International Journal of Applied Power Engineering (IJAPE)
Vol. 15, No. 3, September 2026, pp. 1458~1474
ISSN: 2252-8792, DOI: 10.11591/ijape.v15.i3.pp1458-1474

Hybrid AC/DC and conventional AC house efficiency for net zero energy homes

Taufik[1,2], Heru Nurwarsito[2], Tyler Bury[1], Rahman Azis Prasojo[1,3]
[1]Electrical Engineering Department, Cal Poly State University, San Luis Obispo, USA
[2]Faculty of Computer Sciences, Universitas Brawijaya, Malang, Indonesia
[3]Electrical Engineering Department, Politeknik Negeri Malang, Malang, Indonesia

Article Info

Article history:

Received Jan 26, 2026
Revised Jul 17, 2026
Accepted Aug 15, 2026

Keywords:

Copper loss
Hybrid AC/DC distribution
Hybrid house
MATLAB Simulink modeling
Power conversion efficiency
Net-zero energy home
Residential efficiency

ABSTRACT

The transition toward net-zero energy homes (NZEH) requires residential electrical systems that can efficiently integrate renewable generation, battery storage, and both AC and direct current (DC) loads. Although DC and hybrid AC/DC residential systems have been widely studied, limited work directly compares hybrid AC/DC and conventional AC house architectures under different grid standards, power levels, and AC/DC load ratios while considering DC bus losses. This study presents a MATLAB/Simulink-based steady-state efficiency comparison between hybrid AC/DC and conventional AC residential electrical systems. Twelve models were developed, consisting of six hybrid AC/DC and six conventional AC configurations under 120 V/60 Hz and 230 V/50 Hz standards. The models include PV generation, battery storage, inverter, AC/DC converter, multiple-input single-output (MISO) converter, and line-resistance effects. Results show that hybrid AC/DC houses achieve 4–11% higher efficiency than conventional AC houses when DC load demand remains below approximately 1.5–2.0 kW, mainly due to reduced conversion stages. At higher DC load levels, the efficiency advantage decreases because of copper losses in the 48 V DC bus. Increasing the DC bus voltage to 60 V reduces current-related losses and extends the efficient operating range. These findings indicate that hybrid AC/DC distribution is most suitable for residential applications with low-to-moderate DC demand, such as lighting, electronics, communication devices, and other DC-compatible appliances. The main contribution of this study is identifying the operating range, efficiency limit, and practical design implications of hybrid AC/DC residential distribution for future NZEH applications.

Corresponding Author:

Rahman Azis Prasojo
Electrical Engineering Department, Politeknik Negeri Malang
Malang, Indonesia
Email: rahmanazisp@polinema.ac.id

1. INTRODUCTION

Efficient, sustainable conversion and use of electricity are increasingly critical. Modern life telecommunications, transportation, computing, and basic lighting-depends on reliable power, and demand continues to rise. In 2023 the U.S. consumed ~4.07 trillion kWh of electricity; heating and cooling dominate residential use, while computing, refrigeration, ventilation, cooling, and lighting lead in the commercial sector. The global electricity demand will grow by roughly 33–75% by 2050 [1]. Yet much of today's electricity still comes from fossil fuels. In the U.S., about 60% of 2023 generation was from fossil sources, primarily natural gas and coal [2], resulting in ~4,807 million metric tons of CO_2 emissions, with ~1,427 million metric tons attributable to the electric power industry [3]. These trends underscore the urgency of cleaner, more efficient energy practices aligned with international commitments such as the Paris Agreement.

At the same time, renewable energy adoption especially photovoltaics (PV) is accelerating. PV inherently produces direct current (DC), which is typically converted to AC for consumption and grid export. Many residential devices (e.g., LED lighting, phones, and laptops) are themselves DC, so grid AC is often converted back to DC, compounding conversion losses. Allowing PV-generated DC to serve DC loads directly can avoid unnecessary DC-AC-DC conversion stages and improve building energy efficiency. Previous studies report that DC distribution can increase building energy efficiency by up to 18.5%, particularly when PV, battery storage, and DC-native loads are integrated on the DC side [4].

The concept of the DC House is built on the idea that most modern renewable sources and household devices natively operate on DC, and therefore bypassing repeated AC/DC conversions can improve efficiency, reliability, and affordability. Recent studies on residential DC microgrids show that DC distribution can improve building energy efficiency by reducing conversion stages between PV systems, battery storage, and DC-native household loads. For example, [4] reports that DC distribution can increase building energy efficiency by up to 18.5% [5]. Beyond efficiency, the DC House is part of a broader shift toward DC microgrids, in which distributed renewable generation, storage, and DC-native loads interact seamlessly to reduce conversion losses, enhance resilience, and simplify integration with smart grids [5]. Recent reviews of residential DC microgrid energy management systems further indicate that control architecture, energy management, storage coordination, and cost optimization are essential issues for practical residential implementation [6]. Another DC house project proposed in [7] demonstrates how low-voltage DC systems can provide scalable, affordable, and flexible electrification solutions for remote or rural communities. By relying on renewable and by directly supplying DC loads, this system minimize infrastructure costs while offering efficiency improvements of more than 15% compared to traditional AC-based solutions. However, while the DC House demonstrates the efficiency and accessibility potential of fully DC-based systems, it does not reflect the realities of grid-connected residential homes that must accommodate both AC and DC loads.

Hybrid AC/DC residential systems have therefore emerged as a practical intermediate architecture between conventional AC homes and fully DC homes. In this architecture, the existing AC network can continue supplying high-power AC appliances, while a dedicated DC bus can supply DC appliances directly from PV or battery sources. Recent hybrid DC-AC home studies using rooftop solar and MATLAB/Simulink simulation show that a dedicated DC bus can be combined with the conventional AC bus to supply residential loads more efficiently [8]. Similarly, studies on front-end AC/DC converters in hybrid AC/DC smart homes highlight the importance of converter control, DC-grid interfacing, and power quality when renewable energy, storage, electric mobility, and native DC technologies are integrated into residential systems [9]. Low-voltage DC supply and utilization systems have also been identified as an emerging approach for integrating distributed solar generation, storage, DC loads, and smart-home applications, although voltage level selection, protection, control, and standardization remain important challenges [10].

Therefore, the main research problem is not only whether DC distribution can reduce conversion losses, but under what residential operating conditions a hybrid AC/DC architecture provides a measurable advantage over a conventional AC house. This study addresses that problem by developing and comparing hybrid AC/DC and conventional AC house models under 120 V/60 Hz and 230 V/50 Hz grid standards. The analysis evaluates efficiency gains from reduced conversion stages, identifies the DC load range where hybrid AC/DC distribution remains beneficial, and quantifies the effect of DC bus line losses at different power levels. The contribution of this study is a comparative simulation framework that links hybrid AC/DC residential architecture with practical design limits, including DC load level, bus voltage, and economic feasibility for net zero energy homes (NZEH) applications.

2. BACKGROUND

2.1. Net zero energy homes (NZEH)

Net zero energy homes (NZEH) are residential homes designed to produce as much energy as the energy used by the home's residents within a year. These homes are extremely energy efficient and are designed to reduce energy need [11]. Current NZEHs are designed with improving thermal insulation, renewable energy generation, and energy-efficient appliances to reduce their carbon footprints [12]. These homes offer improved reliability during power outages, enable long-term savings on energy costs, and promote a sustainable way of living. A prominent example is the Acton Passive House in Massachusetts [13], which utilizes high-performance insulation, airtight seals, and an efficient heat pump for low-energy thermal comfort. The home is also equipped with highly efficient appliances and a PV array for energy generation. The home utilizes efficient PV on its roof while taking advantage of large windows and high-quality insulation to maintain a thermally comfortable living environment.

2.2. DC house concept

AC power systems have drawbacks, particularly in residential electrical systems where lossy conversions from AC to DC occur. This issue becomes even more crucial with the increasing prevalence of devices and systems that rely on DC power, particularly considering that the conversion loss can range from 17% to 35% [7]. One solution for these conversion losses is to utilize a purely DC electrical system.

DC-operated homes have been considered an alternative to the existing AC residential homes to facilitate the NZEH. These DC homes are an alternative, especially for rural electrification, where the houses are powered by solar panels and the location is economically unviable for access to the AC grid [7]. These homes, also known as nano-grids, are entirely powered by DC energy generation and can operate off the grid. This DC power is typically generated from renewable sources such as PV and stored in a battery energy storage system (BESS).

Several potential benefits such as reduced power losses, as DC loads can be supplied directly, and improved resilience during grid power outages. The robustness of DC systems is exemplified by the development of portable PV solutions with DC-first architectures, which provide sustainable and rapidly deployable energy in off-grid or emergency scenarios [14]. Furthermore, the reduced conversion steps with a pure DC system can improve power supply reliability [15]. BESSs can be more easily integrated and are potentially more efficient due to the lack of conversion steps for DC loads required in conventional AC systems [16].

