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Mapping the development of various solar thermal technologies with hype cycle analysis

Mohammad Dehghanimadvar[1], Reza Shirmohammadi*[2], Farzin Ahmadi[3,4], Alireza Aslani*[2], Kaveh R.Khalilpour[5,6]

[1]School of Photovoltaic and Renewable Energy Engineering, University of New South Wales, Sydney, New South Wales, Australia
[2]Department of Renewable Energies and Environment, Faculty of New Sciences and Technologies, University of Tehran, Iran.
[3]Department of Energy System Engineering, Faculty of Mechanical Engineering, K. N. Toosi University of Technology, Tehran 11365-4435, Iran
Department of Mechanical Engineering, School of Engineering, Aalto University, FI-00076, Aalto, Finland
[5]School of Information, Systems and Modelling, University of Technology Sydney, NSW, Australia
[6]PERSWADE Centre, Faculty of Engineering and IT, University of Technology Sydney, NSW, Australia
Corresponding Authors: Reza Shirmohammadi; mail addresses: r.shirmohammadi@ut.ac.ir, Alireza.aslani@ut.ac.ir

Abstract

This paper focuses on the technological development of solar thermal technologies through the analysis of patent records and search traffic. First, various solar thermal technologies are reviewed and discussed. Then, the related published patents are analysed. To improve the accuracy of patents retrieval, a new framework is proposed and employed based on the combination of keywords and keycodes. In this new framework, the proposed methodology can enhance the retrieved patent pool resolution by eliminating the patent with the relevant title but irrelevant technology scopes. Furthermore, new technological features such as technology attractiveness and acceleration are introduced and applied to solar thermal technologies. These two introduced features help to recognize interested areas by industrial players in the technological field. The pace of technology being developed and becoming matured could be identified by how fast the industry invests in technology by protecting its intellectual properties. The logistic S-curve is employed for assessing the current state of solar technologies on the technology life cycle. The market diffusion of each solar thermal technology is assessed by developing adoption curves using search traffic. Finally, the hype cycle of solar thermal technologies is demonstrated by combining the two technological assessment graphs. Through the proposed methodology, 8740 related patents are retrieved and screened. The analysis shows that Photovoltaic-thermal has the highest share in published patents and the parabolic trough and evacuated tube collectors are in their maturity phase. The

parabolic dish collector is identified as one of the highest accelerated technologies and also located near the maturity phase. Therefore, it can be predicted that the next technology reaching the maturity phase would be the parabolic dish collector. Overall, all solar-heat driver cycles are in their growth stage, but the Rankine cycle is more developed. Text analysis determines the main challenge with cycles is the operation and maintenance that should be overcome to meet the maturity phase.

Keywords: Adoption curve; Flexibility and compatibility; Hype cycle; Solar thermal technologies; Technology assessment; Technological life cycle

1. Introduction

Energy demand is one of the imperative issues for society from environmental and socio-economic perspectives. In the lack of viable energy alternatives, since industrialisation, there has been a significant dependence on fossil fuels which has led to one of the most critical global challenges of our time, the climate change[1, 2]. For this matter, different forms of renewable energy have been taken into account, the development of which becomes increasingly vital [3-6]. Because of its availability and sustainability characteristics, solar energy has been considered the most promising solution to face climate change challenges [7-9]. Till recent times, the devices which harness solar energy -regarding their conversion method- were divided into two categories, namely heat and electricity, with examples including various thermal collectors (heat) and photovoltaic (PV) modules (electricity) [10, 11]. In recent times, however, a third category has also emerged, which is a hybrid of heat and electricity. The so-called hybrid PV/T collector merges both energy conversion methods and improves the overall solar energy utilisation efficiency [12].

Solar thermal systems include specific energy converters which are able to collect and transform the sun's radiation into available energy. This is possible with the use of solar thermal collectors, which are specific heat exchangers responsible for converting the received solar radiation into internal energy of an exchange medium (like air, water, oil, and recently nanofluids). This technology is utilized in various purposes/applications, such as industries and residential sectors, water purification, chemical plants, drying of agricultural goods, and power production [13-19]. Solar collectors are divided into different categories, as shown in Fig. 1 [20].

Given that solar thermal technologies are at various stages of development, their fair comparison requires knowledge or prediction of their current technological maturity and readiness as well as their development trajectory. Attaining the knowledge of each stage of technology development renders insight into the future of technology and inform relevant policy and investment planning activities. Numerous technical solutions are available in the market, while the deployment of new technologies entails a variety of different challenges. For these matters, a comprehensive technological assessment may aid investors and policymakers to recognize the best investment and decision opportunities for evaluating the proper and appropriate strategies and planning procedures [21-24]. The technology life cycle (TLC) is proven as a reliable approach for identifying the status of technological maturity. This approach could be a useful tool for researchers to understand the technologies criteria[25]. Likewise, the Hype cycle diagram has been proven as one of the most promising and credible ways to assess technologies. This study attempts to determine the current state of each solar thermal technology in the life cycle curve and project their maturity trajectory as well as their market readiness. Answering these questions can be done by technological life cycle analysis. Then, the market penetration of each solar thermal technology can be investigated and evaluated by the adoption curve. For the technology life cycle, an alternative approach, however, as one of the basic techniques, is trend analysis. By taking into account historical time series analysis and fitting for projection. This approach is only based on one indicator, which is the time series trend, and most likely is resulting in the wrong direction [26]. Input data has a considerable impact on the results. Input data for this approach could be patents, papers, news and investments and characteristics involved with them such as citation, investment size, journals or news quality. However, one of the most reliable sources for these types of analyses is patent pools. Not only they are representative of technology know-how, but also they have commercial potential. Herein, we used four different indicators which are: patent trends, patent citation, patent family, granted patent for technology development metrics and search traffic as technology adoption metric.

The novelty of this research is to recognize the status of these technologies in the life cycle and adoption curve to draw the solar thermal technologies hype cycle for the very first time. Although previously these tools have been employed by researchers in different areas [27-30], depicting the technology development stage of solar thermal technologies has not been discussed yet, to the best of the authors' knowledge. To build up a firm methodology, two new features are introduced and discussed: technology attractiveness and accelerations. By employing these features and adding them up with other tools such as text analysis, we introduced a firm methodology for depicting the different life stages of a technology. To examine our assumptions and proposed methodology, solar thermal technologies have been employed. In the following sections, first, the concept of solar thermal energy and its related technologies is explained. Secondly, an overview of the adoption curve and the life cycle phenomena is described briefly. After gathering data from trustworthy sources and executing patent analysis, the life cycle and adoption diagrams for each technology will be represented. Then, the hype diagram will be eventuated for each technology by combining these two schemes. Finally, the results diagrams will be discussed for each technology with further elaboration on the implications.

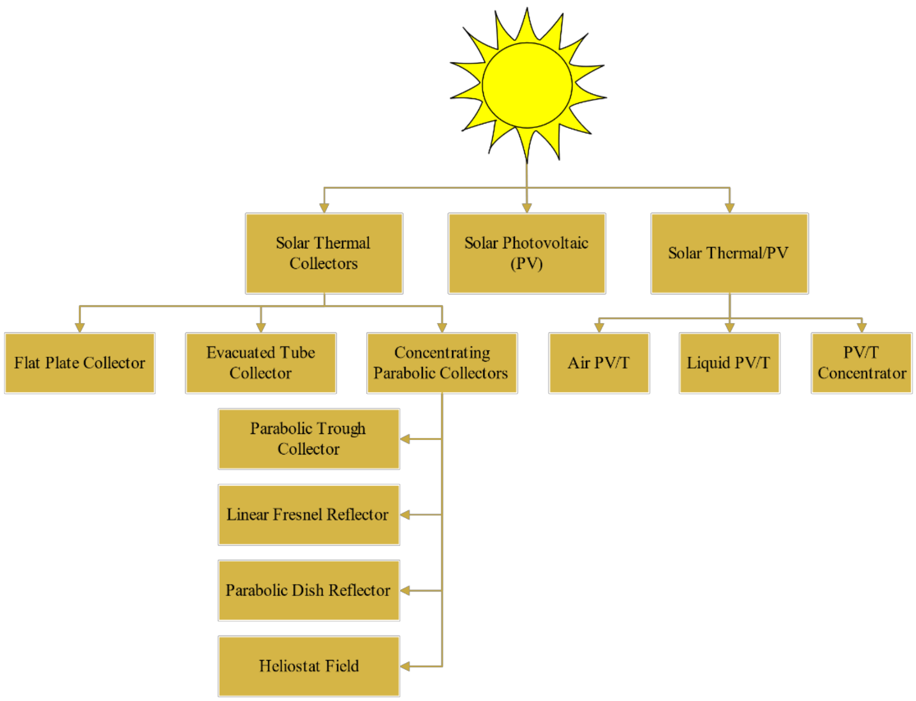


Fig. 1 Solar technologies classification [20]

2. Solar Thermal Technologies

Because of its wide-reaching availability, solar energy is considered an ideal source for satisfying the energy demands around the globe [31]. This technology includes solar collectors for absorbing solar irradiation and converting it into a transport medium. In general, the solar collectors have been categorized into concentrating and stationary. Stationary collectors have the same area for both absorbing and intercepting the sunlight, while sun-tracking collectors typically have concave reflecting exteriors for intercepting and concentrating solar radiations into a minor receiving zone, through which it increases the irradiation flux. Usually, flat plate collectors (FPC) and evacuated tube collectors (ETC) are used for low-temperature purposes (up to 100 °C) [32, 33]. However, concentrated solar collectors are more promising for medium temperature levels (100–300 °C).

In some cases, the ETC could be utilized in temperatures lower than 150 °C, whilst in application with higher temperature, compound parabolic collectors (CPC), linear Fresnel collectors (LFC), and parabolic trough collectors (PTC) are capable of operating in more than 300 °C. In the high-temperature range, PTC has the highest technological maturity [3, 34], along with the solar dish collectors, to be considered as promising options for very high-temperature ranges above 500 °C [35]. In the following, a review is presented of the various types of solar thermal technologies.

2.1 Flat Plate Collectors

The flat-plate collector (FPC) is considered the main core of any solar thermal system with various applications within the temperature range of 60-100 °C purposes from residential to industrial applications. FPC is known as the most conventional type of solar systems with its undemanding design and low cost. This collector can heat up to 100 °C more than the environment. A Flat surface absorbs solar radiation as much as possible and subsequently transfers it to thermal energy. The heat transfer fluid (HTF), which is flowing under the absorber, collects this thermal energy via a convection mechanism and stores it for future use [36]. An isometric view of a conventional FPC is illustrated in Fig. 2. As it is shown, the essential components of the FPCs are:

i. Glazing or transparent top cover(s) made of glass or plastic minimises heat losses, including convection and irradiation, from the absorber plate.
ii. A flat absorber plate (usually metallic) collects the incoming solar irradiation, which will be transformed into thermal energy. The black colour is used in general; however, various types of coating have been suggested in the literature [37, 38].
iii. Integrated heat transfer passages, which are consisted of tubes, channels, and passages near the absorber plates, are made to circulate the HTF used to extract the thermal energy carried out by the plate.
iv. Insulation materials are used in order to minimize conductive heat losses.
v. Collector box or casing are used for covering the elements described above and prevents any penetration.

In general, FPC is fixed in place and does not require tracking. The orientation of collectors should be adjusted to a straight line with the equator. The optimum tilt angle of a collector is expected to be equal with the location's latitude, with an angle variation around 10-15° concerning its application [39].

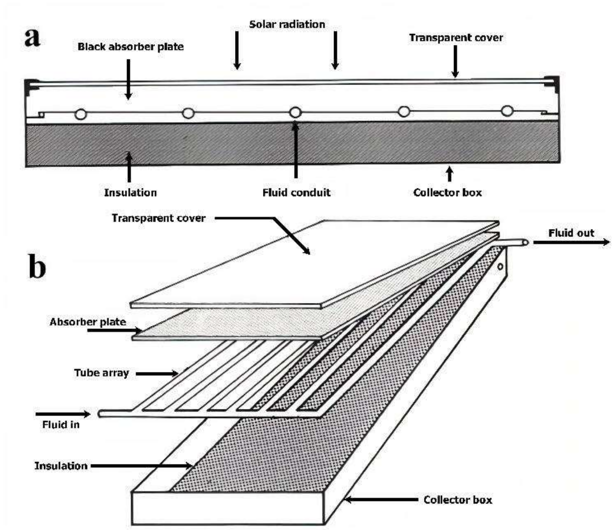


Fig. 2 (a) Exploded view and (b) isometric view of a flat-plate collector [40]

Through considerable efforts made by research, the basic principle of flat-plate collectors is well-known. Currently, the main focuses are on developing new materials for higher performance. Due to lower costs and weight, polymetric materials can be considered as potential materials for enhancing FPC's performance. Accordingly, absorbers material such as biopolymers, polymers with gold films and nanoparticles of silver are recent studies in the literature[41]. Another effective method to improve thermal efficiency is to use selective coatings on the FPC absorbers[42]. The best absorbers for FPCs, due to improving optical absorptivity, were investigated to be epoxy coatings (zinc phosphate) and anti-corrosive with catalyst[43]. Another material that can enhance thermal stability and improve the productivity of FPC is Phase Change Materials (PCM)s. Paraffins are one of the most adopted PCM in FPCs[43].

2.2 Evacuated Tube Collectors

The ETCs transform the captured solar energy into heat through a solar water/air heater [44]. ETC provides both advantages of an absorber with selective exterior coating and also vacuum insulation. Therefore, ETC has higher efficiency but more costly compared to FPC in the temperature range above 80 °C. For this reason, ETC is more operational in a cold and cloudy climate compared to FPC. The energy produced by ETCs can be utilized for air conditioning in residential and commercial sectors [13, 45, 46]. The unique design of ETCs comprised of heat pipe evacuated solar collectors along with U-tube solar are widely exploited for supplying domestic water and space heating. A schematic of U-tube type ETC is shown in Fig. 3. The vacuum tube is the key element of solar thermal utilization due to its effectiveness in high-temperature applications [47-51]. Liquid-vapor phase change materials are used in ETC, which cause a high-efficiency heat transfer. These collectors include a heat pipe surrounded by a vacuum insulated tube for minimizing heat losses. The pipe is made of copper, attached to an absorber plate. The heat pipe consists of a fluid (like methanol) that experiences an evaporating-condensing cycle (to saturated or superheated vapor). In this process, solar heat evaporates, the liquid evaporates by heat resulting from the sun, and the generated vapor flows through the heat sink segment where it gets condensed and subsequently thermal energy transferred to the HTF (e.g. water). The condensed fluid returns naturally to close the cycle [10, 52].

