RESIDENTIAL SOLAR ENERGY STORAGE SYSTEM: STATE OF THE ART, RECENT APPLICATIONS, TRENDS, AND DEVELOPMENT □□□□□□□□□□□□□□□□□□□□□□□□□

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RESIDENTIAL SOLAR ENERGY STORAGE SYSTEM: STATE OF THE ART, RECENT APPLICATIONS, TRENDS, AND DEVELOPMENT

住宅太阳能储能系统：最新技术、近期应用、趋势和发展

Yaseen Al-Husban [a,*], Mohanad Al-Ghriybah [a], Ahmed Handam [b], Takialddin Al Smadi [c], Rabie'ah Al Awadi [d]
[a] Department of Renewable Energy Engineering, Faculty of Engineering, Isra University
P.O. 11622, Amman, Jordan, yaseen.alhusban@iu.edu.jo, mohanad.alghriybah@iu.edu.jo
[b] Faculty of Engineering, National Research University "Moscow Power Engineering Institute"
Moscow, 111250, Russia, Handamahmed@gmail.com
[c] Faculty of Engineering, Jerash University
P.O Box: 311, Post Code: 26150, Jerash, Jordan, dsmaditakialddin@gmail.com
[d]Ministry of Public Working and Housing
Amman, 11118, Jordan, Rabee.aloudi@mpwh.gov.jo

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Abstract

The use of energy storage devices is essential for the development and maintenance of zero-energy structures. They are necessary for optimal usage of renewable energy sources and for managing the intermittent nature of energy supply and demand. Many different types of storage systems (electrochemical, thermal, mechanical, etc.) are either commercially available or close to being developed for usage on a building scale. Different technologies have different capabilities and features, therefore it's important to find a system for evaluating your possibilities before diving into a techno-economic study. All aspects of current and emerging energy storage technologies, as well as their uses, future prospects, and historical contexts, are subjected to a rigorous evaluation. Energy storage techniques such as electrochemical and battery storage, thermal storage, thermochemical storage, flywheel storage, compressed air storage, pumped storage, magnetic storage, chemical and hydrogen storage, and redox flow storage are all covered. New studies on alternative energy storage methods, along with major advancements and discoveries in the field, are also discussed.

Keywords: Energy Storage Systems, Renewable Energy, Solar Energy, Residential Storage Systems, Trends, Development

摘要 储能设备的使用对于零能耗结构的开发和维护至关重要。它们对于可再生能源的最佳使用和

管理能源供需的间歇性是必要的。 许多不同类型的存储系统（电化学、热能、机械等）都可以在市场上买到或接近开发用于建筑规模。不同的技术具有不同的功能和特性，因此在深入进行技术经济研究之前找到一个系统来评估您的可能性非常重要。当前和新兴储能技术的所有方面，以及它们的用途、未来前景和历史背景，都经过严格的评估。涵盖电化学和电池存储、热存储、热化学存储、飞轮存储、压缩空气存储、抽水蓄能、磁存储、化学和氢存储以及氧化还原流动存储等储能技术。还讨论了关于替代储能方法的新研究，以及该领域的重大进展和发现。

关键词: 储能系统、可再生能源、太阳能、住宅储能系统、趋势、发展

I. INTRODUCTION

Energy security is one of the essential concerns that the world is always searching for new techniques and technologies to address considering the current climate and political climate. Researchers in the energy sector are primarily interested in two things: lowering overall energy use and locating new energy sources. Incentivizing the use of renewable energy sources as a replacement for traditional energy sources may cut emissions of hydrocarbons and other hazardous substances [5, 64].

In 2018, energy consumption rose by 2.13 percent, the quickest rate in the last decade [3]. To keep up with this increased demand, we must increase our energy production. The critical issue is what sorts of alternative energy sources and processes may be altered to fulfill this need. Fossil fuels, which have devastating effects on the environment, can no longer be considered a viable option for providing for the world's energy demands and must be phased out [6]. Considering nuclear energy's low carbon dioxide emissions, it could seem like a viable option, but the price tag is through the roof, and there are other concerns, including security, to consider. Since air pollution contributes to global warming, there is an immediate need to rely on renewable energy sources, energy recovery, and recycling technologies to lessen the environmental damage caused by these factors. Sustainable and widely applicable renewable energies, including wind, solar, geothermal, bioenergy, and hydropower, provide the greatest approach to meeting the world's growing energy needs. However, owing to their volatility and unpredictability, renewable energy sources like wind and sun often cannot function independently in a power plant [7]. Because of this, scientists have been looking for workarounds or synergistic combinations, and they've found that energy storage systems (ESSs) may help solve the problem when used in tandem with renewable energy [8].

Connected solar PV systems may either consume their generated electricity locally (for self-use) or export it back into the grid (export). In addition to self-use through storage and discharge of PV output from an energy storage system, instantaneous self-use is conceivable. Battery packs and load regulators make up energy storage systems, which store photovoltaic (PV) output by using the in-built storage capacities of various household appliances. Customers' capacity to self-use photovoltaic (PV) production has been hindered by a dearth of choices for affordable energy storage [9]. Additionally, PV export remuneration in most large countries decreases consumer incentives to invest in technology that would enhance their own use [9, 10]. Both of these paradigms are becoming less relevant because of a decrease in the cost of batteries [11, 12], the advancement of low-cost load control devices [13], and a decrease in the conventions providing for grid export [14]. These tendencies point to the increasing integration of storage and load control devices into future photovoltaic (PV) systems, which will increase the value of PV systems via increased levels of self-use.

