#564: Comprehensive integration of renewable energy technologies within residential grids – short review

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Abstract: This paper provides a comprehensive review of the integration of renewable energy technologies (RETs) within residential grids, with a particular emphasis on solar and wind energy systems. It examines recent advancements, challenges, and future trends in this field, highlighting the importance of improving energy efficiency, flexibility, and reliability within residential power systems. The review also explores the environmental impacts and integration challenges associated with solar power systems, offering sustainable innovations to mitigate these concerns. Furthermore, the paper discusses the critical role of battery storage systems and smart technologies in ensuring a stable energy supply while managing demand effectively. The integration of complementary energy sources, such as geothermal and biomass, is also considered to enhance grid stability and energy security. In addition, the paper underscores the significance of Phase Change Materials (PCM) and other thermal energy storage solutions in boosting energy efficiency in buildings. Through this review, we provide valuable insights into the current state of RET applications and their potential to drive the transition towards more sustainable, resilient residential energy systems.

Keywords: Renewable Energy Technologies (RETs); Residential Grids; Solar and Wind Energy; Energy Efficiency; Phase Change Materials (PCM)

1. INTRODUCTION

The increasing global demand for energy, alongside the urgent need to address climate change, has intensified the focus on renewable energy technologies (RETs). Among these, solar and wind power are at the forefront of transforming residential energy systems. These technologies provide cleaner alternatives to fossil fuels, contributing to reduced greenhouse gas emissions and enhanced energy independence (Fokaides et al., 2020). As governments push for sustainable energy solutions, the integration of RETs in residential grids has become essential to meeting climate goals. Solar and wind energy are well-suited for residential use due to their availability and technological advancements (Nwaigwe et al., 2019). Solar photovoltaic (PV) panels and small-scale wind turbines can fulfill a significant portion of household energy needs, especially when supported by energy storage systems to balance production and consumption (Shaqsi et al., 2020). However, the intermittent nature of these energy sources presents a challenge for grid stability, making it crucial to implement advanced energy storage, smart grid technologies, and efficient energy management systems (Mariano-Hernández et al., 2021). Battery storage systems are a key solution, storing excess energy during peak production for later use (Shaqsi et al., 2020). In conjunction with solar PV panels or wind turbines, these systems can create self-sufficient microgrids, reducing dependence on traditional power grids. Additionally, smart grid technologies optimize energy use, ensuring greater flexibility and efficiency in managing supply and demand (Fokaides et al., 2020).

This review also highlights the importance of thermal energy storage technologies, such as Phase Change Materials (PCMs), which help regulate building temperatures and reduce the reliance on heating and cooling systems (Nandy et al., 2023). The environmental impacts of RET integration are also addressed, noting concerns such as material sustainability and land use (Tawalbeh et al., 2021; Rabaia et al., 2021). This paper provides a comprehensive review of the integration of RETs in residential grids, with a focus on solar and wind energy. It examines technological advancements, environmental challenges, and future trends to offer insights into how RETs can contribute to more sustainable and resilient energy systems.

2. INTEGRATION OF RENEWABLE ENERGY IN RESIDENTIAL GRIDS

As the global push towards sustainable energy intensifies, renewable energy technologies (RETs), particularly solar and wind power, have become integral components of residential power systems. The increasing adoption of these technologies' stems from their potential to significantly reduce greenhouse gas emissions, decrease reliance on fossil fuels, and improve energy independence. RETs in residential grids not only offer environmental benefits but also contribute to long-term economic savings by lowering energy costs. However, integrating these intermittent energy sources into residential grids poses several challenges that necessitate innovative technological solutions and advanced grid management systems (*Nwaigwe et al., 2019*).

2.1. Solar and wind power integration

Solar and wind power are the most prevalent forms of RETs integrated into residential grids due to their availability and scalability. Solar photovoltaic (PV) systems convert sunlight into electricity, making them ideal for residential installations. Homeowners can generate their electricity during peak sunlight hours and even sell excess energy back to the grid in regions with net metering policies (*Shaqsi et al., 2020*). Wind energy, though less common in urban residential areas, is also increasingly adopted in rural or suburban areas with higher wind speeds. Small-scale wind turbines offer an additional renewable energy source that can complement solar power generation, especially in regions where sunlight may be inconsistent, but wind conditions are favorable.

