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Review

Solar Energy Harnessing Technologies towards De-Carbonization: A Systematic Review of Processes and Systems

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Abstract: Solar energy, derived from the inexhaustible energy of the sun, has emerged as a promising solution to mitigate the environmental challenges posed by fossil fuel consumption and global climate change. This work explores the underlying principles of solar energy exploitation, focusing on energy collection technologies as the primary means of solar energy conversion. The physics of the state-of-the-art mechanisms, the photovoltaic effect, and the advancements that have driven the transformation of solar energy into a viable and sustainable alternative energy source are also examined. Through a comprehensive review of relevant literature and pioneering research, this study highlights the immense potential of solar energy and its role in shaping a cleaner, greener future. Towards de-carbonization, the various exploitation technologies are divided into direct and indirect in order to optimize resource utilization. Accounting for the most important advantages presented, solar-based utilization processes are perhaps the only ones that provide access to energy for all to satisfy their vital needs. As nations continue to embrace solar energy and invest in its development, we move closer to achieving a more sustainable and environmentally friendly world for generations to come.

Keywords: solar energy; sustainable energy systems; climate change; de-carbonization; renewable energy sources; energy harnessing technologies

Citation: Nikolaidis, P. Solar Energy Harnessing Technologies towards De-Carbonization: A Systematic Review of Processes and Systems. *Energies* **2023**, *16*, 6153. https://doi.org/10.3390/en16176153

Academic Editor: Elisa Artegiani

Received: 7 August 2023
Revised: 18 August 2023
Accepted: 22 August 2023
Published: 24 August 2023

1. Introduction

The escalating concerns regarding greenhouse gas (GHG) emissions and finite fossil fuel resources have propelled scientists and engineers to explore alternative and renewable energy sources (RES). Among these, solar energy stands out as a remarkable prospect because it is abundant, renewable, and emits no direct pollutants during operation. This introductory review delves into the fundamental principles of solar energy conversion through photovoltaic technology, shedding light on the progress and potential of harnessing the sun's energy for a cleaner, sustainable energy future.

As concerns surrounding climate change continue to grow, the potential of solar power to curb GHG emissions and mitigate environmental degradation becomes increasingly apparent. By analyzing existing studies and projections, this section highlights solar power's role in transitioning towards a sustainable, low-carbon energy system and reducing humanity's dependence on finite fossil fuels [1]. Elaborating on the worldwide potential of solar energy involves understanding the vast availability of solar energy resources across different regions and their implications for global energy transformation. Here, the worldwide potential of solar power in terms of solar irradiance, technological advancements, and the role it can play in addressing global energy challenges are discussed. Solar irradiance refers to the amount of solar energy received per unit area over a specific period [2]. One of the most significant advantages of solar power is that it is virtually available everywhere on Earth, although the intensity of solar radiation varies based on geographical location, time of day, and weather conditions. Regions close to the equator generally receive higher solar irradiance throughout the year, making them prime candidates for solar energy deployment [3]. However, even regions with lower solar irradiance can still harness solar power effectively through advancements in photovoltaic technology and energy storage systems.

Continuous research and technological advancements have significantly increased the efficiency and reduced the cost of solar power generation worldwide. Improvements in PV cell materials, manufacturing processes, and tracking systems have led to higher energy conversion rates and overall system performance. Additionally, innovations in energy storage technologies, such as lithium-ion batteries and grid integration solutions, have addressed the intermittent nature of solar power and enabled a more stable and reliable energy supply. These advancements have unlocked the full potential of solar power, making it an increasingly competitive and attractive energy option globally. The worldwide potential of solar power is closely tied to its capacity to accelerate the global energy transition towards sustainable and low-carbon sources [4]. As nations strive to reduce their carbon footprint and combat climate change, solar energy has emerged as a key enabler in achieving these goals. By investing in solar power infrastructure, countries can diversify their energy mix, decrease reliance on fossil fuels, and reduce greenhouse gas emissions, thereby contributing to a cleaner and greener future.

Another aspect of the worldwide potential of solar power is its role in addressing energy access challenges, particularly in remote and underserved regions. In many parts of the world, communities lack access to reliable electricity due to limited grid connectivity. Solar power, with its decentralized nature, offers a viable solution to bridge this energy gap. Off-grid solar systems, such as solar home systems and microgrids, can provide electricity to remote areas, empowering communities and improving socio-economic conditions [5]. Countries around the world have recognized the vast potential of solar power and are actively promoting its deployment through supportive policies and incentives. Feed-in tariffs, tax credits, and net metering are some of the mechanisms implemented to encourage investment in solar energy projects [6]. International collaborations and agreements also play a significant role in driving solar power adoption on a global scale, fostering knowledge sharing, technology transfer, and investment in solar infrastructure.

Compared to other renewable energy sources, solar energy offers several major advantages, making it a compelling option for sustainable energy generation. First of all, it is abundant and freely available. The sun emits an immense amount of energy, and this resource is virtually limitless. Unlike fossil fuels, which are finite and depleting, solar power provides a constant and inexhaustible supply of energy, making it a reliable and sustainable option. In addition, it can be harnessed virtually anywhere on Earth, as long as there is access to sunlight [7]. This widespread geographical distribution makes solar energy accessible to a broad range of regions, including remote and off-grid areas where establishing traditional power infrastructure may be challenging and costly. By using solar energy, we can significantly reduce our carbon footprint and combat climate change. It helps to minimize air and water pollution, protecting the environment and public health.

Technically, solar-based systems are modular, allowing for flexibility in design and scalability. They can be adapted to suit various energy needs, from small residential installations to large utility-scale solar farms. This flexibility makes solar power suitable for both centralized and distributed energy generation, offering versatility in energy planning and implementation [8]. By making use of such systems, decentralized energy generation is enabled, meaning that it can be produced close to the point of consumption. This reduces the need for long-distance transmission infrastructure and enhances energy independence for communities and nations, reducing vulnerability to disruptions and enhancing energy security. These devices operate silently, without noise pollution. This characteristic is particularly advantageous in urban areas and near residential developments, where noise from traditional power generation sources can be a concern. Furthermore, unlike conventional power plants, which require significant amounts of water for cooling, solar power plants do not consume water during electricity generation. This feature is especially valuable in water-scarce regions, where solar power can contribute to sustainable water management [9].

Once a solar power system is installed, the operating and maintenance costs are relatively low compared with other energy sources. Solar panels have no moving parts, reducing the risk of mechanical failure, and require minimal maintenance over their long lifespan (typically 25 to 30 years). As a result, solar power constitutes an economically attractive choice for long-term energy investments. On the other hand, the solar industry has become a significant source for job creation and economic growth. As the demand for solar installations increases, more job opportunities are created across various sectors, including manufacturing, installation, maintenance, and research and development. Based on the aforementioned critical advantages, solar energy can play a vital role in sustainable development. According to the extensive literature, there has not yet been a comprehensive review that evaluates all potential pathways to harness solar energy. This study stands out from others in that it provides a distinct classification of the processes that, either directly or indirectly, can increase the utilization of solar energy as a primary energy resource.

A wide variety of technologies and systems already exist for harnessing solar energy. Distinguished in direct and indirect processes, they continue to evolve and improve, leading to increased efficiency, reduced costs, and expanded application possibilities. In this work, the most important technologies are presented. The critical characteristics of the respective harnessing processes are provided and discussed in detail, along with their potential applications. The performance features of each method are also included in order to offer a comprehensive overview and auspicious comparison. The review is organized as follows: The direct harnessing systems are shown in Section 2. The indirect techniques are demonstrated in Sections 3–5, where the heat, electricity, and hydrogen storage systems are explained, respectively. The conclusions are drawn in Section 6.

2. Direct Harnessing Systems

Solar energy can be directly used with the aid of some well-known processes. Either immediately in the form of heat or after its conversion into electricity, this kind of RES can be used for the most common services such as space heating, domestic hot water, water pumping, seawater desalination, cooking, and so on. Figure 1 accommodates the direct harnessing methods along with the mechanisms that allow for the solar energy to be stored and used when needed, also referred to as indirect methods.

2.1. Space Heating/Cooling

The energy stemmed from the sun can facilitate the transition from the currently active to the modern passive houses (Passivhaus), nearly-zero energy buildings (nZEBs), and net-zero energy buildings (NZEBs). Passive houses (PHs) maintain comfortable and pleasant temperatures throughout the year with minimal energy consumption, regardless of climate or region. They utilize solar heat, internal heat sources, and heat recovery efficiently, so that even on cold winter days, there is no need for a conventional heating system [10].

In Central Eope, PHs use up to 90% less energy for heating than conventional houses, requiring less than 1.5 L of oil or 1.5 cubic meters of natural gas per year to heat one square meter of a dwelling [11,12]. A passive house of 100 square meters costs 10% more than a standard house. This cost is negligible compared with the energy savings achieved by a PH.

It is noted that the financial benefits come not only from the obvious reduction in the cost of energy consumed but also from the increase in the value of the building, the improvement of the performance of the mechanical equipment, the reduction of maintenance costs, etc. However, there are also the operational benefits, which help manage the building by improving comfort and safety levels as well as overall operation and efficiency. Last and one of the most important benefits are the environmental benefits that mainly concern the reduction of carbon dioxide emissions and/or other pollutants (including GHGs), the reduction of energy needs, and the preservation of natural resources, while simultaneously improving the environmental profile of the building [13].

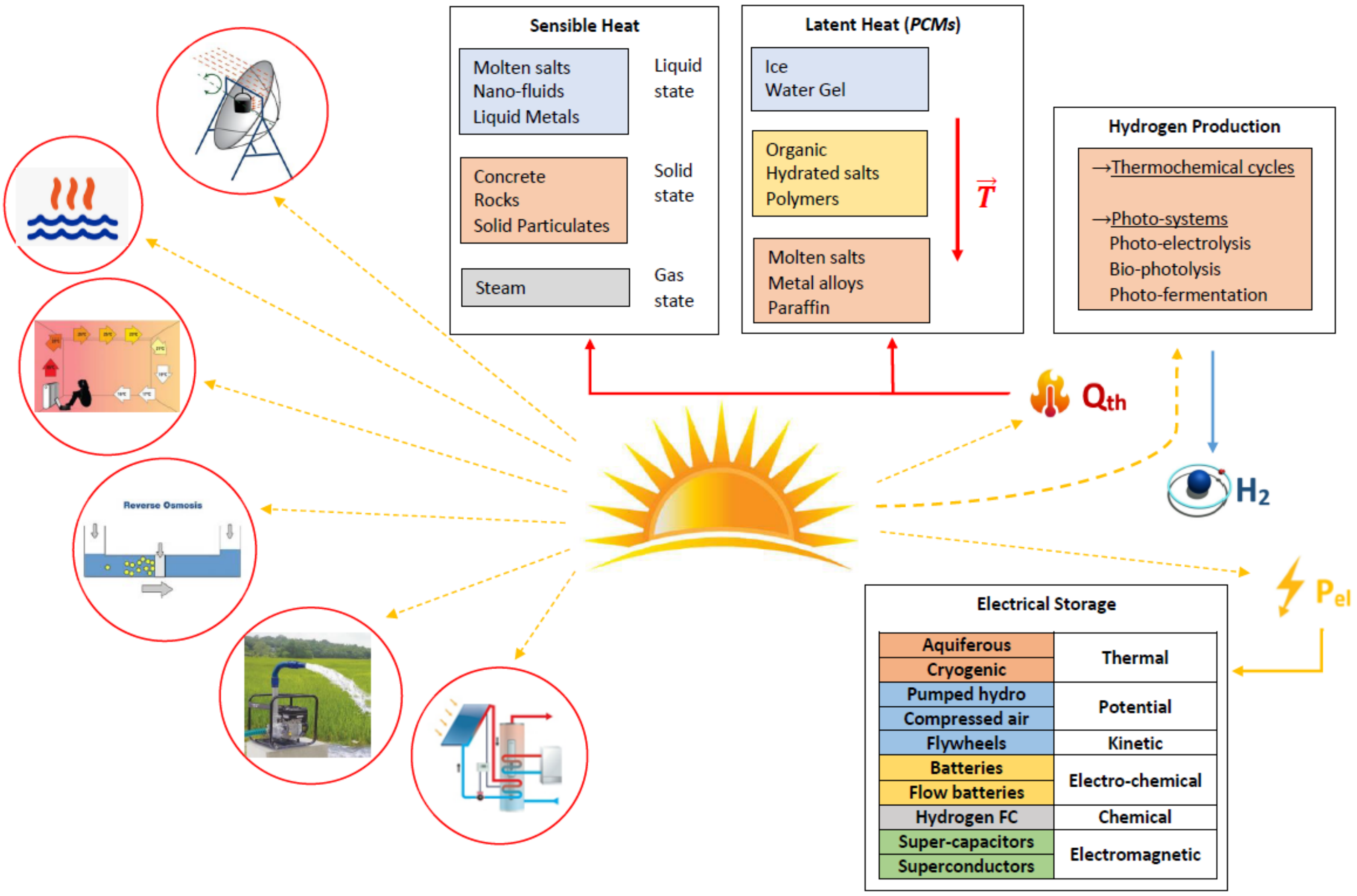


Figure 1. Direct and indirect methods for solar energy harnessing.

However, PHs, nZEBs, and NZEBs pose certain disadvantages, which are fortunately limited [12,14–16]. First, in the case of poor construction, negative effects appear. More specifically, the disadvantages concern the existence of noise as well as the risk of thermal losses. Another disadvantage is the limitation of space due to larger masonry [17]. There may still be difficulties in converting a conventional building into a passive one due to spatial constraints. Finally, there is a lack of suitable manufacturers, contractors, and materials for the construction of passive buildings.

The mechanisms that enable passive heating are known as passive solar heating systems. Passive solar heating systems are the structural elements of the building that, utilizing the principles of physics (the laws of heat transfer), collect solar energy, store it in the form of heat, and distribute it in the space without active mechanical systems. The collection of solar energy is based on the greenhouse effect, and in particular, the entry of solar radiation through glass or other transparent material and the trapping of the resulting heat inside the space covered by the glass [18]. They are usually attached to south-facing building facades (for northern latitudes), which should not be shaded during the winter. Passive solar technologies are combined with the required thermal protection (thermal insulation) as well as the required thermal mass of the building or the use of phase change materials to store and deliver heat to the space with a time delay.

Passive solar systems are divided into three main categories based on the way they capture and release solar heat, namely direct, indirect, and isolated gain systems. Direct solar gain is the easiest and least expensive way to heat a space [19]. The sun's heat is collected and stored indoors. Solar radiation enters through a glass opening oriented to the south and heats the space. This solar radiation is absorbed by structural elements such as walls and floors. The thermal mass of these structural elements helps to minimize sudden temperature changes from day to night and also stores heat during periods without sunlight. The conditions required for the efficient operation of the system are the following: (a) a south conservatory with a large area; (b) the thermal mass inside the building is large enough to absorb temperature changes; and (c) insulation on the outer side of the shell.

In indirect-gain systems, thermal mass collects and stores heat directly from the sun and then transfers it indoors. The main difference with direct solar gain systems is that the sun's rays do not cross the space since the thermal mass is essentially an external surface in the south. Isolated-profit systems are similar to indirect-profit systems. Their difference is that the collection surface and the heat reservoir are separated. Typical examples of an isolated gain system are the attached greenhouse and the thermosiphon panel. Figure 2 includes some representative systems of solar passive systems, including solar chimneys, thermal-mass walls, greenhouses, solar patios, the Trombe wall with its variations, physical and technical shades, and air vents.