The current study evaluates all applications and current developments concerning integrated home solar energy storage systems to illustrate the criteria that determine each system's performance. All of the systems' properties, as well as their benefits and drawbacks, will be explored. Depending on the storage systems and settings, a complete comparison will be offered. This will be supplemented by a presentation of current research on various energy storage methods and the evolution of each area.

II. CONCEPTUAL FRAMEWORK OF THE ENERGY STORAGE SYSTEM

Power plants often used their own local fuel, or fuel they had previously stored, as their primary source of energy storage throughout monopoly periods [15]. Coal-fired power plants were mandated by authorities to store enough fuel to last for up to 20 days in the event of a fuel supply outage, allowing them to keep generating energy even while the problem was being resolved. Overcapacity in both generation and the network was often enabled by the on-demand nature of electrical power delivery. A central authority controlled the schedules for electricity production and changed them based on the day of the week, the season, and the time of day. Fuel costs accounted for the bulk of operating expenses after the initial investment in system infrastructure like power plants and the grid had been recouped [1].

There has been much research on how energy storage may be used to stabilize renewable energy sources like solar and wind [16]. Table 1 is a review of the main technologies' costs and technical specifications. Pumped hydropower (PHS) [18], compressed air energy storage (CAES) [17], and flywheel energy storage (FES) are all examples of such technologies [18]. This is according to a study by a group of researchers led by Chen et al. [19]. Additionally, capacitors and superconducting magnetic energy storage are two other options for storing energy, although they are not accounted for here due to their infancy.

Table 1.
Summary of energy storage technologies [1]

Energy Storage Type	**Technology**	**Energy**	**Project cost ($/kWh)**	**Efficiency**	**Grid-Level Utility Generation**
Mechanical	Pumped hydro	to 100 GWh	106–200	70–85	Transmission
	Compressed air	to 10 GWh	94–229	40–75	Transmission
	Flywheel	10–100 kWh	4320–11520	70–95	Grid Distribution
Electrochemical	Li-Ion	to 100 MWh	393–581	85–98	Grid Distribution/Household
	Lead Acid	To 10 MWh	358–631	75–90	Grid Distribution/Household
	Flow cell	100 kWh and above	686–1307	60–85	Grid Distribution
Chemical	Hydrogen	10 kWh and above	n/a	25–45	Grid Distribution
	Methane	1 MWh and above	n/a	25–30	Grid
Thermal	District heating heat pump powered by concentrated solar energy	kWh-MWh	n/a	Technologically reliant	Grid Distribution

In 2018, PHS has the greatest installed capacity of any company in the world at 153 GW, making it the most established and mature storage technology [20]. A PHS installation may provide time-shifting, peak-lopping, valley-filling, and seasonal control of energy production and consumption, among other things. However, it is costly in terms of both time and money invested, restricted in terms of where it can be built, and subject to delays owing to the need for environmental licenses. Like PHS, CAES is a technology with a restricted geographic reach despite its ability to provide adaptable power quality services. The McIntosh facility in the USA, with a capacity of 290 MW, and the Huntorf plant in Germany, which was commissioned in 1978, which has a capacity of 110 MW, are the two largest CAES facilities in the world today. Compressed air is stored in salt caverns at both plants. Positive outcomes, such as arbitrage possibilities and reduced emissions, were found in an analysis of CAES's effect on the Irish market, which has a high proportion of renewable generating capacity [17].

However, CAES's reaction time is too slow to offer the necessary supplementary services at this moment. However, with the advent of second-generation CAES technology, subterranean caverns are no longer required; instead, compressed air may be stored in an above-ground structure and used by small and medium-sized gas generators [21]. Having such storage available might threaten the battery sector since it could be placed wherever the network needs it the most. It is recognized that intermittent renewable energy generation poses challenges, and that energy storage is a potential solution [22].

Flywheel technology progressed rapidly during the Industrial Revolution as a smoothing mechanism for steam engines [18]. When a system-connected flywheel was subjected to a system disturbance [23], the frequency nadir and the ROCOF dropped. Inertia for the system might be provided by flywheels, which are a type of energy storage. It has been shown that increasing the system load in a micro-grid with PV and wind output using two fly wheels linked together has no damaging impact on frequency. Several flywheels are in use for commercial energy storage in the United States and the United Kingdom [24]. However, the widespread construction has just recently begun. Sites of decommissioned power plants with excess grid capacity might host grid-scale flywheel installations. Such areas would have room to expand, industrialized zones, technical expertise, and an easily accessible electrical grid. FES can inertia, reserve, regulate frequency, and respond to frequency. It has been used to solve similar power problems in applications like manufacturing and data storage, where tight frequency and power limits apply.

Due to recent developments in materials, magnetic bearings, and power electronics, flywheel technology is now a viable choice for energy storage. The essential question is whether or not a flywheel is useful as a utility or distributed-generation power quality device. As the price of batteries has decreased, they have become an increasingly popular option for supplementing intermittent renewable energy sources like solar photovoltaics (PV) and wind power. The various battery technologies discussed in [25] range from the more conventional lead acid types used in the car and heavy-duty vehicle sectors to the more recent flow cell types that may find use in the energy storage sector. Regarding portable devices and energy storage, however, lithium-ion battery technology has emerged as the clear frontrunner. Lithium-ion batteries provide many benefits over other battery technologies, including a high energy density, low self-discharge, a lightweight design, adaptability, and low maintenance needs. However, temperature monitoring is required for lithium-ion installations, and cooling systems may be required in certain cases depending on the local climate.

