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RESEARCH ARTICLE RENEWABLE ENERGY

Techno-Economic Feasibility of Parabolic Trough Solar Steam for Thermal Enhanced Oil Recovery

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ABSTRACT

This study rigorously evaluates the techno-economic feasibility of parabolic-trough collector (PTC) for thermal enhanced oil recovery (EOR) by benchmarking it against conventional diesel-fired boiler steam supply across geographically diverse thermal-EOR fields. Site-specific direct normal irradiance data from NREL's NSRDB are used to characterize the solar resource and size the collector aperture area. Techno-economic calculations and scenario evaluation are conducted using HOMER Pro, while the proposed PTC configuration includes thermal energy storage with an equivalent duration of 6 h/day and is assessed under a representative capacity factor of 0.6, reflecting partial coverage of steam-load demand. A harmonized levelized cost of energy (LCOE) framework is applied to both configurations under consistent financial assumptions to enable an apples-to-apples comparison. Results show that boiler-based LCOE is strongly driven by local diesel pricing and heat-duty requirements the Netherlands (NLD) exhibits the highest boiler LCOE, whereas Venezuela (VEN1) yields the lowest. A second Venezuelan case (VEN2) produces an anomalously high boiler LCOE around 4.5, attributable to an exceptionally large reported heat duty; it is therefore treated as an outlier with elevated uncertainty. PTC investment inputs are parameterized using NREL benchmark unit costs 24.375 SAR/kW installation, 712.5 SAR/m^2 solar field, and 93.75 SAR/kWh thermal storage. Beyond cost competitiveness, solar steam substitution provides a credible pathway for fuel displacement and associated CO_2 mitigation; reported solar-EOR deployments indicate annual CO_2 reductions ranging from 104 to 636,720 tCO_2/year, depending on plant scale.

الجدوى التقنية والاقتصادية لتوليد البخار الشمسي باستخدام المجمعات الحوضية القطعية المكافئة من اجل الاستخلاص الحراري المعززللنفط

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الكلمات المفتاحية

الاستخلاص المعزز للنفط
الطاقة الشمسية
الحقن الحراري
التحليل التقني-الاقتصادي
توليد البخار
مجمع القطع المكافئ

الملخص

تُقيِّم هذه الدراسة بصورةٍ منهجية الجدوى التقنية-الاقتصادية لتوليد البخار باستخدام مجمّعات القطع المكافئ (PTC) في تطبيقات الاستخلاص المعزَّز للنفط حرارياً (EOR)، وذلك عبر مقارنته بإمداد البخار التقليدي من مراجل تعمل بالديزل في حقول حرارية متنوعة جغرافياً. تم الاعتماد على بيانات الإشعاع الشمسي المباشر العمودي الخاصة بكل موقع من قاعدة بيانات الموارد الشمسية الوطنية (NSRDB) التابعة لـ المختبر الوطني للطاقة المتجددة (NREL) لوصف المورد الشمسي وتحديد مساحة فتحة المجمّعات. أُجريت الحسابات والمحاكاة وتقييم السيناريوهات باستخدام برنامج (HOMER Pro). يتضمن النظام المقترح تخزين الطاقة الحرارية لمدة مكافئة 6 ساعات/يوم، وتم تقييمه عند معامل قدرة 0.6 لتمثيل التغطية الجزئية لطلب البخار. ولتحقيق مقارنة عادلة، طُبِّق إطار موحَّد لتقدير التكلفة المستوية للطاقة (LCOE) على الخيارين تحت افتراضات مالية متسقة. تُظهر النتائج أن LCOE للمراجل يتأثر بقوة بسعر الديزل المحلي ومتطلبات الحمل الحراري؛ حيث سجّلت هولندا أعلى قيمة، بينما حققت فنزويلا (الحالة الأولى) أدنى قيمة. كما ظهرت حالة فنزويلية ثانية بقيمة شاذة مرتفعة (4.5) نتيجة حمل حراري مُبلّغ عنه استثنائياً، لذا عُوملت كحالة ذات عدم يقين أعلى. إضافةً إلى التنافسية الاقتصادية، يوفّر إحلال البخار الشمسي مساراً لخفض استهلاك الوقود وتقليل انبعاثات ثاني أكسيد الكربون (CO_2)، مع تخفيضات سنوية مُبلّغ عنها تتراوح بين 104 و636,720 طن CO_2/سنة بحسب حجم المشروع.