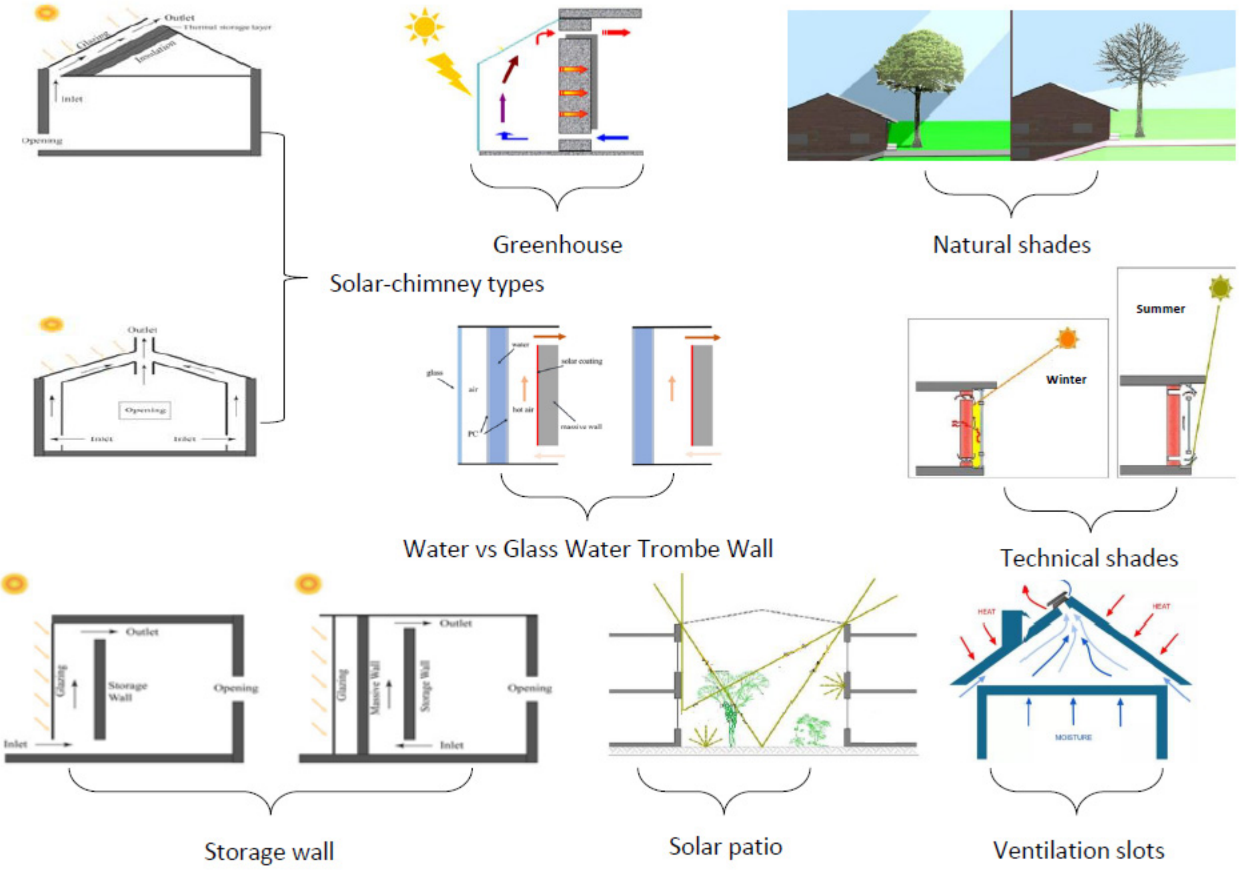
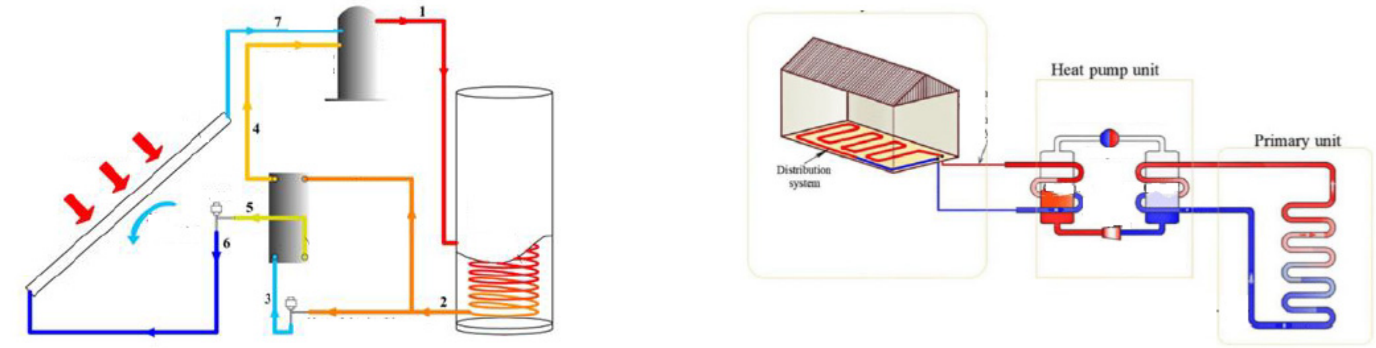


Figure 2. Passive systems for solar space heating.

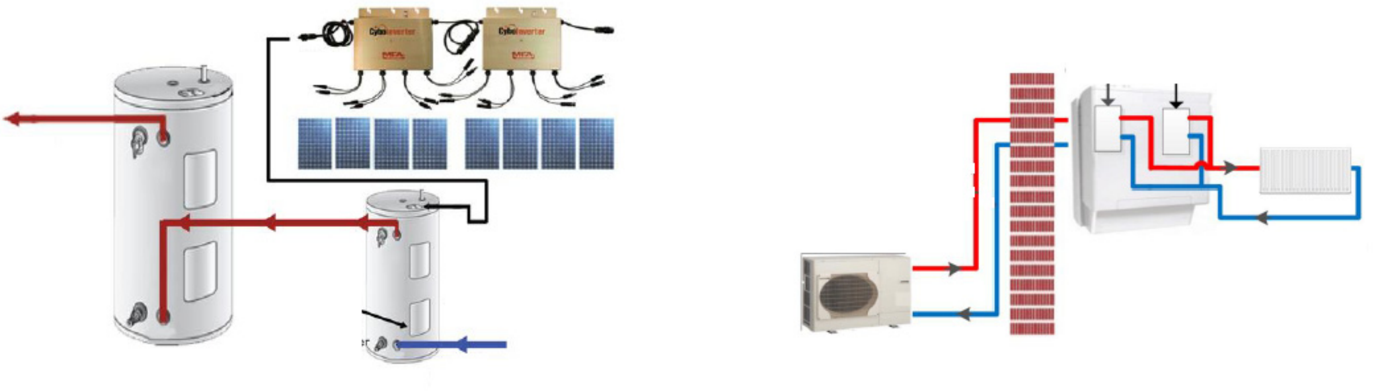
2.2. Domestic Water for Use or Space Heating

There are two different ways to convert solar energy into hot water for use: the direct conversion using solar panels and the indirect conversion using photovoltaics to produce electricity, which is used to heat the water by means of a thermal element or a heat pump. It is possible for a system to contain all systems simultaneously by using a heat exchanger with multiple inlets for thermal elements. Solar space heating collectors have gained significant interest in the last decade as they are considered a viable and efficient solution for space heating applications. The most common structure of a system is demonstrated in Figure 3, where the provided service is carried out either by solar thermal through collectors or solar electricity via PVs and electric heaters or heat pumps.



(a) Solar-thermal water heating

(b) Solar-thermal space heating



(c) Solar-PV water heating

(d) Solar PV space heating

Figure 3. Simulation of solar thermal for (**a**) water heating and (**b**) space heating and solar PV for (**c**) water heating and (**d**) space heating.

Solar collectors for space heating operate in a temperature range between 40 °C and 90 °C. The operating temperature depends on the type of collector used and the system design. In general, flat collectors operate at lower temperatures, while evacuated tube collectors can operate at higher temperatures due to their higher efficiency. The performance of solar collectors for space heating depends on several factors, such as collector design, orientation, weather conditions, and location. According to a study by Akram et al. [20], the efficiency of solar collectors for space heating varies between 50% and 80%. Additionally, the study reported that the efficiency of evacuated tube collectors was higher than that of flat plate collectors. The energy density of solar collectors for space heating depends on the surface of the collector, solar radiation, and efficiency. According to [21], the energy density of a solar thermal collector for space heating ranges from 50 W/m^2 to 1000 W/m^2. The study also reported that energy density increases with increasing solar irradiance and collector efficiency. The cost per installed kilowatt of solar collectors for space heating depends on several factors, such as collector type, system design, installation cost, and location. Based on the research presented in [22], the cost per installed kilowatt of solar thermal collectors for space heating ranges between $1200/kW and $2500/kW. It was concluded that the cost per installed kilowatt decreases as the system size increases.

The lifespan of solar space heating collectors depends on several factors, such as the type of collector used, the quality of the materials used, and maintenance practices. The lifetime of solar space heating collectors ranges from 10 to 25 years. The life of evacuated tube collectors was higher than that of flat collectors [23]. The maintenance requirements of solar space heating collectors depend on several factors, such as collector type, system design, and location. They include cleaning the collector surface, checking fluid levels, and inspecting the system for leaks. Although the expenditures are kept at very low levels, they are proportional to the system size in terms of installed capacity [24]. Considering the high initial cost and low operation cost, the life-cycle cost of such systems heavily depends on climatic conditions in different regions, the heater type, and the number of occupants per assessed facility. Consequently, the payback period constitutes a comparable metric between solar collectors, which can be examined with the aid of Table 1 [25].

Table 1. Solar collector features for water heating purposes.

Collector Type	Outlet Temperature (°C)	Water Tank Temperature (°C)	Efficeiency (%)	Payback Period (yrs)
Flat plate	27–60	45–65	52–80	2.92–4.53
Evacuated tube	27–60	45–65	55–80	3–10
Compound parabolic	66–80	37–65	65–80	-

The autonomy in hours for space heating also depends on the size of the collector, the solar radiation, and the design of the system. For space heating, it ranges from 6 to 10 h. Overall, compared with electric heating by utilizing the sun, solar thermal collectors are a sustainable and environmentally friendly source of energy, reducing dependence on fossil fuels and providing a reliable source of energy in remote areas. They can be simply integrated with other renewable energy sources, such as wind and biomass. On the contrary, the indirect conversion of the heat may provide a more flexible use. During the cold months, a heat pump can be turned on via an automated valve and continuously provide the facility with hot water from the solar panels. In the warm months, a heating element can take place and operate as long as needed.

Many households still use heating systems that make use of fossil fuels or electricity, which are becoming increasingly expensive and environmentally harmful. Heat pumps offer an alternative to traditional systems. A space-heating heat pump is an efficient and environmentally friendly way to keep homes warm. Heat pumps can draw heat from the environment, such as air, ground, or water, and use it to heat a space. The operating principle of a heat pump is based on the thermodynamic cycle of refrigeration. The heat pump takes heat from the environment, such as air, ground, or water, and uses a refrigerant to transfer the heat to the space to be heated. The refrigerant is compressed, which raises its temperature, and then flows through a heat exchanger, where it releases heat into the space. The coolant then returns to its original state and is ready to absorb more heat. This cycle repeats as long as the heat pump is running.

The operating temperature of a heat pump for space heating depends on the heat source and the heat sink. In general, the colder the heat source, the more difficult it is to extract heat from it. The ideal temperature range for air-source heat pumps is between 0 °C and 40 °C, while for ground-source heat pumps it is between -5 °C and 25 °C. Water-source heat pumps can operate in a wider temperature range, from -5 °C to 35 °C [26,27]. These temperature ranges may vary depending on the specific model and manufacturer. The efficiency level of a heat pump is measured by the coefficient of performance (COP). COP is the ratio of heat output to energy input. A COP of 3 means that for every unit of input energy, the heat pump produces three units of thermal power. The COP of a heat pump depends on the temperature difference between the heat source and the heat sink. The greater the temperature difference, the lower the COP. For example, a heat pump with a COP of 4 at an outdoor temperature of 7 °C may have a COP of 2 at an outdoor temperature of -7 °C. A heat pump's COP can also be affected by other factors, such as compressor and heat exchanger performance [28].

2.3. Water Pumping

A pump is any mechanical means by which it is possible to transfer a quantity of liquid from one altitude level to another that is higher, or from a low-pressure space to another high-pressure one. The problem of wasting energy and water can be found all over the world. Water pumping stations operate mainly empirically, based on the experience of the workers. Such behavior causes energy waste and high operating costs, which are completely undesirable [29,30]. Pumps play a key role in saving both energy and water. They account for 20% of the world's total energy consumption, and thus their monitoring becomes more important to reduce energy waste. Pump performance deteriorates for a variety of reasons, including cavitation, sludge settling, water hammering, electrical failures, and mechanical failures.

In general, pumps consist of one or more rotating rotors mounted on a shaft, which is driven by an engine and always rotates at the same time inside a housing (chamber, casing). The housing has liquid inlet and outlet openings. Impeller blades of a suitable shape are mounted on the rotating rotor. The rotor, together with the vanes, is called an impeller. As the impeller rotates, the fluid gains angular acceleration, creating a centrifugal force that carries the fluid toward the periphery of the casing to be removed from the outlet opening. As the liquid moves away from the center to the periphery, the pressure in the center decreases, and a new amount of liquid moves towards the low pressure point, resulting in a steady flow [31].

The pumping efficiency decreases when the pumped water has a high temperature. This increases the possibility of creating atmospheric phenomena inside the pump and can lead to reduced water flow and pressure, as well as increased wear and tear on the pump's internal components. For example, a common pump used in a house to draw water from a source may have an efficiency rating of close to 50–60%. This means that only half to 60% of the energy used by the pump is converted into actual water-pumping work. However, there are more efficient pumps that can have an efficiency rating close to 80–90%, and some specialized pumps can have even higher efficiency ratings. It is important to choose a pump with a high degree of efficiency to reduce energy consumption and save money on the electricity bill [32,33]. Fortunately, the temperature of the water drawn depends on many factors, including the source and the climatic conditions of the area. In general, the temperature of the water at the surface of a body of water, such as a river or lake, can vary significantly depending on the season and climatic conditions. In regions with cold winters, the water temperature can reach freezing temperatures, while on hot summer days it can rise to 20–30 °C [34].

In cases where water is pumped from deep wells or boreholes, the water temperature can be constant throughout the year, as the soil temperature at great depths remains constant relative to climatic conditions. Water pumping is not significantly affected by the temperature of the water being pumped, but temperature can affect pumping performance. However, pumping water can be done with specialized pumps that are designed to meet specific conditions, including water temperature. For example, there are pumps that are specially designed for pumping high-temperature water from geothermal wells or from thermal power plants [35]. Combined with PV for the provision of electrical energy, the major advantages of water pumping systems include: (a) they offer a continuous and uniform movement resulting in constant water flow and pressure; (b) a safe operation is guaranteed and able to be coupled with electric motors and high-speed internal combustion engines or air turbines in case of renewable curtailments; (c) the capital and O&M costs regarding the overall system remain at quite low levels; and (d) they provide good inertia to complete a necessary process before shut down in case of an outage.

Figure 4 shows a typical system consisting of a water pump supplied by PV modules. In remote and isolated areas, the socio-economic benefits become superior since access to clean and safe water for drinking, cooking, washing, and other domestic and industrial uses is achieved in the absence of fossil fuels and at the lowest possible cost. In agricultural and industrial processes, efficiency and utilization factors can increase due to the adjustable nature and control ability of pumps.

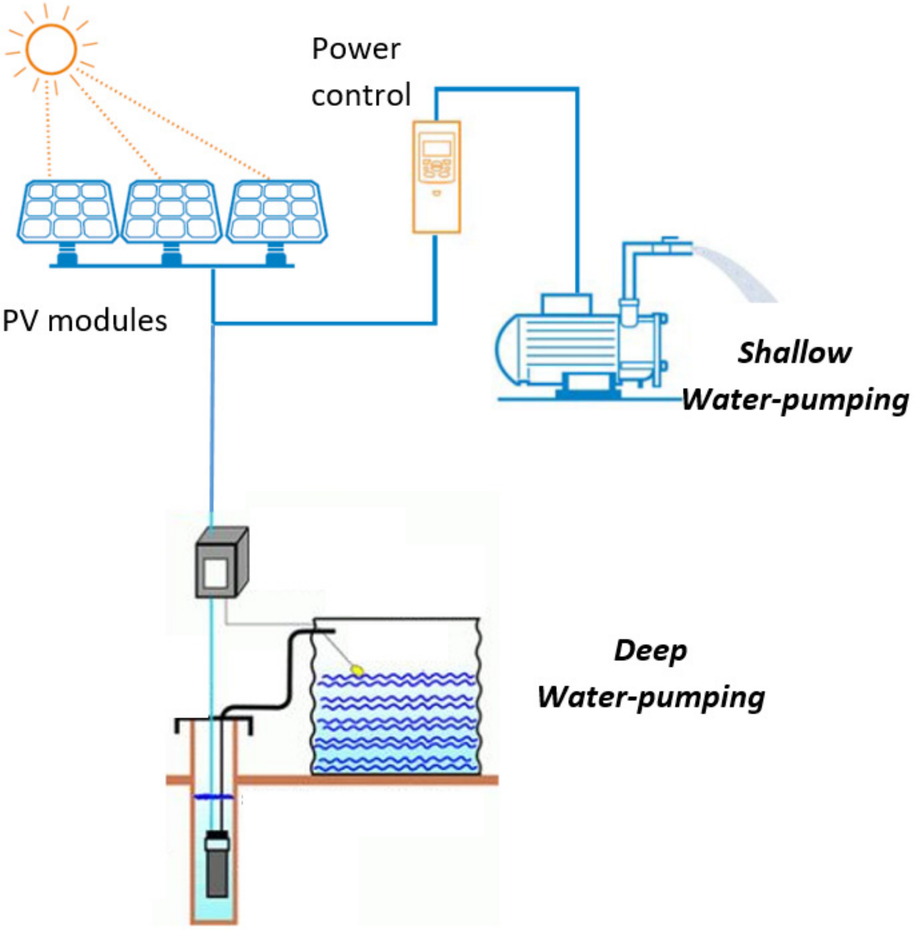


Figure 4. Typical framework for solar PV-water pumping systems.