The high initial investment required to implement extensive use of battery energy storage systems is the main barrier to their general adoption. Establishing the nameplate duration, which is the ratio of the BES energy and power, is the first step in establishing the pricing of BES [1]. If the nameplate duration of a BES is less than 0.5 h, it is regarded to be short in duration; if it is between 0.5 and 2 h, it is considered medium in duration; and if it is more than 2 h, it is considered long in duration. Generally, BES with shorter durations costs less each installed watt, whereas BES with longer durations costs less per kilowatt hour. Batteries of the right size are regularly recommended to customers to build solar PV systems for their homes. While considering the benefits of voltage support, frequency management, reserve, and emissions reduction, the price of this storage must be weighed against the price of expanding the network, running peaking plants, displacing renewable energy, and capacity contracts for marginal plants. Energy storage using lithium-ion batteries has a decreasing levelized cost of energy (LCOE) over time. An industry group has found that the LCOE for lithium ions has dropped to \$187/MWh, which is much lower than the LCOEs for solar (\$57/MWh) and wind (\$50/MWh) [26].

The demand for lithium-ion batteries is predicted to quadruple between 2015 and 2020 due to the increasing popularity of electric automobiles and portable battery devices [27]. As a result, there is now more demand for lithium raw materials. Lithium's primary source of raw material is either a pegmatite-type of solid granite or an underground Salt Lake in liquid form. Both techniques need considerable processing of the starting material to provide the necessary lithium metal. 50% of the world's lithium deposits are located in Chile, Bolivia, and Argentina. Demand has led to higher raw material costs, but this hasn't had a significant influence on battery costs, which are still declining. However, this pricing balance could shift if lithium-ion batteries take over as the primary energy storage options. In lithium-ion batteries, the cathode is often made of cobalt. Concerns have been expressed about the mining circumstances and its linkages to harmful health problems since the Democratic Republic of the Congo provides more than half of the cobalt that is mined worldwide [28]. The questions are, therefore, whether there are enough raw material sources to fulfill the growing demand, if extraction and treatment techniques have a low negative effect on the environment and human health, and whether used batteries can be recycled. Energy storage in the form of lithium-ion batteries is being championed as a means to a more environmentally friendly and just economy, but there are serious concerns that must be addressed first. China has taken the lead in lithium-ion battery industry, and its plans to combat climate change via increased renewable energy generation should keep it at the forefront for the foreseeable future.

Battery usage in portable devices and for energy storage is expanding, which is driving up global demand for batteries. According to data from [29], 1.4 GW of BES were implemented worldwide in 2017. According to this study, the global energy industry would expand to 8.6 GW by 2022. With 246 MW, Australia has the most electrical capacity in the world (mainly made up of a single battery of 100 MW). Due to its high concentration of home behind-the-meter installations, Australia is a great place to try out cutting-edge gadgets. The need for a national response to climate change has been heightened by recent bushfires and damage to the Great Barrier Reef in Australia, and parties working to halt climate change have fiercely opposed the planned opening up of additional coal deposits in Queensland. The United States has the greatest available power, with 431 MWh. Particularly in the United States, there has been consistent development, with the states of Massachusetts and New York setting legislative requirements for energy storage. However, regarding the number of BES installations that occur behind the meter, California is far and away the leader among all other US states. This is at least in part due to the rising popularity of solar panels for residential usage in the state and the need of storing energy throughout the day for use during the peak demand periods in the morning and evening.

When PV is combined with BES, it provides further operational benefits and cost savings. Operational benefits include optimizing time of use pricing, having access to frequency management, avoiding distribution and transmission-related failures, and delaying network growth [30]. Co-locating PV and ES equipment saves costs by up to 8% by sharing infrastructure costs including permits, wiring, and site layouts. [31] compare and contrast the outcomes of using a community battery in conjunction with PV with those of using a battery at the residential site (behind the metre). Community batteries are more beneficial from a systemic perspective since they allow for more power sharing between the grid and battery than do batteries at the residential level, which results in increased self-supply and better motivation and involvement by the consumer. Furthermore, BES is transportable, flexible, and straightforward to deploy compared to PHS and CAES. When combined with renewable energy sources, such as solar, the scalability and compactness of BES systems expand their application possibilities. Single-digit kW and utility-scale measurements are available for commercial BES (greater than 100 MW). Residential and commercial PV systems work effectively when paired with small-scale batteries. But there are obstacles to such deployments, such high costs, current network operator practises, and limited rates. The hydrogen and methane industries, which store chemicals, are in their infancy. Hydrogen produced from surplus energy has the advantages of a high power density, underground storage capacity, and emission-free combustion when burned with oxygen, but it also has the disadvantages of being costly to manufacture and having certain inherent safety risks. Although methane may be used with the existing gas infrastructure, it is rather expensive.

Electrical energy storage (EES) is a technique that stores electricity produced during low-demand, low-generation-cost hours or from intermittent sources of power for use during peak demand and high-generation-cost periods or during times when no other output is available [2, 32]. During off-peak hours, such as between 3 and 6 p.m. on a typical day, energy storage is charged from a baseload production plant (Figure 1). By balancing supply and demand, energy storage between 6 a.m. and 6 p.m. helps keep the voltage and frequency steady.

