-Use programs may not be universally suitable for all consumers, particularly those who rely on electricity for essential activities during peak hours [4].

TABLE I
ELECTRICAL PRICE CHANGE IN THE USA

State	Cost of electricity	Previous year	Change
Arizona	14.74 ¢ / kWh	14.20 ¢ / kWh	+3.8%
Arkansas	13.26 ¢ / kWh	11.02 ¢ / kWh	+20.3%
California	28.38 ¢ / kWh	24.99 ¢ / kWh	+13.6%
Colorado	14.61 ¢ / kWh	13.49 ¢ / kWh	+8.3%
Connecticut	25.90 ¢ / kWh	21.01 ¢ / kWh	+23.3%
Florida	15.48 ¢ / kWh	12.90 ¢ / kWh	+20.0%
Georgia	13.95 ¢ / kWh	12.42 ¢ / kWh	+12.3%
Illinois	14.40 ¢ / kWh	13.97 ¢ / kWh	+3.1%

In addition, developing countries face challenges related to excessive energy demand, which leads to frequent blackouts. A comprehensive study in Africa reveals that power interruptions significantly impact firm sales, profits, and productivity for companies lacking backup generators while not affecting those with such backup systems [5]. Additionally, safety concerns arise for individuals, dependent on medical devices, as power outages resulting from excessive demand and supply shortages can affect health or even pose life-threatening situations [6], [7]. Losing lighting further contributes to increased crime rates, reduced perceptions of security, and disrupted recreational and social activities [8], [9].

This paper proposes an approach to managing peak-hour electrical demand. Leveraging a hybrid solar system integrated with AI and RE technologies, this study introduces a power model to reduce dependence on the grid during peak periods. Central to this model is a power management controller, which optimizes the allocation of power resources between PV production, battery backup, and utility grid usage.

Almutasim Billa A. Alanazi is a Ph.D. candidate with the Electrical and Computer Engineering Department, The University of Arizona, Tucson, AZ USA (e-mail: abalanazi@arizona.edu).

Hal S. Tharp is Associate Department Head of Electrical and Computer Engineering and Associate Professor of Electrical and Computer Engineering with the Electrical and Computer Engineering Department, The University of Arizona, Tucson, AZ USA (e-mail: tharp@arizona.edu).

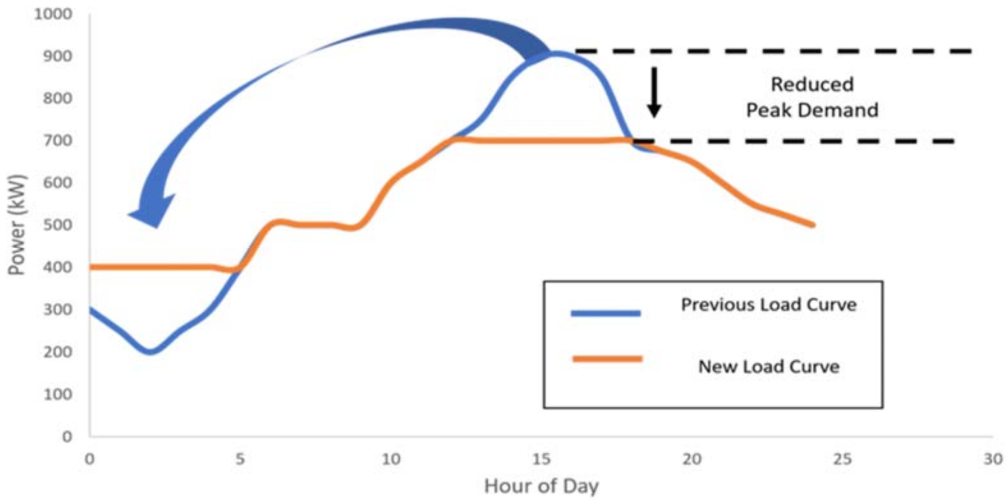

Fig. 1 TOU effect of power usage during day hours [3]

