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Evaluating the Market Potential of Concentrated Solar Thermal Technology for Different Applications in the MENA Region

Missing financial and regulatory frameworks lead to low development and stagnating costs of concentrated solar thermal technology. Nevertheless, in locations with high direct normal irradiance (DNI) such as the Middle East and Northern Africa (MENA) region, the technology could become competitive, being promised a learning rate of 10–20%, and boost local economies. This study aims to identify potential business cases and evaluate the increased technology's investment likelihood in the region, focusing on Egypt. A thorough market assessment on the structure, regulatory framework, demand, and potential revenues was conducted for the power and process heating sector. A SWOT analysis was performed considering the local context and competing technologies. Egypt was shown to offer local manufacturing potential, regulatory framework, and renewable energy (RE) strategies, facilitating the technology's deployment. Moreover, the market is already open for private investment and selected international funds are directed toward CSP development. High initial technology cost, subsidized fuel and electricity prices for industry, alongside lack of long-term financial incentives and awareness of potential long-term benefits for the economy were identified as the most significant threats. High solar heat demand for industrial processes and large potential for concentrated solar heat (CSH) application were identified. Yet, the market is decentralized and the processes are very diverse, moreover retrofitting may pose risks alongside the high upfront investment and additional land costs, which makes concentrated solar heat applications less attractive for the Egyptian industrial sector. Hence, for concentrated solar technology deployment, financial incentives and a regulatory framework specifically directed toward the technology would be necessary. [DOI: 10.1115/1.4051744]

Keywords: concentrated solar power, concentrated solar heat, solar heat for industrial processes, energy market, SWOT analysis, renewable energy

1 Introduction

The transition from a fossil fuel-based energy system to a majority of electricity generation from renewable energy (RE) sources requires political and economic incentives, public acceptance, and technological readiness. Great steps toward the incorporation of renewables in the energy sector have been taken globally. In particular, the electricity generation from wind power and solar photovoltaics (PV) has increased rapidly in the past years. In 2020, the two technologies represent 86% of the global renewable capacity additions [1]. The electricity from both solar PV and wind is fluctuating in nature. The highly volatile generation pattern, alongside the low power capacity factor, complicates power availability prediction. Other renewable energy technologies, such as biomass, hydropower, or concentrated solar power (CSP) with integrated thermal storage, enable a higher capacity credit and dispatchability. In particular, the benefits offered by CSP with thermal storage are argued to be of value in a prospective "fully renewable" energy system [2].

Concentrated solar power relies on the concentration of direct radiation, constraining its potential locations to regions with high direct normal irradiance (DNI) [3]. Only few years ago, the necessity of support for research and development and larger investment was addressed in the context of both solar technologies, PV and CSP, to enable cost reduction and unlock the global potential [3]. Governmental subsidies and incentives led to an immense net-price regression of PV components in the past years. Nowadays, PV is offering some of the lowest levelized costs of electricity (LCOE) of any generation technology (similar to wind power [4]). Mostly China, Europe, and North America contribute by 36%, 24%, and 12% to the global cumulative PV installations, respectively [5]. While the PV levelized costs have become competitive, the expected learning rate for CSP of approx. 20% was not attained [2].

The first installations of CSP plants date back to the 1980s in the USA [6]. The energy crises primarily propelled the first developments of the technology. When the effects of the crises ceased, the deployment of CSP stagnated [2]. Since 2007, the market share of CSP power plants has increased in few countries [6]. Figure 1 shows the electricity generated from CSP. The values show a very small electricity generation compared with generation from PV that reached 720 TWh in 2019 [8]. Yet, mostly the lack of political incentives, in combination with high costs due to a still rather low state of development, led to a deficiency in the sector's progress [9].

With increased CSP technology investments in high DNI countries (around 2500 kWh/m^2 annually), the technology costs are expected to reduce significantly through technology learning and increase the competitiveness of CSP globally. This paper aims to evaluate the potential for initiating investments in concentrating solar thermal technology in the Middle East and Northern Africa (MENA) region with Egypt as a case study.

First a brief technical overview about the available concentrating solar thermal technologies is presented. A market analysis is then

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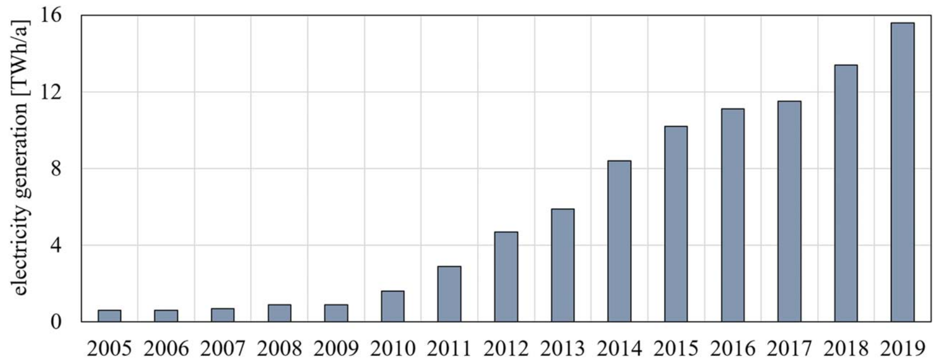

Fig. 1 Global electricity generation from CSP plants [7]

conducted to identify the technology learning potential and to review the technology's potential in the MENA region. After the hypothesis of potential cost reduction led by investments in high DNI countries is confirmed in the preliminary analysis, a more thorough market assessment is conducted for Egypt. The market structure, regulatory framework, and policies are assessed, and the demand and potential revenues are evaluated. Considering the local context and competing technologies, a SWOT analysis is conducted, identifying the potential strengths, weaknesses, opportunities, and threats of concentrated solar power. This focusses on two high potential business cases.

2 A Brief Technological Overview

For different applications, different concentrated solar technologies should be considered. Concentrated solar thermal technologies are divided into line focusing and point focusing technologies. Each set of technology offers different advantages but has its own drawbacks. Point focusing technologies such as solar power tower and parabolic dish collectors can offer higher achieved temperatures through their high concentration ratios. However, point focusing systems require two-axis tracking systems to track the sun's motion more precisely during the day, which leads to more complex control systems. Line focusing technologies conversely require one-axis tracking systems. The concentration ratios of the line focusing technologies—parabolic trough collectors and linear Fresnel collectors—are significantly lower than that of point focusing technologies due to the fact of focusing the irradiation on larger absorber areas, thus reaching lower temperatures.

Parabolic trough collectors are the most used solar thermal collectors, dominating the CSP market share worldwide for power applications up to date [10]. The collectors offer not only a decent efficiency but also mitigation of financial risks [11] through their wide use and level of maturity. The parabolic collectors design includes the use of one-axis tracking system for moving the whole system including the collectors and absorber, resulting in many moving parts in the system and requiring many flexible hoses and joints. Such connections are weak points and limit the collectors for reaching higher temperatures [12,13].

Parabolic trough collectors are commercially more mature for up to medium range temperature applications (up to 400 °C). The choice of each technology is highly dependent on the application it is assigned for. The collector's outlet temperature is dependent on the working fluid used. Thermal oils are the most widely used working fluids in parabolic trough collectors and can reach 393 °C. After being heated in the collectors, the thermal oil is used to produce steam in a separate cycle, for the steam to be expanded in steam turbines for electricity generation. In the early stages of the technology's development, the trough collectors were also used for producing steam for industrial applications through direct steam generation.