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Introduction

Global climate targets for a sustainable future and the need for decarbonization are driving the trend towards more sustainable energies and less carbon-intensive industrial practices. In sectors where energy consumption is high, the problem of emission sources is very daunting for those using high-temperature heat for processes. As a result, the importance of renewable heat sources, especially those which can be dispatched for more sustainable operations, cannot be overemphasized as a tool for fuel savings and emission reductions [1-3].

This remains one of the economically important activities around the world, and from market outlooks, this trend is supposed to continue through 2030 [4, 5]. The technology mix in the enhanced oil recovery (EOR) market is still predominantly dominated by thermal methods, indicative of the continuous steam-intensive recovery operations. A market context viewed in Figure 1 together points to the need to identify feasible pathways to reduce carbon intensity and fuel exposure of thermal EOR without undermining operational reliability [6,7].

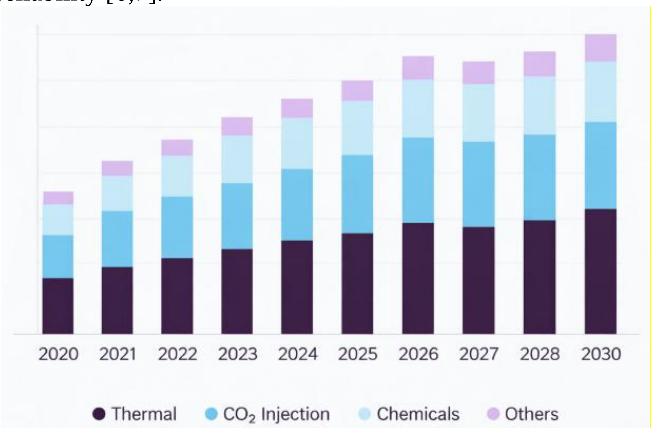


Figure 1: EOR market outlook by technology from 2020–2030. Reproduced with permission [7]

From a reservoir and production stand-point, hydrocarbon recovery typically occurs at a primary, secondary, and tertiary or 'enhanced oil recovery' stage. As tertiary EOR, other techniques involving injection are used when natural drive mechanisms and secondary recovery techniques are deemed less effective. Of particular interest among these techniques for heavy oil production is thermal EOR and specifically steam injection, which long ago became recognized as an important factor in heavy oil production due to its ability to increase oil mobility by reducing its viscosity by means of heating. As might be expected, costs were traditionally and markedly influenced by energy source and prices used for firing a boiler to generate steam [4, 8-10].

Solar enhanced oil recovery (S-EOR), hence, has drawn considerable interest as a means of partially replacing oil-based steam with solar thermal energy while ensuring field operability. Its implementation, however, is non-trivial due to the requirements of continuous steam injection with a guaranteed heat supply, as opposed to the intermittent nature of solar resources and the typically high capital cost of solar thermal systems [11-13].

To precisely establish the feasibility of S-EOR, it is important to compare solar-based steam generation to more conventional systems under common assumptions, considering a set of fields that reflect the geographic diversity of solar resources and operating conditions, as an aspect that has been highlighted in the chosen field map as presented in Figure 2 [14].

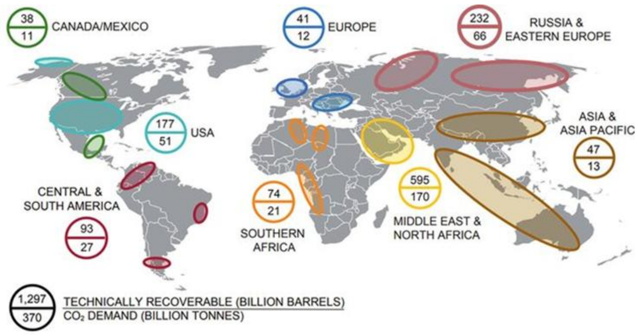


Figure 2: Global map showing the selected S-EOR fields considered in this study for evaluating solar-assisted steam generation. Reproduced with permission [7]

The S-EOR in general, encompasses the broader scope of the S-EOR literature with regard to the integration of solar energy into steam generation in thermal EOR with the general application of hybridization methodologies, which attempt to offset a percentage of boiler duty or apply solar steam generation with favourable resource availability. Despite the diversity in the literature, there is a homogeneity with regard to the motivation behind the research, which aims to reduce fuel costs, exposure, emissions, and improve the overall resiliency of steam-dependent processes. Designs, as with most applications, tend to be an integration with existing boiler designs, as opposed to replacement, to ensure dispatchability [15, 16].

