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Feasibility of Concentrating Solar Power as a Solar Fuel for Electrical Power Stations: A Case Study of Ubari Gas-Power Station in Libya

Hala J. El-Khozondar[1,2*], Mostafa A. Andeef[3], Yasser F. Nassar[4], Rifa J. El-Khozondar[5], Hilmy Awad[6]

[1]Department of Materials and London Centre for Nanotechnology, Imperial College, LondonSW7 2AZ, UK
[2]Electrical Engineering and Smart Systems Departments, Islamic University of Gaza, Gaza, Palestine
[3]Mechancal Eng. Dept., Faculty of Engineering, University of Fezzan; Fezzan, Libya
[4]Mechancal & Renewable energy Eng. Dept., Engg, Faculty, Wadi Alshatti University, Brack, Libya
[5]Physics Department, Al-Aqsa University, Gaza, Paletine
[6]Department of Electrical Technology, Faculty of Technology and Education, Capital University, Egypt

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ABSTRACT

This study affirms the economic viability and environmental advantages of employing concentrated solar power (CSP) as an alternative energy source for electricity generation in the gas-fired power plants at the Ubari station-Libya. The main objective of this study is to provide technical and economic information about the solar power tower (SPT) and parabolic trough concentrator (PTC) to the Libyan government and engineers to encourage fostering sustainable development in the region by mitigating oil depletion by a specific percentage and redirecting it towards petrochemical industries with higher economic returns. Utilizing the System Advisor Model program, various technologies for generating electricity from concentrating solar energy were compared, considering diverse hours and storage capacities. The levelized cost of energy served as a benchmark for the comparative analysis. The findings indicate that the CSP technology of the solar power tower field is optimal, constituting approximately 43.6% of the capacity factor. The proposed generation system's ideal design characteristics include a SPT capacity of around 400 MW, a thermal storage tank with a capacity of 11,332 m³, approximately 508 hectares needed for field construction, a project capital cost of approximately $186,102,644, and the levelized cost of energy of about 13.48¢/kWh. The estimated annual crude oil savings amount to about 3,187,726 barrels, equivalent to approximately $243,637,912. The prevention of approximately 1,735,060 tons of CO2 from being released into the atmosphere is associated with an estimated environmental damage cost of about $130,129,247.

دراسة جدوى الطاقة الشمسية المركَّزة كوقود شمسي لمحطات توليد الطاقة الكهربائية: دراسة حالة محطة أوباري الغازية في ليبيا

هالة جارالله الخزندار[1،2،*]، مصطفى عبدالقار النظيف[3]، ياسر فتحي نصَّار[4]، رفعه جارالله الخزندار[5]، حلمي عواد[6]

الكلمات المفتاحية

الطاقة الشمسية المركزة
الوقود الشمسي
المركزات الشمسية ذي القطع المكافئ
برج الطاقة الشمسية
محطة اوباري الغازية
ليبيا

الملخص

تؤكد هذه الدراسة الجدوى الاقتصادية والفوائد البيئية لاستخدام الطاقة الشمسية المركَّزة (CSP) كمصدر بديل لتوليد الكهرباء في محطات الطاقة العاملة بالغاز، مع تطبيق عملي على محطة أوباري في ليبيا. ويتمثل الهدف الرئيسي من هذه الدراسة في تزويد الحكومة الليبية والمهندسين بمعلومات تقنية واقتصادية حول تقنيتي برج الطاقة الشمسية (Solar Power Tower – SPT) والمجمّع الشمسي ذي القطع المكافئ(Parabolic Trough Concentrator – PTC) ، وذلك لدعم التوجه نحو التنمية المستدامة في المنطقة من خلال تقليل استنزاف النفط بنسبة محددة وإعادة توجيهه إلى الصناعات البتروكيميائية ذات العوائد الاقتصادية الأعلى. تم استخدام برنامج **System Advisor Model (SAM)** لمقارنة تقنيات مختلفة لتوليد الكهرباء من الطاقة الشمسية المركَّزة، مع الأخذ في الاعتبار ساعات التشغيل المختلفة وسعات التخزين الحراري المتنوعة، حيث استُخدم **التكلفة المستوية للطاقة (LCOE)** كمؤشر أساسي للمقارنة. وأظهرت النتائج أن تقنية برج الطاقة الشمسية تُعد الخيار الأمثل، حيث تمثل حوالي **43.6%من معامل السعة**. وتشير خصائص التصميم المثلى لنظام التوليد المقترح إلى قدرة برج شمسي تبلغ نحو **400 ميغاواط**، وسعة خزان تخزين حراري تقارب **11,332م³**، ومساحة أرض مطلوبة للإنشاء تبلغ حوالي **508 هكتارا**، مع تكلفة استثمارية إجمالية تُقدَّر بنحو **186,102,644دولارًا أمريكيًا**، وتكلفة مستوية للطاقة تبلغ حوالي **13.48سنت/ك Wh**. كما يُقدَّر الوفر السنوي في النفط الخام بنحو **3,187,726برميلًا**، أي ما يعادل تقريبًا **243,637,912دولارًا أمريكيًا**. إضافةً إلى ذلك، فإن منع انبعاث ما يقارب **1,735,060طنًا من ثاني أكسيد الكربون سنويًا** يرتبط بتقليل أضرار بيئية تُقدَّر قيمتها الاقتصادية بحوالي **130,129,247دولارًا أمريكيًا**.

*Corresponding author
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Abbreviations

CSP	Concentrated Solar Power
LCOE	Levelized Cost of Energy
TES	Thermal Energy Storage
DNI	Direct Norma Irradiation
SAM	System Advisor Model
PTC	Parabolic Trough Concentrator
SPT	Solar Power Tower
GECOL	The General Electricity and Renewable Energy Company of Libya
SM	Solar Multiple
PB	Power Block

Nomenclature

$\boldsymbol{A}$	Aperture area of the CSP solar field; m^2,
CF	Capacity factor,
C_{CSP}	Capital costs of the system,;$,
$\boldsymbol{C_{CO2}}$	Annual environmental damage cost; $,
$\boldsymbol{DNI}$	Direct normal irradiance; W/m^2,
$\boldsymbol{E_{PB}}$	Electrical energy generated by the power block; kWh,
$\boldsymbol{E_{CSP}}$	Energy collected by the CSP field,
$\mathbf{EF_{CO2}}$	CO_2 emission factor; kg CO_2/kWh,
$\boldsymbol{H_i}$	Total incident solar energy; kW,
$\boldsymbol{h_{i,TF}}$	Enthalpy of the thermal fluid inlet; kJ/kg,
$\boldsymbol{h_{o,TF}}$	Enthalpy of the thermal fluid outlet; kJ/kg,
$\boldsymbol{H_{TES}}$	Duration of thermal storage; h,
$\boldsymbol{h_{TES}}$	Total number of energy storage hours; h,
$\boldsymbol{Q_{u,CSP}}$	Useful power delivered by the CSP field,
$\boldsymbol{\dot{m}_{TF}}$	Mass flow rate of heat thermal fluid; kg/s,
$\boldsymbol{P_{PB}}$	Capacity of the power block; MW,
$\boldsymbol{O\&M_{CSP}}$	Annual operating and maintenance costs of the system; $,
I	Interest rate,
N	Lifespan of the system; year,
$\boldsymbol{\theta_i}$	Solar incident angle,
$\boldsymbol{\eta_{CSP}}$	Efficiency of the CSP field,
$\boldsymbol{\eta_{PB}}$	Efficiency of the power block,
$\emptyset_{CO2}$	Carbon social cost; $/ton$CO_2$.
$\boldsymbol{\eta_p}$	Overall energy efficiency of the plant,

Introduction

Energy (in all of its forms) is the primary engine of human society's progress. According to statistics, fossil fuels account for approximately 80% of primary energy utilized globally [1]. It is anticipated that the quantity of electrical energy utilized will double over the next 20 years, with the rise in energy consumption being caused by population growth and technological advancement [2]. On the other side, this will result in greater environmental degradation and a dramatic shift in the ecosystem, leading to a slew of environmental issues such as global warming, climate change, disease spread, starvation, drought, and desertification.

The scenario is similar in Libya, where growing population and economic expansion have boosted energy demand, resulting in increased need for electric power producing power plants and distribution networks.