Linear Fresnel collectors have lower optical and thermal efficiencies compared with parabolic troughs. However, Fresnel collectors offer other advantages. The technology's simpler design offers various benefits making the technology an attractive option. The simple structure and the use of flat or slightly curved mirrors have various implications on both manufacturing and operation and maintenance costs. Wind loads in Fresnel collectors are lower compared with parabolic trough collectors [14,15].

Unlike parabolic trough collectors, the design of Fresnel collectors comprises the use of a stationary absorber, only the collectors have to rotate, thus, eliminating the need for all moving joints and connections. Linear Fresnel collectors can be identified as a more suitable technology for industrial process heat applications [15] because of their maturity operating with water as a working fluid through direct steam generation [16]. Linear Fresnel collectors are also suitable for power production applications by reaching higher temperatures as a result of using either direct steam generation or molten salts. The technology is suitable for reaching low, medium, or high temperatures (up to 550 °C) [16,17]. The technology is still considered a new market entrant for electricity production and is still not widely used as the parabolic trough collectors. Only 3% of all commercial CSP projects were using linear Fresnel collectors in 2018 [16].

Solar power tower is the solar thermal technology that attracted most research and development recently. Compared with parabolic trough collectors, the technology utilization in commercial projects was lagging behind. In 2018, less than 20% of commercial CSP project were based on the tower technology [16]. However, the number of planned and to be commissioned projects utilizing the technology increased significantly. Figure 2 shows the capacity and number of commissioned projects or to be commissioned for the different technologies between 2018 and 2023 [18]. It is clear, that the solar tower technology's share in the market will significantly increase, that will even exceed the parabolic trough technology. It is also clear that the linear Fresnel collectors market share will stay very limited in comparison with the other two technologies. 380 MW of CSP planned capacity are defined as "not specified" because it is not yet clear which CSP technology will be used in these projects.

The design of the technology includes numerous heliostats tracking the motion of the sun on a two-axis tracking system and focusing the solar irradiance on a central receiver mounted on top of a tower. The solar tower has the great advantage of reaching higher temperatures than can be reached by line focusing technologies. High temperatures of up to 565 °C could be reached using direct steam generation [10] or molten salts. When using air as a heat transfer fluid, temperatures of up to approximately 1000 °C are reachable [16].

The technology is most suitable for power capacities ranging between 10 and 200 MW_{el} [16]. Other working fluids like supercritical CO_2, liquid metals and solid particles that can reach higher temperature levels are extensively under research and development

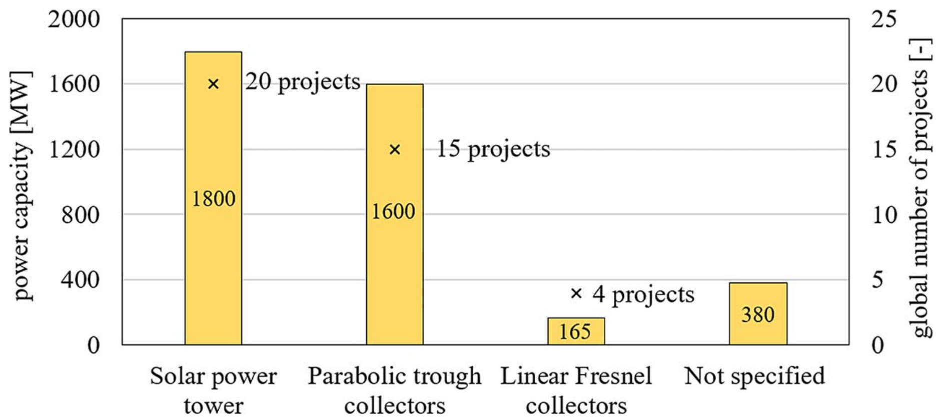

Fig. 2 CSP commissioning projects break-down per technology between 2018 and 2023 [18]

for utilization in solar power towers [19,20]. Apart from electricity production, solar tower use is also very suitable for other industrial applications demanding high temperatures like hydrogen production and other solar fuels (fuels produced through solar thermal energy).

Dish collectors comprise a parabolic dish focusing the solar irradiance on a focal point located above the center of the dish that powers a sterling engine. Dish collectors have the highest concentration ratios among all concentrating technologies reaching up to 2000–3000 and temperatures of up to 1500 °C through a two-axis tracking system. The use of the technology is considered for small applications. Dish collectors are commercially not mature as they are complex and costly [15,21]. Thus, their potential use is excluded from the current study.

3 Assessment and Discussion

The aim of the technology assessment, market assessment, and benchmarking is to identify the strengths, weaknesses, opportunities, and threats of selected business cases for the concentrated solar thermal technology under consideration of the market structure, demand, and regulatory framework as well as the potential technology development.

3.1 Technology Assessment. In this section, the investment in concentrated solar thermal technology in the past and present is assessed to evaluate the potential of investment in the technology in the near future and the expected cost reduction of the technology associated with an increase in investments. Moreover, the concentrated solar thermal resource potential, as well as the business opportunities of the technology for the MENA region (using Egypt as an example) are discussed and two business cases are selected for further and more thorough assessment. It is worth mentioning that at present many research publications are dealing with the implementation of the different possible applications of concentrated solar thermal technologies such as in Refs. [22,23]. However, within this study, only potentially feasible industrial scale technologies are being evaluated, whereas small-scale systems are not considered.

3.1.1 Concentrated Solar Technology Investment Cost and Learning Rate. In most developed countries, there is a low resource availability for CSP; this may explain the low number of existing CSP plants [2,24,25]. Hence, the expected reduction of the relatively high investment costs through technology learning was not realized in the recent growth phase [4]. The implementation of financial and regulatory frameworks in regions with reasonable DNI [2] would incentivize investments in the technology and drive its learning curve. Moreover, the increased awareness of CSP being complementary to PV but not in direct competition [26] would benefit the technology growth as well.

Despite rather low growth in installed capacity up to date [2,24], CSP costs were shown to continuously fall [25]. Recent studies showed that CSP technology's specific investment cost was reduced in the past years, while the average capacity factor increased. This led to a significant reduction in the LCOE by 46% (2012–18) and is expected to be further reduced by 35% until 2030 [26]. Moreover, the recently signed power purchase agreements resulted from auctions suggest that CSP technologies may become competitive soon [25].

When analyzing the cost development of CSP projects using identical technology, the technology reaches an average learning rate of 8.5% (5–12%, Spain, and the USA) [24,27]. Thus, the expected learning rate of 10% [2] is considered to be more realistic than the initial rate of 20% [3].

Market growth, e.g., through large-scale projects and rising project experience, amplified mass production, and levels of automation, combined with the use of technology development (improved components and materials) are drivers for the cost regression of CSP technology, which is expected to occur in the upcoming years [6]. A study conducted in 2018 indicated that CSP cost reduction will result from the increased capacity installation rather than research and development [28]. In other words, for CSP costs to be reduced significantly to reach competitive values, the continuous addition of CSP capacity must achieve the necessary growth to allow technology learning [4]. The Center for Mediterranean Integration recently drew attention to the most current bids for CSP projects suggesting that the technology's LCOE may range between 0.05 and 0.07 $/kWh by 2022 in high DNI countries including most of the MENA region and first become cost-competitive toward fossil fuel-based electricity generation [4].