In parallel, there is a mature body of work on the parabolic trough solar-thermal systems with industrial process heat and steam supply. This addresses collector-field sizing, optical/thermal performance, and system-integration constraints, and commonly identifies TES as one major enabler to improve dispatchability [17]. Storage can shift solar heat to match demand windows, reduce curtailment, and increase the effective utilization of the collector field, but it adds additional investment-and-performance trade-offs that must be properly evaluated using techno-economic framing [18, 19].

Techno-economic studies in this area most often rely on a levelled cost metric comparator-between solar-thermal systems and conventional boiler alternatives-such as LCOE or cost of steam [20, 21]. These studies reach a self-consistent conclusion: that competitiveness is determined by a linked set of drivers, including local fuel price, solar resource, steam duty, capacity factor, assumed financing/lifetime, and the degree of storage and hybridization. But it is possible for conclusions to differ among different studies due to the great differences in assumptions; further, input assumptions on performance and cost are not always harmonized [22].

The major shortcoming in all previous studies is that they generally lack a wide range of case studies, which may be carried out in a few geographic locations with limited operating conditions. Thus, "where solar thermal steam for EOR is most viable" cannot be generalized further. Additionally, in the previous studies, EOR potential is generally evaluated in terms of technical viability without properly benchmarking economics across several locations, and environmental potential is evaluated without properly benchmarking fuel displacement against a cost matrix [23, 24].

These gaps have important implications for decision processes. For the field screening and early stage of feasibility, a framework that not only facilitates comparison across locations but also measures the transparency of the framework in ways that allow the identification of dominant feasibility drivers is necessary. A rigorous multilocation benchmark, wherein a solar-assisted configuration is assessed relative to a reference configuration using a unified set of assumptions with a consistent boiler configuration, might offer valuable insights in the prioritization of deployment and conditions under which SASTS becomes compelling propositions [25-28].

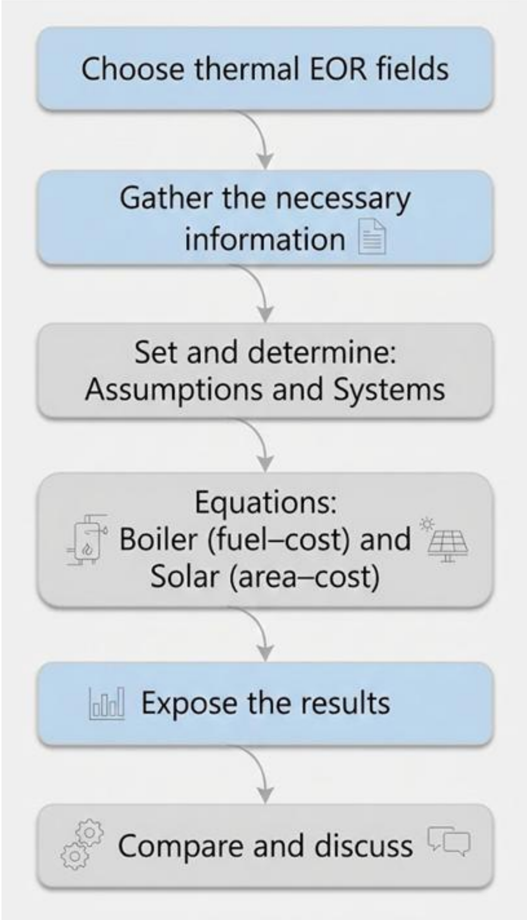
Even though there exists an increasing number of publications on aspects relevant to S-EOR and solar thermal steam supply systems, in fact, there is a need to establish a benchmark that consistently compares parabolic trough solar thermal steam generation systems with thermal storage across locations with a conventional boiler baseline, while also illustrating the impact of site-level variability with respect to solar resources, steam demand, and fuel pricing on techno-economic competitiveness and ranking. To this end, a benchmarking tool is established in this work through a unified benchmarking tool in HOMER Pro.