Figure 1 illustrates the increasing demand for power in Libya. The data used for this figure is sourced from the General Electricity and Renewable Energy Company of Libya (GECOL), indicating it's likely a reliable source specific to Libya's energy sector. Figure 1 shows that there's a significant growth rate in the demand for energy, with an anticipated yearly rise between 8 and 10%. This infers that by 2024, the demand for energy is expected to reach 9 GW [3].

By 2025, Libya hopes to enhance electricity capacity by adding 10% of total capacity using renewable sources. Nonetheless, due to the country's security condition, this plan was suspended in 2011. Following the country's relative security in 2020, the state revised its strategic plan, which it revealed during the COP27 summit held in Sharm El-Sheikh, Egypt, from 8-14 November 2022, with the goal of increasing the contribution of renewable energy in the mix of electric power generation in Libya to 30% by 2030 and 50% by 2050. This will be accomplished by the use of concentrated solar, solar photovoltaic, and wind energy [4].

Renewable energy sources, which are considered sustainable and ecologically benign, are among the potential alternatives to existing energy sources [5]. Concentrated solar power plants are among the greatest ways to create energy, particularly in regions with strong solar radiation and lengthy daylight hours. Concentrating technologies are gaining popularity owing to their sustainability, cleanliness, and capacity to connect with other systems, as the energy provided by these stations in 2021 reached 6,837 MW globally, a 33% increase from 2015 [6,7].

The major countries in this industry are Spain and the United States of America, with 61% and 18% of total energy output, respectively. Other nations in the area, including Morocco, Egypt, the United Arab Emirates, and Saudi Arabia, have expressed an increased interest in these technologies, owing to the availability of solar resources and their governments' determination to implement the plan to transition from traditional to clean power.

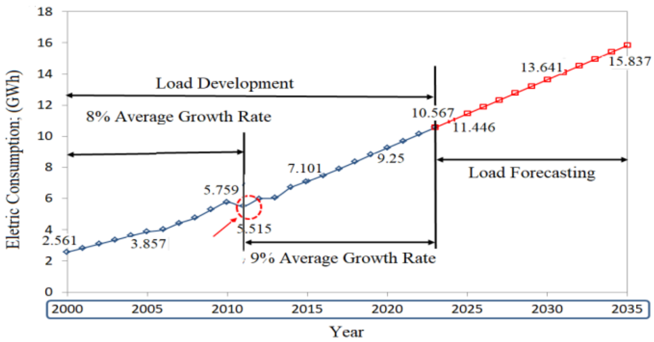

Figure 1: Development of increasing demand for electric power, Libya

Concentrated solar energy technologies rely on converting solar energy into thermal energy, which drives turbine turbines, and concentrated solar energy systems range from tiny units that create a few kilowatts to massive stations that generate several megawatts [8]. Algeria envisions synergizing its natural gas with solar energy through integrating concentrating solar power into natural gas combined cycles. The pioneering 150 MW Hassi R'Mel power plant is the world's first integrated solar combined cycle facility, and three additional hybrid units, each with a 70 MW CSP capacity, are set to be completed by 2018 [5]. Belgasim et al. [3] investigated the economic viability of a 50 MW parabolic trough power plant. The simulation suggests that, despite suboptimal solar conditions on the North coast, Libya has the potential for cost-effective implementation of CSP technology.

Situated in the heart of North Africa, Libya covers 1,759,540 km^2, with the majority being desert. This geographical feature positions Libya as one of the most promising countries for harnessing solar energy, boasting substantial potential with 6,000 Wh/m^2/day of direct normal solar irradiation, along with an annual sunshine duration of 4,000 hours [9].

Figure 2 provides a visual representation of the daily total direct normal solar irradiation (DNI) map. Direct normal irradiation refers to the amount of solar radiation received per unit area, perpendicular to the sun's rays. This map delineates regions based on their DNI values, highlighting areas where the DNI exceeds 5 kilowatt-hours per square meter per day (kWh/m^2/day). The significance of this threshold lies in its relevance to the effective utilization of Concentrated Solar Power (CSP) technologies. By indicating areas with DNI values surpassing 5 kWh/m^2/day, Figure 2 serves as a guide for identifying regions where solar resources are sufficiently abundant to support the efficient operation of CSP technologies [10]. As per the German Air Center report, each square kilometre of this region has the potential to generate solar energy equivalent to one and a half million barrels of crude oil annually [11].

In reaction, the European Council approved a regional proposal aiming to generate 20 gigawatts (GW) of electricity from solar and wind energy in Mediterranean nations. The initiative centers on establishing a grid connecting North Africa and Europe, leveraging the ample solar and wind energy resources in North Africa to provide both continents with renewable energy, as illustrated in Figure 3 [12].

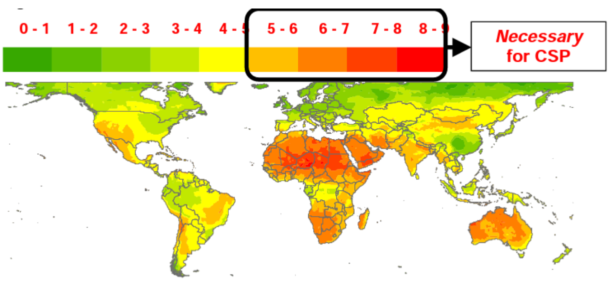

Figure 2: Daily total direct vertical solar radiation map

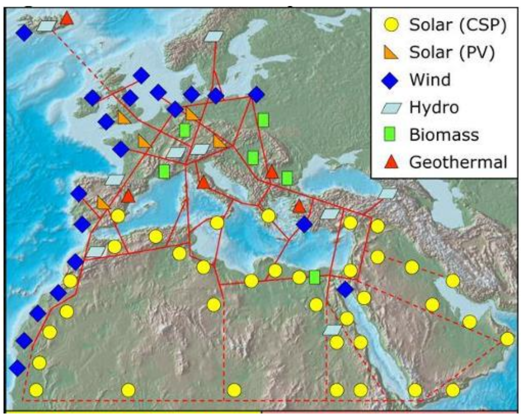

Figure 3: Europe's plan to exploit solar and wind energy in the Middle East and North Africa

This work seeks to promote sustainable development in Libya by localizing the concentrated solar energy industry, aiming to balance energy demand and preserve the local environment. It specifically assesses the economic and environmental feasibility of replacing fossil fuels with concentrated solar energy in the electric power generation sector. The primary objective is to offer a reliable assessment of the CSP potential in Libya, serving as a roadmap for implementing solar energy projects. The focus extends to concentrated solar power plants in the Sahara and the Middle East, evaluating the energy-environmental-economic landscape and identifying success factors for the widespread adoption of concentrated solar energy systems.

Numerous global studies have explored the technical and economic potential of concentrated solar energy technologies in diverse locations [13-31].

In Morocco, where the largest CSP using PTC technology is employed to convert solar irradiation into thermal energy for electricity generation, Bouhal et al. [13] conducted an assessment of the thermal performance of PTC technology and its relevance to potential projects outlined in the Moroccan Solar Plan. The assessment involved annual simulations across six distinct climatic sites, revealing that both location and climate play pivotal roles in determining the overall performance of PTC systems.

Meanwhile, in Algeria, Mihoub et al. evaluated the viability of CSP plants in selected regions of southern Algeria utilizing the System Advisor Model (SAM) software. Their findings underscored the significant influence of technical parameters (such as plant efficiency, annual energy production, and solar field size) and Direct Normal Irradiance (DNI) on the performance of CSP plants. They highlighted the Central Receiver Tower Power Solar Plant, featuring thermal energy storage and backup systems utilizing molten salt as a heat transfer fluid and storage medium, as a promising option for bolstering Algeria's power system compared to other alternatives. Their analysis yielded promising metrics including Levelized Cost of Energy (LCOE) at 15.11 Cent/kWh, Capacity Factor (CF) at 87%, Annual Energy production at 376 GW, and Thermal storage hours at 15 h [14].

Furthermore, Hafez et al. [15] provided insightful forecasts for the utility-scale solar energy market in Saudi Arabia. Their study involved testing various CSP and photovoltaic (PV) technologies under hourly climatic data from ten different sites across the kingdom using SAM software. The results indicated that among all solar energy technologies, PV PTC systems emerged as preferred candidates in the Saudi energy market due to their lower LCOE. Notably, the study revealed that the Solar Village site showcased the lowest electricity generation cost of 0.06$US/kWh achieved by PTC technology.