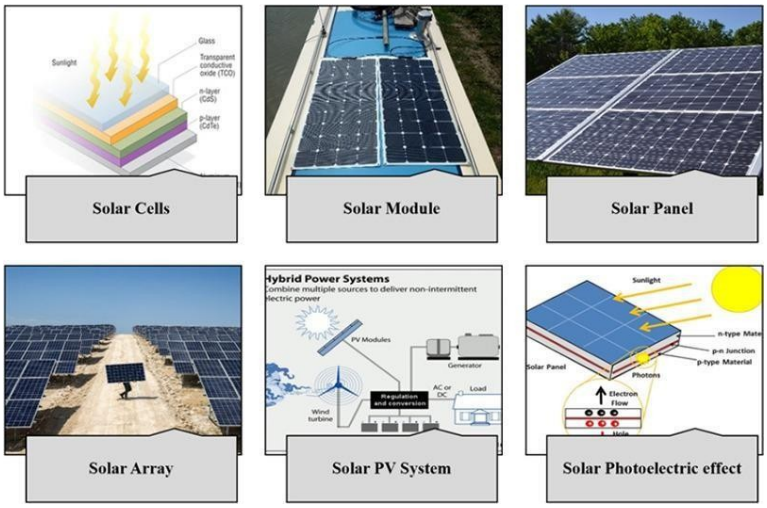

Figure1: Integrating solar into residential grids

Despite their promise, solar and wind power are inherently variable. Solar PV systems depend on daylight and weather conditions, while wind turbines require sufficient wind speeds to operate effectively. This variability presents challenges for maintaining a consistent and reliable energy supply, particularly during periods of high demand or low energy production. Therefore, integrating solar and wind into residential grids requires solutions that can manage and stabilize this energy flow (Rabaia et al., 2021).

2.2. Flexible grid systems and smart technologies

The successful integration of RETs into residential grids relies on the development of flexible grid systems that can accommodate the variability of renewable energy generation. These grids must be capable of adjusting energy supply to match demand dynamically, especially during peak usage periods. Smart grid technologies, which use digital communication systems and real-time data analytics, have emerged as a solution to this challenge. Smart grids enable two-way communication between energy producers and consumers, allowing for more efficient management of energy distribution (see Figure 2). By using predictive algorithms, smart grids can forecast energy demand and adjust energy supply, accordingly, optimizing the use of renewable energy resources while minimizing waste (Fokaides et al., 2020).

Figure 2: Research Trends in the field of Sustainable Energy for the Built Environment

Moreover, smart grids facilitate the integration of multiple renewable energy sources. While solar and wind are the primary RETs for residential grids, complementary energy sources such as geothermal and biomass can enhance grid stability. Geothermal energy provides a reliable source of power by tapping into the Earth's internal heat, while biomass energy, derived from organic materials, offers a consistent supply of renewable energy. These complementary energy sources help smooth out the variability of solar and wind, ensuring a more stable and dependable energy supply for residential users (Nwaigwe et al., 2019).

2.3. The role of battery storage systems

One of the critical components in integrating RETs into residential grids is the use of battery storag e systems. Battery storage allows excess energy generated during periods of high solar or wind production to be stored for later use. This stored energy can then be used during times when renewable energy generation is low, such as nighttime or cloudy days, thus maintaining a steady and reliable energy supply (Shaqsi et al., 2020). In residential settings, battery storage systems are often paired with solar PV panels or small wind turbines to create self-sufficient microgrids. These microgrids reduce dependence on traditional power grids, enhance energy independence, and provide homeowners with a backup power source during outages.

Advancements in battery technology have made these systems more efficient and cost-effective, further encouraging their adoption in residential applications. Lithium -ion batteries, for example, are commonly used in residential energy storage due to their high energy density, long cycle life, and relatively low cost. In addition, ongoing research into next-generation battery technologies, such as solid-state batteries and flow batteries, promises to further improve energy storage capabilities, making RET integration in residential grids even more feasible and efficient (Shaqsi et al., 2020).