Currently, new CSP installation capacities are trending toward larger capacities unlike the plants build earlier. At present, Morocco and the United Arab Emirates have the largest CSP installations among MENA countries followed by Saudi Arabia, Egypt, Algeria through hybridization with natural gas-fired plants (integrated solar combined-cycle) and Kuwait. Some of these countries have plans to proceed further with more installations. Other countries in the region like Jordan, Lebanon, and Tunisia have already expressed interest in CSP and are currently cooperating with institutions like the World Bank for either identifying suitable sites or developing projects [29]. It is expected that all such efforts and projects will directly influence the learning curve of the technology.

3.1.2 Concentrated Solar Thermal Technology Potential in the MENA Region and Egypt. Although most of the MENA region countries are rich in oil and gas reserves, some countries in the region have limited resources. The foreign dependency rate on fossil fuels has reached more than 90% in countries like Jordan,

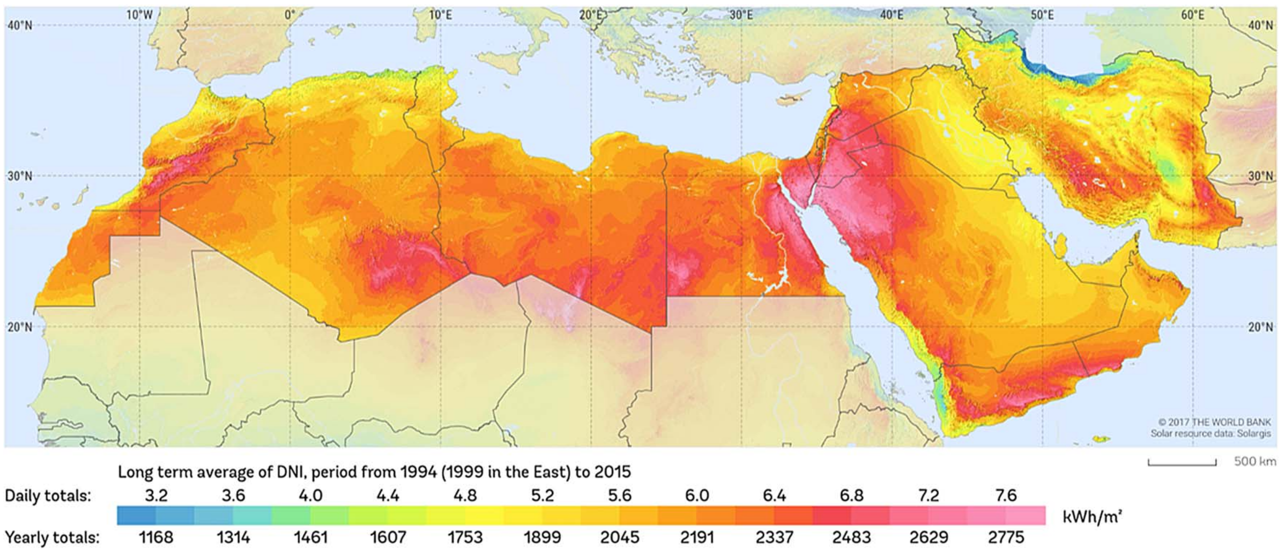

Fig. 3 DNI map for the MENA region [31]

Morocco, and Lebanon [30]. However, similar to other countries in the region, they are blessed with solar resources as illustrated in Fig. 3. Increasing energy demand among countries in the region in combination with short reserves of fossil fuels and high energy costs are common topics. In contrast to the excellent direct normal irradiance in the MENA countries, only few CSP plants exist and little practical experience is available (e.g., operation schemes, capital investment, operation and maintenance costs, conceptual design, impact on the grid) [32]. The concept of CSP may play a significant role in power generation and other sectors in high DNI countries. Hence, political decision-makers in the MENA region are recently pursuing the concept more intensely in particular due to the potential local value-added, apart from the possibility for integration with thermal storage [6].

In 2012, the international competitiveness of different MENA countries to develop a local solar industry was assessed by the World Bank. The study confirmed that both Egypt and Morocco offer the highest manufacturing attractiveness for CSP components [33,34]. Several materials used to produce solar components are excessively available in Egypt, such as steel, stainless steel, and glass [35]. Moreover, these countries have low cost of labor and low-cost energy for industrial usage, as well as a relevant manufacturing ability [34]. Egypt additionally receives solar radiation of 2000–3200 kWh/m^2 per annum, one of the highest levels in the world [35]. The Egyptian minister of electricity and renewable energy announced in the renewable energy outlook for Egypt, that by 2020, CSP plants should reach a share of local content of 50% in Egypt [36]. Initiatives such as "the Middle East and North Africa Concentrated Solar Power Knowledge and Innovation Program" by the World Bank and the Clean Technology Fund indicate that funds for investments in CSP technologies are available. Almost similarly to what happened during the development and construction of the first integrated solar combined-cycle plants in Egypt and Morocco, as the Global Environment Facility (GEF) approved grants of $50 million and $43.2 million to push the technology's development in the region [37,38].

3.1.3 Potential Business Cases for Concentrated Solar Thermal Technology in the MENA Region and Egypt. In this section, different prospective areas of application for concentrated solar technology are assessed as potential business cases. The utilization of concentrated solar thermal technology for (a) power generation, (b) heat generation, (c) refrigeration (d) desalination, and (e) hydrogen production were undertaken through a preliminary assessment to select the most likely business cases to be assessed more thoroughly.

(a) Power generation

Through an ambitious strategy, Egypt intends to reach a 20% share of renewable energy in the state's electricity supply in 2022. The share should further increase to reach 42% by 2035 [39]. According to prior sources, the 2035 strategy foresaw initially 700 MW of capacity provided by CSP plants [40]. Thus far, the integrated solar combined-cycle power plant in Kuraymat with a capacity of 140 MW has a solar share of 20 MW. In 2018, the International Renewable Energy Agency (IRENA) showed the expected evolution of Egypt's electrical capacity increase through RE. The report showed a very optimistic scenario that CSP evolution is on track with the planned 100 MW in 2022, which would increase to 4.1 GW in 2030, then 8.1 GW in 2035 [36]. However, only one planned 100 MW CSP project in the West Nile area has been so far announced by the government [41–43]. In 2020, the tender was further postponed due to surplus capacity [44].

In contrast to the slow development in CSP deployment in Egypt, the PV sector flourished (Sec. 3.3.1). The collocation and hybridization of CSP and PV have recently been widely assessed in a number of studies. The aim of this approach is to use the low PV electricity cost during daytime and the greatest advantage of CSP for producing electricity through thermal storage during nighttime. Thus, lowering the LCOE of the entire plant and enabling matching electricity supply and demand regardless of sunshine. If compared with CSP-alone plants having the same capacities, the reduction in LCOE of the CSP-PV collocation concept was shown in a study to be 22.6% [45] and in another study to even reach 35% [46]. In another study comparing the CSP-PV collocation concept with the hybridization concept by means of an electric heater, a further reduction of approximately 23% was achieved in the case of the hybrid plant [47]. Through the increased benefits of combining both technologies, it is expected that the global market will witness an increase in the number of CSP-PV projects in the future. Projects like NOOR Energy 1 in the United Arab Emirates, Cerro Dominador and Copiapo in Chile, and the combination of Redstone CSP plant with Jasper and Lesedi PV plants in South Africa were announced. The projects are based on the collocation concept of CSP and PV. Whereas, NOOR Midelt 1 in Morocco will be the first hybrid CSP-PV plant using excess electricity from PV to increase the temperature of the molten salt storage using an electrical heater and thus increasing the cost efficiency of the plant. In 2017, the United Arab Emirates' NOOR Energy 1 set a world record of 0.073 $/kWh. Not long time afterward, Morocco's NOOR Midelt 1 project broke the record with signing its power purchase agreement at a record lowest bidding price of 0.07 $/kWh. Both projects comprise PV as well and are expected to be commissioned in 2022 [29,48]. Such combinations would have direct influence on the CSP investment cost learning rate. Hence, CSP and in particular hybrid CSP-PV projects could become more attractive for the MENA region in the near future.

