

**Solar Synergy: Unifying PV Energy and Smart Home Solutions**

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## **Abstract**

Optimizing energy efficiency through the synergy of solar photovoltaic (PV) and smart home technologies involves integrating essential smart home devices with a solar PV system that encompasses both a battery bank and a connection to the grid. This approach aims to reduce energy expenses by efficiently managing energy resources in two primary operational modes: normal power operation and power disruption mode. During normal power operations, when solar PV energy and grid electricity are available, smart home devices such as thermostats, lights, and smart plugs work in tandem to optimize energy usage. Their goal is to ensure that a sufficient portion of PV-generated electricity is directed to the batteries for charging. By doing so during nighttime, overcast days and high-demand periods, the system can minimize reliance on grid electricity, resulting in cost savings on the energy bill. During power disruptions or outages, the solar PV system and battery backup solutions step in to provide uninterrupted electricity to critical smart home components to ensure the continued safety and protection of the household. Simultaneously, smart home devices like smart thermostats, smart lights, and smart plugs play a crucial role in minimizing energy consumption. Their efforts aim to extend the battery charge and improve its overall lifespan, reducing expenses associated with the installation of more costly battery banks. In essence, the synergy between smart home technology and solar PV systems offers not only energy cost savings during normal operations but also enhanced resilience and cost-effectiveness during power disruptions.

**Keywords:** solar PV, solar storage, hybrid solar PV, smart home, smart thermostat, energy efficiency, energy cost savings, energy bill reduction

## **Solar Synergy: Unifying PV Energy and Smart Home Solutions**

The integration of solar PV and smart home solutions marks a significant step toward energy-efficient living by revolutionizing how we generate and consume energy. Solar PV systems have emerged as a prominent solution, harnessing the power of the sun to generate electricity. Recent advancements in solar PV technology such as high-efficiency solar cells and panels, high-efficiency inverters, solar backup batteries, and software have significantly improved energy efficiency. According to EcoFlow estimates, a 7.15-kWh solar array will fully cover the electricity bill for a household with below 965 kWh average usage or save approximately \$125 a month (EcoFlow, 2023).

With consistent technological improvements, hybrid solar PV systems with backup storage have emerged as a promising solution. These systems, which are grid-connected with battery storage, serve multiple purposes: providing backup power during grid outages, optimizing electricity costs through energy shifting, and increasing the self-consumption of solar energy (Solar Technologies, 2022). However, challenges such as high battery costs and limited lifespan need to be addressed to make these systems more accessible to homeowners, a goal that can be potentially achieved through effective management of energy consumption.

The concept of smart homes has gained momentum in recent years, offering homeowners greater control, convenience, and efficiency in energy management. Installing smart thermostats alone can yield significant savings, with approximately 12% saved on heating and 15% saved on cooling, translating to about \$140 annually (Smart Energy, 2023). Efficient home energy management complements hybrid solar PV by enabling the installation of smaller backup batteries, prolonging their lifespan and thus decreasing overall costs.

Furthermore, integrating smart home systems with hybrid solar PV addresses vulnerabilities in smart home functionality, particularly during outages. With an uninterrupted power supply from hybrid solar PV batteries, smart homes become robust energy efficiency, security, and hazard prevention solutions, operating continuously.

In our study, we highlight the benefits of integrating solar PV systems and smart home technologies with a comprehensive overview of their combined benefits and operational modes. Benefits include reduced energy consumption and environmental impact, reduced energy bills, prolonged solar battery lifetime, decreased cost of the solar PV installation, shortened payback time, and uninterrupted smart home functionality for house security, safety, and energy efficiency.

### **Constructing a Case Study: Exploring the Integration of Solar PV and Smart Home Systems**

To demonstrate the benefits of integrated solar PV and smart home systems we utilized a cutting-edge hybrid solar PV system alongside essential smart home devices in a typical property located in Charlotte, NC.