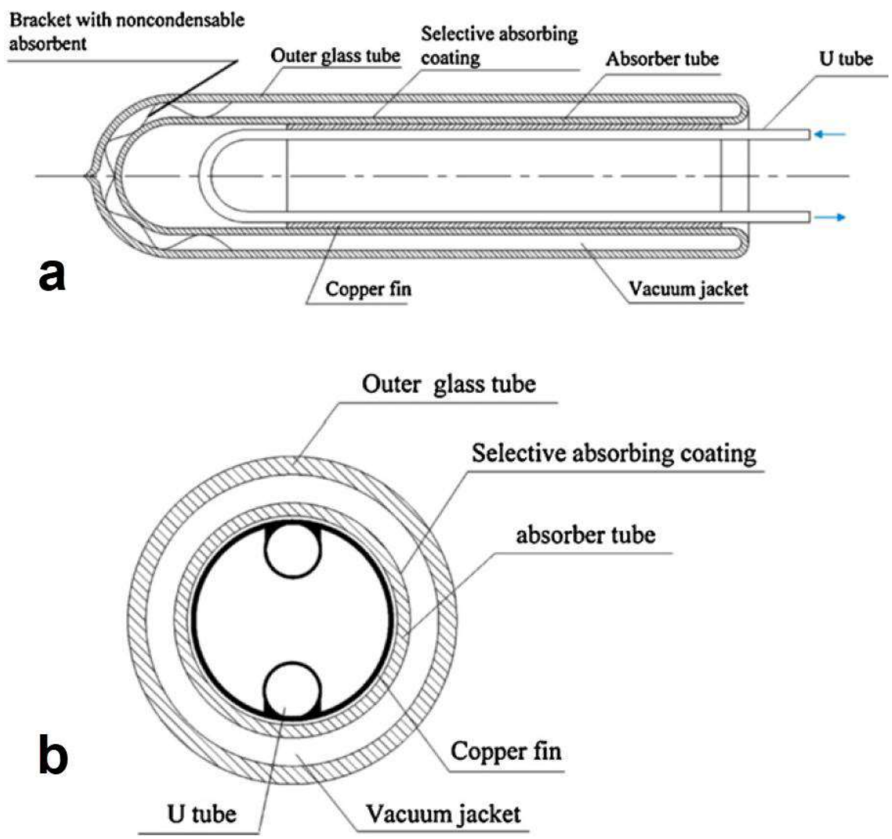


Fig. 3 (a) Schematic and (b) cross-sectional view of an ETC with U-tube [10]

Considering the role of materials is essential for improving heat transmission or reducing heat loss within tubes. In order to accomplish this, researchers have investigated a variety of materials, including absorbent shapes or heat shields. Kim and Seo[47] used four distinct forms of absorbers to investigate the functional viability of evacuated tube collectors, assessing each absorber's influence on the collector's thermal performance independently. Using flat micro-heat pipe arrays, Wang et al.[53] compared conventional and transparent solar air collectors. The performance of the collector was evaluated by varying the absorption coating positions in the absorber tube. Solar air collectors with a conventional design have a thermal efficiency of around 8% lower than transparent ones. A unique evacuated tube collectors design was the subject of Felinaski and Sekret[54] empirical study , which uses phase change material to store thermal energy and maintain a high temperature throughout the night. One of the major challenges of the proposed system is the shadowed section of evacuated tubes that does not receive solar light. This results in uneven thermal energy transfer to PCM. Thus, the problem has been solved by directing the sun radiation towards the shaded portion of the tube by using a compound parabolic reflector. Using nanofluid in working fluid is another approach for modifying the evacuated tube collector performances. The impacts of various nanofluids at varying volume fractions on the thermal performance of the system have been demonstrated in a number of empirical and computational studies[55]. The usage of nanofluids as a preferred working fluid has gained a high degree of dependence due to positive efficacies in the systems' thermal efficiency. It was also discovered that using nanofluid collectors cuts the cost of power and pollutants dramatically[56].

2.3 Concentrating Collectors

Higher temperatures above the FPC range could be achievable via concentrating solar irradiations on a small collection zone. The concentrating solar collector is considered one of the most promising technologies in the high-temperature range, which could be utilized for thermal power plants or industrial sectors [32, 57-60]. Their mechanism, which typically requires solar tracking systems, summarizes into intercepting solar irradiation onto an aperture area and eventually an absorber. In this technology, sunbeams are concentrated to a lower area before being converted to thermal energy. Mirrors or lens can be utilized in the concentration process through which solar irradiation is reflected or radiated. [10]. As is shown in Fig. 4, The concentrating collectors are classified as [61]:

- Parabolic Trough Collector
- Linear Fresnel Reflector
- Parabolic Dish
- Heliostat Field

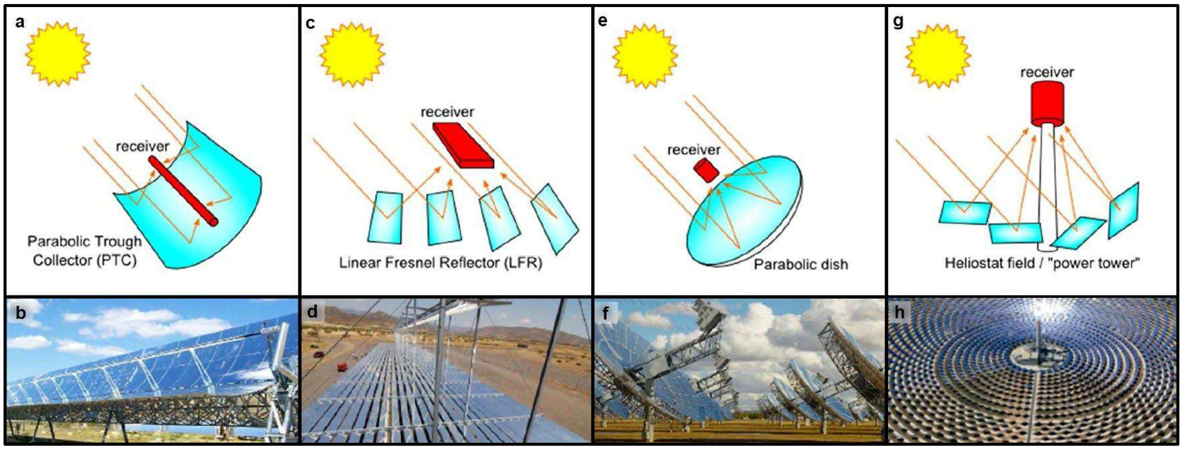


Fig. 4 Schematic and photos of different Concentrating solar collector configurations [62]: (a) illustration and (b) photograph of a PTC [63] (c) drawing of a Linear Fresnel Reflector (LFR) and (d) the FRESDEMO LFR project demonstration at Plataforma Solar de Almeria in Spain [64] (e) Illustration of a parabolic dish and (f) Maricopa solar project in Arizona (g) Illustration of a central receiver with heliostat field plant and (h) Solar Tres in Sevilla, Spain [65]

2.3.1 Parabolic Trough Collector

Parabolic Trough Collectors (PTC) is considered as a linear concentrating collector suitable for an operational temperature range of 150-400 °C [66]. In general, TPCs are made from parabolic trough reflective glasses equipped with a single-axis tracking system, which reflects the solar irradiation to a receiver sited in the focal axis of it. The receiver is comprised of a vacuum-sealed glass tube and absorbing pipe. The concentrated irradiation increases the fluid temperature that circulates into the absorber tube, and respectively the thermal energy is generated [67]. Nowadays, PTC is used in large-scale applications with the integration of numerous collectors in a solar field to generate heat energy at temperatures more than 250 °C (Fig. 5). PTCs are used for other applications, like heat-driven cooling systems, low-temperature heating systems, desalination, and purification. Different fluids are utilized in the absorbing tubes, such as synthetic oil, which has been widely used in most PTCs with an operating temperature lower than 400 °C and around 30-100 concentration ratio [68]. However, other transfer mediums are suggested in the literature, like molten salt and nanofluids [69, 70]. Nanofluids are known as a promising alternative because of their improved thermo-physical properties. Several experimental studies have been conducted in the nanofluids area [71-73]. Carbon nanotubes (CNT) have excellent characteristics compared to other nanoparticles. Another alternative has been studied to investigate the direct production of water and steam in absorber tubes [74]. Currently, the largest solar thermal facility has been constructed, located in the Mojave Desert with 354 MW capacity [75]. A 2 MW capacity solar plant has been established in Spain to investigate steady-state and transient flow behavior into a direct steam generation with PTCs [76]. Most of the environmental restrictions for developing solar thermal plants are like conventional ones. So far, locations suitable for solar applications like deserts happen to be away from residents, with plenty of available lands.

In contrast, water accessibility could be an issue while solar thermal systems typically consume less water than other large energy facilities. The water necessity is profoundly reliant on the entire installed rather than the standalone collector. For these reasons, the collector's type may vary for any application with respect to the proposed location, which depends on ecological (mostly land and water) availabilities [77].

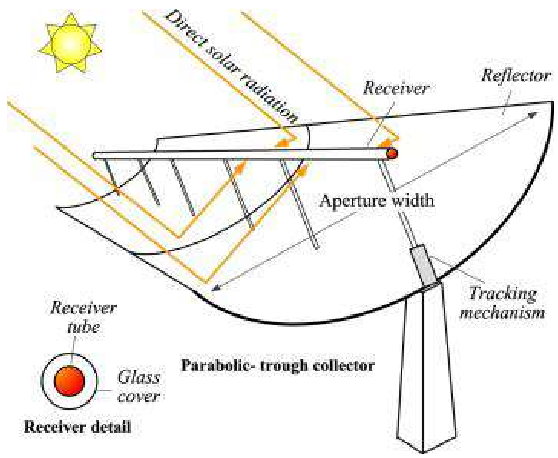


Fig. 5 Detailed view of PTC [78]

2.3.2 Linear Fresnel Reflector

The LFR varies from PTCs because of its absorber tube, which is sited above the reflector field, as illustrated in Fig. 6. The reflectors, including several numbers of row mirrors, concentrate the solar irradiation into a stationary receiver for heating and evaporating water [74]. LFR can be treated as split PTCs, which is not required to be in a parabolic shape. In general, LFR is comprised of: (i) many mirrors adjacent to the ground, (ii) a linear tower-mounted receiver (iii) a solar tracker system [79, 80]. Concerning the linear Fresnel lenses, Augustin-Jean Fresnel -a French physicist- built the first prototype in 1822. The discovery was about the foundation of the glass ring prisms for deflecting the incoming sunlight to a focused narrow beam [81]. In the literature, several documents have studied the performance of linear Fresnel lenses. Two-stage devices such as the primary and secondary optical elements have gained more attention among scholars [82, 83].

Moreover, analytical and simulation investigations were initiated with new approaches with a significant interest in the ray-tracing methods [17–19]. To improve the efficiency, novel technologies are proposed, such as PV/T and beam splitting technique for both Fresnel and trough concentrating [84-87]. The LFRs are usually juxtaposed with PTCs, because of their similarities. Some advantages of LFR are the simplicity and stationary absorbers to remove the moving junction challenges and thermal expansion common in PTC [88]. Nevertheless, because of its higher optical loss, PTCs are more thermally efficient than LFR [89]. The LFC relative low optical efficiency is mainly due to the blockage and shading challenges [90]. These problems could be solved by enhancing the absorber size and elevating the expensive towers. However, the key advantage of LFR is the usage of flat or convex reflectors, which are quite economical compared to parabolic mirrors. While the significant portions of our energy needs require medium temperature ranges, LFR, which is a low-cost technology, is a popular option, as noted by some researchers [90-92].

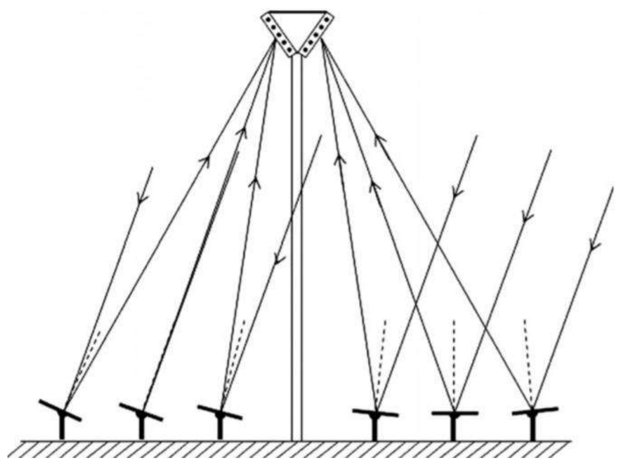


Fig. 6 Schematic of an LFR, designed with two receivers [80]

2.3.3 Parabolic Dish Reflectors

Parabolic Dish Reflector (PDR) systems are able to deliver temperatures up to 1500 °C. Since the receivers are arranged all over a collector field, such as PTCs and PDRs are so-called distributed-receiver systems. As can be depicted from Fig. 7, PDR is a point-focusing collector, which concentrates sun rays into a receiver sited at the focal plane of the dish equipped with a two-axis sun tracking system. The reflector structure should trace the sun completely to reflect the sunbeam onto the receiver. Applying the concentrating collector makes it possible to generate high-temperature level heat with high concentration ratios, representing PDR as a promising solution for mainstream applications [93]. Several types of absorbers with different dish collector designs have been investigated in the literature [94-97]. Also, different cavities have been explored in which the cylindrical shape has been used more often [98-100]. Other studied cavities were found to be conical, spiral, and hemispherical designs.

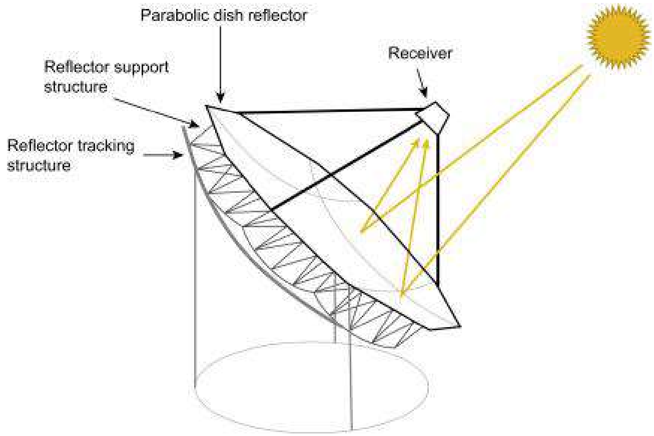


Fig. 7 Schematic of a PDR system [101]

Studies investigated PDRs can be categorized into three topics, PDRs design, PDRs receivers and working fluids. Castellanos et.al.[102] presented a method for determining the optimal dish angle, which helps to improve heat flow over a receiver cavity. A sizing algorithm and a determination of the opto-geometric parameters have also been developed in their studies. In another study[8], optical and thermal analyses were performed in order to determine the optimal location of the receiver from the concentrator in order to optimize optical efficiency as well as improve the flux distribution on the receiver. The heat flux distribution in the receiver influences the temperature attained, according to their findings. Like other solar thermal technologies, lots of numerical and experimental investigations are concentrated on measuring the increase in thermal efficiency by analysing the varieties of the working fluid. The experiment conducted by Loni et.al.[103] demonstrated that nanofluids increase efficiency to 12.9% by using hemispherical, cylindrical cavity receivers with MWCNT/oil nanofluids. In another research, Loni et.al.[104] compared three different nano-fluids, namely; Al_2O_3/oil, CuO/oil, SiO_2/oil in three shapes of receivers. They observed a marginal increase in pressure drops and thermal efficiency. Alnaqi et.al.[105] used three different nanofluids containing multiwall carbon nanotubes-MgO as nanoparticles in thermal oil as a base fluid. They showed that a reduction in the pressure drop penalty can be observed when nanofluid is used instead of a base fluid which resulted in an increase in energy efficiency.

2.3.4 Heliostat Field

Heliostat Field Collectors (HFC), so-called power towers, employ an arrangement of heliostat mirrors (usually flat or vaguely concave) for reflecting the solar irradiation onto a central receiver. The central receiver systems (Fig. 8) are suggested as an economical alternative for generating cheaper electricity compared to PTC technology due to their great capabilities in integration with different energy systems such as conventional and organic Rankine cycle and higher energy production systems with gas turbines that operate in temperatures more than 1000 °C, and this consequently improves the efficiency and energy outputs [106]. Three general configurations have been suggested for the collector and receiver systems. Firstly, heliostats surround the receiver tower consisted of an exterior heat-transfer surface with a cylindrical shape. Secondly, the heliostats are placed in the north of the receiver consisted of an enclosed heat-transfer surface (the northern hemisphere). Thirdly, the heliostats are set in the north of the receiver tower consisted of a vertical plane with a north-facing heat-transfer surface [107]. Mainly, water steam is utilized at the receiver, but molten nitrate salt has been used in some cases. The molten salt has some advantages, which are the possibility to start the process faster due to its single-phase state and also well suited for heat storage purposes. Implementing an oversized tower compared to the generator allows the system to store the surplus heat. The maturity of data on HFC arises from the demonstration projects built in the Mojave Desert, specifically Solar 1 and Solar 2. In Andalusia, Spain, the Solar Tres Tower is the latest development intended to construct upon the Solar 2 project and turn into the first commercial power tower system using molten salt.

Similarly, the first commercial water-steam power tower, PS10, and the largest solar tower, PS20, are in development located in Seville, Spain. Nevertheless, several pilot plants have been built in different areas which are still working [108]. Minimum thermal transport occurs with implementing The central receiver required due to its higher optimum temperatures in the range of 500 °C [109] and stagnation temperatures around 1750 °C [94].

