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A cross-scale ‘material-component-system’ framework for transition towards zero-carbon buildings and districts with low, medium and high-temperature phase change materials

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ABSTRACT

Transition towards a carbon-neutral district energy community calls for carbon elimination and offsetting strategies, and phase change materials (PCMs) with substantial potential latent energy density can contribute significantly to carbon neutrality through both carbon-positive (like PCM-based thermal control in solar PVs) and carbon-negative strategies (like waste-to-energy recovery). However, roadmap for PCMs’ application in carbon-neutral transition is ambiguous in the current academia, and a state-of-the-art overview on latent thermal storage is necessary. In this study, a comprehensive review was conducted on cutting-edge technologies for carbon-neutral transition with latent thermal storages. Both carbon-positive and carbon-negative strategies in the operational stage are reviewed. Carbon-positive solution mainly focuses on energy-efficient buildings, through a series of passive, active, and smart control strategies with artificial intelligence. Passive strategies, to enhance thermal inertia and thermal storage of building envelopes, mainly include free cooling, solar chimney, solar façade, and Trombe walls. Active strategies mainly include mechanical ventilations, active water pipe-embedded radiative cooling, and geothermal system integration. The ultimate target is to minimise building energy demands, with improved utilisation efficiency on natural heating (e.g., concentrated solar thermal energy, geothermal heating, and solar-driven ventilative heating) and cooling resources (e.g., ventilative cooling, geothermal cooling, and sky radiative cooling). As one of the most critical solutions to offset the released carbon emission, carbon-negative strategies with PCMs mainly include cleaner power production and waste heat recovery. Main functions of PCMs include energy efficiency enhancement on cleaner power production, steady steam production, steady heat flux via the latent storage capacity, and pre-heat purpose on waste heat recovery. A thermal energy interaction network with transportation is formulated with PCMs’ recovering heat from internal combustion engines and spatiotemporal energy sharing, to provide frontier research guidelines. Future studies are recommended to spotlight standard testing procedure and database, benchmarks for suitable PCMs selection, seasonal cascaded energy storage, nanofluid-based heat transfer enhancement in PCMs, anti-corrosion, compatibility, thermochemical stability, and economic feasibility of PCMs. This study provides a clear roadmap on developing PCMs for transition towards a carbon-neutral district energy community, together with applications, prospects, and challenges, paving the path for combined efforts from chemical materials synthesis and applications.

1. Introduction

Household energy consumption accounts for a significant portion with the accounting for about 40% and 26% of total energy consumption in North America and Europe, respectively (Talebi et al., 2018). The utilization of fossil fuels as the world’s primary available energy source

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over the past few decades has led to their depletion and increased the levels of CO_2 emission. Many researchers have predicted that CO_2 emissions will cause global temperatures to rise by 1–3.5 °C with sea levels rising by 15–95 cm in 2050 (Alam et al., 2014). The rising global temperature will lead to climate change, thereby resulting in a plenty of natural catastrophes throughout the world. Considering the progressive growth of household energy consumption, national strategies for zero-carbon/carbon-neutral energy communities have been formulated worldwide to reduce CO_2 emissions from residential building sectors (He et al., 2021; Krarti and Aldubyan, 2021). An energy community typically deploys renewable energy technologies to fulfil most of energy requirements. Due to their primary goal of promoting generation and utilization of clean energy, energy communities are also known as sustainable energy communities, or district energy communities (Krarti and Aldubyan, 2021). However, the common renewable energies (e.g., solar energy and wind energy) are always intermittent and unstable. In this context, technologies with additional flexibilities are reviewed on renewable energy systems to address their intermittency and instability. In recent years, energy storage technologies have received considerable attention on heat transfer mechanism (Qiu and Li, 2020) and thermal performance (Feng et al., 2019), due to the improvement in renewable energy dispatchability, simultaneously synergizing different energy sectors (Parra et al., 2017).

To fully utilise renewable energy, different forms of energy storages are required in the practical applications. Functions of these energy storage technologies can mitigate mismatches between supply and demand on the electric grid, and have potentially supported the integration of different renewable energy technologies into the electric grid. Energy storage technologies also can supply temporary storage when electricity is abundant or relatively cheap, and distribute the stored energy when electricity becomes scarce or more expensive (Speidel and Bräunl, 2016). In the energy community, common forms of energy storage technologies can be classified into the following categories: sensible and latent thermal energy storage, electrical storages (e.g., batteries, supercapacitors, and compressed air storage), chemical and hydrogen storages (Parra et al., 2017). Compared to electrical, chemical and hydrogen storages, thermal energy storages are relatively cheaper, faster response, and more flexible temperature range for multi-cascade applications, but with lower energy quality. In recent years, the latent thermal energy storage (LTES) technology has received increasing attention in reducing energy demands through thermal buffering (Jankowski and McCluskey, 2014), decreasing peak power through peak shaving (Riahi et al., 2021), stabilizing power supply by addressing power fluctuation and intermittence (Jouhara et al., 2020), highlighting its significance in addressing global warming and energy challenges (Li et al., 2021).

1.1. Latent thermal energy storage technologies

Generally, heat storage densities of LTES technology are 5–10 times higher than that of sensible thermal energy storage (Sharma et al., 2009), which is more reliable and secure than thermochemical heat storage systems. Since the temperature of the latent heat material is almost constant during the phase transition, which can supply a large amount of thermal energy with a relatively stable temperature. As the most common form of LTES technologies, phase change materials (PCMs) have been explored for several decades, and they are currently used mainly in thermal management and energy storage for both energy conservation and thermal control objectives (Arteconi et al., 2012). The thermal energy stored and released by these PCMs can be used for various functions such as photovoltaic (PV) panels, solar thermal, building envelopes, air conditioning, air/water heating and cooling systems, industrial waste heat utilization, and solar power generation (Hassan et al., 2022). Recent advances and challenges related to solar photovoltaic and wind energy, electrified transportation, energy transformation, and building air conditioning, have rekindled enthusiasm for phase change energy storage exploration (Faraj et al., 2020). Thermal storage with PCMs can buffer transient thermal loads, balance renewable energy generation and demand, store grid-scale energy, and recover waste heat, etc. (Feng et al., 2022; Li et al., 2019c; Yan et al., 2020a). The application of energy storage systems in the energy community could contribute to reducing building energy consumption and promoting the transition towards carbon neutrality. Compared to other energy storage methods (e.g., electrochemical cells), PCMs are more attractive, as they are with relatively lower cost and directly integrated with various renewable energies, such as solar-to-thermal, geothermal, and waste heat (Prieto and Cabeza, 2019a).

Over the past several decades, a plenty of researchers have investigated the application of various PCMs in buildings. PCMs have already been considered as a positive solution to improve energy effectiveness and enhance thermal performance of building materials, demonstrating its promising research directions for effectively reducing carbon emissions in the community buildings. Rathore et al. (Rathore and Shukla, 2019) conducted a critical review on the application of macro-encapsulated PCMs for energy efficiency in buildings. Various methods for integrating macro-encapsulated PCMs into the building envelope are retrospectively examined. Influences of different methods on indoor thermal environment and reduction of cooling loads were also analysed. In addition, research results can provide frontier guidelines on macro-encapsulation techniques, thermal energy storage methods, and suitable PCMs selections for encapsulation. Wijesuriya et al. (Wijesuriya et al., 2022) explored the energy efficiency and load flexibility capabilities of PCMs integrated building envelopes, in which 80% of the total energy load was derived from renewable energy. The required net heat storage was firstly determined to fully manage demand variations in utility grid, and then the operating parameters of energy storage systems were optimised through integrated building energy simulations. However, some studies have also illustrated some negative impacts of PCMs applications in construction materials, such as weakened mechanical properties, increased costs, and chemical instability (Wang et al., 2022).

In order to address negative impacts of PCMs and exploit PCMs for thermal management, many parameters need to be considered when selecting LTES materials, including phase change temperature, high thermal energy storage density, recyclability, chemical stability, mechanical strength and low corrosion of the storage containers. Thermal conductivity dominates others in determining the thermodynamic charging/discharging cycles of the LTES system (Tao and He, 2018). The improvement of thermal conductivity has been a major concern in recent decades, and many researchers have carried out a plenty of studies on the thermal conductivity enhancement of latent heat storage systems for different application scenarios. For instance, Liu et al. (Liu et al., 2022a) summarised and analysed the enhancement approaches of heat transfer performance of LTES systems for solar heating. The major approach is to add high thermal conductivity materials, such as high thermal conductivity porous media and nanomaterials. However, the porous medium material can improve the thermal conductivity of PCMs and simultaneously weaken the influence of natural heat convection in PCMs (Agyenim et al., 2010). There are also numerous studies considering adding different fins to enhance the heat transfer performance of LTES systems. Although some diverse fin configurations have been investigated and evaluated for different systems, most assessments have been performed based on their individual assumptions and limitations. Accordingly, Eslami et al. (Eslami et al., 2021) comprehensively reviewed different fin designs for various LTES systems and critically discussed the influences of different geometric parameters (e.g., fin thicknesses, lengths, spacings, numbers, angles, and shapes). The interactions between the fin configuration and other design parameters (e.g., shell geometry as well as fluid flow rate and temperature) were also investigated. Results demonstrated that the optimum number, spacing, and length of fins can be found in each scenario, while some parameters (e.g., fin thicknesses) are less important in enhancing the overall heat transfer performance of the LTES systems.

1.2. Temperature-cascaded PCMs applications

Using different temperature PCMs as LTES system has been recognised as one effective technology for heat transfer enhancement and efficiency improvement. The phase change temperature determines the various application scenarios of PCMs. It is necessary to select PCMs with comparable temperature intervals after ascertaining the application scenarios, in order to maximise their latent heat modulation performance. According to different application scenarios, common PCMs can be divided into the integration of low-, medium-, and high-temperature LTES systems. A considerable number of researchers have conducted in-depth studies and analyses of various PCMs for different temperature application scenarios. Li et al. (Li et al., 2021) presented a comprehensive and updated retrospective overview of LTES technologies, by particularly focusing on medium- and high-temperature PCMs for heat storage, recovery and utilization. Potential approaches of the design and optimization of LTES heat exchangers were determined for heat storage and recovery, addressing the knowledge gap between current research and future technological developments. Different types of PCMs and thermal conductivity enhancement methods were also summarised and analysed, with applicability of LTES heat exchangers under different heat sources (e.g., solar energy and industrial waste heat). Zhu et al. (Zhu et al., 2021) investigated the effectiveness of Trombe walls integrating PCMs in modulating the indoor thermal environment under hot summer and cold winter climates in China. Results showed that the optimal melting temperatures of different PCM layers in this integrated system were 16.5 °C and 27.75 °C. The optimised PCMs integrated application in Trombe walls decreased the annual total heating and cooling loads by 13.52% comparing with the traditional Trombe walls. Tunçbilek et al. (Tunçbilek et al., 2020) studied the optimal parameters of PCMs being installed into typical building bricks under Maramara climate conditions in Turkey. They indicated that the optimal melting temperature of PCMs varied from 18 °C in summer to 26 °C in winter for each year.

As an attractive solution for off-site industrial waste heat recovery, the removable energy storage system can be applied to recover and store industrial waste heat generated at a relatively low temperature (100–400 °C) and transport them to district residential communities for domestic hot water and building heating requirements. Du et al. (Du et al., 2021) presented the recent updates on PCMs applied in removable energy storage systems, including the conceptualization of capturing, storing, and transporting waste heat from the industrial waste heat source to the demand location. A comparative analysis of different types of removable thermal energy storage containers was also presented for applications in the residential sectors to provide heating and cooling services.

The demands for high-temperature energy storage are increasing at a rapid growth rate, especially with the development of the circular economy as one of effective solutions to mitigate global warming. Latent heat storage can be utilised in conventional power plants, waste heat recovery, and concentrating solar power plants to enhance thermal effectiveness (Fallahi et al., 2017). Compared to sensible thermal storages, LTES systems with PCMs are strongly considered for these applications due to their high energy density. Opolot et al. (Opolot et al., 2022) conducted a comprehensive summarization and analysis of LTES systems using PCMs with melting temperatures of 500 °C and above, and also examined the thermophysical properties and availability of potential PCMs. In addition, they carried out a discussion on the potential integration of LTES systems into concentrated solar power plants. Cárdenas et al. (Cárdenas and León, 2013) retrospectively investigated some PCMs, including the inorganic salt compositions and metallic alloys, which can potentially be used as storage media in high-temperature (above 300 °C) LTES systems. The aim of this study is to provide a comprehensive thermophysical property database for researchers to facilitate material selection of high-temperature PCM applications.

The development of cost-effective and reliable high-temperature PCMs for solar thermal energy storage is an essential measure for prospective applications of concentrated solar thermal technologies. The inorganic eutectic salts have already become the most promising candidates for high-temperature PCMs due to the low cost-effectiveness, high melting temperature, and potential melting heat. However, the inorganic salts have relatively low thermal conductivity and thermal stability. Besides, corrosion issues of packing materials at high temperatures restrain its widespread applications in practice. In recent years, a plenty of researchers have focused on the development of composite high-temperature PCMs, in which high-temperature molten salts are encapsulated as PCMs by supporting materials to improve the corrosion resistance, and enhance the thermal stability and thermal conductivity of the encapsulated materials. Jiang et al. (Jiang et al., 2019) presented an overview on current tendencies and latest advancements for high-temperature (>300 °C) PCM composites about the preparation and classification. They also discussed the influences of the already developed high-temperature PCM composites on their melting point, melting latent heat, heat transfer and thermal stability properties. The recommendations were also provided for the most efficient thermal energy storage system to be manufactured for practical applications.

1.3. Scientific gaps and objectives

From the above-mentioned analysis, PCMs have received increasing attention for various applications from perspectives in advanced integrated systems with renewable energy, innovative system designs (e.g., active and passive systems), intelligent operations and controls over the past few decades, demonstrating its promising prospects in carbon emission reductions in building sectors, and carbon-neutral district energy community transformation. However, the roadmap for the application of PCMs to low-carbon buildings and carbon-neutral community transition is ambiguous in the current academia. Furthermore, an in-depth up-to-date overview on latent heat storage technologies and fundamental roles are missing. Moreover, potentials in energy saving and decarbonization of low, medium and high-temperature PCMs are not clear, especially considering difference in metrology parameters in different climate zones. Based on these scientific gaps, this study will conduct the comprehensive and state-of-the-art literature overview to interconnect PCM fundamentals, PCM components and energy system integrations for district decarbonization. Research originality and novelty are listed as follows:

i) a clear roadmap on low-, medium- and high-temperature PCMs is provided, in respect to ambiguous temperature boundary, classifications and application scenarios. Furthermore, temperature-cascade PCMs are provided, in terms of common types, thermophysical properties, encapsulation techniques and selection criteria of PCMs;
ii) heat transfer enhancement strategies are provided from perspectives of thermal conductivity, heat transfer area, multistage and cascaded latent energy storages;
iii) novel structural design and smart operation strategies on PCM integrated components are provided in buildings, together with novel passive, active, and artificial intelligence-assisted strategies;
iv) cutting-edge techniques of LTES applications are comprehensively provided, in respect to carbon-neutral district energy community, biobased PCM production, solar energy applications (e.g., solar thermal energy systems, solar power energy systems, and solar thermal power plants), other natural energy utilization (e.g., natural cooling/heating sources, geothermal energy, sky radiative cooling, and waste-to-energy from city power plants, industry and mobility), and waste-to-energy techniques.

The objectives of this study are summarised as: 1) providing a clear roadmap for the selection, development, and application of PCMs in renewable energy use and energy-saving; 2) interconnecting with decarbonization and carbon-neutral transformation through advanced material innovations and smart system integrations; 3) clarifying prospects and challenges for scientific and practical applications of PCM-related technologies, and pave path for collaborative endeavors and cross-disciplinary research.

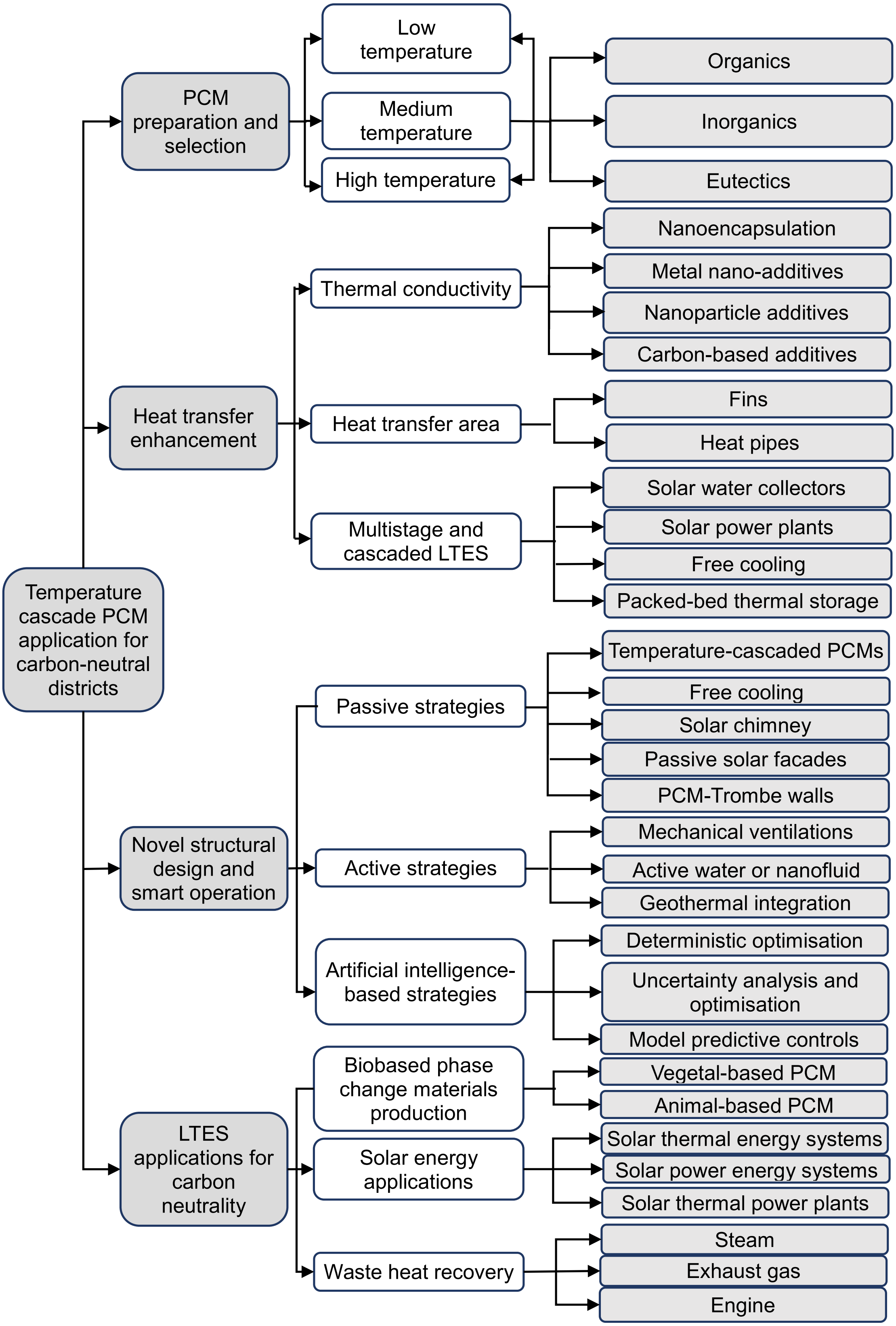


Fig. 1. Research roadmap on temperature cascade PCM application for carbon-neutral districts.