In Malaysia, Islam et al. [16] identified PTC and SPT fields as optimal technologies for CSP. Aly et al. [17] found economic feasibility in integrating CSP technology into power generation in Tanzania. Andika et al. [18] examined the technical and economic impact of design changes in TES-type CSP systems, revealing cost variations with different storage types. Purohit [19] explored the potential of CSP in India, indicating feasibility in Rajasthan and Gujarat. Fritsch et al. [20] investigated the economic feasibility of a CSP plant using liquid sodium, while Zhang et al. [21] analyzed the relationship between thermal storage capacity and production costs.

Furthermore, the growing interest in hybrid system typologies is underscored by numerous ongoing pilot projects worldwide. Notable examples include the Noor Energy project in the United Arab Emirates, which integrates 700 MW of PTC and SPT technologies with a 250 MW Photovoltaic (PV) solar system [22]. Similarly, the Qinghai project in China is combining 100 MW of Concentrated Solar Power (CSP) with 900 MW of PV [23], while the Shagaya

Renewable Energy Park in Kuwait aims for a total installed capacity of 3.2 GWe, incorporating CSP, PV, and wind power, with completion projected by 2030 [24]. Ali et al. [25] proposed a hybrid system featuring concentrated solar dishes and a wind farm in Egypt, demonstrating the superior performance of concentrated solar dishes over PV solar systems. Yasser et al. suggested a hybrid renewable system consisting of CSP and biomass for Brack City, Libya, which addresses electricity, heating, and cooking gas needs while tackling the region's waste management challenges. The technical and economic feasibility of the proposed system was assessed using SAM software, yielding an estimated Levelized Cost Of Energy (LCOE) of $0.075/kWh [26].

Drawing from the literature review conducted, the authors observed a lack of existing technical, economic, and environmental comparative analyses of concentrating solar technologies tailored to the specific conditions of the site under consideration. Consequently, the authors endeavored to fill this gap by providing a tailored comparison that aligns with the characteristics of the study site. Furthermore, researchers highlighted in the literature review emphasized that each site possesses unique factors influencing the selection of appropriate technology, thus underscoring the novelty and relevance of our study.

The study makes the following contributions:

1. Demonstrating the proven economic feasibility and environmental advantages of employing CSP as an alternative fuel for electricity generation.
2. Introducing a thorough energetic, economic and environmental comparison of various CSP technologies.
3. Developing mathematical models to estimate the environmental impact of CO_2, facilitating the conversion of pollution impact into significant economic values for determining the Levelized Cost of Energy (LOCE).
4. Offering an exhaustive comparison of concentrating solar power technologies in Libya.

The subsequent sections of the paper comprise four main parts: Section two outlines the energy situation of the chosen site. Section three details the research methods and methodology, presenting the dynamic simulation methods employed for comparative CSP technologies and achieving the study's goals. Section four presents and discusses the results. The fifth section contains conclusions and recommendations, concluding with a list of references used in the study.

Key information about Ubari power station

The Ubari gas station is situated in the city of Ubari in western Libya, located (26.566°N and 12.679°E), approximately 900 km south of the capital, Tripoli. Essential design considerations for any electrical station encompass electrical loads and fuel consumption [32]. Data from the Control, Monitoring, and Operation Unit at Ubari Station for 2022 indicates an annual electric energy production of 2,748.4 GWh and an annual fuel consumption of 5,594,118 barrels of oil.

Figures 4 and 5 provide detailed insights into the electric power generation and hourly fuel consumption patterns observed throughout the year 2022 at the Ubari gas station.

Materials and Methods

The following provides a simplified explanation of each technology used in the study, which compared the costs of two different methods of producing electricity from concentrated solar energy: SPT and PTC fields.

Parabolic trough concentrator (PTC) field

The PTC plant, depicted in Figure 6, is an advanced solar technology featuring curved mirrors within parabolic troughs. These mirrors focus sunlight onto a thermal fluid, such as water or Therminol-VP, in interconnected solar collectors arranged in north-south rings within the solar field. This design enables efficient sun tracking. Steam production, powered by thermal mass from the solar field, and thermal energy storage ensure electricity generation continues even after sunset. The system's flexibility allows seamless integration with other conventional or renewable energy systems [33].

Solar Power Tower Field (SPT)

The SPT is also known as central receiver technology. The solar field is made up of numerous rows of axial circular series that include flat or low-curvature arrays. Heliostats were gathered from several sun-tracking mirrors and directed solar energy onto a central receiver to generate a lot of heat. Central receivers are characterized by size, cavity, particles, and exterior receivers, and their temperature may reach 800 degrees Celsius with a concentration of 600 to 1000 times the sun. Figure 7 is a schematic representation of a solar tower power plant. China contributes 37%, with the United States accounting for 19%. This system has a high temperature suitable for driving various types of power cycles, including Rankine and Brayton steam cycles, due to its flexibility, and it can be combined with TES systems for power generation after sunset [34].