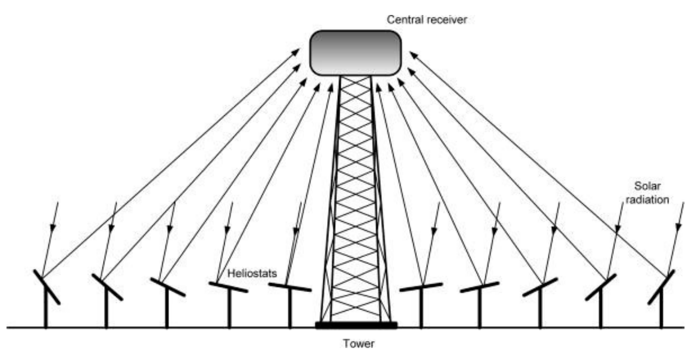


Fig. 8 Schematic of an HFC system [110]

2.4 Thermal-PV Hybrids

Both thermal and electrical energies could be generated from the sun. One of the primary methods for enhancing the efficiency of solar systems is integrating with combined heat and power generation (CHP). Solar CHPs can play an essential part in helping climate mitigation far more than the conventional systems, which exploit the benefits of utilizing solar from economic and environmental viewpoints. In recent decades, the use of solar for CHP purposes is developing increasingly worldwide [111]. This technology might be a great alternative in the industry for energy-producing without emitting any greenhouse gases [112]. A PV/T collector is a component capable of generating electricity and attends as a heat absorber, which led to the simultaneous production of heat and power. Because of the fluctuating demand for heat and electricity, it appears to be a novel idea to develop a device capable of complying with both needs. PV cells employ a portion of the incident sun rays for generating electricity, but unfortunately, a large portion of the irradiation is converted mostly into thermal waste in the cells, which will increase the undercoat temperature of PV. The outcome of this effect is declining module efficiency. The PV/T technology retrieves the wasted heat fraction then utilizes it for practical applications. Initially, in 1981, Andrews [113] studied the performance of different hybrid systems consisting of PV and a flat plate thermal collector for solar energy utilization. The simultaneous cooling of the PV module keeps the efficiency at a satisfying range, but the PV/T collector proposes a good approach for applying solar with the best overall efficiency. In the present decade, several studies and development projects regarding PV/T technology have been conducted with an uprising range of activities. Some of the attractive advantages of the PV/T technology are [114]:

- Dual-purpose: could deliver electricity and heat at the same time;
- Efficient and flexible: the cogeneration efficiency is more than separated systems, which make PV/T very attractive, especially for rooftops with limited space;
- A wide range of applications
- Low-cost and practical: PV/Ts are easy to retrofit/integrate
- Types for PV/T collector

The design of PV/T systems may differ regarding their applications, which are mainly domestic hot water systems, air-conditioning systems for building, and cooled PV concentrators. The global market for thermal and PV solar technologies is overgrowing and has now reached a very considerable size. The technical feasibility of PV/T technology is demonstrated to be significant, and its other advantages for PV/T similar development can be predictable. PV/T, other than domestic heating, has a wide range of applications such as glazed PV/Ts and for marketing purposes like ventilated PV to preheat air throughout the winter to heat the area and afford a force for natural ventilation throughout the summer. There are several forms of PV/T system based on the type of PV plate, design specifications, heat absorber fluid (water/glycol or air), and also the concentration of the income sunrays. Hence, PV/T products could be categorized as [10, 115]:

- Liquid PV/T collector
- Air PV/T collector
- PV/T concentrator

2.5 Conversion of Thermal Energy into Mechanical Power

PDR systems can produce electricity from a central power converter that harnesses the absorbed sunbeams from individual receivers and transport it through an HTF to the energy conversion systems such as the Stirling engine (Fig. 9) [58, 116, 117]. The PDR or Dish Engine focuses the light coming from the sun through a focal point receiver. The mentioned reflectors could be facetted-segmented surfaces or a single parabolically shaped surface manufactured in a forming operation[118]. The mounting structure is dependent on the type of reflectors, which are implemented. The system needs to be tracked in a two-axis way continuously as the concentrated sun lights are directed through a receiver at the single focal point. The receivers that are used the most include Sterling engines; though, PV plates, heat pipes, micro-turbine, and other engines have also been included [77] .Therefore, the most potential is in the dish engines, as one of the PDRs holds the highest record for the highest solar to electricity efficiency with 31.25% [119]. If we use the 2-axis tracking mechanism, dish engines are capable of capturing the highest amount of solar energy, attaining optical efficiencies around 94%, and concentration ratios in the ranges between 500-2000. If a concentration ratio is 500, the stagnation temperatures would be near 1285 °C [94]. If we use the correct materials, reaching temperatures of above 1000 °C are possible [120]; One manufacturer of a 25 kW Dish Engine agrees that their system could produce around 60,000 $kWh.year^{-1}$, besides if we could find a good desert location, using dishes which are situated every 500 m^2 would equate to a power average of 14 $W.m^{-2}$ [121].

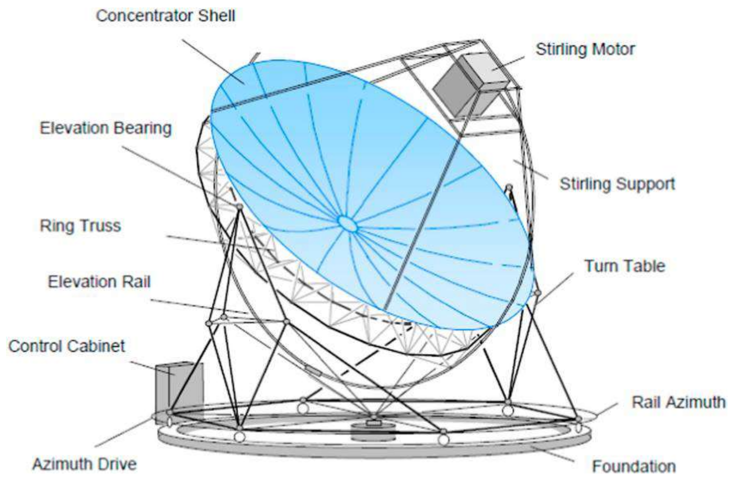


Fig. 9 Dish engine coupled with Stirling engine [58]

The concentrating solar thermal collectors integrated with CHP plants have been investigated extensively in the recent decade. These studies are mostly focused on evaluating the concentrating collectors for various applications [122]. In recent years, the Organic Rankine Cycle (ORC) has turned into a promising way as a small-scale energy system. Using solar ORC has many advantages, such as reducing the emission of Carbon monoxide (CO), Carbon dioxide (CO_2), and other polluting gases that cause global warming and environmental problems. Besides, ORC could be integrated with different types of low-density thermal sources for power generation. In the early 1970s, the study of the solar ORCs started both theoretically [123, 124] and experimentally [125]. Wolpert et al. [126] has examined a low-temperature solar ORC system for generating electricity. Delgado-Torres et al. has investigated the ORC system integrated with a different type of stationary collectors, which includes flat plate collectors, evacuated tube collectors, and compound parabolic collectors [127]. In this research, twelve different substances have been used as the operating fluids for ORC. Helvaci et al. [128] has studied a thermal system experimentally by utilizing a flat-plate collector as a thermal source of the ORC.

3. The Hype Cycle Model

Although various approaches through qualitative or quantitative bases have been employed by the researchers for assessing technology development, in this research, as mentioned earlier, TLC, adoption curve, and hype cycle have been applied. Knowing the current state and developments of TLC has advantages in estimating the future of technology development and evaluating investment decisions[129, 130]. The S-curve is the prevailing approach to the analysis of the TLC that observes patent applications that are made throughout the time. The adoption curve, which shows sales volume or revenue pictured against time as a bell-shaped curve with recognizable stages representing the introduction, growth, maturity, and decline of the product [131, 132]. The hype cycle model could be made by adding these two different relations/curves after Hubert Delay, which shows the shape of the hype curve for the latest technologies, as represented in Fig. 10 **Error! Reference source not found.**[21, 133, 134].

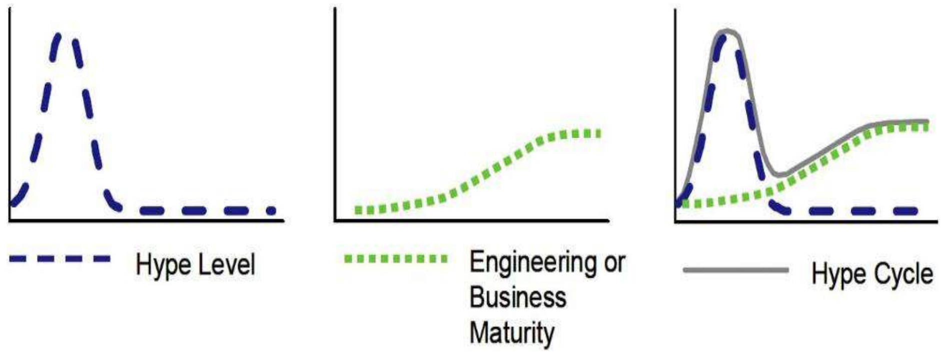


Fig. 10 Two curves which form Hype cycle [135]

The hype cycle model, which Gartner Inc. introduced in 1995 [136], explains the path that generally a technology has to undertake. One of the best approaches for merging the concepts of S-curve and adaptation diagram is the Hype cycle. This tool introduces a visual demonstration of maturity and acceptance of technologies and shows the potential of these technologies to address different business issues and affect the culture of the community (Fig. 11). The Hype Cycle provides an understanding of how technology develops with time, impacts the community, and offers a suitable source of visions to manage the execution of specific business targets. The curve includes five key areas [136]:

1. *Technology trigger*: When a technology is announced or demonstrated, it triggers the cycle. People's awareness about the technology starts to rise, and it attracts the coverage of the first media. Venture Capitalists and adopting companies try to capitalize on possible first-mover advantages.

2. *Inflated expectation peak*: this phase is usually known by high expectations boosted or excited, especially because of media coverage. As a result of a bandwagon effect, companies are willing to invest without even having a clear strategy.

3. *Trough of disillusionment*: due to the overenthusiasm and the investments that are hyped, the technology is going to face commercial adaptions that are not exact according to performance or revenue expectations. The disappointments are going to spread rapidly and negatively hyped by the media this time.

4. *Slope of enlightenment*: after a while, a few of those first investors who continued with the technology start to see some net benefit and get their motivation back once again. With the arrival of more investors, the understanding of the new technology grows, resulting in better performance. This is when technology starts to be socialized.

5. *Productivity plateau*: the technology is valued realistically. Due to the thriving market demonstrations, we have the acceleration of the adaptation.

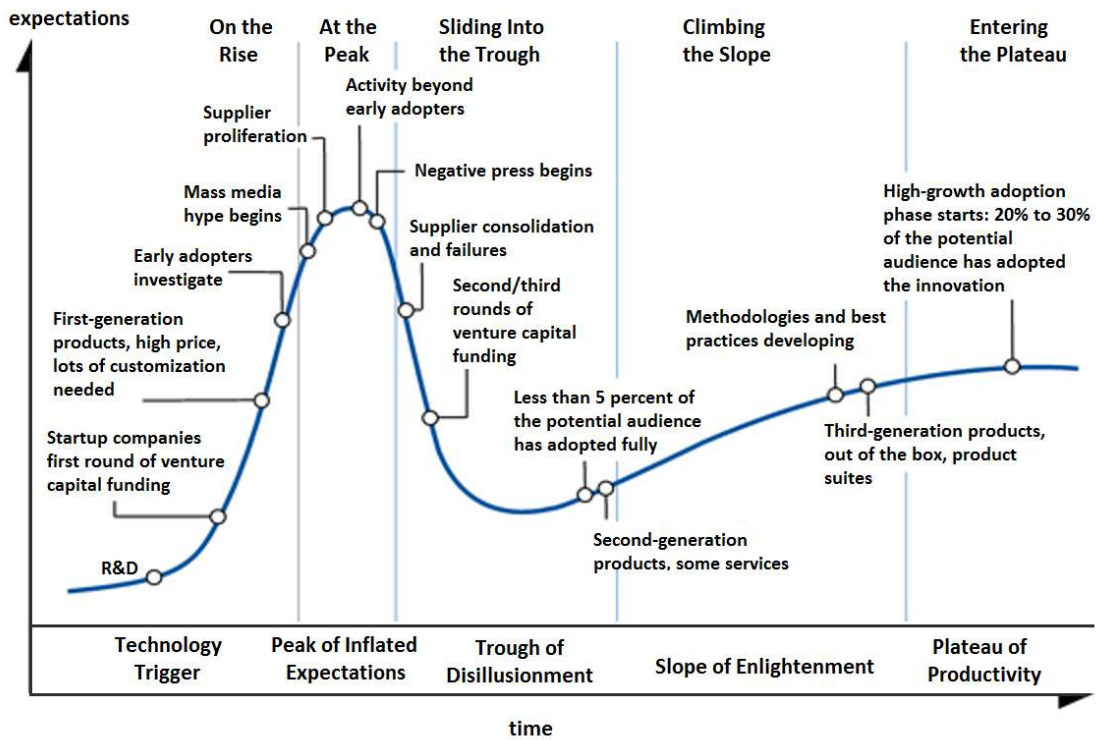


Fig. 11 Hype cycle and its standing indicators [136]

In the literature, the hype cycle has been used for the study of various technologies, of which some are reviewed here. One of the very early studies is the one by Fenn and Raskino [136], who analyzed the best way to identify the novel innovation at the right moment. They discussed the definition of the hype cycle comprehensively. In their study, they determined a methodology for analyzing technologies with a hype cycle. Konrad [137] studied the hype-disappointment cycles by assessing the hype cycle over the life cycle of electric-commerce and interactive television. Jarvenpaa and Makinen [138] conceptualized a framework for the hype cycle. They analyzed the MP3, Blu-ray, and Bluetooth technologies in the LexisNexis by considering bibliometric as an indicator. There has been extensive prior research either in conceptualizing the hype cycle or applying this approach to other technologies concerning their future development. In the renewable energy context, the application of TLC and the hype cycle is at an increasing pace. Jamali et al. [19] implemented the TLC to determine the expediency of the operational industries and PV technologies. They used the PV generation to determine the future path of each technology in addition to their current situation in the technological development cycle. The number of patents has been used as an indicator in their research. Ruef and Markard [139] investigated the influence of changes on the expectations of novelties on fuel cell technologies, particularly the stationary ones. Konrad et al. [140] considered the hype cycle as a decision-making tool at organization and innovation systems model. They studied its importance in the field of stationary fuel cells. A new approach has been discussed by Jun [141] for the experimental assessment of the hype cycle system. The search traffic was used for assessing the hybrid cars hype cycle as a case study in this research. In fact, Jun [141] used search traffic of hybrid cars and their market share to depict the hype cycle. Khodayari et al. [142] assessed their hype cycle of energy storage technologies by combining the search traffic and TLC. They used Google trend and patent data. In renewable energy technologies, biofuels and hydrogen have been assessed by Aslani et al. [143] and Dehghanimadvar et al. [144]. Scrutinizing the literature reveals the shortcomings in technological assessing other renewable energy technologies. To this extent, this research aim is to first evaluate the technological development through patent analysis and TCL. Then, by obtaining the search traffic, estimates the current situation of each discussed solar thermal technologies in the hype cycle.

4. Methodology and Approach

To analyze the solar thermal technologies, adequate, reliable, and relevant data is required. As aforenoted, two main data are utilized in this research: patent and search traffic. Although patents are almost often accessible, extracting a related patent to the considered topic always is tricky. Top firms in the field try to protect their innovation by patenting. Nonetheless, the patenting procedure requires publishing them. Therefore, the availability of patents in a public way may not be suitable in the completive markets. Thus, to find the patent, in addition to related keywords, codes are also required. The code, here Cooperative Patent Classification (CPC), is a unique system for classifying the patent in related groups and subgroups. To get rid of noises in the extracted database, both codes and keywords should be employed. By noises, it means the patents which are not related to the topic. Fig. 12 shows the research framework. After recognizing solar thermal technologies through an in-depth literature review, all of the technologies will be searched by their names. The obtained data then were screened thoroughly by CPC codes to avoid any noises, which will be discussed further. Currently, various online patent search databases are available. Nevertheless, in this research, Patentinspiration[1] is used due to its broad database, which is based on the European Patent Office (EPO) Documentation Database (DOCDB) with worldwide coverage [144]. Although the other patent online databases are available such as the United States Patent and Trademark Office (USPTO)[2], the European Patent Office Espacenet[3], PATENTSCOPE[4] and other ones, we found Patent inspiration more user-friendly in search engines. This feature enables us to search with CPC codes. The level of detail CPC provided leads users to specifically choose their technology. Compares to International Patent Classification (IPC) codes, CPC allocates entire groups of codes to renewable energies.