(b) Process heat generation

Apart from electricity production, heat is considered one of the highest potential CSP business opportunities in Egypt through its extensive use in the industry. Heat is identified as the biggest source of energy in the industrial sector. CSH used for industrial purposes also known as solar heat for industrial processes (SHIP) has a very high potential for reduced system costs that could be reached by manufacturing the system with high local content reaching up to 60–70%. The payback period of CSH projects in Egypt could range from 3 to 5 years within the next period and could continue going down as the electricity and gas prices will increase [35].

Industries as pharmaceutical, textile, chemical, plastic, metal fabrication, cleaning, drying, and food and beverage were identified as industries with high thermal energy demand [49,50]. All of these industries exist in the MENA region. Solar heat for industrial applications has been subject to research during the past years. The technology has been implemented and already proved its technical viability. Yet, using solar energy in the industry is still very limited [14].

In 2019, the market shares of solar heat for industrial processes stood at less than 0.02%, which is considered negligible. However, the market is considered to be expanding as in 2018, 108 new projects were implemented worldwide that account for 37.6 MW_{th}. By the end of 2018, the total installed worldwide capacity was 567 MW_{th} [51].

A leading example using solar heat for industrial processes in the MENA region is Jordan, the country that imports around 94% [52] of its energy. The country implemented two projects in 2015 and 2017. The first installed system provides the pharmaceutical manufacturing company RAM Pharma with saturated steam at 166 °C and 6 bars needed in its industrial process. The system's installed peak capacity is 222 kW_{th} [53]. The second system was installed for a tobacco production facility that belongs to the company Japanese Tobacco International. The system installed peak capacity is 700 kW_{th} where steam is not only produced for providing heat needed for the industrial process but also for air conditioning of on-site buildings [54,55]. Both SHIP projects utilize linear Fresnel collectors through the direct steam generation technology. The two projects are considered to be the first two projects of their kind in the region.

In 2018, the World Bank Group in collaboration with Fraunhofer ISE (Germany) presented a study regarding the competitiveness of CSH in six countries in the MENA region. It was indicated that the reduced system efficiency (around 40%) makes the competition with conventional boiler with an efficiency of around 80% challenging. However, the study revealed that for Jordan, Lebanon, Palestine, and Morocco, investing in CSH is already competitive as heat production with diesel is costlier, which may even reach up to three times in case of Jordan. For Egypt, the diesel fuel cost was shown to be significantly less expensive than in other countries. Thus, as long as subsidies are present, CSH will not be competitive [56].

(c) Refrigeration

Rising space cooling demand puts much strain on the power generation sector [57] in most countries in the MENA region due to their climatic conditions. More frequent heatwaves are anticipated to induce increased cooling demand [58]. Most of the cooling demands match the solar irradiance and sunshine hours in the MENA region. Thermally driven refrigeration machines could be an alternative for electrically driven refrigeration machines. Thus, solar cooling could be used for reducing the dependence on electrical grids and powering air conditioning systems [59]. Thermally driven cooling systems have been used for many years and were driven by waste heat from industrial processes [60]. CSH could be used in solar air conditioning, reducing peak loads and extreme operation of electricity grids during hot weather. Solar thermal cooling systems are commonly available for very large cooling capacities to benefit from the economies of scale effect and the improved system performance [60].

Absorption, adsorption, and desiccant systems are the types of solar thermally driven refrigeration systems [61]. Absorption systems account for 70% of the total installed systems. With the help of hot water generated by CSH, absorption and adsorption refrigeration machines can produce cold water. Absorption machines do not require very high temperatures for driving (80 °C–120 °C for single-effect and 120 °C–180 °C for double-effect absorption) [60] which the linear Fresnel collectors could easily and feasibly provide. The technology is suitable for buildings and is present in the market for installations ranging from 50 kW to 200 kW. Furthermore, solar adsorption machines use lower water temperatures, can be used for larger capacities (50 kW–500 kW), are suitable for industrial air conditioning, and process cooling beside their use in commercial buildings. Solar desiccant systems are suitable for residential and commercial buildings and are best known for reducing moisture and controlling the amount of fresh air [60].

The two main disadvantages of any of the solar thermally driven refrigeration systems is the low thermodynamic performance and the low economic feasibility especially if used exclusively for space cooling [60]. To increase the economic feasibility, and depending on the demand, it is advisable to combine space cooling with other processes to increase the return on investment [60,61]. A novel concept of integrating a solar power tower into a cogeneration plant was proposed in Ref. [62]. The new configuration is used for proving electricity and thermal energy that could be used for driving an absorption refrigeration machine, air conditioning system, or any other thermal application. The study proved that such concept provides economic advantages by combining both applications.

(d) Desalination

Rising water demand either for drinking, irrigation, or industrial purposes is a threat for water scarcity in the MENA regions. Most territories in the region are considered as arid lands [63]. Low-cost energy from fossil fuels made conventional thermal desalination and electrically powered reverse osmosis (RO) desalination prevalent in the Middle East [64]. The MENA region contains almost half of the total desalination capacity worldwide (48%), where only Saudi Arabia's capacity is 15.5% followed by the United Arab Emirates with 10.1% [65]. The MENA region is foreseen to further rely on water desalination [64]. Egypt is also considered an arid country with a great potential threat of water scarcity [66]. In 2020, the government announced a 5 year plan to add 47 water desalination plants with a total installed capacity of 2.44 million m^3/day [67].

Concentrated solar thermal energy can also offer water desalination possibility for Egypt and the whole region. The region has scarce water resources, but an abundance of solar resources and saline water [68]. Various desalination technologies, such as multi-stage flash (MSF), multi-effect distillation (MED), or low-temperature distillation, could be powered by the heat provided from the CSP or RO desalination could be powered by electricity provided from CSP. The different solar thermal desalination technologies were thermo-economically analyzed for implementation in Egypt in Refs. [69–71]. Many concepts even included the cogeneration of electricity and fresh water in Egypt (e.g., in Ref. [72]) or other countries in the MENA region, e.g., Saudi Arabia, Algeria, and Qatar [73–76]. It was shown that cost reductions could be achieved by combining CSP with MED that recently gained attention due to its improved thermal performance and lower energy consumption compared to MSF [71]. Comprehensive studies for projects involving more than one government such as TRANS-CSP, AQUA-CSP, and MED-CSD were conducted for many countries in the region and concluded that CSP will be a key factor for producing water and electricity in the future of the region [77–79]. In a study conducted in different locations, it was found that the MED powered by CSP could be more suitable for the Gulf region while the RO power by CSP could be more suitable for the North Africa region [71].

Egypt has inaugurated the MATS cogeneration project in 2018. The project is considered the first of its kind in the country utilizing concentrated solar power at a pre-commercial scale that can produce electricity and desalinated water. The project has an installed capacity of 1 MW_e and 250 m^3/day of desalinated water. Heating and cooling of buildings could also represent another cogeneration option in such plants [80,81]. Solar thermal desalination is possible at various temperature levels making it suitable for using different solar thermal technologies. However, no commercial large-scale projects have been yet implemented. Solar thermal desalination will require technology learning not only for the concentrated solar thermal components but also for the thermal desalination part of the plant. Hence, desalination is not further discussed as a business case in this work.