2. Methodology

A systematic and comprehensive overview on temperature-cascade PCMs for carbon-neutral districts was conducted based on the following diagram, as demonstrated in Fig. 1. The investigated PCMs include low-, medium-, and high-temperature, with respect to organics, inorganics and eutectics. To improve the charging/discharging efficiency, heat transfer enhancement strategies are reviewed, from perspectives of enhancement in thermal conductivity and heat transfer area, together with multistage and cascaded LTES design. For the thermal conductivity enhancement, reviewed techniques include nano-encapsulation, metal nano-additives, nanoparticle additives and carbon-based additives. For the increase in heat transfer area, both fins and heat pipes were reviewed. Multistage and cascaded LTES systems are designed for solar water collectors, solar power plants, free cooling and packed-bed thermal storage. Afterwards, novel structural design and smart operation were reviewed, including passive, active and artificial intelligence (AI) -based strategies. Passive strategies are mainly focused on passive design, whereas active strategies are mainly focused on mechanical ventilation, active water or nanofluid-based cooling/heating and subsystem integration (e.g., geothermal energy system). Due to the superiority in accurate performance prediction of nonlinear systems with high efficiency, AI-based strategies mainly include deterministic optimisation, uncertainty analysis and optimisation, and model predictive controls. Last but not the least, applications of LTES for the carbon neutrality transition were reviewed, including biobased phase change materials production, solar energy applications and waste heat recovery. Biobased PCMs, which are environmental-friendly with high thermodynamic performance, mainly include vegetal-based and animal-based PCMs. Considering different energy forms, applications of PCMs in solar energy systems mainly include solar thermal energy systems, power energy system and thermal power plants. Furthermore, PCMs for waste heat recovery were also reviewed, from the industrial factory, power plant, and mechanical power equipment in the mobile thermal energy storage vehicles (e.g., the internal combustion engine, and fuel cell system). Depending on the heat recovered heat transfer fluids or devices, PCMs-based waste heat recovery systems can be classified into steam, exhaust gas and combustion engines.

This study can be divided into four main sections. Section 3 shows a systematic overview on PCM preparation and selection in different temperature levels. Section 4 demonstrates heat transfer enhancement, from perspectives of thermal conductivity, heat transfer area, multistage, and cascaded LTES. Section 5 shows novel structural design and smart operation, including passive, active, and AI-based strategies. Afterwards, fundamental roles and applications of LTES for carbon-neutrality transition are reviewed, from perspectives of biobased PCM production, solar energy applications, and waste heat recovery. Based on the availability of the proposed PCMs-based heat recovery systems, a thermal energy interaction network was structured for interactive energy sharing in the smart city. Both challenges and opportunities are presented in terms of PCMs' characteristics, systematic configuration and design of PCMs integrated systems, robust and reliable system operation, and system optimisations, respectively. Last but not the least, energy saving and decarbonization potentials for each type of PCM are estimated. Outlook and recommendations are provided, including establishment of standard testing procedure and database, cascaded LTES systems, heat transfer enhancement in PCMs with nanofluid, anti-corrosion effect between PCMs and container materials, durability and stability of PCMs over long-term operation, benchmark for suitable PCM selection and so on.

3. PCM preparation and selection

PCMs, as one of the most efficient technologies for the storage and release of exogenous energy (e.g., solar, geothermal, and other renewable energy technologies), have been widely recommended for theoretical research and practical utilization in different fields (Liu et al., 2021b; Qin et al., 2021; Zhou et al., 2021, 2020b). The temperature range for low-, medium-, and high-temperature PCMs, is ambiguous in different application scenarios. For example, for building applications, the temperature range is relatively low (<40 °C) when PCMs are applied for cooling. The medium- and high-temperature PCMs are normally with melting temperatures at 40–80 °C and >80 °C for space heating and domestic heating, respectively (Du et al., 2018; Oró et al., 2012). However, in the fields of solar power generation or high-temperature energy storage systems, phase change temperature of PCMs exceeding 200 °C is considered as high-temperature PCMs (Crespo et al., 2019). With respect to real applications, in community building energy systems, low-temperature PCMs are mainly used in regulating indoor and built environment, such as building envelopes (Liu et al., 2018b), ventilation systems (Arumugam et al., 2022), and air conditioning systems (Wang et al., 2002), etc. Medium-temperature PCMs are mainly applied in solar heating/cooling (Hu et al., 2015; Kumar et al., 2021), and waste heat recovery (Wu et al., 2021), etc. High-temperature PCMs are mainly used in industrial waste heat utilization and recovery (Du et al., 2021), and concentrated solar power plants (Elfeky et al., 2022; Prieto and Cabeza, 2019a), etc. This section aims to holistically review temperature range and applications of low, medium, and high-temperature PCMs.

3.1. Low-temperature PCM types and thermophysical properties

The common low-temperature PCMs can be mainly divided into organic and inorganic PCMs. Organic PCMs mainly include paraffin and non-paraffin (e.g., fatty acids, eutectics and mixtures). A plenty of studies show that, through thousands of charging/discharging cycles, organic PCMs rarely crystallise and supercool, and are usually non-corrosive and very stable in practical applications. These characteristics can popularise the application of organic PCMs with easy encapsulation materials. However, there is no organic PCMs that can satisfy requirements for various application scenarios (Singh et al., 2021). Paraffin and fatty acids are the most commonly used low-temperature organic PCMs, which have various melting point temperatures (from about -182 to 135 °C) and high latent heat (from about 180 to 230 kJ/kg) (Drissi et al., 2019), with chemically stable, non-toxic, and non-corrosive characteristics. However, organic PCMs generally have a relatively low thermal conductivity (from 0.18 to 0.24 W/(m·K) (Li et al., 2019d)), which decreases the energy storage efficiency during charging and discharging processes. Composite PCMs with adjustable phase change temperatures and latent heat are effective solutions, especially with stable physical and chemical properties (Cai et al., 2020). Currently, it is common to combine fatty acids with fatty alcohols to form binary low eutectic mixtures, or to mix concentrated fatty acids to form multi-fatty acid eutectic mixtures, or to mix fatty acids with paraffin to prepare binary composite PCMs (Zhao et al., 2021).

Inorganic salt hydrate PCMs are non-flammable and inexpensive with a relatively high latent heat and thermal conductivity. For example, the thermal conductivity of $CaCl_2·6H_2O$ is 1.08 W/(m·K), which is almost four times that of common organic PCMs. However, the inorganic PCMs are commonly susceptible to supercooling, leading to irreversible reduction of phase change latent heat. In addition, the chemical stability of salt hydrate PCMs is relatively poor, leading to corrosion in the encapsulation container (Li et al., 2016). Inorganic PCMs can be further classified as compound and eutectic. A eutectic material is a mixture of two or more ingredients that uniformly melt and freeze during the crystallization process to form a mixture of component crystals. The eutectic always has the melting and freezing process without segregation, and there is almost no opportunity to separate the individual ingredient (Pirvaram et al., 2019). Thermal properties of low-temperature PCMs with high potentials for building energy savings are summarised in Table 1.

Various properties, e.g., physical, thermal, chemical and economic

Table 1
Low-temperature PCMs with high potentials in building energy savings.

PCM component & composition (wt.%)	Type	Melting temperature (°C)	Heat of fusion (kJ/kg)	Ref.
Paraffin RT4	Organic	2–4	281	(Wu et al., 2017)
Paraffin RT25	Organic	26.6	232	(Nouira and Sammouda, 2018)
Paraffin RT35	Organic	36	240	(Ma et al., 2018)
Paraffin RT54	Organic	54	190	(Kabeel et al., 2016)
$CaCl_2·6H_2O$	Inorganic	29.9	191	(Hasan et al., 2015)
$Mn(NO_3)·6H_2O+MgCl_2·6H_2O$	Inorganic	15–25	125.9	(Kenisarin, 2010)
Lauryl alcohol/ Cetyl alcohol (80:20)	Eutectic organic	20.01	191.63	(Philip et al., 2020)
Lauric acid/ Hexanediol (30:70)	Eutectic organic	36.92	177.11	(Han et al., 2017)
Decanoic acid/ Tetra Decanoic (78:22)	Eutectic organic	20.5	153	(Kahwaji et al., 2016)
Capric/Cetyl alcohol (70:30)	Eutectic organic	22.89	144.92	(Veerakumar & Sreekumar, 2018)
Lauric/Myristil alcohol (40:60)	Eutectic organic	21.3	151.5	(Chinnasamy & Appukuttan, 2019)
PEG 2000/ PEG10000 (20:80)	Eutectic organic	54	185	(Ansu et al., 2020)
1, 4 Butanediol behenic acid	Fatty acid	74	209	(Cabus et al., 2013)

properties of the selected PCMs, and product safety, availability, adaptability and cost, are critical selection factors for low-temperature PCMs in practical applications (Nazir et al., 2019). With regard to the selection of PCMs in low-temperature energy storage systems, it is necessary to consider the desirable properties as listed in Table 2.

In practical applications, it is difficult to find one ideal low-temperature PCM that satisfies all requirements simultaneously. In addition to considering non-toxicity and harmlessness to the environment, the phase change temperature is the dominant characteristic, as the PCMs can fully utilise the latent heat only when the phase change temperature corresponds exactly to the operating conditions. Latent heat is a straightforward indicator to quantify the PCM's heat storage capacity. PCMs with high latent heat can maximumly reduce the overall volume of energy storage systems. Furthermore, low costs of PCMs can promote the market commercialization with low system payback time (Nazir et al., 2019).

Table 2
The desirable properties for the selection of PCMs in low-temperature energy storage systems (Ben Romdhane et al., 2020; Zhou et al., 2012).

Thermodynamic properties	Suitable phase change temperature High latent heat
Physical properties	High density and small volume change Small vapour pressure under working temperature Small storage capacity loss during cycling charging/ discharging processes
Kinetic properties	Adequate nucleation and crystallisation rate No-subcooling
Chemical properties	Long-term chemical stability Corrosion resistance of the vessel material No-toxicity and no-flammability
Other properties	Commercially available, abundant and cost-competitive.

3.2. Medium-temperature PCM types and thermophysical properties

The medium-temperature PCMs can also be divided into three categories: organic, inorganic, and eutectic PCMs according to its phase change temperature and material composition. In respect to low-temperature PCMs, organic PCMs for medium-temperature applications have advantages of chemically stable, non-corrosive, non-toxic, and non-phase separation (Xu et al., 2015). The main components of medium-temperature inorganic salt PCMs refer to nitrate, chloride, carbonate, fluoride, sulfate and their component mixture. These inorganic materials generally have a relatively high working temperature, specific heat, thermal stability and liquid convective heat transfer coefficient, but their viscosity, saturated vapour pressure and price are still low (Zhang et al., 2018). Some salts and salt components have a melting temperature over 150 °C, which are suitable for the application in waste heat recovery systems (Xu et al., 2015). Thermal properties of medium-temperature PCMs that are suitable for carbon-neutral communities in the literature are summarised in Table 3.

Poor thermal conductivity is also the important factor, restraining the widespread application of medium-temperature organic PCMs. Therefore, the development of organic composite PCMs with high energy storage density and thermal conductivity has attracted increasing interests. Inorganic materials with a relatively high thermal conductivity can be added into organic PCMs through melt blending to increase the overall thermal conductivity of the mixed material, whereas the latent heat can be slightly reduced due to the decreased volume of PCMs (Al-Maghalseh and Mahkamov, 2018). Currently, the metal nanometre and carbon-based materials are the most commonly used inorganic materials with high thermal conductivity (Wu et al., 2020).

In order to prevent the medium-temperature PCMs from leakage, appropriate encapsulation forms are critical. Unlike low-temperature PCMs, the common encapsulation form for medium-temperature PCMs is macro-encapsulation. However, micro-encapsulation could be performed at low temperatures due to the simplicity of production and the commercialization of comparatively mature process, which was mainly manufactured by plastic capsules. Many studies have shown that the appropriate macro-encapsulation form is also one of effective techniques to enhance the heat transmission area between the medium-temperature PCMs and the surrounding heat transfer fluid. However, the selection of suitable encapsulation materials is full of challenges, to simultaneously address volume expansion problems without any reactions with the encapsulated internal PCMs and thermo-physically stable at high temperatures. Metallic encapsulation PCMs with macro-encapsulation are widely applied in medium-temperature solar systems. However, metallic encapsulation is not available for the long operation of latent heat storage applications under corrosive conditions (Jacob and Bruno, 2015).

Therefore, more flexible encapsulation materials are required to accommodate the variations of volume and vapour pressures during solid-liquid phase changes, which are related to the stabilisation of the encapsulation containers. Some researchers have recommended the use of high-performance polymers as encapsulation materials for medium-temperature PCMs. Although these materials are not commercially available, they have good properties and great potentials, and these polymers as encapsulation materials will contribute to reducing the weight of the storage tank and can significantly reduce installation difficulties. Gupta et al. (Gupta et al., 2020) investigated the thermo-mechanical properties of polymeric materials that could be used to encapsulate PCMs for medium-temperature solar applications. Polytetrafluoroethylene, polyether ether ketone, and polyether ketone were selected as encapsulation materials, and the selected PCM was A164, with a melting temperature of 164 °C. The thermomechanical properties measurements results indicated that, the selected polymers showed high-temperature stability and could be used as encapsulation materials for medium-temperature PCMs. These results will provide the foundation for their applications as the encapsulation materials of PCMs for

Table 3
Thermophysical properties of medium-temperature PCMs.

Application scenarios	PCM component & composition (wt.%)	Type	Melting temperature (°C)	Heat of fusion (kJ/kg)	Ref.
Solar energy utilizations	Erythritol ($C_4H_{10}O_4$)	Organic	118	339	(Yuan et al., 2019)
Solar cooling applications	D-mannitol ($C_6H_{14}O_6$)	Organic	165	341	(Peiró et al., 2015)
Waste heat and solar energy applications	$AlCl_3$	Inorganic salts	192	280	(Pielichowska and Pielichowski, 2014)
Solar energy utilizations	KCL-$LiNO_3$ (50–50)	Eutectic compounds	165.6	201.7	(Huang et al., 2014)
Solar thermal plants	$LiNO_3$—$NaNO_3$-KNO_3 (30–18–52)	Eutectic compounds	123	140	(Olivares and Edwards, 2013)
Concentrating photovoltaic-thermoelectric applications	NaOH-KOH (24–76)	Inorganic salt compounds	147	205	(Cui et al., 2016)
Solar process heat or waste heat recovery applications	Galactitol	Fatty acid derivatives	179.8	246.4	(Solé et al., 2014)
Solar industrial process heat supply and heat recovery in industrial batch processes	Lactitol	Fatty acid derivatives	146	135	(Solé et al., 2014)
	Maleic acid	Organic compounds	141	385	
Solar cooling applications	Hydroquinone	Organic compounds	168–173	205.8	(Gil et al., 2018)

medium-temperature solar energy utilisations.

As with the selection criteria for low-temperature PCMs, the thermophysical, chemical, kinetic and economic properties also need to be considered when selecting medium-temperature PCMs for practical applications (Mohamed et al., 2017; Wei et al., 2018). However, the selection of medium-temperature PCMs is not an easy process and requires careful consideration of the combined other properties, including melting temperature, thermal conductivity, corrosion, reliability, affordability, and also including the compatibility with encapsulation materials. In addition, the selection of medium-temperature PCMs needs to be evaluated on a case-by-case basis, considering the design and installation location of the medium-temperature LTES system.

3.3. High-temperature PCM types and thermophysical properties

High-temperature PCMs have been mainly applied in concentrated solar power plants to generate power through steam power cycles (Liu et al., 2021a). Common high-temperature PCMs are mainly composed of inorganic salts, metals or metal alloys. Compared to inorganic salts, metals and alloys have some critical advantages (e.g., high melting temperature, high melting latent heat, and high thermal conductivity), like Al-Si, Al-Si-Mg and Al-Si-Cu. However, applications of metals and alloys are significantly limited by expensive costs and corrosion to building materials (He et al., 2015). By contrast, some inorganic salts, such as nitrates, carbonates and chlorides, have also been widely studied as high-temperature PCMs, because of their relatively low cost and suitable thermal properties. However, inorganic salt high-temperature PCMs also have some shortcomings that hinder their large-scale application, e.g., corrosion, undercooling, low thermal conductivity, and poor thermal stability, providing both challenges and opportunities for future research on high-temperature PCMs (Jiang et al., 2017).

The usage of molten salts as an energy storage medium in high-temperature LTES systems has several advantages. The generally high melting point of molten salts ensures that they have a wider range of applications. They are also relatively thermal-stable for application in the high-temperature energy storage system. In addition, molten salts have a high specific heat, low viscosity, and low vapour pressure. Nitrates and their low eutectics are storage mediums in high-temperature energy storage, but they will decompose at temperatures above 600 °C. Several researchers have reported on hundreds of fluorides, chlorides, carbonate-based salts, and metal alloys as suitable high-temperature storage media in the temperature range of 200–1000 °C.

In practical applications, researchers often use eutectic mixtures of two and/or three molten salts for PCMs rather than a single salt. They obtain the desired melting temperature by changing the ratio of each ingredient. Eutectic mixture PCMs show a higher energy storage density comparing with a single salt with the same temperature range. However, co-fusion blended molten salt PCMs suffer from low thermal conductivity and leakage of the molten PCMs, restraining the heat transfer rate during charging/discharging processes. Therefore, for systems using molten salt PCMs as a high-temperature energy storage medium, low thermal conductivity and leakage problems of molten salt PCMs need to be addressed, imposing challenges on the selection of a suitable encapsulation container or encapsulation technology (Raud et al., 2017).