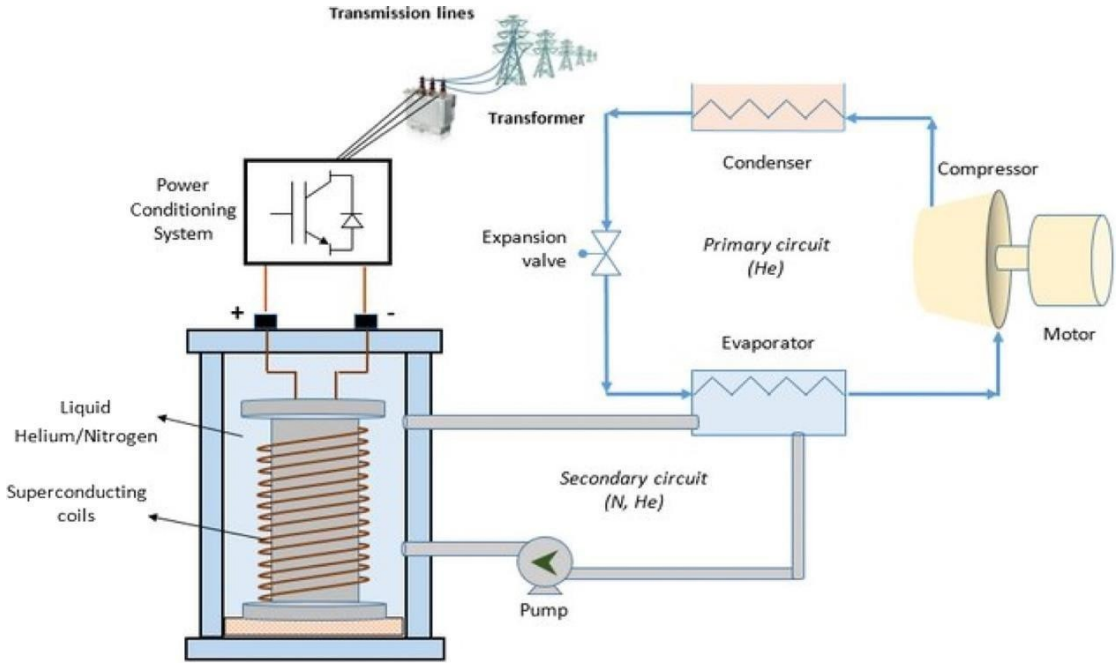

Figure 3: Diagram of superconducting magnetic energy storage system source (Pavlos Nikolaidis, 2017)

2.4. Thermal energy storage (TES)

In addition to electrical energy storage through batteries, thermal energy storage (TES) systems play a vital role in stabilizing energy supply in residential grids. TES systems store energy in the form of heat or cold, which can later be used for space heating, cooling, or water heating in residential buildings. Phase Change Materials (PCMs) are a popular TES technology that absorbs and releases thermal energy during phase transitions, such as from solid to liquid. By incorporating PCMs into building materials, homes can maintain more stable indoor temperatures, reducing the need for traditional heating and cooling systems (Nandy et al., 2023). TES systems can also be integrated with renewable energy sources to maximize energy efficiency. For instance, excess solar energy generated during the day can be stored as thermal energyand used for space heating at night. This reduces reliance on grid electricity and enhances the overall efficiency of the energy system. TES is particularly useful in regions with high temperature variations between day and night, as it helps mitigate the impact of these fluctuations on energy demand (Jarimi et al., 2019).

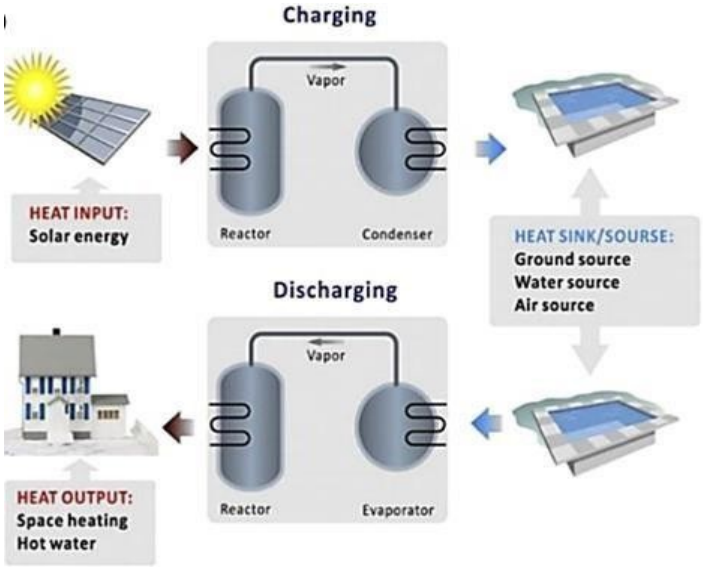

Figure 4: Thermal Heat Storage (Jarimi et al., 2019)

2.5. Environmental and economic impacts

While RET integration in residential grids offers numerous environmental benefits, such as reducing carbon emissions and decreasing reliance on fossil fuels, it is not without its challenges. The production and disposal of solar panels, wind turbines, and battery systems involve energy-intensive processes and the use of rare earth materials, which can have negative environmental impacts if not managed sustainably (Tawalbeh et al., 2021). Additionally, large-scale adoption of RETs in densely populated urban areas raises concerns about land use and the aesthetics of residential neighborhoods.

Economically, RETs offer long-term cost savings for homeowners by reducing electricity bills and increasing energy independence. However, the initial costs of installing renewable energy systems and battery storage can be prohibitive for some households. Government incentives, subsidies, and policies that support renewable energy adoption are critical for making these technologies more accessible and affordable (Rabaia et al., 2021).

3. INTEGRATION AND ENVIRONMENTAL IMPACT OF SOLAR POWER SYSTEMS

The integration of solar power into residential and industrial grids is increasingly seen as a key strategy in transitioning to sustainable energy systems. However, integrating solar energy into electrical grids poses significant technical and environmental challenges. According to Mekhilef et al. (2018), one of the primary difficulties lies in managing the intermittent nature of solar energy. Solar power generation fluctuates based on weather conditions and time of day, creating a mismatch between energy supply and demand. This intermittency requires more advanced grid management systems, such as smart grids, to optimize the use of solar power and ensure stability. In particular, solar energy's variability demands innovations in energy storage and demand-side management to prevent power outages or excess energy loss (Mekhilef et al., 2018).