However, DC systems also have drawbacks, such as ground fault circuit interrupters (GFCIs) are not widely produced for DC use, partly due to DC Arcs being difficult to detect in the time domain [17]. Other issues, such as a lack of standards and regulations are other hurdles for purely DC systems to be implemented [16]. Hence, issues such as the unstandardized DC bus have prompted researchers to explore ways for a DC smart wall plug that can accept various input and output DC bus voltage levels [15]. Another drawback is that many high-power electric appliances rely on AC power due to their large induction motors. In a purely DC system, an inverter will be necessary to power some of these appliances. Additionally, many of these DC systems rely on renewable energy sources, such as PV, which is heavily dependent on weather conditions. Therefore, a DC house may require multiple energy sources to make it operate reliably with minimal interruption.

Multiple input sources would require a multiple-input single-output (MISO) converter to allow more than one energy source to connect to a DC house. This converter type can accommodate different input sources and combine them into a controlled single DC output, making it suitable for integrating PV, battery storage, and other DC sources in a hybrid residential system [18]. Previous research on this matter includes the DC House Project at Cal Poly State University, with similar research also conducted in the Philippines and Indonesia [7]. Other research includes the DC Nanogrid House by Purdue University [19], microgrid research conducted by InstantOn in Hawaii, and numerous other off-grid energy projects. Recent studies on residential DC microgrids show that the DC House concept is strongly supported by the natural compatibility between rooftop PV, battery energy storage systems, and modern DC loads. Residential PV systems normally require power electronic converters to interface with household loads and the grid, but DC-side integration can reduce unnecessary conversion stages and improve overall energy efficiency [4]. Nevertheless, the practical deployment of residential low-voltage direct current (LVDC) systems still faces several unresolved challenges, including voltage-level selection, protection coordination, fault isolation, control strategy, standardization, and availability of suitable DC appliances and devices [10]. Therefore, although fully DC residential systems offer clear efficiency advantages, their implementation remains more suitable for specific applications such as off-grid, rural, or demonstration systems than for typical grid-connected homes. While DC homes are being researched, a hybrid AC/DC house presents another potential approach for facilitating the future NZEH, especially in developed, urban settings.

2.3. Hybrid AC/DC house

While DC electricity is widely used in many devices today, the predominant form of electricity transmission is AC. This existing infrastructure makes AC advantageous relative to DC distribution. Therefore, completely replacing existing AC infrastructure is impractical. Unlike fully DC homes, hybrid AC/DC architectures can supply electric loads through both conventional AC power and a separate DC bus that can be powered from renewable energy sources. Previous work on hybrid AC/DC microgrids for nearly/net-zero energy buildings shows that AC and DC sub-grids can be coordinated through power electronic interfaces and control strategies to improve renewable energy utilization, support power exchange between AC and DC sides, and reduce unnecessary conversion stages [20]. Figure 1 depicts the basic diagram of the hybrid AC/DC house.

Hybrid AC/DC homes require coordinated energy management among PV generation, battery storage, grid supply, AC loads, and DC loads. Previous reviews show that EMS design is essential for optimizing power flow, reliability, operating cost, and DER–storage coordination [6]. Therefore, evaluating hybrid AC/DC homes should consider not only their architecture, but also their operating conditions and efficiency limits under different AC/DC load ratios.

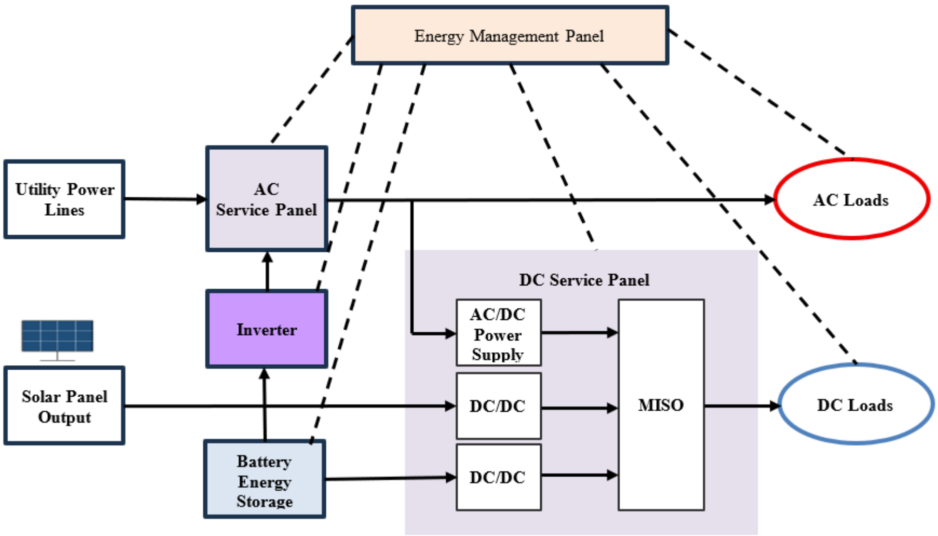


Figure 1. Hybrid AC/DC House component layout, featuring an energy management system to control power distribution and various supply types

Mitigating the current practice of converting solar panel DC into AC and then back to DC for devices will ultimately help maximize the electrical efficiency. Additionally, the hybrid AC/DC house approach would employ BESS to store generated energy while demand is low, thus simultaneously enhancing the resilience of the home's electricity during power outages. Researchers in Shenzhen, China, are addressing the hybrid AC/DC microgrids for commercial buildings with smart interlinking units, which are complex control architectures for various supply scenarios and load types [19]. Other research explores the operational costs and demand response associated with the size of DC loads using this hybrid approach [19]. This study will conduct comparative studies between hybrid AC/DC and conventional AC houses. The DC house will not be included in the study, as the future NZEH requires the house to be grid-connected.

In summary, conventional AC homes remain mature and grid-compatible, but repeated DC-AC-DC conversion reduces efficiency when PV, battery storage, and DC-native loads are used. Fully DC homes can reduce conversion stages, but their deployment is still limited by protection, voltage standardization, appliance availability, and compatibility with existing infrastructure. Hybrid AC/DC homes provide a practical compromise by retaining the AC network while adding a DC bus for selected DC loads. However, their benefit depends on AC/DC load ratio, DC bus voltage, conductor losses, and control strategy. This gap motivates the present comparison between hybrid AC/DC and conventional AC homes under different grid standards, power levels, and load ratios.

3. SYSTEM MODELING AND METHODOLOGY

This study develops and compares detailed models of conventional AC and hybrid AC/DC residential electrical systems to evaluate efficiency and cost implications for NZEH. Both models incorporate PV arrays, BESS, and AC grid connections, ensuring consistency in inputs while differing in how loads are supplied. The modeling process involved multiple levels of block diagrams to define architecture, component specification, and operating conditions. Simulations were conducted in MATLAB/Simulink. Figure 2 shows the flowchart of this study.

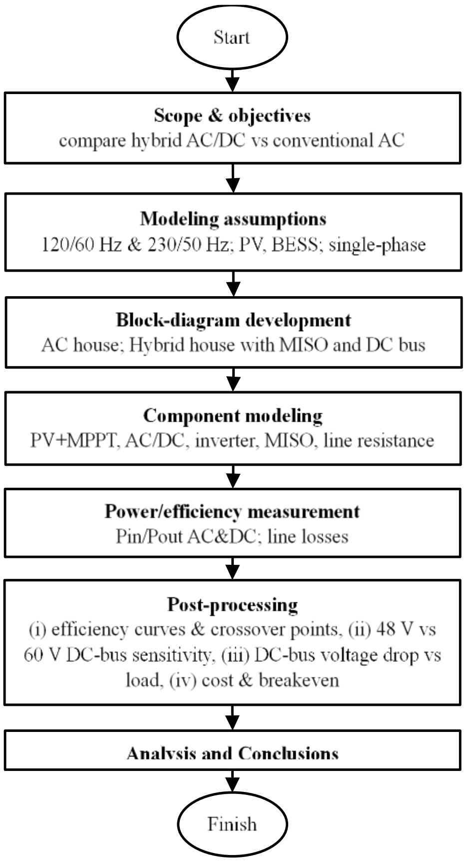


Figure 2. Flowchart of the study

3.1. Modeling assumptions

To ensure a fair and consistent comparison, both the conventional AC and hybrid AC/DC house models were developed using identical input sources: the AC grid (120 V/60 Hz or 230 V/50 Hz), a rooftop PV array, and a battery storage system. In the AC house, all loads—whether inherently AC or DC—are powered through the AC distribution bus, with DC loads receiving power via individual AC/DC converters at each outlet. In contrast, the hybrid house incorporates a dedicated DC bus supplied by a MISO converter, allowing DC loads to be powered directly from the PV array or battery without multiple conversion stages [18]. Both configurations assume single-phase connections typical of residential systems. Table 1 summarizes the key engineering specifications and justifications applied in developing and comparing the two models.

