

The Emergence of Phase Change Material in Solar Thermal Energy: A Scientometric Review

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Phase change material (PCM) features an attractive option due to its solar thermal storage capability to assist the cooling/heating process especially during night operation, thus contributing to the reduction of energy cost and carbon footprint. This study aims to analyse the emergence of PCM in the application of solar thermal energy. Subsequently, to envisage Technology Readiness Level (TRL) and commercialisation opportunity based on historical and contemporary research trends. This review encompasses of peer-reviewed literatures from Scopus database for one decade between 2010 and 2019. Based on the review, there is a moderate growth on the research related to PCM-solar thermal at 22% of emergence rate from the past one decade. China has dominated in this research development by concurring approximately 22% from the number of research articles published globally. It can be concluded that the application of PCM in solar thermal energy system is at TRL 5 which reflects research and development (R&D) progress is at intermediate prototypical development based on the trend of academic publication. Furthermore, based on the review, PCM features great potential in commercialisation opportunity due to its vital contribution as a frontier material/substance in overcoming the challenges of energy and environmental insecurity.

Keywords: phase change material; solar thermal energy; renewable energy; LHTES

I. INTRODUCTION

Solar energy has been resilient through the Covid-19 crisis and its demand is expected to increase for the next few decades which may overtake coal as the primary means of producing electricity (IEA, 2020). Massive transformation to solar energy is a wise decision to enormously mitigate the global warming as well as carbon footprint. This scenario underlines that solar would be the future king of energy surpassing the traditional fossil fuel power generations.

At present, phase change material (PCM) emerges as an alternative approach to solar thermal energy storage. It can be used to mitigate the changes in energy demand between peak and off-peak periods. In solar energy storage, energy is transferred to the PCM in the form of latent and sensible heats. Between these two, latent heat thermal energy storage (LHTES) is more attractive and viable because of its high energy storage capacity in small volume with charging and

discharging heat at constant temperature (Zeinelabdein *et al.*, 2018; Rathore *et al.*, 2020). Essentially, many review articles have been published related to the hybrid thermal energy storage with PCM (LHTES). For instance, PCM material preparation and selection (Jiang *et al.*, 2019; Li *et al.*, 2019; Wang *et al.*, 2019; Asgharian & Baniasadi, 2019), enhancement of PCM properties via nanomaterial (Badenhorst, 2019; Qiu *et al.*, 2019; Allahbakhsh & Arjmand, 2019) encapsulation material of PCM (Liu *et al.*, 2018; Cárdenas-Ramírez *et al.*, 2020) as well as process system engineering approach for hybrid thermal storage with PCM mechanism (Asgharian & Baniasadi, 2019; Ehms *et al.*, 2019; Jiménez-Xamán *et al.*, 2019). Contrary, this study aims to analyse the emergence of PCM in the application of solar thermal energy. Subsequently, to envisage Technology Readiness Level (TRL) and commercialisation opportunity based on historical and contemporary research trends.

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II. MATERIALS AND METHOD

Two analyses are conducted to meet the focus of this review paper. Bibliometric analysis of Scopus publication is used to predict PCM-emergence rate by assessing the growth of research publications. Similar scope of study has been done by Pandita *et al.* (2014) where they predicted the growth of research output at Indian medical research institutions. The emergence rate or annual growth rate is evaluated based on Equation 1, while identification of technology maturity (TRL) is performed based on the assessment of curated articles by determining the contemporary state of research (literature, laboratory, field testing (simulation), field testing (prototype) and commercial stages) and application trend.

$$Er = \frac{\left(\frac{EV}{BV} - 1\right) * 100\%}{Y} \quad (1)$$

Where, Er is emergence rate or annual growth rate, EV and BV are the publication number in subsequent year and initial year respectively, while Y is the number of years (period).

Additionally, this work also analysed recent research focus and country's involvement. For visualisation of research collaboration, VOSviewer software is used to create networking map for country co-authorship (Van Eck and Waltman, 2010).