2.4. Seawater Desalination

The continued growth of the world's population and economy has resulted in an increased demand for fresh water. About 70% of the world's population is expected to face a water deficit by 2025. Almost 50% of the world's population exists within 200 km of the sea, and only 0.5% of the earth's water sources are available as clean water for domestic and agricultural needs. Therefore, desalination would be one of the viable options to meet freshwater needs. Desalination is the process of extracting excess salt minerals from salt water, and this technology was commercialized during the Second World War. Different desalination technologies are currently commercialized, and all technologies require energy [36,37].

Reverse osmosis (RO) is a water purification process that uses a semi-permeable membrane to remove dissolved salts, ions, and other impurities from water. It is a form of filtration where water is forced through the membrane, leaving behind contaminants on one side and producing purified water on the other. This process is commonly used in various applications, including desalination of seawater, water treatment, and the production of high-purity water for industrial processes. The heart of the reverse osmosis system is the semi-permeable membrane. This membrane has very tiny pores that allow water molecules to pass through but prevent larger particles, such as salts, minerals, and other impurities, from passing. To initiate the process, external pressure is applied to the water to overcome the natural osmotic pressure. Osmotic pressure is the force that drives water to move from a region of lower solute concentration to a region of higher solute concentration. By applying pressure, the natural osmotic flow is reversed. Water molecules, being smaller than the dissolved salts and impurities, can pass through the membrane and move from the more concentrated side (feed water) to the less concentrated side (purified water). The semi-permeable membrane blocks the larger ions and impurities, allowing only pure water molecules to pass through. The rejected impurities form a concentrated brine or wastewater stream that is discharged separately [38,39].

The chemical reactions in reverse osmosis are primarily physical and not chemical in nature. The process is based on the principles of diffusion and osmosis, which do not involve chemical reactions. The dissolved salts and impurities in water remain in their ionic or molecular form but are physically separated from the water molecules by the membrane. However, there might be some minor chemical reactions that occur due to the presence of certain ions or molecules. For example, some RO membranes have surface functional groups that can interact with specific ions to facilitate or hinder their passage through the membrane [38]. These interactions are more related to the physical properties of the membrane and the dissolved substances than chemical reactions in the traditional sense. A PV desalination plant is depicted in Figure 5 [40]. The system usually consists of the basic elements of solar panels, which constitute the main source of energy; the desalination unit that is used to convert salt water into fresh water through the distillation process; storage tanks for the seawater feed and the fresh water product; piping and valves to link and regulate the flow of water; and several control and monitoring systems to optimally regulate the desalination process, increasing efficiency and lowering cost at a reliable and secure level [37].

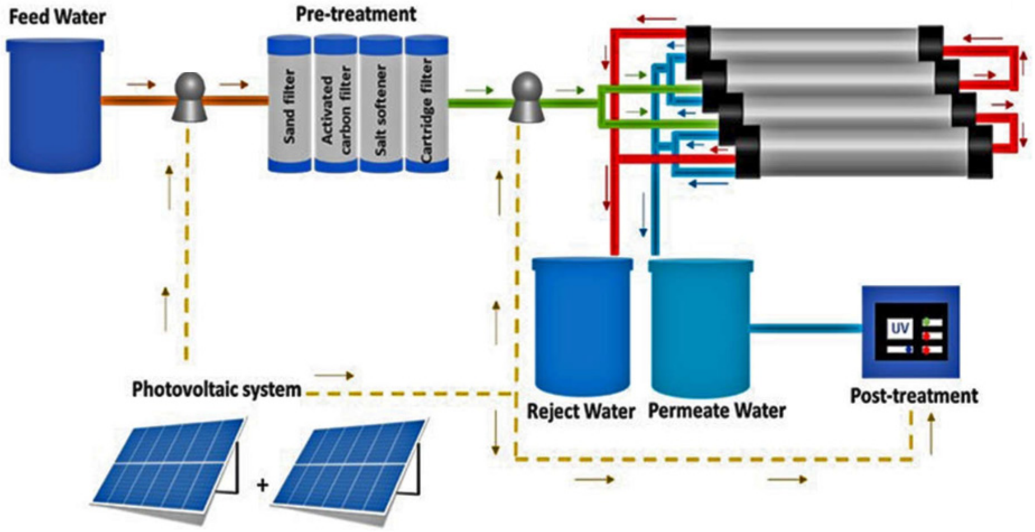


Figure 5. Demonstration of seawater desalination from PV systems.

The efficiency of a solar panel system for combined desalination can vary depending on several factors, such as the efficiency of the solar PV panels, the design of the desalination plant, and the quality of the water source. According to the sources, the efficiency of solar desalination systems can range from 30% to 80%. This can be further deteriorated by decreasing sunlight hours and increasing ambient temperatures. Two representative examples can be seen in Figure 6, where the hourly variation in temperature and incident solar radiation is given for summer and winter days.

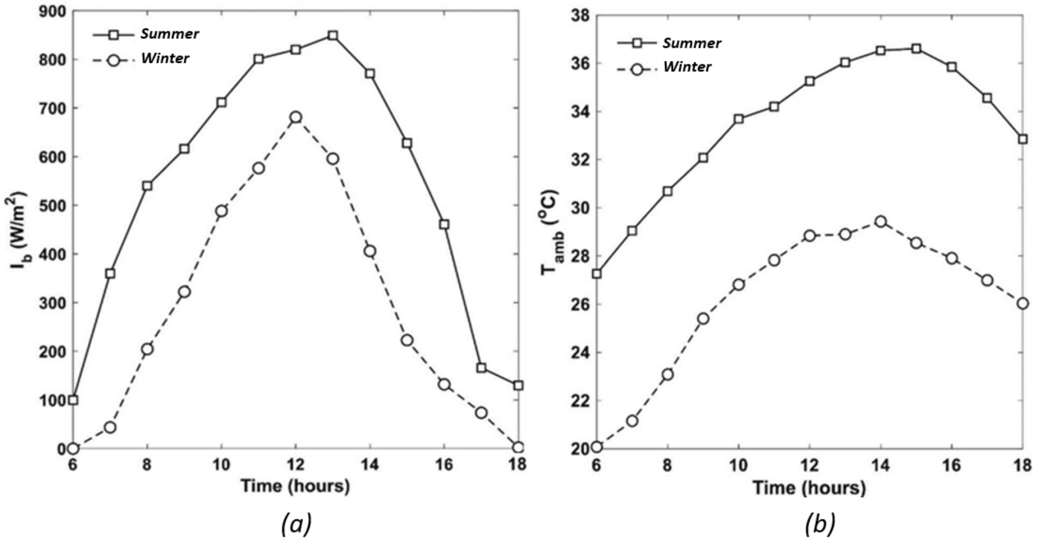


Figure 6. Hourly variation of incident (**a**) solar radiation and (**b**) temperature.

2.5. Solar Cooking

Solar cookers are an environmentally friendly and economical alternative to traditional cooking methods. They use solar energy to cook food, reducing the need for fossil fuel combustion and consequent GHG emissions. However, the performance of solar cookers can vary depending on the design and materials used. In Figure 7, some innovative designs for solar cooking systems are illustrated.

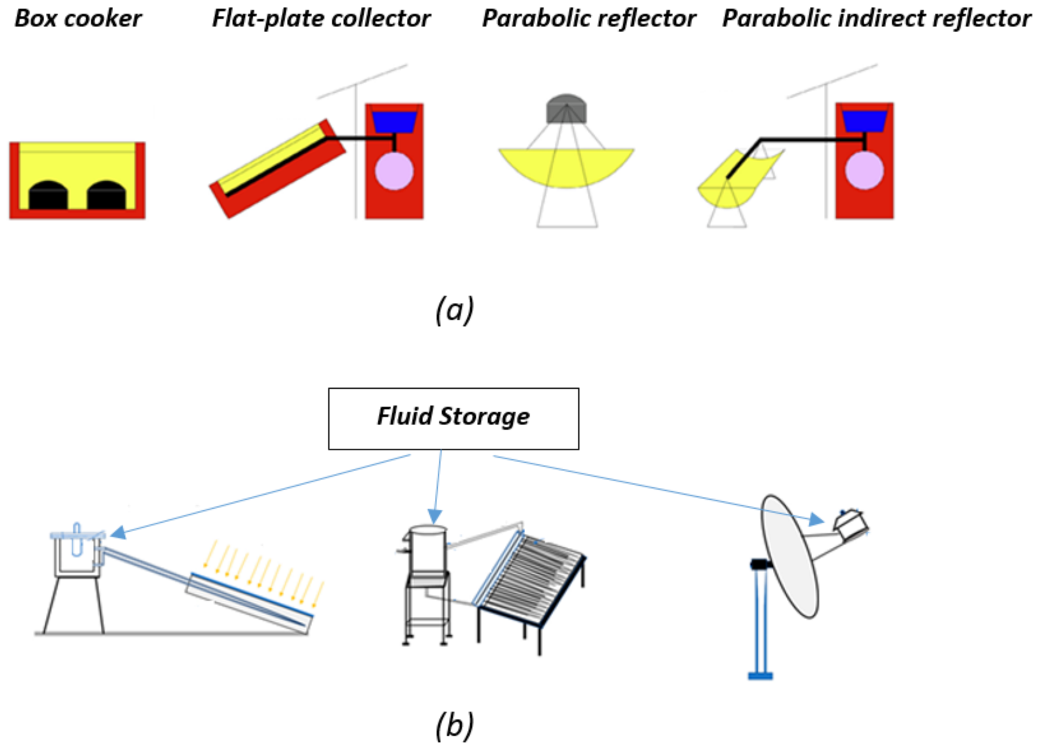


Figure 7. Main topologies for solar cooking (**a**) without and (**b**) with thermal storage.

Solar box-cooker types are the most common type of solar kitchen. They consist of an insulated box with a transparent lid, which allows sunlight to enter and heat the cooking chamber. The efficiency of a box-type solar cooker can range from 20% to 40%. Efficiency can be improved by using a reflector to direct more sunlight into the cooking chamber [41].

Following are the parabolic solar cookers, which use a parabolic reflector to focus sunlight onto a cooking vessel. The efficiency of a parabolic solar cooker can range from 25% to 45%. Performance can be improved by using a tracking mechanism to keep the reflector pointed at the sun. The next category involves funnel-type solar cookers and rectangular cookers that are capable of using multiple reflectors to direct sunlight into a cooking vessel. The efficiency of a solar-panel cooker of this type can range between 25% and 40%. Their overall performance can be improved by using a larger reflector and optimizing the angle of the reflectors. Finally, the hybrid solar cookers combine solar energy with other heat sources such as biomass or electricity. The efficiency of a hybrid solar cooker can range between 30% and 50% and can be increased by optimizing the combination of solar and other heat sources.

The temperature range for solar cooking was found to be between 100 and 120 °C. Studies also found that the performance of solar cookers increased with increasing cooking temperatures, suggesting that a higher temperature is desirable for effective solar cooking [42]. The temperature achieved during solar cooking can vary depending on the type of solar cooker used. The temperature in parabolic solar cookers can reach up to 300 °C, while box-type solar cookers have a lower temperature range of up to 120 °C [43]. In addition, the operating temperature for solar cooking strongly depends on the insulating material used in the solar cooker. The use of insulating material increases the temperature inside the solar cooker, reducing heat loss, which improves the efficiency of solar cooking. Overall, the operating temperature of solar cooking is affected by several factors, such as the type of solar cooker used, geographic location, weather conditions, type of food being cooked, and insulation materials. However, most of the studies report an operating temperature range of 100–150 °C for solar cooking [44].

While solar cookers may initially be more expensive investments than traditional cooking methods, they can save money in the long term. Solar cookers use free, renewable energy from the sun, meaning they require no fuel or electricity. This can lead to significant cost savings, especially for people living in areas where fuel or electricity are expensive or difficult to access. Moreover, solar cookers have a longer lifespan than traditional cooktops, which require frequent maintenance and replacement. Also, solar cookers do not emit harmful pollutants, which can lead to health problems and incur additional medical costs. In contrast to the capital costs, the O&M costs make their employment viable in combination with their long lifespan, which exceeds ten years in most cases, according to the type.

Solar cooking has emerged as a sustainable and environmentally friendly method of cooking food, especially in areas with abundant sunlight. It is relatively cheap to build and requires no operating costs, eliminating the need for open stoves, which can pollute indoor air and lead to respiratory problems. It provides a means of cooking food without relying on the electrical grid, making it ideal for remote and off-grid areas. A significant advantage is the lack of open flames, which makes solar cooking safer than traditional cooking methods, especially for children. On the negative side, it is highly dependent on sunlight, making it less effective on cloudy or rainy days. Also, cooking times are generally longer with solar cookers compared with traditional methods, which can be a disadvantage for those with limited time. Solar kitchens have limited capacity and are not ideal for cooking large quantities of food [41,45]. However, research and development (R&D) programs are already focused on storage candidates. Currently, the most competitive materials are materials with high heat capacity that are able to store vast amounts of solar energy in their mass. Next-generation cookers may concern phase change materials (PCM), the principal operation of which will be examined in the following sections.

2.6. Solar Lighting

Natural sunlight is beneficial for human health and well-being, as well as for showcasing colors accurately in indoor spaces. Solar lighting tubes, also known as solar tubes, sun tubes, or light pipes, are innovative daylighting systems that bring natural sunlight into interior spaces that might not have access to traditional windows or skylights. These tubes use a combination of reflective surfaces and optical technologies to capture sunlight from outside and then transfer it indoors, providing illumination without consuming electricity. They are particularly useful for areas like windowless rooms, hallways, closets, and other spaces where natural light is limited or unavailable.

Solar lighting finds ready application in residential, commercial, and industrial sectors by making use of tubular devices, which mainly exploit some lenses to form different topologies and modern designs. A dome or collector located on the roof or exterior of a building is designed to capture sunlight. This dome is usually made of a transparent material that allows sunlight to enter while protecting the interior from the elements. The captured sunlight is then directed downward through a highly reflective tube or pipe. This reflective tube ensures that light is effectively bounced along its surface, even if the tube bends or turns, maximizing the amount of light that reaches the interior space. As the sunlight travels down the tube, it is diffused to provide even lighting throughout the interior space. Some solar tubes incorporate diffusers or lens systems that spread the light and reduce glare, creating a soft and natural illumination similar to regular daylight. This offers the ability to operate even on cloudy days [46]. At the end of the tube inside the building, there is an interior fixture that distributes the diffused sunlight into the room. This fixture is designed to seamlessly blend with the interior décor.

A basic paradigm is depicted in Figure 8. Utilizing these topologies, three main operations are offered: daylight supply, dimmer capability, and emergency nightlight. Specifically, the whole lens system is activated to effectively transport the maximum natural light using on/off services. The ability to adjust the brightness is provided by appropriately selected lenses choosing the dimming function, whereas in spaces like hallways, closets, or bathrooms, the residence's way is lit up via a mini PV-battery-supported system. Regarding the advantages, the most important merit of solar lighting tubes is that they can transport sunlight through pipes, absorbing only the useful energy for lighting purposes and rejecting heat. In addition, solar tubes require no electricity to operate, making them a highly energy-efficient system as well as an environmentally friendly solution. Moreover, they can be particularly useful for spaces where privacy is important, as they allow light to enter without compromising privacy like windows or other openings [47].