Zhou et al. (2019) highlights the role of energy storage systems, particularly battery storage, in addressing the challenges of integrating solar energy into the grid. Battery storage allows excess energy produced during peak sunlight hours to be stored and used during periods of low production, helping to stabilize the grid. However, the production, use, and disposal of batteries bring environmental concerns, including resource depletion and the generation of hazardous waste. Zhou et al. argue that improvements in battery technology, such as solid-state batteries, could reduce environmental impact while enhancing energy storage efficiency (Zhou et al., 2019). These advancements are crucial for expanding the feasibility of large-scale solar integration. In terms of environmental impact, Fthenakis and Kim (2019) provide a comprehensive lifecycle assessment of solar photovoltaic (PV) systems, revealing both the benefits and potential drawbacks. Solar energy offers clear advantages in reducing carbon emissions compared to fossil fuels, but the manufacturing and disposal phases of solar panels can have significant environmental impacts. The production of PV panels requires rare materials like silicon,silver, and cadmium telluride, which are resource-intensive and can contribute to environmental degradation through mining and processing. Additionally, the end-of-life disposal of PV panels raises concerns about the accumulation of electronic waste, as current recycling infrastructure is insufficient to handle the expected surge in decommissioned solar panels in the coming decades (Fthenakis & Kim, 2019).

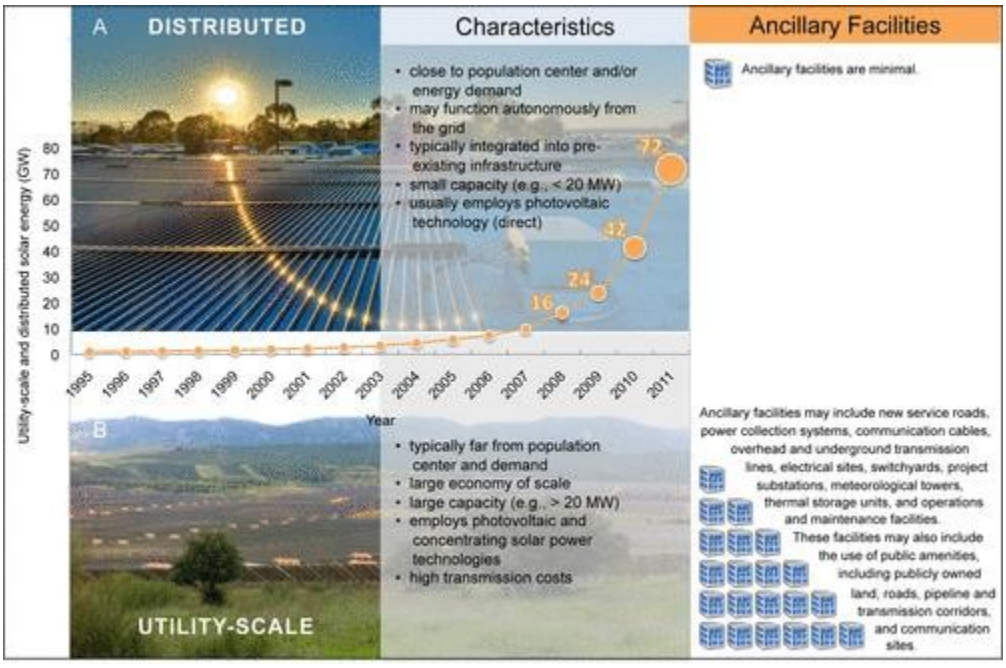

Figure 5: Utility-scale and distributed solar energy global installed capacity in gigawatts (GW) over time. (Hernandez etal., 2014)

Site selection for solar farms is another critical factor in reducing environmental impacts. Large-scale solar installations require vast areas of land, which can disrupt ecosystems and lead to land-use conflicts. Hernandez et al. (2014) emphasizes the importance of selecting appropriate sites that minimize ecological disruption, such as degraded lands or rooftops in urban areas. Their research also points to the potential for agrivoltaics, where agricultural activities are combined with solar installations, allowing dual land use that supports both food production and energy generation. This strategy can mitigate the negative impacts of land conversion while contributing to renewable energy goals (Hernandez et al., 2014). In terms of operational efficiency, Jordan and Kurtz (2020) examine the degradation rates of PV panels over time, which affect both their energy output and environmental footprint. PV panels degrade at a rate of about 0.5% to 1% per year, depending on factors like material quality and environmental conditions. This degradation reduces the overall energy yield of solar installation and, as panels age, decreases the return on the energy investment required to produce them. The authors recommend that future solar projects consider the use of more durable materials and explore innovations in panel recycling to extend the lifespan of PV systems and reduce their long-term environmental impact (Jordan & Kurtz, 2020).

Tsiropoulos et al. (2020) suggest that policies promoting circular economy principles—such as enhanced recycling of solar panel components—are essential for mitigating the environmental costs of solar power systems. Their study emphasizes that governments and industries must collaborate to create more robust recycling infrastructure and regulations that ensure the recovery of valuable materials from decommissioned solar panels. By doing so, the solar industry can move towards more sustainable practices that align with the broader goals of renewable energy adoption (Tsiropoulos et al., 2020). While solar power offers considerable environmental benefits by reducing reliance on fossil fuels, its integration into the grid and its full lifecycle environmental impacts must be carefully managed. From smart grids and advanced energy storage solutions to improved recycling methods and sustainable site selection, overcoming these challenges will require coordinated efforts from researchers, policymakers, and industry leaders to ensure that solar energy can be harnessed sustainably.