The main simulation parameters were selected to represent practical residential distribution conditions. The AC buses of 120 V/60 Hz and 230 V/50 Hz represent the two dominant residential supply standards used globally. The 48 V DC bus was selected because it is commonly discussed in LVDC residential systems and provides a practical compromise between safety, appliance compatibility, and conductor loss [10]. PV and battery capacities were scaled according to low-, medium-, and high-power residential cases, while the battery capacity was sized to support the average load for six hours. The inverter THD limit was maintained below 5% following IEC 61727 requirements for grid-connected PV systems.

Table 1. Hybrid AC/DC house and conventional AC house specifications

Engineering Specification	Justification
AC Bus: 120 V 60 Hz and 230 V 50 Hz	Most common AC buses worldwide.
DC Bus: 48 V	Common LVDC level for residential DC distribution, balancing safety, appliance compatibility, and conductor losses [10].
300 W to 12 kW	Minimum and maximum loads are based on research of developing and developed country residential electrical systems.
Photovoltaic system power: 0.5, 2, and 5 kW	Power requirement range for high-power-capacity homes in high latitudes to low-power-capacity homes in low-latitude regions.
Battery system storage: 3.3, 12, and 39 kWh	Energy requirements to run average loads for six hours.

3.2. Block diagram development

A total of six conventional AC house models were developed to represent different system topologies and power capacities (low, medium, and high-power household). Once the AC models were validated, hybrid AC/DC counterparts were created by modifying the original topologies to incorporate a mixed-supply configuration. In the hybrid models, a MISO converter was introduced to integrate both the battery charge controller and the AC/DC converter. The charge controller connects the PV and battery DC inputs, while the AC/DC converter interfaces directly with the AC bus. Together, these two inputs feed the MISO converter, whose single output establishes the 48 V DC bus supplying the household's DC outlets.

Figure 3 shows the conventional AC model, in which the PV and battery energy sources are processed through an inverter and then supplied to AC loads. Any DC loads in this setup require an additional AC/DC conversion stage. Figure 4 shows the hybrid AC/DC model, which enables both AC and DC loads to be powered more directly—AC loads remain supplied through the inverter and AC bus, while DC loads draw power from the 48 V DC bus through the MISO converter.

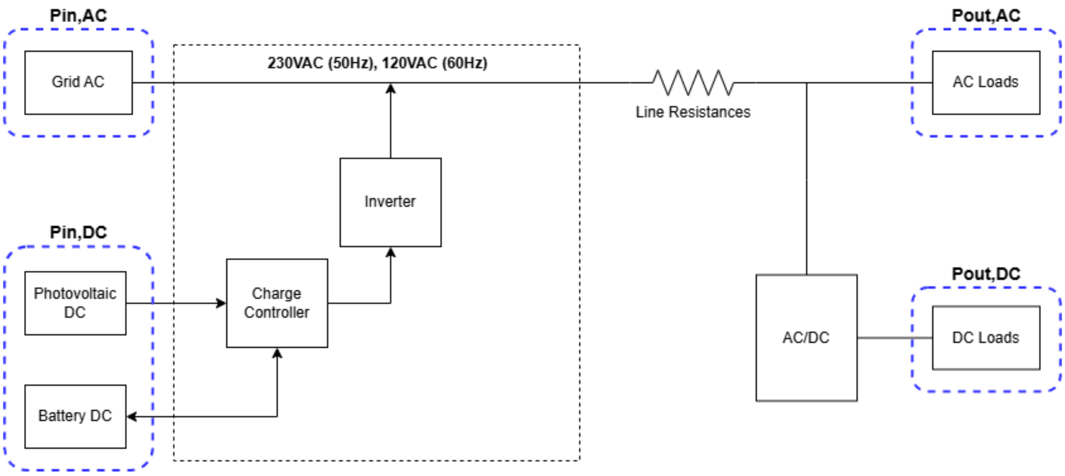


Figure 3. Conventional AC House simplified schematic

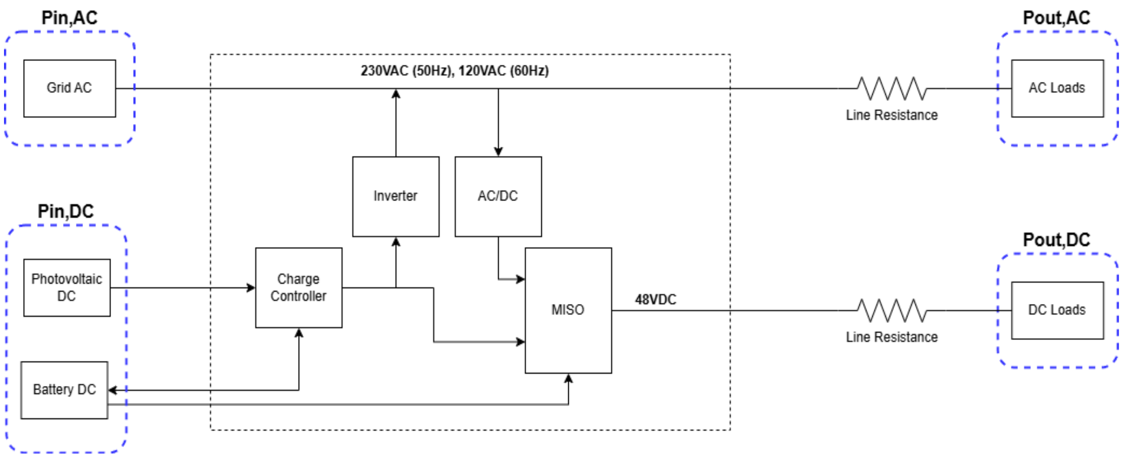


Figure 4. Hybrid AC/DC House simplified schematic

3.3. Power and efficiency measurement

Power measurements were recorded after the system reached steady-state operation, typically between 0.12 s and 0.20 s, depending on the transient response of each model. The overall efficiency for all house models was determined using (1).

$$\eta = \frac{P_o}{P_{in}} = \frac{P_{out,AC} + P_{out,DC}}{P_{in,AC} + P_{in,DC}} \quad (1)$$

The input and output powers for both AC and DC sides were calculated separately before combining them to obtain the total system efficiency. For AC measurements, the average power was computed according to (2):

$$P_{avg} = \frac{1}{T}\int_0^T v(t) \cdot i(t)dt \quad (2)$$

where,
$v(t)$ = instantaneous AC voltage.
$i(t)$ = instantaneous AC current.
$T = \frac{1}{f_g}$ = Period from the grid frequency (either 50 Hz or 60 Hz).

Because all AC loads were modeled as purely resistive, the output power $P_{out,AC}$ represented only active power with negligible reactive components. For DC quantities, instantaneous power was calculated using (3).

$$P(t) = v(t) \cdot i(t) \quad (3)$$

The DC input and output powers ($P_{in,DC}$ and $P_{out,DC}$) were measured once the system reached steady state to avoid transient fluctuations. These instantaneous values were then averaged over the sampling window to obtain consistent and comparable power results across all load and topology configurations.

This study focuses on steady-state comparative efficiency rather than dynamic performance. Power values were recorded after the initial transient settling period to ensure consistent comparison between topologies. Loads were represented as aggregated active-power demands, and converter efficiencies were modeled using fixed average values to isolate the effect of system architecture and conversion-stage reduction. Therefore, the results indicate comparative efficiency trends, while transient response, nonlinear and constant-power loads, and load-dependent converter efficiency require further investigation.

3.4. Component modeling

The primary subsystems for both conventional and hybrid house configurations were modeled and simulated in MATLAB/Simulink to accurately represent power flow and conversion efficiency.

- PV array and maximum power point tracking (MPPT) controller: The photovoltaic subsystem employs a perturb-and-observe (P&O) algorithm to regulate a buck converter, ensuring operation at the maximum power point (MPP). The converter supplies power to both the battery and the inverter, achieving an average conversion efficiency of approximately 96%.
- AC/DC power supplies: The AC/DC converters are modeled as full-bridge rectifiers followed by buck converters, stepping down 120/230 V AC to 24 V DC suitable for typical electronic loads. These units represent device-level adapters commonly found in residential environments.
- Inverter: The inverter consists of a DC-DC boost stage, a unipolar PWM-controlled full-bridge inverter, and an LC output filter to ensure sinusoidal voltage at the output. The simulated inverter performance achieved total harmonic distortion (THD) levels within the IEC 61727 standard, maintaining values below 5%.
- MISO converter: The MISO converter integrates inputs from the PV array, battery, and AC/DC grid supply to sustain a regulated 48 V DC bus. This configuration enables seamless power sharing among sources and enhances overall system flexibility and efficiency for hybrid operation.

3.5. Simulation modeling

The house models were tested under multiple load cases (low, medium, and high power), simulating daily residential consumption patterns. Efficiency calculations were performed by comparing input and output power at each stage, with line losses also modeled for the DC bus. The conventional AC house Simulink model establish a baseline system for comparison against the hybrid topologies. As shown in Figure 5, the PV source is connected through a MPPT charge controller, which regulates the charging of the DC link. The inverter then converts this DC power to 120 Vrms, 60 Hz AC, matching grid standards. The load circuits modeled in the right section of the diagram. This configuration reflects the conventional residential setup in which all devices, including inherently DC appliances, receive power through AC distribution.