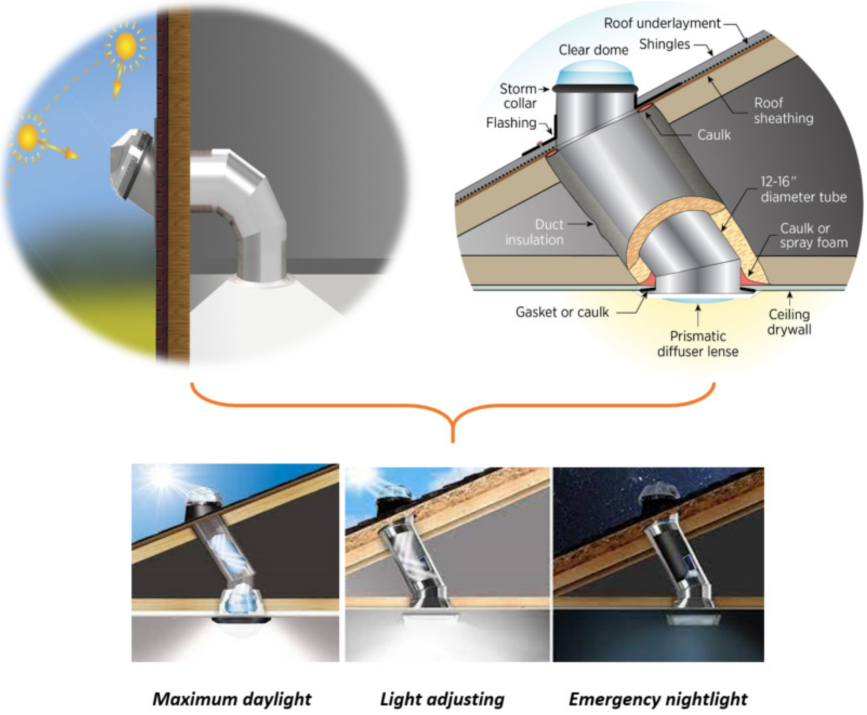
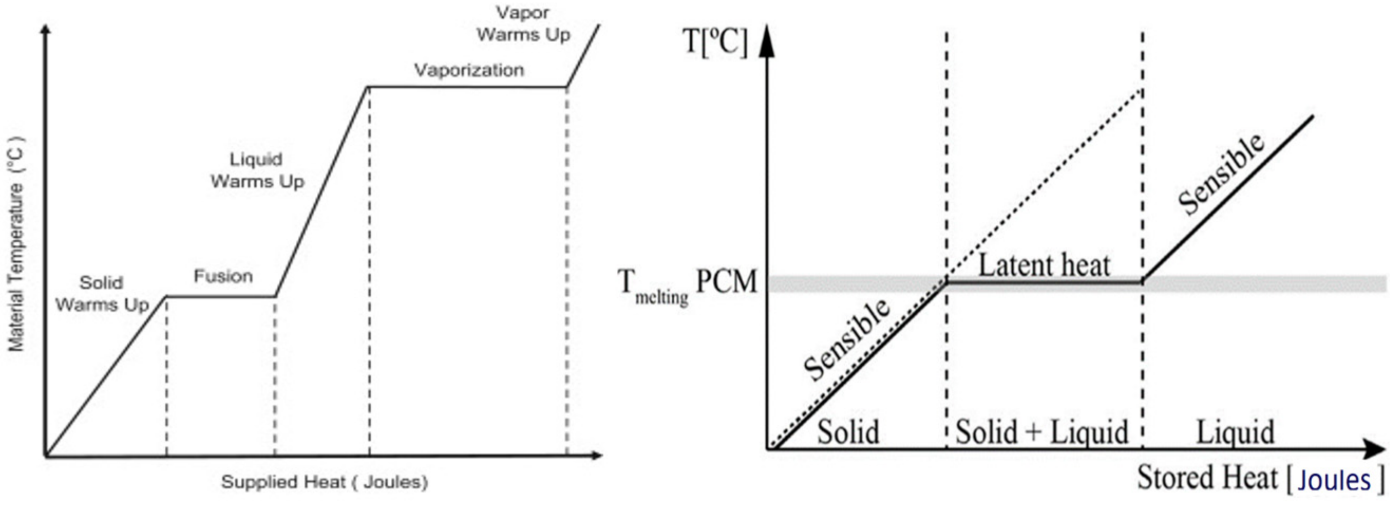


Figure 8. Principal function of solar tubes in lighting services.

3. Thermal Storage Systems

This section provides a broad overview of storage technologies as a means to indirectly exploit solar energy. Based on the extensive literature, great efforts are made in order to constantly increase the share of RES in energy systems and reach the imposed targets by 2023 and 2050. Nowadays, uncertainty is added both on the production and consumption sides due to extreme and difficult-to-predict weather events, the presence of new complex and active electric appliances, the increasing number of electric vehicles (EVs), and the distributed RES. The sector electrification concept leads to net-load profiles that fluctuate even more unevenly [48], requiring enhanced tools for clustering [49], accurate forecasting [50], efficient generation [51], and spinning reserve scheduling [52]. Alternatively, generation-demand mismatches can be lowered by decoupling the time between production and consumption by making use of storage systems.

Thermal storage can definitely facilitate production-demand heterosynchronization with the aid of some well-known processes. These techniques rely on sensible and latent heat. Latent heat is the heat absorbed or released by a substance during a material's phase change, such as melting or boiling. It is called "latent" because it is not detected by a thermometer and the temperature of the substance remains constant during the phase change. In contrast, sensible heat is heat that can be detected by a thermometer and results in a change in temperature. Sensible heat can be transferred by conduction, convection, or radiation, while latent heat is only exchanged during a phase change. Therefore, they are divided into sensible-heat systems, which are sub-categorized by the state of their storing medium into liquid, solid, and gas systems, whereas the latent heat methods mainly relate to phase change materials (PCMs), including ice, water gels, organic and polymer materials, hydrated salts, metal alloys, paraffin, etc. The temperature over the supplied and stored energy for sensible and latent heat storage is presented in Figure 9 [53,54].



(a) *(b)*

Figure 9. (**a**) Supplied versus (**b**) stored thermal energy for PCMs.

3.1. Sensible Heat

This type of energy storage involves heating a material, such as a liquid or solid, to store thermal energy. Thermal energy can be released as heat when needed, such as during cooking or space heating. Sensible heat storage can be achieved through direct storage, such as in water tanks or rocks, or indirect storage via heat exchangers. Based on the state of the storage medium, the following categories can be identified:

- Solid storage involves storing solar heat in solid materials such as stones, concrete, or bricks. These materials have a high thermal mass, which means they can store large amounts of heat for long periods of time. Solid storage is commonly used in passive solar buildings and some solar cooking systems.

- Liquid storage involves storing solar heat in liquids, such as water or oil. Liquid storage can be done either in a single tank or in two tanks (one for hot and one for cold fluids) connected by a heat exchanger. Liquid storage is commonly used in active solar heating and cooling systems.
- Gaseous storage involves storing solar heat in superheated gases, including steam. PCMs have a high energy density, which means they can store large amounts of heat in a small volume. Although they are commonly used in solar thermal energy storage systems for residential and commercial applications, sensible heat storage constitutes a retrospective procedure following the latent heat process (which is achieved by utilizing PCMs) in larger-scale industrial and energy-intensive plants.

3.1.1. Solid-State Thermal Storage

In general, solid media usually consist of materials with pores, where heat storage and transfer take place in the form of air flow through them. The storage capacity of sensible heat storage media depends on the value of their specific heat capacity. To allow for the storage to be realized, heat transfer fluids (HTF) are needed in order to enable thermal flow from the source to the storage medium. Water has the highest specific heat capacity, which is why it is the most used medium, and it is also an economical solution. As the main energy carrier, the water is located in suitably shaped tanks where it is heated using solar energy. For temperatures above 100 °C, other liquids with a higher boiling point are preferred, depending on the intended application [55]. Sensible heat storage (SHS) systems using water as a medium usually exhibit efficiencies in the wide range of 50–90%.

Figure 10 represents a typical simulation of thermal storage in concrete formations. Apart from concrete, rocks and solid particulates are also examined. The solar energy is transferred from the collector with the heat transfer medium to the storage container that includes the solid material, in our case the cement, where, through triodes, the water moves towards the cement and to the various heaters together with the steam generator, which make up the part of the system related to electricity generation, but this work focuses purely on the system related to heat storage. There is also a barrel, known as an expansion vessel, that is able to protect the system from the expansion of the steam so that it does not explode. Inside the cement, there are tubes that act as a heat exchanger in which the heat is transferred from the heat transfer medium to the solid.

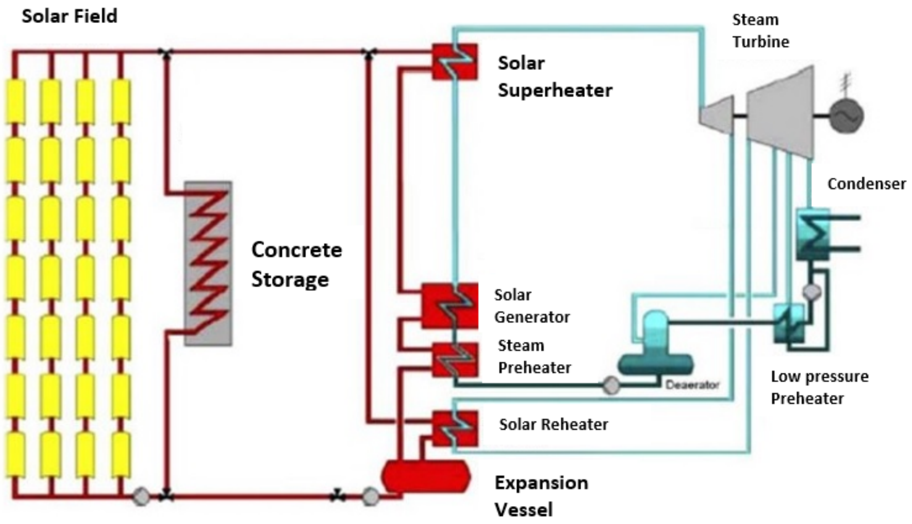


Figure 10. Simulation of a solar thermal plant with embedded concrete storage.

The cement has an operating temperature of 200–400 °C, so the system does not suffer from probable damaging hazards such as de-bonding of the pipes from the cement [56].

According to [57], cement types are capable of withstanding temperatures greater than 500 °C. The lifetime of a solar energy collector is estimated at around 25 years, covering the time horizon of a long-term economic analysis without the need for its replacement. Further advantages relating to the passive storage system in cement include the low cost of the working medium, satisfactory heat transfer in and out of the solid medium due to the good contact between the solid medium and the pipes, their friendliness to the environment, and their simplicity in design. On the other hand, the disadvantages are the cost of the alternator, the long-term instability, and the fact that generally, thermal energy storage (TES) systems provide low energy densities.

The energy density of cement based on [58] ranges from 850 J/Kg·K to 882 J/Kg·K. It depends on the type of cement used in each case and whether there is an iron framework within its body structure. The efficiency of TES systems can be generally calculated as follows:

$$\eta_{TES} = \frac{E_{th,d}}{E_{th,c}} \tag{1}$$

where $E_{th,d}$ is the heat released from the system and $E_{th,c}$ is the heat injected into the TES system. Cement, by its nature, does not require much maintenance, and its cost varies between 750 and 850 EUR/m^3 [59]. The cost for the collector is 250 EUR/m^2, and it may need to be replaced every 25 years. For the other parts of the system, nothing has been mentioned regarding their lifetime, so based on the articles, it will be considered that the collector is the most vulnerable part of the system, and from that, it is determined by the collector, since if it breaks, then there is an issue with the smooth operation of the system. The cost of the container varies for the different storage methods; only in the case where thermal oil is used, its price is 1000 EUR/m^3. The cost of maintenance and operation of the system in percentage is 1% [57,60].

Solid-particle thermal energy storage (SPTES) is an emerging technology that has the potential to improve the performance and reliability of thermal energy storage systems. This work will specifically deal with sensible heat thermal energy storage materials that store thermal energy in their specific heat capacity (Cp). This technology involves the use of solid particles as a storage medium, which are heated or cooled in periods of low demand and are still used to provide heat or cold during periods of high demand. During the process of absorbing thermal energy, no phase change occurs, and the materials show an increase in temperature. The amount of heat stored is proportional to the density, volume, specific heat, and temperature variation of the storage material. In addition to solar radiation, this technology has also been studied as a potential solution for storing and using thermal energy from various sources, including waste heat recovery and industrial processes.

The operating principle of SPTES is based on quite simple energy cycles. Solid particles, such as stones, sand, or ceramics, are heated or cooled using a medium called a heat transfer fluid, such as air or water, during periods of low demand. The heated or cooled particles are then stored in a container until they are needed to provide heat or cold during periods of high demand. When heat or cold is required, the particles pass through a heat exchanger (HEX), where their thermal energy is transferred to the heat transfer fluid, which is then used to provide the required heating or cooling. The heat transfer fluid can also be used to cool or heat the solid particles during the charging or discharging process. Below, we can see such a proposed arrangement [61]. A demonstration of the SPTES plant is included in Figure 11.

Sunlight is reflected and concentrated by solar field heliostats in a central tower. The particles flow through the receiver at the top of the tower, collecting concentrated sunlight. After reaching the desired temperature, the solid particles are moved from the conveyor system to a hot storage tank, where the material is collected until it is moved to a heat exchanger (HEX) to transfer the high-temperature heat to the power generation cycle. The spent heat particles are then transferred to a (relatively) low temperature storage tank to be stored until they can be moved back to the solar receiver at the top of the tower to collect solar heat again [62].

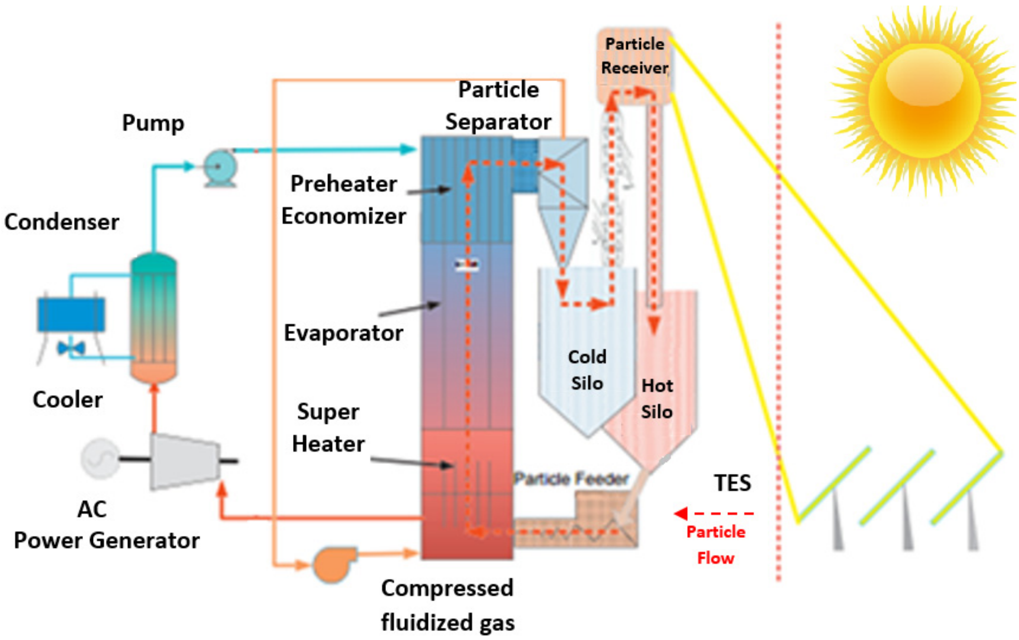


Figure 11. Simulation of solar thermal plant with embedded solid-particulate storage.

The type of solid particles used in SPTES can vary depending on the specific application and operating conditions, but some common examples include:

Rocks and minerals: Certain types of rocks and minerals can be used as thermal storage media due to their high thermal conductivity and heat capacity. Examples include basalt, limestone, and silica sand.

Metal oxides: Certain metal oxides, such as aluminum or magnesium, can be used as thermal storage media due to their high thermal conductivity and chemical stability at high temperatures.

Carbon-based materials: Carbon-based materials such as activated carbon and graphite can also be used as thermal storage media due to their high thermal conductivity and ability to absorb and release heat.

The choice of solid particles used in SPTES depends on several factors, such as cost, thermal conductivity, thermal stability, and the heat capacity required for the specific application. In the table below (Table 2), we can identify various characteristics of mineral metals used in SPTES.

Table 2. Performance indices pertaining to solid-state storage systems based on sensible heat.

Type	Porosity (%)	Density (tn/m^3)	Compressive Strength (MPa)	Thermal Conductivity (W/m·K)	Sensible Heat Storage Capacity (MJ/m^3·°C)
Granite	1.02–2.87	2.5–2.6	100–300	2.8	1.44–2.88
Quartzite	0.22–22.1	2.2–2.8	100–350	2	1.75–2.5
Marble	0.40–0.65	2.5–2.9	150–300	7.7	3.822
Basalt	0.65–0.81	2.6–2.7	50–200	3.2	1.68–2.52
Hornfels	0.8–2.3	2.4–2.8	100–200	1.5	2.56–2.88

Naturally available earth materials such as stones, sand, gravel, etc. can be used for sensible heat storage. They are suitable for use as fillers in thermoclinic single-tank thermal energy storage systems, where they are arranged in a packed bed structure within a container. The heat transfer fluid (HTF) flows through the packed bed and exchanges heat through direct contact. Earth materials are cheap, readily available, non-toxic, non-flammable, and act as both a heat transfer surface and a storage medium. Direct contact not only reduces the need for expensive heat exchangers but also increases the contact surface between HTF and the thermal storage medium. Thermal oil is the most commonly used HTF for direct heat exchange with filler materials such as rock and sand in large CSP plants. However, other HTFs, such as air, are also used in smaller space-heating solar thermal systems in homes.