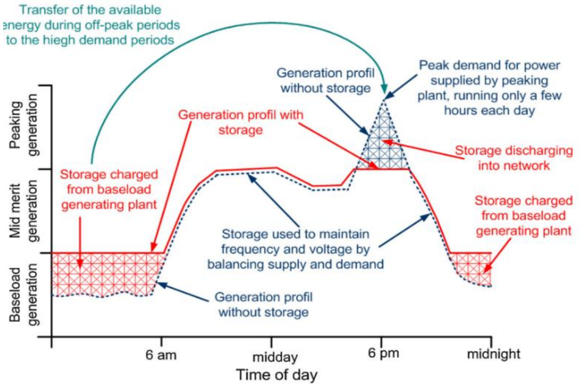

Figure 1. The basic concept of energy storage [2]

III. RESIDENTIAL SOLAR ENERGY STORAGE SYSTEM

To keep up with the world's rapidly increasing energy demand and guarantee energy sustainability, the next generation of power grid infrastructure and services will have to include energy storage and the integration of renewable energy. As a means of meeting demand and mitigating the unpredictability of renewable energy production, energy storage might be used by grid operators [33]. Local energy storage helps electricity users control their energy expenses more effectively by enabling them to react to demand-side management signals and consume less energy. Regarding demand-side management strategies for easing grid congestion, dynamic pricing is among the most effective. The efficiency of the system is contingent on the customer-facing energy management software's ability to regulate supply and demand for electricity in response to market fluctuations in electricity prices. Increased adaptability in energy management may be possible via the distribution of locally generated renewable power to residential and commercial consumers and through the optimization of renewable energy's role in lowering electricity bills.

In an attempt to use energy from customer-sited distributed renewable production and to further enhance stability and dependability with much more customer-sited renewable power accessible at the utility retailer, customers are allowed to sell energy back to the utility at a price set by the utility on a dynamic basis. This implies that the customer may make money off of the sale of both renewable electricity and stored energy, whether the latter was obtained from the grid or the former from renewable sources. Since the energy storage system can provide power back to the grid, it functions as a bidirectional energy exchange system. With the introduction of variable pricing for buying and selling energy, consumers will have greater control over their energy use and storage. In addition to recouping the cost of storing the item, the payback decreases the net cost to the customer. An intelligent energy management system that investigates these factors for effective management may provide substantial advantages if energy is stored and controlled in real time [34].

The development of a reliable energy management system is fraught with difficulties. Given the unpredictability and day-to-day variability of the renewable energy sources used in the energy storage system, it is challenging to provide reliable estimates of daily energy usage [35]. It is important to remember that there is a cost to battery operation that must be balanced against the benefit of energy storage for either power supply or energy resale. When planning for the future, energy management becomes more complicated when a bidirectional energy flow and a dynamic pricing mechanism are used [36]. Because of the grid, there is a greater variety of control options for the energy flowing between the storage batteries and the system, renewable production, and loads. It is more challenging to make command choices about when and how much energy should be sold, stored, or used because of the profit that may be earned by selling energy at an unexpected price. Additionally, it is difficult to optimize the control choices over time due to the limitations imposed by the battery capacity. To address these issues, we set out to develop a real-time energy management strategy that reduces overall system costs with little information on the system's behavior under different conditions [37].

Power grid operators and aggregators have looked at energy storage as a possible solution to the variability of renewable supply. Extensive research has been conducted on energy storage control, assessment of its role in renewable generation, power balancing with fixed or flexible load management, and phase balancing. There has been studies conducted on residential energy storage systems, both with and without the integration of renewable energy sources, to determine which of these two approaches could be more effective in lowering the cost of power. The only subject of discussion in these assessments was the acquisition of energy. The authors propose, instead, off-line storage control methods for dynamic systems, which consider both load prediction and day-ahead scheduling. Since historical data on load and renewable generation is readily available, and since the cost of using batteries is ignored [37].

Battery storage systems have emerged because of the need for electrical power and energy applications. It is becoming more common to install solar photovoltaic (PV) systems in homes with battery storage, which allows the homeowner to save any extra energy produced by the PV system during the day and use it later when the sun goes down. System owners will have a better chance at realizing the financial benefits of combining solar PV with storage systems if a sustainable and affordable battery market is fully developed. Both lead-acid and lithium-ion batteries are now the most common choices for use in solar photovoltaic (PV) systems that need the usage of rechargeable batteries. However, lead-acid batteries have lower starting and operating expenses (O&M) than lithium-ion batteries do, although lead-acid batteries have a larger negative impact on the environment. However, owing to their relatively low energy densities (30–50 Wh/kg) and limited cycle lives, lead-acid batteries are not the best option for energy management. Lead-acid batteries are extensively used as backup power (200–1000 cycles).

However, lithium-ion batteries have been steadily developed and used in solar PV applications, both for utility-scale solar farms and solar roofs, due to their better energy density (up to 300 Wh/kg) and life cycle (up to 10,000 cycles). Despite their many advantages, the higher cost of lithium-ion batteries might be attributed to their specialized packaging needs and built-in overcharge protection mechanisms. Due to factors including material, operating mode, management system, and geography, the size and cost of battery storage systems for residential-scale applications might vary greatly throughout the world. Values for capacity vary from 1.2 to 100 kWh, with prices per kWh sitting between 400 and 1100 USD. We looked at websites based in Jordan and the USA to get a feel for prices and dimensions. In Jordan, a lead-acid battery storage system has been integrated with off-grid solar photovoltaic installations for homes. Regulations and support for energy storage systems in Thailand are presently primarily oriented at R&D efforts as part of the country's Smart Grid Master Plan [38].