The hybrid AC/DC house model was constructed to evaluate the benefits of integrating a DC distribution bus alongside the conventional AC network. Unlike the purely AC system, this configuration supplies DC loads directly from the PV array and battery, thereby reducing the need for multiple AC–DC conversion stages. As shown in Figure 6 and Figure 7, the model is divided into two main sections. The upper half of Figure 6 includes the MPPT charge controller, battery, and inverter. The PV source is regulated by the MPPT controller to charge the DC link and battery storage. The inverter converts DC to AC power for conventional household loads and operates in coordination with the battery to maintain system stability.

The lower half of Figure 7 contains the AC/DC supply converter and the MISO converter. The MISO converter allows DC loads to be powered either directly from the PV/battery source or from the AC/DC converter connected to the grid. This arrangement enables flexible power routing, as DC appliances can draw energy directly from DC sources with minimal conversion losses, while AC loads are supported through the inverter stage.

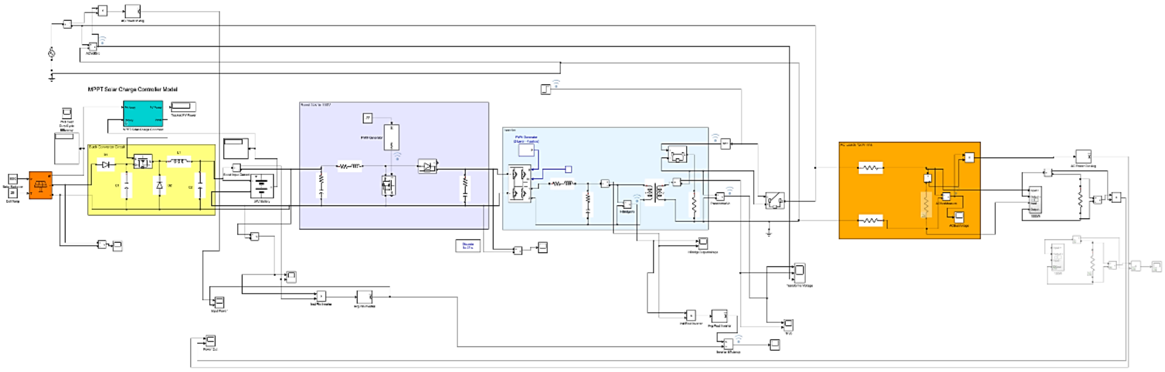


Figure 5. AC house model for 120 Vrms at 60 Hz in Simulink

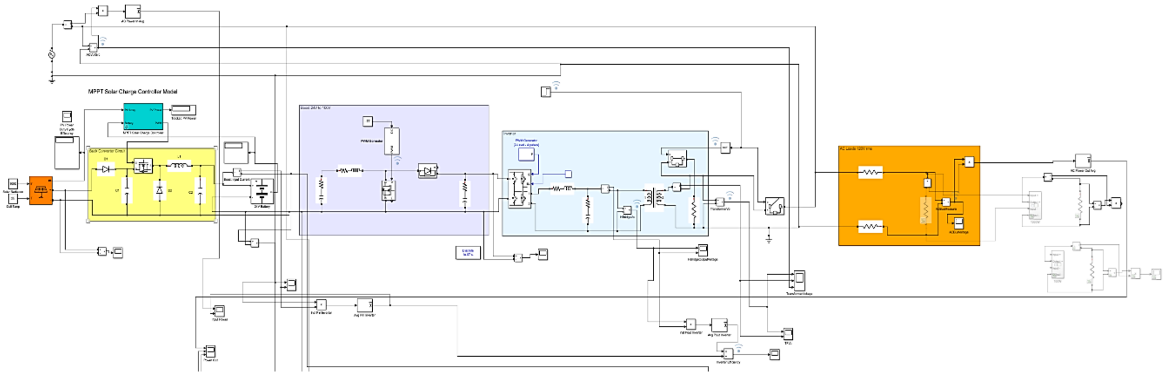


Figure 6. Upper half of the hybrid house model in Simulink, including the charge controller, battery, and inverter stages

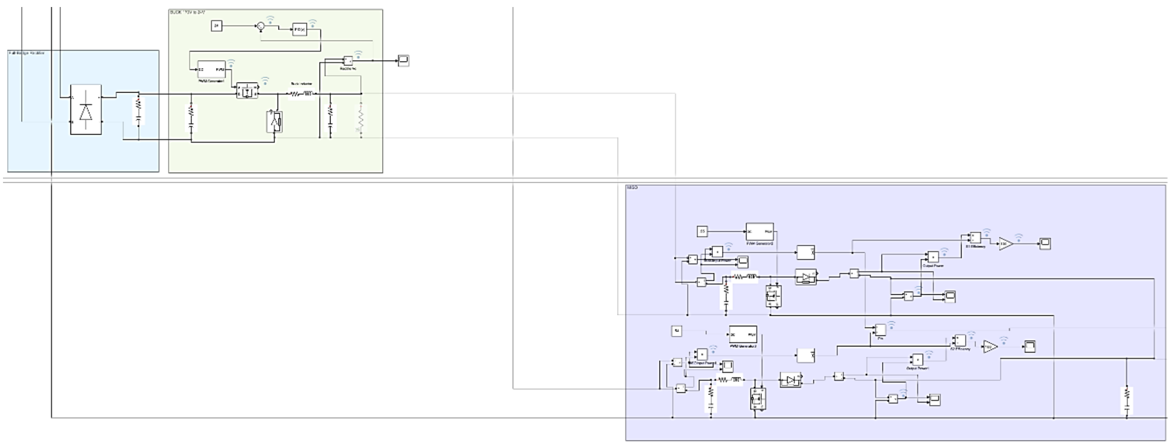


Figure 7. Lower half of the hybrid house model in Simulink, including the central AC/DC converter and MISO converter

4. RESULTS AND DISCUSSION

This chapter presents the outcomes of the modeling and simulation of twelve different house configurations under varying AC and DC load conditions.

4.1. Systematic testing matrix

To comprehensively evaluate the performance of both the conventional AC and hybrid AC/DC house models, a systematic testing matrix was developed, as summarized in Table 2. Each house configuration—low-, medium-, and high-power—was simulated under a range of total load conditions. The simulations also considered varying AC/DC load ratios to capture realistic household consumption patterns across different regions and power capacities.

Table 2. Load configurations and component specifications for conventional AC and hybrid AC/DC house models

Power capacity type	Total load [W]	AC/DC ratio 1:0		AC/DC ratio 0.75:0.25		AC/DC ratio 0.5:0.5		AC/DC ratio 0.25:0.75		AC/DC ratio 0:1		PV size [W]	Battery size [W]	Battery size [Ah]
		AC load [W]	DC load [W]	AC load [W]	DC load [W]	AC load [W]	DC load [W]	AC load [W]	DC load [W]	AC load [W]	DC load [W]			
Low power	100	100	0	75	25	50	50	25	75	0	100	500	3.3	137.5
	200	200	0	150	50	100	100	50	150	0	200			
	300	300	0	225	75	150	150	75	225	0	300			
	400	400	0	300	100	200	200	100	300	0	400			
	500	500	0	375	125	250	250	125	375	0	500			
	600	600	0	450	150	300	300	150	450	0	600			
	700	700	0	525	175	350	350	175	525	0	700			
	800	800	0	600	200	400	400	200	600	0	800			
	900	900	0	675	225	450	450	225	675	0	900			
	1,000	1,000	0	750	250	500	500	250	750	0	1,000			
Medium power	1,000	1,000	0	750	250	500	500	250	750	0	1,000	2,000	12	500
	1,500	1,500	0	1,125	375	750	750	375	1,125	0	1,500			
	2,000	2,000	0	1,500	500	1,000	1,000	500	1,500	0	2,000			
	2,500	2,500	0	1,875	625	1,250	1,250	625	1,875	0	2,500			
	3,000	3,000	0	2,250	750	1,500	1,500	750	2,250	0	3,000			
	3,500	3,500	0	2,625	875	1,750	1,750	875	2,625	0	3,500			
	4,000	4,000	0	3,000	1,000	2,000	2,000	1,000	3,000	0	4,000			
	4,500	4,500	0	3,375	1,125	2,250	2,250	1,125	3,375	0	4,500			
	5,000	5,000	0	3,750	1,250	2,500	2,500	1,250	3,750	0	5,000			
	5,500	5,500	0	4,125	1,375	2,750	2,750	1,375	4,125	0	5,500			
	6,000	6,000	0	4,500	1,500	3,000	3,000	1,500	4,500	0	6,000			
	10,000	10,000	0	7,500	2,500	5,000	5,000	2,500	7,500	0	10,000			
High power	1,000	1,000	0	750	250	500	500	250	750	0	1,000	5,000	39	1,625
	2,000	2,000	0	1,500	500	1,000	1,000	500	1,500	0	2,000			
	3,000	3,000	0	2,250	750	1,500	1,500	750	2,250	0	3,000			
	4,000	4,000	0	3,000	1,000	2,000	2,000	1,000	3,000	0	4,000			
	5,000	5,000	0	3,750	1,250	2,500	2,500	1,250	3,750	0	5,000			
	6,000	6,000	0	4,500	1,500	3,000	3,000	1,500	4,500	0	6,000			
	7,000	7,000	0	5,250	1,750	3,500	3,500	1,750	5,250	0	7,000			
	8,000	8,000	0	6,000	2,000	4,000	4,000	2,000	6,000	0	8,000			
	9,000	9,000	0	6,750	2,250	4,500	4,500	2,250	6,750	0	9,000			
	10,000	10,000	0	7,500	2,500	5,000	5,000	2,500	7,500	0	10,000			
	11,000	11,000	0	8,250	2,750	5,500	5,500	2,750	8,250	0	11,000			
	12,000	12,000	0	9,000	3,000	6,000	6,000	3,000	9,000	0	12,000			