### *The Hybrid Solar PV System*

Our cutting-edge solar PV system harnesses the latest in solar storage technology, consolidating charge controllers, batteries, and inverters into a single, innovative solution. These systems are ideal for off-grid and hybrid solar PV setups and can be seamlessly integrated with smart home solutions. For our demonstration, we selected The SunPower Equinox Home Solar System paired with the SunPower SunVault™ Storage backup battery (SunPower, 2024b). Renowned for its efficiency (22.6%) and integrated design (Fig.1), this system minimizes roof space requirements and is available nationwide (SolarReviews, 2024).

### *Essentials of the Smart Home Systems*

Our smart home devices address four key aspects of homeowner life (Fig. 2): enhancing energy efficiency and cost savings, bolstering security against intrusions, safeguarding against hazards like fires and floods, and enhancing overall comfort and convenience (Adapses, 2024). These devices can be seamlessly integrated with solar PV systems, optimizing solar energy use, enhancing battery management, and prolonging the lifespan of the PV systems.

### *The Property*

Our featured property is an average-sized home in Charlotte, NC managed by Duke Energy utility company with an average electricity cost of 13 cents per kWh and a fixed-rate plan. The property is a typical two-story, 2,000-square-foot house with a southern-faced roof area of about 700 square feet oriented at an azimuth of 230 degrees with a typical pitch of 18.5 degrees. With an average monthly energy consumption of 1,200 kWh, totaling 14,400 kWh annually, this property is positioned at a latitude of 35 degrees. It receives an average of 5.04 Peak Sun Hours (PSH) per day (NREL, 2024).

## **Building an Integrated Solar PV and Smart Home System**

### *Sizing a Solar PV System*

Solar PV system sizing involves employing a standardized formula to determine its appropriate size (Adapses, 2024). This formula calculates the Solar PV System Size in kWh by dividing the Daily Energy Consumption by the product of the % Roof Performance and Peak Sun Hours (PSH). The % Roof Performance is derived from the formula:

#### *%Roof Performance*

$$= 100\% - (Your\ Altitude - Roof's\ Tilt) \div 3 + (Your\ Azimuth - 180) \div 6$$

Considering factors such as property size, roof efficiency, and location, the estimated ideal size for this property's solar PV system is 8 kW. Employing SunPower Maxeon 3 series 400 W SPR-MAX3-400 solar panels, the system requires 20 solar panels and 2

SunVault (13 kWh) battery banks, each with a maximum usable energy of 12 kWh, to support 8 hours of backup operation (SunPower, 2024a).

This configuration, featuring two batteries, efficiently reduces electricity costs during winter nights when heating is active and summer days when cooling systems are in use. However, it's essential to acknowledge that the actual performance of our 8 kW solar PV systems may be reduced by approximately 14% due to derating factors, solar panel operating temperature, inverter efficiency, and others (NREL, 2024).

According to the NREL calculator, the actual yearly AC output of our 8 kW solar PV system will be about 10,974 kWh, resulting in a 76% reduction in energy usage from the grid and an economic benefit of \$1,427 per year. Nonetheless, this significant reduction entails a substantial upfront cost due to SunPower's high-efficiency equipment, which, even after a 30% federal rebate, averages \$21,000 including installation, with a payback time of approximately 15 years (\$21,000/\$1,427) (MarketWatch Guides, 2024).

While we deliberately selected this high-end, expensive solution to showcase the potential impact of a smart home system on energy efficiency and savings, it's worth noting that more affordable solar PV systems are available on the market, with payback times ranging between six and 11 years.

### *Selecting Energy-Efficient Smart Home Devices*

Choosing the correct energy-efficient smart home devices can significantly enhance household energy management. These devices, namely smart thermostats, smart lights, and smart plugs, form the cornerstone of energy-saving in smart home systems.

In our project, we opted for the Google Smart Learning Thermostat, renowned for its ability to save an average of 2000 kWh annually (EnergyEarth, 2024). By intelligently adjusting heating and cooling settings based on seasonal demands and occupancy patterns, this thermostat ensures efficient energy use. Moreover, its AI-driven functionality adapts to homeowners' habits, further minimizing energy consumption.