The present study helps achieve the above by:

1. A framework for comparing a configuration using a parabolic trough solar thermal steam system with thermal storage, versus a more conventional fuel-fired boiler configuration, using an apples-to-apples approach.
2. A geographically diverse evaluation set of thermal EOR fields, as depicted in Figure 2, where there exists variability of solar resource and economic factors
3. A driver-centric LCOE calculation tool that determines what factors are most impactful and what causes differences in competitiveness across locations.
4. Actionable outputs for screening purposes that emphasize the most favourable contexts for S-EOR and its associated reduction potentials for GHG emissions by fuel displacement.

Methodology

The approach starts with the identification of the targeted thermal EOR fields and the collection of the necessary input data. Later, the steam requirement, the identified system configuration, and the considered technical and economic assumptions are determined, as shown in Figurer 3. The underlying thermodynamic and economic equations are used to calculate the boiler-based and solar-based steam production. Finally, the obtained results are presented and analysed to facilitate a comparison among the considered locations.



Figurer 3: Flowchart summarizing the main steps of the proposed techno-economic feasibility assessment. Created by the authors

Thermal enhance oil recovery

The selected thermal EOR fields were chosen depending on the availability of information to meet the required steam demand at each location. The required information includes the consideration of ambient temperature and solar radiation. The main parameters considered in the calculation include steam pressure, steam quality, steam temperature, and steam rate. However, other important parameters considered include solar radiation and fuel prices, as shown in Table 1.

System and assumptions

Boiler system

In the first configuration, a conventional fuel-fired boiler is used to produce the necessary steam for the thermal EOR process, as depicted in Figure 4. In this conventional configuration for the baseline model, water is pumped to the boiler to produce steam by converting heat energy from fuel combustion into steam for direct application to the oil recovery process [30]. The performance and cost of the system are calculated based on specific assumptions for technical and economic parameters used for the calculations.

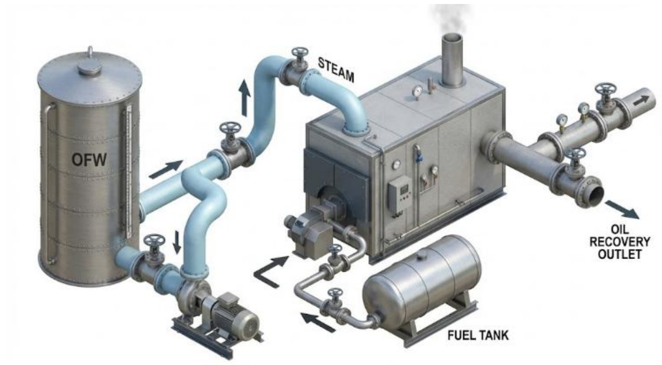


Figure 4: Conceptual schematic of the conventional fuel-fired boiler system for steam generation and delivery to the oil recovery process. Created by the authors

One of the important assumptions is inlet water temperature equals the average of the annual ambient temperature of the location, since the source of the water for this system will be sea or river water near the location [31]. Table 2 shows the assumption of the boiler system.

Table 1: Key operating parameters of selected thermal EOR fields worldwide, including steam injection method, steam pressure, steam quality, steam temperature, steam requirement, and oil production rate (BOPD) [29]

Location	Symbol	Steam injection method	Steam Pressure (Psig)	Steam quality (%)	Steam temperature (ºC)	Steam required (kton/day)	Oil production (BOPD)
Coalinga, California, USA	USA	Steam drive	406	80	229	1.40	27,000
Cold Lake, Alberta, Canada	CAN 1	CSS	1500	80	314	0.262	150,000
Peace River, Alberta, Canada	CAN 2	SAGD	915	95	278	0.64	80,000
Estreito, Brazil	BRA 1	CSS and Steam drive	333	75 - 80	219	15.8	28,000
Carmópolis, Brazil	BRA 2	Steam drive	129	75 - 80	179	1.00	18,100
Tia Juana, Venezuela	VEN 1	CSS and Steam drive	500	80	252	7.25	20,500
Bachaquero, Venezuela	VEN 2	CSS	1394	80	307	0.362	40,000
Duri, Indonesia	IDN	Steam drive	475	70	237	198	236,000 - 285,000
Issaran, Egypt	EGY	Steam drive	680	80	260	0.3965	5,000 – 6,000
Amal-West, Oman	OMN	Steam drive	1160	80	311	7.50	358,000
Cruse E, Trinidad	TTO	Steam drive	1000	80	283	0.317	35,000
Schoonebeek, Netherlands	NLD	SAGD	350	80	225	9.00	18,870

Table 2: Boiler system input assumptions and parameters used in the energy balance and cost calculations [32]