The low-power house was designed for small residences with a peak demand of 1 kW and two circuits, representing households typical in rural Indonesia and India. The medium-power model reflects a small residence with a peak load of 6 kW and eight breakers, consistent with modest homes in the U.S. or U.K. The high-power model represents large family homes with up to 12 kW peak demand and twenty breakers, typical of suburban households in the U.S. PV and storage values were selected based on load profiles and prior electrification studies. Battery sizing was derived from the average load over a six-hour period, while PV sizing followed references [21], [22]. From each of the four topologies, three capacity levels were created, resulting in twelve total models. Each model was tested with multiple combinations of AC and DC loading to quantify efficiency. Each load was further subdivided into five AC/DC ratios, producing 165 test cases per topology. In total, approximately 660 test cases were conducted across the four topologies.

4.2. Breaker configuration and resistance modeling

The number of breakers, PV size, and battery sizing for each of the three power capacity homes are shown in Table 3. The number of breakers determined the number of circuits the house model contained. The battery sizes were calculated from the average load, taken from the range of total loads in Table 2, over a 6-hour period. PV sizes are justified from [21], [22].

Table 3. Organization of breaker count and DC source specifications

House model	Number of breakers	PV size [W]	Battery size [kWh]	Battery size [Ah]
Low power	2	500	3.3	137.5
Medium power	8	2,000	12	500
High power	20	5,000	39	1,625

The conductor/line resistances were calculated for the 120 V and 230 V circuits, assuming 12 AWG, single-core copper, was used in all the homes. 12 AWG is the standard conductor used for residential general-purpose power applications in the U.S. due to its 20 A-30 A ampacity. The copper length varied among the low, medium, and high-power house models, as it is assumed that home size increased proportionally with peak power demand. House sizes based on power capacity are shown in Table 4 [23]. Total conductor length varied between the house models as well. For the medium and low-power homes, it is assumed their total conductor length was the same as the home square footage. For the high-power home, the 1.5 ft of conductor length per home square footage is used to approximate copper length due to generally larger room sizes, resulting in proportionally greater distances from outlets to the main breaker.

Table 4. House model specifications for total conductor length and circuit count

House model	Home square footage [ft^2]	Total conductor length [ft]	Number of circuits
Low power	500	500	2
Medium power	1,000	1,000	8
High power	2,514	3,771	20

Line resistance calculations could then be made to approximate line loss throughout the home. The wire resistance of copper single-core 12 AWG is 1.588 Ω/1000 ft. Using (4), the resistance of the total conductor length could be calculated.

$$R_{total} = l_{total} \cdot \frac{R_{AWG}}{1{,}000ft} \quad (4)$$

The conductor resistance was then divided evenly by the number of circuits, under the assumption that each circuit is the same length. From each circuit resistance, the phase and neutral line resistances were then placed into the model.

In 120 V_{rms} residential electrical systems, 240 V_{rms} outlets can also be present for high-power loads such as electric ranges, electric water heaters, and more. These 240 V outlets require a split-phase transformer connection from the grid and can use gauges between 10 AWG and 4 AWG depending on load requirements. While 240 V is not present in the 120 V house models, the circuits were still modeled with 6 AWG wire and copper resistance compensation for the voltage difference. Compensating for the copper resistance from the use of 120 V on a 240 V circuit can be done using (5). In short, the conductor resistance on the modeled 240 V circuits can be divided by 4 on the 120 V bus, as shown.

$$P = (240V) \cdot I_{240V} = (120V) \cdot I_{120V}$$

$$I_{240V} = \frac{1}{2} I_{120V}$$

$$P_{240V} = P_{120V} \rightarrow I_{240V}^2 R_{240V} = I_{120V}^2 R_{120V}$$

$$\left(\frac{1}{2} I_{120V}\right)^2 R_{240V} = I_{120V}^2 R_{120V} \quad (5)$$

$$R_{120V} = \frac{R_{240V}}{4}$$

4.3. Control flow of converters

The real-world hybrid house systems will require a logic unit to operate as a central controller for efficiently operating the different conversion stages. This controller is needed to prevent the inverter and power supply from operating simultaneously, as this simultaneous operation would cause an inefficient DC-to-AC-to-DC conversion to occur. The control flow for this logic unit is presented in Table 5.

Table 5. Control flow of hybrid converters

Inverter	AC/DC converter
ON	OFF
OFF	ON
OFF	OFF

The hybrid system uses a rule-based energy management strategy to coordinate power sharing among the PV array, battery, AC grid, inverter, AC/DC converter, and MISO converter. In the first operating state, when AC load demand exists, the inverter supplies the AC bus, while the MISO converter supplies DC loads from the PV/battery side whenever DC demand is also present. In the second state, when DC load demand exceeds the selected threshold of half the house power capacity, the AC/DC converter provides an additional input to the MISO converter to support the DC bus. In this condition, the inverter is turned off and the AC grid supplies the AC loads to avoid inefficient DC-AC-DC conversion. In the third state, when there is no AC load and DC demand is low, both the inverter and AC/DC converter are turned off, and the MISO converter supplies the DC bus from the PV/battery side only. This control strategy improves efficiency by prioritizing direct DC supply for DC loads, reducing unnecessary conversion stages, and preventing simultaneous inverter and AC/DC converter operation. It also supports DC bus stability by allowing the AC/DC converter to assist the MISO converter when DC demand becomes high.

4.4 Efficiency comparison of AC and hybrid AC/DC houses

The comparative efficiency of hybrid AC/DC and conventional AC houses was evaluated under varying DC load conditions. Figures 8-10 present efficiency curves for low-, medium-, and high-power house models at both 120 V and 230 V. In all low-power cases (Figure 8), the hybrid model consistently outperformed the conventional model across the entire 1 kW range. Efficiency improvements of 1–10% were observed, particularly in the 230 V hybrid model, where the advantage was most pronounced at lower loads.

For medium- and high-power models (Figures 9 and 10), the hybrid approach demonstrated higher efficiency up to approximately 1.5–2 kW of DC load. Beyond this threshold, efficiency declined due to increased resistive (I^2R) losses in the 48 V DC bus. Despite this limitation, the range of household DC loads in typical residences is likely to remain below 2 kW, suggesting that the hybrid system provides efficiency benefits under realistic conditions.

Figure 11 further highlights this crossover behavior, showing that hybrid systems maintain superior efficiency for total loads up to 2 kW. Under conditions where the inverter could be switched off and the MISO converter alone supplied DC loads, the hybrid model achieved notable gains. This trend is consistent with recent hybrid DC-AC residential and residential PV-DC integration studies, which show that supplying DC loads through a dedicated DC bus can reduce unnecessary conversion stages [4], [8]. Compared with previous DC distribution studies, the efficiency gains in this work are more conservative because conductor losses in the 48 V DC bus are explicitly included. This indicates that hybrid AC/DC design should consider not only conversion-stage reduction, but also DC bus voltage and feeder layout.