III. DISCUSSION

A. Bibliometric Analysis: Emerging Research Trend

The emergence of PCM in the application of solar thermal energy is investigated via bibliometric analysis. This review involves scientometrics analysis on Scopus database from year 2010 until 2019 by combining the following keywords: "phase change material" and "solar thermal energy". A total of 2304 journal articles within the keywords are recapitulated as shown in Figure 1. From the number, approximately 10% of them involved work related to literature review studies. While the remaining included research related to area of energy and PCM characteristic, laboratory/pilot-scales studies (design and application) and as well as modelling and simulation analysis based on various application area. Figure

1(a) illustrates that energy, engineering and material are the popular research areas in the PCM-solar thermal energy trend thus underpinning the significant of this work in exploring the research and technology evolution of PCM in solar thermal energy.

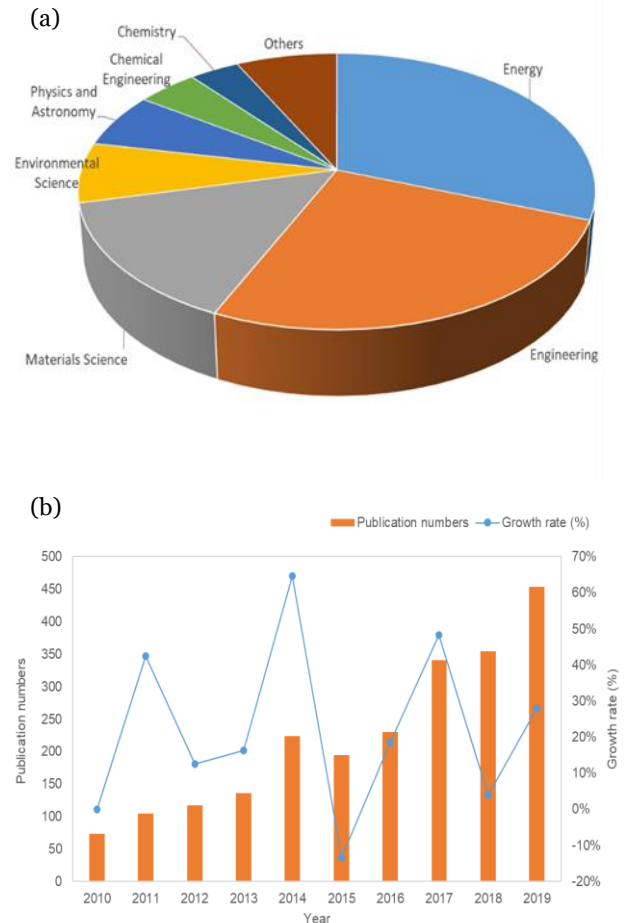


Figure 1. Research trend of journal articles published in Scopus database from year 2010 until 2019; (a) Research area/scope, and (b) Publication number.

In addition, there is moderate growth on the research related to PCM-solar thermal energy at average annual growth rate of 22% from the past decade as shown in Figure 1(b). It can be observed that the application of PCM-solar thermal energy in the global competitions first increased to the peak of 60% in 2014 and then decreased to less than 20% in the following years, before its continuous growth towards 2020. This annual growth demonstrates the emergence rate of PCM-solar thermal energy studies through the progression of publications numbers. Whereas it can be a vital indicator for the PCM potential in solar thermal energy application.