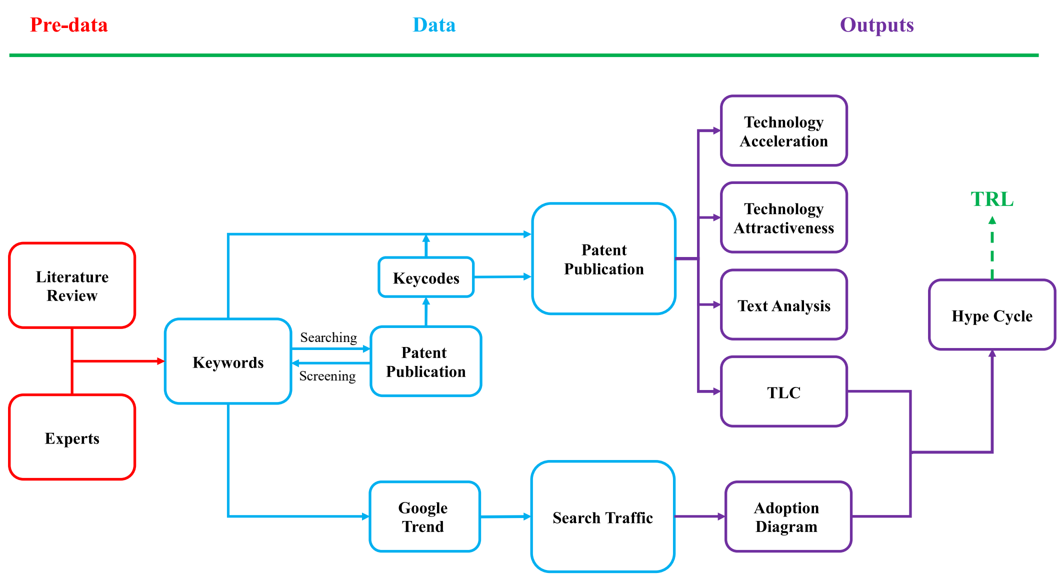


Fig. 12 The research framework utilised in this study

To be more accurate, each technology should be patented by a specific CPC code. Sometimes there are two or more CPC codes assigned to the particular technology. Besides, the allocated code to the technology may have some applications in other technologies that are not relevant to what is looking for. Therefore, combinations of codes and keywords could be the case[24]. Table 1 shows the CPC codes and related keywords that have been for searching each solar thermal technology. There are two exceptions, as can be seen in Table 1, “Dish Collectors” and “Flat Plate Collectors.” The specific code that describes the “Dish Collectors”

[1] https://www.patentinspiration.com
[2] https://www.uspto.gov/patents/search
[3] https://worldwide.espacenet.com
[4] https://patentscope.wipo.int/search/en/search.jsf

is already existed. Deep screening and analysis prove that all extracted patents under "Y20E10/42" are related to this technology.

Table 1 The CPC codes and keywords for solar thermal technologies

Technology	CPC	Description
Rankine Cycle	Y02E10/46 + F03G6/003	Conversion of thermal power into mechanical power, e.g., Rankine, Stirling solar thermal engines + having a Rankine cycle
Stirling Cycle	Y02E10/46 + Keywords	Conversion of thermal power into mechanical power, e.g., Rankine, Stirling solar thermal engines + "Stirling cycle" OR "Stirling machine" OR "Stirling cycle engine" OR "Stirling engine" OR "Sterling cycle" OR "Stirling thermodynamic cycle" OR "Stirling-cycle" OR "Stirling cycle machine" OR "Stirling machines" OR "Stirling engines" OR "Stirling cycles"
Brayton Cycle	Y02E10/46 + Keywords	Conversion of thermal power into mechanical power, e.g., Rankine, Stirling solar thermal engines + "Brayton cycle" OR "Brayton cycles" OR "Brayton cycle engine" OR "open Brayton cycle" OR Brayton OR "Brayton-cycle"
PV/T	Y02E10/60	Thermal-PV hybrids
Parabolic Trough Collector	F24S23/74 + Keywords	with trough-shaped or cylindro-parabolic reflective surfaces + "parabolic collector" OR "compound parabolic reflector" OR "parabolic cylinder reflector" OR "parabolic concentrator" OR "parabolic trough reflector" OR "parabolic trough" OR "parabolic cylindrical mirror" OR "parabolic cylindrical reflector"
Dish Collectors	Y20E10/42	Dish collectors
Fresnel Lenses	F24S23/30 + Keywords	Arrangements for concentrating solar-rays for solar heat collectors with lenses + "Thermal" AND "Fresnel Lenses"
Heliostat Field Collector	F24S2050/25 + Keywords	"Calibration means, Methods for initial positioning of solar concentrators or solar receivers" + "heliostats field"
Flat Plate Collector	Keywords	("flat-plate collector" OR "flat-plate type")
Evacuated Tube Collector	F24S10/45 + Keywords	in absorbing elements surrounded by transparent enclosures, e.g., evacuated solar collectors "the enclosure being cylindrical" + "evacuating tube" OR "vacuum connection tube"

In this research, patent publications are considered since patent publication indicates the evaluated patent. The other term is a patent application. Every year, a relatively large number of documents are filed as a patent. The term patent application is used for such documents that have not been assessed yet. When all related patents to each solar thermal technology have been extracted, an analysis will take part. Besides technological trends, a patent can provide valuable information about the value and importance of technology. To this extent, technology acceleration, technology attractiveness, and top patents in terms of family patent and citation are discussed. Deep text analysis has been done to determine the keywords that are mostly repeated after "problems" and "drawbacks" in the patent. The mentioned extracting website has recommended these keywords. After all, the technological trend of each solar thermal technology with the help of extracted patent publications are drawn. In the next step, the technology penetration in the market should be assessed. An objective analysis of technology adoption is conducted using a macroscopic methodology that overcomes the limitations of survey-based approaches, followed by a shift away from the conventional focus on technologies and instead looks at the market from the perspective of industry players. To better understand how upcoming technologies are adopted, we focus on search traffic, which we argue will provide better insights. Besides providing information about consumers' behaviour, search traffic also provides macro-level information about the entire population. Most of all, search traffic is a method worth exploring due to its economic advantages in terms of time and expense. This study examines a method of utilizing search traffic to understand how technology adoption is determined and the wealth of data that industry players are unconsciously leaving behind.

For this purpose, global search traffic of each technology is extracted by employing the Google trend. Finally, by employing the adoption diagram after indicating TLC locations, for the very first time, the hype cycle of solar thermal technologies has been curved. After all, to validate the combination of the S-curve model and adoption diagram, or in other words, the technology status in the hype cycle, the Technology Readiness Level (TRL) is employed. Two assumptions are considered for this methodology, first, the patent trend represents technological growth and second, the Google trend shows technological penetration. Although they are well-known assumptions, to examine them, other patent features, as explained previously, are taken into account, which is technology attractiveness and technology acceleration. As noted earlier, TRL is used to validate our results through these assumptions.

5. Results and Discussion

The total number of the extracted patent for by discussed methodology is 8760. All the patents can be categorized into eight groups of technology. Each technology has been discussed earlier. The first result of investigating the published patents in solar thermal technology domains is illustrated in Fig. 13. As is obvious, PV/T, with more than 50% number of patents, is the hottest domain in solar thermal technology.

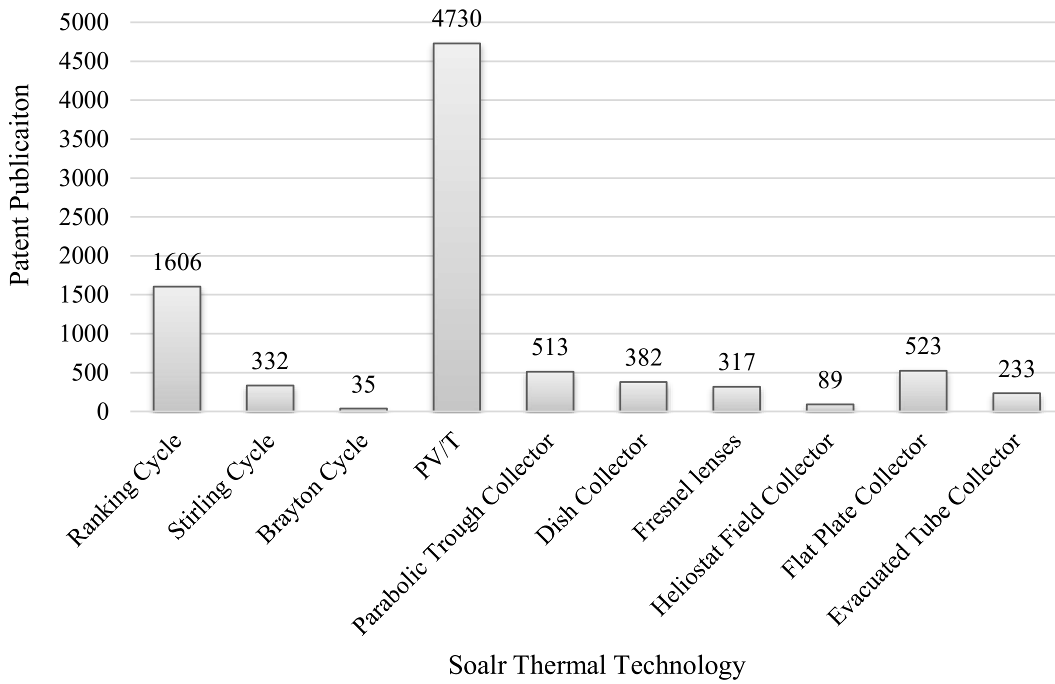


Fig. 13 Patents distribution in the solar thermal technology domain

Converting solar irradiation to mechanical energy and further to electricity has a considerable number of published patents among solar thermal technologies, except PV/T. One of the main reasons that converting solar irradiation to mechanical energy has been paid lots of attention by firms could be electricity which is the most applicable form of energy. One of the most common and competitive ways for converting solar thermal to mechanical and then to electricity is to use the Rankine cycle. The aim of using the Rankine cycle is to convert solar energy to a mechanical one for further usage. However, this convertion can reach to 70% [145]. As like other renewable-based technologies, capital and operation costs of cycle design are the main issues. A parade of researchers has been working on the technical issues and finding the solution for various challenges; however, from the economical point of view, advanced work should be done to make this technology more affordable for local and global markets [146]. The other technology for converting solar thermal to mechanical power is the Stirling cycle. In solar-based power generation, the Rankine cycle using liquid metal has the highest efficiency. While the Stirling cycle is going to be commercialized, some barriers should be solved. The efficiency problem of this technology has been discussed throughout the decades. The researchers have made lots of efforts to increase the efficiency of the Stirling cycle [147]. The other competitive cycle in terms of efficiency for converting solar thermal power to mechanical work is the Brayton cycle. The lower cost of the Brayton cycle in where microturbines are used can demonstrate this technology as an efficient technology. Using air as a working flow in the open Brayton cycle is one of the applicable benefits, specifically in water-scarce countries [148]. Nevertheless, the Brayton cycle is one of the most considerable power generation systems and promising technologies for near-future space application. The ability of multiple starts brings up the idea to have long time reliability [149]. Capturing heat and photon from sunlight at the same moment would be a beneficial idea.

The PV/T is the second-highest published patent in solar thermal technologies. During past decades, this technology got greater attention by researchers due to having a feature of harvesting energy in various thermal and electrical ways [150]. It is significantly discussed by researchers, while temperature increases, the output of photovoltaics solar cell will be decreased. However, cooling down the system in PV/T can enhance the overall output. To maximize the harvested thermal energy from the sun, recently using nanofluids and phase change material are raised. One of the most primitive and common solar thermal technology is flat plate collectors. About 6% of the total published patent assigned to this technology. For domestic application, the idea of using flat plate collectors is so simple, the dark plate with the pipes in which transfers the solar irradiation energy to water, air, or other fluids. Fig. 13 illustrates the trend of published patents in each technology in the past 20 years.

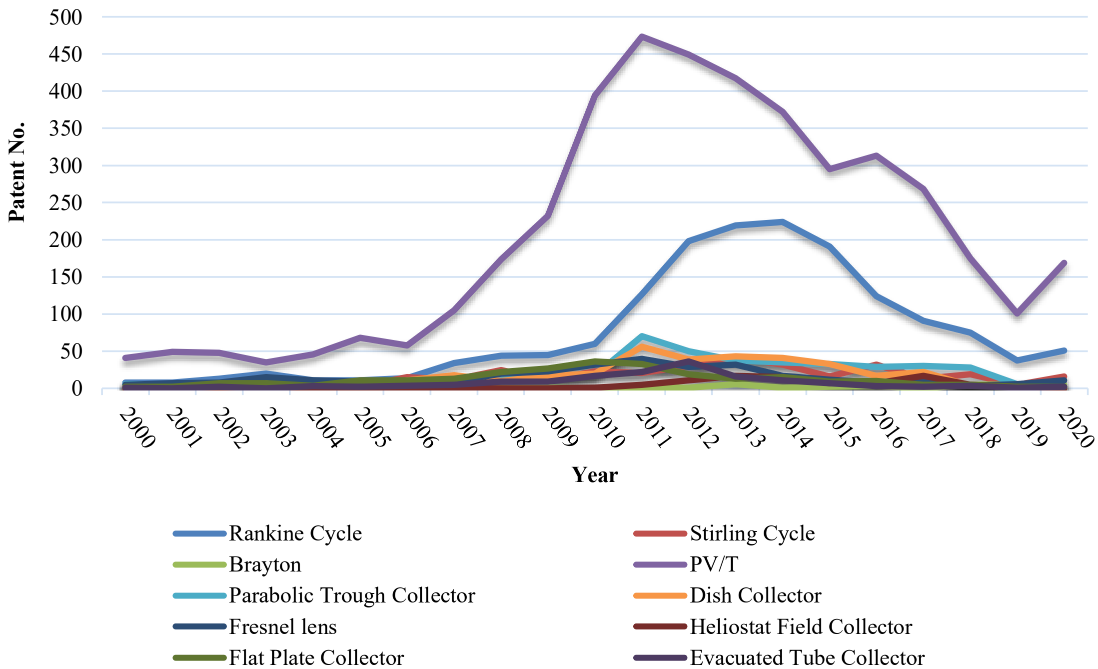


Fig. 14 Solar thermal technologies patent trends

The solar thermal technologies patent trends are mostly dominated by PV/T followed by Rankine cycle, Fig. 14. The historical patents data and the current situation of each technology could be helpful for policymakers or researchers to determine the best path for the future. One of the considered technologies is the technology of converting solar thermal power to mechanical power. As is discussed earlier, Rankine, Stirling, and Brayton cycles play a critical role in this domain. The Rankine cycle technology can produce electricity on a wide scale of watts to megawatts. This versatility makes it a reliable technology for further usage. The installed capacity of the Rankine cycle peaked at 1700 MW in 2013, which was an effective stride for the development of this technology [151]. Although Rankine cycle technology has experienced a decline in published patent, this technology is receiving significant industry attention, which will be discussed in the following. Depending on factors such as condenser pressure (as determined by ambient temperature) and regenerative feedwater heating and pressure, the converting efficiency of power cycles will change slightly. For instance, when reheat is used in a steam Rankine cycle, higher turbine inlet pressures are achieved without compromising the quality of steam (higher moisture)[152]. In terms of efficiency, Stirling engines held the record for using solar energy to generate power at 31.25%[153]. Possibly as a non-solar problem: Stirling engines haven't penetrated enough markets to fit in with low costs and reliability. Recent attention has shifted to integrating storage by using PCM, though[154]. However, like other renewable-based technologies, capital and operation costs of cycle design are the main issues. A parade of researchers has been working on the technical issues and finding the solution for various challenges; however, from an economical point of view, advanced work should be done to make this technology more affordable for local and global markets.