Boiler system		
Lower Heating Value (Diesel)	42.60	MJ/kg
Boiler Thermal Efficiency	86.1	%
Feedwater Inlet Temperature	25	℃
Time of System Operation	8760	$h/year$
Fuel Type	Diesel (distillate)	-
Fuel price	Varies by location	SAR/L

Parabolic trough system

The second configuration produces the necessary steam through the solar thermal system, as shown in Figure 5. In this research, the solar system is considered to be of parabolic trough collector (PTC) type because of its maturity and successful implementation in various S-EOR projects around the world. Operating and pilot projects of solar thermal systems are listed in Table 4, which verifies the suitability of PTC technology for steam production in EOR projects.

To determine quantitatively the thermal performance and cost of the solar-based steam supply, a set of technical and economic assumptions was used. These assumptions cover a set of values related to optical efficiency, thermal efficiency, solar representation, lifetime, cost factors, and other relevant values required to determine capital annualization and LCOE [33]. The assumptions used in determining the solar-based steam generation and its cost are presented in Table 3.

In the cost assessment section, the economic inputs were mainly obtained from the NREL (2010) cost study, which presents benchmark values for the installation cost, operation and maintenance (O&M), and other associated costs for PTC systems. These assumptions are presented in Table 5 [1].

Figure 5: Conceptual schematic of the PTC system supplying steam for thermal EOR operations. Created by the authors

Table 3: Solar system input parameters and assumptions applied in the incident heat, required collector area, and cost estimation model [34, 35]

Solar system		
Optical Efficiency	75	%
Thermal Efficiency	55	%
Specific Heat of Water	4.18	$kJ/kg \cdot K$
Latent Enthalpy	2257	kJ/kg
Initial Water Temperature	25	℃
Solar Collector Area	15000	$m^2/unit$
Thermal Storage Equivalent Duration	6	h/day

Table 4: Reported performance and environmental benefits of representative S-EOR projects worldwide (thermal output, steam production, fuel savings, and CO_2 reductions) [22, 24, 28]

Project name	Location	Peak Thermal Output (MW)	Energy Output (GWh/year)	Daily Steam Output (Tons)	Total Project Area (km^2)	Commissioning year	Gas Savings (Million Btus/year)	CO_2 Emissions Saved (Tons/year)
McKittrick	California	0.3	0.4	2	1.925×10^{-3}	2011	1,952	104
Amal I	Oman	9	12	50	0.0462	2012	47,437	2,514
Amal II	Oman	8	12	50	0.0462	2020	47,437	2,514
Miraah	Oman	330	445	2,000	0.7812	2017	1,897,461	100,679
Ma'aden Solar I	Saudi Arabia	1,500	3000	14,000	7	2026	12,000,000	636,720

Table 5: Unit cost assumptions for the solar thermal configuration derived from the NREL cost model, including installation, O&M, solar field, and thermal storage components [1]

Solar system Cost		
Installation	24.375	SAR/kW
O&M	168.75	$SAR/kW\cdot year$
Solar Field	712.5	SAR/m^2
Thermal Storage	93.75	$SAR/\ kW$h
Time of storage	6	h/day
Capacity factor	0.6	-

Lastly, a set of general assumptions that apply to all configurations was used, following the methodology proposed by the Office of Industrial Technologies, and these assumptions are presented in Table 6.

Table 6: General assumptions applied to both the boiler and solar system analyses [24]

General assumptions		
Time of Steam Operation	8760	h/year
MARR	10	%
Lifetime	30	years

Model Limitations and Uncertainty Drivers

It is worth noting that the current assessment is meant to be a comparative, early-stage screening-level assessment across various locations, rather than a more detailed investment-grade design study. Toward that purpose, a number of model simplification and uncertainty factors should be taken into consideration when making use of such results. First, it is worth noting that the solar resource model is based on a representation of the annual average DNI values, which does not take into account any possible effects of hourly/seasonal variability, dispatch constraints, etc., on collector field utilization and storage charge/discharge characteristics. Additionally, steam demand is modelled based on simplified continuous operation, typical of that utilized in thermal EOR applications.