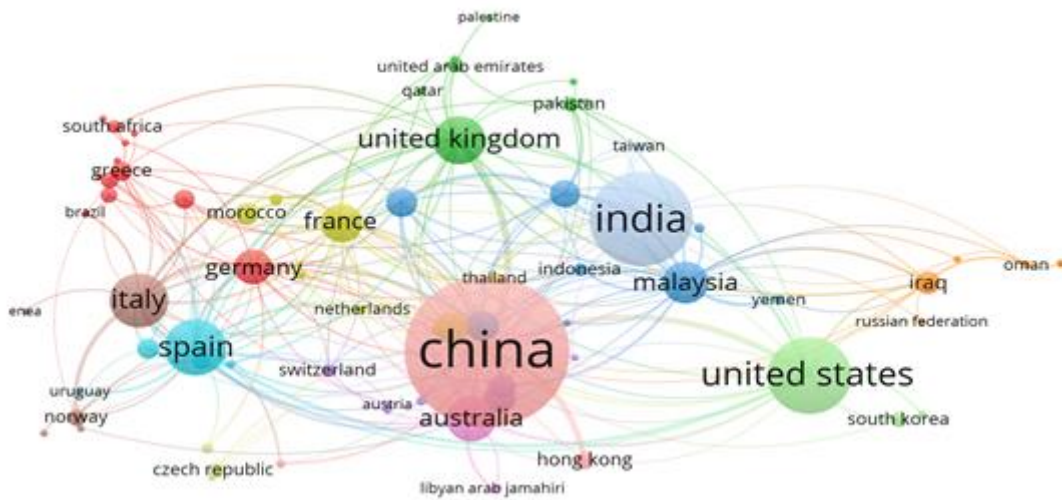


Figure 2. Network visualisation map of country co-authorships in PCM application in solar thermal energy research

From Figure 1(b), the PCM-research evolution spiked notably in year 2015 onwards with the major research focuses on energy and engineering. This is associated with the global demand towards mass utilisation of renewable energy to reduce dependency on fossil fuel, especially from International Agency. This circumstance may be influenced by the recent Paris Climate Agreement (UN, 2020) and 2030 Agenda for Sustainable Development Goal (UN, 2020) which resulted to the boosting of extensive research on PCM-solar thermal energy in recent years.

Figure 2 illustrates the collaboration network of countries who had at least five articles co-authorship. The thickness of lines indicates the strength of collaboration, and the node size signifies the number of publications of the country. Meanwhile, the colors represent the collaboration clusters. From the lines and nodes, China is dominating in this research exploration and produced major international collaborative research, follows by India and US. China has published the highest number of published articles accounted to 610 (22% from the total publications), followed by India (281 publications) and US (248 publications). Interestingly, Malaysia is one of the emerging countries involved in the PCM-solar thermal energy studies thus underpinning the significant contribution of this work for Malaysian researchers. It can be noticed that PCM research has been gaining much attention specifically from countries with the highest population rate and rapid economic growth such as China, India and US (Countries in the world by population (2021), 2021).

From the networking map, three significant collaboration clusters can be distinguished; red cluster included China and Australia, blue cluster gathered Malaysia and India, and green cluster encompassed of US and UK. These clusters evident that research collaboratives activities were stimulated via region of influence. Please take note in this work, we only emphasised two significant countries for each cluster.

B. Technology Readiness Level (TRL)

Identification of technology readiness towards commercialisation is vital to academics involved in research, innovation and technology development (Setiawan *et al.*, 2018). Essentially, TRL concept indicates maturity of specific technology which is reflected by Level 1: Concept evaluation (Basic principle approved) to Level 9: Successful Deployment (Actual system proven in operational environment) as illustrated in Figure 3 (NASA, 2021; Martínez-Plumed *et al.*, 2021). Few studies have been conducted to analyse the TRL such as in the food processing surfactant technology (Setiawan *et al.*, 2018) and composite recycling technology (Rybicka *et al.*, 2016). Nevertheless, to the best of author knowledge, there is no comprehensive analysis has been conducted in determining the TRL of PCM in thermal energy storage application. Thus, this work is significant not only to determine the contemporary research trend but to forecast the technology diffusion. Subsequently, to measure how much effort can be exerted in the context of academic perspective.

Based on the Scopus database, there is a consistent publication trend of literature review articles related to the PCM-solar thermal energy storage such as in the application of photovoltaic (Ma *et al.*, 2019; Waqas *et al.*, 2018; Hasan

et al., 2018), solar drying (Sandali *et al.*, 2019; Berville *et al.*, 2019; Shalaby *et al.*, 2014), solar collector (Zayed *et al.*, 2019; Khan *et al.*, 2018),