Metal alloys, as the promising high-temperature latent PCMs for practical applications, show higher weight-energy density, higher thermal conductivity, and higher thermal stability properties, comparing with molten salts, and have been extensively studied in academia (Fernández et al., 2017). Compared to the commonly used molten salts in high-temperature energy storage systems, silicon and boron have a considerable energy density. Thermal properties of high-temperature PCMs that were suitable for carbon-neutral energy communities in the literature are summarised in Table 4. High-temperature PCMs are mainly applied in concentrated solar power, wind power, and waste heat recovery systems.

The incompatibility and leakage problems of high-temperature PCMs with encapsulation or supporting materials are more serious than those of low and medium-temperature PCMs. Some studies use ceramic materials to encapsulate Al-Si alloy PCMs to overcome the corrosion problem. In addition, the thermal expansion of high-temperature PCMs during the melting process is another major problem in the application of shell-encapsulated PCMs, which may cause the shell materials to crack and cause the melted PCMs to leak. Therefore, it is necessary to develop special encapsulation technologies or materials to solve the encapsulation problem of high-temperature PCMs (He et al., 2015; Walczak et al., 2018).

4. Heat transfer enhancement on latent energy storage

As one of the most challenging and urgent issues, low energy storage and release efficiency in PCMs have been studied during charging and discharging processes. Tao and He (Tao and He, 2018) systematically reviewed heat transfer enhancement of PCMs, in terms of classification and recent development. Results indicated that, most common materials for thermal conductivity enhancement include metal foam, expanded graphite, carbon nanomaterial and metal oxide particles. However, the integration of high-conductive additives will contrarily decrease the enthalpy due to the reduced specific volume. Ibrahim et al. (Ibrahim et al., 2017) systematically reviewed heat transfer enhancement of

Table 4
The high-temperature PCMs for applications in carbon-neutral energy communities.

Application scenarios	PCM component & composition (wt.%)	Type	Phase change temperature (°C)	Heat of fusion (kJ/kg)	Ref.
Concentrated solar power	KNO_3	Pure molten salts	337	167	(Wei et al., 2018)
Concentrated solar power	Na_2CO_3–Li_2CO_3 (42–58)	Molten salts compounds	498.3 ± 0.1	330.8 ± 0.6	(Jiang et al., 2017)
Concentrated solar power	Na_2CO_3–K_2CO_3 (47.19–52.81)	Molten salts compounds	706.92	133.14	(Jacob et al., 2019)
Curtailed wind power and concentrated solar power generation	Na_2CO_3-Li_2CO_3 (57–43)	Molten salts compounds	500.35		(Li et al., 2019a)
Waste heat recovery, and concentrated solar power generation	NaLiCO3	Molten salts	500.2	348.5	(Li et al., 2019b)
Concentrated solar power	$Mg_{84}Cu_{16}$	Eutectic alloys	488	232	(El Karim et al., 2019)
	$Mg_{59}Cu_{41}$	Eutectic alloys	550	138	
Solar energy and industrial exhaust heat	Al–Si (87.8–12.2)	Metal alloy	580	499.2	(Fukahori et al., 2016)
Solar thermal/power systems	$MgCl_2$/KCl/NaCl (60/20.4/19.6)	Molten salts compounds	380	400	(Michels and Pitz-Paal, 2007)

PCMs, from perspectives of extended surfaces (fins or heat pipes) and thermal conductivity enhancement (porous materials, nanoparticles). In addition, techniques for increasing heat transfer area include finned tube and encapsulated PCMs. Furthermore, the uniformity of the heat transfer can be realised via cascaded PCMs, thermodynamic analysis and optimization. In this section, a holistic overview was conducted in heat transfer enhancement from perspectives of adding high-conductive additives, increasing effective heat transfer area, and temperature-dependent cascaded LTES technique with thermodynamic optimization.

4.1. Porous media and nanoparticle additives for heat transfer enhancement

In the academia, strategies for thermal conductivity enhancement can be mainly classified into nanoencapsulation in PCMs (Liu et al., 2015), metal-based nano-additives (Hashem Zadeh et al., 2020), nanoparticle additives (Kibria et al., 2015; Nakhchi et al., 2021; Yang et al., 2020) and carbon-based additives (Shi et al., 2013; Wang et al., 2013; Yang et al., 2016). In terms of nanoencapsulation, Liu et al. (Liu et al., 2015) reviewed nanoencapsulated PCMs in latent functional thermal fluid, in terms of enhancement of thermal storage capacity and thermal conductivity. For the metal-based nano-additives, Zadeh et al. (Hashem Zadeh et al., 2020) added copper foam and Cu/GO nano-additives to improve the PCM charging power by four times.

Nanoparticle additives have also been studied, including both metal-based nano-additives (Hashem Zadeh et al., 2020), nanoparticle additives (Kibria et al., 2015; Nakhchi et al., 2021; Yang et al., 2020). Yang et al. (Yang et al., 2020) reviewed nanoparticle additives for enhancement of thermophysical properties of PCMs. The roles of nanoparticle additives in PCMs include improvement in stored/released energy and solar power generation. Zhang et al. (Zhang et al., 2019) adopted a novel sunlight-driven PCM considering the combination of polyethylene glycol (PEG) and Ag nanoparticle-functionalised graphene nanosheets (Ag–GNS). The composites showed high photothermal conversion efficiency ($\eta = 88.7$–92.0%), due to strengthened light absorption capacity and decreased thermal radiation of Ag. Furthermore, these composites also showed enhanced thermal conductivity (49.5–95.3%), high thermal energy storage density (>166.1 J/g), high heat energy storage/release rates and form-stable properties. Nakhchi et al. (Nakhchi et al., 2021) studied the combined nanoparticles and stair fins on thermal performance enhancement of LTES system. Results showed that the 1.5% nanoparticles can enhance the energy storage capacity by 9.1%. Kibria et al. (Kibria et al., 2015) holistically reviewed the thermophysical properties of nanoparticle dispersed PCMs. Results indicated that, carbon nanotubes and carbon nano fibre show superior performances on the properties.

Carbon-based additives have been regarded as more promising additives. Lin et al. (Lin et al., 2018) reviewed methods for thermal conductivity enhancement of PCMs, from perspective of additives and encapsulations. Thereafter, researchers are mainly focused on carbon-based additives in PCMs for heat transfer enhancement. Wang et al. (Wang et al., 2013) developed a novel material containing single-walled carbon nanotubes (SWNTs) and shape-stabilised polymeric PCMs for solar thermal energy storage. The experimental testing results indicated that, the novel hybrid material had a more extensive absorption of sunlight and excellent form-stable properties. Shi et al. (Shi et al., 2013) applied nanographite additives in PCMs for thermal conductivity and shape-stabilization. Experimental testing results indicated that, paraffin can keep its shape up to 185.2 °C with 2 wt.% graphene loading. Yang et al. (Yang et al., 2016) implemented graphene aerogels in PCMs for improvement in thermal conductivity, light-to-thermal storage and shape-stabilization. Results indicated that, the incorporation of 0.45 wt % graphene oxide (GO) and 1.8 wt% graphene nanoplatelets (GNP) in the polyethylene glycol can improve the thermal conductivity from 0.31 to 1.43 W/(m·K).

4.2. Enlargement of heat transfer area

Furthermore, enhancement in heat transfer area mainly includes fines and heat pipe. In terms of heat pipe, Ebrahimi et al. (Ebrahimi et al., 2019) studied the melting process of PCMs integrated tube heat exchanger, as illustrated in Fig. 2. Results showed that, the heat pipe around the shell can decrease the total melting time by 91%. Merlin et al. (Merlin et al., 2016) comparatively investigated the influences of different structural configurations for thermal contact between the exchanger and the PCMs on the Overall Heat Transfer Coefficient (OHTC). Results showed that, PCMs embedded in Expanded Natural Graphite (ENG) matrix has the maximum OHTC of about 3000 W/(m^2·K).

In terms of fins, He et al. (He et al., 2020) investigated the dynamic melting behaviour and performance enhancement solutions of a directly accessible thermal energy storage container. The PCM melting mainly includes thermal conduction, and convective heat transfer. Furthermore, plain fins can improve heat transfer performance due to large surface contact area. Weng et al. (Weng et al., 2019) designed branch-structured fins (V, Y and X shapes) for heat transfer improvement in PCMs for thermal management of battery. Due to the increasing of heat transfer area via heat transfer channels, the X-shape shows the best performance with the maximum temperature of the cell below 47 °C. Different types of fins are demonstrated, as shown in Fig. 3. Khan and Khan (Khan and Khan, 2020) explored the role of extended fins in thermal improvement of LTES system. Depending on different increasing magnitudes of extended surfaces, the wire-wound fins with nano-PCM and 1% graphene nano-platelets are the optimum solution for latent heat storage. Karami and Kamkari (Karami and Kamkari, 2020)

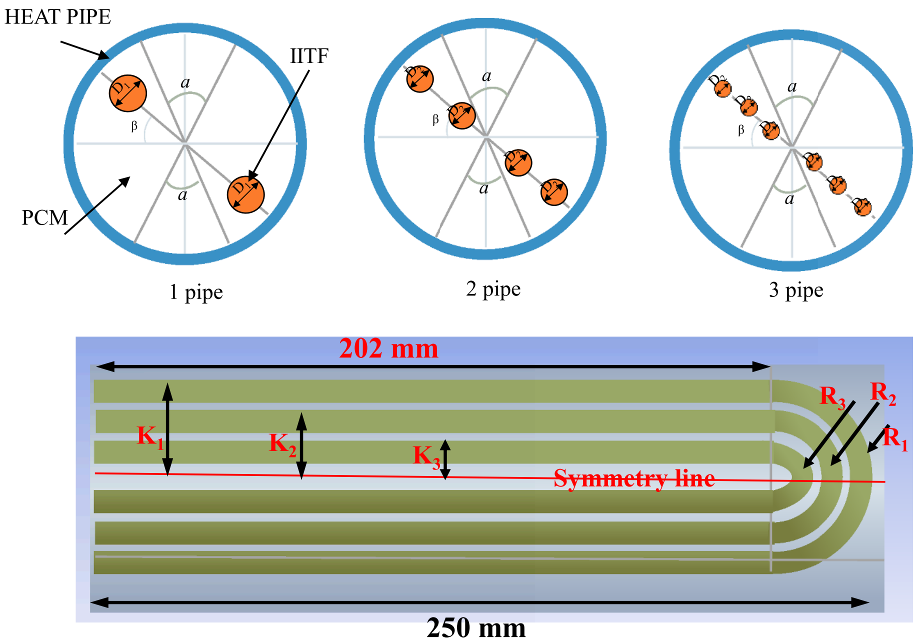


Fig. 2. Structure diagram of PCMs integrated shell and tube heat exchanger (Ebrahimi et al., 2019).

experimentally studied the impact of perforated fins on heat transfer enhancement of PCMs. Experimental results indicated that, compared to solid fins integrated PCMs, the perforated fins can improve the Nusselt number by 30% and decrease the melting time by 7%.

Furthermore, combined solutions with fines and heat pipe (HP) have also been studied. Compared to thermal conductivity approach (heat pipe-copper foam, HP-CF) with better solidification performance, the enhancement of heat transfer area (heat pipe-fins) shows better melting performance (Zhang et al., 2020). Compared to HP only, the HP-Fin and HP-CF can reduce the total melting and solidification time by 82.70% and 89.03%, respectively.

4.3. Multistage or cascaded LTES technique and thermodynamic optimization

Cascaded and multi-stage LTES system is an effective approach to enhance the thermal efficiency of PCMs. The multistage or cascaded LTES techniques have been widely used in storage tanks of solar water collectors (Zayed et al., 2019), solar power plants (Michels and Pitz-Paal, 2007), free cooling (Mosaffa et al., 2014, 2013), molten-salt packed-bed thermal storage (Wu et al., 2016), and latent storages (Aldoss and Rahman, 2014; Fang and Chen, 2007; Peiró et al., 2015; Tian and Zhao, 2013). Ahmed et al. (Ahmed et al., 2020) designed cascaded-layered PCMs as efficient and cost-effective LTES alternative. The parametrical and comparative analysis provides optimal layer structure, thickness and fusion temperature for thermal energy efficiency improvement. Mao and Zhang (Mao and Zhang, 2020) designed PCM cascade tanks for concentrating solar thermal power applications. Results showed that, with the decreasing of porosity from 0.6 to 0.1, the energy storage capacity and usage rate can be increased from 86.07% to 86.67%, together with the increase of total energy storage from 5.2×10^{12} to 1.3×10^{13} Wh.

Fig. 4 demonstrates the cascaded PCMs with different layers for medium- and high-temperature storages. The general principle is that, the fusion temperature of different-layered PCMs is decreased along the flow direction of the heat transfer fluid (HTF) during the charging process. However, during the discharging process, the fusion temperature of different-layered PCMs is increased along the flow direction of HTF. The HTF-dependent deployment strategy on PCMs with different melting temperature can improve the PCM storage efficiency via the enhancement of the average temperature difference between PCMs and HTF.

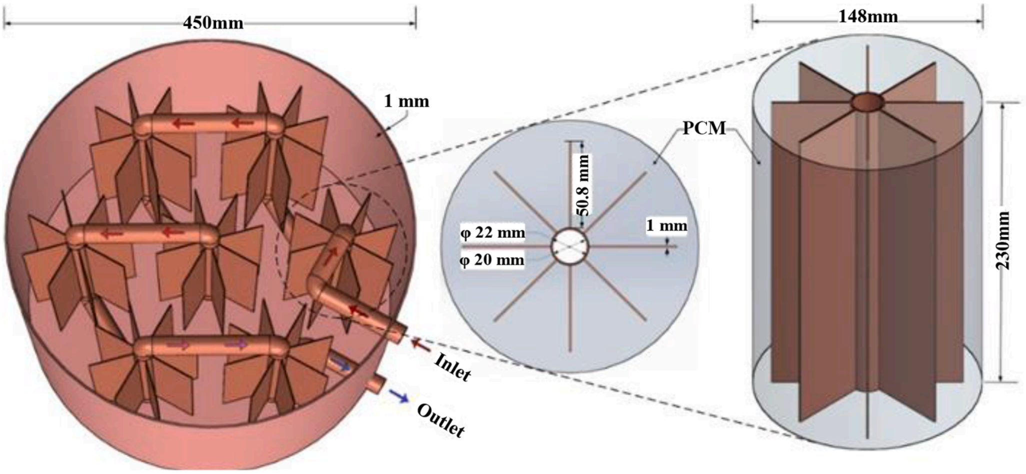
5. Novel structural design and smart operation strategies in buildings

With a large amount of latent heat, PCMs have been widely used in some building energy systems, to postpone indoor temperature response through thermal inertia, reduce cooling/heating load with natural energy resources (e.g., nighttime cooling, sky radiative cooling, solar heating and so on), enhance solar PV efficiency and so on. Zhou et al. (Zhou et al., 2020b) systematically reviewed passive/active PCMs integrating building energy systems to improve their thermal and power energy performance. Nowadays, the rapid development of AI promotes the energy-intelligent and smart buildings. Machine learning (ML)-based flexible design and smart control (Zhou et al., 2020e) can improve the operational performance with enhanced heat transfer. Furthermore, stochastic uncertainty-based design can improve the operational reliability (Zhou and Zheng, 2020c; Zhou et al., 2020f). In this section, a holistic and comprehensive review was conducted on PCMs integrated smart operation strategies in buildings.