(e) Hydrogen production

Other prospective application for concentrated solar thermal technology is the production of hydrogen, solar fuels, and fertilizers. In case of hydrogen production, hydrogen can be produced by thermally splitting oxygen and hydrogen from water molecules through thermochemical reactions [82]. Such thermochemical process uses the high-temperature concentrated solar energy to induce the reaction in endothermic chemical reactors [83]. Although some thermochemical processes can use the temperatures achieved by CSP systems today, the technology is still low-efficient, immature, and risky [84]. On the other hand, the thermochemical process can offer the great advantage of establishing a thermodynamic pathway for producing solar fuels with high solar-to-fuel efficiencies without utilizing expensive metal catalysts [85].

In combination with electricity produced from PV, in another process, the high-temperature thermal energy provided by the concentrating technologies can be used in high-temperature steam electrolysis (600 °C–1000 °C) to produce hydrogen from water splitting without any CO_2 production [16,84].

Both processes are still in the research phase for developing materials that can withstand such high temperatures for producing receivers, insulations, or catalysts needed for hydrogen production [12]. Other technical problems also exist, such as reactor design, start-up, shutdown, and part-loading requiring further research and technical solutions first, before being able to compete with hydrogen production through electrolysis, the technology that is present today [16,85].

Regarding the solar technology, most of the research in this field is being focused on the solar tower as it can reach the highest temperatures today and having the potential of reaching even higher temperatures.

It is apparent that the application of concentrated solar technology for hydrogen generation, solar fuels, or fertilizers still requires further development before being commercialized. In particular, in the MENA region, the business case would only be applicable with immense external subsidies. Thus, the business case for hydrogen generation will not be considered in this work.

Through the assessment, CSP for electricity generation and CSH for industrial processes are considered to have the highest potential business cases ready for implementation in Egypt and thus will be the focus of the analysis.

3.2 Market Assessment

3.2.1 Electricity Market Structure and Policies in Egypt. In 2000, Egypt initiated the electricity market's unbundling process toward a legal separation by undertaking reform law number 164. The Egyptian Electricity Authority (EEA) was subsequently reorganized into the Egyptian Electricity Holding Company (EEHC) [86,87]. The unbundling was recommenced in 2001 [88], separating the core functions into five generating, one transmission, and seven distribution companies. Moreover, private investment was permitted to contribute to up to 49% of the separate corporate entities' shareholding within generation and distribution [87].

In 2002, the previous dispatch processes were replaced by an internal wholesale power pool [86]. The horizontal unbundling continued in 2002 and 2004 with the repeated division of the distribution companies. The reforms occurred without an independent regulatory agency.

The Egyptian electricity supply chain is vertically integrated. In the first step toward unbundling the market, the power generation and supply were opened for competition. Transmission and distribution are not subject to market forces and remain natural monopolies [89]. The market comprises 16 government-owned utilities: six electricity generation companies, one electricity transmission company (EETC), and nine electricity distribution companies [39].

Owning the vast majority of the distribution assets alongside the entire transmission system, the Egyptian Electricity Holding Company is the core player [90]. Apart from the EEHC, the New and Renewable Energy Authority (NREA), a number of independent power producers, and about a dozen small independent service providers (either generation or distribution) operate under the umbrella of the Ministry of Electricity and Renewable Energy [86,91].

Today, the Egyptian electricity market mainly operates according to the single-buyer market model [89,90]. The Electricity Transmission Company (EETC), a state-owned company that was previously an EEHC subsidiary [90], purchases electricity from all generators and sells it to the distribution companies as well as customers connected to the transmission grid (extra-) high-voltage networks [86].

The New and Renewable Energy Authority (NREA) was established in 1986 to commence commercial renewable energy projects [92]. The Authority devotes its efforts particularly to the development of wind and solar power alongside the implementation of energy conservation programs [36,90]. Other energy carriers are supported by other institutions (e.g., Hydro Power Plants Authority, Nuclear Power Plants Authority [91]) under the supervision of the EEHC [36].

The Egyptian Electric Utility and Consumer Protection Regulatory Agency (EgyptERA), is an independent legal entity (regulatory agency) founded in 2000 and became independent in 2015 with the issuance of the new electricity law number 87/2015. EgyptERA oversees that all electricity sector participants meet the rules and regulations and has the authority of granting licenses for the producers, transmission operators, and distribution companies [90,93]. Since the new electricity law was implemented, EgyptERA is mandated to review and adjust the electricity prices in accordance with both producer and consumer interests [94]. The new electricity law establishes a broad framework to deregulate the current single-buyer market model and to gradually introduce a competitive market [89,90], as the law separated the state-owned and operated Egyptian Electricity Transmission Company into an autonomous transmission system operator and for the first time allowed third party access to the transmission and distribution grid [95].

3.2.2 Heating Sector, Policies, and Regulatory Framework in Egypt. A market for heat as such does not exist in Egypt. Thus far, heat demands are widely met by fossil fuels. The gradual phase-out of fuel subsidies leads to rising costs of fossil fuels [96]. Increasing fuel prices alongside exemptions from customs duties on renewable equipment [97], and other introduced renewable energy policies and regulations [43] imply a strong business case for solar heat used for industrial processes [35].

To reduce the fossil fuels energy demand, the New and Renewable Energy Authority started in the 1980s developing solar thermal technologies for industrial processes and domestic application alongside solar thermal electricity generation. Several pilot plants were developed to substitute fossil fuels for process heat generation in the textile, food, and pharmaceutical industry [98]. The majority of plants stopped operation in 2005, despite significant fuel and CO_2 savings alongside the gathered operational and maintenance experience. The largest pilot solar process heat project in Egypt that resulted from the efforts, is El Nasr solar industrial process heat and waste heat recovery system that was constructed to provide El Nasr pharmaceutical factory with 1.33 MW_{th} (1.3 ton/h of saturated steam). The local content reach within the project to more than 70% [99]. The project was financed through a grant from the African Development Fund. The project was completed in 2003 and commissioned in 2004 [100,101]. However, the project is currently not operational [35].

In December 2014, an ongoing project on "Utilizing Solar Energy for Industrial Process Heat in Egyptian Industry" implemented by the United Nations Industrial Development Organization (UNIDO) was approved for financing by the GEF. The project's goal is to develop a market environment for industrial process heat, focusing on three industrial sectors with the highest solar heating potential in Egypt [102]. The German company Industrial Solar GmbH named Egypt as the biggest market for CSH in the MENA region [35]. In 2016, the German company Protarget AG announced constructing a solar thermal energy system for generating steam required by a hotel laundry facility in El Gouna, Egypt. In combination with the already installed heavy-oil-fuel boiler, the system should reduce the yearly consumption of 700 ton by 80% [103]. However, until now there is no confirmation about the project realization.

3.3 Demand, Potential Revenues, and Competing Technologies. In 2019, the economy in Egypt was forecasted to grow at a rate of 6.8% per year for 10 years. Hence, Egypt was placed among the top of the fastest-growing economies globally (until 2027). Whereas industrial production is a dominant contributor to development in Egypt's economy, contributing by nearly one-third of the gross domestic product (GDP) in 2017 and is growing at a rate of 3.5% annually [35]. The positive development of the Egyptian economy would favor investments in both the electricity and heating sectors as the majority of demand is associated with the industry. The developments of the annual electricity consumption, the population, and GDP for Egypt are shown in Fig. 4. The total electricity production in 2019/2020 is estimated using the total electricity production in 2018/2019 (199.8 TWh) with the same 1.6% increase from the year before [39].