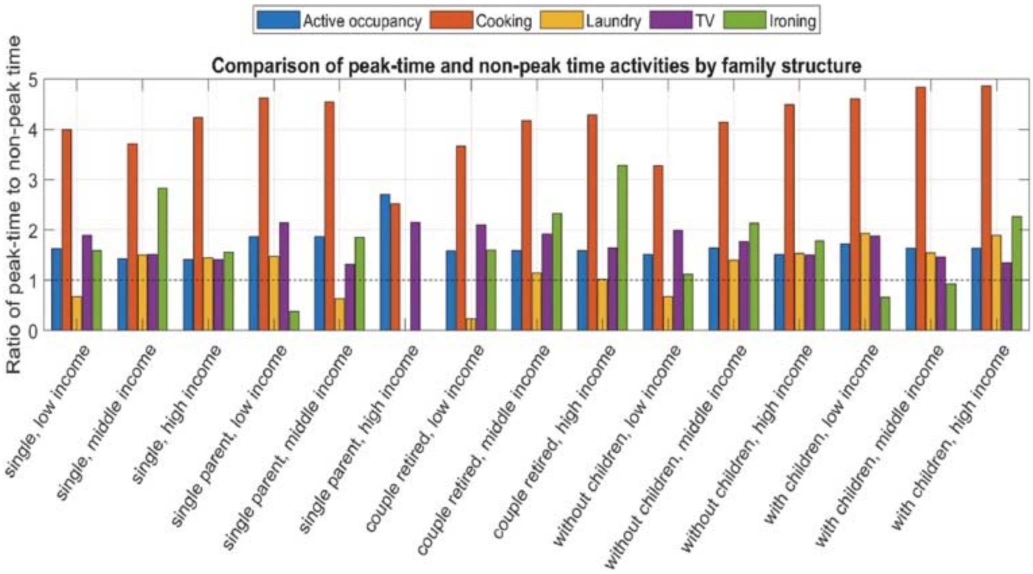

Fig. 2 Comparison of peak-time and non-peak time activities by family structure [13]

The primary objective of this research is to explore the efficacy of this integrated approach in mitigating excessive demand during peak hours, thereby enhancing energy stability and efficiency for both utilities and consumers. This study offers a viable alternative to traditional demand management strategies, such as Time-Of-Use programs, by reducing reliance on conventional grid infrastructure and promoting RE sources.

II. Literature Review

A. Time-of-Use Pricing During Peak Hours

The adoption of Time-of-Use (TOU) pricing has become a prominent strategy in managing peak hour demand and optimizing energy consumption. Various studies such as [10]-[12] have demonstrated the positive influence of TOU pricing on consumer behavior. This approach encourages a shift in energy consumption to off-peak hours, subsequently alleviating strain on power plants during peak periods.

However, the recognized benefits of TOU pricing come with a set of challenges, as illuminated by several studies that delve into its implementation during peak hours. A recent study in 2021, utilizing data from the 2014–2015 UK Time Use Survey [13], employed clustering techniques to categorize households based on similarities in activities during peak times. The study aimed to identify households differently affected by TOU tariffs across various socio-demographic parameters.

Fig. 2 derived from this study, presents visual representation of the peak-to-off-peak ratios of occupancy and energy-related activities categorized by income group and household composition. The key distinction is that activities with ratios below 1 are primarily performed during off-peak periods compared to peak times. For instance, the study reveals that laundry activities predominantly occur off-peak for single in the low-income group, couple retired, and households without children in the low-income group.

The findings underscore a significant point: TOU pricing may not be universally suitable for all customers due to diverse lifestyles. Families with children, for example, face challenges adhering to TOU pricing plans, particularly when peak hours coincide with the period when kids return from school which add limitation and constrained flexibility for activities such as cooking, laundry, and TV time. Equity and affordability concerns are further highlighted, emphasizing that TOU pricing may disproportionately impact for low-income households.

The same disparities apply on industries, especially those with continuous processes, where the challenge lies in shifting energy-intensive operations to off-peak hours, potentially affecting competitiveness and operational efficiency.

Moreover, the complexity inherent in TOU pricing models and intricate pricing structures contributes to consumer confusion. This complexity hinders consumers' ability to make informed decisions about energy usage during peak hours. Also, the transition to electric vehicles (EVs) also encounters obstacles under TOU pricing, where higher on-peak rates may discourage EV charging during peak hours, posing a potential impediment to the broader adoption of electric transportation and sustainability goals.

Therefore, while TOU pricing offers several advantages, it acknowledges and addresses the challenges associated with its implementation during peak hours. However, this paper considers consumer behavior, equity concerns, industrial flexibility, pricing model simplicity, and the new increase in demand due to emerging technologies like electric vehicles. Therefore, an alternative approach is proposed to mitigate the mentioned concerns. The proposed model aims to provide utilities, customers, and communities with a solution that overcomes the challenges associated with TOU pricing.