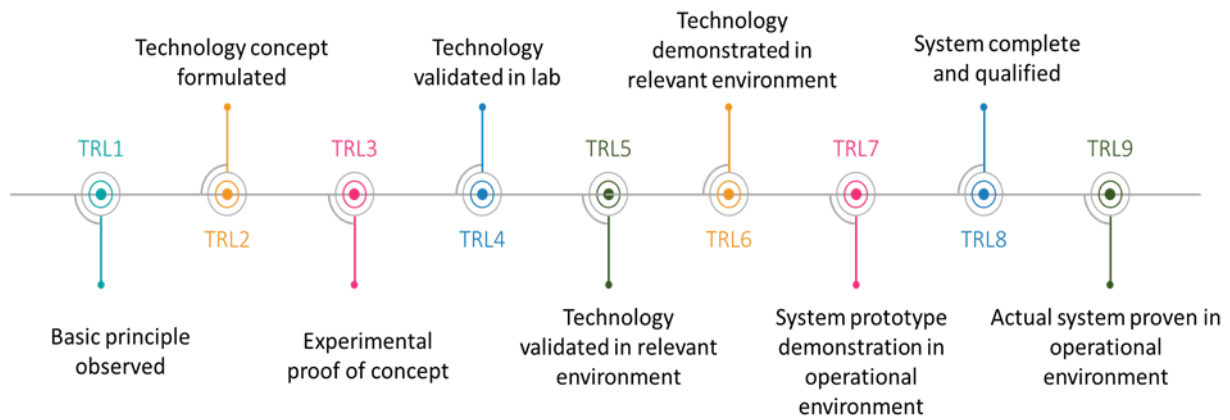


Figure 3. Technology Readiness Levels (TRLs) framework

solar air heater (Haldorai *et al.*, 2019), and solar water heater (Kee *et al.*, 2018; Sadhishkumar & Balusamy, 2014). Additionally, number of reviewed articles have been conducted related to the space heating, ventilation and cooling (HVAC) system (Ma *et al.*, 2019; Monghasemi & Vadiee, 2018; Al-Abidi *et al.*, 2012). This trend is due to the high demand pertains to sustainable and affordable thermal human comfort as discussed in (Yang & Matzarakis, 2019; Mastrucci *et al.*, 2019). Other reviews have been critically discussed for instance in term of PCM nanocomposite material (Qiu *et al.*, 2019; Allahbakhsh & Arjmand, 2019; Jiang *et al.*, 2019; Arshad *et al.*, 2019; Dheep & Sreekumar, 2014; Yuan *et al.*, 2014; Yang *et al.*, 2019; Peng *et al.*, 2018), PCM latent heat/thermal performance (Sarbu & Dorca, 2019; Lin *et al.*, 2018; Fan & Khodadadi, 2011) and PCM solar energy storage modelling and simulation (Asgharian & Baniasadi, 2019; Jiménez-Xamán *et al.*, 2019; Ehms *et al.*, 2019). These publication scenario (from the academic perspective) reflects moderate research/technology progress but feature an emerging potentiality via its high availability and visibility on the literature studies, where it was evident that the PCM-thermal energy storage studies have been surpassing TRL 2.

Referring to the Scopus database, an experimental setup of LHTES using two commercial PCMs (refine paraffin wax blend and fatty alcohol blend) coupled with solar collector for

domestic hot water system has been developed by Dogkas *et al.* (2019). It was observed that fatty alcohol blend was able to return 79% of total energy used for charging process compared to refine paraffin wax, at 64%. Back then, Calvet *et al.* (2011) employed a commercial latent heat storage composited with graphite for a prototype solar thermosiphon hot water system based on the experimental setup. It was proven that the addition of consolidated expanded natural graphite may enhance the thermal power up to 138% if compared to water (without graphite). Meanwhile, Desgrosseilliers *et al.* (2011) designed an LHTES (using lauric acid as the PCM) system coupled with a domestic hot water solar thermal system and was tested at apartment in Halifax, Canada. They found that utilisation of LHTES was able to store latent heat in less than 6 hours and withdraw within less than 3 hours, which exhibited a good performance of LHTES when integrated with hot water system.

Interestingly, PCM has been used as LHTES in laboratory/pilot prototypal stage since 2010. For instance, Bayón *et al.* (2010) developed a LHTES (using $\text{KNO}_3/\text{NaNO}_3$ as the PCM) prototype system integrated with actual solar thermal power plant for direct steam generation. Those prototype has been tested at the largest concentrating solar technology research located in Spain. It was indicated that the developed prototype was capable to store and deliver energy corresponding to 40 kW_{th} and 50 kW_{th} , respectively.