Battery and solar PV cell prices continue to drop. Because of variables like weather, location, and time, the availability of renewable energy sources like wind and solar may be erratic. If energy storage devices are deployed, they may help mitigate these swings and store energy for later use. As more nations invest heavily in increasing their usage of renewable energy, demand for battery management systems (BMS) is anticipated to increase. One estimate puts the worldwide BMS market at $12.23 billion by 2025; Grand View Research Inc. released that figure in their June 2019 report.

A home microgrid is a household that has its own electrical grid and maximizes the energy efficiency by combining photovoltaic (PV) systems, energy storage, and intelligent energy management. Therefore, increasing the percentage of photovoltaic energy in the electrical microgrid has 41 various benefits in terms of lowering emissions, raising environmental awareness, and having a minimal effect on the environment. Nevertheless, new energy management systems must save costs and guarantee a reliable energy supply. Generally, today's academics and engineers are concerned with energy storage and the most efficient management of solar microgrids. In the past and in the future, researchers will use various sophisticated and elementary optimization techniques.

IV. FUTURE ENERGY DEVELOPMENT AND THE POSSIBILITY OF SOLAR ENERGY STORAGE

Over time, incentives from support policies like feed-in-tariff and net metering will decrease due to factors including rising installation, falling prices of photovoltaic (PV) solar panel systems, and the PV intermittency problem. Self-consumption is gaining popularity as an energy strategy because power used locally has a greater economic value than electricity exported [39]. Although solar resources are available, they only offer electricity on an intermittent basis; nevertheless, electrical energy storage (EES) can continue to maintain the stability of the power grid in a manner that is both practical and economically feasible. In-depth research with optimal solutions is needed to simultaneously determine the energy storage technology, the storage capacity, and the operational strategy.

China will soon set a deadline for the end of sales of traditional internal combustion engine vehicles to smooth the transition to more widespread use of electric vehicles (EVs). More than 20% of all cars sold in the United States by 2025 are projected to be "new energy vehicles" meaning electric or plug-in hybrid EVs. It was stated in July 2017 that traditional passenger autos will be banned in the United Kingdom and France by 2040. Traditional autos would also be illegal in India by 2030, since this is the date that was announced. To make the switch to EVs more quickly, the requisite infrastructure and support must be developed more quickly. However, there are still challenges in integrating the electricity system with EVs. The potential growth of the market for PV-integrated automobiles with battery storage is sparked by this breakthrough [40].

Figure 2 shows that PV capacity is expected to rise dramatically over the globe, providing 16% of global electricity by 2050. An expansion of this magnitude would pose economic and technical challenges to integrating solar power into the grid because of the intermittent and random nature of solar energy production [65]. While research into power grid enhancements and new service offerings has been conducted in the area of electrical energy storage (EES), more work is needed to fully understand the role that smart grids play in modern power infrastructure. The EES market is expanding, but there are no standardized methods for comparing the effectiveness of different EES components within a PV system [3].

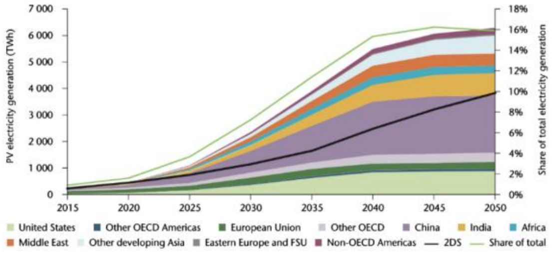

Figure 2. Variations in solar PV's global market share and its impact on electricity production [3]

Significant problems, including communication, control, short-circuit protection, electrical isolation, and surge protection, need interconnection standards that cater for the demands of both distributed generating owners/operators and distribution firms. Distribution firms and owners/operators of dispersed generation must collaborate to create these regulations, despite the existence of technical standards for the performance, design criteria, and capacities of PV systems [41]. Not too far off, there will be a need to establish guidelines for the EES used in PV installations.

Although large-scale PV generation can reduce industry generation costs and mitigate the impact of uncertain carbon pricing policies and nondeterministic future fossil fuel prices, there are costs associated with creating surplus energy for storage or transmission to the external grid. PV power is very unpredictable and volatile, which leads to poor power quality, specifically Volt/Var control issues. In order to guarantee the safe and reliable functioning of PV generators, several studies have concentrated on finding solutions to stability difficulties and establishing control methods. Future dependability of the power grid may hinge in significant part on the manner in which energy reserves and dispatches are managed [42]. Tamimi et al. [43] analyze three potential setups, all of which have a system capacity of up to 2GW: centralized farms with voltage control capabilities; centralized farms without voltage regulation capacities; and distributed units. Rooftop solar installations and other forms of distributed generation are favored above large-scale solar farms in this analysis. While research into power system transient stability and tiny signal stability has been conducted, further analysis of PV power producing systems of varied sizes and capacities at varying levels of penetration is required.

Methods to lessen the volatility in the power production, such as (1) EES usage, (2) dump load use, and (3) PV power curtailment, have been examined to enhance system stability on a 10 MW residential PV system [44]. In other words, if one can enhance the consistency of PV's output power, they will also lose money. It is determined that the best cost-effective strategy is a combination of EES and power reduction.