3.3.1 The Electricity Price Development, Electricity Demand, and Capacity Plans in Egypt. In 2013–2014, three countries in the MENA region announced subsidy reform in the electricity sector, namely, Egypt, Tunisia, and Jordan [104]. In 2014, the government of Egypt announced to gradually start phasing out the energy subsidies. Electricity subsidies were planned to be phased out gradually starting 2015 and over the course of 5 years [96]. The phase-out program was planned to take full effect until 2020 and the consumers would pay the electricity prices without any governmental subsidies. However, in order not to overburden the citizens with the rapid increase of electricity prices, the government postponed the full phase-out unit 2022, which was extended again by three more years until 2025. Electricity prices in Egypt are divided into different tiers according to voltage being ultra-high, high, medium, or low. Only for the highest three tiers, electricity prices differ according to the consumption either being during peak time or not. No difference in electricity prices for residential purposes based on peak time. Instead, prices are divided into tranches according to the consumption range. The overall average electricity price increase for all voltages from 2015 until 2020 ranged between 15% and 40% yearly [105]. The government uses the money from subsidies elimination for further developing the electricity sector by extending the electrical transmission network and installing new capacities including renewable energy. The elimination of subsidies would also relieve the government from the heavy financial burden and would enable investment in CSP.

Figure 5 shows the development of the electrical installed capacities in Egypt by type. As of June 2019, the total installed electricity generation capacity was 58.4 GW to meet the electricity peak demand of 31.4 GW [39]. The average growth rate of the installed capacities was 12.9% per year during the period 2014/2015 till 2018/2019, where, between June 2017 and June 2018 the growth rate of the installed capacities reached its peak of 22.4% [39]. The demand for electrical capacity is anticipated to grow at an annual rate of 6.2%. The reserve margin is expected to remain high, 65% to 87% by 2035 [106].

The operation policy of the existing thermal power plants is based on considering natural gas as the primary fuel due to its evident economic and environmental advantages compared with other fossil fuels. The total use of natural gas in power plants in

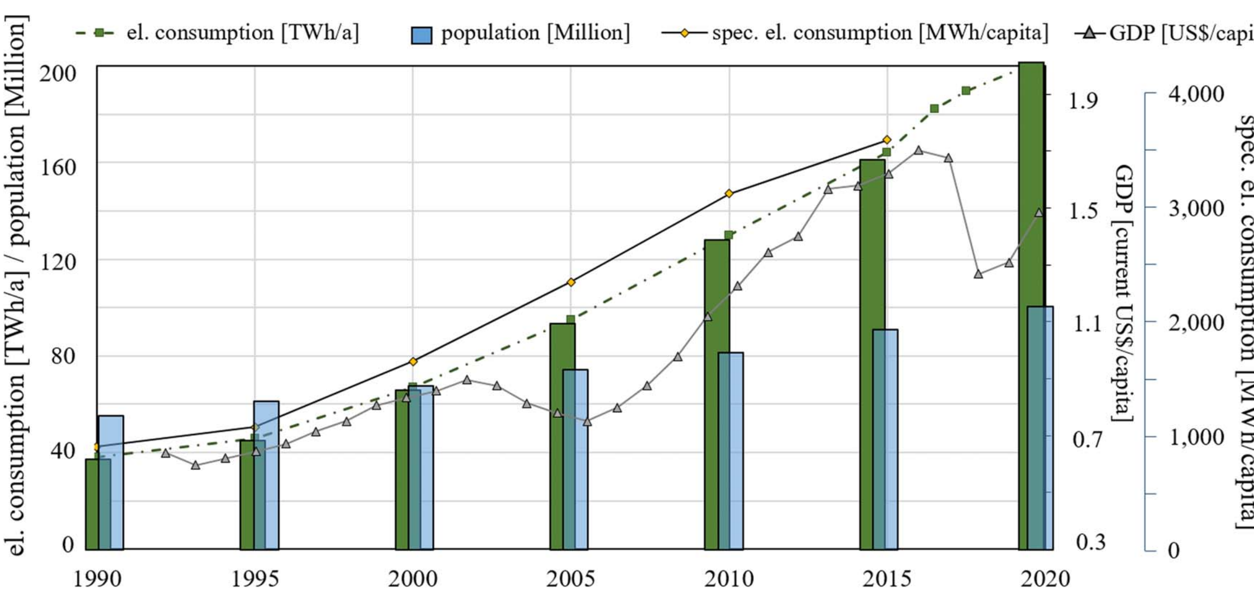

Fig. 4 The developments of annual electricity consumption in TWh and MWh/capita, the population and GDP for Egypt from 1990 to 2020

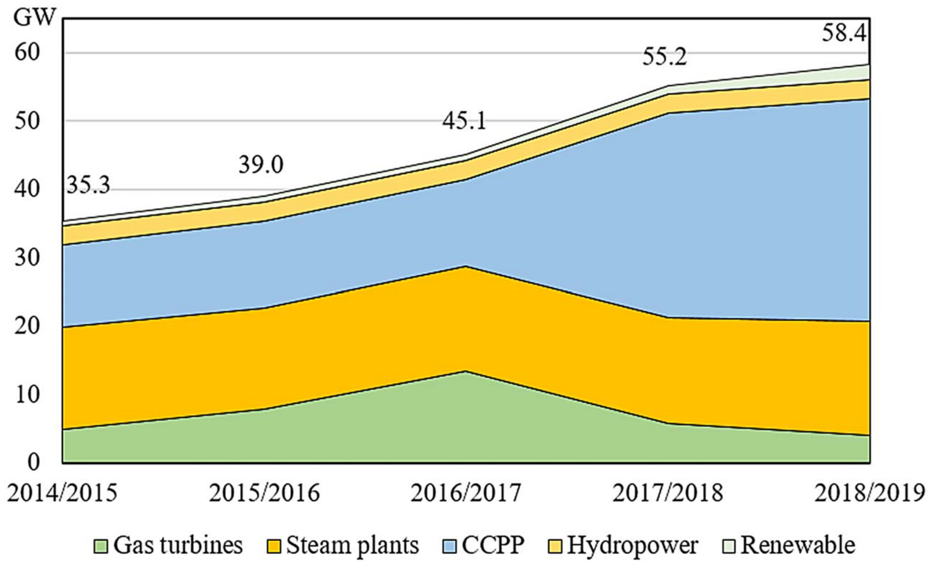

Fig. 5 Development of the electrical installed capacity by generation technology in Egypt [39]. CCPP: combined-cycle power plant.

Egypt reached 85.5% in 2017/2018 [42], which increased to 94.7% in 2018/2019 [39]. Yet, for electricity production purposes, the natural gas price has been fixed for several years and until now at 3 $/MMBtu [105]. The Ministry of Electricity and Renewable Energy has adopted its electricity sources' new diversification strategy, decreasing fossil fuel dependency and increasing renewable energy share. Natural gas and other oil products' contribution should be reduced to 49% of the total installed generation capacity by 2030, decreasing from 90% in 2014/15 [36]. However, due to the huge additions of thermal plants such as the three combined-cycle power plants (CCPPs) totaling to 14.4 GW added only in 2017–2018 [42], the country had to cancel or postpone some RE projects. Furthermore, more thermal capacities are still expected as the 2250 MW CCPP in Luxor, the not-yet specified coal-fired power plant capacity [39] and the $29 billion 4800 GW first nuclear power plant in Egypt [36,107]. Such significant large thermal capacities would jeopardize developing CSP projects in Egypt.