5.1. Passive strategies

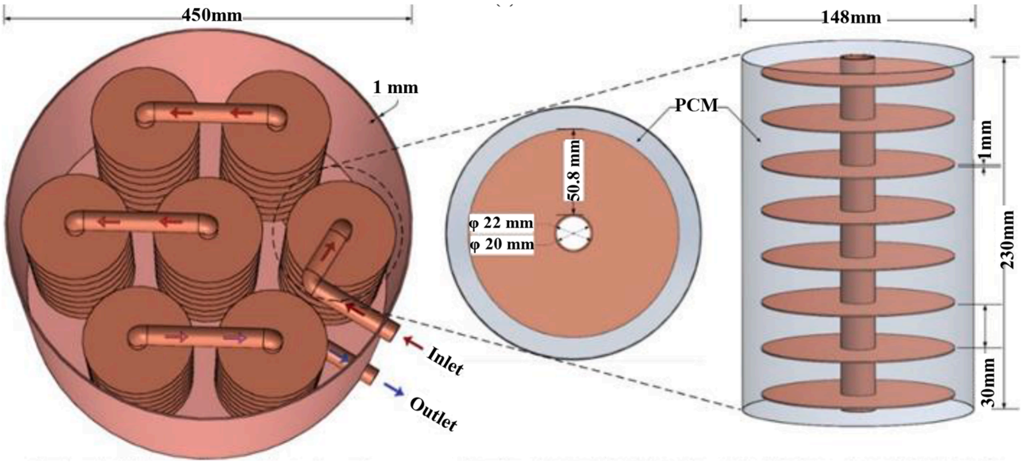
5.1.1. Temperature-cascaded PCMs

Due to the temperature stratification and heat transfer along the flow direction of HTF, the deployment of temperature-cascaded PCMs, following the temperature difference, can improve the PCM storage efficiency via the enhancement of the average temperature difference between PCMs and HTF. In respect to different temperature levels, the temperature-cascaded PCMs have been widely used in solar thermal collector systems (Zayed et al., 2019), solar hot water system (Teamah et al., 2018), cooling storage (Cheng and Zhai, 2018), concentrating solar power systems (Shabgard et al., 2012), cascaded packed bed thermal energy storage (Khor et al., 2020) and so on. Christopher et al. (Christopher et al., 2021) systematically reviewed cascaded configurations on PCMs for performance enhancement for different stage numbers. The schematic diagram of the multistage phase-change heat storage is illustrated in Fig. 5(a). Results showed that the optimal stage number of cascaded PCMs is dependent on inlet temperature of HTF,



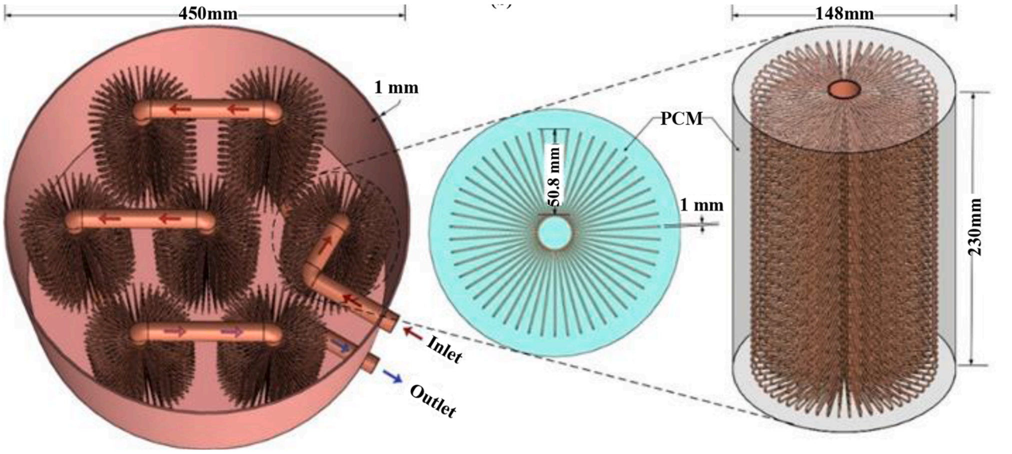
Shell-and-tube heat exchanger with longitudinal surfaces Top view- Computational domain Isometric view-Computational domain

(a)



Shell-and-tube heat exchanger with circular surfaces Top view- Computational domain Isometric view-Computational domain

(b)



Shell-and-tube heat exchanger with pins surfaces Top view- Computational domain Isometric view-Computational domain

(c)

Fig. 3. Heat exchanger with extended surfaces: (a) longitudinal fins, (b) circular fins; (c) wire-wound fins (Khan and Khan, 2020).

mass flow rate, mass ratio of PCMs, and type of heat exchanger. In general, a stage number from 3 to 6 is recommended, whereas the stage number higher than 10 will provide minimal improvement of the thermal performance. In terms of low-temperature PCM (melting temperature at 13–17 °C), the comparison between single-stage and three-stage cold storage units (Cheng and Zhai, 2018) indicates that, the cold charging rate can be improved by about 11%–35% in the cascaded cold storage unit. For the high-temperature storage, Peiró et al. (Peiró

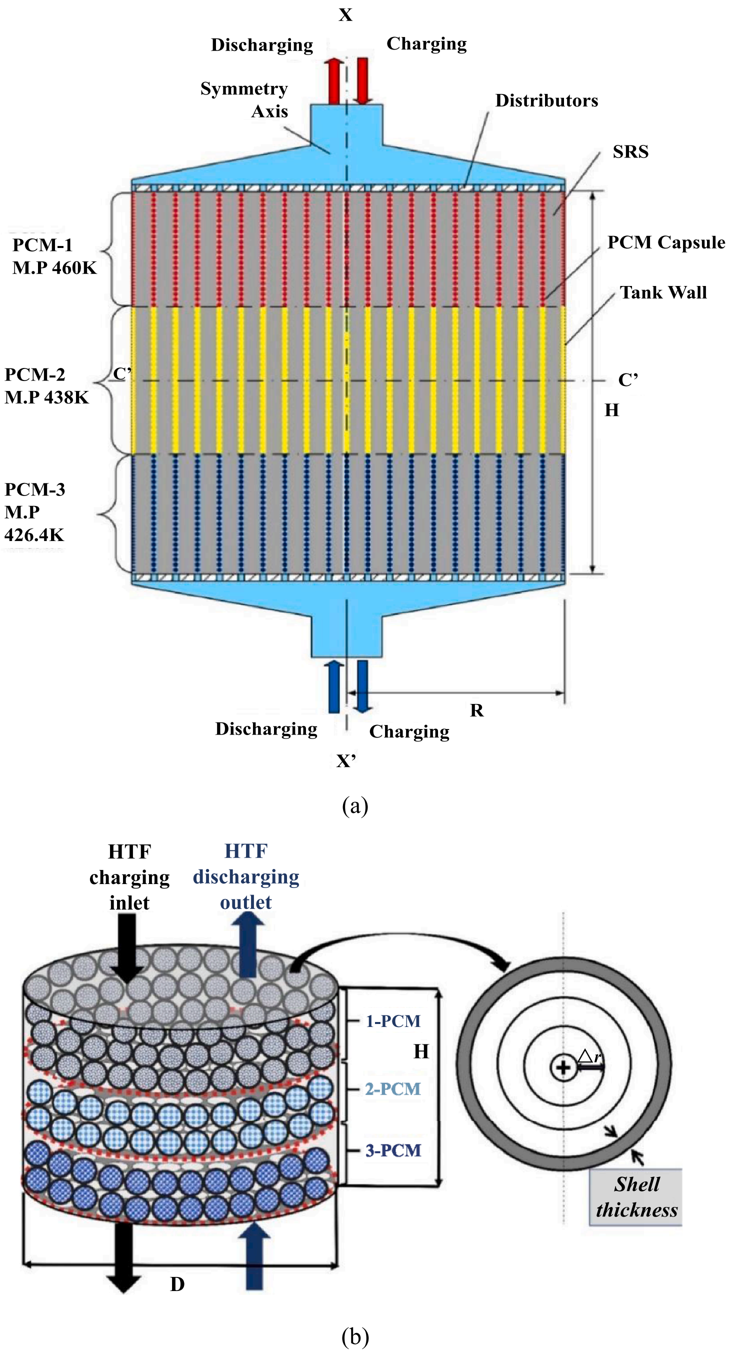
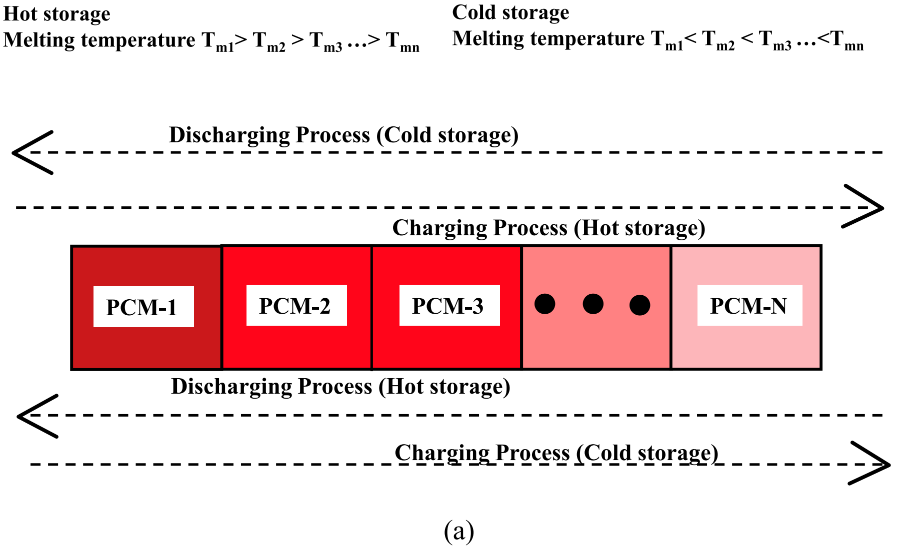


Fig. 4. Diagram of the cascaded layered PCMs for: (a) medium-temperature (Ahmed et al., 2020); (b) high-temperature packed bed thermal storage system (Mao and Zhang, 2020).

et al., 2015) compared cascaded and single PCM configuration for LTES system, and concluded that the multiple PCM effectiveness can be improved by 19.36% comparing with the single PCM configuration. Through the discretion on heat conduction differential equation, following the discrete node graph, as shown in Fig. 5(b), Xu and Zhao (Xu and Zhao, 2015) conducted the parametrical analysis on cascaded PCMs for energy efficient utilization. Results showed that, cascaded PCMs can extend applicable temperature scope, and the uniform temperature distribution is beneficial for thermal efficiency improvement.

5.1.2. *Free cooling*

In the climate zones with a large temperature difference between day and night, PCMs enable to store cooling energy during the night, and the stored energy can be discharged to cool the indoor air during daytime. Depending on the physical position of integrated PCMs, PCM-free cooling systems include ceiling (Turnpenny et al., 2000), floor (Takeda et al., 2004) and side-wall systems (Liu et al., 2018a). Alizadeh et al. (Alizadeh and Sadrameli, 2016) reviewed PCMs integrated free cooling techniques for building performance enhancement. Thambidurai et al. (Thambidurai et al., 2015) systematically reviewed PCMs based free cooling strategies for sustainable buildings. Waqas and Din (Waqas and Din, 2013) systematically reviewed PCMs based free cooling for building energy savings, from perspectives of climatic applicability, economical and environmental feasibility. Results indicated that, the



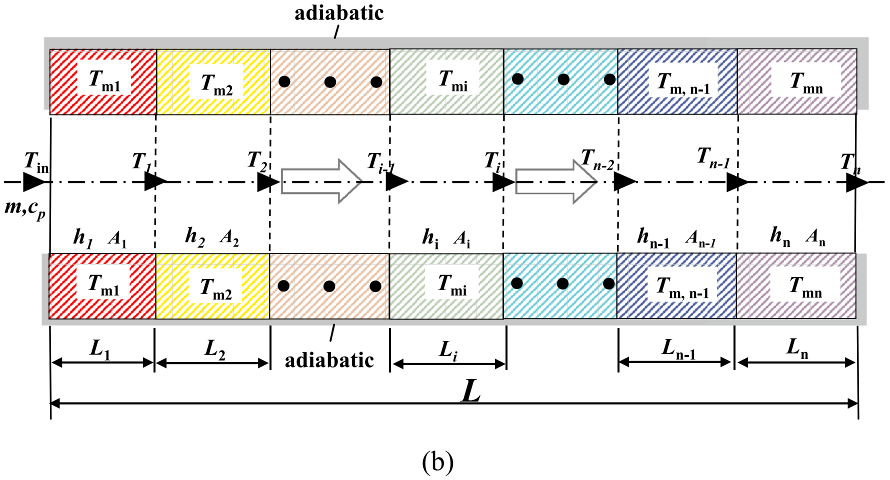


Fig. 5. Multistage phase-change heat storage: (a) schematic diagram (Christopher et al., 2021); (b) discrete node graph (Xu and Zhao, 2015).

passive free cooling technique is feasible in the climate zones with diurnal temperature difference between 12 and 15 °C. Furthermore, compared to conventional air-conditioning systems, the free cooling can reduce the electricity consumption with decreased CO_2 emission.

However, in the extreme climate with high rate of heat, the passive approach with building envelope is not feasible (Iten et al., 2016), and active methods are worthy to be explored. Prabhakar et al. (Prabhakar et al., 2020) evaluated the PCM effectiveness for natural cooling storage with night ventilation. The comparison in 15 different cities indicate that, PCM passive cooling system was ineffective in hot arid conditions, whereas in the temperate condition, the PCM effectiveness can be increased to 40% under temperature-controlled ventilation strategy.

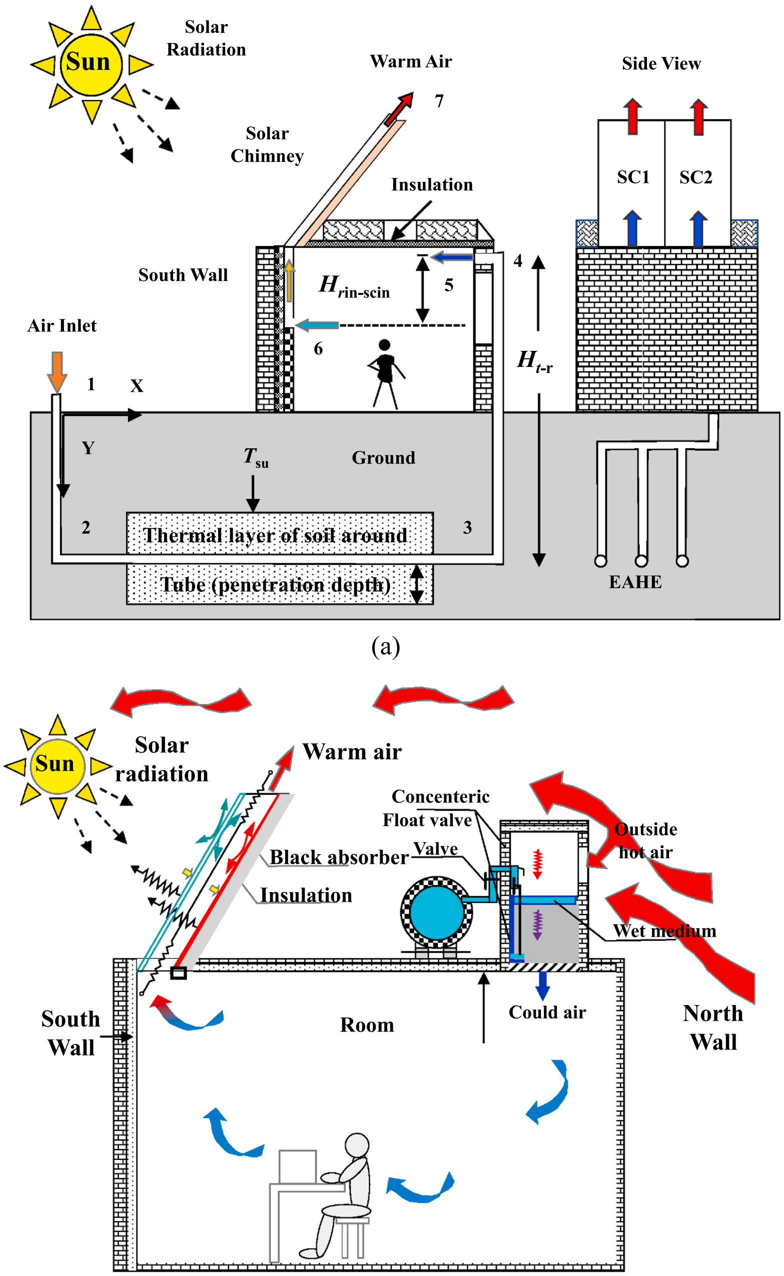
5.1.3. *Solar chimney*

Driven by the buoyancy force, the solar heated air flows upward with low density and indoor air flow circulates to promote the natural ventilation. Most of researchers are mainly focused on modelling development for performance prediction (Jiménez-Xamán et al., 2019; Vargas-López et al., 2019), parametrical analysis (Chen and Chen, 2020; Fadaei et al., 2018a) for system design, and integration with other renewable systems. The main driving force for natural ventilation is the buoyancy force due to temperature difference between PCMs and air. Monghasemi and Vadiee (Monghasemi and Vadiee, 2018) reviewed the progress of PCMs integrated solar chimney for cooling and heating applications. Jiménez-Xamán et al. (Jiménez-Xamán et al., 2019) reviewed PCM-based solar chimneys, from perspectives of modelling approaches and applications. Results showed that, Computational Fluid Dynamics (CFD) approach is a powerful tool, but with considerable computational time. By contrast, the Global Energy Balance (GEB) approach is computationally efficient and flexible for the integration with building performance simulation programs. Vargas-López et al. (Vargas-López et al., 2019) systematically reviewed five typical mathematical models of solar chimney based on global energy balance. The proposed transient mathematical model for a double-channel solar chimney with PCM enables designers and engineers to evaluate the potential benefits.

In terms of parametrical analysis, Fadaei et al. (Fadaei et al., 2018a) experimentally investigated the effects of PCMs on the thermal performance of solar chimney. The comparative and parametric analysis indicates that, PCMs can enhance the absorber temperature from 69 to 72 °C, and increase the maximum air velocity from 1.9 to 2.0 m/s. In terms of optimal porosity and particle diameter, Chen (Chen and Chen, 2020) conducted the parametrical analysis of a solar chimney with sieved plate thermal storage beds containing phase change capsules. Through the parametrical analysis, compared to the Basalt bed, the PCM bed can improve the heat storage capacity by 19.4% but increase the charging time by 7%. Furthermore, integration with other renewable systems has also been studied. The development of solar chimney techniques can provide opportunities for the integration with other renewable systems, such as earth-air heat exchanger (Maerefat and Haghighi, 2010b), evaporative cooler wind tower (Abdallah et al., 2013), cooling cavity (Maerefat and Haghighi, 2010a) and PV systems (Salari et al., 2020), as shown in Fig. 6. However, optimization strategies and control systems are worthy to be well investigated for the further performance improvement.

5.1.4. Passive solar facades

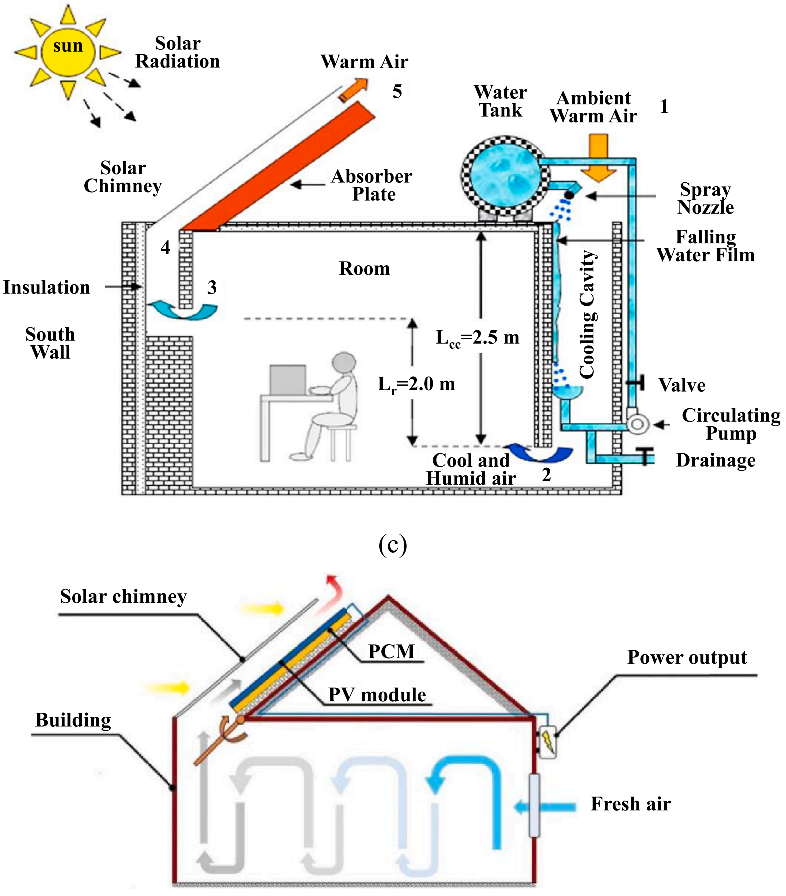
Through the enhancement in thermal inertia of building envelopes, integration of PCMs can delay the indoor temperature response, with magnitude reduction and time shifting in peak temperature (De Masi et al., 2020; Rathore et al., 2022). Furthermore, energy storage through PCMs coupled with ventilation and solar radiation, can improve the renewable energy utilisation efficiency. Zhu et al. (Zhu et al., 2018) reviewed development of PCM in buildings over past 10 years, and concluded that nearly 60% studies were on envelopes. Weinläder et al. (Weinläder et al., 2005) passively integrated PCMs in double glazings to reduce heat loss and heat gain. Advantages for PCM-glazing systems include low U value (around $0.3-0.5\ W\,m^{-2}K^{-1}$, compared to 0.8 for the double glazing), improvement in thermal comfort in winter, low heat gain in summer, and night-time natural cooling energy storage. Gracia et al. (Gracia et al., 2015) designed an innovative ventilated facade with PCMs for space cooling applications, as illustrated in Fig. 7. The cooling energy stored in PCMs can provide cooling for 3 or 4 h at the peak cooling demand period. Liu et al. (Liu et al., 2019a) numerically studied the thermal performance of PCMs integrated multilayer glass curtain façade. In order to compromise the thermal and solar transmittance performance, the recommended PCM thickness is 20 mm. With the storage of solar thermal energy, the PCM-concrete panel can reduce the peak temperature by 1 °C and achieve energy saving of 3% (Drissi



(a)

(b)

Fig. 6. Integrated solar chimney with (a) earth-air heat exchanger (Maerefat and Haghighi, 2010b), (b) evaporative cooler wind tower (Abdallah et al., 2013), (c) cooling cavity (Maerefat and Haghighi, 2010a), (d) PV systems (Salari et al., 2020).