Moreover, in terms of representing the cost of the boiler, it should also be noted that in such representation, there exists generalized formulas or correlations, like the “true cost of steam” approximation, to estimate the cost. Such formulas, in turn, may not reflect regional accounting, contracting, and utility pricing methods. In addition, regional transport issues, differences in labour and construction rates, as well as inflation or market pricing fluctuations, may affect the absolute levels of benchmark unit costs assigned to the solar-field and thermal storage components, although trends between locations will remain relevant.

The key determinants of uncertainty in this study are as follows: (i) Inter-annual variability in DNI and its corresponding associated model uncertainty, (ii) Price and procurement conditions related to diesel fuel, (iii) Uncertainties related to field operating conditions for some cases, as indicated by outlier behaviour, such as the case related to VEN2, and (iv) Technology-related uncertainties related to soiling, ambient conditions, and integration issues in the locations.

Therefore, results related to LCOE calculations ought to be interpreted with the understanding that they are largely comparative in nature, and the best locations ought to remain a priority in further and more accurate site-specific studies.

Mathematical modal

Boiler system

Initially, the required steam generation is quantified by employing specific enthalpies of feedwater at the inlet and steam produced at the outlet, and then the corresponding enthalpy rise is calculated with reference to steam tables [34].

$$\dot{q}_{\text{out}} = \dot{m}_{\text{steam}}(h_{\text{out}} - h_{\text{in}}) \quad (1)$$

This will enable the estimation of the amount of fuel needed to produce the target steam output, taking into account the efficiency of the boiler [35].

$$\dot{q}_{\text{in}} = \dot{m}_{\text{fuel}}\, LHV \quad (2)$$

$$\eta_{\text{boiler}} = \frac{\dot{q}_{\text{out}}}{\dot{q}_{\text{in}}} \quad (3)$$

$$\dot{m}_{\text{fuel}} = \frac{\dot{m}_{\text{steam}}(h_{\text{out}} - h_{\text{in}})}{LHV} \quad (4)$$

These will provide the estimated amount of fuel needed to produce steam by boiler system. Which will be extended to determine the cost of this system and the LCOE of compression. However, the cost of the fuel yearly is dependent on the fuel price, thus it has been found in Table 7.

$$C_{\text{fuel}} = \dot{m}_{\text{fuel}} \times FP \quad (5)$$

In the U.S. Department of Energy, the parameter named "steam cost" was found, which has several source costs such as fuel, water supplied, water treatment, power, and maintenance and labour, and this parameter equals 130% of fuel costs [28].

$$C_{\text{steam}} = 1.3\, C_{\text{fuel}} \quad (6)$$

Since there are various types of capacity of the steam, the cost will change. Therefore, the cost is calculated using the "cost to capacity" method. Also, ($Cref$ and $Sref$) are taken from the same paper, and (m) is the slop, which is usually taken as 0.6 [28].

$$C_{\text{capital}} = C_{\text{ref}}\left(\frac{S}{S_{\text{ref}}}\right)^m \quad (7)$$

$$A = C_{\text{capital}} \times \frac{i(i+1)^N}{(i+1)^N - 1} \quad (8)$$

$$\text{LCOE} = \frac{A + SC}{\sum_{t=1}^{8760} \dot{q}_{\text{out}}(t)} \quad (9)$$

Parabolic trough system

In a PTC system, the required steam output is achieved by converting solar irradiation into incident power on the aperture of the collector, which is then transferred to the working fluid to produce steam [22].

$$\dot{Q}_{\text{incident}} = \frac{\dot{Q}_{\text{out}}}{\eta_{\text{optical}}\, \eta_{\text{thermal}}} \quad (10)$$

$$A_{\text{required}} = \frac{\dot{Q}_{\text{incident}}}{\text{DNI}} \quad (11)$$

According to the cost model presented by NREL[35], the total cost of the PTC trough system comprises the solar field cost, insulation and installation costs, and thermal energy storage system costs.

$$C_{PT} = SP \times A_{\text{required}} \quad (12)$$

$$C_{\text{instal}} = \dot{Q}_{\text{out}} \times IP \quad (13)$$

$$C_{st} = \dot{Q}_{\text{out}} \times t_{\text{day}} \times SP \times CF \quad (14)$$

After that, the total capital cost is converted to an equivalent annual cost using annuitization (capital recovery factor), and the LCOE is evaluated accordingly [20].

$$A = (C_{PT} + C_{\text{instal}} + C_{st}) \times \frac{i(i+1)^N}{(i+1)^N - 1} \quad (15)$$

$$\text{LCOE} = \frac{A + SC}{\sum_{t=1}^{8760} \dot{q}_{\text{out}}(t)} \quad (16)$$

Annual energy output is calculated by annual operating time, so that LCOE is calculated by the annualized cost, in SAR/year, versus annual energy output in kWh/year.