Our selection for smart plugs was the TOPGREENER Smart Mini Wi-Fi Plug with Energy Monitoring. This plug not only powers down connected appliances when not in use or when the house is vacant but also provides real-time energy consumption data. This enables homeowners to remotely manage power usage, potentially saving up to 1000 kWh annually (Oakter, 2024).

For the home's lighting system, we selected Philips Hue Smart Bulbs, which are recognized for their reliability and energy-efficient LED technology. With up to 80% energy savings compared to traditional lighting, smart lights significantly reduce electricity consumption. On average, households can save around 1500 kWh per year by transitioning to LED lighting, which typically accounts for 15% of total electricity usage (Energy.gov, 2024).

Collectively implementing these three smart home devices can save approximately 4500 kWh of energy annually, resulting in savings of \$585 per year. While these

devices slightly consume energy and initial investment ranges from \$300 to \$500, depending on available utility rebate programs, the long-term benefits far outweigh the upfront costs.

It is worth noting that it is essential to ensure investing in reliable devices and software to avoid common problems and pitfalls associated with smart home automation specifically when a vendor goes out of business and discontinues support. Essential tips and strategies for creating a reliable smart home are described in detail on the website Adapses.com (Adapses.com, 2024).

### **Maximizing Energy Efficiency: Integrating Solar PV and Smart Home Systems**

Table 1 presents a breakdown of monthly energy usage derived from a typical Duke Energy utility bill for this house type, alongside monthly average sunlight hours (PSH) for the region, the calculated AC output generated by a Solar PV system of 8-kW capacity, and the simulated Smart Home energy savings (NREL, 2024).

For the smart home system simulation, we employed conservative estimates for smart plugs (500 kWh/year) and smart lights (1000 kWh/year) providing 3% and 7% monthly energy savings, respectively. For the smart thermostat, energy savings amount to 20% during the months it is in use, or 14% (2000 kWh) annually. According to this data, the Solar PV system produces 10,974 kWh, resulting in 76% annual savings.

However, during winter, the energy savings are only 39% due to reduced solar exposure on panels, with an average PSH of approximately 3.63. Moreover, winter places increased strain on the battery backup system due to reduced daylight hours and frequent power outages, while household energy usage rises for heating and lighting purposes. As a result, smart thermostats and smart lights become pivotal in enhancing energy efficiency during the winter months, working in tandem with solar power to bolster savings.

In contrast, summer experiences peak solar PV output, while cooling becomes the primary energy draw. Here, the smart thermostat regulates consumption, ensuring ample energy reserves for battery backup during high-demand periods, cloudy days, and outages.

Figure 3 demonstrates the combined benefits of solar PV and smart home systems based on the data presented in Table 1. Typical monthly energy consumption from the Duke Energy bill is represented in grey, while calculated output from Solar PV and simulated savings from smart home devices are highlighted in orange and blue, respectively. During winter, smart home devices nearly double the savings from the solar PV system, adding another 29%, primarily from the smart thermostat and smart lighting, covering 68% of energy demand. In other seasons, the integrated smart home and solar PV systems meet household energy needs entirely, with surplus electricity available for sale back to the grid, offering additional benefits.

The notable result from the incorporation of the smart home system is a total energy reduction of 14,740 kWh (3,500 kWh from smart home plus 10,974 kWh from solar PV)

equating to \$1,882 in annual savings and effectively trimming the payback period from 15 years down to 11 ( $\$21,000/\$1,882$ ). Our study underscores the pivotal role of reducing the years required for return on investment through smart home integration and accurately managing its functionality. Furthermore, coupling this with increasingly accessible solar PV solutions can yield even more remarkable outcomes.

The benefits from the integration of these two systems, however, extend beyond simply summing the benefits of each. Instead, it provides homeowners with a unified, mutually beneficial solution, elevating both energy efficiency and home safety to new levels.