The shape, density, and size of clouds, as well as the speed with which they obscure the sun, may have a significant impact on PV performance [45]. Accurate predictions of incident solar radiation and environmental variables have a significant impact on the design and operation of PV and EES systems. Due to its intermittent and dynamic character, solar resource makes precise estimation of available solar irradiation at a given time instance a non-deterministic task. As a result, improved techniques of forecasting and prediction must be created so that a more accurate assessment of the solar irradiance resource and the surrounding ambient state may be made.

The theoretical forecasting methods for solar resources and PV power have been thoroughly analyzed by Wan et al. [46]. Although various models have been created recently to anticipate solar resources and the power production of utility-scale PV plants, the inherent imprecision of factors like temperature, cloud cover, dust, and relative humidity make reliable solar power forecasting difficult. Predictions for PV power systems may be made using one of four common types of models: statistical, AI-based, physical, or hybrid. Predictions may be made using statistics as long as the target variable and related data are provided. A novel data-driven prediction model for solar irradiance is developed, which combines spatio-temporal (ST) and autoregressive with exogenous input (ARX) techniques. Simulated findings using real solar data from PV installations in California and Colorado demonstrate the proposed model's ability to provide accurate forecasts for 1 and 2 h horizons [47]. Artificial intelligence (AI) algorithms are widely used in solar energy modeling and prediction because of their superior learning and regression capabilities. Physical models employ information from the sun and photovoltaics to predict solar irradiation and power production.

V. POTENTIAL USES FOR SOLAR ENERGY STORAGE

Energy storage is a key component of many cutting-edge systems, including those for renewable energy integration, improved energy efficiency in buildings, cutting-edge transportation, and peak-load reduction. Different types of energy storage systems are available for various uses. There are occasions when a single energy storage technology cannot meet all the needs of an application, and that is when hybrid energy storage comes into play. When the system is located in a space- or cost-constrained region, such as a dense metropolitan center, the storage mass is typically an essential metric owing to weight and cost limits. As the need for energy storage grows, innovative systems that can accommodate a broad variety of power and energy densities must be developed. We'll look at how energy storage may be put to use in various settings, including utility companies, renewable energy facilities, commercial and residential structures, and public transit.

Widespread use may be found for several forms of energy storage. Since PCMs can melt and solidify across a broad temperature range, they are appealing for use in various contexts, these include off-peak energy storage, waste heat recovery, greenhouses with solar panels, indoor solar water heating and cooling, greenhouse solar heating and cooling, and solar space heating and cooling in buildings. There is potential for using solar energy to recycle otherwise wasted heat [48]. There are many potential uses for flywheels. Liu & Jiang [49] detail some of them, including on the International Space Station, in Low Earth Orbits for earth observation missions, to increase the overall efficiency, to transfer power in pulses for hybrid electric vehicles, and to guarantee the quality of the power supply. Several researchers have proposed using asphalt concrete pavements to capture and store solar energy [50]. Some asphalt concrete pavements may be made more conductive, more insulating, or able to store more thermal energy than their equivalents by employing aggregates and other additives (such limestone, quartzite, lightweight aggregate, copper slag, and copper fibre).

As additional energy storage solutions have become accessible, their integration into utility networks has become a priority. Energy storage deployed at any of the five major subsystems in electric power networks (generation, transmission, substations, distribution, and end users) may help strike a better balance between customer demand and generation. Grid equipment, such as generators and motors, is vulnerable to harm from power instability brought on by intermittent power output, such as that produced by different renewable energy sources. Including energy storage in renewable energy systems increases the proportion of renewable energy used, improves the overall efficiency of the system, and provides grid management and maintenance with greater flexibility.

Energy storage's many applications in power systems have been investigated by Koohi-Kamali et al. [51]. These applications range from increasing the use of renewable energy sources to improving frequency control, providing operational reserve, and bolstering micro-intelligent power grids. The principles of operation and practical applications of many storage systems are reviewed, including flywheel storage, electrochemical storage, pumped hydroelectric storage, and compressed air storage. The storage methods described and evaluated by Vazquez et al. [52] are batteries, electrochemical double-layer capacitors, regenerative fuel cells, compressed air energy storage, flywheels, small-scale mechanical energy storage, and thermoelectric energy storage.

Due to the growing fluctuation in both demand and supply, energy storage devices are becoming an increasingly important part of smart grids. Redox flow batteries, Na-beta alumina membrane batteries, novel Li-ion chemistry, and lead-carbon technologies are only some of the grid-based electrochemical storage systems that Yang et al. [47] study. They also look at ways in which these technologies might be made more affordable and efficient to expand their current market reach. The potential and uses of lithium-ion, redox flow, and sodium-sulfur batteries have been explored by Dunn et al. [53]. For power leveling, grid frequency support/control, and voltage sag reduction, flywheel energy storage devices have been emphasized by Mousavi et al. [54] due to their quick recharge time and high-power density. Because of their high power density, they can store much energy in a compact package. [55] argue that future power grid resilience may be improved by investing in research into the modular deployment of flywheels.

Rapid growth in the use of renewable energy sources helps fulfill worldwide demand for electricity and reduces the environmental impact of the electrical sector. The inherent unpredictability of these resources, however, magnifies the technical and economic challenges connected with their management and exploitation when they are integrated on a large scale. Due to the unreliable output of renewable energy sources, energy storage systems are crucial. The ability to store and later dispatch excess renewable energy is key to increasing the proportion of renewable power generated. Combined with the distributed nature of storage, the intermittent nature of renewable energy sources becomes even more of a problem. Scalable, modular, long-lasting, low-maintenance energy storage technologies have been offered by Beaudin et al. [56] for distributed renewable energy harvesting. Almost all types of batteries, as well as flywheels, capacitors, SMES, and other similar technologies, belong here (excluding lead-acid batteries).