Choosing sand or natural rock as a fill material can reduce the amount of HTF required to charge and discharge thermal energy to the tank by up to 80%. Local availability, low cost, density, thermal capacity, and thermal conductivity are decisive criteria for choosing the best rocks, sands, etc. for use as packed bed fillers. Other desirable properties, such as high surface hardness for resistance, low porosity to prevent oil penetration, high mechanical strength, etc., are also considered. The chemical composition and mineralogy of rocks and sands are also studied, as they affect their degradation due to thermal oil flow over a long period of time. Grirate et al. [63] studied various rock samples for TES suitability. They carried out the TGA analysis, where granite and marble lost about 3.3% and 2.9% of their weight, respectively, at a high temperature of about 350 °C. Granite is composed of minerals that contain hydroxyl bonds that break at high temperatures, leading to weight loss. The marble is mainly composed of $CaCO_{3,}$ and its weight loss was caused by the escape of CO_2 during heating. Other rock types, such as quartzite, basalt, and hornfels, were thermally stable up to 400 °C with zero weight loss. Based on the above, it was concluded that all rock types have almost similar thermo-physical characteristics and are suitable for use as filler materials for temperatures operating up to 350 °C. Past research data indicate that quartzite is the best among the rock types, with a high thermal conductivity of 7 W/m·K and a higher thermal storage capacity of 3822 $kJ/m^3 \cdot K$.

Rocks of various sizes, such as stones, pebbles, and small gravels, are used for bed fillings, while sand with a smaller grain size in the range of 0.074–4.5 mm can be used in a fluidized bed. The sand consists mainly of the mineral quartz, with a high content of silicon (SiO_2) exceeding 90%. Fine sand and other small-sized particles such as ceramics (alumina, silicon carbide), dry cement powder, coal, etc. are used in air suspensions to directly collect heat from concentrated solar radiation. The particle size of the suspension is controlled using a cyclone separator set at an appropriate grain size cut-off point. These solid particles are thermally stable even at very high temperatures in the solar power tower type (SPT) CSP unit, and direct absorption of solar radiation improves efficiency [64]. Therefore, they are best suited for use as suspended solids in a thermal energy capture/storage system.

One of the critical factors in SPTES performance is the operating temperature. The operating temperature of SPTES varies depending on the type of solid particles used and the desired application. In general, SPTES systems can operate at temperatures ranging from −50 °C up to 1000 °C. The choice of operating temperature is crucial to achieving high energy storage density, high efficiency, and low cost. For low-temperature applications such as space heating and cooling, the operating temperature is usually between 100 °C and 250 °C. For high-temperature applications such as industrial process heating and cooling, the operating temperature can reach up to 1000 °C [65].

The performance level of SPTES is measured by the energy storage capacity of each particle. The energy storage capacity is determined by the amount of thermal energy that can be stored in the solid particles and the size of the storage container, and the specific efficiency is determined by the amount of thermal energy that can be extracted from the solid particles and the efficiency of the heat exchanger. SPTES has a higher energy density and longer storage times compared with traditional thermal energy storage systems, making it a more efficient and economically viable solution. Additional factors that can affect the performance of this technology are:

Particle properties: The properties of the solid particles used in the SPTES system, such as size, shape, density, and thermal conductivity, can significantly affect the energy storage capacity and system performance.

Heat transfer fluids: The choice of heat transfer fluids used in the SPTES system can have a significant impact on its performance. Factors such as the heat capacity, viscosity, and thermal conductivity of fluids must be carefully considered.

Charge and Discharge Rates: The rate at which heat is transferred during charge and discharge cycles can affect system performance. Fast charging and discharging rates can lead to thermal stresses and shorten system life.

Temperature Range: The temperature range in which the SPTES system operates can also affect its performance. Lower temperatures can reduce system performance, while higher temperatures can lead to thermal stresses and shorten system life.

Thermal Insulation: The thermal insulation of the storage tank is critical to minimizing heat loss and maximizing the energy storage capacity of the system.

System design: The overall design of the SPTES system, including the configuration and layout of the storage tank, heat exchangers, and other components, can also affect its performance.

SPTES lifetime depends primarily on the type of solid particles used in the vessel design as well as various other factors such as cycle frequency and operating temperature. This frequency refers to the number of times the storage material is subjected to a complete heating and cooling cycle. Operating temperature affects storage material degradation and storage container corrosion. Properties of the storage material, such as thermal stability, thermal conductivity, and chemical stability, also play a critical role in determining the lifetime of SPTES. In addition, the quality of the components used can affect the durability and reliability of the system. In general, SPTES systems have a lifetime of over 20 years. The solid particles used in SPTES corrode over time, but the storage vessel is designed to withstand the high temperatures and pressures encountered during the charging and discharging processes.

The amount of stored heat in a solid depends on the *Cp* of the medium, the temperature change ($\Delta T = T_H - T_L$), and the amount of storage material m and is defined as

$$Q_s = \int_{T_L}^{T_H} m \cdot C_p dT \tag{2}$$

SPTES systems offer several advantages over other TES technologies, such as lower cost, higher energy density, and longer storage life. Furthermore, SPTES systems can be designed to operate at higher temperatures than other TES systems, making them particularly suitable for applications requiring thermal energy at high temperatures. However, SPTES systems also have some disadvantages. For example, solid particles can be prone to abrasion and degradation over time, which can reduce system performance and lifespan. Additionally, handling and transporting the solid particles can be difficult, which can increase the cost and complexity of the system.

3.1.2. Liquid-State Thermal Storage

In this subsection, three categories of liquid states are examined, i.e., molten salts, nanofluids, and liquid metals. The analysis includes, among other things, their operating temperatures, their efficiency, their energy density, their costs, their lifetime, their maintenance requirements, and finally their advantages and disadvantages. Liquid storage can be done either in a single tank or in two tanks (one for hot and one for cold fluids) connected by a heat exchanger. It is commonly used in active solar heating and cooling systems. Liquid metals have shown significant potential as sensible heat storage materials in various thermal energy storage applications. Sensible heat storage involves storing thermal energy in a medium by changing its temperature rather than undergoing a phase change (as in latent heat storage). Figure 12 demonstrates the most popular devices capable of gaining the needed high temperatures by relying on concentrated solar power (CSP).

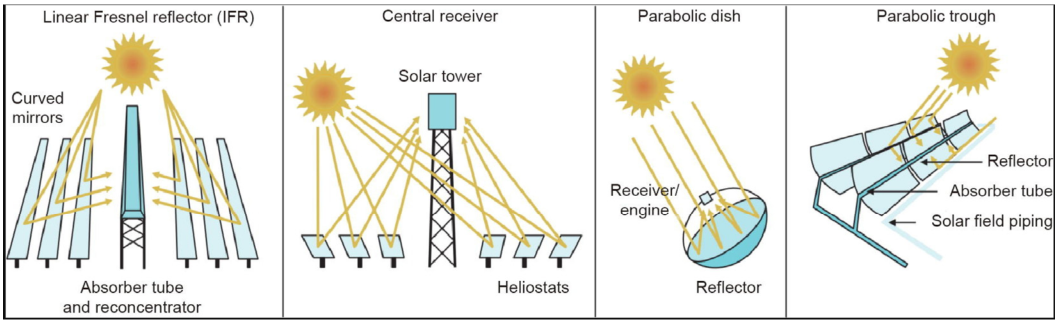


Figure 12. Main topologies for concentrated solar power systems.

Molten salts have been used as sensible heat storage materials in solar power plants due to their high thermal stability, low cost, and good heat transfer properties. It is proven that molten salts have a high energy storage capacity and can be used as the main heat transfer fluid, allowing efficient energy storage and transfer [66]. The research performed in [67] reports that a $LiNO_3$-$NaNO_3$-KNO_3 eutectic mixture had a high melting point, good thermal stability, and excellent heat transfer properties, making it a suitable candidate for high-temperature energy storage applications. The thermal performance of a direct-contact thermal storage system using molten salt as the storage medium possesses a higher energy storage density than other systems using water or PCMs.

However, some limitations relating to the molten salt treatment still remained, including the corrosion of storage tank materials and the formation of solid deposits on heat transfer surfaces. Also, the use of molten salt as a HTF in a parabolic trough collector can cause solid deposits to form on the heat transfer surface, thus reducing the overall efficiency of the system.

Nanofluids are a class of advanced heat transfer fluids that have gained significant attention in recent years due to their enhanced thermal properties. A nanofluid consists of a base fluid (typically water, oil, or ethylene glycol) blended with nanoscale particles, such as metallic, oxide, or carbon-based nanoparticles. The addition of nanoparticles to the base fluid results in a fluid with unique heat transfer and thermal storage capabilities, making them promising candidates for various applications, including thermal storage. Nanofluids have gained attention in recent years as potential heat transfer fluids due to their improved thermal properties compared with traditional heat transfer fluids. The use of nanoparticles in base fluids can lead to improved thermal conductivity, heat capacity, and heat transfer coefficient. The study [68] reviewed the use of Al_2O_3-water nanofluids in a shell-and-tube heat exchanger for thermal energy storage. The results showed that the use of nanofluids improved the thermal performance of the system compared with the use of pure water. The use of graphene oxide–water nanofluids in a shell-and-tube heat exchanger is also examined for thermal energy storage, with the expectation of improving the thermal conductivity and heat transfer rate of the system.

Different types of nanoparticles in base fluids, such as Fe_3O_4, CuO, and TiO_2, create some concerns with respect to precipitation and aggregation of nanoparticles and high production costs in some practical applications. Aiming to make the processes more cost-effective, hybrid nanofluids have gained research interest. Their key advantages are enhanced thermal conductivity, increased specific heat capacity, temperature stability, better heat transfer rates, and compatibility with existing systems [69]. Nanoparticles in the nanofluids facilitate better heat transfer due to their high surface area-to-volume ratio, resulting in improved thermal conductivity compared with conventional fluids. They have the ability to store thermal energy more effectively, increasing the specific heat capacity of the nanofluid. This allows for a higher amount of thermal energy to be stored in a smaller volume. Hybridizing the nanofluids exhibits greater stability at higher temperatures, making them suitable for applications that involve high-temperature thermal storage. Hybrid nanofluids can efficiently transport and disperse heat within the storage medium, promoting more rapid charging and discharging processes. Finally, they can often be used in existing thermal storage systems without the need for major modifications, providing a cost-effective upgrade.

The last category concerns liquid metals such as sodium, potassium, and their alloys, which have been extensively studied as heat transfer fluids and thermal energy storage media. Liquid metals have emerged as promising candidates for thermal energy storage at high temperatures due to their unique properties, such as high thermal conductivity, low viscosity, and excellent stability at high temperatures. A high energy storage density of up to 18.6 MJ/m^3 can be achieved by making use of a liquid metal heat pipe for thermal energy storage. Liquid gallium TES medium reaches high temperatures in the range of 400–700 °C and has a specific heat capacity rated at 329 J/kgK [70]. Due to their high thermal conductivity, wide operating temperature range, and high energy density, liquid metals show great potential as SHS mediums for high-temperature applications. However, the use of liquid metals poses some challenges regarding material compatibility, corrosion, and toxicity concerns for certain applications. More research is needed to address the challenges associated with the development of suitable containment materials and systems, leading to a broader adoption of liquid metals for efficient TES solutions. A comparative overview of the liquid-state TES systems is presented in Table 3.

Table 3. Performance indices pertaining to liquid-state storage systems based on sensible heat.

System	Operating Temperature (°C)	Energy Density (MJ/m^3)	Efficeiency (%)	Life-Cycle (yrs)	Specific Cost ($/kWh)
Molten salts	250–565	498	95	30	200
Nanofluids	100–400	145	98	10	700
Liquid metals	500–1000	775	92	-	5000

3.2. Latent Heat

Latent heat energy storage systems incorporate phase change materials such as water gel and ice for use in building applications and a host of other materials for higher-scale industrial and power applications, such as hydrated salts, organic and polymer materials, molten salts, metal alloys, and paraffin. Latent heat transfer with high-thermal-density materials has been considered a promising technology to save energy by reusing the waste heat stream. Latent heat is the heat released or absorbed by a body or thermodynamic system during a constant temperature process [71].

Latent PCMs, also known as latent heat storage materials, are a type of phase change material that stores and releases large amounts of thermal energy as it undergoes a phase change between solid and liquid or between liquid and gas. During this phase change, the material absorbs or releases a large amount of latent heat, which can be used for heating or cooling applications. They are commonly used in various industries, such as construction, transportation, and electronics, to improve energy efficiency and reduce energy consumption. They can be used in insulation systems, heating and cooling systems, and thermal energy storage systems.

The application of solar energy for cooling purposes requires an interconnection or energy conversion system, usually in the form of a solar air conditioner and chiller. Among the various types of chillers available, the absorption chiller is the most efficient cooling system due to its low energy consumption and the economic feasibility of being integrated with the solar system. Figure 13 offers a daily representation of an adsorptive solar ice maker. Ice packs and water gels have become extremely popular to keep materials at around 0 °C. The temperature range of water gel and ice as phase-change materials depends on their specific composition and intended application. For example, a water gel used for thermal energy storage in buildings can be formed, melted, and solidified at temperatures of 0 °C to 30 °C. If one wishes to obtain a PCM based on water below 0 °C, then salt can be added to the water. This will be the freezing point. However, you notice a significant reduction in latent heat and a broadening of the melting/freezing point.

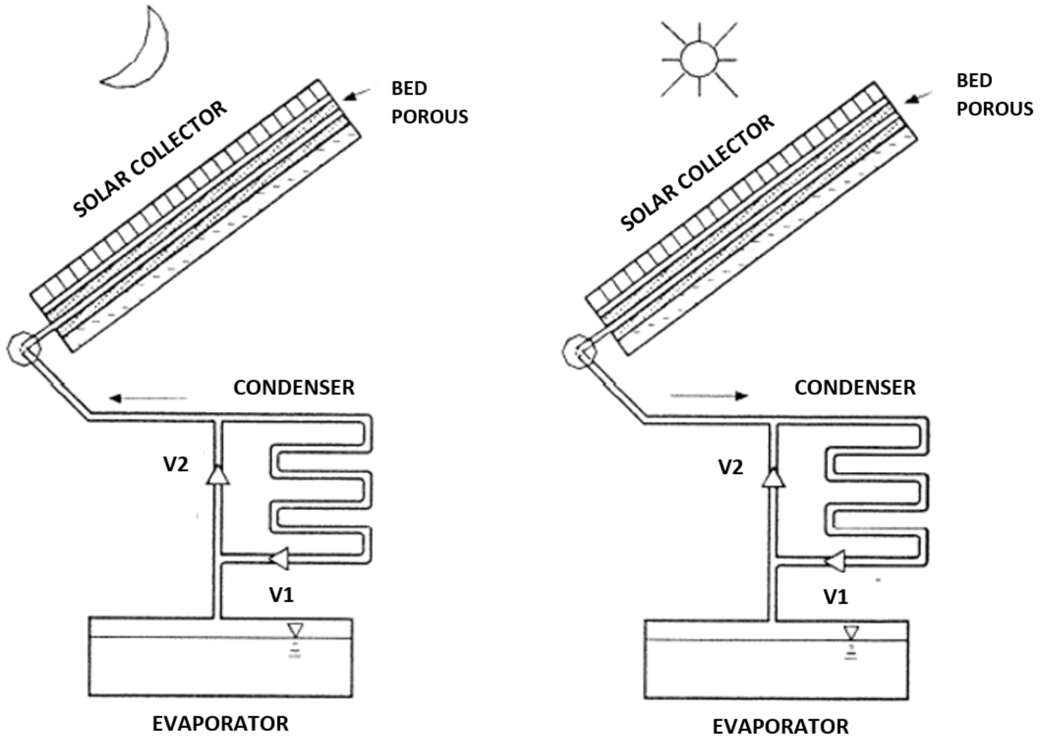


Figure 13. Schematic diagram of an adsorptive solar ice maker.

The level of performance of water gel and ice as phase change materials depends on several factors, including the specific composition, operating temperature range, and application. First of all, it can be affected by the environment, including temperature and humidity. Some further metrics account for the heat of fusion, thermal conductivity, stability, and repeatability. Water has a high heat of fusion, meaning it can store and release large amounts of heat energy during the melting and solidification processes. It presents a relatively high thermal conductivity compared with other PCM materials, which means it can transfer heat more efficiently. Water gels are generally stable and do not separate over time, making them a reliable and long-lasting choice for thermal energy storage and management applications. Additionally, water gels are highly repeatable and can go through multiple melting and solidification phases without suffering significant degradation or loss of performance. For example, the efficiency decreases significantly with increasing collector temperature. The efficiency ranges from about 12–20% [72]. The autonomy of water gel PCMs in hours at thermal level is a specific parameter that can vary depending on several factors, such as the size and type of the PCM system. The PCM chart of such a representative system can be observed in Figure 14.