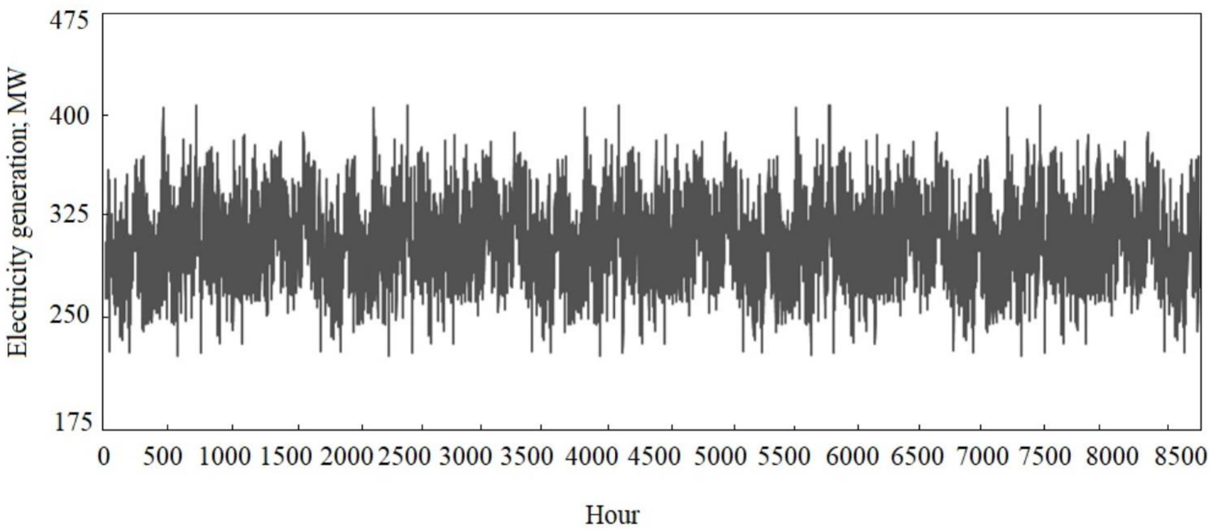

Figure 4: Electricity production at Ubari gas-power station

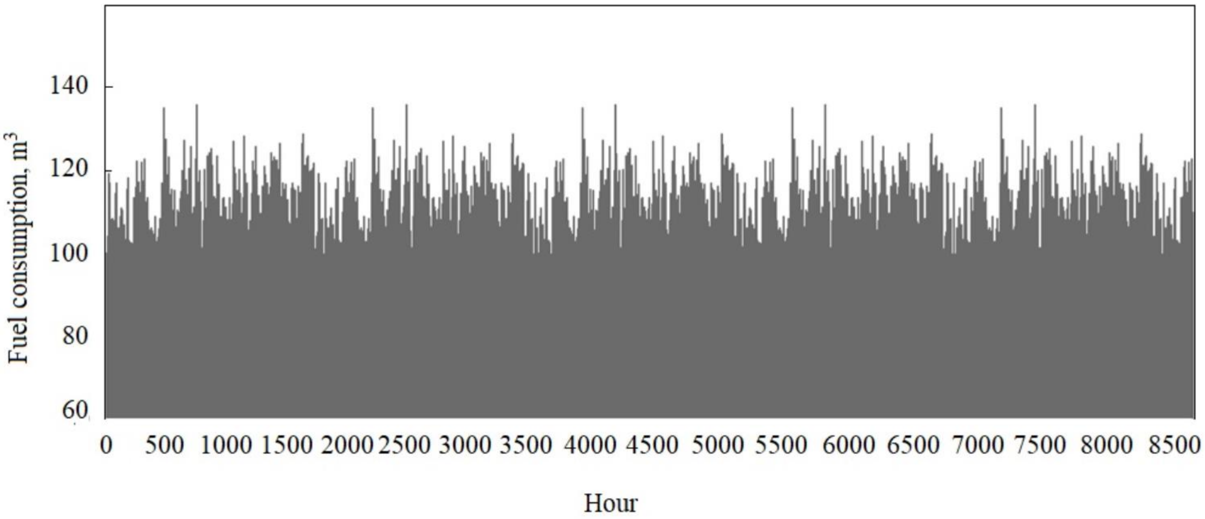

Figure 5: Fuel consumption at Ubari gas station

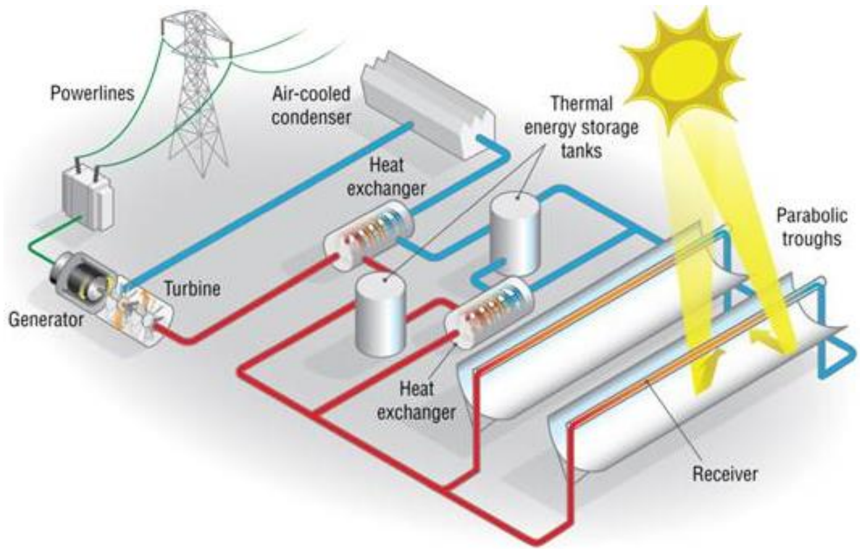

Figure 6: Electric power plant based on a PTC
[source: https://www.researchgate.net/figure/Parabolic-trough-solar-plant-with-two-tank-molten-salt-storage-system_fig4_252007369]

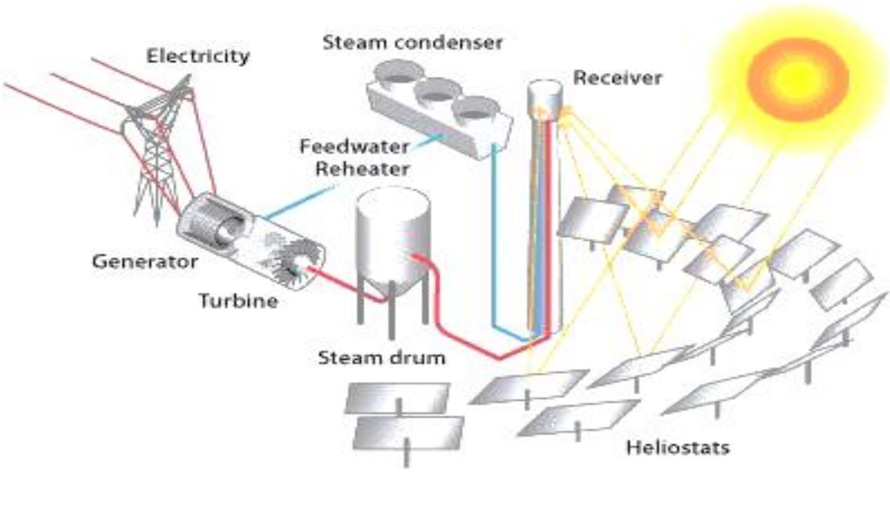

Figure 7: Solar power tower SPT station to generate electric power.
[Source: https://www.google.com/url?sa=i&url=https%3A%2F%2Fwww.sciencedirect.com%2Ftopics%2Fearth-and-planetary-sciences%2Fheliostats&psig=AOvVaw39TwEhk]

Table 1: Comparison of concentrated solar power systems

Indicator	Unit	PTC	SPT
Capacity Limits	MW	10 -250	10 -200
Concentration Ratio	-	50 – 90	300 – 100
Tracking System Type	-	Single-axis	Doble-axis
Operating Temperature	°C	290 – 390	250 – 500
Energy Cycle	-	Steam and organic Rankine	Steam Rankine and Brayton
Electric Efficiency /Annual Solar	%	10-16	20 – 35
Capital [37]	$/kW	6,710	7,663
Capital [37]	$/m^2	424	476
Operation and Maintenance Cost	$/kWh	0.012 – 0.02	0.034
Water Consumption	m^3/MWh	3 (wet cooling) 0.3 (dry cooling)	2-3 (wet cooling) 0.25 (dry cooling)
Land Use [38]	km^2/MW	0.025	0.036

Table 1 includes a comparison between concentrated solar energy systems. PTC and SPT fields are suitable for power generation between 10 to 200 MW among these systems [15]. As for the efficiency of converting solar energy into electricity, the PTC achieves lower efficiency than the SPT field. The PTC has the capability to integrate with energy storage through either direct or indirect means, employing two molten salt tanks. For SPT plants, direct medium storage systems can be utilized [35, 36].

The majority of the total installation expenses for both PTC and SPT plants are attributed to the cost of the components comprising the solar field, as stated in a bulletin by IRENA [39]. The breakdown depicted in Figure 8 illustrates the distribution of capital costs for both types of power stations. Specifically, in PTC plants, the tower component constitutes 39% of the overall installation costs. In SPT plants, while the solar field remains a significant expense, its share is relatively lower compared to PTC, accounting for approximately 28%, with substantial portions allocated to the receiver (18%) and power block (16%) [39].

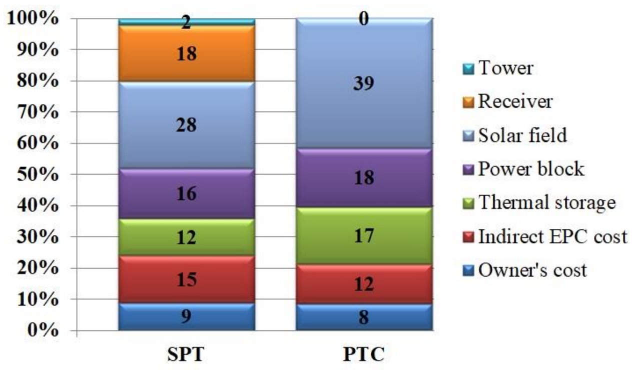

Figure 8: Breakdown of the capital cost of the SPT and PTC power stations

The National Renewable Energy Research Laboratory (NREL) developed the dynamic simulation software System Advisor Model (SAM, version 2020.11.29), which was used to simulate CSP systems for SPT and PTC fields. Software for forecasting dynamic performance and assessing the financial viability of different renewable energy projects is available for free. Photovoltaic, concentrated photovoltaic, parabolic trough, solar central receiver, Fresnel linear reflectors, parabolic dish solar concentrator, biomass energy, geothermal energy, and wind energy are among the various system types it supports [15]. Figure 9 shows how the calculations and data flow were represented during the research.

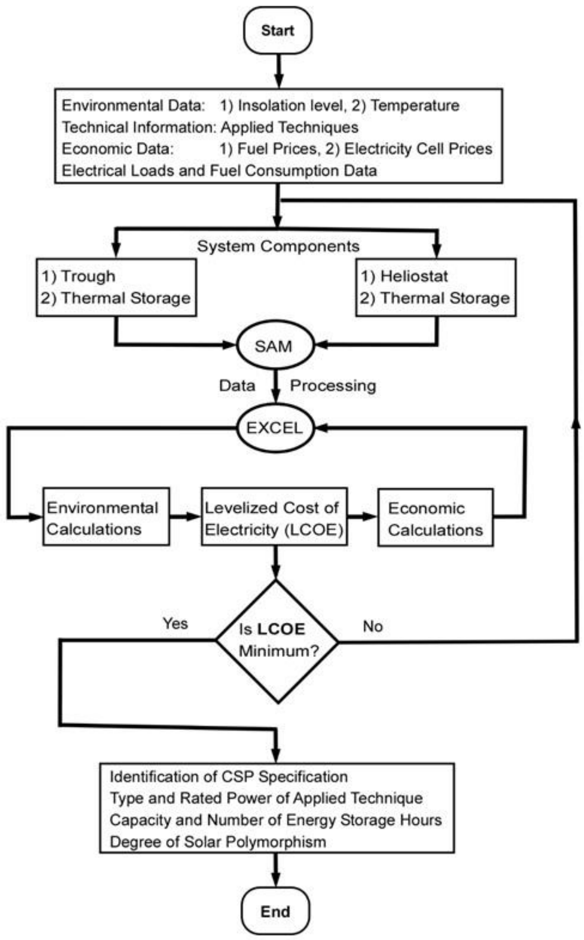

Figure 9: Flowchart of applied research methodology

Assumptions, limitations, and uncertainties

In order to facilitate the analysis, the following assumptions are made:

1. Ignoring insurance rates, inflation, and scrap value in the economic calculations;
2. Ignoring the gradual decline in energy production;
3. Ignoring the increase in load.