B. Mitigation of Peak Hour Issues through Engineering Innovative Approaches

In the pursuit of addressing challenges associated with peak-hour energy demand, researchers have ventured beyond conventional strategies, as exemplified in [14]. This particular study delves into the impacts of solar PV systems and devises a mitigation strategy that leverages distributed energy storage systems integrated with solar PV units.

This approach hinges on the effective use of distributed energy storage systems to tackle peak-hour challenges. Fig. 3, which encapsulates the target results, provides a visual representation of the strategy's effectiveness. The red line symbolizes PV production, while the black line represents the load demand. Notably, the evening peak is denoted as T with t_1 as the beginning and t_2 as the end.

The strategy involves utilizing surplus solar PV power during the PV peak, storing it in batteries, and subsequently employing the stored energy during the evening peak to support the load and reduce reliance on the utility grid.

This approach proves effective in addressing evening peaks, and it is particularly beneficial during PV peaks, such as those occurring in summer when the surplus solar PV power reaches the maximum. However, a drawback is the lack of a sustainable solution for utilities in day peaks, and low PV production such as in the winter season (few sun hours) or cloudy and rainy days.

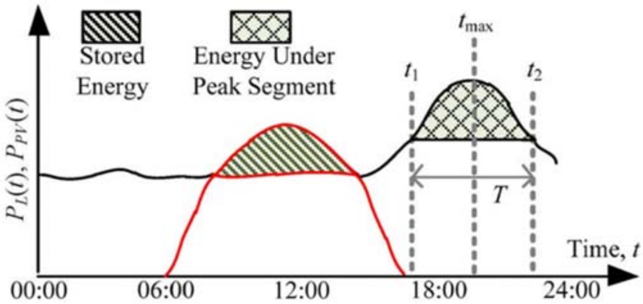

Fig. 3 Distributed energy storage systems integrated with solar PV units to mitigate peak hours issue [14]

In contrast, the presented model offers a more comprehensive and reliable solution across all seasons. The model incorporates a hybrid solar system, allowing batteries to be charged either from PV power or utilities during off-peak times. This versatility ensures that the load primarily relies on PV and backup batteries, reducing dependence on utilities during peak times. This guarantee of reliability throughout the year distinguishes the model from strategies that may be contingent on specific weather conditions.

The conservative nature of the presented model underscores its reliability and adaptability, making it a promising solution for peak-hour energy demand challenges. By integrating hybrid solar systems and strategically utilizing stored energy, this model showcases a robust approach that enhances energy sustainability and resilience against unpredictable weather patterns, providing a potential avenue for utilities seeking a reliable solution for peak-hour demands.

III. Methodology of The Proposed Model

A. Hybrid Solar System

In alignment with traditional solar panel systems features, the hybrid system functions as a dependable backup supply, combining solar energy and battery storage to ensure a continuous power source, even post-sunset, since the battery can be charged from the utility grid via the hybrid inverter in the evening time.

B. Charging Strategies

To optimize battery capacity, surplus energy generated by the PV system charges the batteries when solar production exceeds demand. In scenarios where the PV system cannot sufficiently charge the batteries before peak times (e.g., due to clouds or evening hours), the batteries can be charged through grid utilities during off-peak times. This dual-charging strategy will make sure that the batteries are fully charged before the peak hours.

C. Continuous Power Supply

Ensuring a continuous power supply involves harnessing solar energy during the day and utilizing stored battery energy and utility backups during periods of low PV output, thereby maintaining grid stability, reducing reliance on fossil fuels, and promoting sustainable energy practices. The flexibility to draw from the grid, when necessary, enhances the system's reliability, establishing it as a cost-effective and sustainable solution for meeting electricity needs.

D.Power Drive Controller

The hybrid solar system is managed by power controller. This controller's primary goal is to ensure load demands are met from solar system production, backup batteries, and grid utility utilizing pymgrid [15], an open-source Python microgrid simulator for applied AI research, as the reinforcement learning (RL) platform optimizes actions in a virtual microgrid environment.

E. System Connection

Fig. 4 elucidates the connection and operation of the proposed model. It illustrates the integration of solar panels, batteries, and the grid, showcasing dynamic interactions and energy flow within the hybrid solar system. Fig. 4 serves as a guide to understanding the physical and operational intricacies of the proposed model.