(c)

(d)

Fig. 6. (*continued*).

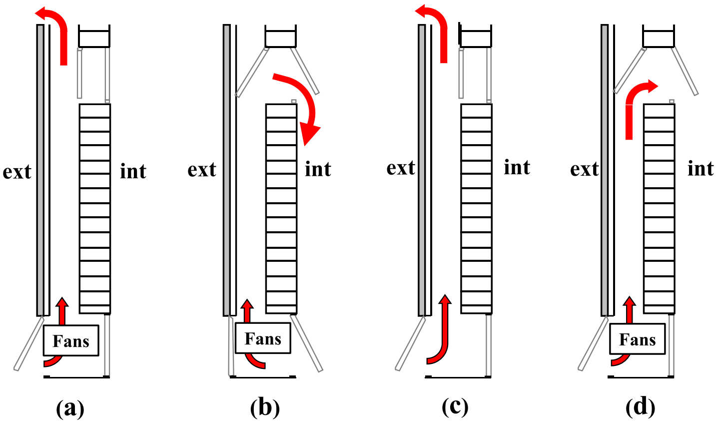


Fig. 7. Operational modes: (a) charging process, (b) discharging process, (c) overheating prevention, (d) free cooling (Gracia et al., 2015).

et al., 2020).

5.1.5. PCM-Trombe walls

PCM-Trombe walls with multiple functions have been studied, for both cooling and heating. Functions of PCM-Trombe walls mainly include solar thermal storage, nighttime natural cooling (e.g., sky radiative cooling), natural ventilation, indoor radiative cooling, and so on. For the heating application, Omara and Abuelnuor (Omara & Abuelnuor, 2020) comprehensively reviewed PCM-Trombe walls for solar energy storage. Results indicated that the improvement of thermal storage capacity of walls can enhance the thermal circulation of indoor air and decrease the fluctuations of indoor air temperature. Zalewski et al. (Zalewski et al., 2012) experimentally studied the solar energy storage and release performance of a small-scale PCM wall, as illustrated in Fig. 8. Results indicated that PCMs can avoid the solar beam radiation with the stored heat released into indoor environment during the night. Ling et al. (Ling et al., 2019) numerically studied optimal PCM integration in ventilated walls. Despite of the multi-objectives, the optimal phase change temperature and heat fusion of PCMs can be fitted into a curve. Gracia et al. (Gracia et al., 2013a) experimentally investigated the

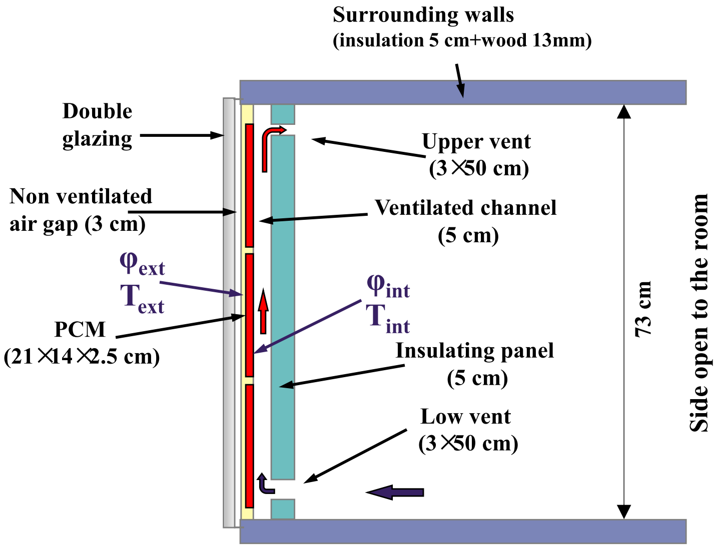


Fig. 8. The structural configuration of PCM-Trombe wall (Zalewski et al., 2012).

energy performance of a ventilate PCM facade during winter period. Results showed that, acting as a latent storage unit, PCMs can decrease the electrical consumption of the HVAC systems via the energy storage from solar energy.

In addition, PCM-Trombe wall for cooling application has also been studied. Gracia et al. (Gracia et al., 2013b) studied a ventilated PCM façade for nighttime free cooling storage. Results showed that, night free cooling with PCMs can avoid daytime overheating and reduce cooling load, especially with the increased thermal resistance of the exterior façade. Zhou et al. (Zhou et al., 2018b) investigated the heat transfer mechanism of PCMs integrating wallboard system with embedded water-based radiative cooling. Parametrical analysis indicated that, the energy storage and release efficiency are 16.8%/18.9% for exterior/-interior PCMs, respectively.

5.2. Active strategies

Compared to passive strategies, active design strategies are full of more controllability and higher efficiency, whereas the additional input energy is necessary, and operational reliability leads to higher maintenance cost, due to complicated system design (Tang et al., 2020). Zhou et al. (Zhou et al., 2021) comprehensively reviewed novel PCM-based cooling strategies for building application. Results showed that, PCM wallboards, active cooling and integrated geothermal cooling are promising techniques. In this subsection, active strategies for PCMs integrated building energy systems have been reviewed, including mechanical ventilation, nanofluid-based cooling/heating and geothermal energy integration.

5.2.1. Mechanical ventilations for natural energy utilization

Osterman et al. (Osterman et al., 2012) conducted a comprehensive overview on PCMs based cooling technologies for buildings. Cao et al. (Cao et al., 2018) investigated the dynamic melting performance of a latent heat storage unit. Xie et al. (Xie et al., 2016) experimentally investigated the thermal response of PCMs under mechanical ventilation, with different air temperatures and velocities. Santos et al. (Santos et al., 2018) designed mechanical ventilation system to charge PCM thermal storage for indoor built environment control. Increasing PCM cooling capacity and heat transfer area are effective strategies for system performance improvement. Wang and Niu (Wang and Niu, 2009) investigated a novel air-conditioning system that is a combination of cooling ceiling (CC) and a microencapsulated phase change material (MPCM) slurry storage tank, as shown in Fig. 9. By pumping the MPCM slurry into the ceiling panels for cooling energy discharge, a 0.52 m^3 tank can cover the cooling demand of a 18.4 m^2 south room. Gholamibozanjani and Farid (Gholamibozanjani and Farid, 2020) designed an active PCM storage system for space cooling/heating, as illustrated in Fig. 10. In New Zealand, southern hemisphere, with the adoption of the

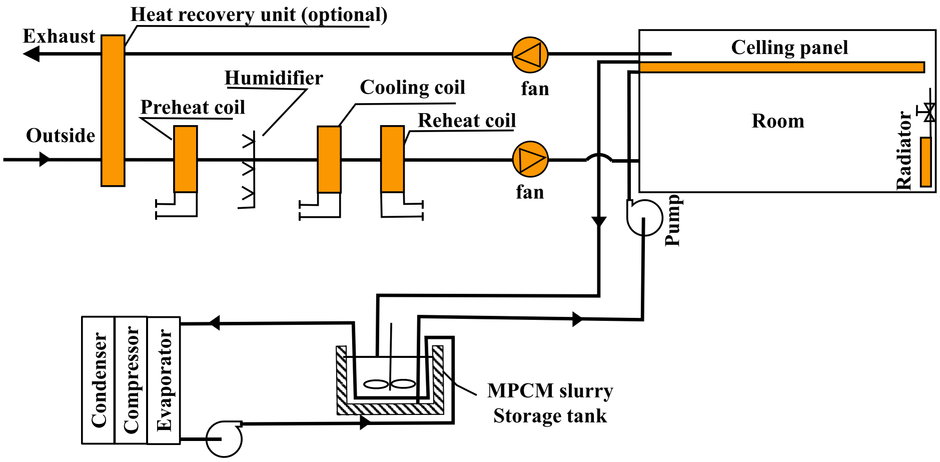
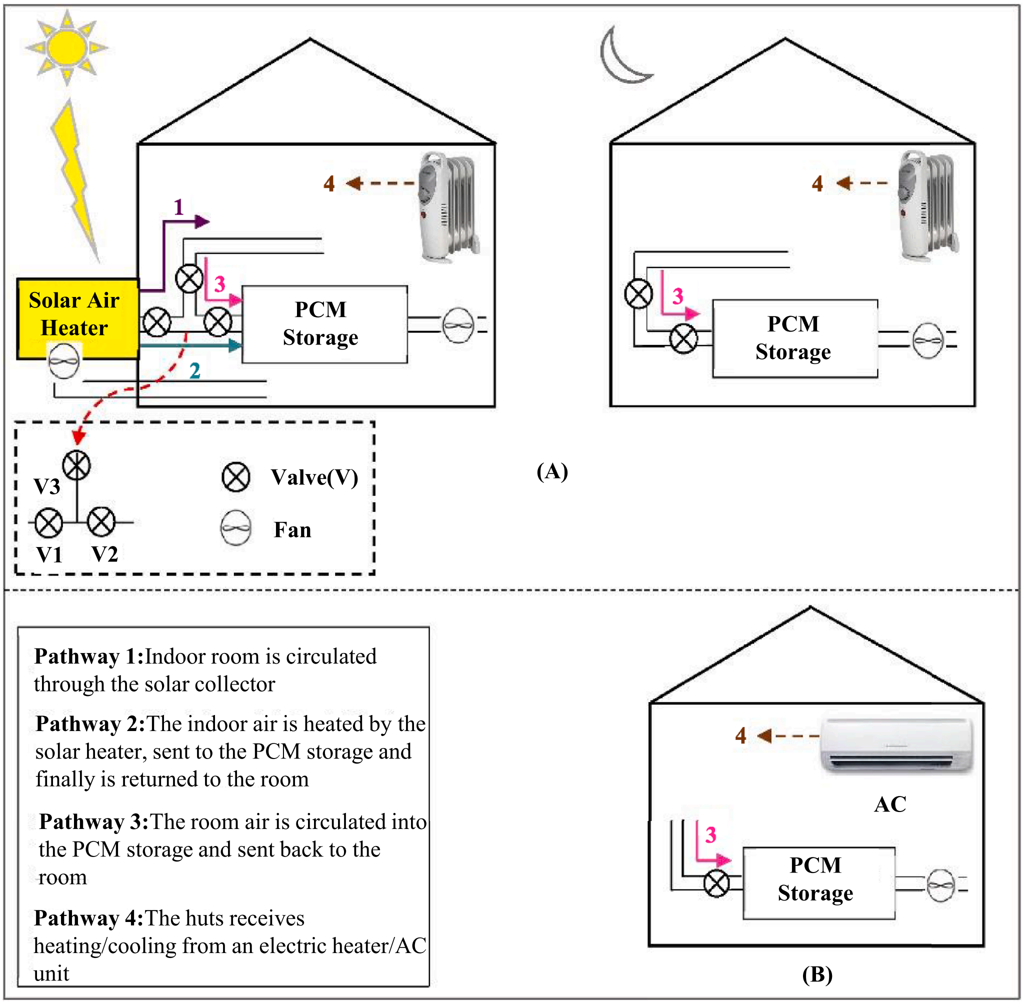


Fig. 9. Schematic diagram of the cooling ceiling integrating with MPCM slurry tank (Wang and Niu, 2009).



Pathway 1: Indoor room is circulated through the solar collector

Pathway 2: The indoor air is heated by the solar heater, sent to the PCM storage and finally is returned to the room

Pathway 3: The room air is circulated into the PCM storage and sent back to the room

Pathway 4: The huts receives heating/cooling from an electric heater/AC unit

Fig. 10. PCM integrated mechanical ventilation for (a) space heating and (b) space cooling (Gholamibozanjani and Farid, 2020).

proposed ventilation strategy, the accumulative heating energy can be saved by 40% in May, and 30% in March/April.

5.2.2. *Active water or nanofluid-based cooling/heating integration*

In addition to mechanical ventilation, active water or nanofluid-based cooling/heating systems have also been studied. Jobli et al. (Jobli et al., 2019) experimentally and numerically investigated dynamic performance of a capillary-Tube embedded PCM component for space heating, as shown in Fig. 11. Results indicated that, non-uniformity of temperature distribution need to be addressed as the flow rate in the capillary tube was less than 800 ml/min. Integrating solar thermal energy, as an active heating source, with PCMs for space heating have also been studied. Li et al. (Li et al., 2020) explored the thermal performance of a solar thermal system integrating active PCM heat storage wall, as demonstrated in Fig. 12. Kong et al. (Kong et al., 2017) studied both passive and active combined strategies for building energy performance improvement, and concluded that PCMs play the dominated roles in indoor thermal comfort and energy efficiency of buildings.

A novel distributed renewable system was proposed, integrating

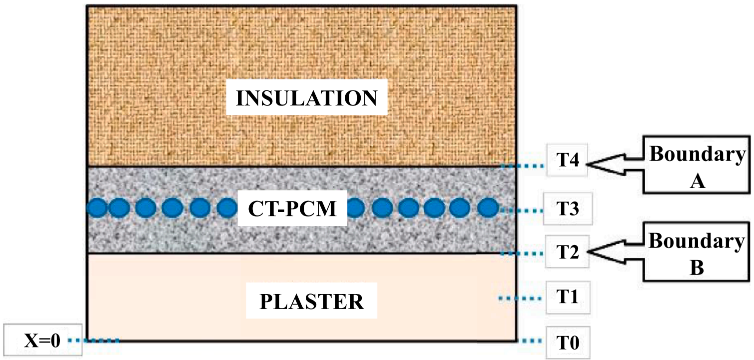


Fig. 11. Geometry for numerical simulation (Jobli et al., 2019).

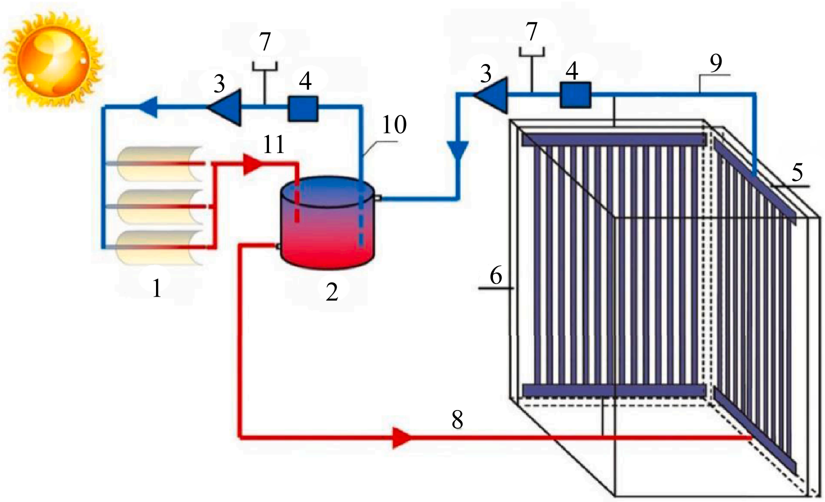


Fig. 12. Schematic diagram of the STS-APHSW (Li et al., 2020).

hybrid ventilations, radiative cooling and active water-based PV cooling (Zhou et al., 2020b). The structural configuration is shown in Fig. 13, which demonstrates a PCMs-PV hybrid system integrating active cooling and hybrid ventilations. The active strategies include active water-based PV cooling, indoor radiative cooling and mechanical ventilation. Mechanical ventilation is operated when the fan is turned on.

5.2.3. *Geothermal system integration*

Geothermal energy, with abundance in quantity and energy supply stability, is one of renewable energy resources for indoor and built environment regulation (Liu et al., 2021c, 2019f, 2022b). However, due to the mismatch between cooling and heating load, seasonal thermal imbalance will lead to performance stability and low efficiency. PCMs, with considerable latent heat, can overcome seasonal thermal imbalance with compensating renewable energies (e.g., solar energy, and radiative cooling energy). Main functions of PCMs include the reduction of outlet air temperature fluctuation, annual/seasonal thermal balance between cooling and heating, enhancement in heat transfer and COP, and so on (Alavy et al., 2021; Alkhwildi et al., 2020; Liu et al., 2019c).