On the other side, the country wants to encourage local and international investors to invest in RE projects and induce the local industrial sector to manufacture the different components of RE technologies [42]. To support its new strategy, in 2017, the government of Egypt has adopted a favorable policy through investment law no. 72/2017, which provided tax incentives to boost renewable energy [108].

Until June 2018, the share of RE in the total installed capacity in Egypt was only 2.1% [42]. However, the year 2019 has witnessed the addition of the largest number of new state-owned and private-sector RE projects, increasing the RE share in the installed generation capacity to 3.9%. Such capacity increase resulted in a significant year to year RE growth rate of 94% representing the highest growth rate among all other electricity sources [39]. Among the RE projects, 1465 MW from Benban PV park that has been commissioned under the Feed-in Tariff (FiT) scheme (two-phases), the project is considered to be Africa's largest solar park [109]. Also, Ras Ghareb 262.5 MW wind farm under the build own operate (BOO) scheme through the private sector [110] and the 580 MW Gabal El Zayt wind farm that is owned by the New and Renewable Energy Authority [111] were commissioned.

The latest "NREAmeter" periodical document released by the New and Renewable Energy Authority in January 2021 indicates that the total renewable energy installed capacities reached 1643 MW from solar energy (including 20 MW CSP in Kuraymat), 1375 MW from wind energy. The total installed renewable energy capacity reached 6 GW including hydropower, representing around 10% of the total electrical installed capacity. Also the actual electricity production from RE reached 23.7 TWh/a representing around 11.7%. Other projects under construction are 500 MW of wind energy and 3 MW biomass. The document also revealed that 1700 MW of wind energy projects and 830 MW of solar energy projects are under development. However, the document did not clearly indicate a separate figure for CSP projects [112]. As a result of the growing number of PV and wind projects, the government announced prioritizing the implementation of 2400 MW pumped hydro storage plant that will cost $2.7 billion [39]. In December 2020, the government announced the cancellation of a 200 MW PV plant in West Nile area that was already in the tendering process with the qualified companies. The reason for cancellation is that the country is having surplus electricity amid lower demand and other projects are already in progress. However, other planned projects will not be canceled [113]. Investing in CSP would not only provide flexibility but also would help the country save money from huge storage projects.

The transition of the electricity market in Egypt has paved the way for the first RE investments. The government's plans are supporting the development of RE technologies with particular emphasis on local content (50%) and manufacturing; in particular, the Benban project showed the Egyptian government's willingness to lead the solar energy sector. Yet, thus far, there is only one 100 MW CSP project (West Nile area) in the planning phase despite previous plans of larger CSP installations. In the first place, PV installations might seem to be the largest competitor to CSP technology for electricity generation in Egypt, apart from gas-fired power plants. However, hybridization of both technologies can play an essential role in CSP development in the country. This could also help decision-makers taking further actions that would benefit the local economy and allow the market to benefit from the advantages offered by CSP with its thermal energy storage capability.

In light of the state's interest not only to provide energy but also developing an advanced waste management system to improve environmental, health, and living conditions of Egyptian citizens and achieve economic returns, the Egyptian cabinet has approved in 2019 a feed-in tariff for the waste to energy projects [114]. The maximum plant capacity would be 20 MW and the feed-in tariff would be limited until reaching a total of 300 MW capacity. This step also proves the government's willingness to further diversity the country's energy sources through new technologies. This would not come in direct completion with CSP development as it is targeting different capacity ranges.

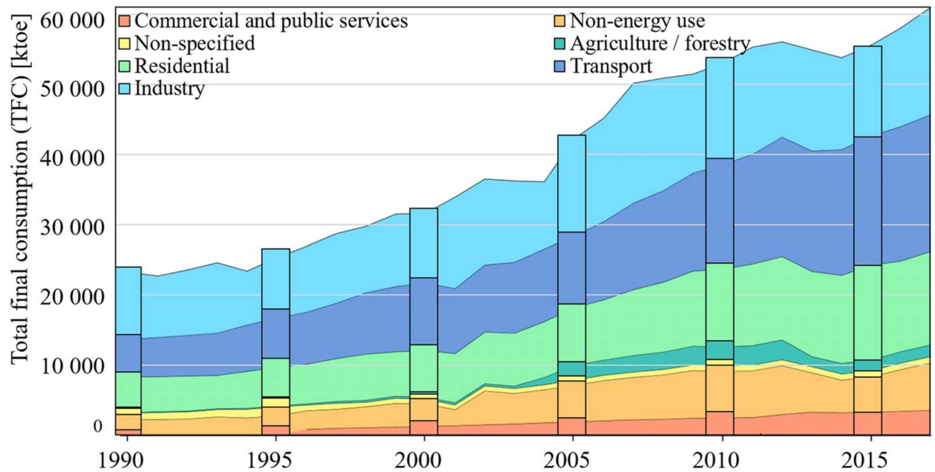

Fig. 6 Total final energy supply by sectors in Egypt for the years 1990–2017

3.3.2 Process Heating Demand and Potential in Egypt. The industrial sector in Egypt utilizes electricity or fossil fuels such as gas, kerosene, diesel, and heavy oils. Around 28% of electricity consumption in Egypt is consumed by the industrial sector [105] and nearly 30% of the total final energy demand in Egypt is associated with industrial thermal energy demand, including both heating and cooling [115]. Process heat is most commonly provided by simple boilers [35]. Despite fluctuations of the different fuel prices, the prices are still being heavily subsidized for the industry. However, the subsidies are decreasing as a result of the energy subsidy reforms. The rising fuel prices should create a more favorable environment for the deployment of SHIP in Egypt. Despite the previously mentioned efforts and Egypt being considered the biggest market for CSH in the MENA region, no company could be identified, which currently uses solar heat for industrial processes.

Approximately 60% of the industrial sector's total energy requirement is used to supply industrial process heating in Egypt (106.6 TWh/a in 2017) [98]. The total final energy supply by sectors in Egypt for the years 1990–2017 in Fig. 6 show that the industrial sector is one of the biggest energy demanding sectors. The Global Environment Facility identified chemical, textile and food industries in Egypt to have the highest solar heating potential. Industrial process heat is estimated to account for 7%, 23%, and 33% of the energy consumption in the chemical, textile, and food industries in Egypt, respectively [115]. The greatest potential for concentrated solar heating was discovered to be within high-temperature distillation, steam production, and drying [116].

Despite the tax exemptions for RE equipment [108], solar components are costly due to inflation and currency pressures through the free fluctuation of the Egyptian pound. Moreover, the solar energy branch is still associated with imported or locally assembled PV panels. Apart from the lack of awareness, CSH might require additional land use that might not be necessarily available at locations where process heat is required and is associated with additional costs. With respect to land cost in addition to the high upfront investment, CSH costs are hindering its deployment in Egypt, despite the fuel savings. Moreover, the complexity associated with CSH integration of a new heat source introduces potential risks that the large industries commonly try to avoid and, thus, a lack of familiarity with CSH technology exists [117]. Hence, specific additional political incentives such as subsidies and rebates, grants, loans, and more tax reliefs, such as pollution tax incentives, would be necessary to use the apparent solar heating for industrial processes potential in Egypt.