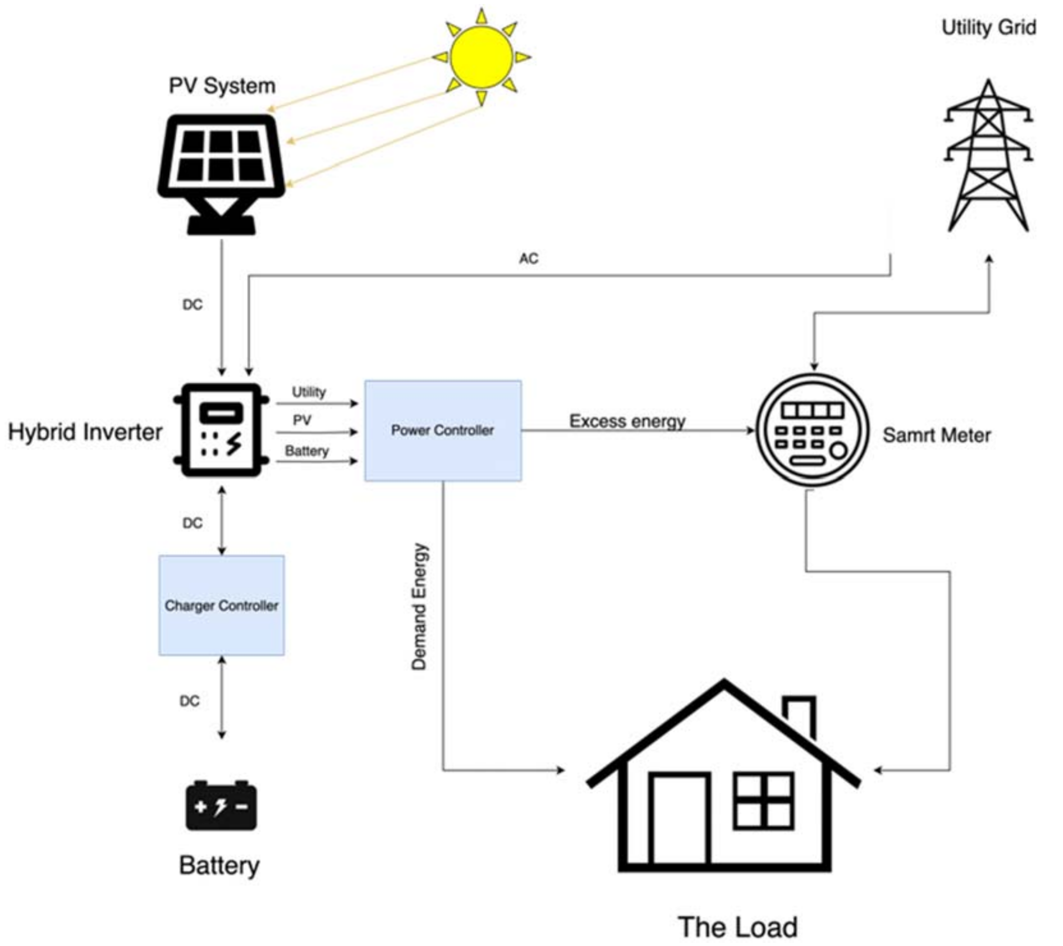

Fig. 4 Proposed model visualization

IV. System Design and Set up

This section provides the design and set-up of a residential solar power system in Tucson, AZ, using 25 PV models of RCE solar connected to a hybrid inverter. The system's design is facilitated by HelioScope, a cloud-based solar design software [16] to observe PV production throughout the year. The system was set up with an azimuth angle of 180° (south) and a tilt of 27°, as indicated by Fig. 5. The optimal azimuth angle for Tucson, AZ is highlighted in Fig. 6 from Google Map, where the orange line represents sunrise, and the red line represents sunset, with their positions varying throughout the seasons due to the tilt of the Earth's axis. In the northern hemisphere like USA, the Sun's rising position shifts north of east and its setting position moves north of west during the summer. Conversely, in the winter months, both sunrise and sunset occur at locations farther south along the horizon. The chosen azimuth angle and tilt are crucial for maximizing solar exposure and energy production throughout the year.

The battery capacity was only selected to cover the peak periods of 10 kWh capacity, and the Power controller was designed via pymgrid, taking into account the state of charge (SOC) to be 20% and 80% Depth of Discharge (DOD) to maintain good battery life. The power controller considers the problem as a Markov Decision Process (MDP), which contains the observations of the load demand, then gives actions of the battery discharge and the grid import based on the PV production to maintain the met of the load demand.