Qin et al. (Qin et al., 2021) investigated a novel vertical air-soil heat exchanger (VASHE) integrated with PCMs, as shown in Fig. 14. Parametrical analysis on PCM types, structures and locations can provide technical guidance on geothermal energy utilisation. Zhou et al. (Zhou et al., 2018a) applied PCM-filled earth-air heat exchanger to pre-cool the supply air. Results showed that, 0.83 °C decrease in supply air can be noticed due to the PCM storage, contributing an enhancement of 20.24% for the cooling capacity. The performance on a tubular-shape PCM (Liu et al., 2019b) indicated that, the peak temperature and fluctuation of the outlet air decreasing from 25.74 °C and 3.59 °C to 21.01 °C and 0.62 °C. Zhou et al. (Zhou et al., 2020a) studied the thermal performance of a

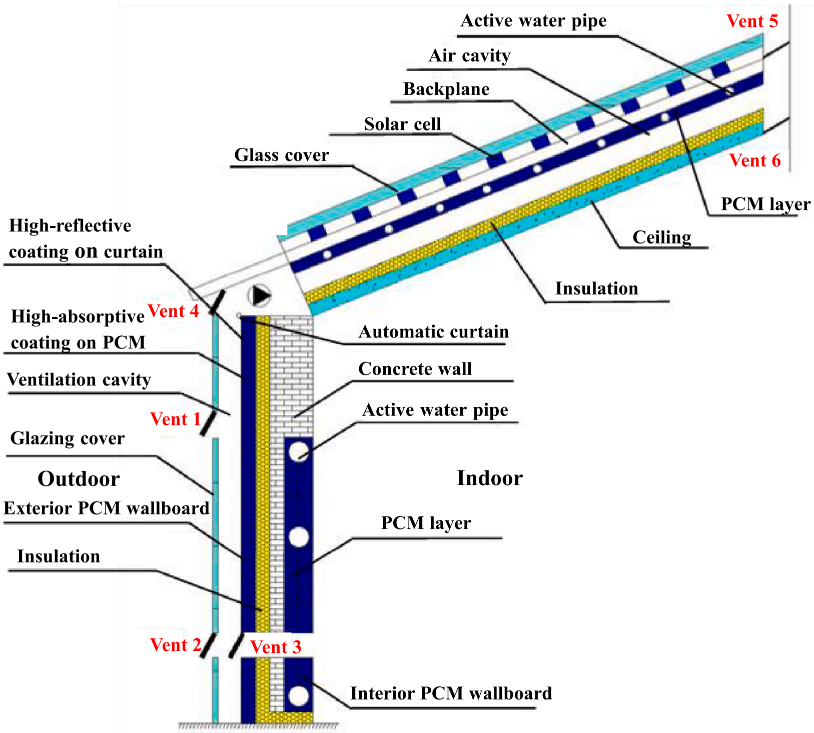


Fig. 13. Schematic diagram of a distributed renewable system (Zhou et al., 2020b).

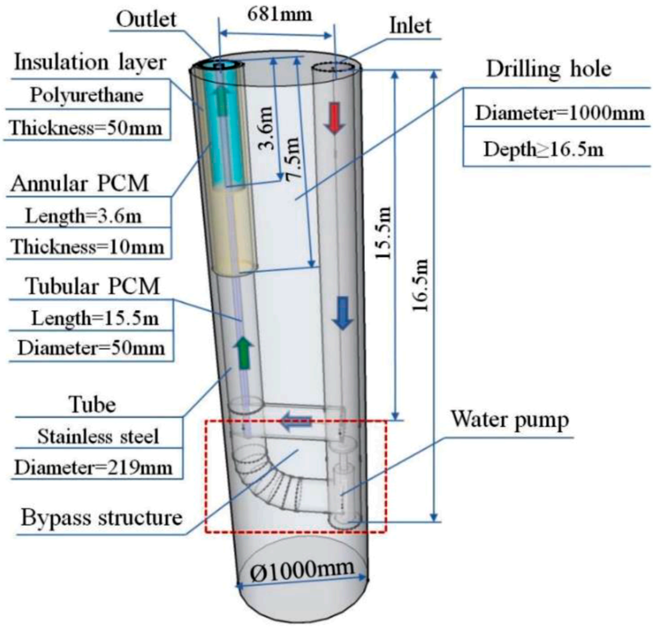


Fig. 14. Diagram of the VASHE system (Qin et al., 2021).

cylindrical PCM-assisted earth-air heat exchanger (CPCM-EAHE), as shown in Fig. 15. The continuous 20-day operation indicates that, the adopted PCM can improve total cooling output by 20.05%, together with the controlled outlet temperature fluctuation within 1 °C.

5.3. AI-based strategies

In addition to hybrid system integrations, optimal design, reliable operation, and smart controls are critical to improve the energy flexibility, reliability under extreme condition, and robustness under uncertainty scenarios. However, great challenges are proposed, including highly computational load and prediction accuracy. Nowadays, ML with superior performance prediction capacity, can be applied for optimisation on geometrical and operating parameters, robust analysis under input uncertainties, and smart control strategies.

5.3.1. Deterministic optimisation with supervised ML

In respect to system optimisation, performance prediction models with high efficiency and accuracy have attracted widespread interests. The machine can be well trained with AI, through the continuous learning and error correction processes, so as to make excellent predictions. Supervised ML, with multiple linear regression, back-propagation neural network and support vector regression, shows adaptivity and reliability in performance predictions of various nonlinear system, such as building energy cooling, heating and electricity (Zhou and Zheng, 2020a), thermal and visual performance of aerogel glazing systems (Zhou and Zheng, 2020d), and PCMs-PV systems (Zhou et al., 2020d). Fadaei et al. (Fadaei et al., 2018b) designed an artificial neural network to dynamically predict the thermal performance of a PCM integrated solar chimney system. Through the back-propagation for update of wight factor, the well-trained model can lead to correlation between the predicted values and the experiments, for all outputs higher than 99%, together with the average value of the relative errors less than 3%.

Instead of returning back to mathematical models (conventional optimisation approach), the optimisation engine in the ML optimisation approach will call for ML-based surrogate models for stochastic performance predictions within input variable range. Due to the high efficiency of well-trained surrogate models in performance prediction, the new approach will provide promising solutions for computational complexity in optimisation of nonlinear systems. Zhou et al. (Zhou et al., 2019) developed an artificial neural network based multivariable optimization method, to maximise the power generation with optimal geometrical and operation parameters. The comparison between different optimisation algorithms highlights the necessity for the development of advanced algorithms. Considering the contradiction between improved PV efficiency and associated power consumption of active cooling pumps, Tang et al. (Tang et al., 2020) conducted the exergy-based optimisation to reach a trade-off solution through optimal combination of parameters. Results indicated that, compared to the Taguchi standard orthogonal array (849.9 kWh), the overall exergy of the hybrid renewable system shows a higher exergy at 872.06 kWh, by 2.6%.

The procedure of ML-based optimisation is demonstrated in Fig. 16, with respect to different optimisation algorithms. The core technique is the development of ANN-based optimisation function, contributing to the reduction on thousands of case performance simulation for each thread.

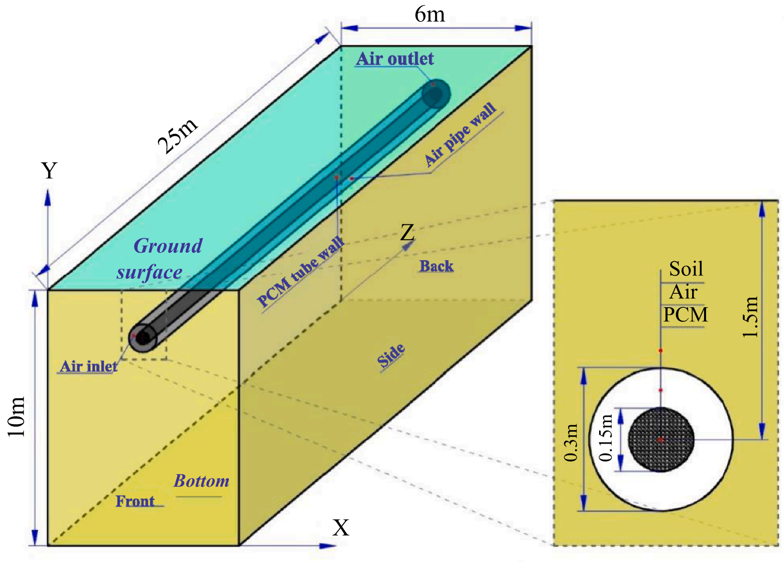


Fig. 15. Diagram of the CPCM-EAHE system (Zhou et al., 2020a).

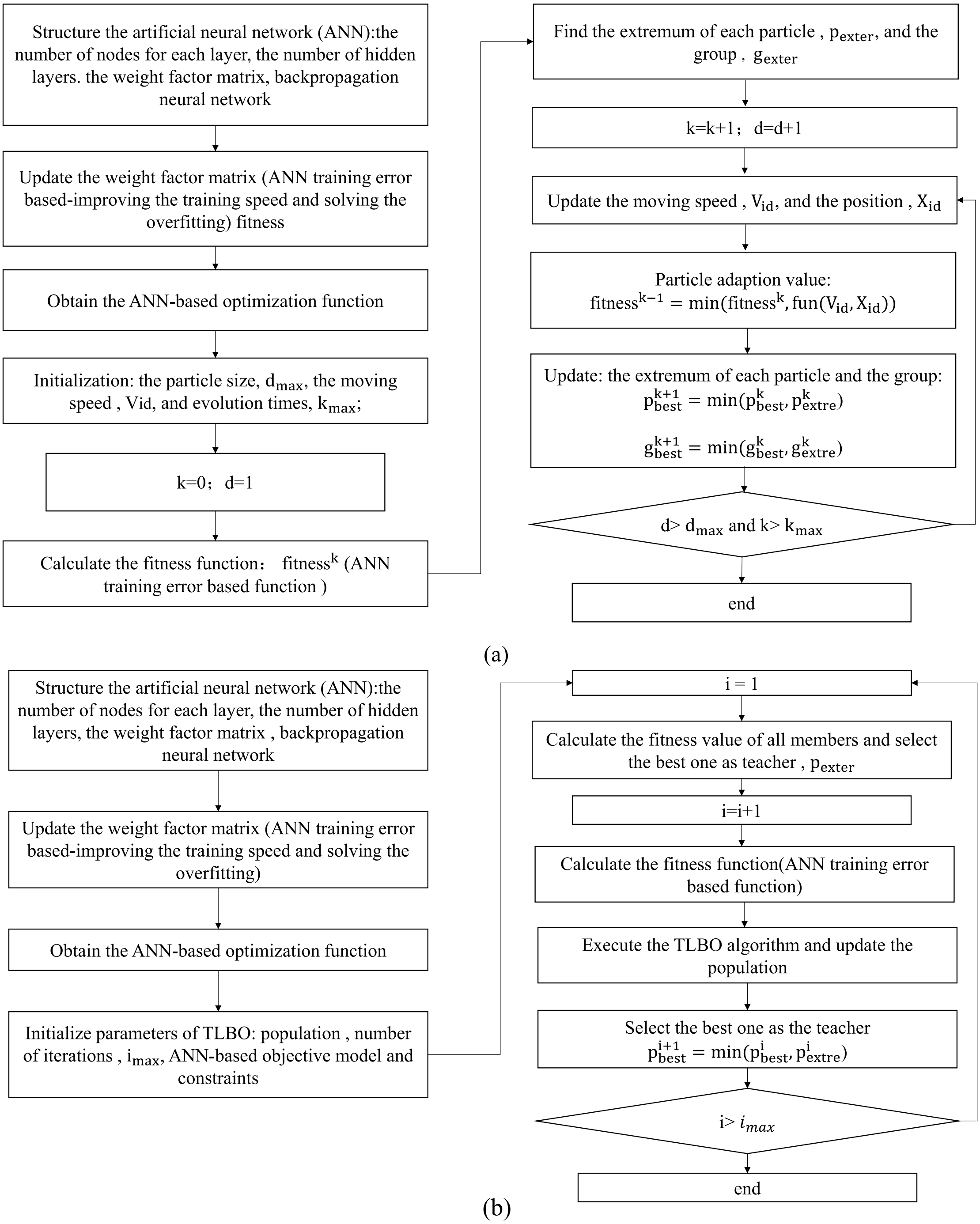


Fig. 16. (a) the PSO and (b) the TLBO for surrogate-model based optimization (Zhou et al., 2019).

5.3.2. *ML-based uncertainty analysis and optimisation for robust design*

Considering the scenario uncertainty of multivariant during the real operation, reliability of deterministic-based performance is questionable. ML-based uncertainty analysis and optimisation are necessary. However, compared to deterministic performance analysis, the uncertainty-based analysis is full of heavy computational load, due to thousands of calculations. Surrogate models, trained by ML algorithms, can make accurate prediction with high efficiency (Zhou and Zheng, 2020b). Zhou et al. (Zhou et al., 2020c) conducted the uncertainty analysis on a hybrid PCM-PV system, in terms of meteorological, design and operating parameters. Results showed that the consideration of scenario uncertainty can enhance the power generation from 1776.9 to 2635.6 kWh. Furthermore, Zhou and Zheng (Zhou and Zheng, 2020c) conducted a multi-level uncertainty optimisation on a hybrid PCMs-PV system, by integrating a well-trained surrogate model in heuristic algorithm for the global optimisation. The proposed approach includes five steps, as illustrated in Fig. 17. In the Step 1, accurate model was trained and validated. The optimisation function was characterised in the Step 2, to as to guide the optimisation algorithm to find the optimal solution in the Step 3 and 4. Finally, the optimal results are searched in the Step 5.

5.3.3. *AI based smart control strategies*

The timely response on PCM behaviour and sufficient reaction in

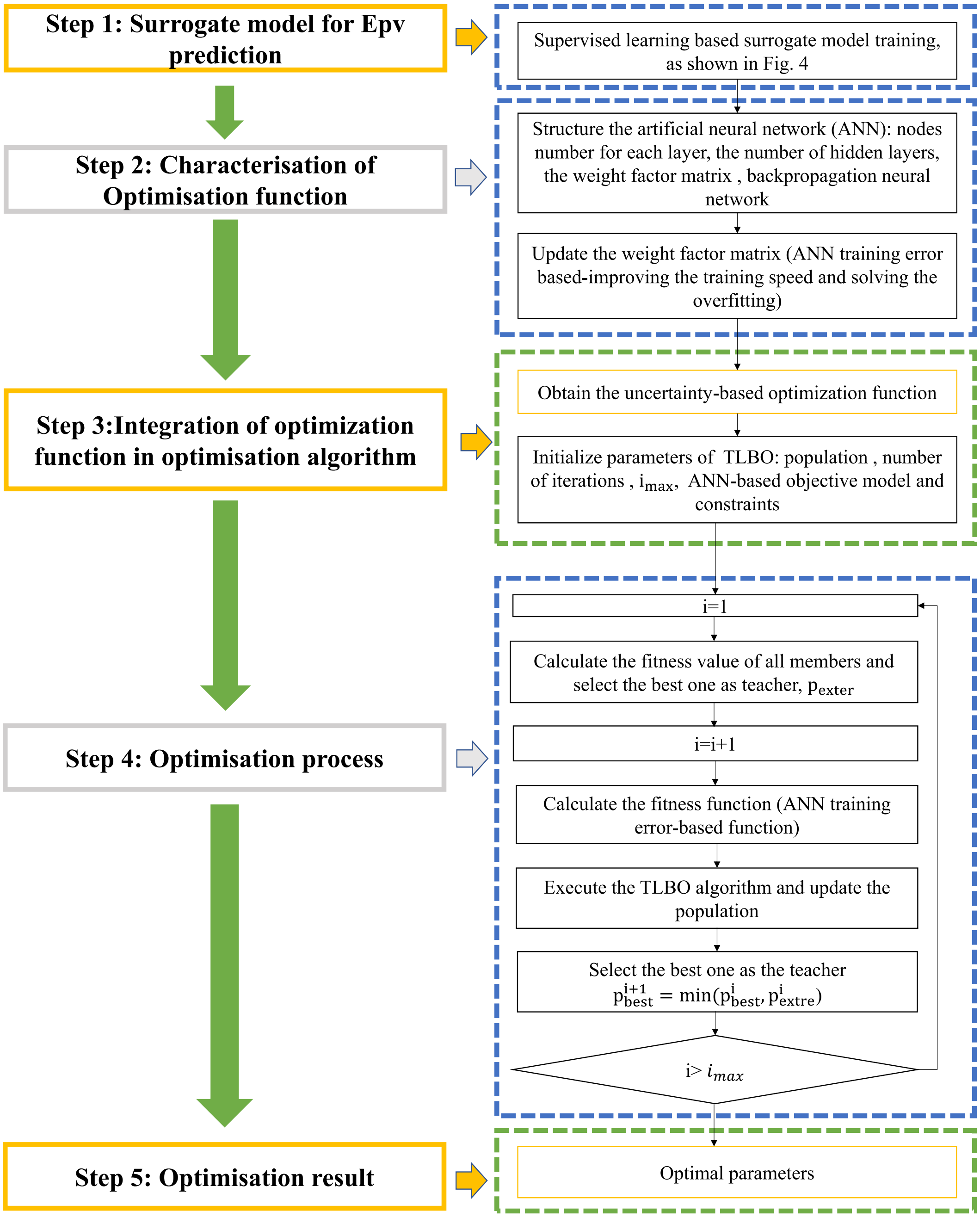


Fig. 17. Steps for multi-level uncertainty-based optimisation, with the flexible integration of machine learning (Zhou and Zheng, 2020c).

accordance with energy demands, will affect the energy storage and release efficiency of PCM and load coverage reliability. However, the effectiveness is dependent on meteorological parameters, thermal conductivity, heat transfer effectiveness, load profiles and so on. AI techniques have been applied in natural thermal storage. According to weather forecast data for space heating/cooling, Gracia et al. (Gracia et al., 2020) proposed smart control strategies on a PCM wall for natural thermal energy utilisation, with respect to schedule of operation and placement of PCMs. Results showed that, smart control algorithms can improve system performance with avoidance in system faults.

Smart control on active devices with optimisation and ML techniques have been studied. Zhou et al. (Zhou et al., 2020e) reviewed intelligent control with ML applications in PCMs integrating energy systems. The review clarified that, ML is very promising for improving thermal performances via agent modelling and model predictive control. By adopting the reinforcement learning for decision making (such as PCM charging/discharging, switch on ventilation modes, fan speed and etc.) at each state (Gracia et al., 2016), the net reward-penalty value is maximised, i.e., investment in the form of thermal energy obtained from PCMs (reward) minus electrical energy consumed by the ventilators (penalty). Tang et al. (Tang et al., 2020) conducted the exergy-based optimisation using a supervised ML based optimisation approach. By using the proposed method, the total exergy was increased from 849.9 to 872.06 kWh with an improvement of 2.6%. Ousegui et al. (Ousegui et al., 2019) optimised the air flow rate of fans, using the inverse method, to achieve the totally melted/solidified PCMs for free cooling.