Since the only design restriction was to supply the PB with a capacity of only 100MWe, the primary limitation of the current research is the absence of the effect of the optimal configuration of the considered CSP plants. The following are the main sources of ambiguity in the CSP analysis:

1. The technical, economic, and climatic input data: About 2.76% of the uncertainty in solar radiation resources can be attributed to instrumentation [40]. Another area of uncertainty is the cost of renewable energy infrastructure. According to Yasser and Alsadi [41], there is a 360% difference in the cost of solar energy equipment. A variance of this kind in the unit capital cost would add a great deal of uncertainty to the LCOE estimate.
2. Making use of tangible models Uncertainty in the geometry and property assumptions for each system component leads to an aggregated uncertainty at the system level that typically tends to be higher than the uncertainty in an empirical model because the physical model is more flexible than the empirical model [37].
3. System performance and output, including long-term impacts: A cause of uncertainty is thought to be the decline in the CSP field's and the PB's performance. In Years 2 and later, SAM applies a constant degradation rate to the system's total annual energy output during the course of a one-year simulation [37].
4. Additional sources of uncertainty include the thermal fluid's properties and the origins of heat losses [42].

When taken as a whole, these uncertainties increase the uncertainty surrounding the anticipated energy yield as [43]:

$$\text{Total Uncertainties} = \sqrt{\sum (\text{Individual uncertainty})^2} \quad (1)$$

$$\text{Individual uncertainty} = \sqrt{\sum_{i=1}^{N} \frac{(x_i - \overline{x})^2}{N(N-1)}} \quad (2)$$

Where x_i is a value in the data set, $\overline{x}$ is the average of the data set, $\overline{x} = \frac{1}{N}\sum_{i=1}^{N} x_i$ and N is the number of data points in the data set.

The lack of decision-making regarding the investment of these systems is thought to be caused in part by the uncertainty surrounding the economy, which has caused the deployment of CSP plants in Libya to be delayed. Despite the nation's suitability for thermal solar energy applications, the PV solar market in the country is expanding significantly, while the CSP market has not shown any growth [44].

Energy modelling of the CSP systems

Given that SAM software was employed in this paper for analyzing the thermal and economic performance of PTC and SPT, this section discusses fundamental parameters essential for designing and analyzing any CSP station. The total incident solar energy (H_i) received by CSP field is given as [45]:

$$H_i = DNI.A.COS\theta_i \times 10^{-3}\ ;\ \text{kW} \quad (3)$$

Where: DNI is the direct normal irradiance; W/m^2, A denotes to the aperture area of the CSP solar field; m^2 and θ_i refers to the solar incident angle [46]. While the useful power ($Q_{u,CSP}$) delivered by the CSP field is estimated by:

$$Q_{u,CSP} = \dot{m}_{TF}\left(h_{o,TF} - h_{i,TF}\right);\ \text{kW} \quad (4)$$

Where: $\dot{m}_{TF}$ is the mass flow rate of heat thermal fluid; kg/sec, $h_{i,TF}, h_{o,TF}$ are the enthalpy of the inlet and outlet of the thermal fluid; kJ/kg. Accordingly, the efficiency of the CSP field (η_{CSP}) can be estimated from:

$$\eta_{CSP} = \frac{Q_{u,CSP}}{H_i} \quad (5)$$

Consequently, the efficiency of the PB (η_{PB}) is:

$$\eta_{PB} = \frac{E_{PB}}{Q_{u,CSP}} \quad (6)$$

Where: E_{PB} is the electrical energy generated by the PB; kWh. Thereby, the overall energy efficiency of the plant (η_p) is given as:

$$\eta_p = \eta_{CSP}\ \eta_{PB} \quad (7)$$

The solar multiple (SM) is defined as the ratio between energy collected by the CSP field (E_{CPS}) and energy required by the power block (E_{PB}) at nominal conditions, and given as [45]:

$$SM = \frac{E_{CPS}}{E_{PB}} \quad (8)$$

The duration of thermal storage (H_{TES}) can supply energy for operating the power block is expressed as [46]:

$$H_{TES} = \frac{P_{PB} h_{TES}}{\eta_{PB}} \quad (9)$$

Where: P_{PB} is the power of the power block (MW), h_{TES} represents the total number of energy storage hours (h), η_{PB} states for the power block efficiency. Also, the capacity factor (*CF*) of 100MWe capacity CSP can be predicted from [47]:

$$CF = \frac{\sum_{h=1}^{8760} E_{PB}}{8760 \times 100MW} \quad (10)$$

Where, the number 8760 refers to the number hours of a year. Utilizing the equations mentioned earlier, one can derive additional energetic, economic, and environmental metrics. These metrics include the quantity of fossil fuel saved, the potential reduction in greenhouse gas emissions, mitigation of ecosystem degradation, and the financial savings that can be allocated to enhancing living conditions and infrastructure within the country.

Economic Evaluation of Concentrated Solar Power

There are no dedicated sources addressing the economic assessment of Concentrated Solar Energy in Libya. However, certain references investigate the potential for investing in this technology within the country [48]. Determining the LCOE involves considering various factors such as investment costs, maintenance and operation expenses, and environmental revenue. It's crucial to highlight that the LCOE rating is subject to variation across countries and is influenced by factors like weather conditions, fossil fuel costs, and local regulations. The LCOE can be quantified in terms of annual energy yields (E_{PB}), capital (C_{CSP}), operation and maintenance expenses ($O\&M_{CSP}$), as well as costs related to environmental damage as in equation (8) [49-55]

$$LCOE = \frac{\frac{i(i+1)^n}{(i+1)^n - 1} C_{CSP} + O\&M_{CSP} - C_{CO2}}{E_{PB}} \quad (8)$$

Where: C_{CSP} represents the capital costs of the system ($), $O\&M_{CSP}$ is the annual operating and maintenance costs of the system ($), E_{PB} denotes the annual energy yield by the CSP (kWh/year), C_{CO2} is the annual environmental damage cost ($), and i is the interest rate and is assumed to be equal to 8% [15], and n is the lifespan of the system and is assumed to be 30 years [56]. The electricity generation in Libya is 100% based on fired fossil fuel power stations. The annual CO_2 environmental damage cost C_{CO2} can be expressed as [57,58]:

$$C_{CO2} = EF_{CO2} \times E_{PB} \times \emptyset_{CO2} \quad (9)$$

EF_{CO2} is the CO_2 emission factor [kg CO_2/MWh], E_{PB} is the annual energy generated by the offered system [MWh], and $\emptyset_{CO2}$ indicates the carbon social cost $/ton$CO_2$. The average carbon price has been set at least $75 per ton CO_2 by the end of the decade [59], and would rise to $85 a ton in 2030 [60].

Results and Discussions

Two types of electric power generation techniques from concentrated solar energy have been studied, which are the STP field and the PTC field, with different capacities (100-200-300-400-500-600-700) MW, under several solar multiple, and for multiple storage capacities (0-2-4-6- 8-10-12) hours using the dynamic simulation program SAM version 29.2.2020.

Energy Analysis of PSC plants

The dynamic simulation of concentrated solar energy systems was carried out under the climatic condition for the year 2022 of the city of Ubari city as shown in the Figure 10. It can be seen from Figure 10 (ii) that the hottest time in the year goes from March to September. Similarly, Figure 10 (ii) shows that the windiest times in the site are around May and June.