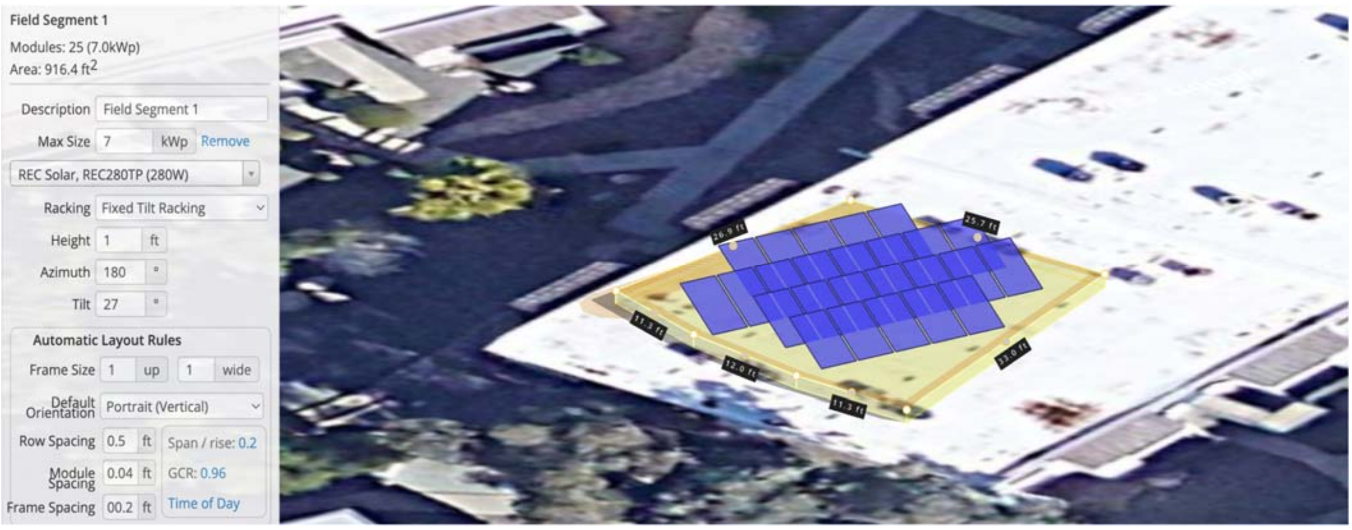

Fig. 5 HelioScope design of the PV system

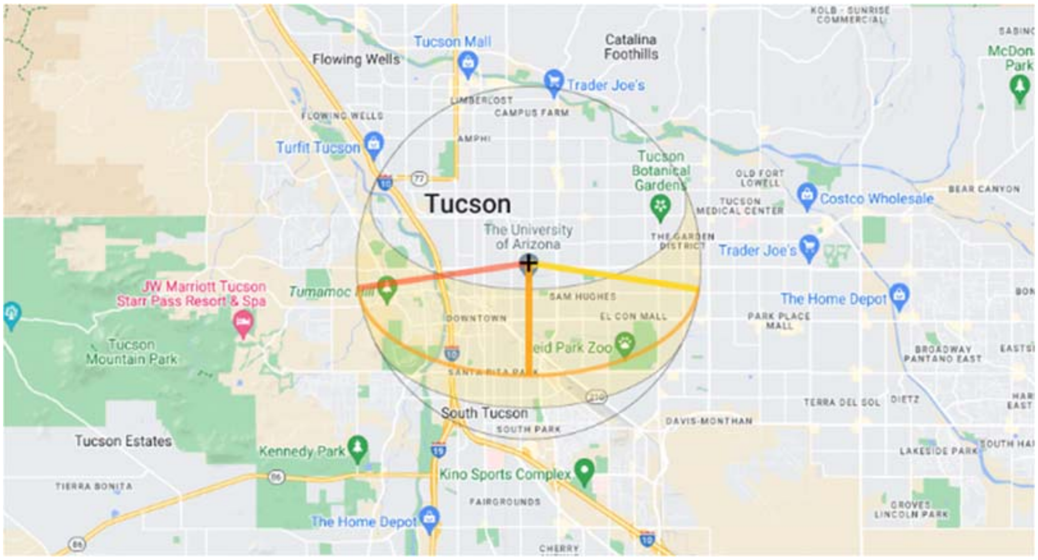

Fig. 6 The optimal azimuth angle for Tucson, Az

V. Results and Analysis

A. Efficiency and Annual Energy Production

Solar Software- HelioScope simulation account for energy PV losses. Therefore, it acknowledges that not all PV panels achieve perfect energy production due to factors like shading, reflection, mismatch, and cell temperature. The system's overall performance is presented in Table II, comparing the average annual production from simulation to an ideal system without losses.