[57] explored the usage of energy storage devices for wind power, including water reservoirs, compressed air, batteries, flow batteries, fuel cells, kinetic energy from flywheels, magnetic fields from inductors, and electric fields from capacitors. Flywheel energy storage systems have been recommended by Mousavi et al. [54] for storing wind energy because of their favorable dynamics and rapid response time. Multiple examples are presented to illustrate the experiments with wind flywheel coupling and the corresponding control approaches used to achieve the smooth power regulation. [55] suggest using flywheels rather than batteries as a form of energy storage because of the frequent shifts in power generation.

Rehman et al. [58] explored various PHES hybrid systems, including wind-hydro, solar PV-hydro, and wind-PV-hydro. Dursun and Alboyaci [59] examine the current and potential uses of pumped hydro in wind energy applications in Turkey, as well as the relevance, necessity, and contribution of wind-hydro pumped storage systems in meeting Turkey's electric energy demand. They observed that conventional plant output and wind curtailment may be significantly reduced if PHES were used as a standing reserve in rigid generating systems.

The development of more efficient modes of transportation on land, sea, and in the air has increased the need for more sophisticated energy storage solutions. Hybrid electric vehicles use energy-storage devices such as flywheels, ultra-capacitors, batteries, and hydrogen storage tanks for fuel cells instead of the gasoline tanks and internal combustion engines used in conventional vehicles. High power density for quick power discharge (especially during acceleration), enormous cycle capacities, high efficiency, easy operation, and the ability to recover energy during braking are all desirable qualities in an automotive energy storage system. Regarding electric ground vehicles, batteries are often used as the primary energy storage device. Due to their higher power density compared to batteries, electrochemical capacitors may be used in electric and fuel cell vehicles. An electrochemical capacitor may store energy from regenerative braking and function as a short-term energy storage with high power capacities in various contexts.

Energy storage is gaining importance as a tool to facilitate the generation-side renewable energy penetration into buildings and as a buffer to meet the fluctuating demand from building occupants (on the demand side). During the planning and design phases, key performance indicators given by [60] may be used to evaluate technical solutions and compare various storage systems. One can tell a lot about a battery by looking at its volume, optimum charge and discharge power, depth of charge, durability, specific cost, maximum self-discharge rate, storing weight, and achieved energy/cost savings.

There is a large body of literature on storage materials and their classifications, current advancements, thermal storage use circumstances and performance, limits, and possible improvements for building purposes due to the widespread adoption of thermal energy storage [61-63]. Benefits accrue to communities and buildings whether the storage period is short (a few days) or lengthy (a few months). One possible use is moving power consumption away from peak times and toward off-peak times, using thermal energy storage, for example. Having this capability makes it a useful resource for demand-side management initiatives [60]. According to Zhang et al. [4], buildings using TES systems are constantly being improved via R&D to address technical challenges such as sub cooling, segregation, and material compatibility. Figure 3 shows how phase change materials (PCMs) may improve the thermal capacity of storage while maintaining a constant operating temperature, and subsurface thermal energy storage and recovery systems are another example. Phase change materials (PCMs) are another example, since they may be used to improve storage capacity at a constant temperature without requiring a change in operating temperature.

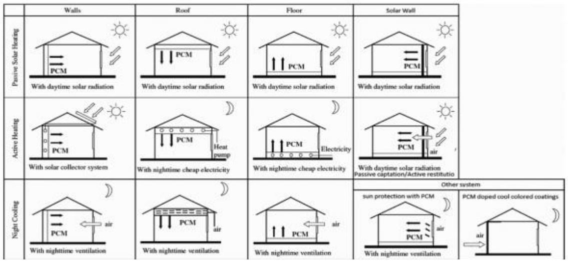

Figure 3. Construction PCM's many guises and effects (Reproduced from [4])

VI. SUMMARY OF FUTURE TRENDS AND DEVELOPMENT

Technical learning about the future growth of investment costs of long-term storage is the foundation for the examination of prospective outcomes based on the future prospects. The International Energy Agency's data is used to simulate the quantities associated with each individual technology [3]. Note that since hydrostorage has reached such a mature level, we do not consider the possibility of additional technical learning. Figure 4 illustrates how the prices of several technologies for the long-term storage of energy might grow in the future, depending on the level of technical advancement that occurs between now and 2050.

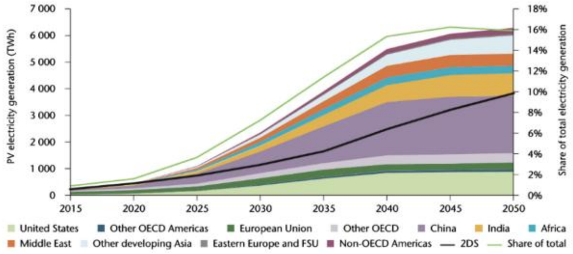

Figure 4. Worldwide trends for power production from solar photovoltaic systems and their percentage of overall energy output [3]

The costs of power-to-gas (PtG) technologies are expected to drop significantly between now and 2050, mostly because of learning effects. This trend will be observed during the period up to 2050. For hydropump storage on a long-term basis (more than a year), prices are likely to go up rather than down in the near future. This is primarily because there are not enough locations available that have affordable rates and a low level of acceptability. The prices of all centralized long-term storage solutions will eventually become too expensive in a market environment that is dynamic, rendering them incapable of being competitive.