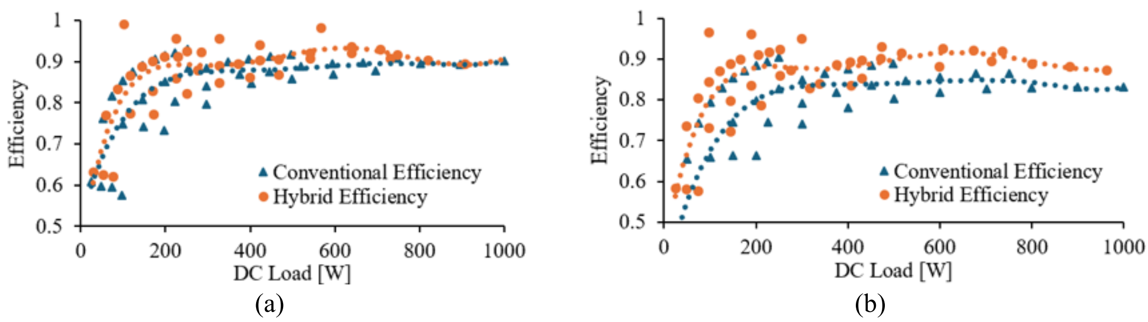
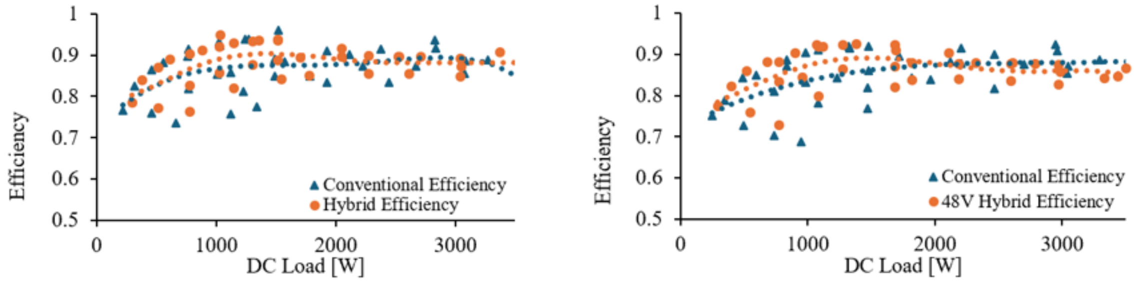
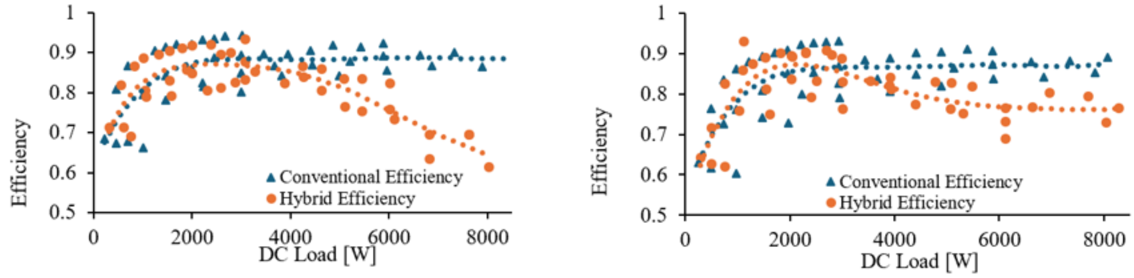


Figure 8. Low-power efficiency curves for conventional and hybrid houses: (a) 120 V and (b) 230 V



(a) (b)

Figure 9. Medium-power efficiency curves for conventional and hybrid houses: (a) 120 V and (b) 230 V



(a) (b)

Figure 10. High-power efficiency curves for conventional and hybrid houses: (a) 120 V and (b) 230 V

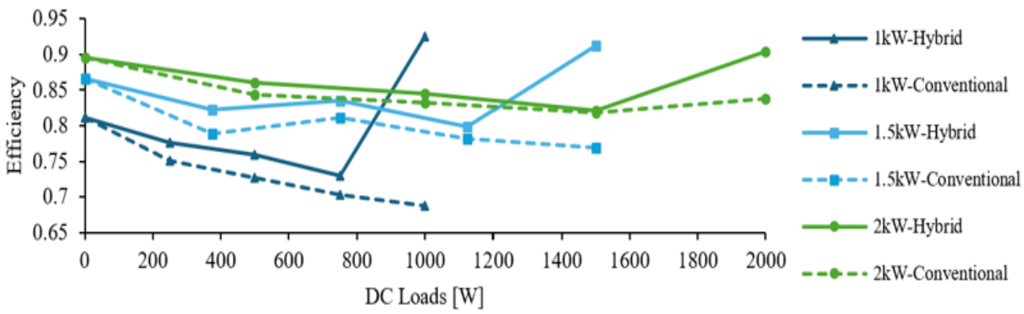


Figure 11. Efficiency of the 230 V hybrid house vs. 230 V conventional house for total DC loads of 1 kW, 1.5 kW, and 2 kW

The impact of bus voltage was also investigated. Figure 12 compares hybrid houses operating with 48 V and 60 V DC buses. The 48 V system exhibited modest gains of 1–4% over the conventional AC house at low DC loads but lost efficiency beyond ~1.6 kW. In contrast, the 60 V system sustained 5–7% efficiency improvements up to 2–2.5 kW, confirming that higher DC bus voltages reduce copper losses and extend the range of hybrid superiority.

These results are consistent with previous studies showing that hybrid DC-AC residential architectures can reduce unnecessary conversion stages by supplying DC loads through a dedicated DC bus while retaining the existing AC network for conventional high-power appliances [8]. The observed efficiency improvement at low-to-moderate DC load levels also agrees with residential PV integration studies, which indicate that DC-side integration of PV, battery storage, and DC-native loads can improve building energy efficiency by reducing repeated DC-AC-DC conversion processes [4]. However, the reduction in efficiency at higher DC load levels shows that the benefit of hybrid AC/DC distribution is not unlimited; conductor loss, bus voltage selection, and load distribution must be considered carefully in practical house design.

This conclusion is reinforced by the line loss analysis in Figure 13. DC losses increase quadratically with load for both 48 V and 60 V buses, but the 60 V bus significantly reduces I²R losses compared to 48 V. AC line losses remained relatively negligible across the same range, further emphasizing the importance of optimizing DC bus voltage in hybrid house designs. These results indicate that hybrid AC/DC homes are most suitable for low-to-moderate DC loads, such as LED lighting, electronics, communication devices, and other DC-compatible appliances. At higher DC demand, increasing the DC bus voltage or redesigning the DC feeder layout may be needed to reduce copper losses. Practical implementation should also include energy management to coordinate PV, battery, grid, and AC/DC load allocation, as emphasized in [6].

Although the 60 V DC bus reduces current and copper losses compared with the 48 V bus, its practical use requires careful safety and protection design. Higher DC voltage may require DC-rated breakers, appropriate conductor insulation, fault isolation, arc-fault mitigation, polarity protection, and compliance with applicable LVDC residential safety requirements. Therefore, the 60 V result should be interpreted as an efficiency-oriented design option rather than a direct implementation recommendation without protection assessment.

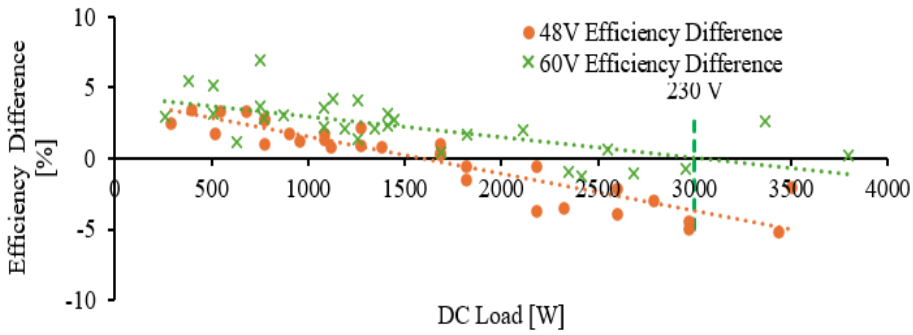


Figure 12. Efficiency difference between the 48 V hybrid (orange) and 60 V hybrid (green) vs. conventional house for Medium-Power 230 Vrms

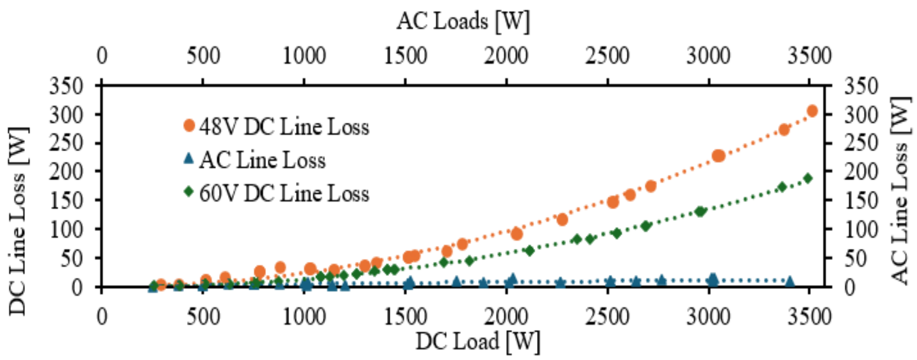


Figure 13. 48 VDC and 60 VDC vs. AC, line losses with increasing load from the medium-power MISO converter. DC losses are shown in orange while AC losses are shown in blue

4.5. DC bus voltage drops

The stability of the DC bus was also examined for the medium-power house model (6 kW peak load) using the MISO converter. Figure 14 illustrates the outlet voltage as the DC load increases in increments of 600 W, distributed evenly across four outlets. The results show a clear downward trend: as DC load increases, the bus voltage drops proportionally. At typical residential demand levels below 1–2 kW, the bus voltage remains stable between 47 V and 47.5 V, which is within acceptable limits for most consumer devices. Since modern electronic equipment generally incorporates internal voltage regulation, this modest variation suggests that additional measures such as smart outlets may not be necessary.