To find out which solar thermal technology is more attractive to the industry, three factors are introduced, namely; technology attractiveness, technology accelerations and TLC. Using these factors simultaneously will result in a more accurate hype cycle. One of the advantages of using these factors, since they are complementary to each other, is the consistency in the result. The industry tends to invest in technologies that already have or will gain market share, or in other words grants the intellectual properties that will result in profitable commodities or services. Thereby, the ratio and also rates of granted patents to published ones can be an important factor to depict the solar thermal technologies' hype cycle.

The first factor is the ratio of granted patents to the published ones. The patent protection requires considerable payment through its 20-year life. Thus, the ratio of granted patents to total patents in that specific technology determines the value of that technology. This ratio for each solar thermal technology is presented in Fig. 15.

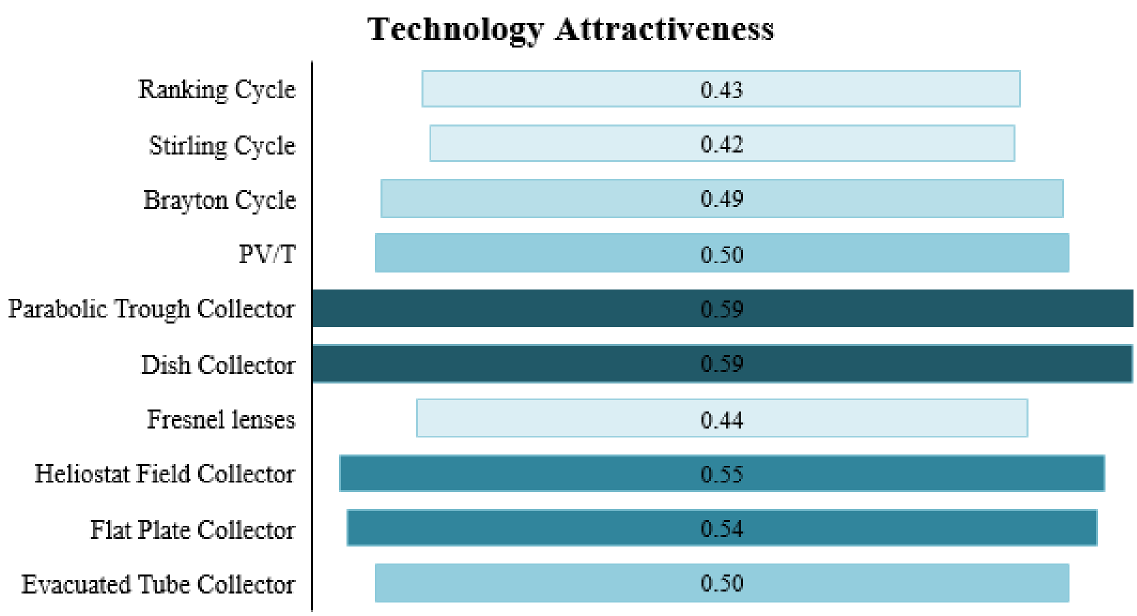


Fig. 15 Solar thermal technology attractiveness

Two technologies have the highest ratio of granted to published patents, which are parabolic trough collector and dish collector. Previously, it is determined that the highest number of published patents related to PV/T and Ranking cycle, which their technology attractiveness results are 0.50 and 0.43, respectively. Alternatively, in other words, only 50%

and 43% of total published patents in PV/T and Ranking cycle technologies got granted. Two arguments can be raised.

- First, although the attractiveness ratio is higher in dish collector technology than PV/T, fewer efforts have been made in this technology. Thus, the PV/T is more attractive than the dish collector. The number of the granted patents in PV/T technologies is 2373, but the sum of this number in all other technologies is 1956. Therefore, it can conclude that more investments are being taken place in PV/T technologies compares to other ones.
- Second, in the very first era of emerging dish collector technology, a patent might be granted, and by emerging of new technologies, the granting process has been slow down and slipped away. Thus, still, the ratio of granted to published patent is high for dish collector technology.

To answer these arguments, analyzing the acceleration of granted and published patents in the last ten years could be the case. To obtain the technology acceleration, a regression of the granted and published patents is required. For simplicity, the best linear regression is used; hence, the slope of this regression can determine the acceleration of the technology. Fig. 16 shows the result of the technology acceleration of various solar thermal technologies.

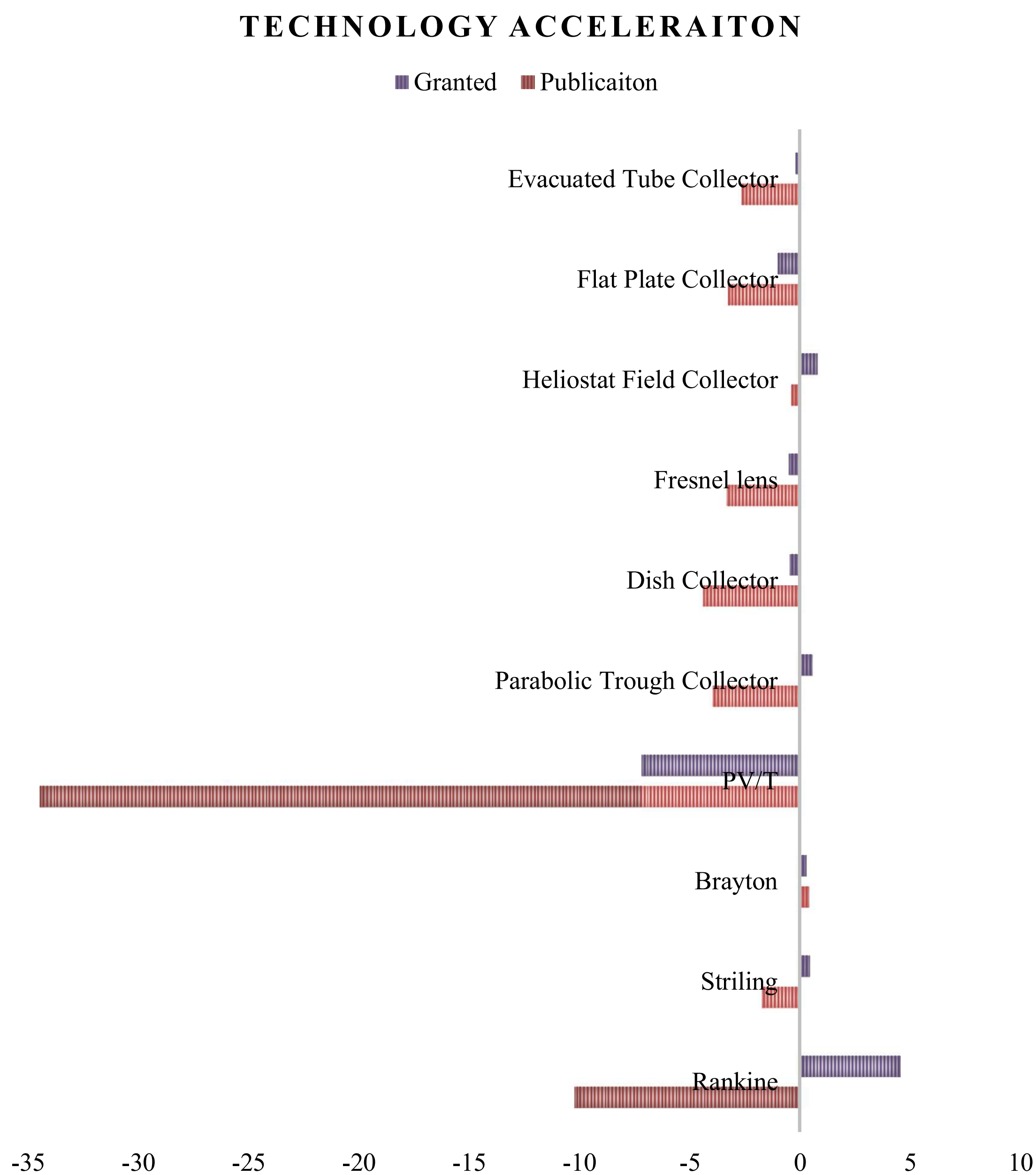
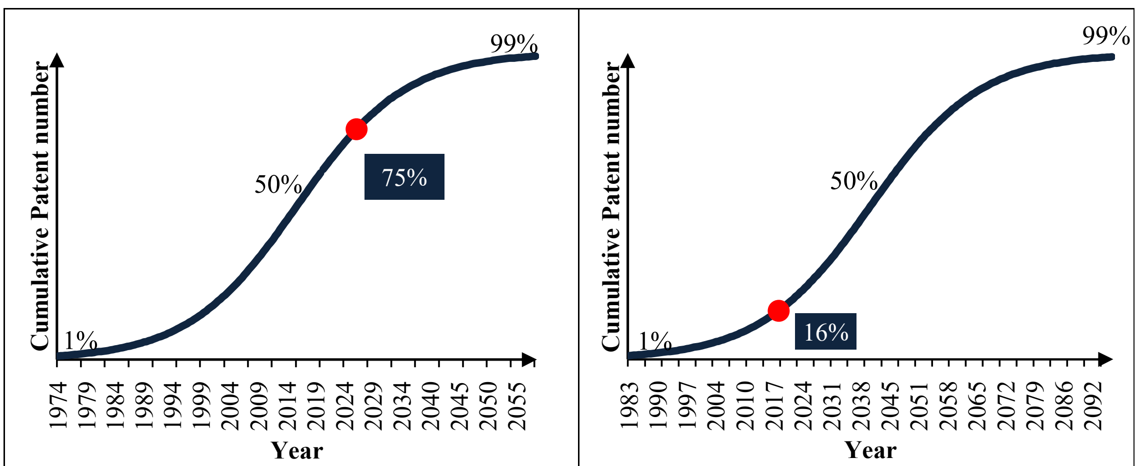


Fig. 16 Technology acceleration of solar thermal technologies

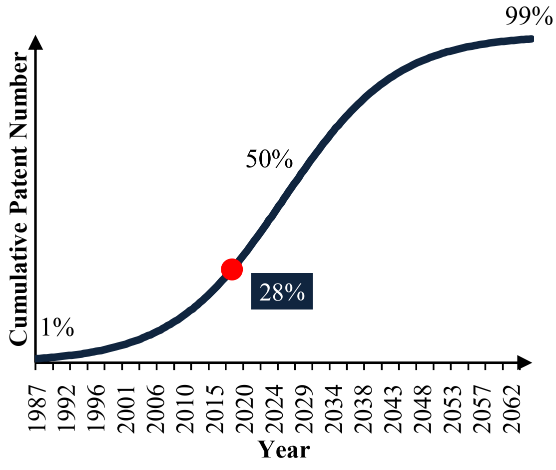
All solar thermal technologies have negative acceleration in publishing patents through the last ten years, except the Brayton cycle. The PV/T technology experiences the largest downward slope in both, number of published and granted patents in the past ten years. On the other hand, technologies that convert solar irradiation to mechanical energy and further to electricity show a positive acceleration in the granted patents. Among thermodynamic cycles, only the Brayton cycle has positive acceleration in granted and published patents. According to the mentioned arguments, between dish collector and parabolic trough collector, due to having positive acceleration in granted patents, parabolic trough collector has a better condition for gaining attention by industry. The obtained results are without bias and are representative of the technological assessment of solar thermal technologies by considering patent data. The value of published patent trends will be more discussable when are considered in the TLC platform. To this extent, the next sub-section is analyzed the TLC of solar thermal technologies.

5.1 Technological Life Cycle Analysis

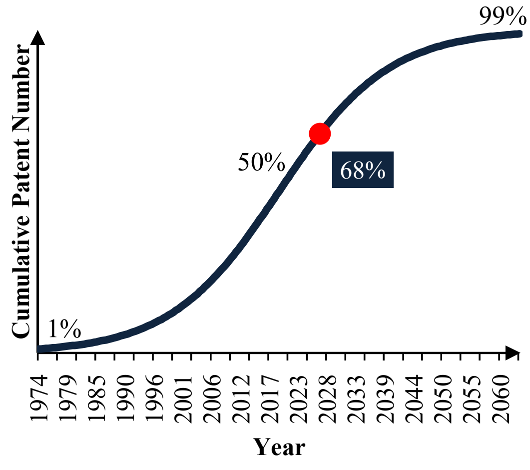
Technological forecasting can bring up insight into the future if not even shape it. The three main stages in the technological life cycle, as is stated earlier, are emergence, growth and maturity. Technology in each state demonstrates a specific condition. In this research, the emergence state indicates from 1% to 30%, while the growth phase starts at 30% to 80%. Finally, the maturity phase locates within 80-100% interval. The percentage ranges are validated with the TLC curve. The results are shown in Fig. 17. The first analyzed technology is the Rankine cycle and shows that the Rankine cycle technology is in the growth stage. Reviewing various applications of Rankine cycle technology popped out the fact that the main contribution of this technology is on the water base instruction. Using a water pump in an arid or remote area for irrigation or providing required water for living respectively. Harvesting adequate electricity to drive water for further usage belongs to many years. The advantage of using this system for pumping water besides using solar free energy is the low cost of maintenance and construction [146].