Energy storage is an important component of the future of energy, along with supply-side demand management. To keep occupants, warm after heating the building for the first time, thermal mass stores the heat for an extended period. When designing a building, it is crucial to have a firm grasp of how end-users act so that you may subtly modify the structure's behavior to suit users' needs. The end-user is afforded some degree of agency, and the needs of the power network operator are met, when these features are modified via selective fabric retrofits and selective occupancy controls.

During times of local grid congestion, battery deployment may work with electric automobiles and/or electric heat pumps, while thermal storage will meet the thermal comfort needs when running with heat pumps. Vehicle-to-grid technology enables these kinds of battery and electric vehicles to function as autonomous demand-side response units. Combining these technologies can help us address many of the new difficulties confronting low-voltage networks as we attempt to minimize the amount of carbon 2 created by our energy consumption. Despite this move, relatively few resources are allocated toward improving the low voltage network, which is where most of the problems lie. It is unclear how fast technologies are being adopted or how well they function in real-world applications. No one knows how quickly new technologies are being adopted. The costs of delaying electricity network investment are not yet determined.

VII. CONCLUSION

Free-standing or grid-connected photovoltaic systems are only two examples of how this technology might be used. Its modular design makes it easy to adjust its size, from miniature (portable) to massive (solar field-scale). Energy derived from this source does not contribute to global warming since no greenhouse gases are released during its production or usage (production, transformation, or consumption). Load management and energy storage systems working together might decrease the price of PV and increase its efficiency. State-of-the-art, current, applications, trends, and progress in household solar energy storage systems are summarized in this review research: integrating photovoltaics (PV) with energy storage in smart buildings, the significance of solar energy storage considering possible future storage options.

It is critical to find ways to reduce electricity costs (such as using depreciated wind power plants that are no longer receiving subsidies) and to increase full-load hours (such as using only a portion of the production profile of wind power plants with no peaks and a high number of full load hours). To put storage technology to use in the real world, both of these are needed. New storage options will only make sense if they are constructed in parallel with grid expansions and if new excess production, particularly from variable RES, becomes likely. It is only under these conditions that its implementation will be cost-effective.

Generally, although energy storage systems have gotten a considerable amount of attention, the design of these systems still must be improved before this technology can be used in a domestic context. Because of this, research opportunities exist regarding storage strategies and systems. Because of its dependability and low overall cost, short-run sensible heat storage will continue to be the industry standard until additional advancements are realized.

This paper presents a detailed bibliometric analysis of thermal energy storage (TES) applied to different levels of the built environment. The literature search with the Scopus database and different queries for three main categories, in particular in buildings, districts, and roads and bridges, were done. The main conclusions, divided by sections drawn from the bibliometric analysis, are the following:

- “Buildings” is the main category for which TES is studied. Indeed, the implementation of different legislative bases and policies of energy efficiency related to buildings has led to a rapid increase in research output after 2010, especially in Europe.
- The USA was the first country to publish pertinent findings relating to the use of TES in buildings, with the main goal of reducing cooling demand by using optimal control approaches. While the most pertinent studies from China are based on materials, the research trend in Europe is mostly based on the application of latent heat thermal energy storage using passive approaches and demand-side management systems.

Latent heat energy storage was the technology that generated the most interest compared to other technologies, both at the system and material levels, according to the keyword analysis. However, there is no specific category mentioned in the studies on buildings. In fact, studies of demand-side management or optimization, where the user profile plays a crucial role, are the only ones that specifically mention this.

District thermal energy networks are an excellent technique for increasing energy efficiency and lowering gas emissions, despite the lack of particular directives or rules in most world's nations. TES implementation studies increased after 2013, with Europe taking the lead in the research because of its appeal in northern nations.

- TES is mostly explored at the system level in districts, primarily in connection with solar applications and cogeneration systems. On a district level, the incorporation of seasonal TES, such as borehole or subterranean TES, is an important issue. Sensible heat technologies, such as water tanks paired with heat pumps and cogeneration systems, have stronger importance when demand-side management tactics are considered.

Despite the absence of specific guidelines or regulations in most world's countries, district thermal energy networks are recognized as a great way to improve energy efficiency and reduce gas emissions. After 2013, there was a rise in TES implementation studies, with Europe having the lead in the study because of its popularity in northern countries.

- In districts, TES is mainly investigated at the system level, primarily in relation to solar applications and cogeneration systems. The inclusion of seasonal TES, such as borehole or underground TES, is a significant issue at the district level. Demand-side management strategies give sensible heat technologies—like water tanks coupled with heat pumps and cogeneration systems—more significance.
- The application of TES to roads and bridges has attracted few researchers and is still in its infancy. Even though the first research on this particular topic was published in 1989 in Japan and the US, only a few universities began showing an increased interest in it after 2009. With Japan, China currently produces the most papers, while interest is still low in Europe. As a result, it is possible to identify TES applied to roads and bridges as a research need with various potential study topics.

The keyword analysis separates studies into two major categories.

- Although borehole and geothermal TES are frequently integrated into pavements, keywords related to those technologies do not appear, likely because the authors' keyword choices are not closely related to the topic at hand.

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