### **Unifying PV Energy and Smart Home Solutions**

Integrating the essential smart home devices with the hybrid solar PV system that encompasses both a battery bank and a connection to the grid (Fig. 4) will synergize mutually beneficial effects in two primary operational modes: normal power operation and power disruption mode.

#### *Normal Power Operation*

During normal power operations, when solar PV energy and grid electricity are available, smart home devices such as thermostats, lights, and smart plugs collaborate to optimize energy consumption. Their objective is to prioritize directing a sufficient portion of PV-generated electricity toward battery charging. This strategy minimizes reliance on grid electricity during night hours, overcast days, and peak-demand periods, reducing energy costs. This optimization is particularly advantageous when operating under a time-of-use (TOU) billing schedule, effectively cutting expenses during high-demand periods.

#### *Power Disruption or Outages*

During power disruptions or outages, the solar PV system and battery backup solutions seamlessly supply uninterrupted electricity to critical smart home components, including security cameras, video doorbells, smart lights, smart thermostats, flood and fire protection devices, and essential appliances. This ensures ongoing safety and protection for the household.

In such situations, smart home devices such as smart thermostats, smart lights, and smart plugs play a vital role in minimizing energy consumption. Their combined efforts aim to prolong the battery charge and enhance its overall lifespan, thereby reducing expenses related to installing more expensive battery banks and maintenance costs.

Many solar batteries, like SunPower's SunVault Storage, come with a 10-year limited warranty, typically within the payback period. This implies that after paying off the solar PV system, homeowners might need to invest in replacing the battery storage. By intelligently monitoring energy usage from the backup battery system with smart home devices, one can extend their lifespan, minimizing additional expenses associated with the solar PV system.



Furthermore, because the Smart Home system reduces energy consumption by approximately 24% annually, it becomes feasible to downsize the backup storage from two to one SunVault battery, further reducing upfront costs and shortening the payback period.

In our demonstration of integrated solar PV systems, we used one of the more expensive solutions to showcase the impact of smart home technology on energy efficiency and cost reduction. However, there are more affordable solar PV systems and longer-lasting backup batteries available for integration with smart home setups, offering homeowners even greater benefits.

### **Conclusion**

By integrating smart home technology with a solar PV system, we enhance home energy efficiency concurrently with the PV system installation, reducing energy waste by 24%. Advantages of the integrated solar PV with backup storage solution and smart home system include reduced energy consumption and environmental impact; reduced energy bills; prolonged solar battery lifetime; decreased cost of the solar PV installation; shortened payback time; and uninterrupted smart home functionality for house security, safety, and energy efficiency. These benefits become increasingly significant amid ongoing utility rate inflation. Opting for integration of the smart home systems with solar PV offers a dependable solution to mitigate reliance on the grid and mitigate the impact of frequent outages, especially during stormy seasons.

### **Conflict of Interest**

The author has no conflicts of interest to disclose.



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**Table 1**

*Monthly household energy consumption and energy savings from solar PV and smart home systems. Solar irradiation and solar PV AC output are derived from the NREL PVWatts® Calculator (NREL, 2034).*

Month	Household Energy Consumption kWh	Solar Irradiation (PSH) kWh/m2/day	Solar PV AC Output kWh	Smart Home Energy Savings kWh
January	2,101	3.47	693	603
February	1,472	4.26	753	435
March	675	4.81	925	88
April	860	5.68	1,022	101
May	953	6.58	1,191	108
June	1,200	6.64	1,137	362
July	964	6.46	1,135	299
August	833	5.88	1,039	264
September	655	5.45	954	87
October	1,187	4.43	824	124
November	1,291	3.78	705	386
December	2,249	3.01	596	642
Annual	14,400	5.04	10,974	3500

### SunPower Solar PV with a Backup Battery Storage Solution

*Fig. 1. SunPower's complete solar PV solution has high-efficiency solar panels, backup battery storage, and inverters with the control system and software (SunPower, 2024).*