Figure 11 showcases results obtained through SAM software simulations under design point conditions for a 100 MWe capacity SPT plant in Ubari city. The graphs display hourly thermal power incidents, total power output, and grid-supplied power. Figure 10 (i) and Figure 11 reveal a strong correlation with Direct Normal Irradiance (DNI) and peaking during a long period starting from March to September months. The annual average incident thermal power is approximately 263 MWt, leading to an annual gross electrical power generation of about 48.0 MWe, with an electric power injection to the grid of 44.7 MWe. Consequently, the annual energy yield is 375.358 GWh, accompanied by a capacity factor of 47.6%.

Figure 12 depicts the monthly overall efficiency (η_p) of the SPT plant, with an estimated annual average efficiency of about 18.3% and a maximum of 36.5%, recorded at 11:30 in September, reaching 41.5%. Meanwhile, Figure 13 illustrates SAM-simulated results for a 100 MWe PTC plant in Ubari. The annual average incident thermal power is approximately 231 MWt, generating 37.4 MWe, injecting 34.2 MWe to the grid, resulting in an annual energy yield of 288.507 GWh at a 36.6% capacity factor.

Figure 14 illustrates the average monthly overall efficiency (η_p) of the PTC plant. The estimated annual average efficiency is approximately 14.7%, with the maximum recorded at about 33.8%. The peak efficiency of 37.8% occurs at 14:30 in April. In summary, considering identical climatic, design, and operational conditions, SPT technology outperforms PTC technology. However, in all scenarios, concentrated solar power proves superior to PV solar technology under the same conditions. For instance, a 100MW PV capacity yields about 172.508 GWh annually with a capacity factor of 19.7%, highlighting the weather-dependent limitations of PV solar technology, as noted by local researchers [61-65].

Economic and Environmental Analysis

The concentrated solar field's solar multiple plays a crucial role in designing concentrated solar energy systems, given the cost implications of field size. A large field incurs high costs, while a small one may compromise the field's fundamental functionality, leading to suboptimal capital utilization [56]. Integrating concentrated solar energy with thermal storage presents a lucrative and adaptable option for strategic electric power generation, aligning with the increasing emphasis on clean, renewable energies in power generation [67]. Consequently, this study assesses the impact of both the solar multiple and the heat reservoir capacity for both types. The selection of the lowest LCOE is employed to distinguish between available options, as depicted in Figures 15 and 16 based on the analysis results. It is also show that as the hours of thermal storge increase the LCOE increases. Moreover, the LCOE for the SPT is lower that LCOE for the PTC at same solar multiple.

Libyan crude oil holds significant importance in the national economy, contributing to various industries, including chemical, petrochemical, and fuel. In chemical and petrochemical sectors, it serves as a raw material for producing a range of products such as plastics, fertilizers, dyes, and medicines [68]. Additionally, in the fuel industry, Libyan crude oil is transformed into energy sources like kerosene, diesel, and liquefied natural gas.

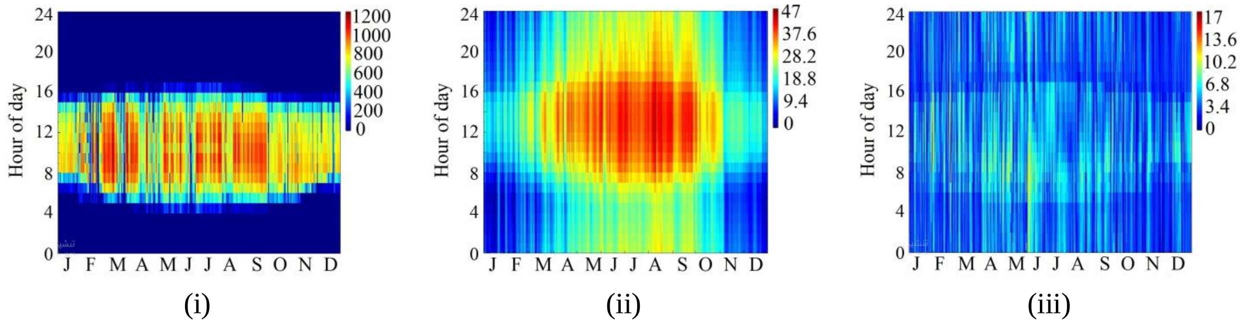

Figure 10: Key climatic parameters for Ubari city: (i) DNI, (ii) Ambient Temperature and (iii) Wind speed

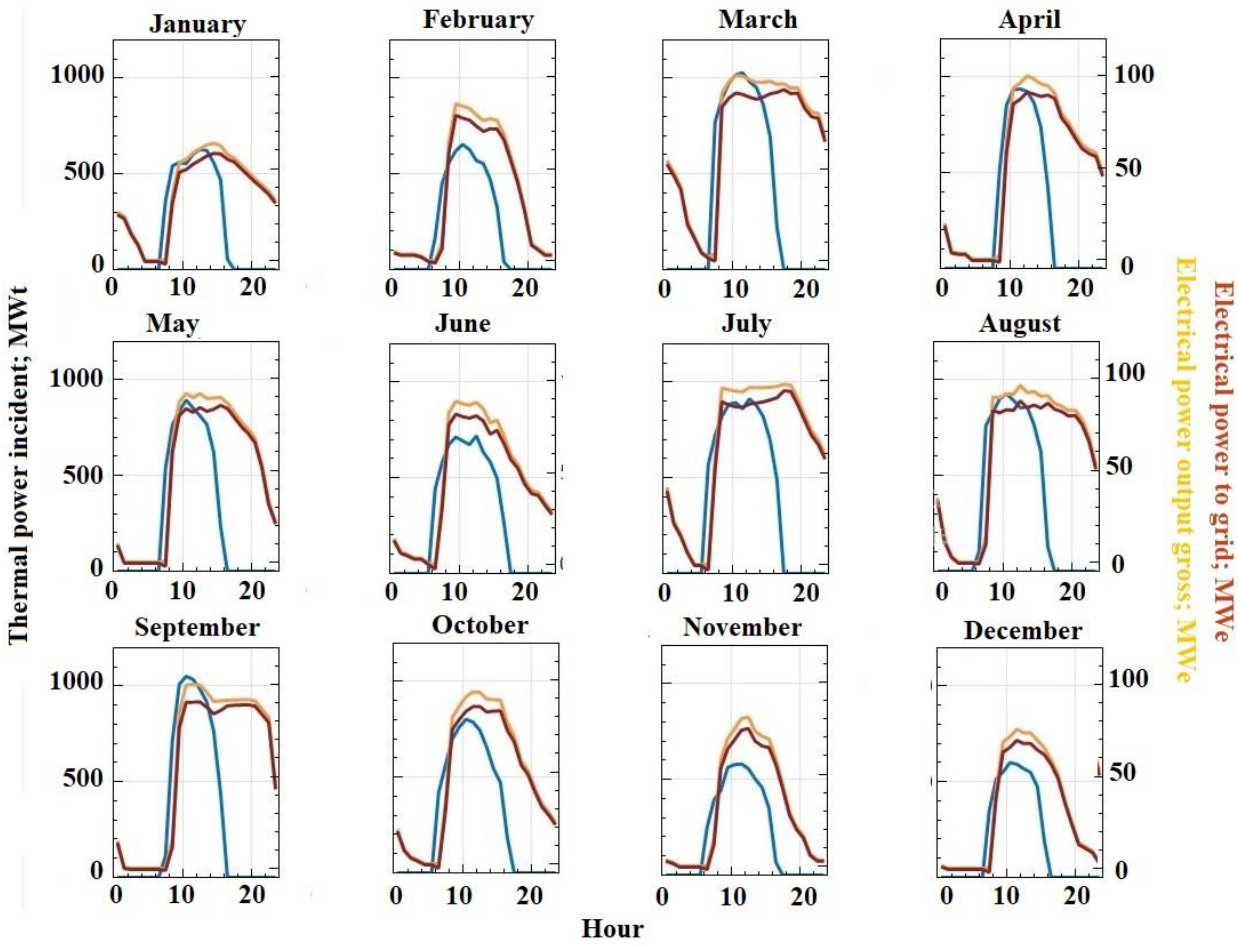

Figure 11: Monthly averages - hourly thermal power incidents, gross electrical power output, and total power injected to the grid for a 100 MWe SPT plant in Ubari, Libya