3.4 Egypt Concentrated Solar Thermal Technology SWOT Analysis Results

Strengths	Weaknesses
Associated with concentrated solar thermal technologies in Egypt in general	
(1) Commitment of the Egyptian government to implement RE strategies and targets	(1) High upfront/initial capital cost of technology
(2) Large solar potential and availability of land	(2) Technology still not (widely) deployed in Egypt
(3) Political stability and recovering GDP	(3) Lack of practical experience and know-how about CSP technologies
(4) Market is open to private investment	(4) Technical complexity of the systems especially in part-load operation
(5) Incentives for local and foreign investors	(5) Lack of public financing resources
(6) Materials available (glass, steel, etc.), low-cost labor and infrastructure available	(6) Lack of possible financial incentives, e.g., feed-in-tariff scheme for CSP
(7) Existence of human capital stock in academic, professional, and engineering fields	(7) Subsidized fuel prices and electricity prices for industry
(8) Cutting down emissions	(8) Lack of awareness of potential long-term benefits of CSP technology for the economy
For (a) power generation	
(9) Planning of new CSP capacities	(9) No recent tenders for CSP
(10) Legal framework is already developed	(10) Excess installation of conventional installed power capacity
(11) Several RE pilot projects are already in place	(11) Low costs of standalone PV installations (without storage)
	(12) Currently no need for base-load installations

Continued

Strengths	Weaknesses
(12) Licensing procedure for RE projects, standards, and experience exists (13) Avoid additional storage projects' costs for supporting other volatile RE projects	
For (b) process heating	
(14) Adequate funding for applied research (15) Gradual removal of subsidies from fossil fuels (16) Much research and development of technology focused on the region (17) Large potential and cost savings	(13) Lack of professional expertise in technical and economic appraisal of technology (14) Reduced efficiency compared with conventional boilers used (15) Missing heating market and structure of the industrial sector

Opportunities	Threats
Associated with concentrated solar thermal technologies in Egypt in general	
(1) Willingness to fund, e.g., MENA CSP Knowledge and Innovation Program (2) Attractive investment climate (3) Large potential for local manufacturing (4) Positive influence on labor market, e.g., engineers and technicians (5) Protecting fossil fuel reservoirs and the environment (6) Combination with thermal desalination (7) Future possibilities for green hydrogen, solar fuels, and fertilizers production	(1) Majority of funds from abroad, instability of local economy (2) Inflation and volatility of currency (3) Volatile geopolitical situation in the region (4) Uncertain and risky investment for local and foreign investors and for the local banking sector (5) Many governmental institutions concerned with the realization of RE projects
For (a) power generation	
(1) Egypt aims to become a net exporter through extended cross-border interconnections (2) Potential for sector coupling (3) Egypt plans for diversification through RE (4) CSP could provide dispatchable base-load electricity (5) Economic infeasibility of large-scale PV plants with batteries as storage (6) Hybridization with PV offers reduced LCOE and higher capacity factors	(6) Uncertain and retroactive policies (e.g., cancellation of plans for tenders) (7) Operational challenges of hybrid systems (8) High investment costs of dry cooling systems (9) High cost of CSP storage capacity (increased solar multiple)
For (b) process heating	
(7) Decentralized energy efficiency approach (8) Develop commercial and industrial capabilities through cooperation with international specialized companies (9) Solar cooling could be associated with CSH	(10) Return on investment hard to estimate (versus high upfront costs) (11) Increased complexity and potential risks when integrated into existing industrial plants (12) Lack of available land next to the existing industrial plants interested in the technology

A SWOT analysis was adopted to identify and distinguish between the different aspects associated with the deployment of the concentrated solar thermal technology for electricity and heat production in Egypt. As a result of the analysis, it was observed that the general policies and regulations supporting the development of renewable energy are already in place. For a more sustainable electricity and heat markets, the authors propose that the government should consider the following as a starting point:

- promoting the increased technological benefits of the CSP,
- including and increasing the share of CSP in its energy mix and developing more specific policies and incentives such as a CSP feed-in-tariff as a result of its significant advantages over other kinds of renewable energy technologies,
- adopting the hybridization concept for an easier market penetration, and
- quantifying all the economic aspects and their short- and long-term impacts on the economy of the country as well as the impact on the society through the huge available production infrastructure being able to act as a technology exporter for the whole region.

4 Conclusion

The reviewed pertinent literature confirmed that increased CSP technology investments in high DNI countries will lead to a significant reduction in the technology's costs and an increase of its competitiveness on the global RE market. In the performed market analysis, the technology's learning potential was quantified and its potential in the MENA region was reviewed. Many benefits for the region and in particular in the case study of Egypt were identified. The Egyptian electricity and heating sectors, respective market structures, policies, and regulatory frameworks were presented and their effects on two business cases: concentrated solar power for electricity generation (1) and concentrated solar heat (CSH) for industrial processes (2), were assessed. Considering the local context and competing technologies in the country, the potential strengths, weaknesses, opportunities, and threats were identified and discussed for both business cases.

The market assessment showed why Egypt was selected as an example for the MENA region. The country is in the transformation process of its energy sector toward a competitive market and the government has already taken various steps in both the electricity and heating sector for achieving such goal. Egypt was shown to be the most suitable market for both CSP and CSH in the region, being one of the fastest-growing economies, receiving one of the highest levels of solar radiation worldwide and allowing a great manufacturing potential in the region. The reviewed studies and initiatives showed that investment potential for concentrated solar power and heating projects exist. However, the current local incentives such as tax exemptions for RE equipment are not sufficient.

The Egyptian electricity market has started its unbundling process, is open for private sector financing, and RE is receiving great attention concerning the country's diversification plans until

2035. Yet, solar energy is still mostly solely associated with PV panels. Financial incentives for CSP, in particular, are missing. Egypt managed to attract investments in PV and wind energy through the feed-in-tariff program. After lowering the risks and consequently interest rates, currently private sector PV and wind projects are taking place based on competitive bidding schemes. Similar to PV and wind, a feed-in-tariff could be needed in case of CSP to attract investment and initiate the CSP market first. Such feed-in-tariff program should be designed to meet the country's demand and policies. Investing in CSP would not only provide flexibility but also would help saving money from huge storage projects for supporting PV and wind projects. Any of the three mature CSP technologies could be deployed for electricity projects in the country without preference. The authors also highly recommend considering the CSP-PV integration concept due to its benefits.

A market for heat as such does not exist in Egypt. The potential for concentrated solar heating for industrial processes is very large. Yet, potential risks associated with retrofitting existing plants as well as costs associated with the installation area alongside the decentralized and diverse application area are major barriers to the technology's deployment. The subsidies for fuels (for electricity generation) and electricity (for large consumers) are still rather high, making it hard for concentrated solar power or heat to compete with fossil fuel-based generation technologies. The high upfront investment alongside currency volatility and missing long-term financial incentives make revenues hard to estimate. The authors recommend using the LFCs for solar heating purposes as a result of its increased maturity with this concept and low cost.

Finally, the deployment of both technologies and in particular the increase of local manufacturing for either technology would provide great benefits to Egypt and the MENA region. This necessitates the implementation of financial and regulatory frameworks. For CSH in particular, the barrier is higher. This would require building more awareness and financial incentives for individual industries through subsidies and rebates, grants, loans, and other tax reliefs as pollution tax incentives.

Conflict of Interest

There are no conflicts of interest.

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