4. RECENT ADVANCES IN SUSTAINABLE BUILDING AND PHOTOVOLTAIC TECHNOLOGIES

The rapid development of photovoltaic (PV) systems has significantly contributed to global efforts toward sustainable energy production. However, the environmental challenges associated with their manufacturing, use, and end-of-life disposal have raised concerns about their overall sustainability. Recent research from 2022 to 2024 has focused on addressing these issues by advancing technologies that enhance the environmental and economic value of PV systems. These innovations involve optimized design, new material development, reduction in hazardous materials, improved recycling methods, and the careful selection of installation sites. Additionally, progress in sustainable building technologies is creating more energy-efficient, low-carbon structures that integrate seamlessly with PV systems to enhance overall building performance.

4.1. Environmental challenges and innovations in pv systems

Photovoltaic systems, while lauded for their ability to generate renewable energy, are not without their environmental downsides. One of the most pressing concerns involves the pollution generated during the manufacturing process. Zhong et al. (2023) identified that the production of solar panels requires energy-intensive processes, including the purification of silicon and the manufacturing of modules. This results in considerable emissions of greenhouse gases and other pollutants. However, recent advancements in manufacturing technologies have helped mitigate these impacts. For example, the use of passivated emitter and rear cell (PERC) technologies has improved the efficiency of solar cells, allowing more energy to be generated from the same surface area, which reduces the environmental cost per watt of electricity produced (Zhong et al., 2023).

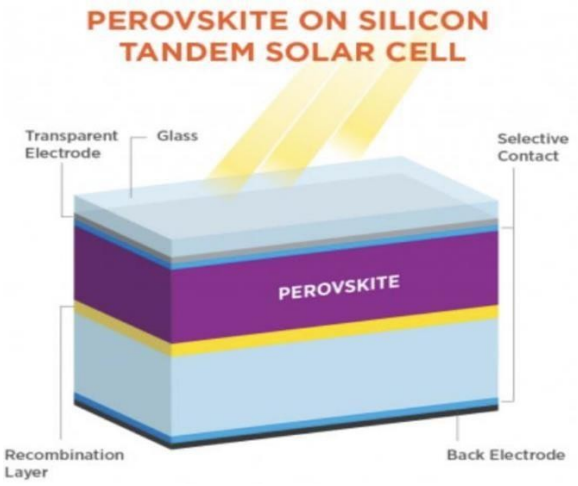

Figure 6: Perovskite on Silicon Tandem Solar Cell (Wang et al., 2023)

Another critical area of research is the development of new materials for PV systems. Conventional PV panels rely heavily on silicon, which is abundant but requires significant energy for purification. Researchers are now exploring alternatives like perovskite solar cells, which have shown promise due to their lower production costs and energy inputs. Wang et al. (2023) reported that perovskite materials not only have the potential to reduce the carbon footprint of PV systems but also offer higher efficiency rates compared to traditional silicon-based panels. These advancements could revolutionize the industry by providing more affordable and environmentally friendly options for solar energy production (Wang et al., 2023).

In addition to material innovation, the reduction of hazardous materials used in PV systems has become a priority. Singh et al. (2022) discussed the dangers associated with toxic substances such as cadmium and lead, which are found in some types of thin-film PV cells. These hazardous materials can leach into the environment during manufacturing, use, or disposal, posing risks to both human health and ecosystems. In response, there has been a push toward developing non-toxic alternatives and improving encapsulation techniques that prevent the release of harmful substances. This shift is essential for ensuring that PV technologies can be scaled up without exacerbating environmental harm (Singh et al., 2022).

4.2. Recycling and end-of-life management

As PV systems reach the end of their operational life, disposal and recycling have emerged as significant environmental challenges. It is estimated that millions of tons of solar panel waste will accumulate in the coming decades. Recycling solar panels is not yet a widespread practice, largely due to the complexity of separating and recovering valuable materials such as silicon, silver, and aluminum. However, Kim et al. (2022) highlights recent advancements in recycling technologies that could change this dynamic. Researchers have developed processes to effectively recover up to 90% of materials from decommissioned solar panels, making it economically viable to recycle them. This development not only reduces the environmental burden of PV systems but also creates a circular economy in the solar industry (Kim et al., 2022).

Furthermore, innovations in panel design are making it easier to recycle PV systems. Li et al. (2023) demonstrated that modular panel designs allow for easier disassembly and material recovery. These designs are particularly important as the global demand for solar energy increases, driving the need for more sustainable end-of-life management practices. With proper recycling infrastructure in place, the solar industry can significantly reduce its reliance on virgin materials and decrease the environmental impact associated with raw material extraction (Li et al., 2023).