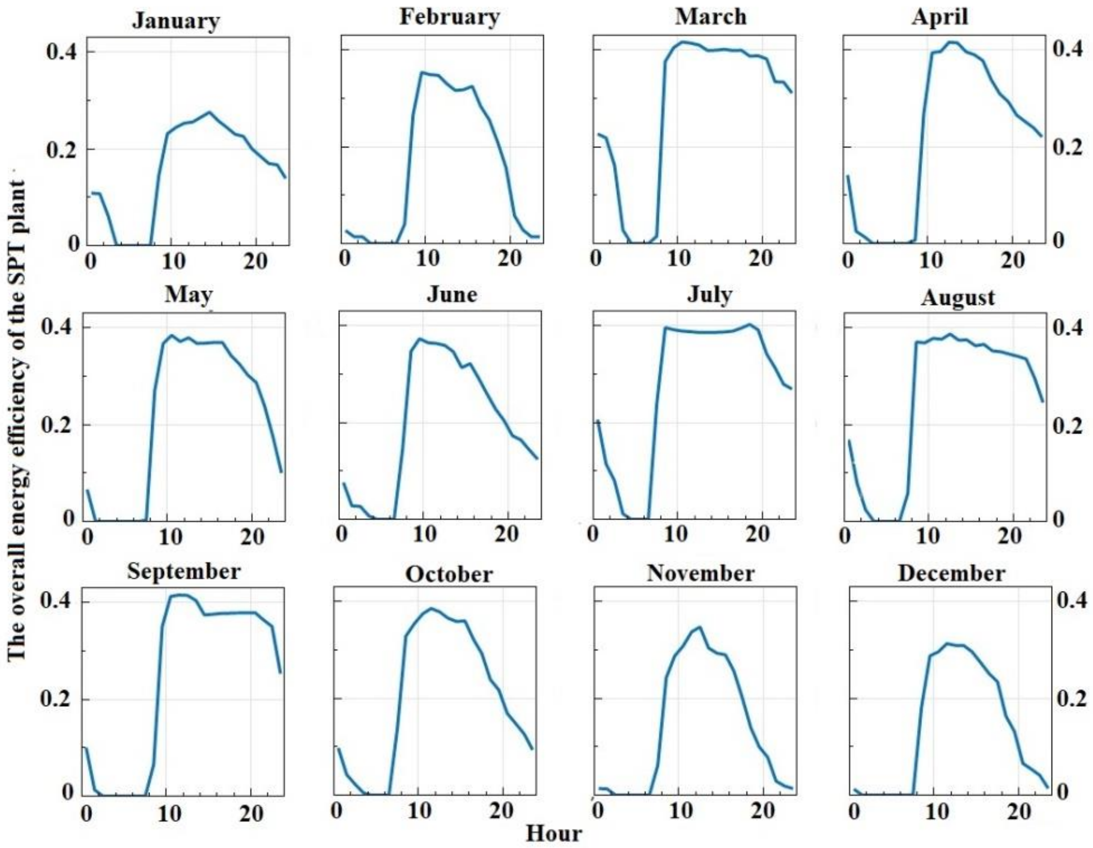

Figure 12: Monthly average hourly overall energy efficiency for 100 MWe capacity SPT plant in Ubari city – Libya

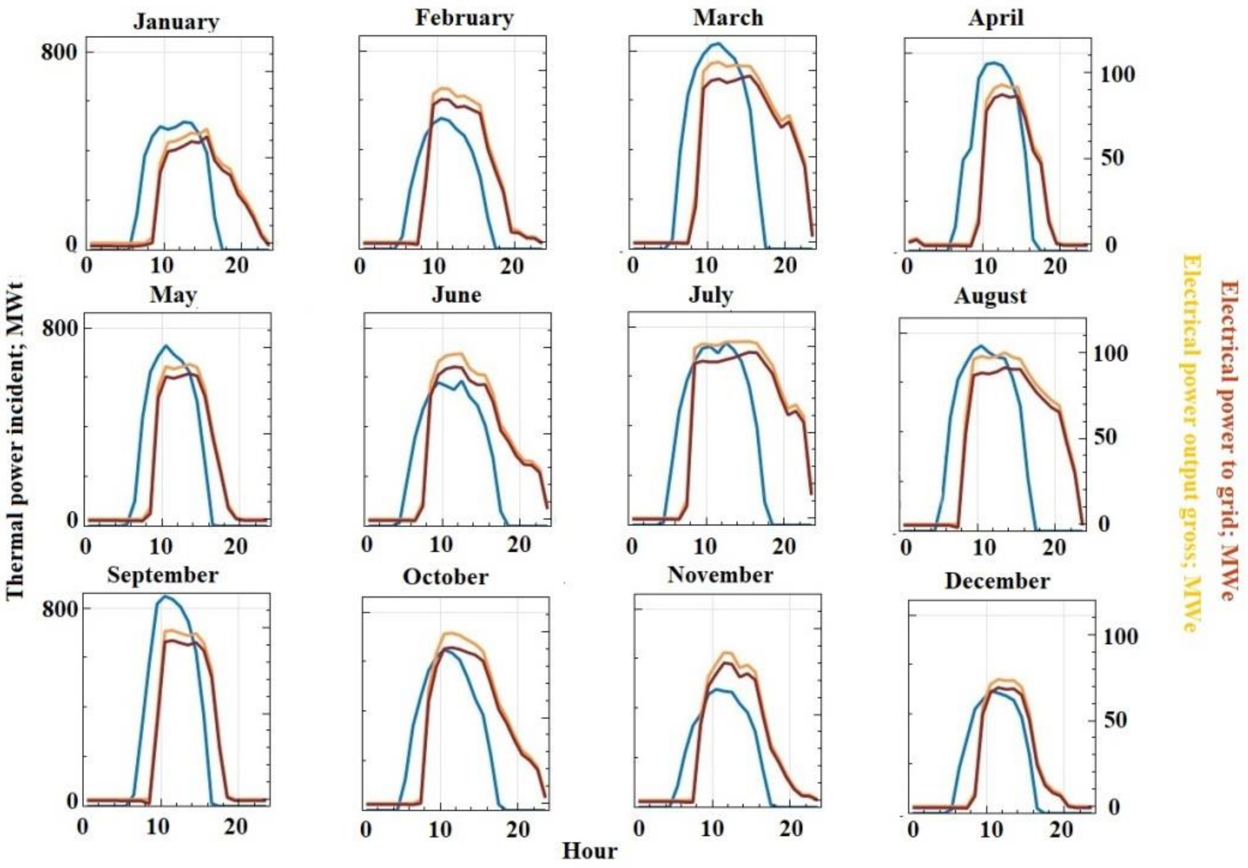

Figure 13: Monthly average hourly thermal power incident, gross electrical power output, and total electrical power injected to grid for 100 MWe capacity PTC plant in Ubari city – Libya