The energy storage density depends on the latent heat of fusion and describes the amount of energy stored in the material. This is the main advantage of solid-liquid phase change materials, which can store a certain amount of energy in a much smaller material weight and volume. Solid-to-liquid transitions usually have little latent heat, while liquid-to-gas transitions are not desirable in closed systems due to the large volume change. The energy density of a water gel can be calculated by multiplying the specific heat of fusion of water by the amount of water contained within the gel. Using water gel for thermal energy storage can lead to significant cost savings over time. For example, a water gel-based thermal energy storage system in a building can reduce energy costs by reducing the need for heating and cooling, which can lead to lower energy bills and reduced carbon emissions. An analysis shows a 20% reduction in cooling load when PCM materials are used in comparison to conventional building materials. The cost is slightly lower for liquid heat transfer flat plate collectors than for solar panels. The main reason is that at the temperatures required for air conditioning, flat collectors show higher efficiencies.

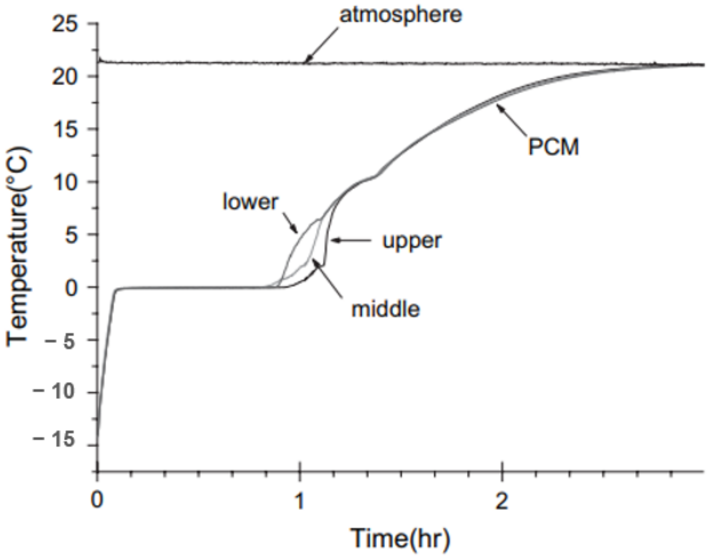


Figure 14. The PCM chart for systems based on water-gel.

Some general maintenance requirements for water gel-based PCM materials may include a typical inspection, a simple cleaning process, and protection against moisture formation. A regular check for signs of damage or wear is adequate. If damage is found, it should be repaired or replaced to maintain optimal thermal energy storage performance. The cleaning process may involve the manual removal of dust or debris that may accumulate on the surface. This can help maintain the material's performance by preventing the build-up of insulating materials that can affect its ability to absorb and release thermal energy [73]. Finally, these systems are sensitive to moisture, so it is important to protect them from exposure to excessive moisture. If the material gets wet, it should be allowed to dry completely before use. Nonetheless, they offer considerable benefits, including being non-toxic and environmentally friendly. They contain no harmful chemicals or substances, making them a safer and more sustainable choice compared with other PCM materials. Compared to other PCM materials, they are relatively low-cost, which makes them a potential choice for thermal energy storage and management applications.

Organic PCMs store and release thermal energy by melting and solidifying, respectively. With a melting temperature of 40 °C and a solidification point of 33 °C, they exhibit high energy storage capacity per unit mass, good thermal stability, and can be easily synthesized. PCM hydrocarbons store and release thermal energy through formation and decomposition, respectively. The melting and solidification points are observed at 7 °C and −8 °C, respectively, indicating a wider operating temperature range. They are characterized by high energy storage capacity per unit mass, relatively high thermal conductivity, and abundant reserves as raw materials [74]. Higher temperatures and a narrower phase-change band are observed in systems with polymer PCMs. A polymer may exhibit a melting point at 56 °C and a solidification point near 50 °C, providing an operating temperature range of 6 °C. However, the thermal stability, together with the ability for high energy storage per unit mass, are reserved. Moreover, this kind of PCM can be easily synthesized.

Among the most promising types of PCMs for solar energy storage are molten salts, metal alloys, and paraffin. Molten salts are ionic compounds that melt at high temperatures, usually above 100 °C, to form a liquid state. They consist of positively charged ions, such as sodium (Na^+) or potassium (K^+), and negatively charged ions, such as chloride (Cl^-) or nitrate ($NO_3{}^-$). Molten salts have unique properties that make them useful in various industrial applications, such as as a heat transfer fluid in high-temperature processes, as a catalyst in chemical reactions, and as an energy storage medium in renewable energy systems. When used as an energy storage medium, molten salts are heated to high temperatures and stored in insulated tanks. The stored thermal energy can later be used to generate electricity or provide heat for industrial processes.

Molten salts have high thermal conductivity and thermal capacity, which makes them capable of storing large amounts of thermal energy with high efficiency. The high operating temperature range of molten salt-based systems also makes them a promising solution for high-temperature CSP applications. However, there are still challenges associated with the use of molten salts, such as corrosion and the high cost of installation and maintenance of storage tanks. The energy density of 220–450 MJ/kg is lower than some other TES systems, such as metal alloys, regardless of the high temperatures (600–1000 °C). Nevertheless, such systems can achieve a high efficiency of up to 97%, which is due to the high thermal conductivity and specific heat capacity of the molten salt [75].

Metal alloys are materials consisting of two or more metallic elements combined to form a new material with specific properties. The properties of metal alloys can be different from those of the individual metals that make up the alloy and can be tailored to meet specific specifications. The most common alloys used for solar energy storage applications are based on binary systems of eutectic mixtures of different metals. These alloys have an eutectic point, which is the lowest melting point of the mixture, and the melting point is determined by the composition of the alloy. Some of the common binary alloys used for solar energy storage applications include sodium-potassium alloy (Na-K), copper-indium alloy (Cu-In), lead-bismuth alloy (Pb-Bi), and tin-bismuth alloy (Sn-Bi). The energy conversion performance of metal alloys can be affected by factors such as heat transfer mechanisms, alloy composition, and system design. In general, metal alloys can achieve quite high energy conversion efficiencies (of the order of 92%) due to their high thermal conductivity and latent heat storage capacity [76]. In terms of operating temperature, the study found that the system operated in a temperature range of 100–250 °C, which is suitable for many solar thermal energy storage applications. The energy density of alloy-based thermal energy storage systems is affected by factors such as alloy composition, system design, and operating temperature range. The energy density of metal alloy-based PCMs ranges between 40 and 80 MJ/kg [77]. This can vary depending on the specific alloy composition and melting temperature.

Paraffin has been studied as a phase change material for thermal energy storage applications due to its high latent heat of fusion, low cost, and abundance. When paraffin undergoes a phase change from solid to liquid, it can store a significant amount of thermal energy. During the phase change, the paraffin absorbs heat from the surrounding environment and uses it to break the intermolecular bonds between the paraffin molecules, allowing the material to transition from a solid to a liquid state. When the paraffin cools and solidifies, it releases the stored heat energy back into the environment.

Paraffin has many advantages as a phase-change material for thermal energy storage applications. Paraffin-based materials are non-toxic, non-corrosive, and have low flammability, which makes them safe to use in a wide range of applications. Additionally, paraffin has a relatively low melting point, which allows for a wider operating temperature range compared with other phase-change materials. However, some challenges do exist associated with the use of paraffin as a phase-change material for thermal energy storage. For example, paraffin has a relatively low thermal conductivity, which can limit the rate of heat transfer during the melting and solidification processes. This can lead to longer charge and discharge times for the thermal energy storage system. In addition, paraffin has a lower energy density compared with some other phase change materials, which can lead to larger storage tanks needed to store the same amount of thermal energy [78].

Overall, paraffin appears very promising as a potential PCM for thermal energy storage applications, but more research is needed to optimize its performance and address some of the challenges associated with its use. The operating temperature range for a thermal energy storage system using paraffin will depend on the specific paraffin used and the design of the storage system. In general, paraffin has a relatively low melting point, which allows for a wider operating temperature range compared with some other phase change materials. For example, some paraffins have melting points as low as 18 °C, while others have melting points as high as 70 °C. The operating temperature range for a paraffin-based thermal energy storage system will depend on the specific application and the desired temperature range. For solar thermal energy storage applications, the operating temperature range can be designed to match the temperature range of the solar collector system, which is typically between 60 and 150 °C. Typically, the energy conversion efficiency of a paraffin wax system was about 60%, while the charging and discharging times were 3 and 5 h, respectively [79]. Table 4 lists some performance parameters and economic metrics relating to the molten salts, metal alloys, and paraffin used as PCMs for TES.

Table 4. Performance indices pertaining to representative storage systems based on latent heat.

System	Operating Temperature (°C)	Energy Density (MJ/kg)	Efficeiency (%)	Life-Cycle (yrs)	Specific Cost ($/m^3)
Molten salts	600–1000	220–450	97	20–30	327–588
Metal alloys	100–250	40–80	92–96	>25	~550
Paraffin	60–150	120–220	60	>20	~190

4. Electricity Storage Systems

Photovoltaic technology, based on the photovoltaic effect, is at the core of solar energy conversion. When sunlight interacts with certain materials, it induces the liberation of electrons, generating a flow of electric current. This process forms the basis of PV cells, the building blocks of solar panels. Through the utilization of semiconductor materials, PV cells enable the direct conversion of solar photons into electricity, rendering solar energy a feasible and economically viable option for power generation. The interaction between photons and electrons in the semiconductor material plays a crucial role in converting sunlight into electricity. The electronic structure, bandgap, and charge separation mechanisms within the PV cells are dissected to reveal the intricacies of solar energy conversion [80]. Throughout the years, research and technological innovations have significantly enhanced the efficiency and scalability of PV systems. A tremendous amount of research has been done around the evolution of PV technology, including the introduction of new materials, novel manufacturing processes, and advancements in device architectures [81]. These breakthroughs have made solar power more affordable and reliable, positioning it as a competitive energy option within the broader energy landscape.

Electrical energy storage (EES) constitutes an indirect pathway for solar energy harnessing. The solar-electricity route involves PV systems of various scales according to the applications of intended use and their classification in the power chain. This way, the EES applications are classified into power quality services, which require rapid response and high power densities, and bridging power services, which get online in mid-term and provide support until disturbance prevention and management services are called upon through commands issued by the network operators. Relating to scale, PV installations can be found both at the transmission (high-voltage) and distribution (either medium-voltage or low-voltage) grids, though they are currently employed as necessary substitutes in microgrids, virtual power plants, and hybrid RES systems [31]. Figure 15 shows a representative example of a solar PV-EES system with a two-level (DC-to-DC and DC-to-AC) power conditioning system (PCS).

According to the intended EES task, different EES technologies are favorable or unfavorable as per some performance characteristics. To this end, each application is characterized by its autonomy requirements (supplying duration) in the short-term, medium-term, and long-term. A similar classification regards the storage time and distinguishes the EES devices into short-term for those presenting a high self-discharge rate (SDR) and long-term for technologies that exhibit minimal SDR. A further parameter refers to the number of charging/discharging cycles needed. This feature promotes EES systems with high cycling capability for the most frequent EES applications.

The generated electricity from PV modules cannot be directly stored. Therefore, it can be converted into other forms of energy that can be adequately stored, forming the charging procedure. When needed, electricity is retrieved by making use of reversible processes during the discharging task. Based on the energy form into which the electrical energy is converted for storage, the various EES technologies are classified as thermal, mechanical, chemical, electrostatic, and electromagnetic. Thermal energy storage (TES) involves aquiferous and cryogenic mechanisms. The mechanical techniques are subdivided into kinetic-energy flywheels and potential-energy systems, which accommodate pumped-hydro energy storage (PHES), compressed air energy storage (CAES), gravity energy storage (GES) [82], pneumatic (PES), and spring (SES) systems [83]. The chemical EES includes battery energy storage (BES), flow battery (FES) devices, and regenerative H_2 storage (HES). Finally, the electromagnetic storage is realized by supercapacitive (SCES) and superconducting (SMES) elements.

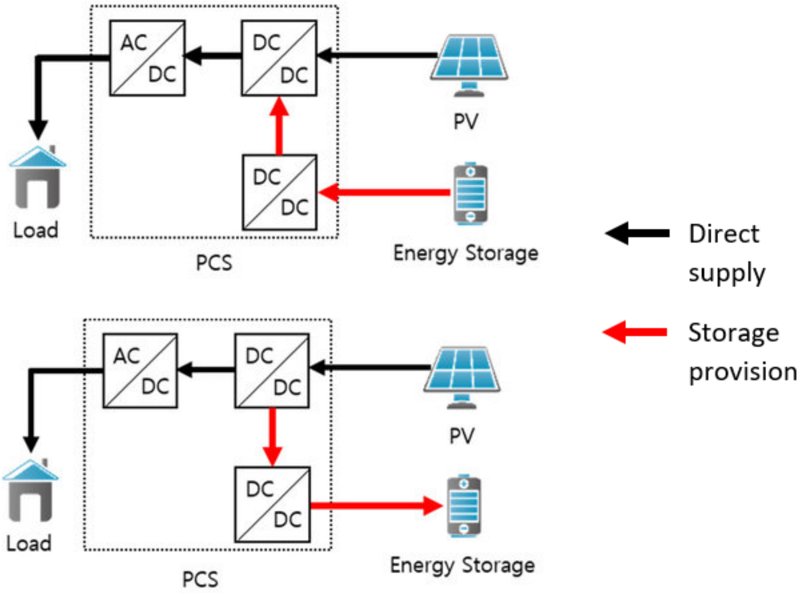


Figure 15. Simulation of charging/discharging cycles for solar-PV integrations.

The various EES applications are demonstrated in Figure 16, while the most essential EES technologies are discussed based on the requirements and preferences of these power-chain applications. The most critical metrics pertaining to the assessed EES technologies are tabulated in Table A1. TES systems involve multi-step conversion processes. Initially, solar power is converted into electricity with the aid of PVs. The generated electric energy is transformed into thermal energy via electric elements, and thermal energy is stored. When needed, the heat is recovered and re-converted into electricity via aquiferous or cryogenic systems. These multi-stage procedures deteriorate overall efficiency, which is of utmost importance when assessing EES participation [84]. A flow diagram of the TES process is depicted in Figure 17.

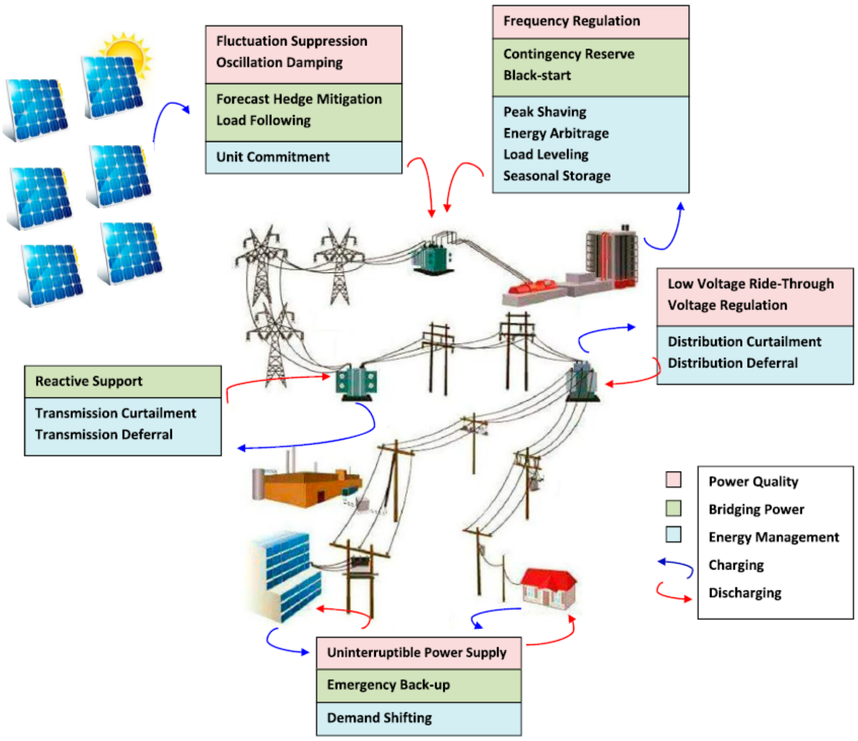


Figure 16. Electricity storage applications in potential power system operations.