B. PV Monthly Production

Table III delves into monthly solar access at the selected location in Tucson, accounting for factors such as shading from trees, sun position, and various weather conditions like clouds and rain. The second row of Table III quantifies the system's power production in kilowatt-hours (kWh) for each month. This detailed monthly breakdown allows a thorough understanding of how the solar system's performance is influenced by varying conditions. Additionally, Fig. 7 complements this information by visually representing the solar power produced for each month in a bar diagram, offering a more intuitive grasp of the monthly variations.

C. Analysis of PV Production

According to the Energy Information Administration (EIA), in 2022, the typical U.S. residential electric-utility customer purchased an average of 10,791 kWh of electricity annually, equivalent to a monthly average of approximately 899 kWh. Among the states, Louisiana recorded the highest annual electricity purchases per residential customer at 14,774 kWh, while Hawaii had the lowest at 6,178 kWh per residential customer [17].

A typical household requires approximately 30 kWh daily, which, when divided by 24 hours, results in an average of 1.25 kW for each hour to power the home throughout the day.

Considering the average Monthly PV production, Table III, the system will cover the load needs during the summer period, as the monthly production exceeds the average requirement (899 kWh), thereby increasing independence from the utility grid. However, during peak hours, the demand sometimes doubles to almost 2.5 kW, and the hybrid solar system, including the power controller, will play a crucial role in ensuring sustainability by reducing dependency on the utility grid.

D.Power Controller Operation during Peak Hours

Figs. 8 (a) and (b) depict the results of controlling energy from power sources during a summer peak, under the assumption of clouds in the last hour, which reduce PV.

In Figs. 9 (a) and (b), the winter season controller operation is shown with low PV production, demonstrating how battery and utility backups collaborate to effectively meet load demands.

TABLE II
COMPARING THE AVERAGE ANNUAL PRODUCTION FROM SIMULATION TO AN IDEAL SYSTEM WITHOUT LOSSES

Description	Output		% Delta
Irradiance (kWh/m^2)	Annual Global Horizontal Irradiance		2,134.7
	Plane of Array (POA) Irradiance	2,440.6	14.3%
	Shaded Irradiance	1,362.6	-44.2%
	Irradiance after Reflection	1,318.2	-3.3%
	Irradiance after Soiling	1,291.9	-2.0%
	Total Collector Irradiance	1,307.2	
Energy (kWh)	Ideal		9,166.5
	Output at Irradiance Levels	9,044.6	-1.3%
	Output at Cell Temperature Derate	8,518.0	-5.8%
	Output After Mismatch	5,491.2	-35.5%
	Optimal DC Output	5,480.9	-0.2%
	Constrained DC Output	5,480.5	0.0%
	Inverter Output	5,343.5	-2.5%
	Energy	5,343.4	
Avg. Operating Ambient Temp		21.7 °C	
Avg. Operating Cell Temp		28.6 °C	
Operating Hours		4713	

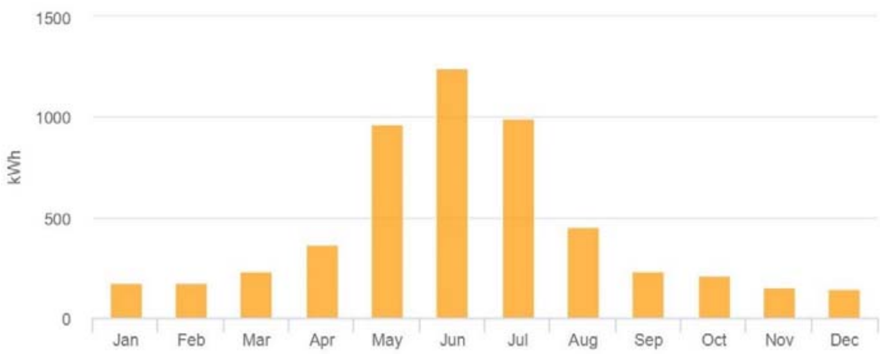

Fig. 7 The average solar system monthly production at the selected location in Tucson