It is important to note that the current literature provide a few studies on AI based smart control strategies on PCM storage systems, and the main focus is on the reinforcement learning for dynamic decision-making on smart control of a PCM integrated ventilated façade. Proposed strategies include schedule operation and flexible placement of PCM (either outside for natural cooling storage or inside for energy release), in accordance with predicted space heating and cooling loads. Future studies can be focused on:

1) enhanced thermal inertia of PCM walls with model-predictive control on smart charging/discharging strategies for pre-cooling/preheating, in terms of forecasted indoor occupancy and indoor setpoint temperature;
2) flexible operational modes (such as natural ventilation, cooling energy storage/release mode, heating energy storage/release mode, insulation mode and so on (Zhou et al., 2019)) and variable frequency water pump control in radiative cooling systems, based on ML predicted meteorological parameters and stochastic indoor cooling load;
3) ML-based thermal comfort controls for energy-saving and overcoming instabilities and frequently overshoot thermostats of traditional control methods, such as on/off, proportional-integral-derivative (PID) and proportional-integral (PI).

6. Techniques of LTES applications for carbon-neutral district energy community

6.1. Biobased PCM production

In order to decrease the embodied energy of buildings, biobased PCMs are promising candidates with thermophysical properties and chemical stability similar as conventional materials. Cabeza (Cabeza, 2021) systematically reviewed bio-based PCMs for building cooling, including plant-based and animal-based PCMs. The review showed that the main materials for bio-based PCMs include fatty acids, coconut oil, fatty esters and coconut fat. The thermal conductivity can be increased by 3% to 300% with the addition of nanoparticles (e.g., CuO). Kenar (Kenar, 2010) developed bio-based grease chemical carbonates based on fatty acids, fatty alcohols, and fatty acid esters. Melting temperature ranged between − 2.2 and 51.6 °C, and the enthalpy was between 144 and 227 J/g. Based on the binary combinations of different bio-based grease chemical carbonates, melting temperatures can be controlled between 12 and 37 °C and the enthalpies was between 135 and 175 J/g (Kenar, 2012). Based on butyl stearate, Balderrama et al. (Balderrama et al., 2018) synthesised a new biobased PCM and encapsulated it in an interconnected porous network. Ravotti et al. (Ravotti et al., 2018) used pure carboxylic fatty esters as PCMs. By chemically reacting with primary linear alcohols through Fischer esterification, the biobased PCM's enthalpy exceeds 190 J/g with melting temperatures between 20 and 50 °C. In terms of the biobased PCMs with high melting temperature, lactones have been employed with wider range of phase change temperature. Ravotti et al. (Ravotti et al., 2019) adopted commercial ε-caprolactone and γ-valerolactone to produce the biobased PCMs with the melting temperatures from – 40 to 290 °C.

Enhancement on thermo-physical properties of biobased PCMs has also been investigated in the academia. Jeong et al. (Jeong et al., 2013) adopted exfoliated graphite nanoplatelets to enhance the thermal conductivity from 0.154 to 0.577 W/(m·K) with better thermal resistance and lower subcooling than the pure bio-based PCMs, whereas the flammable property of the biobased PCMs is higher than conventional organic PCMs. Yu et al. (Yu et al., 2014) explored the impact of weighting ratio of embedded nanomaterial on thermal conductivity and the melting enthalpy. Results indicated that the addition of 5 wt% nanomaterial is the best solution, with the enhancement of thermal conductivity by 336% and no change in the melting enthalpy. Furthermore, nanoparticles, such as CuO (Alomair et al., 2018; Ebadi et al., 2018), Al_2O_3, Fe_3O_4, and TiO (Al-Jethelah et al., 2019), have been employed to improve the thermal conductivity of biobased PCMs, and the dynamic heat transfer process has been demonstrated with underlying mechanism.

6.2. Solar energy applications

Cleaner energy production with reduced reliance on traditional fossil fuels, is another critical solution to promote the carbon neutrality. The application of PCMs can improve renewable energy utilization efficiency. In this subsection, the main focus in on PCMs in solar energy applications, in respect to solar thermal systems, solar power systems, and solar thermal power plants.

1) Solar thermal energy systems

Functions for PCMs in solar thermal systems mainly include design of the geometrical parameters of PCM storage container (Afshan et al., 2020), hybrid materials manufacture (Wang et al., 2013), heat transfer enhancement (Qiu et al., 2019), and stabilization in solar thermal energy supply (Aramesh & Shabani, 2020). Raul et al. (Raul et al., 2018) conducted the parametrical analysis on a latent PCM unit for solar thermal energy storage, and obtained the maximum efficiency of 75.69%. To enhance latent solar thermal storage, Dheep and Sreekumar (Dheep & Sreekumar, 2014) comprehensively reviewed nanomaterials, from perspectives of classification, properties and selection criteria. Afshan et al. (Afshan et al., 2020) conducted the parametric analysis on aspect ratio for a solar latent thermal storage unit. Wang et al. (Wang et al., 2013) developed hybrid materials, consisting of single-walled carbon nanotubes (SWNTs) and PCMs, to enhance solar thermal energy storage with form stability. Qiu et al. (Qiu et al., 2019) comprehensively reviewed micro/nano PCMs for solar thermal storage, and concluded that heat transfer enhancement in PCMs (e.g., porosity and fins) dominated the energy efficiency. Furthermore, integrating PCMs in evacuated tube solar thermal collectors can stabilise the solar thermal energy (Aramesh & Shabani, 2020).

Furthermore, researchers are focused on advanced controls for efficiency improvement, during charging/discharging processes. Serale et al. (Serale et al., 2018) applied a model predictive control (MPC) algorithm with a mixed logic-dynamical approach to smartly control the charging/discharging processes of a latent heat solar thermal system. Compared to the traditional rule-based control, the MPC can decrease the primary energy demand by 19.2%−31.8%. Tyagi et al. (Tyagi et al., 2021) reviewed PCMs for building cooling/ heating, with thermal battery for low-tariff grid electricity shifting.

2) Solar power energy systems

PCMs have also been applied in solar cells, to mitigate the extreme temperature and enhance PV efficiency. Zhou et al. (Zhou et al., 2020b) comprehensively reviewed both passive and active PCM-PV systems, for PV efficiency improvement. The system can utilise ventilative cooling, latent thermal storage and active water cooling. At the initial stage, researchers are mainly focused on passive PCMs integration in the solar cell, to transfer solar heat back to the PCMs without obvious temperature rise. Nouira and Sammouda (Nouira and Sammouda, 2018) designed a PCM-PV panel, and numerically studied the impact of parameters (i.e., wind direction, wind speed and dust accumulation) on power generation. Results indicated that, the PV panel power output can be reduced by 3 W at midday, for the 9-g/m^2 dust deposition. In addition to passive cooling, active cooling with water natural circulation was gradually studied. Sudhakar et al. (Sudhakar et al., 2021) experimentally tested the PV efficiency with PCMs and natural water circulation. Under the experimental testing condition, the electrical and exergy efficiencies can be improved by 12.4% and 8.08%, respectively. Bayrak et al. (Bayrak et al., 2020) comparatively studied the effectiveness of different PV cooling techniques. They concluded that the fin, acting as heat sink shows the highest efficiency, while PV with PCMs and thermoelectric shows the lowest efficiency. Abdollahi and Rahimi (Abdollahi & Rahimi, 2020) indicated that power output can be increased up to 48.23% with the active PCM cooling technique.

3) Solar thermal/power plants

Furthermore, the high-temperature PCMs can be applied in concentrated solar power plants (CSP), to stabilise heat transfer fluid (HTF) temperature (Bhagat & Saha, 2016), LTES for concentrated solar energy [148], and heating energy supply for CO_2 capture (Nathan et al., 2018). The system can promote carbon-neutral and carbon-negative energy transitions. In terms of an organic Rankine cycle-based solar thermal power plant, Bhagat and Saha (Bhagat & Saha, 2016) designed an encapsulated PCM to stabilise the HTF temperature for power generation. Parametrical analysis result indicates that, the decrease in porosity and encapsulation diameter can reduce the variation in HTF temperature. Furthermore, the latent thermal storage for concentrated solar energy has also been studied. Liu et al. (Liu et al., 2020) designed concentrated solar power plants (CSPP) with PCMs, as illustrated in Fig. 18, and concluded that PCMs can improve the efficiency to 70.7%. Prieto and Cabeza (Prieto and Cabeza, 2019b) designed cascade PCM storage systems for solar thermal power plants. Almsater et al. (Almsater et al., 2016) designed evaporation/condensation and fins for performance enhancement of concentrating solar thermal power plants. Results showed that 106% increase in energy storage and 79% increase in discharged energy can be observed. In terms of CO_2 capture, Nathan et al. (Nathan et al., 2018) integrated concentrating solar thermal energy in CO_2 capture, through oxygen-enriched fuel combustion and chemical cycle combustion processes.

6.3. Other natural energy utilization

1) Natural cooling/heating sources

Nighttime natural cooling energy and daytime solar energy have been studied with PCMs. Faraj et al. (Faraj et al., 2020) reviewed PCMs for building cooling. Main functions of PCMs include reduction in indoor temperature fluctuation, building load reduction and shifting. Solgi et al. (Solgi et al., 2019) studied effectiveness of night ventilation (NV) and PCM in different climates. Results showed that, cooling thermostat setpoint and insulation control optimal PCM and NV flowrate. By integrating PCMs in Trombe walls, the annual energy cost can be decreased by up to 3.7% (Ma et al., 2019). Li and Chen (Li & Chen, 2019) studied performance of a PCM Trombe wall. Compared to traditional Trombe wall without PCMs, the integration of PCMs can increase the average temperature by 20.2% at night, with the thermal efficiency at 76.2%. Furthermore, PCMs for seasonal energy storage have been studied. In order to achieve energy-efficient buildings, Gholamibozanjani and Farid (Gholamibozanjani and Farid, 2020) utilised PCMs for natural energy storage, and results showed that, around 40% energy saving can be achieved in cold seasons, and around 30% accumulative energy saving can be achieved in warm seasons. In addition to natural cooling/heating sources, the integration of PCMs in air-conditioning systems through both natural ventilation and mechanical ventilation can reduce discomfort hours by 65%, and further to 83% (Lizana et al., 2019) with heat transfer enhancement between and air and PCMs.

2) Geothermal energy

In the academia, applications on PCMs for geothermal energy utilization include pre-cooling/pre-heating on fresh air through EAHE system(Liu et al., 2021c, 2019d, 2019e), thermal caisson for heating and cooling (Alavy et al., 2021), demand-side management for load shifting (Hirmiz et al., 2019), geothermal district heating (Hassanpour et al., 2020), borehole ground heat exchanger (Yang et al., 2019) and so on. Main functions of PCMs include the reduction of outlet air temperature fluctuation, annual/seasonal thermal balance between cooling and heating, enhancement in heat transfer and COP, and so on.

3) Sky radiative cooling

As one of most promising passive cooling techniques in buildings, nocturnal sky radiative cooling has recently attracted researchers' interest, and the integration of PCMs can improve the energy efficiency without sacrificing indoor thermal comfort. Yan et al. (Yan et al., 2020a) quantified heat removal by nocturnal sky radiation of a pipe-encapsulated PCM wall system. The nocturnal radiation can reduce 54.7%~81.0% of heat by the cooler. Yan et al. (Yan et al., 2020c) analysed the reduction in cooling demand and energy-saving ratio of a nocturnal sky radiator with PCMs. Simulation results indicated that, comparing with the system without PCMs, the internal surface temperature can be reduced by 1.6 °C, together with the decreasing of the cooling requirements and energy-saving ratio at 37.8%–57.8% and 15.7%–24.1%. Yan et al. (Yan et al., 2021) experimentally studied self-activated heat removal on PCMs through the nocturnal sky radiator, as shown in Fig. 19. Heat flux and cumulative indoor heat gain can be reduced by 10.2 W/m^2 and by 29.7%, respectively.

6.4. Waste-to-energy from city power plants, industry and mobility

As one of the carbon offsetting strategies, waste heat recovery can improve energy efficiency with reduced reliance on traditional fossil fuels. With considerable latent heat, PCMs are good candidates for waste heat recovery. PCMs can be applied for waste heat recovery from power

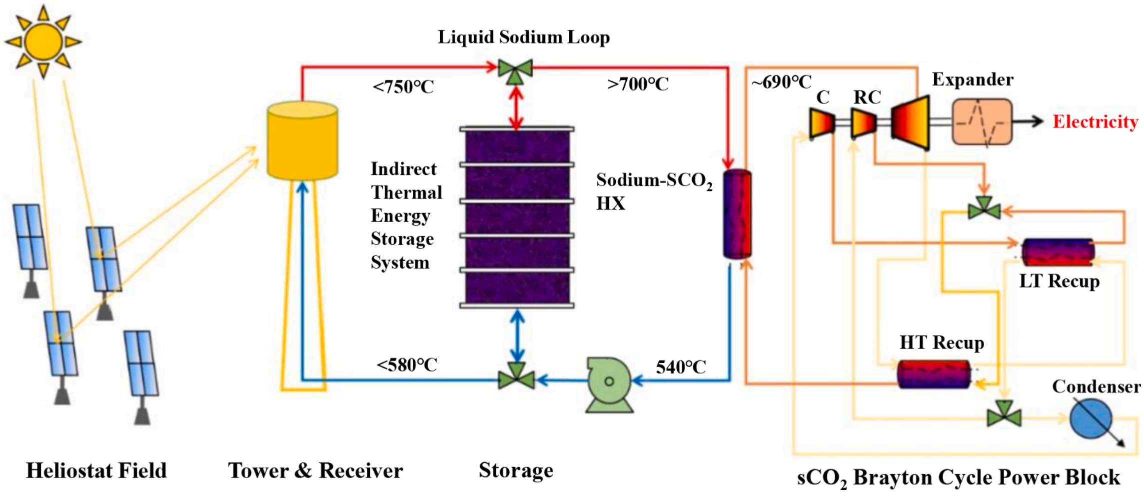


Fig. 18. A concentrated solar power plant (Liu et al., 2020).

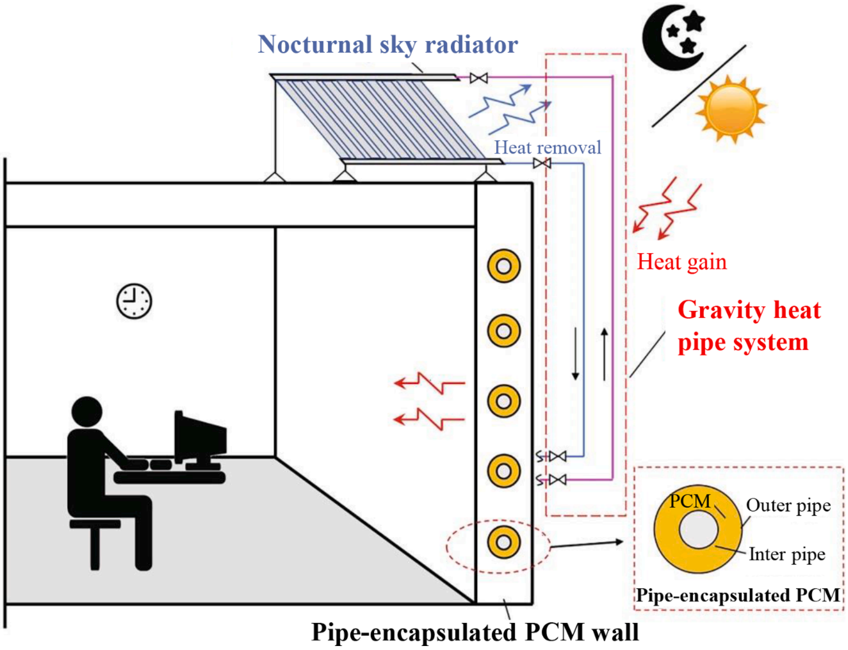


Fig. 19. The pipe-encapsulated PCM wall with nocturnal sky radiator (Yan et al., 2021).

plant, industrial factory, and mechanical power equipment in the mobile thermal energy storage vehicles (e.g., internal combustion engine, and fuel cells). Based on the recovered heat transfer fluids or devices, PCMs-based waste heat recovery systems can be classified into steam, exhaust gas, and combustion engines. In order to ensure steady steam production, Magro et al. (Magro et al., 2018) designed a combustion chamber with a PCM-based refractory brick to overcome the non-homogenous composition and instability of solid waste, as shown in Fig. 20. The PCMs can provide steady heat flux via the latent storage capacity. Results indicated that, the system can improve temperature of superheated steam over 450 °C without using coated superheaters and the electrical efficiency beyond 34%. Royo et al. (Royo et al., 2019) designed a PCM-TES system (melting point of PCMs at 885 °C) to recover exhaust heat for the pre-heat purpose, as shown in Fig. 21. The latent heat recovery system can enhance the air temperature from 650 to 865 °C. Du et al. (Du et al., 2021) reviewed the LTES for low-temperature industrial waste heat recovery. They indicated that, the latent thermal energy storage can reduce the primary energy requirement, exergy losses and the CO_2 emissions by up to 95%, 60%, and 93%, respectively.