Eco-environment Analysis

Since the goal is to perform a comparative analysis between the base case boiler configuration and the parabolic trough solar thermal configuration, the economic evaluation approach for this study will follow the economic evaluation approach based on the levelized cost approach metrics. Specifically, the levelized cost of energy will be adopted as the primary economic evaluation approach because of its ability to facilitate a fair and comparable economic analysis between two or more options through the normalization and subsequent aggregation of the annual energy deliverables. The levelized cost of energy will thus be estimated based on the following equation [19]:

$$LCOE = \frac{\frac{r(1+r)^n}{(1+r)^n - 1} \times C + C_{O\&M} - C_{CO2}}{E_t} \quad (17)$$

where r is the discount rate (MARR), n is the project lifetime, C is the total capital cost, $C_{O\&M}$ is the annual operation and maintenance cost, and E_t is the annual delivered thermal energy (kWh/year). The term C_{CO2} represents the avoided CO_2 environmental damage cost associated with fuel displacement relative to the boiler reference case.

Besides LCOE, the Payback Time Money (PBTM) is given as a complementary indicator that offers the time required to recover the initial investment from annual net income or annual savings. Together, LCOE and PBTM have provided transparency regarding lifecycle cost competitiveness and characteristics of investment recovery [19]:

$$PBTM = \frac{C}{Income} \quad (18)$$

The CO_2 damage-cost term is calculated as [19]:

$$C_{CO2} = EF_{CO2} \times E_t \times \phi_{CO2} \quad (19)$$

where EF_{CO2} denotes the CO_2 emission factor (kg CO_2/kWh) [19], and $\emptyset_{CO2}$ denotes the social cost of carbon (\$/ton CO_2), which is taken as \$ 70/ton CO_2 in this study [23].

Sensitivity Analysis

In order to check the robustness of results obtained from decision-making approaches, a sensitivity analysis was conducted for the most sensitive economic and eco-environmental parameters. In this analysis, changes in diesel price by ±20%, annual-average DNI by ±10%, solar system CAPEX by ±20%, discount rate/MARR from 8-12%, and social cost of carbon $\emptyset_{CO2}$ ranging from 0 to 140 \$/ton CO_2 are assessed on LCOE/Eco-LCOE values as well as on the final choice in terms of option preference: boiler vs. solar-thermal systems configuration. The influence of these parameters is assessed individually by varying one parameter at a time and keeping other parameters at baseline values [34], [35].

Results and Discussion

Meteorological data for all chosen locations were derived from the National Solar Radiation Database (NSRDB-NREL). Finally, based on the average DNI value of each location, the necessary concentrated solar power collector area is calculated, as shown in Table 7 and Figure 7. From the results obtained by the above-described boiler-based method, presented in Figure 6, it is evident that the best location is again related to the NLD, due to the fairly high associated fuel cost, whereas the worst location is related to the VEN 1, due to its moderate heat demand and, particularly, its low fuel price. According to the above, a different result is obtained for the VEN 2, which was not taken into account in the above calculation due to its unrealistic LCOE value derived from the above-described boiler-based method, which was around 4.5 mainly due to the particularly large heat duty of the above location, indicating that relevant data may not be consistent with other data.

To further enhance the quality of the study, several improvements are recommended. First, the analysis should be based on the inclusion of Saudi oil recovery locations and operation data to ensure the quality of the study. Second, the suggested system should be compared with the Ma'aden Solar I project to enable a comparison with an existing solar thermal power plant in Saudi Arabia. In addition, the analysis should be based on the evaluation of various operation modes of the solar system, including full operation without storage, full operation with storage, and the integrated mode with solar energy and the conventional boiler. Finally, the analysis should be extended to include the environmental impacts of the solar system, such as the reduction of CO_2 emissions, to enable the evaluation of the sustainability of the suggested solar power plant.