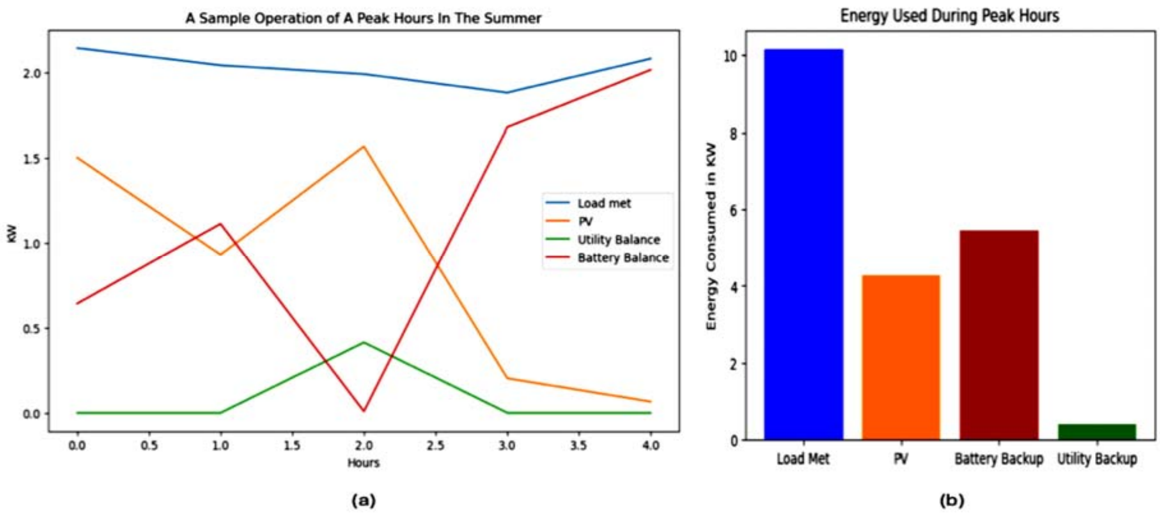

Fig. 8 (a) Controller operation in a summer peak; (b) Used energy during the summer peak

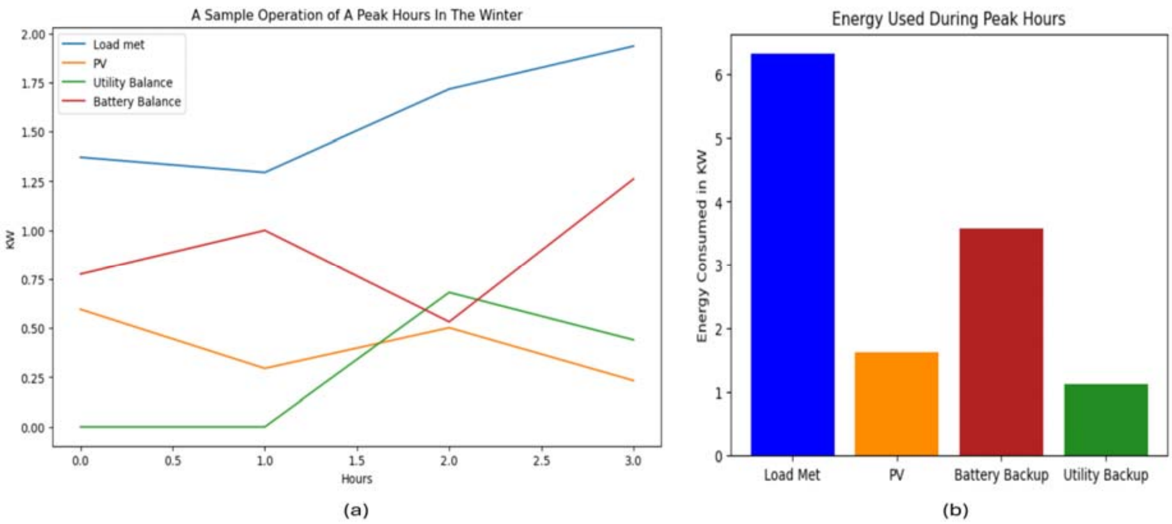

Fig. 9 (a) Controller operation in a winter peak; (b) Used energy during the winter peak