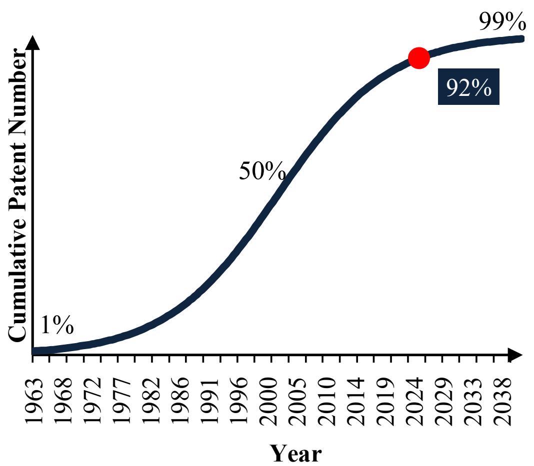
Rankine cycle | Brayton cycle



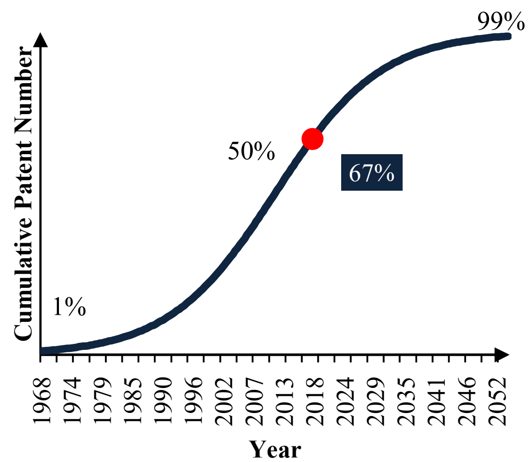
Stirling cycle



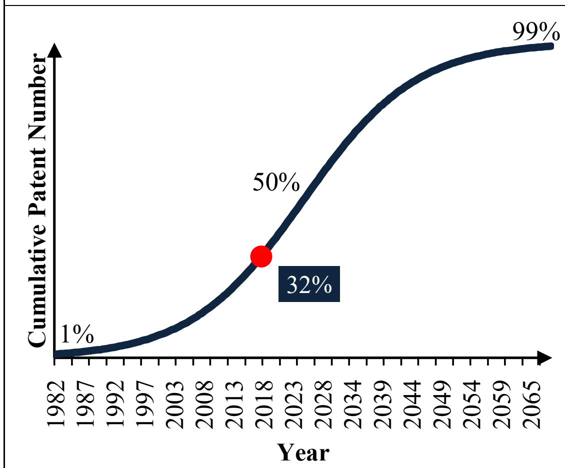
PV/T



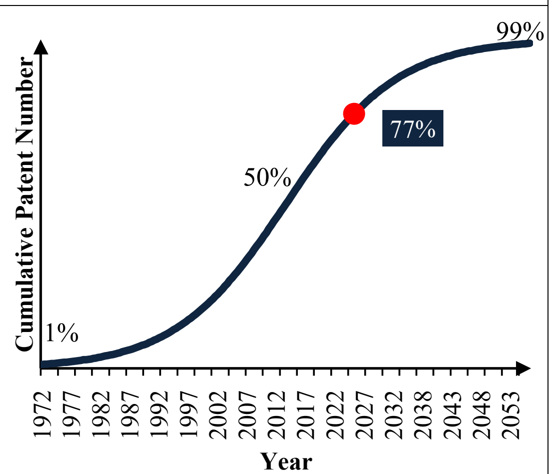
Parabolic through collector



Parabolic dish



Fresnel lens



Heliostat field collector

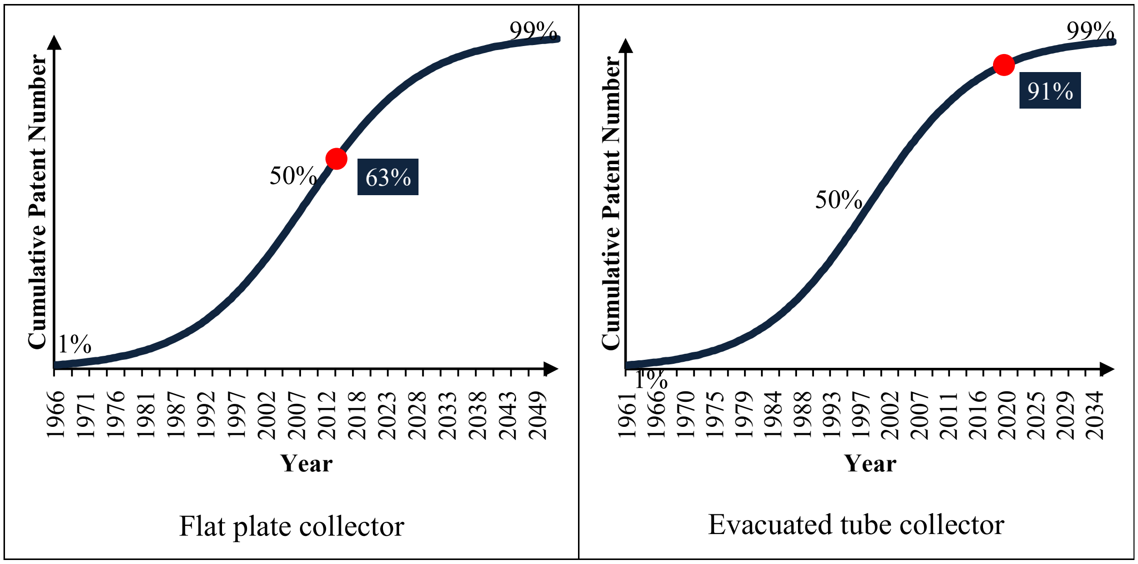
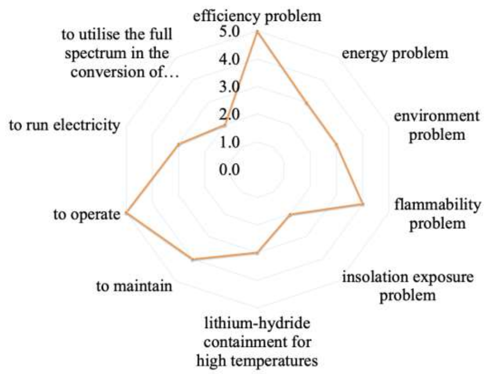


Fig. 17 Technology life cycle of solar thermal technologies

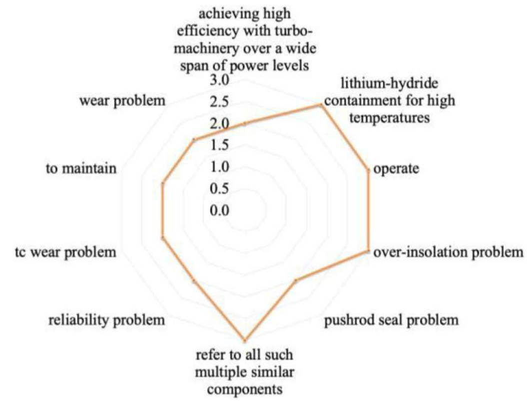
Fresh water production by using reverse osmosis water desalination systems is the other usage of the Rankine cycle in water base construction. While fresh water is one of the main challenges in the near future, finding an appropriate approach to face this challenge is crucial.

Using solar thermal energy to supply fresh water through reverse osmosis water desalination systems has been paid much attention recently [146]. The shortcomings of Rankine cycle technology have been reviewed in vast of research [145, 155-158]. Nonetheless, in this research, text analysis has been applied to the patent pool by utilizing the mentioned website text mining tool. The combination of "phrase + problem" and the number of times they repeated in the patent pool could be an efficient way to find the pattern of key issues. The text analysis gives a broad insight into the main challenges in solar thermal technologies. Alternatively reading each extracted patent can lead to the same figure, it may take a lot of time to have the results though. This analysis can help researchers or policy makers to recognize the main problems in technology commercialization and choose the right direction.

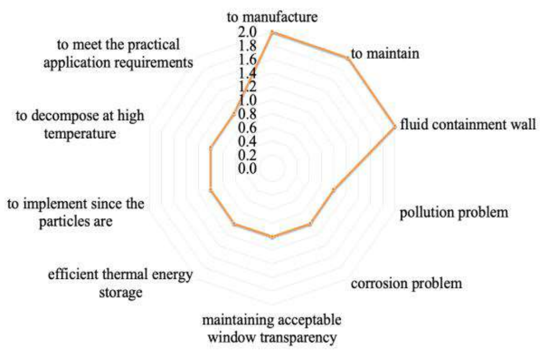
Fig. 18 shows the results of solar thermal technologies patent pool text analysis.



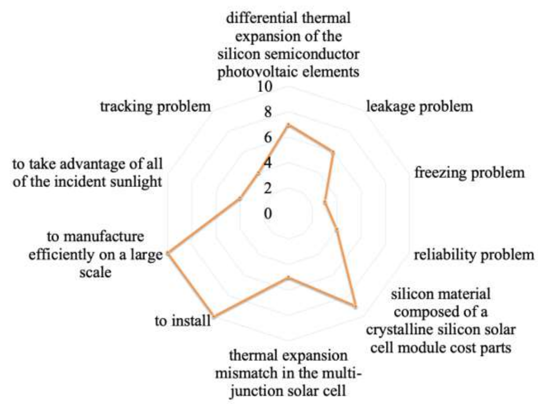
Rankine cycle



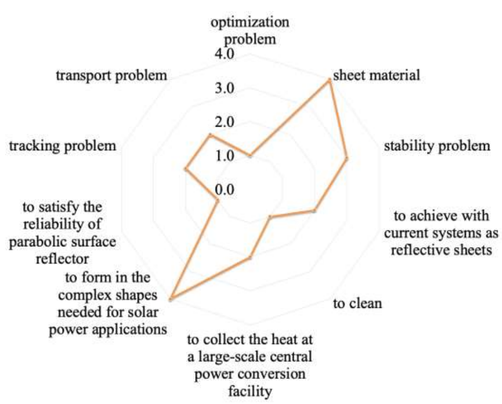
Stirling cycle



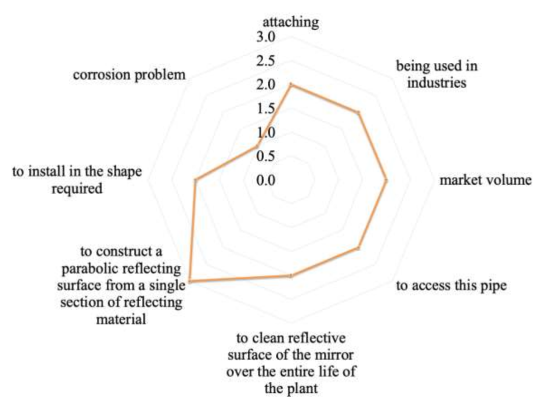
Brayton cycle



PV/T



Parabolic through collector



Parabolic dish

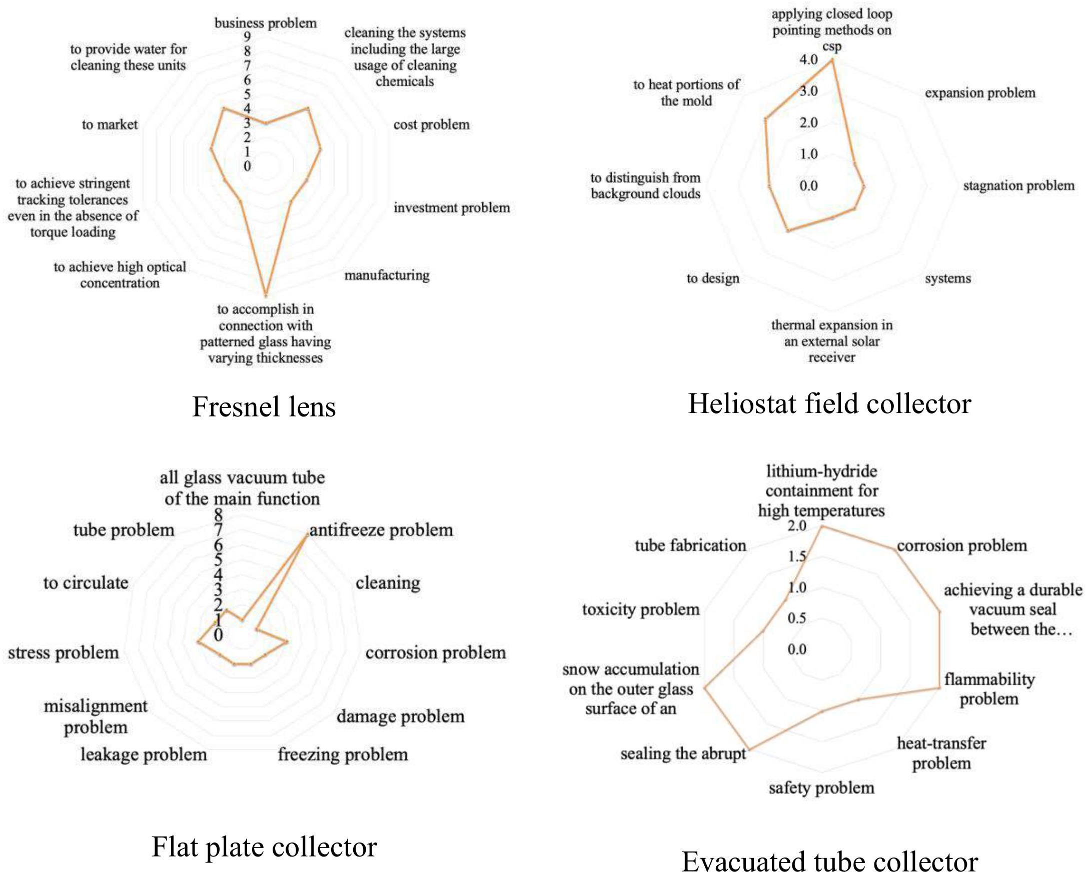


Fig. 18 The text analysis of solar thermal technologies patent pool

Scrutinize the current literature validates the obtained results. The safety consideration related to work fluid for the Rankine cycle has been discussed in most previous studies. The properties of working fluid play an essential role in the power output of the Rankine cycle [159]. In one of the early works in selecting the working fluid by Badr et al. [159], the required criteria for ideal working fluid were discussed. They showed that cost and safety requirements plus availability, thermal stability, and thermodynamic appropriateness are the primary factors for selecting the working fluid. Followed by Badr et al. [159], many researchers have been working on the working fluid [160-162]. In terms of safety consideration, non-flammable, non-explosive, and non-toxic are the main factors. The other two phrases with high frequencies are related to efficiency and operation. Working fluid has also an impact on efficiency and operation. A bad selection could result in low efficiency and expensive operation [157]. The lithium hydride has been gaining attention in the past decades for use as phase change material. The main drawbacks of this material are low thermal conductivity, sub-cooling, and flammability [163]. Besides the Rankine cycle, converting solar irradiation to mechanical energy and further to electricity includes Stirling and Brayton cycles. The TLC of Stirling and Brayton cycles figures are presented in Fig. 17. Accordingly, the current state of both technologies is the emerging phase. Nonetheless, the Stirling cycle is near to pass this stage and enter the growth phase. Integrating solar thermal energy with the gas turbine, Stirling, and Brayton cycles are more recent compared to the Rankine cycle. The shortcomings of the Rankine cycle's low efficiency with a renewable resource, which is limited by the working fluids, provide opportunities for gaseous turbines [164]. Using the supercritical CO_2 Brayton cycle more in spaceships might be one of the reasons for less development compares to the Stirling cycle. The advantage of high efficiency in a compact equipment size renders this opportunity [165].

On the other hand, the Stirling cycle has the highest efficiency among solar thermal power generations by converting nearly 30% of solar irradiation to electricity [166]. This advantage becomes more considerable by the fact that this technology requires lower cost with flexibility from kWs to 100MW [167]. To illustrate the main challenges in these technologies, the text analysis radar diagrams of Stirling and Brayton cycles are shown in Fig. 18. The two highest repeated issues are in common in Rankine and Stirling cycles. Employing phase change material, lithium-hydride, as storage material have been discussed in both technologies by researchers. A computational fluid dynamics study of phase change material for short duration storage systems in dish receivers of Stirling cycle has been carried out by Giovanelli et al. [168] following studies are more considering the optimization modeling than experimental ones [169]. Similar to the Stirling cycle, the Brayton cycle is more considered theoretically in literature than experimentally. The manufacturing challenges of the Brayton cycle can explain by the high pressure and temperature of system operation plus the complexity of system components [164]. The other challenge that the Brayton cycle faces is to maintain the system in a stable condition. The load demand and heat input as transient parameters should be controlled to maintain the recompression cycle at the optimum level. Therefore, control algorithms should be developed for this matter. The phrase “fluid containment wall” refers to the working fluid containment wall that the crankshaft penetrates through this wall to connect to the motor or generator outside of the wall. The pressure and temperature inside the working fluid containment wall make the systems difficult to manufacture and maintain [170]. Utilization of rooftop or any suitable area to produce electricity and provide hot water at the same time for domestic or further applications has gained momentum. PV/T can be an ideal candidate for weak and small roofs as two separate solar thermal and photovoltaic panels are heavy.

The PV/T technology is in the growth stage. Investigation in southern Europe demonstrated that the required thermal and cooling demands in residential buildings could be supplied by this system[171]. Moreover, for ventilation and the pre-heated process by considering heating air by PV/T is another application of this technology. The idea of using fluid to remove the heat from PV is mainly for increasing the PV efficiency [172]. Thus, hybrid PV/T not only impact the PV efficiency but also can heat fluids for further usage. In terms of thermal efficiency, lots of research has been directed to assess the impact of the cooling fluid such as air [173-177], water [178-180], PCM [181-183] and heat pipe [184-187]. Although numerous investigations have been made to analyze the impact of fluid on the thermal performance of the PV/T, the thermal conductivity of the fluid is still a challenge. Applying nanomaterials could modify this issue [188]. Since the PV has been gaining much attention in past decades through promising achievement for the decarbonization economy [189], increase the efficiency at the lowest price could make a considerable impact in PV/T systems as well.

Building applications can benefit greatly from CPVT collectors[190]. Hybrid collectors are a reasonable option for meeting domestic hot water demands, possibly combined with space heating. Houses are the most common with collectors, but large systems for combined use are expected to increase the number of collectors in the future. In addition to meeting the thermal and electrical energy demands of industrial sectors, CPVT collectors are also capable of fulfilling those demands. The low energy density of CPVT systems, as well as their high location and environmental dependency, pose some challenges to their widespread adoption[191].

The main challenges are discussed in the related patent pool. The design and installation of these systems and the building requirements for this matter still need more research [188].

In patents, the issues related to installing the PV/T systems and how they should complement the architectural design of buildings have been discussed. As mentioned earlier, the fluid that is used in these systems has a critical role in thermal performances. One of the issues is the freezing problem in winter, which damages the collector, which can be solved by using PCMs. PCMs have many advantages compared to air and water [188]. According to the literature, leakage, thermal conductivity, and stability are the main drawbacks though [192]. Among various solar thermal technologies, concentrating solar is the most mature one. From medium to large-scale operation, these technologies are mostly located in Spain and the United States [193]. As is discussed earlier, concentrating solar technologies are categorized into four groups; parabolic trough collector, parabolic dish, Fresnel lenses, and heliostat field collector, which their TLCs are shown in Fig. 17.