Nevertheless, it was unable to meet an actual prototype design which was at 100 Kw_{th}. Rea *et al.* (2019) have designed a prototype system of LHTEs (using Al-Si as the PCM) to convert thermal heat to electricity using Stirling engine. Their prototype was setup on top of the commercial solar power tower with ability to dis-integrate solar collection and electricity production. The system showed significant improvement in term of conversion efficiency at 18.5% during discharge period, which outperformed the existing studies conducted in the same field (Rea *et al.*, 2018; Elfeky *et al.*, 2019).

A prototype design of solar assisted HVAC system driven by PCM in thermal energy storage has been initiated as early as 2012. Biswas *et al.* (2013) conducted field testing of prototype nano-PCM (composited with graphite) as interior wallboards to enhance energy efficiency for space heating and cooling for

indoor thermal comfort. This has been tested at natural exposure test (NET) facility in United States. Goia *et al.* (2013) developed a glazing system (using RT35 paraffin as the PCM) system and embedded on the typical office building façade facility at TWINS – Testing Window Innovative System. Table 1 summarises several Scopus publications from 2019 until 2010 with the identification of TRL's range. This TRL identification was conducted based on the qualitative assessment and authors' prerogative subjected to the content of the articles. It can be concluded that TRL 5-7 is the most common stage of PCM-solar thermal storage research. This indicates that the research is still at the intermediate prototypical stage which requires further development, evaluation and investment for commercialisation.

Table 1. The TRL identification based on Scopus publications

Ref	Type of PCMs	Application	TRL	Location (if in the related environment)
Dogkas <i>et al.</i> , 2019	Refine paraffin wax blend and fatty alcohol blend	Domestic Hot water system	3-5	-
Calvet <i>et al.</i> , 2011	Water composited with graphite	Thermosiphon hot water system	3-5	-
Desgrosseilliers <i>et al.</i> , 2011	Lauric acid	Domestic hot water solar	5-7	Apartment in Halifax, Canada
Çakmak & Yildiz, 2011	Calcium chloride hegzahidrat	Solar dryer	3-4	-
Shalaby & Bek, 2014	paraffin wax	Solar dryer	3-4	-
Agarwal & Sarviya, 2016	paraffin wax	Solar dryer	3-4	-
El Khadraoui <i>et al.</i> , 2017	Paraffin	Solar dryer	4-7	-
Bayón <i>et al.</i> , 2010	KNO ₃ /NaNO	Dolar thermal power plant for direct steam generation	6-8	Spain
Rea <i>et al.</i> , 2019	Al-Si	Commercial solar power tower	6-8	-
Biaswas, Lu & Soroushian, 2013	Nano-PCM composited with graphite	HVAC	5-7	-
Goia <i>et al.</i> , 2013	RT35 paraffin	HVAC	5-7	United States
Ma <i>et al.</i> , 2016	RT24 and copper nanoparticle	HVAC	6-8	Solar Decathlon (SD) house, China
Benli, 2011	Calcium chloride hexahydrate	HVAC	5-7	-

IV. CONCLUSION

Incorporation of PCM in thermal energy storage (also known as LHTES) has gained much attention due to its unique design and properties that are able to bridge the gap between energy supply and demand and deals with the diurnal pattern. Based on the Scopus database, there is moderate growth on the research related to PCM-solar thermal at 22 % of emergence rate (annual growth) from the 2010 until 2019. Technology or research maturity was determined at TRL 5-7 which suggests that the research still requires further development, evaluation and investment for commercialisation. This preliminary technology review is solely based on prerogative and authors judgements based on the TRL framework available in (NASA, 2012; Martínez-Plumed *et al.*, 2021) and subjected to the content of published articles. One should take note that this review is totally based on database search which involves only academic articles

though it does not capture other citation/peer-reviewed database such as Web of Science. However, validation from the experts and industrial point of view are required to support the shorthand evaluation of TRL. This present work is able to provide preliminary insight to the researchers and academics in current research portfolio of PCM especially in the application of solar thermal energy. Subsequently, to strategise the commercial development of PCM.

V. ACKNOWLEDGEMENT

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