4.3. Land use and site selection

Large-scale solar farms require significant land areas, which can lead to habitat destruction and land-use conflicts. However, innovative approaches to site selection can mitigate these issues. Tao and Huang (2023) suggest that using previously developed or degraded land, such as brownfields or rooftops, is a more sustainable alternative to developing new greenfield sites for solar farms. By repurposing underutilized spaces, solar installations can avoid competing with agricultural land or sensitive ecosystems. Furthermore, agrivoltaic systems, which combine solar energy production with agricultural activities, have gained traction as a dual-use strategy that maximizes land productivity while generating renewable energy. This approach not only supports food production but also improves land use efficiency, reducing the overall environmental footprint of solar farms (Tao & Huang, 2023).

In addition to land use, technological advancements in PV system placement are addressing environmental concerns. Liu et al. (2022) explored the integration of solar panels into the built environment, such as through building-integrated photovoltaics (BIPV). BIPV systems replace traditional building materials, like roofing tiles or glass facades, with solar panels, allowing for energy generation without additional land use. This technology is especially relevant in urban areas where space is limited, and it offers the added benefit of reducing the building's overall carbon footprint. BIPV systems also improve the aesthetic integration of solar technologies into cityscapes, making them more appealing for widespread adoption (Liu et al., 2022).

4.4. Sustainable building technologies

Beyond PV systems, there has been considerable progress in sustainable building technologies, which focus on reducing the overall energy consumption and environmental impact of buildings. In recent years, the concept of net-zero energy buildings (NZEBs) has gained momentum. NZEBs are designed to produce as much energy as they consume over the course of a year, often through the integration of PV systems. Ahmed et al. (2022) examined the role of advanced insulation materials, energy-efficient HVAC systems, and smart building technologies in reducing energy demand in NZEBs. These innovations, when combined with on-site renewable energy generation like solar power, significantly reduce the operational carbon emissions of buildings (Ahmed et al., 2022). Indoor air quality has also become a key focus in sustainable building technology. The COVID-19 pandemic heightened awareness of the importance of ventilation and air purification systems in maintaining healthy indoor environments. Zhang et al. (2023) reported that energy-efficient ventilation systems, combined with sensors and smart controls, can improve indoor air quality while minimizing energy use. These systems are particularly important in commercial and residential buildings where energy consumption for heating, ventilation, and air conditioning (HVAC) represents a significant portion of the total energy demand. Integrating these systems with PV technologies allows for the creation of buildings that are not only energy-efficient but also healthier for their occupants (Zhang et al., 2023).

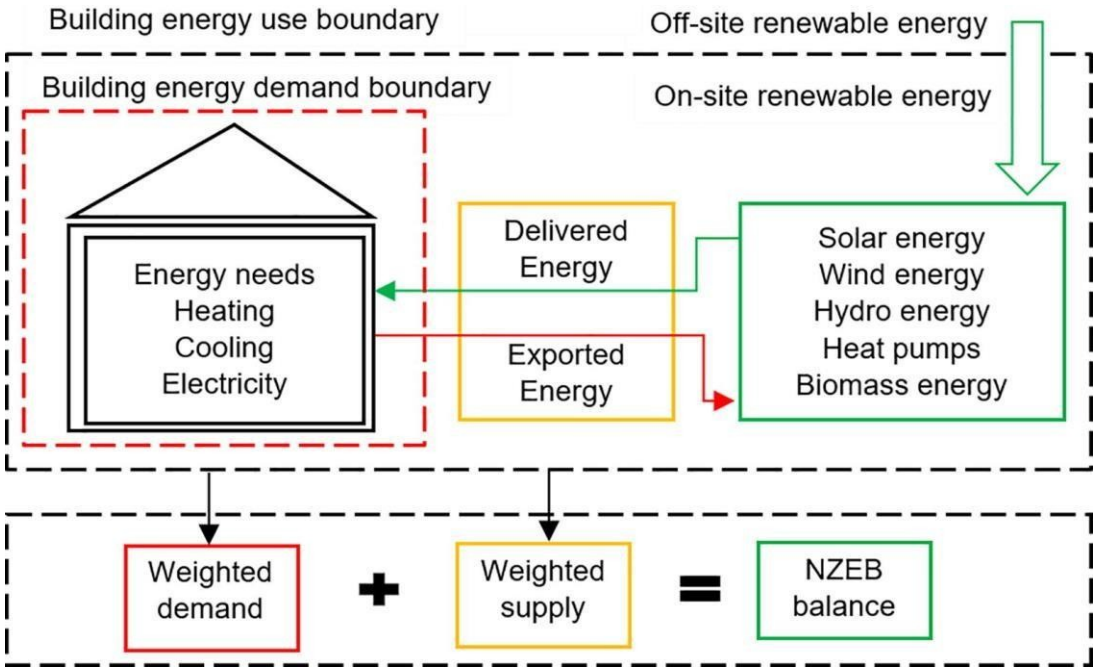

Figure 7: The definition of NZEB. (Ahmed et al., 2022)

Low-carbon building materials are another area of focus. Ding et al. (2023) highlighted the development of materials with lower embodied carbon, such as recycled steel, low-carbon concrete, and bio-based materials. These materials help reduce the overall carbon footprint of construction and, when combined with PV technologies, contribute to the creation of more sustainable and energy-efficient buildings. The use of these materials is becoming more widespread as governments and industries work toward reducing the embodied carbon in the construction sector (Ding et al., 2023).