Parabolic trough collector is the most mature technology among all others. The technology trend of the parabolic trough collector is downward. Indeed, this technology is commercialized, and the number of published patents started to decrease after 2012. Considering features such as promising cost-effective investment besides ease of combination with other renewable resources or even fossil fuels makes the future of solar thermal energy much brighter [60]. A vast of research has been carried out over the decades to enhance the efficiency of this technology. Nonetheless, the most efficient, known, and applicable way in heat and steam generation systems is the parabolic trough collector technology.

The results of the investigation in TLC of other concentrating solar technologies demonstrate that these technologies are near to the maturity stage. In the past two decades, various application of this technology has been tested. Using photo-bioreactors as well as photochemical reactions is one of the utilizations of Fresnel lenses technology [194]. The other applications of this technology are lighting and water pumping. Although the prototypes in small scales have been analyzed, the development is needed for further application on a massive scale. The concentrating solar technologies can compare by various features [195]. Heliostat field collector and parabolic dish are the most expensive concentrating solar technologies in terms of cost for development. The recent novel development in heat transfer fluid for achieving higher cycle efficiency introduces the heliostat field collector as a promising advanced power plant in terms of technology outlook. The piping system in heliostat field collector technology is reduced due to centralized whole piping; therefore, the other advantage of this technology is the low cost of construction and maintenance [195]. The main challenges that are being discussed in their patent pools are shown in Fig. 18. Design the parabolic trough collectors in terms of optic properties can impact the cost of this technology [196]. Due to this challenge, the shape of the reflector in this technology is discussed in the related patent. The phrases that are most repeated in terms of problems are related to the reflectors, even shapes, or the type of material to use. Parabolic dish collector literature shows the same dish design challenge. To achieve a uniform and acceptable irradiance distribution, design the rim angle remarkable impact the parabolic dish collector performance [197]. Since the Molten nitrate salts (KNO_3–$NaNO_3$) are used as heat transfer fluid and energy storage in high operating temperature results in a severely corrosive environment [198]. Hence, besides discussing in the literature [199-201], the text analysis results show that corrosion is an issue in the published patent of parabolic dish collector. The text analysis results of the Fresnel lenses technology patent pool shows that phrases with the highest repetition are related to the economics terms. The main advantage of the Fresnel lenses technology is the potential of overcoming the economic challenges of conventional solar concentrating technologies [202]. Literature supports the text analysis results for Fresnel lenses technology. Kumar et al. [202] discussed that the Fresnel lenses technology could reduce the total investment cost. To avoid trapping dust in the grooves, periodic cleaning is required, which is considered as one of the challenges [203]. The challenges in heliostat field collector technology are more on design and controlling the heliostats aiming point, according to Fig. 18. Flat plate collectors are one of the most studied solar thermal technologies. Domestic and industrial utilization of this technology are limite to in water heating or preheating flow or room heating. The simple idea behind the flat plate collector design and not stand in need of tracker reduces the complexity compared to other solar thermal technologies. The current state of the flat plate collector is the growth stage, howbeit; it has been mostly studied solar thermal technology. Various materials to enhance the thermal proficiency of collectors have been investigated through decades. While one of the challenges is the size of the plate, using nanofluid is suggested to provide the same output in the more compact size. Utilizing polymer to reduce the weight of the plate is the other issue that has been considered a lot [204].

Freezing issues in a cold climate is always a challenge in the flat plate collectors. Wei et al. [205] utilized heat pipes in flat plate technologies for the first time to overcome this shortcoming. Using heat pipes not only helps for better performance of this technology but also can modify the leakage issue between the water-cooling side and the solar heating side [206]. The current state of evacuated tube collector technology is maturity phase. The features such as being the most convenient and efficient in terms of performance make this technology popular. The cylindrical shape of the evacuated tube collector provides this apt quality as it traces the sun passively, whereas the flat plate solar can maximize its output only when the sun is at the top of the plate surface. It was also noted that in terms of maintenance, the evacuated tube collector is easier and inexpensive. Not required to shut down the system in evacuated tube technology while the tube is damaged is the other superiority compare to flat plate collector. In fact, in this situation, the system can continue its operation with lower deficiency [207]. The development of integrated collector/storage solar water heaters combined with PCMs has been a topic of extensive research and development over the past few years. The integration of PCM and evacuated tube collectors in solar cabinet dryers has been investigated by Iranmanesh et.al.[208]. Their research showed the system with PCM had the highest overall drying efficiency of 39.9%, which was greater than the system without PCM. It is also established that using PCM increases the value of the input thermal energy by 1.72%. in another research, Sekret[54] showed using Paraffin in the integrated evacuated tube collectors will increase the total amount of obtained heat by 45%-79%. To sum up, previous research on the impact of PCMs on evacuated tube collectors showed due to the variable intensity of solar radiation during the day, PCMs are used within evacuated tube collectors to maintain a constant water temperature for household use and significantly improved the thermal and energy efficiency. In addition to adding nanoparticles with high thermal conductivity, composing PCMs with porous media[209], adding fins[210], and encapsulating them[211] are the main approaches to improve heat transfer through conduction. According to the study conducted by Fan et.al.[212], nano-PCMs were enhanced nearly 1.7-fold with a 5.0 wt% load, leading to enhanced heat transfer efficiency. The photothermal properties of nanoparticles incorporated into paraffin have been studied experimentally and numerically by Yang et.al.[213]. Paraffin nanoparticles incorporated with ZnO or CuO were found to improve thermal conductivities by 5.87 and 13.12% respectively. These nanoparticles also improved the light absorption efficiency, resulting in higher photothermal conversion efficiency. Working fluid is the final determinant of the thermal functionality of evacuated tube collectors. The thermal performance of solar systems can be influenced by working fluids in either a positive or a negative direction. One of the significant disadvantages of using water as a working fluid is its poor ability to transfer and absorb heat energy. The dispersion of nanosized metallic or non-metallic solid particles into the base fluids has been developed to overcome the deficiencies of such base fluids and improve their thermophysical characteristics. However, using nanofluids has several challenges to overcome, such as cost production, corrosion and erosion of the nanofluid system which resulted in higher maintenance expenses and unclear human health implications[214]. Further improvements in convection heat transfer should also be considered, given the possibility of further increasing the solar thermal storage rate. This can be facilitated by various active strategies, including magnetic fields and ultrasonic fields[215]. It is shown that using an ultrasonic field at power of 150W can enhance the heat transfer rate by around 32%[213]. Using the effect of ultrasonic vibration on n-octadecane melting, Oh et al.[216] determined that PCM melting was up to 2.5 times faster with ultrasonic vibration than with natural melting. They have found a number of complex phenomena, such as cavitation, agitation, and acoustic streaming, are accompanied by ultrasonic vibrations, which are the key cause of melting enhancement[215]. Despite its benefits, heat transfer augmentation using an external field such as ultrasonic or magnetic fields requires extra energy for simultaneous operation. This results in increasing the system's cost and lowering its efficiency[216].

Working fluid is mostly discussed in evacuated tube collector patent pools. As discussed earlier, flammability and toxicity are the main challenges of choosing the proper working fluid

[217]. Generally, in patent analysing, all patents have not the same value, per se. Each specific field of technology may have a core patent that makes a revolution in technical issues or enhance a problem that has been discussed for a long time. In patent analysing, as mentioned earlier, companies to protect their innovation grant their patents. If the innovation that is introduced in the patent has a remarkable value due to non-regional protection of patents, the same patent will publish and grant in another market as well. This process is named as patent family. Another feature that elucidates the value of a patent is the forward citation of that patent. The patents with the highest patent family and citation in each solar thermal technology are listed in Table 2.

Table 2 The most popular patents in each solar thermal technology category

Technology	Patent	Forward Citation	Patent Family	Year	Ref
Brayton Cycle	Thermal heat storage system	2	13	2013	[218]
	Systems and methods for generating electrical power from solar energy	109	1	2004	[219]
Dish Collector	Solar Concentrator Configuration with Improved Manufacturability and Efficiency	8	25	2011	[220]
	Parabolic trough or dish reflector for use in concentrating solar power apparatus and method of making same	60	8	2007	[221]
Evacuated Trough Collector	Heat transfer device	5	31	2012	[222]
	Solar energy collector	81	2	1978	[223]
Flat Plate Collector	Structure with high-heat surface	4	26	1975	[224]
	Solar heating system	83	1	1984	[225]
Fresnel Lenses	Solar energy system with composite concentrating lenses	37	19	1980	[226]
	Planar solar concentrator power module	144	5	2003	[227]
Heliostat Field Collector	Systems and methods for sustainable economic development through integrated full spectrum production or renewable material resources using solar thermal	4	40	2011	[228]
	Concentrating solar power with glasshouses	21	13	2012	[229]
Parabolic Trough Collector	Solar module system of the parabolic concentrator type	0	27	2007	[230]
	Torque transfer between trough collector modules	52	13	2010	[231]
PV/T	Hybrid solar collector	7	31	2012	[232]

	Mounting system for installing an array of solar battery modules of a panel-like configuration on a roof	241	2	2000	[233]
Rankine Cycle	Circulator pump for conveying a liquid and/or gaseous medium	8	19	1983	[234]
	Power plant system for utilizing the heat energy of geothermal reservoirs	152	1	2006	[235]
Stirling Cycle	Method and system for electrical and mechanical power generation using Stirling engine principles	9	14	2006	[236]
	Low temperature solar-to-electric power conversion system	86	1	1993	[237]

Regarding solar thermal systems for buildings, there are two basic categories. The first one, which is known as Building-Added (BA) solar thermal is the elements that can be added to the buildings. The second ones are integrated into the different parts of the buildings, therefore not possible to separate the system from the building envelope unless the entire envelope of the building is replaced, which is known as Building-Integrated Solar Thermal (BIST). As well as aesthetics, BIST systems use less space and are more economically viable[238]. The number of published patents in BA and BIST technologies in total is 304. Although its trend is upward, these technologies are facing several challenges such as the small economic scale, the long payback period, the high required capital and installation costs, and the lack of market information[239]. Another difficulty is the aesthetic challenge of installing PV modules on existing buildings due to structural design issues that make it very difficult to install them. Nonetheless, the application of solar thermal technologies in buildings is gaining more attention by academia and industries. Besides the upward trend, about 62% of the published patent in the building sector are granted. On the other hand, although hydrogen is currently a hot topic, the integration of solar thermal technologies with hydrogen production does not gain enough attention from solar thermal industries.

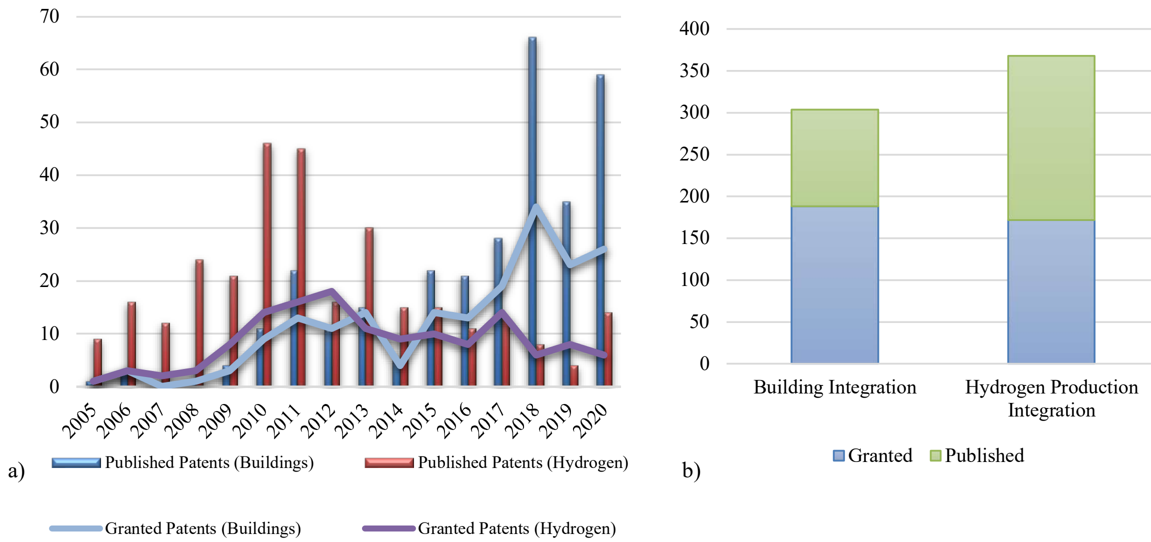


Fig. 19 a) Published and granted patent trends of solar thermal technologies applications in hydrogen and building sectors b) The ratio of granted to published patents in solar thermal integrated building and hydrogen production technologies

A number of ideas have been explored for the generation of hydrogen using solar thermal energy in recent years. In terms of the most important thermochemical ideas, solar thermochemical cycles, solar steam reforming of natural gas, and methane cracking are the most noteworthy. High-temperature electrolysis may also produce pure hydrogen by utilizing renewable power and solar heat[240]. In order to implement solar thermochemical cycles, the biggest challenge is the material's durability to high acids concentration at high temperatures. The near future will emphasize the development and integration of resistant components (ceramics) such as reactors, absorbers, heat exchangers and product separation. It is essential to develop products that improve catalyst systems and coatings for components at reasonable costs. Moreover, further improvements in electrolysis, the second step of the hybrid sulphur process, are required in terms of increasing current densities, reducing overvoltage, and reducing heat losses and side reactions. As a step toward further process development, a solar demonstration plant should be realized after successful experiments at the laboratory scale[241].

To sum up, the current states of all discussed and investigated solar thermal technologies are illustrated in Fig. 20.