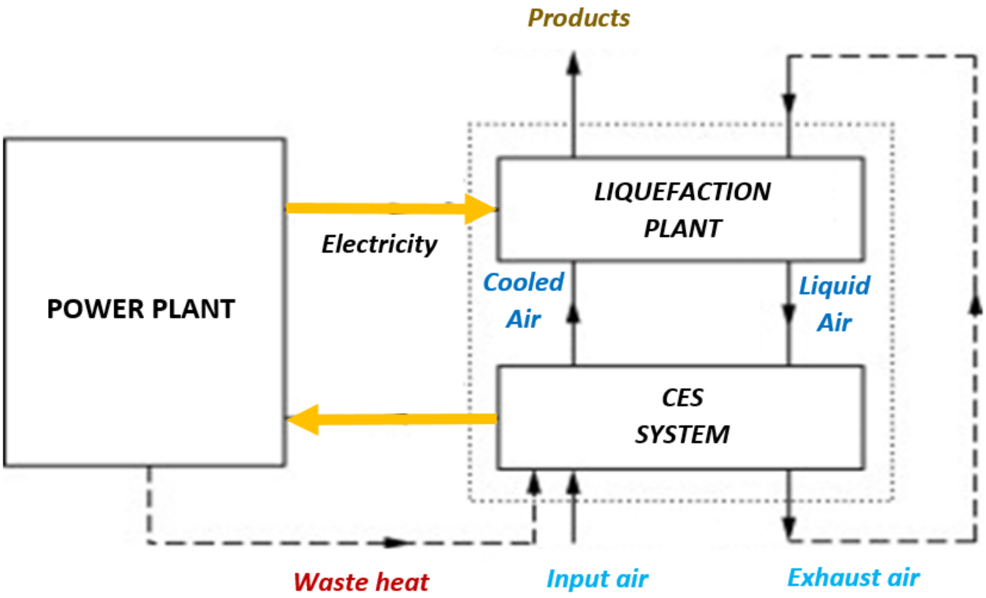
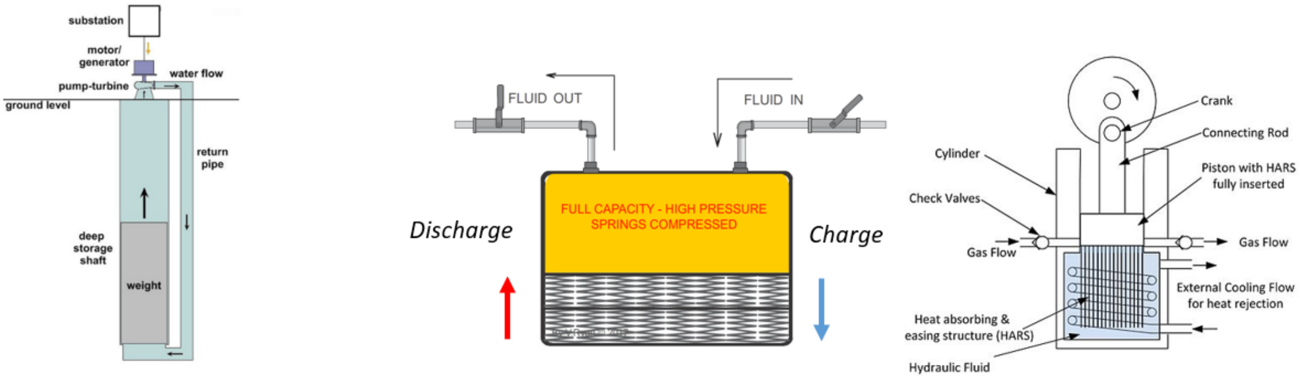
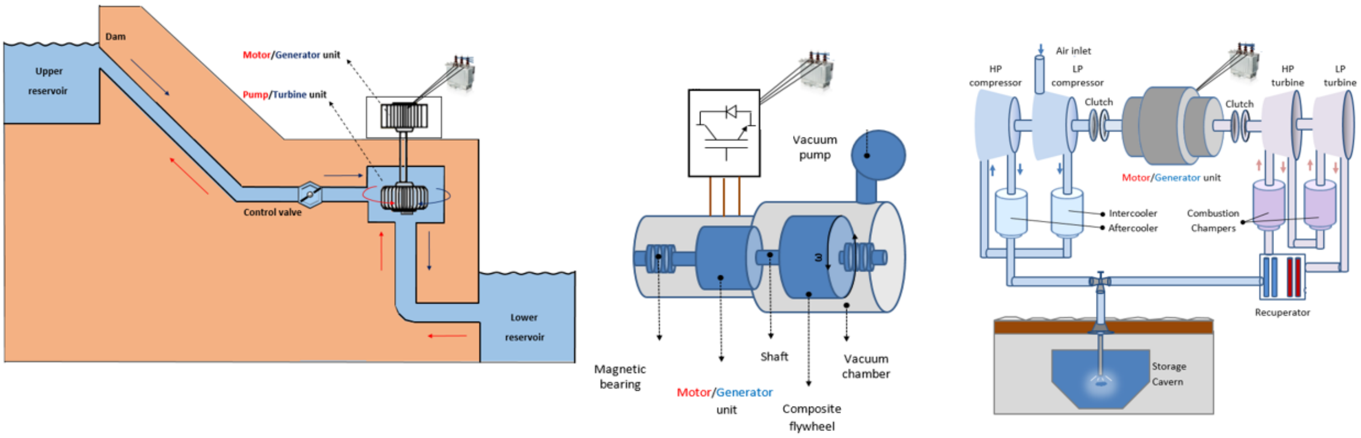


Figure 17. Flow diagram of thermal EES.

PHES and CAES exhibit relatively low performance per unit mass and volume, necessitating large storage reservoirs to achieve a specific power and energy capacity. As a result, they are at a disadvantage compared with FES technology in situations where space and weight constraints are critical factors. The capital costs vary in reverse order concerning energy and power units. PHES technology has the highest power capital cost, making FES more appealing, whereas the highest energy capital cost is associated with FES, favoring the other two, with CAES being slightly less expensive. PHES offers the longest operational lifespan and the lowest O&M (operations and maintenance) cost, while FES boasts the highest efficiency and cycling capability. In contrast, FES systems have higher parasitic losses, leading to a significant daily self-discharge. In contrast, PHES and CAES plants experience negligible losses and an almost zero daily self-discharge rate. The mechanical storage systems are demonstrated in Figure 18.



GES system ***SES system*** ***PES system***



PHES system ***FES system*** ***CAES system***

Figure 18. Demonstration of mechanical energy EES systems.

The cost-effectiveness and low maintenance requirements of lead-acid BES, along with their ability to deliver relatively high power output and efficiency, make them a compelling choice for automotive, telecommunications, and uninterruptible power supply (UPS) applications. Despite their significant environmental impact, this type of battery has found applications in MW-scale stationary setups, particularly when integrated with renewable energy sources. Similarly, nickel-cadmium (Ni-Cd) batteries also have a notable environmental impact. Though they share attributes like high efficiency, specific power, and moderate self-discharge, Ni-Cd batteries provide longer cycling times and a longer lifespan, along with higher energy density and power ratings [85]. However, they become disadvantaged in terms of capital costs and power density.

Nickel–metal hydride (Ni-M-H) batteries represent an improvement, offering higher power and energy densities, lower capital costs, and no self-discharge at the expense of lower efficiency, cycle capability, and lifespan. On the other hand, lithium-ion batteries require the smallest volume and weight for a given energy amount. With an efficiency nearing 100% and extended cycle times, Li-ion batteries find widespread use in portable devices and show promising potential in transportation and small-scale stationary applications. Sodium sulfur (Na-S) technology exhibits the highest efficiency, followed by ZEBRA, while Zn-air and regenerative HES offer a lower efficiency of approximately 50%. In terms of energy density, Zn-air shows promise, while regenerative HES is advantageous for specific energy. Zn-air's limitations lie in cycling capability and power rating, but it boasts a long lifespan and requires low capital investment. Regenerative HESs can match ZEBRA in power density but have lower energy capital costs, limited maintenance expenses, and better cycling capability. ZEBRA, however, suffers from severe self-discharge, unlike Na-S, which has an almost zero daily self-discharge rate. Na-S technology is the most expensive EES investment in this category, and to make other technologies competitive, further research is required to improve round-trip efficiency and reduce costs [86].

Vanadium-redox (VRB) flow batteries surpass zinc-bromine (Zn-Br) and polysulfide–bromine (PSB) in technical maturity, efficiency, cycling capability, specific power, and power density. However, they provide only moderately specific energy and the lowest energy density values, which limits their use in applications requiring bulk energy storage. Enhancements in cycle efficiency and lifetime are necessary to boost competitiveness and contribute to future power system applications. The chemical BES and FES technologies are shown in Figure 19, while Figure 20 illustrates the electrolyser-H_2-fuel cell alternatives.

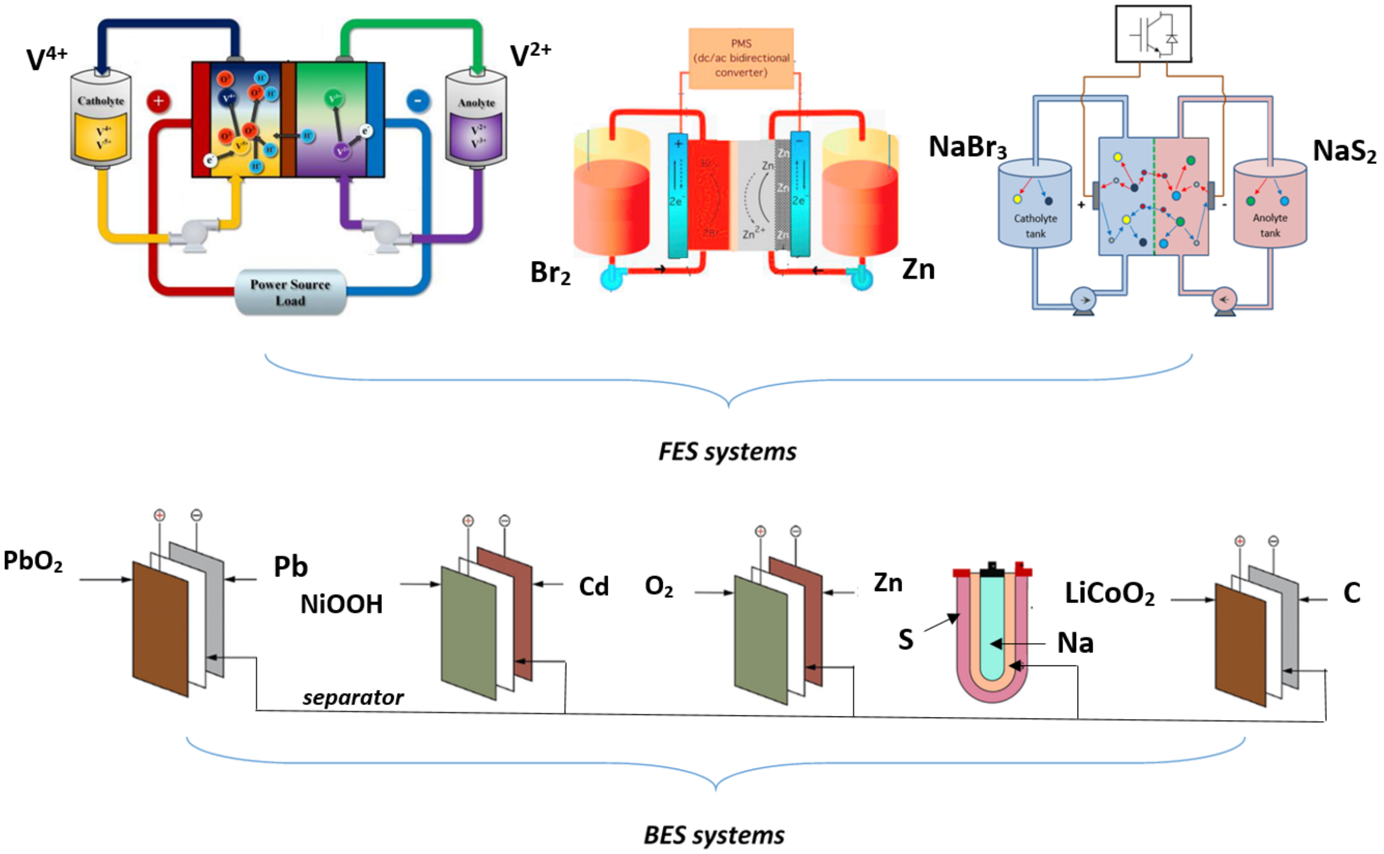


Figure 19. Demonstration of chemical energy EES systems.

Electrolytic production utilizing carbon-free electricity as its energy source for endothermic reactions might be the dominant method to generate significant quantities of hydrogen. This approach circumvents the release of polluting by-products and the handling of hazardous chemicals associated with traditional fuels. The prospect of producing clean and sustainable hydrogen is assured due to the consistent availability of water coupled with access to the electricity grid. Water electrolysis is accomplished through the utilization of electrolysers, with the most prevalent types being alkaline (AEC), proton exchange membrane (PEMEC), and solid oxide electrolysis cells (SOEC). Comprising a cathode and an anode submerged in an electrolyte, the passage of current through these cells facilitates the separation of water into hydrogen, produced at the cathode, and oxygen, evolved at the anode.

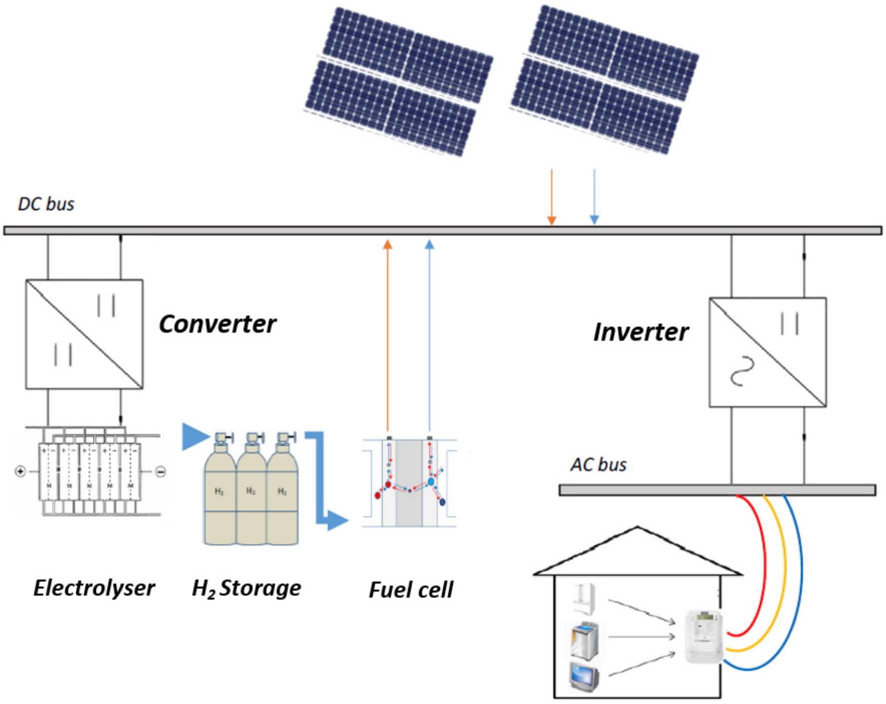


Figure 20. Paradigm of a PV-hydrogen generation system.

Capacitors and inductors are suitable for storing small amounts of energy, but recent advancements have extended their use to larger-scale applications. SCESs have the advantage of offering the highest efficiency and the lowest investment and overall life costs among the mentioned technologies. SMES enjoys the benefit of almost infinite cycling capability and the longest lifespan, though it is less favorable in terms of power and energy performance, as well as capital and O&M costs. Electromagnetic EES technologies suffer from increased parasitic losses, leading to severe self-discharge, making them more suitable for high-power and short-duration applications. SMES does enjoy a slightly advantageous daily self-discharge rate compared with electromagnetic EES technologies [87]. Figure 21 comprises the most essential capacitive technologies of the SCES family.

It is worth noting that the selection task of the most appropriate EES technology that best fits a specific EES application must consider a comprehensive life-cycle cost analysis. This way, a most expensive technology may become advantageous when other performance characteristics are taken into account, such as efficiency, depth of discharge, self-discharge rate, cycling, and calendar lifetime. Consequently, PHES appears promising in various applications such as unit commitment, peak shaving, energy arbitrage, load leveling, seasonal storage, and transmission congestion relief (TCR) without any limitations on the available footprint. CAES is preferred when power-rate constraints prevent PHES from being a viable option. On the other hand, HES facilities are suitable for smaller scales, serving as non-spinning reserves or for small footprint TCR and wind load following applications. In cases of short-term and frequently cycled tasks like fluctuation suppression, forecast hedge mitigation, PV load following, frequency, and voltage regulation, SCES holds the advantage due to its cost-effectiveness.