At higher load levels approaching the MISO converter's maximum capacity, the voltage drop becomes more pronounced, reaching ~42 V. While such conditions are unlikely in typical households, they highlight the importance of considering bus voltage stability in higher-power applications or when multiple DC circuits are aggregated. For real house applications, the DC bus should be prioritized for distributed low-to-moderate DC loads such as LED lighting, electronics, communication devices, and other DC-compatible appliances. High-power motor-based appliances should remain on the AC bus unless suitable DC appliances and protection devices are available. Practical implementation should also consider voltage regulation, DC bus ripple, and power quality assessment, as recommended in AC/DC microgrid building measurement studies [24].

Although this study focuses primarily on steady-state efficiency, power quality and safety remain important considerations for hybrid AC/DC residential systems. Previous work on AC and DC microgrid buildings emphasizes that efficiency evaluation should be complemented by voltage quality and power quality indicators to enable fair comparison between AC and DC building networks [24]. In this study, the inverter output was designed to maintain THD within the IEC 61727 limit, and DC bus voltage behavior was evaluated through voltage-drop analysis. However, increasing the DC bus from 48 V to 60 V, although beneficial for reducing current and copper losses, requires careful consideration of DC-rated protection devices, fault isolation, arc-fault mitigation, polarity protection, conductor insulation, and compliance with applicable LVDC residential safety requirements. Therefore, future work should extend the analysis to voltage regulation under varying load profiles, DC bus ripple, nonlinear loads, transient operating conditions, and protection coordination so that efficiency benefits can be evaluated together with power quality, stability, and safety.

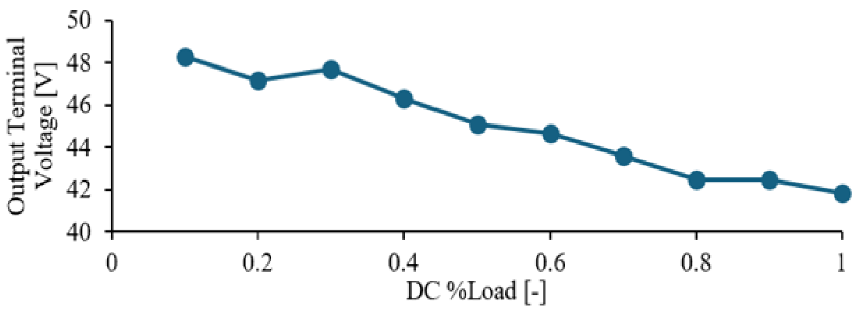


Figure 14. Voltage at the DC outlet with increasing DC load with maximum DC load of 6,000 W

4.6. Cost analysis

To complement the efficiency evaluation, a cost analysis was performed to assess the financial viability of hybrid AC/DC houses. Economic feasibility is an important consideration for hybrid AC/DC residential systems because the architecture requires additional power electronics, DC distribution components, and storage-related interfaces. The study in [25] shows that AC/DC microgrid cost is strongly influenced by storage topology, power electronics configuration, and installation-related factors. Therefore, this section evaluates whether the efficiency improvement of the proposed hybrid AC/DC house can provide a practical financial benefit relative to the additional system cost.

The analysis included the cost of the MISO converter, AC/DC converter, main and DC circuit breakers, and boost converters. Labor costs were excluded due to variability across regions. All hardware costs were calculated in USD. Table 6 summarizes the estimated hardware costs for low-, medium-, and high-power hybrid upgrades.

To evaluate payback periods, the 120 V medium-power house was used, representing typical small family consumption (~29.6 kWh/day). With an average California electricity price of $0.4465/kWh in 2024, a 48 V hybrid house delivering 2% efficiency gains saves ~0.592 kWh/day (~$0.26/day). The $784 hardware investment results in a payback of ~8.3 years. In contrast, the 60 V hybrid model, with ~4% efficiency improvement, saves ~1.184 kWh/day (~$0.53/day), yielding a significantly shorter payback of ~4.1 years. These results indicate that, under the assumed hardware-cost and electricity-saving conditions, the hybrid upgrades may provide an attractive initial payback estimate, especially when higher DC bus voltages are adopted.

It should be noted that this economic evaluation represents a preliminary hardware-cost and electricity-saving payback analysis rather than a complete lifecycle cost assessment. Battery degradation, converter lifetime, maintenance, replacement cost, installation cost, discount rate, and electricity price variation were not included. Therefore, the payback results should be interpreted as an initial feasibility estimate. A future lifecycle economic analysis should incorporate these factors to evaluate the long-term financial performance of hybrid AC/DC residential systems more comprehensively.

Table 6. Hardware cost of hybrid houses

Power type	Main DC breaker cost [$]	Number of DC Breakers [-]	Cost / DC breaker [$]	AC/DC cost [$]	AC/DC power output [W]	Boost cost (x2 boost converters) [$]	Total hardware cost [$]
Hybrid low-power	$13	1	$13	$52	500	$30	$138
Hybrid medium-power	$12	4	$13	$500	2,000	$110	$784
Hybrid high-power	$15	10	$13	$1,025	3,000	$500	$2,170

5. CONCLUSION

This study developed and analyzed hybrid AC/DC and conventional AC house models using MATLAB/Simulink to evaluate steady-state efficiency under different residential power levels, AC/DC load ratios, and grid standards. Twelve models were considered, representing 1 kW, 6 kW, and 12 kW residential load levels under 120 V/60 Hz and 230 V/50 Hz systems. Each model incorporated PV generation, battery storage, inverter, MISO converter, AC/DC converter, and line-resistance effects to enable a consistent comparison between conventional AC and hybrid AC/DC distribution.

The simulation results show that hybrid AC/DC houses provide higher efficiency than conventional AC houses when DC load demand remains below approximately 1.5–2.0 kW. At low-power levels, the hybrid configuration achieved up to 11% higher efficiency, while medium- and high-power models showed efficiency gains of up to 4%. The main efficiency benefit comes from reducing unnecessary DC-AC-DC conversion stages. However, at higher DC load levels, resistive losses in the 48 V DC bus reduce the efficiency advantage. Increasing the DC bus voltage to 60 V reduced copper losses and improved efficiency by approximately 6–7%, although this option requires higher-rated components and careful safety and protection consideration.

The preliminary cost analysis indicates that hybrid upgrades may be economically attractive under the assumed hardware-cost and electricity-saving conditions. Estimated hardware costs were approximately $140 for 1 kW homes, $784 for 6 kW homes, and $2,200 for 12 kW homes. Under these assumptions, breakeven points were estimated at about 8 years for 48 V configurations and as early as 4 years for 60 V configurations. However, these values should be interpreted as initial feasibility estimates because lifecycle factors such as battery degradation, converter lifetime, maintenance, replacement cost, installation cost, discount rate, and electricity price variation were not included.

Overall, the findings indicate that hybrid AC/DC distribution is most suitable for residential applications with low-to-moderate DC demand, such as LED lighting, electronics, communication devices, and other DC-compatible appliances. High-power appliances are better retained on the AC bus unless suitable DC appliances, protection devices, and standards are available. Therefore, hybrid AC/DC architecture offers a practical pathway for improving residential energy efficiency while maintaining compatibility with existing AC infrastructure.

The main limitation of this study is that the analysis is simulation-based and focused on steady-state efficiency, using simplified load models and fixed converter efficiency assumptions. Therefore, future work should proceed toward pilot implementation using a real hybrid AC/DC residential testbed. This validation should include nonlinear and constant-power loads, measured converter efficiency curves, PV intermittency, battery switching, THD, voltage regulation, DC bus ripple, protection coordination, and lifecycle cost assessment. These steps will support practical design rules for applying hybrid AC/DC distribution in future NZEH applications.

FUNDING INFORMATION

This project was supported by the Electric Power Institute at Cal Poly State University, under the Annual Sponsored Student Project Fund.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Taufik	✓	✓		✓					✓			✓		
Heru Nurwarsito						✓				✓				
Tyler Bury		✓	✓		✓				✓					
Rahman Azis Prasojo				✓	✓					✓			✓	

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper.

REFERENCES

[1] U.S. Energy Information Administration, "EIA projections indicate global energy consumption increases through 2050, outpacing efficiency gains and driving continued emissions growth," *U.S. Energy Information Administration*, 2023. https://www.eia.gov/pressroom/releases/press542.php

[2] U.S. Energy Information Administration, "U.S. primary energy consumption by energy source," 2024. https://www.eia.gov/Energyexplained/Us-Energy-Facts/

[3] U. S. Energy Information Administration, "Energy-related carbon dioxide emissions." https://www.eia.gov/outlooks/steo/report/total.php

[4] O. Abdel-Rahim, A. Chub, D. Vinnikov, and A. Blinov, "DC integration of residential photovoltaic systems: a survey," *IEEE Access*, vol. 10, pp. 66974–66991, 2022, doi: 10.1109/ACCESS.2022.3185788.