Table 7: Site-specific solar and economic input parameters (annual-average DNI, diesel price, and ambient temperature) used in the boiler and solar-thermal assessments

Location	Diesel cost (SAR/L)	Average DNI (W/m²)	Average ambient (ºC)
USA	4.24	284.03	8.90
CAN 1	6.32	164.18	2.4
CAN 2	6.32	164.18	1.7
BRA 1	4.48	183.04	28.6
BRA 2	4.48	250.22	26.7
VEN 1	0.02	166.52	21.1
VEN 2	0.02	225.21	21.1
IDN	3.88	193.53	28.9
EGY	1.41	266.78	25.5
OMN	3.20	230.93	27.6
TTO	2.80	227.57	27.6
NLD	6.99	108.96	10

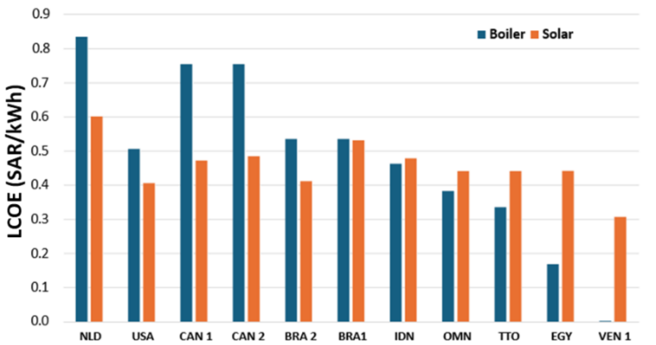


Figure 6: Location-based comparison of the LCOE for steam generation using a fuel-fired boiler vs PTC

Conclusions

This study investigates solar-assisted steam generation for Thermal EOR by comparing a fuel-fired boiler baseline with a parabolic trough collector configuration across a set of geographically diverse EOR fields. The results show that the boiler-based LCOE is mainly determined by the local fuel price and site heat-duty requirements, whereas the competitiveness of S-EOR exhibits strong dependencies on solar resource availability, steam demand, and storage assumptions. If the conditions are favourable, then S-EOR could reduce fuel consumption and associated CO_2 emissions and may attain competitive steam-generation costs relative to conventional boilers. The key barriers include high upfront capital cost, performance variability owing to resource uncertainty, and the necessity for thermal energy storage and appropriate dispatch strategies. Future work should focus on improving system efficiency and reliability while refining site-specific financial and operational models and quantifying uncertainty through sensitivity analyses to enable appropriate investment decisions.

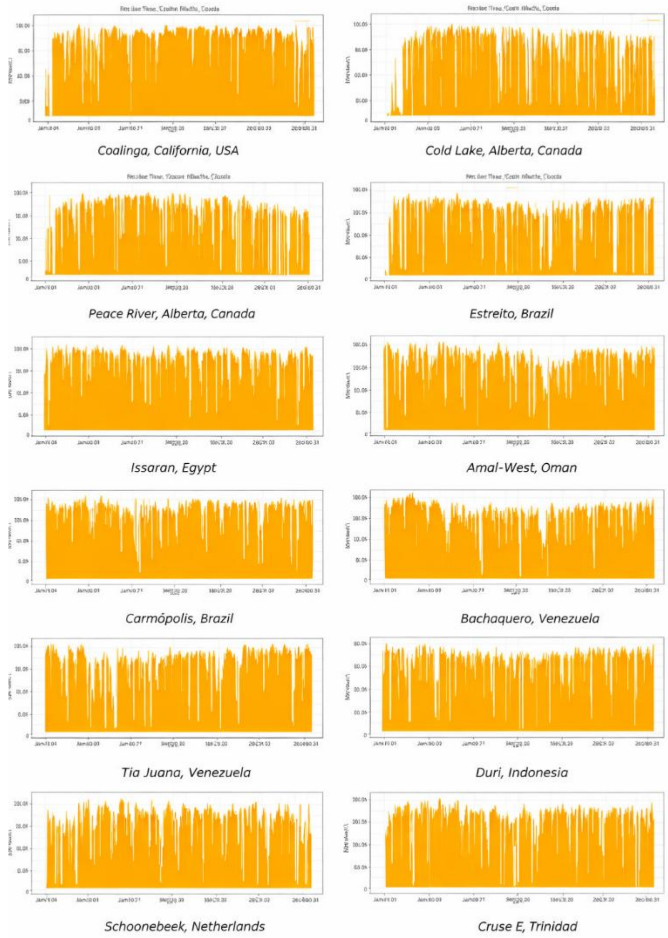


Figure 7: One-year DNI time-series for the selected global thermal EOR fields, derived from NSRDB-NREL data and used to estimate the required PTC area

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