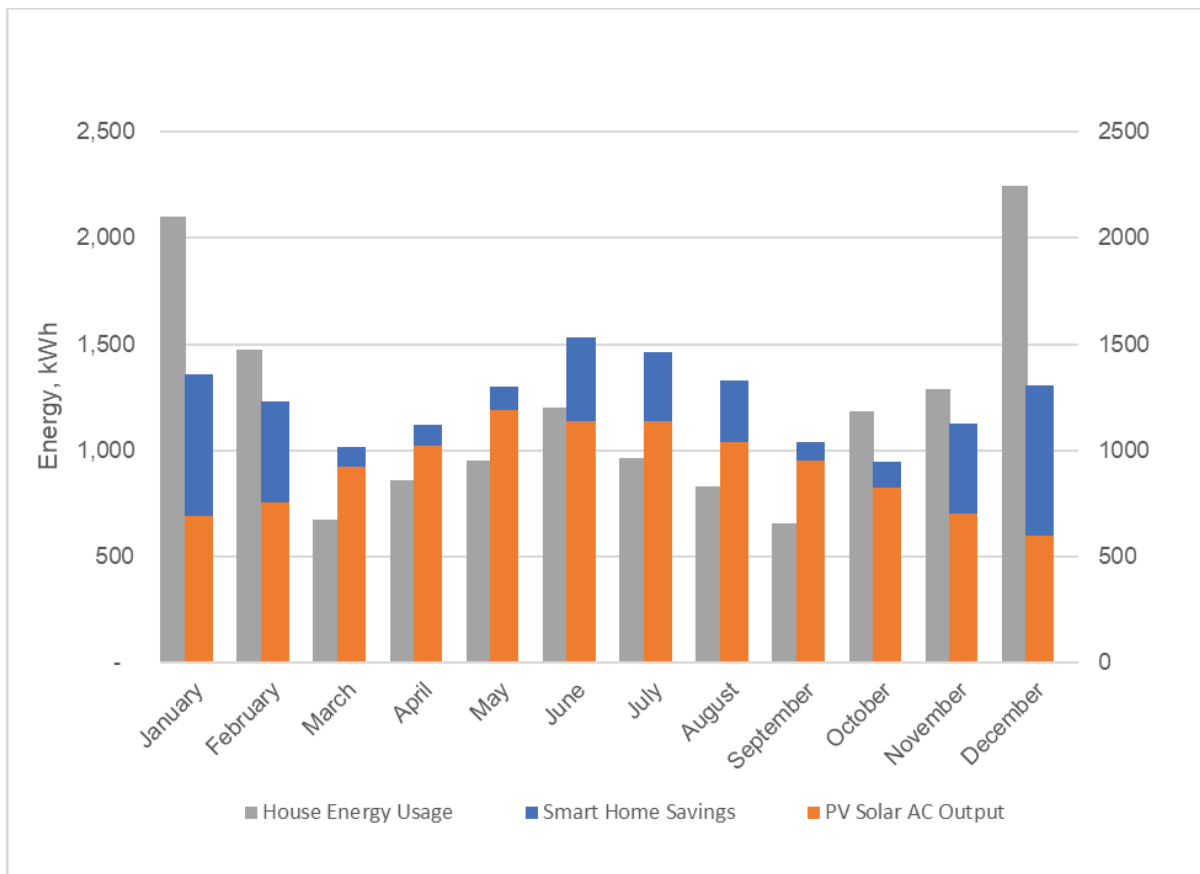
## Essential Smart Home Devices

Fig. 2. Essential smart home devices provide energy efficiency, security, and hazard prevention (Adapses, 2024).



### Integrated Smart Home and Solar PV Energy Savings

*Fig. 3. Monthly energy savings accrue from solar PV output and smart home savings vs. house energy consumption.*



### Integrated Solar PV and Smart Home Solution

Fig. 4. The synergy of integration of a smart home system with a hybrid solar PV solution.