[5] B. T. Patterson, "DC, come home: DC microgrids and the birth of the 'enernet,'" *IEEE Power and Energy Magazine*, vol. 10, no. 6, pp. 60–69, Nov. 2012, doi: 10.1109/MPE.2012.2212610.

[6] S. Ali, Z. Zheng, M. Aillerie, J.-P. Sawicki, M.-C. Péra, and D. Hissel, "A review of DC microgrid energy management systems dedicated to residential applications," *Energies*, vol. 14, no. 14, p. 4308, Jul. 2021, doi: 10.3390/en14144308.

[7] T. Taufik, "Research experience on the DC house project for rural electrification," in *2017 International Conference on Computational Science and Computational Intelligence (CSCI)*, Dec. 2017, pp. 267–270, doi: 10.1109/CSCI.2017.44.

[8] K. Suriyan *et al.*, "A novel reconfigurable hybrid DC-AC home technique with renewable energy resources and converters," *International Journal of Sustainable Engineering*, vol. 16, no. 1, pp. 285–301, Dec. 2023, doi: 10.1080/19397038.2023.2205872.

[9] V. Monteiro *et al.*, "The role of front-end AC/DC converters in hybrid AC/DC smart homes: analysis and experimental validation," *Electronics*, vol. 10, no. 21, p. 2601, Oct. 2021, doi: 10.3390/electronics10212601.

[10] Z. Ma, Y. Li, Y. Sun, and K. Sun, "Low voltage direct current supply and utilization system: definition, key technologies and development," *CSEE Journal of Power and Energy Systems*, vol. 9, no. 1, pp. 331–350, 2023, doi: 10.17775/CSEEJPES.2022.02130.

[11] P. Torcellini, S. Pless, M. Deru, and D. Crawley, "Zero energy buildings: a critical look at the definition," *ACEEE Summer Study Pacific Grove*, p. 15, 2006, [Online]. Available: http://www.nrel.gov/docs/fy06osti/39833.pdf

[12] US Department of Energy, "Aim for zero - zero energy and zero energy ready homes.," *U.S. Department of Energy (DOE)*, 2025, [Online]. Available: https://www.energy.gov/energysaver/aim-zero-zero-energy-and-zero-energy-ready-homes

[13] Phius, "Acton passive house zeroenergy design," 2020. https://www.phius.org/certified-project-database/acton-passive-house

[14] T. Sutikno, W. S. Aji, M. Facta, H. S. Purnama, and T. Wahono, "Portable solar photovoltaic systems for post-disaster emergency power supply: a comprehensive review," *International Journal of Applied Power Engineering (IJAPE)*, vol. 14, no. 4, p. 1071, Dec. 2025, doi: 10.11591/ijape.v14.i4.pp1071-1084.

[15] B. Glasgo, I. L. Azevedo, and C. Hendrickson, "Expert assessments on the future of direct current in buildings," *Environmental Research Letters*, vol. 13, no. 7, p. 074004, Jul. 2018, doi: 10.1088/1748-9326/aaca42

[16] P. D. Granieri, "Smart DC Wall Outlet Design with Improved Load Voltage Detection," California Polytechnic State University, San Luis Obispo, California, 2019. doi: 10.15368/theses.2019.45.

[17] R. Wang *et al.*, "Technology standards for direct current microgrids in buildings: A review," Renewable and Sustainable Energy Reviews, vol. 211, p. 115278, Apr. 2025, doi: 10.1016/j.rser.2024.115278.

[18] J. Soldado-Guamán, V. Herrera-Perez, M. Pacheco-Cunduri, A. Paredes-Camacho, M. Delgado-Prieto, and J. Hernandez-Ambato, "Multiple Input-Single Output DC-DC Converters Assessment for Low Power Renewable Sources Integration," Energies (Basel)., vol. 16, no. 4, p. 1652, Feb. 2023, doi: 10.3390/en16041652.

[19] C. Ardalan, V. Vahidinasab, A. Safdarian, M. Shafie-khah, and J. P. S. Catalão, "Pave the way for sustainable smart homes: A reliable hybrid AC/DC electricity infrastructure," *Electric Power Systems Research*, vol. 210, p. 108128, Sep. 2022, doi: 10.1016/j.epsr.2022.108128.

[20] H. Yu, S. Niu, Y. Zhang, and L. Jian, "An integrated and reconfigurable hybrid AC/DC microgrid architecture with autonomous power flow control for nearly/net zero energy buildings," *Applied Energy*, vol. 263, 2020, doi: 10.1016/j.apenergy.2020.114610.

[21] D. Feldman, V. Ramasamy, R. Fu, A. Ramdas, J. Desai, and R. Margolis, U.S. *Solar Photovoltaic System and Energy Storage Cost Benchmarks: Q1 2021*, NREL/TP-6A20-80694, National Renewable Energy Laboratory, Golden, CO, USA, Nov. 2021.

[22] D. Kumar, F. Zare, and A. Ghosh, "DC Microgrid technology: system architectures, AC grid interfaces, grounding schemes, power quality, communication networks, applications, and standardizations aspects," *IEEE Access*, vol. 5, pp. 12230–12256, 2017, doi: 10.1109/ACCESS.2017.2705914.

[23] Statistia, “Size of new single-family homes in the U.S. 1975-2023,” 2024.
[24] D. L. Gerber, O. A. Ghatpande, M. Nazir, W. G. B. Heredia, W. Feng, and R. E. Brown, “Energy and power quality measurement for electrical distribution in AC and DC microgrid buildings,” *Applied Energy*, vol. 308, p. 118308, Feb. 2022, doi: 10.1016/j.apenergy.2021.118308.
[25] D. L. Gerber, B. Nordman, R. Brown, and J. Poon, “Cost analysis of distributed storage in AC and DC microgrids,” *Applied Energy*, vol. 344, p. 121218, Aug. 2023, doi: 10.1016/j.apenergy.2023.121218.

BIOGRAPHIES OF AUTHORS

Taufik is a tenured full professor in the Electrical Engineering Department at California Polytechnic State University, San Luis Obispo, where he has taught since 1999. He is also an Adjunct Professor in Faculty of Computer Sciences, Universitas Brawijaya, Malang, Indonesia. He earned his B.S. in Electrical Engineering with a minor in Computer Science from Northern Arizona University, M.S. in Electrical Engineering from the University of Illinois Chicago, and Doctor of Engineering from Cleveland State University. Professor Taufik is a Senior Member of IEEE and brings extensive industry experience from companies including Capstone Microturbine, Rockwell Automation, Picker International, San Diego Gas & Electric, APD Semiconductor, Diodes Inc., Enerpro, Renewable Power Conversion, and Sempra Energy. His research interests span power electronics, power systems, rural electrification, energy harvesting, renewable energy, and smart grid technologies. He holds four U.S. patents, has authored two books, and published over 250 technical papers, journal articles, and reports. He has delivered more than 200 keynote speeches and technical presentations, and serves on the editorial review boards of several engineering journals. He has received numerous teaching awards, most notably the 2012 Outstanding Teaching Award from the American Society for Engineering Education - Pacific Southwest Section. He can be contacted at email: taufik@calpoly.edu.

Heru Nurwarsito is a faculty member in the Department of Informatics Engineering, Faculty of Computer Science, Universitas Brawijaya, Indonesia. He holds a doctoral degree in Agricultural Sciences and has an academic background in electrical engineering and informatics. His research interests include artificial intelligence, IoT, smart agriculture, embedded systems, computer networks and security, instrumentation and control, and software engineering. He can be contacted at email: heru@ub.ac.id.

Tyler Bury received the B.S. and M.S. degrees in Electrical and Electronics Engineering from California Polytechnic State University. He is currently a Field Application Engineer at Monolithic Power Systems, Inc. His interests include power electronics, circuit testing and qualification, embedded systems, and electrical system security. He can be contacted at email: tbury@calpoly.edu.

Rahman Azis Prasojo received his doctoral degree in Electrical Engineering and Informatics from Institut Teknologi Bandung, Indonesia, in 2022. He is currently an associate professor in the Department of Electrical Engineering at Politeknik Negeri Malang, Indonesia. He was a 2025 Fulbright Visiting Scholar, conducting postdoctoral research at Electric Power Institute, California Polytechnic State University (Cal Poly), San Luis Obispo, CA, United States. His research interests include power transformer condition monitoring and diagnostics, health index–based asset management, insulating materials (mineral and ester oils), life cycle cost analysis, photovoltaic system performance assessment, and data-driven techniques for electrical asset evaluation. He has received Best Paper Awards at international conferences and has been actively involved in collaborative research and consultancy projects with electric utilities and research institutions. He has authored numerous publications in international journals and conferences and holds several Indonesian patents. He can be contacted at email: rahmanazisp@polinema.ac.id.