5. PHASE CHANGE MATERIAL (PCM) FOAM COMPOSITES FOR BUILDING ENERGY EFFICIENCY

Phase Change Materials (PCMs) are increasingly being recognized as an innovative solution for improving energy efficiency in buildings. These materials have the unique ability to absorb, store, and release thermal energy during phase transitions – typically between solid and liquid states – at specific temperatures. This property allows PCMs to regulate indoor temperatures by mitigating temperature fluctuations, reducing the need for traditional heating and cooling systems. As energy efficiency becomes a critical goal in sustainable building design, PCMs are seen as a promising technology for reducing energy consumption and enhancing occupant comfort.

Table 1: Some recent review and computational studies on PCM and observed knowledge gaps. (Ismail et al., 2023)

Research work	Research type	Main findings	Some limitations/gaps
Rashid et al. (2023)	review	• PCM should be selected based on climatic region • thermal stability of PCM should be guaranteed during its lifetime in construction material • cost of PCM may be one of the main roadblocks affecting wide usage	• the scope of the review did not cover analysis of effect of PCM on the intrinsic properties of building materials
Sharshir et al (2023)	review	• Bubble injections can increase PCM latent heat and reduce temperature penetration • melting temperature should be chosen close to the desired temperature and thermophysical properties of PCM should be considered when designing a system	• No evaluation was done on the effect of the shell material on the thermo-mechanical performance of the construction materials.
Chang et al. (2022)	review	• shell materials for PCM should be selected based on application requirement due to individual advantages and disadvantages of each material • MPCM enhance latent heat storage capacity of PCM and prevent their leakage • preparation methods of micro/nano capsule are rigorous which may not be industrially adopted	• analysis of the influence of shell materials on fresh and hardened properties of construction materials was not carried out
Singh Rathore et al. (2020)	review	• MPCM can improve indoor thermal comfort • proper ventilation system must be put in place to regulate heat released during crystallization of the PCM	• influence of shell material on thermo-mechanical performance of construction materials were not evaluated

Research work	Research type	Main findings	Some limitations/gaps
		• Hybrid PCM may be suitable in regions with broad diurnal temperature range	
Mohseni et al. (2021)	computational	• the energy consumption of model incorporated with PCM reduced by about 71% • environmental analysis of the model showed CO_2 emissions of roughly 264 tons can be reduced in buildings with 50-year service life when integrated with PCM • The payback period would be roughly 16.6 years.	• possible degradation of PCM was not considered as PCM was assumed to completely change phase diurnally during building service life
Wijesuriya et al. (2021)	computational	• Peak electricity demand can be effectively shifted by TES capacity of PCM. • While a single path approach is sufficient to record the heat transfer through PCM drywall, a parallel path method can best capture it across a building envelope with PCM pouches.	• specific heat capacity of PCM for solid and liquid phases were kept equal • the wall panels were analyzed with no insulation
Konstantinidou et al. (2018)	computational	• PCM can provide improved thermal comfort and energy efficiency for buildings in the Mediterranean regions through peak load shifting	• the environmental and economic analysis of using PCM in the Mediterranean regions was not analyzed
Saffari et al. (2017)	computational	• proper melting temperature for PCM based on the climate is crucial during design and application • PCM with a melting temperature close to the maximum value of 26 °C is ideal for lowering annual energy usage in locations with a predominately cooling climate. • In contrast, a PCM with a lower melting temperature of 20 °C offers significant yearly energy benefits in places with a predominately warm climate.	• The enthalpy of the PCM was assumed to be constant and possible density change during phase transition of the PCM was not considered

5.1. Thermal management and energy efficiency

The ability of PCMs to store thermal energy during periods of excess heat and release it when the temperature drops is particularly valuable for buildings. According to Zhou et al. (2022), this feature allows for the moderation of indoor temperatures without relying on active heating, ventilation, and air conditioning (HVAC) systems, thereby lowering energy consumption. When incorporated into building materials, PCMs help create a more stable indoor environment, reducing peak energy demands and improving the energy performance of buildings (Zhou et al., 2022). Additionally, the use of PCMs can extend the lifespan of HVAC systems by reducing their workload, thus lowering maintenance costs and the overall energy footprint of a building. In buildings, PCMs are most commonly used in walls, ceilings, floors, and windows, where they are embedded in construction materials like concrete, gypsum, or foam composites. Foam composites are particularly popular due to their lightweight structure, high porosity, and ability to encapsulate PCMs. These composites can store substantial amounts of heat and provide insulation, making them ideal for sustainable building applications.