In respect to the heat recovery from internal combustion engines, Daniel et al. (Daniel et al., 2022) designed cascaded latent storage systems. The case study indicates that, the latent thermal storage can recover 15% of fuel power. Pandiyarajan et al. (Pandiyarajan et al., 2011) designed a combined sensible and LTES system for diesel engine

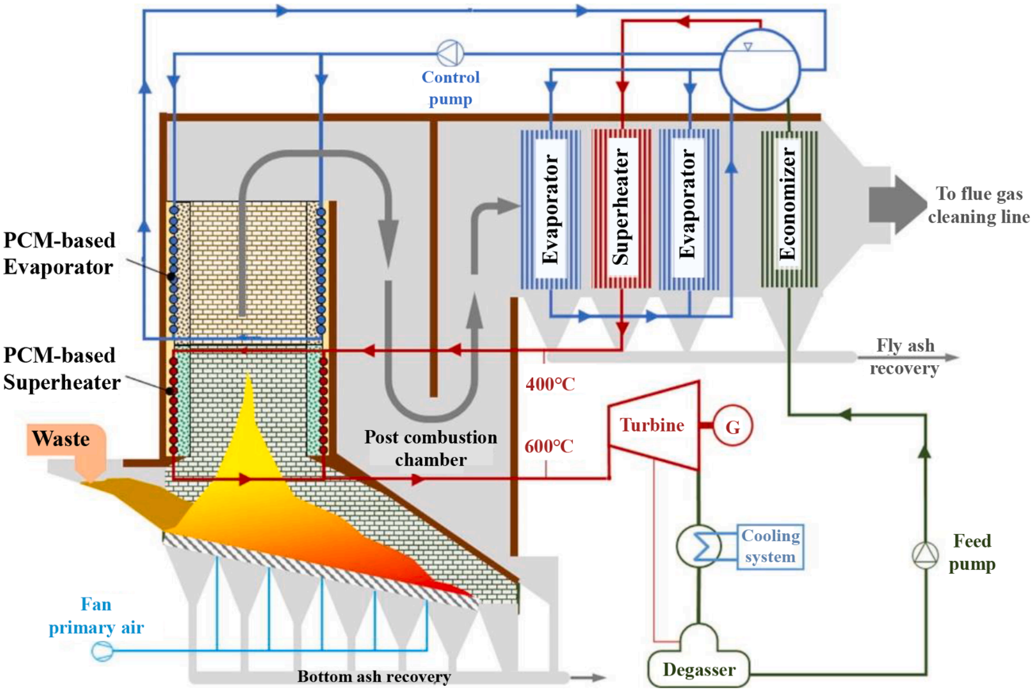


Fig. 20. PCM-based Waste-to-Energy heat recovery system with steam generation (Dal Magro et al., 2018).

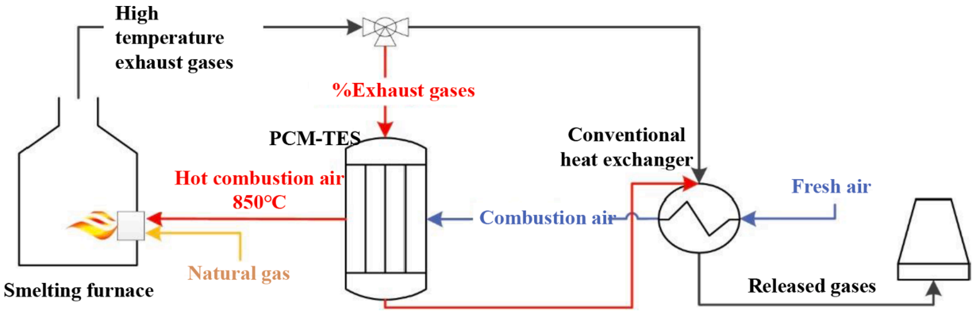


Fig. 21. Diagram for heat recovery with PCM integration for pre-heat of fresh air (Royo et al., 2019).

waste heat recovery. The PCM storage for heat recovery systems can save 15.2% of energy and 1.6% of exergy.

Fig. 22(a) depicts a general working principle of the waste heat recovery in the mechanical power equipment system, in which the exhaust hot air or gas transfers heat to the PCMs integrated spherical capsule to charge the PCMs. The heat in the charged spherical capsules can be thereafter extracted by a heat transfer fluid for the coverage of building heating demands, such as domestic heating, air conditioning and ventilations. Fig. 22(b) shows the PCMs' application for the heat recovery in a hydrogen system. The PCMs enhanced thermal storage tank can collect thermal energy from the electrolyser, the compressor, and the proton-exchange membrane fuel cell. In addition to the PCMs integrated heat recovery system, the recovered energy can also be converted to the cooling energy through the absorption or adsorption cooling system. The general principle of the PCMs integrated heat recovery system for cooling application was shown in Fig. 22(c).

A thermal energy interaction network with PCMs, as shown in Fig. 23, has been formulated, to promote the thermal energy utilisation efficiency of the local heating system. To recover the exhaust heat from different vehicles, the PCMs can be integrated in the internal combustion engine of gasoline vehicle, in the power device in the biofuel vehicle, or in the fuel cell in the hydrogen vehicle. With the participation of vehicles integrated PCMs storage tanks, the thermal energy sharing and interactions within various types of buildings can be realised, so that the thermal energy matching capacity will be improved, with less thermal energy imported from (or exported to) the local thermal grid. In respect to the formulated thermal energy interaction network, several challenges are presented for future studies:

1) Benchmarking of PCM selection is necessary for different types of vehicles, diversified exhaust heat sources and advanced energy conversions. Considering the different operating conditions of power devices for different types of vehicles, scenario-dependent thermo-physical properties are necessary to guide the system design.
2) In respect to the thermal energy interactions within various types of buildings, the impact of the stochastic driving behaviour on the system performance needs to be well investigated.
3) The formulated interactive energy sharing network involves multi-dimensional variables (e.g., the thermo-properties of PCMs, the size of the solar thermal collectors and thermal storage tanks, and the driving schedule of vehicle fleets), and multi-objectives (e.g., the energy storage and the charging/discharging rate in PCMs, the heat recovery efficiency, the initial and operational costs, and the equivalent CO_2 emission). It is necessary to conduct the multivariable and multi-objective optimisations to promote the renewable and sustainable energy network with cleaner power production.

7. Outlook and recommendations

Latent heat storage techniques show significant potentials in energy shifting, energy saving, power supply increase and decarbonization. Low-, medium- and high-temperature PCMs are mainly applied in buildings, solar thermal/solar-driven cooling, and industrial exhaust heat recovery. eIn order to realise the carbon-neutral community, great opportunities are given to PCMs and combined efforts are necessary from different aspects. Future studies can focus on:

1) The selection of PCMs in different scenarios requires standard testing procedures and database to obtain reliable results and data on thermo-physical properties, such as thermal conductivity, density, specific heat capacity, and volume expansion of liquid and solid phases;
2) In order to formulate relevant technical standards for product applications, the following studies need to clarify the boundaries on low, medium and high-temperature PCMs, and provide cutting-edge frontier guidelines for applications;
3) The application of cascaded LTES can improve thermal performance of thermal storage systems. Cascaded LTES systems can also provide opportunities for seasonal energy and optimal amounts of energy through optimal charging/discharging scheduling of PCMs;
4) Nanofluid for heat transfer enhancement of PCMs with ML for predictions on thermophysical properties, thermo-hydrodynamic performance, and radiative-optical performance. Furthermore, the nanofluid-PCMs can be applied in renewable and sustainable energy systems for efficiency and performance improvement;
5) Anti-corrosion effect between PCMs and container materials with compatibility and thermochemical stability will be studied to obtain more promising encapsulated materials of medium and high temperature PCMs, and to develop the database of appropriate encapsulated materials for different PCMs (Vasu et al., 2017); Standard specifications for using specific PCMs with specific types of encapsulated containers will be required in order to easily identify the compatibility of PCMs and containers for different types of systems.
6) Lowering the costs of PCM applications is a highly promising research solution as well as an opportunity for tremendous developments based on PCMs and combined technologies. Economical feasibility needs to be studied, considering the increased initial cost with PCMs and system performance degradation. Furthermore, the durability and stability of PCMs over long-term operation need to be studied;
7) The performances of PCMs are influenced by various factors such as environmental climate, heating/cooling rate, orientation and internal configuration of the construction. Benchmark for suitable PCMs selection through entropy weight and TOPSIS methodology should be conducted to utilise the maximum potentials of the PCMs in the appropriate circumstances (Oluah et al., 2020).
8) The performance of PCMs for utilization in various climates will be evaluated in the future, as well as different integration methods in buildings. Studies will be conducted to analyse the foremost criteria that are considered when selecting and integrating PCMs into building energy systems for a given climate. Studies are still needed to find efficient and affordable materials and to better address technical issues, such as supercooling, segregation and material compatibility.

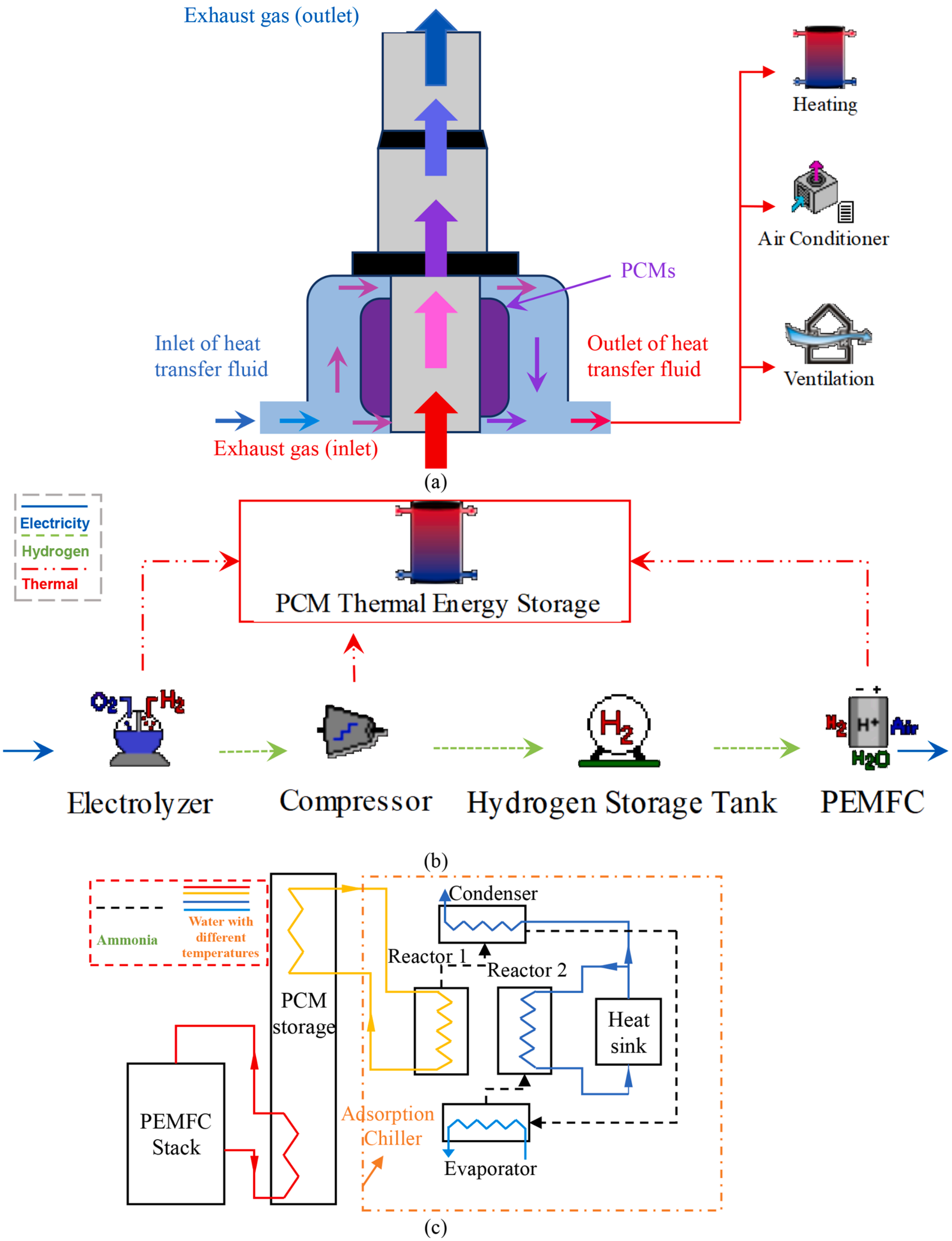


Fig. 22. Schematic diagrams of the PCMs integrated exhaust heat recovery system: a) PCMs for the heat recovery in an internal combustion engine; b) PCMs for the heat recovery in a hydrogen system; c) PCMs for the heat recovery in a fuel cell-driven cooling system (Oro et al., 2018).
(Note: different colors of lines indicate different energy forms and different temperatures. The PEMFC refers to the proton-exchange membrane fuel cells)

8. Conclusions

In this study, a state-of-art review was conducted on cutting-edge technologies for carbon-neutral district energy community transition with latent thermal storages. A cross-scale 'material-component-system' framework was provided to give clear guidelines on energy saving and decarbonisation potentials. Both carbon-positive and carbon-negative strategies in the operational stage are reviewed. The reviewed carbon-

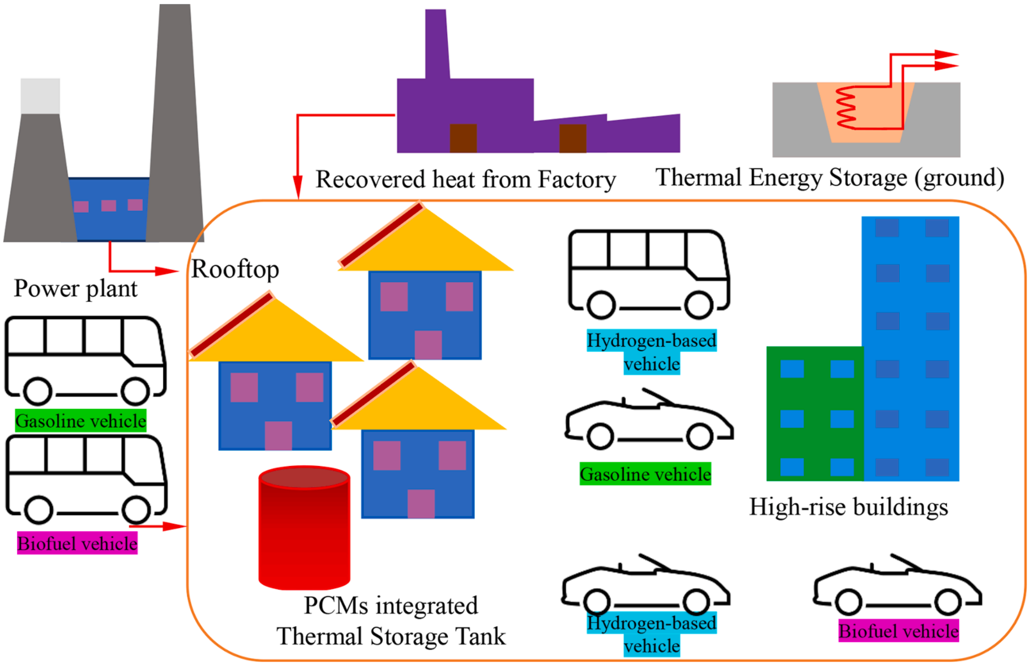


Fig. 23. An example of thermal energy interaction network with PCMs for the heat recovery and storage in the smart city.
(Note: all vehicles are implemented with PCMs for the exhaust heat recovery. Thermal energy interactions within various types of buildings can be realised using the mobility of vehicles fleets. The STC is the abbreviation of the solar thermal collector system.)

negative strategies include cleaner power production and waste heat recovery. Carbon-positive strategy mainly includes energy-efficient buildings, from perspectives of natural heating (e.g., concentrated solar thermal energy, geothermal heating, and solar-driven ventilative heating) and cooling resources (e.g., ventilative cooling, geothermal cooling, and sky radiative cooling). Roles of PCMs in the carbon-neutral district energy community transition are characterised as improvement in power generation efficiency, stabilization in intermittent renewable energy supply, energy-efficient buildings with minimum energy demands, and waste-to-energy recovery. For the widespread acceptance in both industry and commercial market, great endeavours need to be paid to heat transfer enhancement in latent energy storage, including thermal conductivity enhancement with porous media and nanoparticle additives, enlargement of heat transfer area, multistage or cascaded LHS technique, and thermodynamic optimization. In terms of carbon-positive strategy, energy-efficient buildings can be achieved through both passive and active strategies. For the passive strategies, due to enhanced thermal inertia and thermal storage of building envelopes, combined PCM-walls and other energy-efficient strategies (e.g., free cooling, solar chimney, solar façade, and Trombe walls) can achieve energy-efficient buildings. Active strategies include mechanical ventilations, active water pipe-embedded radiative cooling, and geothermal system integration. Furthermore, AI-based strategies can be applied in deterministic optimisation, uncertainty analysis and optimisation for robust design, and model predictive control. In terms of carbon-negative strategies, PCMs can enhance energy efficiency on cleaner power production, from solar thermal/power systems, solar thermal power plants, geothermal and sky radiative cooling energy. Furthermore, waste heat recovery from city power plants, industry and mobile transportations will contribute significantly to carbon-neutral district energy community. The main conclusions are drawn below:

1) Heat transfer enhancement in latent energy storage mainly includes thermal conductivity enhancement with porous media and nanoparticle additives, enlargement of heat transfer area through structural design, and multistage or cascaded LHS according to temperature stratification and temperature difference along the HTF flow direction for thermodynamic optimization. Strategies for thermal conductivity enhancement can be mainly classified into nano-encapsulation in PCMs, metal-based nano-additives, nanoparticle additives and carbon-based additives. The incorporation of 0.45 wt% graphene oxide and 1.8 wt% graphene nanoplatelets in the polyethylene glycol can improve the thermal conductivity from 0.31 to 1.43 W/(m·K). Compared to metal-based additives, carbon-based additives are much better, in terms of density and stability in chemical properties;
2) In response to carbon-positive strategy, PCMs can promote energy-efficient buildings through both passive and active strategies. For the passive strategies, due to enhanced thermal inertia and thermal storage of building envelopes, combined PCM-walls and other energy-efficient strategies (e.g., free cooling, solar chimney, solar façade and Trombe walls) can achieve energy-efficient buildings. Active strategies include mechanical ventilations, active water pipe-embedded radiative cooling, and geothermal system integration. Furthermore, artificial intelligence-based strategies can be applied in deterministic optimisation, uncertainty analysis and optimisation for robust design, and model predictive control. By adopting AI approach for multi-level uncertainty analysis, the power generation of a hybrid PCM-PV system can be improved from 1776.9 to 2635.6 kWh;
3) In response to carbon-negative strategies, PCMs can enhance energy efficiency on cleaner power production, from solar thermal/power systems, solar thermal power plants, geothermal and sky radiative cooling energy. Furthermore, waste heat recovery from city power plants, industry and mobile transportations will contribute significantly to the transition towards carbon-neutral district energy community. Depending on the recovered heat transfer fluids or devices, PCMs-based waste heat recovery systems can be classified into steam, exhaust gas, and combustion engines. Roles for PCMs include steady steam production, steady heat flux via the latent storage capacity and pre-heat purpose;
4) To improve the market acceptance and widespread application, great opportunities are given to PCMs and joint efforts are necessary. Future studies are recommended to focus on standard testing

procedure and database, benchmarks for suitable PCMs' selection, cascaded LHTES for seasonal energy storage, nanofluid-based heat transfer enhancement in PCMs, anti-corrosion, compatibility, thermochemical stability and economic feasibility of PCMs.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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