TABLE III
AVERAGE SOLAR ACCESS AND PRODUCTION PER MONTH AT THE SELECTED LOCATION IN TUCSON

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Solar Access	40.7%	40.6%	42.3%	47.4%	77.8%	97.4%	89.0%	56.6%	43.6%	41.6%	39.1%	38.9%
Average Power (kWh)	172.2	172.2	236.9	367.1	962.7	1,242.7	997.6	453.0	232.7	211.0	151.4	144.0

Both results indicate a notable reduction in reliance on utilities, the reliance was from 3% to 18%, influenced by seasonal variations impacting PV production and corresponding load demands. This highlights the power controller's adaptability and efficiency in managing energy resources across diverse conditions.

VI. CONCLUSION

This paper has presented an approach to reducing reliance on utility services during peak hours, thereby improving overall safety for utilities, enhancing efficiency for customers, and benefiting the environment and community.

The results indicate a significant reduction in reliance on utility service, ranging from 3% to 18%, effectively addressing the critical issue of double demands during peak hours and mitigating associated power outage risks.

As a future research, additional renewable sources, such as wind or geothermal energy, could be integrated into the model. Additionally, investigating the proposed approach across different geographic regions, including urban and rural areas with varying climates and energy demands, could provide valuable insights into its scalability and effectiveness in diverse contexts.

REFERENCES

[1] “Greenhouse gas reporting program (ghgrp),” U.S. Environmental Protection Agency 2022. https://www.epa.gov/ghgreporting/ghgrp-power-plants Accessed: 15 Feb. 2024.
[2] “How Much Does Electricity Cost by State?” EnergySage, www.energysage.com/local-data/electricity-cost/ Accessed 07 Apr. 2024.
[3] “What Is Peak Demand and How It Affects You.” Titan Energy, 23 July 2021, www.titanenergyne.com/peak-demand/ Accessed 07 Apr. 2024.
[4] Torriti, Jacopo. "Price-based demand side management: Assessing the impacts of time-of-use tariffs on residential electricity demand and peak shifting in Northern Italy." Energy 44.1 (2012): 576-583
[5] Cole, Matthew A., et al. "Power outages and firm performance in Sub-Saharan Africa." Journal of Development Economics 134 (2018): 150-159.
[6] Kotková, Barbora, and Martin Hromada. "Adverse event in a medical facility-blackout." International Journal of Power Systems 5 (2020).
[7] Molinari, Noelle Angelique M., et al. "Who's at risk when the power goes out? The at-home electricity-dependent population in the United States, 2012." Journal of public health management and practice 23.2 (2017): 152-159
[8] Matthewman, Steven, and Hugh Byrd. "Blackouts: a sociology of electrical power failure." (2014).
[9] Andresen, Adam X., et al. "Understanding the social impacts of power outages in North America: a systematic review." Environmental Research Letters 18.5 (2023): 053004.
[10] Cousins, Terry. "Using time of use (TOU) tariffs in industrial, commercial and residential applications effectively." TLC Engineering Solutions (2009).
[11] Hussin, N. S., et al. "Residential electricity time of use (ToU) pricing for Malaysia." 2014 IEEE Conference on Energy Conversion (CENCON). IEEE, 2014.
[12] Herter, Karen, Patrick McAuliffe, and Arthur Rosenfeld. "An exploratory analysis of California residential customer response to critical peak pricing of electricity." Energy 32.1 (2007): 25-34.
[13] Yunusov, Timur, and Jacopo Torriti. "Distributional effects of Time of Use tariffs based on electricity demand and time use." Energy Policy 156 (2021): 112412.
[14] Alam, M. J. E., K. M. Muttaqi, and Darmawan Sutanto. "Mitigation of rooftop solar PV impacts and evening peak support by managing available capacity of distributed energy storage systems." IEEE transactions on power systems 28.4 (2013): 3874-3884.
[15] Henri, Gonzague, et al. "pymgrid: An open-source python microgrid simulator for applied artificial intelligence research." arXiv preprint arXiv:2011.08004 (2020).
[16] “Solar Software.” HelioScope, helioscope.aurorasolar.com/. Accessed 16 Jan. 2024.
[17] “How Much Electricity Does an American Home Use?” U.S. Energy Information Administration (EIA), 8 Jan. 2024, www.eia.gov/tools/faqs/faq.php?id=97&t=3. Accessed 11 Mar. 2024.