5.2. Encapsulation techniques and material integration

The encapsulation of PCMs plays a critical role in ensuring their effectiveness and longevity in real -world applications. Encapsulation techniques protect the PCM from external environmental factors, such as moisture or contaminants, while also enhancing the thermal conductivity and durability of the material. There are several encapsulation methods, including direct incorporation, microencapsulation, and macroencapsulation, each offering distinct advantages and challenges.

Li et al. (2021) explored the effectiveness of microencapsulation, which involves coating PCM particles with a thin polymeric or inorganic shell. This method enhances the thermal stability of PCM and prevents leakage during phase transitio ns. Microencapsulated PCMs (MEPCMs) are particularly useful for improving thermal energy storage in foam composites, where the small size of the encapsulated particles allows for uniform distribution within the matrix. However, Li et al. noted that challenges such as thermal degradation and the loss of latent heat storage capacity over time remain critical issues for MEPCMs (Li et al., 2021).

On the other hand, Wang et al. (2023) examined macroencapsulation techniques, where PCMs are enclosed in larger, rigid containers before being integrated into building materials. Macroencapsulation offers better control over PCM's interaction with the environment and prevents leakage more effectively than microencapsulation. However, this technique may result in lower thermal conductivity due to the thickness of the encapsulating materials. To counter this, Wang et al. suggest the use of highly conductive additives, such as carbon nanotubes or graphene, to enhance the thermal performance of PCM foam composites (Wang et al., 2023).

5.3. Performance optimization and future research

Optimizing the performance of PCM foam composites in building applications remains an area of active research. Recent studies have focused on improving the thermal conductivity, storage capacity, and durability of PCMs to make them more suitable for large-scale deployment in buildings. One promising approach is the use of hybrid PCMs, which combine organic and inorganic materials to take advantage of their complementary properties. Zhang et al. (2023) demonstrated that hybrid PCMs, when integrated into foam composites, offer improved thermal conductivity and higher latent heat storage capacity, making them more effective at managing indoor temperatures. Additionally, hybrid PCMs are more resistant to thermal degradation, which extends their operational lifespan in real-world applications (Zhang et al., 2023).

Despite these advancements, challenges such as phase separation, supercooling, and long-term stability continue to limit the widespread adoption of PCM technologies. Phase separation occurs when different components of the PCM segregate over time, reducing the material's overall effectiveness. Zhao et al. (2022) addressed this issue by developing composite materials with enhanced phase stability, which maintain consistent performance across multiple phase transition cycles. Their study suggested that incorporating stabilizers or using nanocomposite PCMs could mitigate phase separation and improve long-term stability (Zhao et al., 2022).

In terms of practical implementation, research is also focusing on the integration of PCMs into existing building systems. Huang et al. (2022) examined how PCMs could be retrofitted into existing buildings to improve energy efficiency. Their findings indicate that PCM foam composites can be applied to older buildings as part of insulation upgrades, leading to substantial reductions in energy use without the need for complete structural overhauls. This makes PCM technologies accessible not only for new, energy-efficient buildings but also for retrofitting older, less efficient ones (Huang et al., 2022).

6. CONCLUSION AND FUTURE WORK

This paper has provided a comprehensive review of the integration of renewable energy technologies (RETs) within residential grids, focusing primarily on solar and wind energy systems. The review has highlighted the significant potential of RETs in reducing greenhouse gas emissions, improving energy efficiency, and increasing energy independence for residential users. By exploring the role of battery storage systems, smart grid technologies, and complementary energy sources like geothermal and biomass, the paper has underscored the need for flexible, reliable, and sustainable energy systems in the residential sector. Additionally, the integration of Phase Change Materials (PCMs) and other thermal energy storage solutions has been discussed as crucial for enhancing building energy efficiency, further contributing to the overall sustainability of energy systems.

However, despite the considerable advantages, several challenges persist. These include the intermittency of solar and wind energy, the environmental impacts associated with the production and disposal of RET components, and the high upfront costs of installation. Addressing these challenges will require ongoing innovation in battery storage technologies, smart grid management, and recycling systems for solar panels and wind turbines. Moreover, public policies and government incentives will play a critical role in making these technologies more accessible and affordable for homeowners.

Future work in this area should focus on improving the performance and efficiency of RETs to further enhance their integration into residential grids. First, advancing battery storage technologies, such as solid-state and flow batteries, will be critical in managing energy variability and ensuring a stable power supply. Additionally, integrating AI and machine learning into smart grid systems will allow for more accurate predictions of energy demand and supply, optimizing the use of renewable energy resources. Further research should also explore the potential of hybrid renewable energy systems that combine multiple energy sources, such as solar, wind, and geothermal, to create more robust and stable energy grids. Investigating new materials for photovoltaic systems, including perovskites and organic solar cells, can help reduce the environmental impact and production costs of solar panels.

The development of more efficient recycling technologies and circular economy models for RET components, particularly for solar panels and batteries, will be essential in reducing the environmental footprint of these systems. As RET adoption continues to grow, future work must address both technological innovations and sustainable practices to ensure a cleaner, more resilient energy future for residential grids.

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