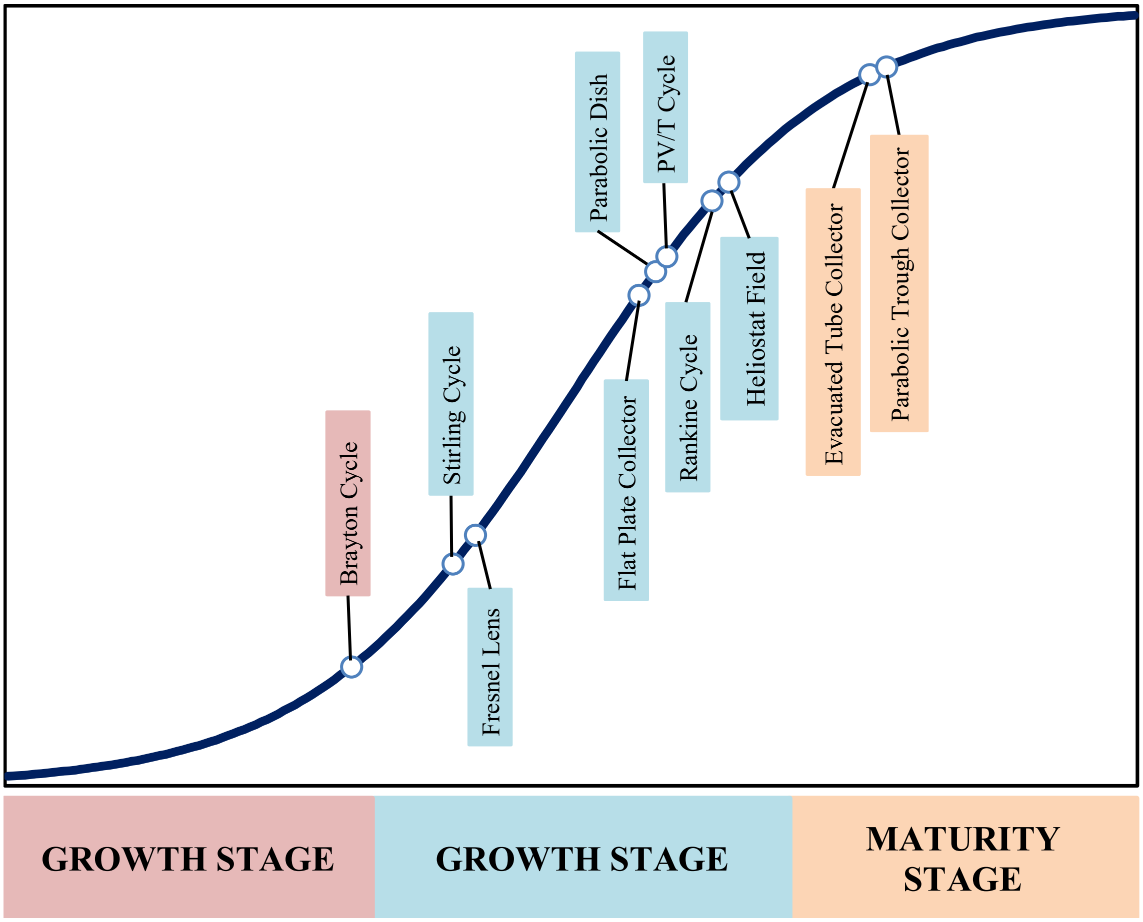


Fig. 20 Solar thermal technologies TLC

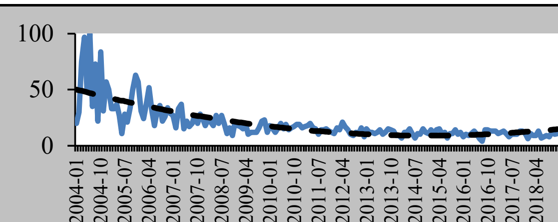
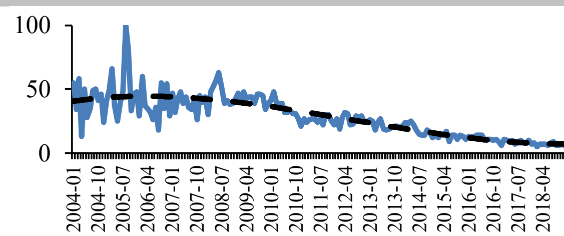
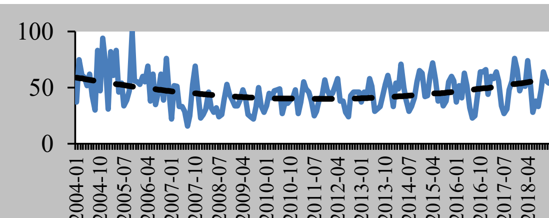
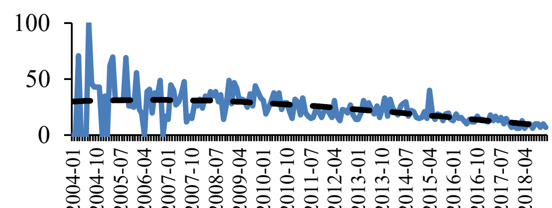
The technological states of various solar thermal technologies indicate that the Brayton cycle is in the emerging stages. The Brayton cycle is near to pass this stage and enter the growth stages. Seven out of ten mentioned technologies are located in the growth stages; however, they almost passed the productivity point. The technologies related to Heliostat field collector are so near to the maturity stage. There are only two technology in the maturity stage: evacuated tube collector and parabolic trough collector. All challenges to each technology are described and compared to the current literature. After assessing the TLC of solar thermal technologies, the adoption curve is required to draw the hype cycle. To this extend, the next steps are dedicated to the adoption curve and hype cycle, respectively.

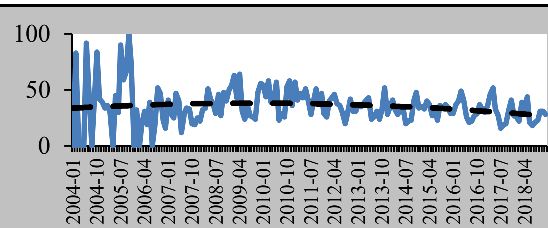
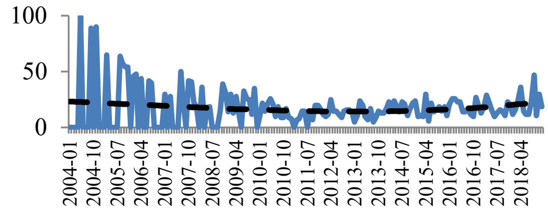
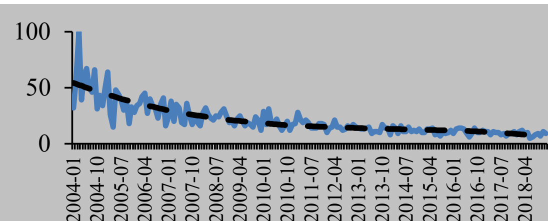
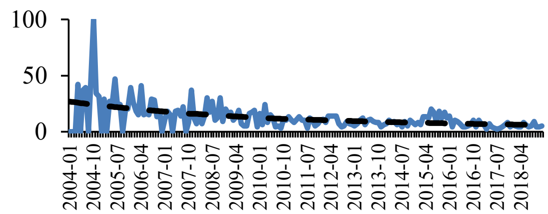
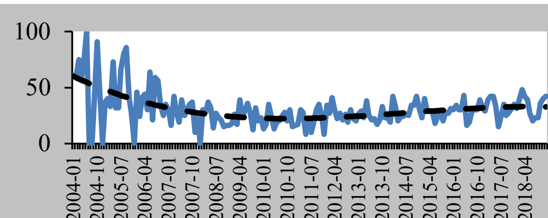
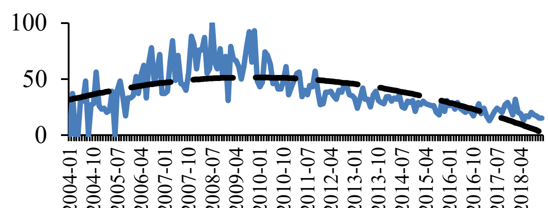
5.2 Technology Adoption Curve Analysis

As was mentioned previously, one of the requirements for drawing the hype cycle is the technological life cycle. The other required tool for this respect is social acceptance. One of the approaches to indicate social behavior for adopting new technology is Google search traffic.

Five periods are defined in the adaptation or acceptance procedure in marketing. At first, the new technology does not receive positive feedback when there is no adequate knowledge of its application. Therefore, the market is not ready yet. Innovators who are the customers of the first period are looking for new technologies for further improvement. The technology approval is next increased progressively by early adopters up to 13.5 %. After that, technology gains the peak share of the market in the maturity period by the early majority. Then, the late majority use technology because of the technology maturity. In other words, the adaptation growth rate is reduced, and the technology goes into the decay period. In the end, the aging process has occurred; and laggards are involved in the technology. The technology adoption curves of discussed solar thermal technologies are illustrated in Table 3.

Table 3 Adoption statuses of solar thermal technologies

Solar thermal technology	Adoption curve	Adoption Status
Rankine cycle		Late Majority/Laggards
Stirling cycle		Early Majority/Late Majority
Brayton Cycle		Late Majority
Fresnel lenses		Early Majority/Late Majority

PV/T		Early Majority/Late Majority
Parabolic trough collector		Late Majority/Laggards
Parabolic dish		Late Majority
Heliostat field collector		Late Majority/Laggards
Flat plate collector		Early Majority
Evacuated tube collector		Late Majority

According to the above table, the statuses of solar thermal technologies are indicated.

5.3 Hype Cycle Analysis

The technological life cycle determines the current states of technology from a technological point of view. Data in which is used in the technological life cycle in this study is published patents. What can get from patent trends is the perspective of technology development. However, are people accept that technology is another main issue that should be answered. In previous sections, both tools have been discussed, and the results of an investigation in solar thermal technologies were indicated. The combination of these two practical tools results in the hype cycle. Therefore, a determination of opportunities and the potential of technologies to solve the market problems can be provided by this tool. Fig. 21 demonstrates the hype diagram of solar thermal technologies.

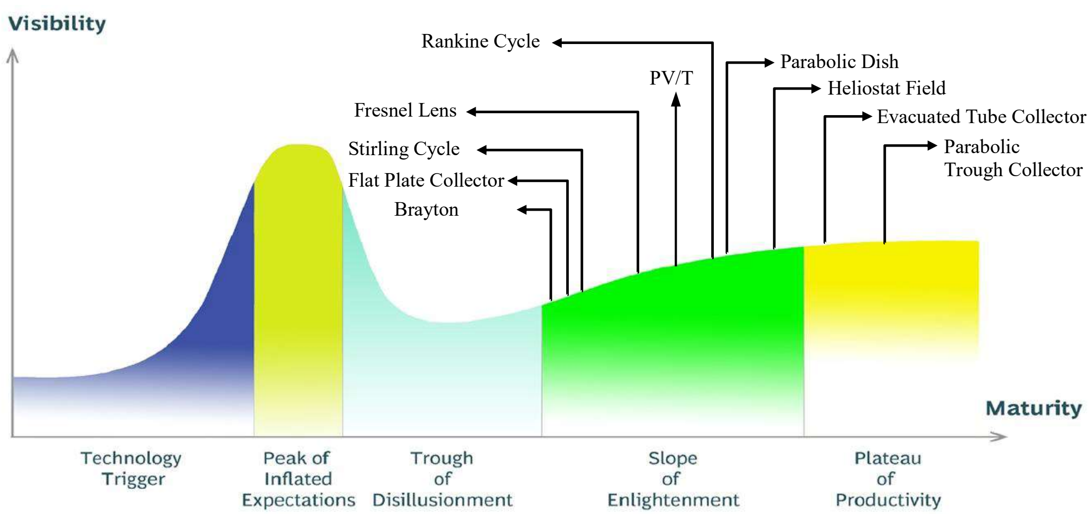


Fig. 21 The hype cycle of solar thermal technologies

According to the above figure, evacuated tube and parabolic trough collector technologies are in the plateau of the productivity phase. As is mentioned earlier, the parabolic trough collector technology is the most mature concentrating solar thermal technologies. Nonetheless, the main issue for development in this technology is heat transfer fluids. By increasing the total amount of heat collected per unit area, subsequently, the thermodynamics efficiency will increase. The other technology in the fifth phase is parabolic tube collector that is none-concentrating solar thermal technology. The evacuated tube collector, as the most efficient and convenient solar thermal technologies, is located in the plateau of the productivity stage. In terms of simplicity, the evacuated tube collector is the best choice, while its manufacturing process is affordable. The fragile collector tubes are one of the main drawbacks.

Further research can be carried out to strengthen the tubes. A combination of evacuated tube collector with other technologies, such as concentrating solar ones, can enhance efficiency. The other technologies are located in the slope of enlightenment. The heliostat field collector is near the plateau of the productivity phase. A new generation or new development is required to pass the current stage. Despite having the highest transformation efficiency, the parabolic dish collector is expensive. The utilization of a tracker might be one of the reasons. Low compatibility for hybridizing is other research that needs development to pass the slope of enlightenment. Among various heat exchanger cycles, Rankine is the most efficient one due to past research. In contrast, the Stirling cycles are more efficient on small scales. The recent movement to develop the Brayton cycle is due to spatial application. Brayton and Stirling's cycles are in the slope of the enlightenment phase; therefore, an improvement in scale upward and downward is required to pass to the plateau of productivity. The enhancement in efficiency in PV technologies could be helpful for PV/T technologies to pass to the fifth phase. Flat plate collector technology is in the slope of enlightenment stage. However, this technology is one the most studied and employed solar thermal technologies. One of the potential answers to this inconsistency is the application of nanofluids and nanoparticles. The flat plate collector is the most used and economical solar collector due to its simplicity in application. This simplicity results in early usage of this technology, but with low efficiency. One of the approaches to enhance the performance is design modification, which has a high cost. However, emerging nanofluids and nanoparticles with interesting thermal characteristics results in the rise of flat plate collector efficiency through thermal enhancement. This enhancement through these materials results in more efforts in the last decades.

5.4 Validation

One of the well-accepted methods for identifying the diffusion of technology into the marketplace is the Technology Readiness Level (TRL). TRLs are one of the well-known measurements that is a systemic approach to assess technology maturity. The increasing complexity of systems to analyse and the lack of objectivity of TRL approach is the main deficiency of this method. However, in this research, since our system is not complex, TRL will be the option for validating our results. Other alternative validation methods will have the same results as mentioned in our system it is not a complex system.

To justify the statuses of investigated solar thermal technologies, the TRL of each one is shown in Table 4.

Table 4 The technology readiness level of solar thermal technologies

Solar thermal technologies	TRL	Ref.
Rankine Cycle	7-8	[242, 243]
Brayton Cycle	6-7	[244, 245]
Stirling Cycle	5-6	[153]
PV/T	8	[246, 247]
Parabolic trough collector	9	[248, 249]
Parabolic dish	8	[248]
Fresnel lenses	6-7	[250]
Heliostat field collector	7-9	[249, 250]
Flat plate collector	6-8	[204, 251]
Evacuated tube collector	9	[250]

The above table indicates the TRL of each mentioned technology. Among various solar thermal technologies, only two of them are in the TRL-9. Evacuated tube and parabolic trough collectors are in the plateau of productivity, which means their market perspective is so strong. The statuses of each technology have been discussed, and the validation of each one can be seen in table 2. For instance, the heliostat field collector is in TRL 7-9, and its current state is at the end of the slope of enlightenment. The required development in construction cost could be helpful to enter to the plateau of productivity. Among technologies of conversion solar thermal energy to electricity, the Rankine cycle has a better situation in the market. The current life cycle state of this technology is the growth phase and, according to the adoption curve, is in the slope of the enlightenment phase. TRL of this technology proves its state, TRL 7-8. Although there was various domestic utilization of PV/T, the manufacturing cost and efficiency issues of PVs are the main barriers. Nevertheless, this technology is on the slope of enlightenment with TRL-8. In order to assess the real market penetration, the installed capacity of solar thermal technologies is considered. Compared to other solar thermal technologies, parabolic trough, flat plate and evacuated tube collectors have been installed more in large-scale solar thermal systems. At the end of 2020, SolarPACES (2021) reports 9.3 Gigawatts

(GW) of power derived from solar thermal power plants, divided into 6.1 GW of operational power, 1.6 GW under construction, and 1.6 GW under development. Parabolic troughs totalled more than 4,000 MW[153]. Flat plate collectors were used in more than 130 large-scale solar thermal plants in Denmark and Austria in 2018 with a total capacity of 1 GW[247]. The PV/T technology is also in high demand on the market. A majority of PV/T installations were in Europe and China, with a total of 810MW (606MW thermal + 208MW solar)[252]. In 2020, Heliostat field collectors had a total installed capacity of 1.7GW[253], reflecting the correct TRL and status. It takes more development for other technologies to be commercialized, as explained earlier.

6. Conclusion

The current state and possibility for the future of technology could bring up the innervational vision to pick an appropriate program for further movements. On the other hand, technology penetration into the market or, in other words, population adoption on innovations makes a vision of economic projections. The combination of these two assessment tools shapes the hype cycle by considering each one's feature. Investigation in the technological assessment of solar thermal technologies indicates evacuated tube and parabolic trough collectors are highly matured and commercialized. These two technologies state in the maturity phase in terms of the technological life cycle. Moreover, evacuated tube technology diffusion is in the fourth stages, while parabolic trough collectors located in the laggard's stage. According to the hype cycle of solar thermal technologies, heliostat field collectors are on the slope of enlightenment, though a new development will put it in the plateau of productivity. Nonetheless, the result of the life cycle shows that this technology will enter to maturity phase in 2027. The acceleration of technological innovation of the Brayton cycle and Fresnel lens collectors have gotten pace and will pass the growth stage in 2037 and 2039, respectively. It is noteworthy to say these technologies are located in the slope of enlightenment. Development in terms of efficiency in large and small scales in addition to decreasing operation cost would be helpful to pass this phase and enter the plateau of productivity. Eventually, for validation, the technology readiness levels of each solar thermal technology have been discussed.

The future direction will be devoted to employing more indicators for assessing technological life cycles. Stochastic technology life cycle analysis based on machine learning approaches can use to employ multi-indicators for technology future forecasting. Moreover, the integration of scientific papers and industrial reports can result in more a accurate technological life cycle. Additionally, related news to the field can enhance the accuracy of the technology adoption curve.

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