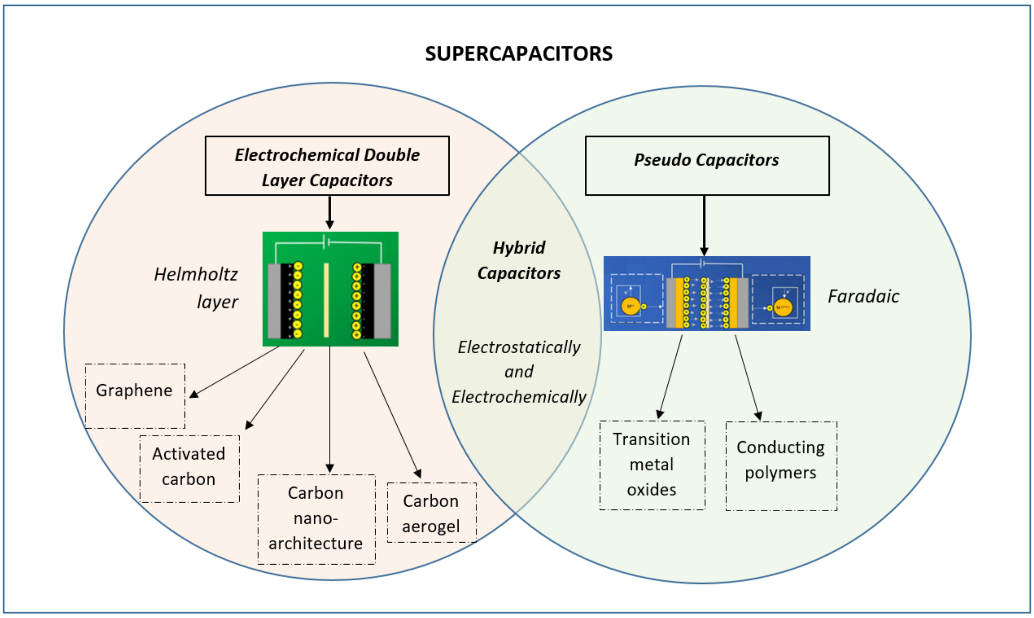


Figure 21. Presentation of the most essential SCES technologies.

When considering uncertainty in investments, advanced lead-acid technology carries the lowest risk, while valve-regulated Pb-acid batteries are favorable for low-voltage ride-through and uninterruptible power supplies. For emergency backup and demand shifting operations, Zn-air constitutes the most cost-effective technology. However, smaller-scale CAES proves to be a better candidate for technology-application pairs based on the min/max range of levelized cost of storage (LCOS). It also holds significant potential for providing black-start capabilities. In the case of reactive support applications, VRB is displaced by Na-S or ZEBRA technologies when considering the overall LCOS range. In summary, different energy storage technologies have their strengths and weaknesses, making them more suitable for specific applications based on factors like cost, efficiency, cycling capabilities, and footprint requirements [88].

5. Hydrogen Storage Systems

Motivated by the increasing requirements for hydrocarbon independence and the transition towards 100% RES systems in modern societies, the generation industry has set hydrogen storage as a top priority, calling for R&D relating to both its production processes and storage methods. Utilizing solar as the primary source of energy, green hydrogen may be produced by exploiting either thermochemical cycles or photosynthetic systems. Specifically, the thermal energy from the sun can be stored in the form of hydrogen fuel via thermochemical cycles. The second category involves photosynthetic hydrogen formation by utilizing the photonic energy derived by the sun and some photosystems, as explained below. After their completion, the produced hydrogen can be stored either as compressed gas, cryogenic liquid, or solid hydride [89]. Figure 22 offers the green routes for hydrogen production utilizing solar energy.

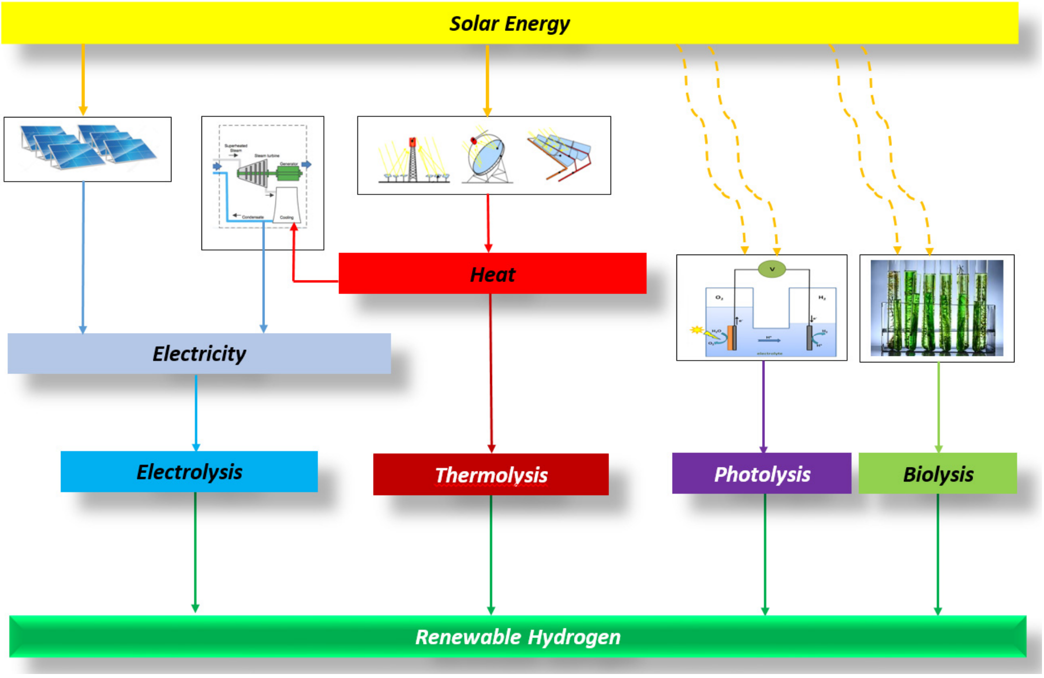


Figure 22. Solar-to-hydrogen pathways.

5.1. Thermochemical Cycles

Thermochemical decomposition, also known as "thermolysis", involves systems capable of concentrating the solar irradiance to achieve high enough temperatures to decompose water (H_2O) into its simplest elements, namely hydrogen (H_2) and oxygen (O_2). It is therefore included in water-splitting methods and constitutes an extremely endothermic process. The water decomposition is carried out above 2500 °C, and thus, it is difficult to be achieved by conventional systems based on CSP [90]. To lower the needed temperatures, several thermochemical cycles have already been proposed and assessed as clean pathways for H_2 production.

Based on the extensive literature, the proposed thermochemical cycles rely on decomposition processes of two types. The first type involves a two-stage cycle using metal oxide (MO_x), consisting of a high-temperature stage to reduce the metal oxide, followed by an oxidation stage to split the water at a lower temperature. A preferred arrangement for the chemical reduction of the metal oxide is to absorb solar energy directly in a receiver reactor. The high temperatures required by chemical processes require a solar receiver reactor capable of operating at these temperatures with high thermal efficiency using a planar cavity receiver configuration, although a specific design will be related to a selected material and a specific process. The two-stage metal oxide thermochemical cycle is represented by the following chemical reactions [91]:

$$\text{Endothermic step}: \mathrm{MO_n} \rightarrow \mathrm{MO_{n-\delta}} + \frac{\delta}{2}\mathrm{O_2} \tag{3}$$

$$\text{Exothermic step}: \mathrm{MO_{n-\delta}} + \delta\mathrm{H_2O} \rightarrow \mathrm{MO_n} + \delta\mathrm{H_2} \tag{4}$$

Using processes falling into this category, hydrogen can be produced at temperatures in the range of 900–1600 °C [92]. The isothermal redox cycle requires high temperatures and pressures, which can lead to increased costs and the need for specialized equipment. In addition, the system requires regular maintenance and monitoring to ensure efficient operation. Finally, the high operating temperature of the cycle can lead to material degradation and reduced system life. As a result, thermochemical cycles based on non-metallic chemical elements (such as sulfur and iodine) gain interest, producing hydrogen at more stages but below 850 °C [93]. Figure 23 simulates a hydrogen production process based on thermochemical water splitting [94]. The multi-stage thermochemical cycles for water-splitting hydrogen production are generally represented by the following chemical equations:

$$H_2O + AB \rightarrow AH_2 + BO \tag{5}$$

$$AH_2 \rightarrow H_2 + A \tag{6}$$

$$BO \rightarrow \frac{1}{2}O_2 + B \tag{7}$$

$$A + B \rightarrow AB \tag{8}$$

These cycles comprise, in general, a hydrolysis reaction (reaction (5)), a hydrogen-evolving reaction (reaction (6)), an oxygen-evolving reaction (reaction (7)), and a reagent-recycling reaction (reaction (8)). For cycle enhancement purposes, the kinetics of the reaction and some influencing parameters are investigated. Results indicate increases in efficiency from 24–28% to 32–37% [91].

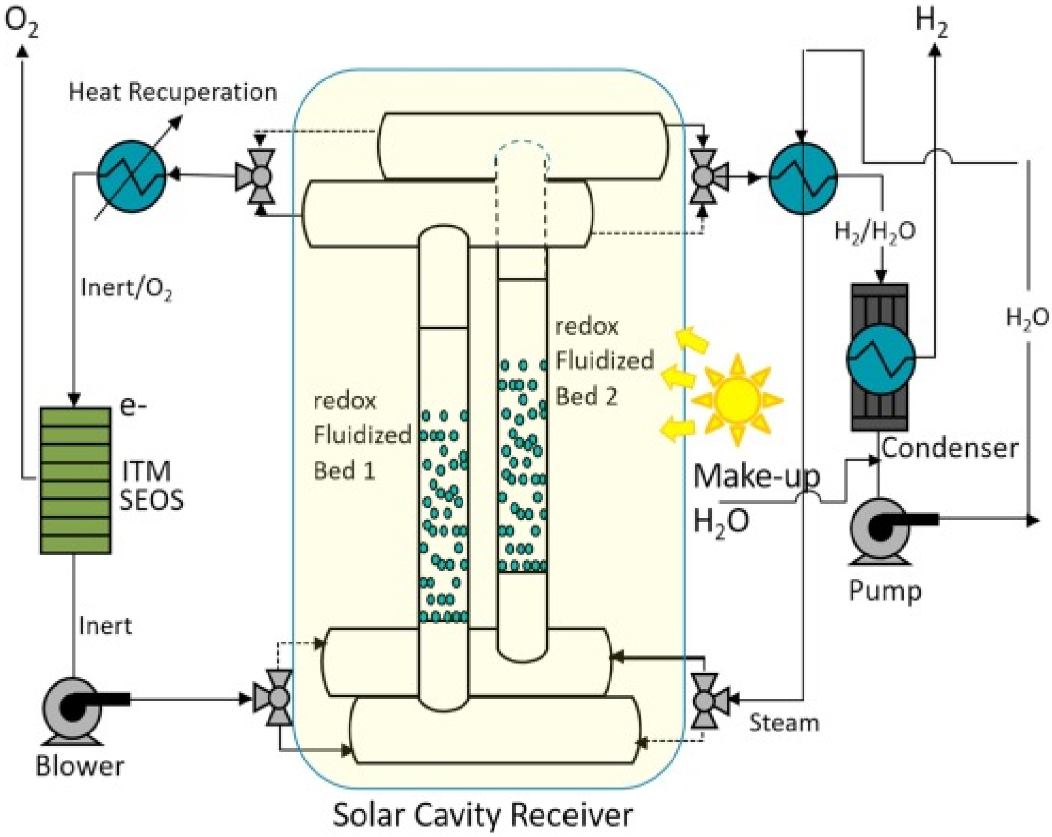


Figure 23. Simulation of a thermochemical cycle process for water splitting.

5.2. Photosystems

Water constitutes an abundant and limitless raw material that can be used for hydrogen production through the aforementioned water-splitting methods of electrolysis and thermochemical cycles, respectively, by making use of electricity and heat. Taking sustainable development into account, the selected hydrogen production mechanisms must guarantee zero GHG emissions released into the atmosphere. Consequently, the last generation category utilizes the sun's light to produce gaseous hydrogen, providing green pathways under mild conditions but at the expense of lower production rates.

Photo-electrolysis and bio-photolysis form the third category of water-splitting processes. Photo-electrolysis (or photolysis) can be achieved using certain semiconducting materials. This process involves the absorption of energy from photons in visible light (pH) to break down water into H_2 and O_2. To achieve successful decomposition, a free energy of 1.23 eV is required, and the separation of electrons and holes demands a high bandgap energy when there is no external bias potential. Unfortunately, this results in a dramatic decrease in photo-conversion efficiency (<1%), necessitating large land areas to collect sunlight and leading to significantly higher production costs [90]. The decomposition process is explained in terms of Equations (9) and (10), which represent the reactions occurring at the anode and cathode of a semiconducting surface, respectively.

$$2\mathrm{ph}^+ + \mathrm{H_2O} \rightarrow \frac{1}{2}\mathrm{O_2} + 2\mathrm{H}^+ \tag{9}$$

$$2\mathrm{e}^- + 2\mathrm{H}^+ \rightarrow \mathrm{H_2} \tag{10}$$

Under specific conditions, certain species of algae can also split water into hydrogen ions (H^+) and oxygen (O_2) through photosynthesis. Depending on the type of algae, hydrogen production can take place through direct (Equation (11)) or indirect (Equations (12) and (13)) bio-photolysis, commonly known as biolysis. Biolysis offers a method for hydrogen production under mild conditions and consumes CO_2, with O_2 being the only by-product. However, it relies on sunlight and requires large reactor volumes to achieve reasonable hydrogen yields. It is also sensitive to the presence of O_2, and the required raw material (algae) can be expensive [95].

$$2\mathrm{H_2O} + \mathrm{light} \rightarrow 2\mathrm{H_2} + \mathrm{O_2} \tag{11}$$

$$12\mathrm{H_2O} + 6\mathrm{CO_2} + \mathrm{light} \rightarrow \mathrm{C_6H_{12}O_6} + 6\mathrm{O_2} \tag{12}$$

$$\mathrm{C_6H_{12}O_6} + 12\mathrm{H_2O} + \mathrm{light} \rightarrow 12\mathrm{H_2} + 6\mathrm{CO_2} \tag{13}$$

6. Conclusions

The major advantages of solar energy position it as a key player in the global transition to sustainable energy. Its role in mitigating climate change, ensuring energy independence, and driving economic development makes it essential for the clean energy revolution. As research progresses, solar power's competitiveness and viability will continue to grow. Within this landscape, a diverse range of solar energy processes have emerged, effectively extending energy access to remote regions and isolated networks. These processes catalyze a spectrum of sustainable applications, spanning from passive housing and solar cooking to domestic hot water provision, water desalination, and irrigation systems. An evident augmentation in the contribution of photovoltaic power is foreseen, bolstered by the evolution of potential electricity storage techniques. These advancements hold the potential to augment power quality, bridge gaps in energy management, and enhance overall service. Noteworthy progress is also witnessed within modern power systems, marked by dynamic configurations encompassing microgrids, virtual power plants, and the proliferating use of electric vehicles. Complementing electricity storage, continuous evaluations of thermal and hydrogen storage technologies persist, focusing on refining efficiency metrics and addressing life-cycle costs. Water-splitting techniques for hydrogen production face challenges in terms of high costs, material degradation, and maintenance. Photosystems offer more secure and efficient hydrogen production, albeit with lower efficiencies and production rates. Solar power benefits are pivotal for a sustainable energy future. Diverse applications and storage methods, along with advancements in hydrogen production, underscore its significance in global energy transformation.

Funding: This research received no external funding.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The author declares no conflict of interest.

Appendix A

All technical characteristics and operational metrics pertaining to the assessed electrical energy storage technologies are tabulated in Table A1.

Table A1. Performance metrics pertaining to the assessed EES technologies.

Technology	Daily Self-Discharge (%)	Lifetime (Years)	Cycling Times (Cycles)	Round-Trip Efficiency (%)	DoD (%)	Response Time	Suitable Storage Duration
PHES	almost 0	30–50	10,000–30,000	70–85	95	min	hours-months
CAES	almost 0	30	8000–12,000	42–54	100	min	hours-months
TES	>50	>25	50,000	40–50	100	s-min	3 h
FES	55–100	20	10^5–10^7	90–95	100	ms	secs-mins
SES	40–60	-	10^6	23	100	ms	mins-hours
GES	10	-	10^6	80	80	s	mins-hours
Pb-acid	0.1–0.2	5–15	200–2000	85–90	80	ms	mins-days
Ni-Cd	0.1–0.2	10–20	1500–3000	60–90	100	ms	mins-days
Zn-air	almost 0	0.17–30	100–300	50	100	min	hours-months
Na-S	almost 0	10–15	1500–5000	89–92	100	ms	secs-hours
ZEBRA	20	10–14	1000	70–85	80	-	secs-hours
Li-ion	0.03	5–15	3000–10,000	~100	80	ms	mins-days
VRB	almost 0	5–10	>16,000	85	100	ms	hours-months
Zn-Br	almost 0	5–10	2000–3500	75	100	ms	hours-months
PSB	almost 0	10–15	800–2000	75	100	ms	hours-months
HES	0.06–3	5–15	20,000	20–50	90	s	hours-months
SCES	20–40	10–12	10^6	85–98	100	ms	secs-hours
SMES	10–15	>20	almost ∞	95	100	ms	$\leq$30 min

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