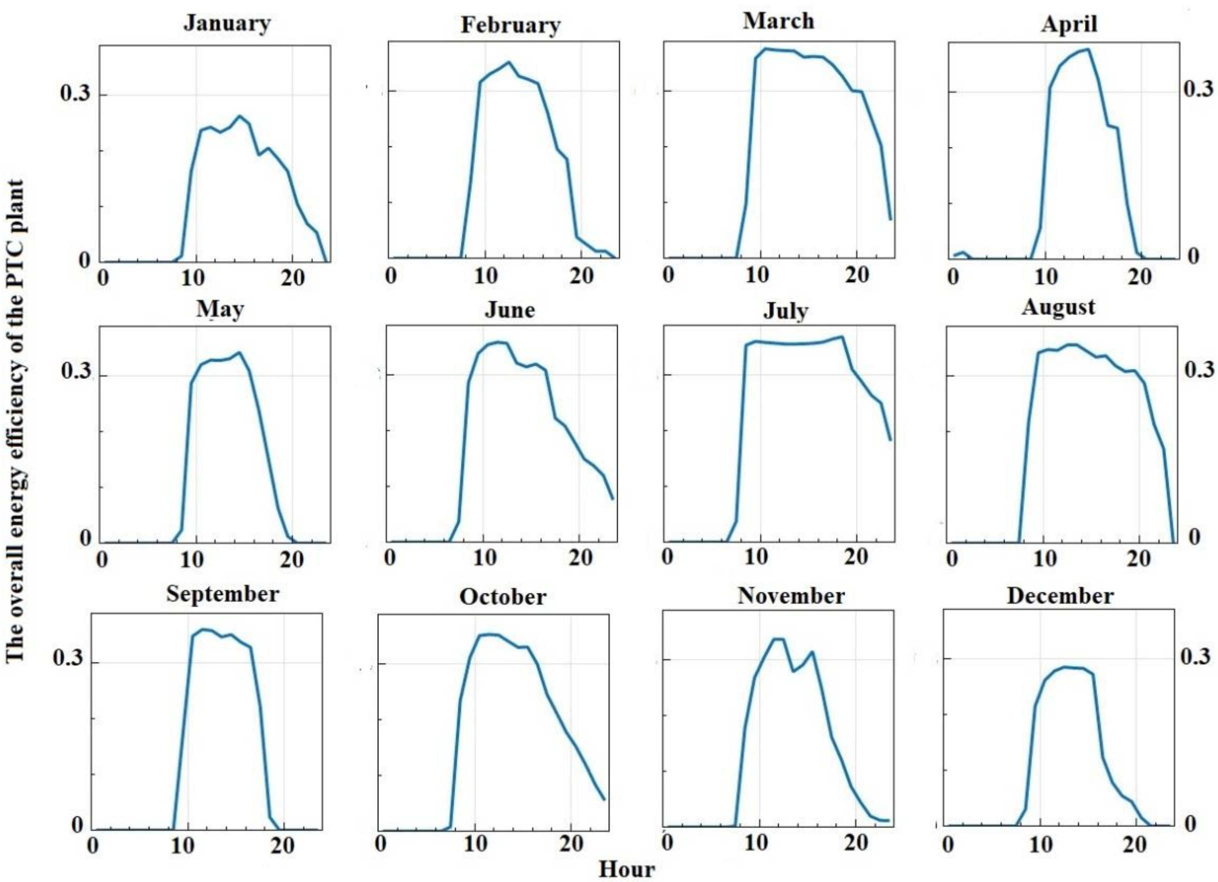

Figure 14: Monthly average hourly overall energy efficiency for 100 MWe capacity PTC plant in Ubari city – Libya

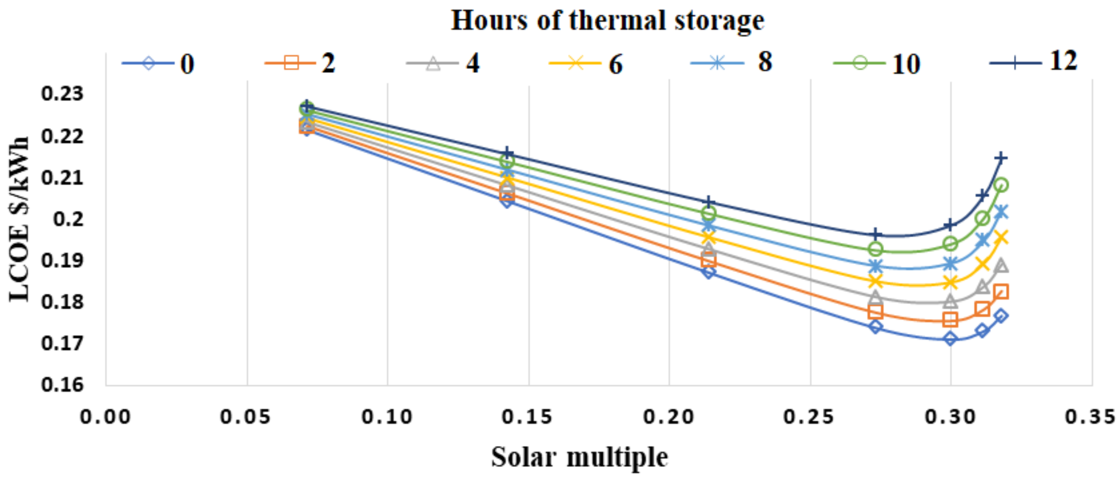

Figure 15: LCOE cost of power generation for PTC

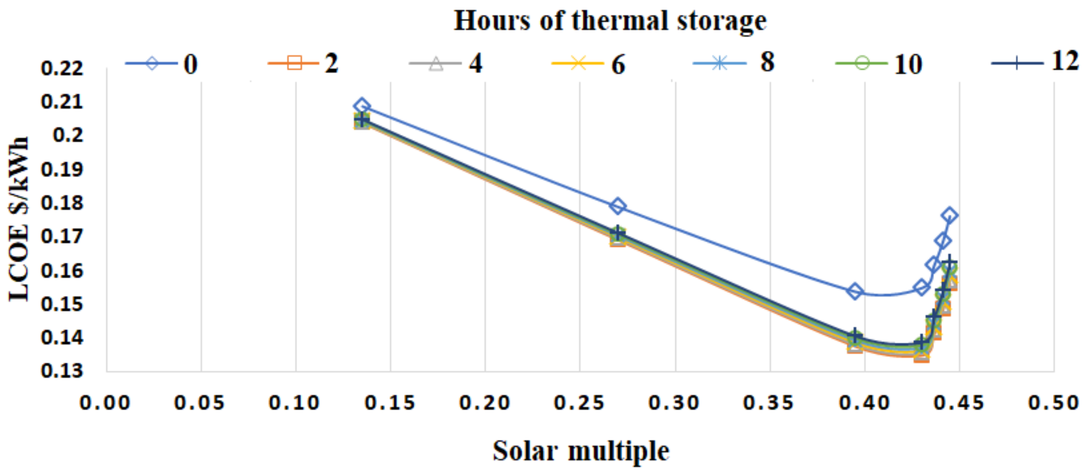

Figure 16: LCOE cost of power generation for SPT

This research aims to explore alternatives to reduce the reliance on burning crude oil for electricity generation in Libyan power plants. The calorific value of crude oil, taken from the Ubari power generation station, is 3.09 kWh/L, and the price of a barrel of Libyan oil reached $76.705 on 6/8/2023, considering a barrel's volume as 159L [69]. The obtained results show that it is possible to save about $243,637,911.5 in case of SPT and $299,336,438 in case of PTC utilizations.

Regarding the environmental analysis, the environmental damage cost of using crude oil in the production of electric power depends on several factors, such as the CO2 emission factor and the carbon social cost [70]. In general, it can be said that the use of crude oil in the production of electric power results in large emissions of greenhouse gases, leading to an increase in global temperatures and climate change, which affects terrestrial and marine life and human health. The CO2 emission factor was 983 kgCO2/kWh [71,72]. The carbon social cost is estimated at $75 for a ton of CO2, which means that the use of crude oil in producing electric power entails a huge cost of environmental damage. According to the study, it is possible to avoid releasing 1,735,057 tons of CO2 into the atmosphere in the case of SPT or 2,131,712 tons in the case of PTC utilizations. This will result in savings of approximately $159,878,342 for PTC and $130,129,247.2 for SPT. The data from Vaderobli et al. [73] were used to calculate the uncertainties, and the resulting tabulates in Table 2. The Table illustrates that the total uncertainties amount to approximately 15.7%. Given that the uncertainty in PV solar technology does not surpass 9.1%, as reported in [74], this uncertainty value is comparatively high.

Table 2: Uncertainties associated with the simulation of CSP plants

Type of uncertainty	Value
CSP system cost per m^2	2.7%
Land cost per acre	3.3 %
Power block cost per kWe	2.4%
Site improvement cost per m^2	1.7%
Solar field cost per m^2	2.6%
Storage system cost per kWht	3.1%
Total uncertainties	15.7%

Conclusions

This study presented the technical and economic possibilities of two different SPT and PTC systems for the power plant to ascertain the optimal CSP technology in Libya and its countries and neighbouring countries with similar solar resources. The main objective of this study was to identify the most suitable CSP technology and to provide decision makers with the technical, economic and environmental inventory of the proposed project. The goal was achieved satisfactorily, and presented here the key findings of the research:

1. The lowest LCOE value for the SPT field was 13.48

cents/kWh, while the LCOE for the PTC field was 17.09 cents/kWh.

2. The optimum capacity of SPT field is about 400 MW with CF of 43.6%. In comparison, the capacity of the PTC is 500 MW with CF of 29.9%.
3. The SPT field has a storage time of 2 hours, while a PTC has a storage time of 0 hours.
4. The area of the field of SPT is 5,076,220 m^2, while the area of the PTC is 4,733,696 m^2.
5. The volume of the reservoir in the SPT is 11332 m^3, while the PTC does not have a reservoir.
6. The capital cost for the SPT is about $1,861,026,432, and the PTC is about $1,551,351,400
7. The annual saved crude oil cost for the SPT is $243,637,912, while the PTC $299,336,438.
8. The annual amount of CO2 prevented from being emitted into the atmosphere is estimated at approximately 1,735,057 ton in case of SPT or 2,131,712 ton in case of PTC
9. The annual environmental damage cost saving for SPT is about $130,129,247.2 while for PTC is about $159,878,342.

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