



Research Article

Modelling and Economic Evaluation of a Solar-Assisted Crude Oil Heating System for Flow Assurance in Pipeline Transportation

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Abstract

Crude oil transportation in the Niger Delta requires effective thermal management to maintain flow assurance. Heat loss, wax precipitation, and increasing viscosity can restrict crude-oil flow and increase operational risks. This study developed an analytical techno-economic framework for solar-assisted heating of a representative 20 km crude-oil pipeline using Nigerian crude-oil properties and Niger Delta solar-resource data. Evacuated-tube collectors and a sensible-heat storage tank were sized, and a 25-year lifecycle cost analysis compared the hybrid solar-plus-gas system with gas-fired and electric-heating references. The model estimated a heating demand of 1.78 MW (15,622 MWh annually); polyurethane-foam insulation contributed 82.7% of total pipeline thermal resistance. An 8,549 m² collector field with 3,490 modules and a 546 m³ storage tank achieved an annual solar fraction of 38.7%. The solar system required USD 3.22 million in capital investment. After including supplementary gas for the 61.3% of annual demand not met by solar, and costing the conventional references against the full annual demand, the estimated annual OPEX was USD 139,840 for solar-assisted heating, USD 351,589 for gas-fired heating, and USD 1.698 million for electric heat tracing. Over 25 years at a 10% discount rate, the corrected lifecycle costs were USD 4.860 million, USD 5.594 million, and USD 17.316 million, respectively. The solar-assisted system had an estimated positive NPV of USD 0.734 million relative to gas-fired heating, an incremental-capital simple payback of 4.8 years, and a discounted payback of approximately 6.9 years. Its LCOH was USD 0.0343/kWh, about 13.1% below the gas-fired reference and 72.0% below electric heat tracing. Monte Carlo analysis using a simplified cash-flow formulation yielded a 100% probability of positive NPV for the investigated parameter distributions. The findings indicate potential for solar-assisted pipeline heating, but supplementary heating remains essential during low-solar periods. Pilot-scale validation and further assessment of hybrid backup strategies are recommended.

Keywords

Solar-Assisted Pipeline Heating, Flow Assurance, Evacuated-Tube Collector, Thermal Energy Storage, Lifecycle Cost Analysis, Levelized Cost of Heat, Niger Delta

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1. Introduction

Crude oil transportation through pipelines remains the most economical method for moving petroleum from production facilities to refineries and export terminals, and its viability depends on maintaining flow assurance throughout the journey [22]. Flow assurance failures, driven by wax precipitation, rising viscosity, and heat loss as crude cools in transit, remain among the most operationally disruptive and costly challenges facing the petroleum industry [8, 22]. Thermal management using electric heating cables, fossil-fuel-powered boilers, or direct-fired heaters is the industry's default response. However, these approaches raise operating costs and contribute significantly to greenhouse gas emissions [38]. As oil-producing economies pursue decarbonisation, solar thermal energy has emerged as a promising alternative source of process heat for pipeline and industrial applications [4, 23].

This challenge is especially acute in Nigeria, where the petroleum industry faces high operational costs and mounting environmental scrutiny from its reliance on gas-fired heaters and electric heating systems. Some major pipelines reportedly consume very large volumes of gas daily for heating alone. These conventional systems represent a significant operating expense and a source of carbon emissions that sits uneasily against Nigeria's climate commitments. Notably, the unreliability of grid power in remote pipeline locations compounds the problem. Nigerian crude oil, produced primarily from the Niger Delta Basin, further complicates matters. The major streams from the prolific Agbada Formation carry substantial wax content, with pour points between 18 °C and 36 °C, and wax appearance temperatures (WAT) ranging from 21 °C to 46 °C [5, 22, 39]. Once pipeline wall temperature falls below the WAT, a wax layer forms and progressively narrows the effective pipe diameter, raising pressure drop, pipe roughness, and energy consumption [8, 30]. Meanwhile, viscosity ranks top among the most operationally significant rheological properties for pipeline design. It can rise by several orders of magnitude as temperature falls toward the pour point [6, 45]. Despite Nigeria's abundant solar resource, averaging 5.25 kWh/m²/day in its oil-producing regions [5], solar thermal technology remains untapped for pipeline heating applications. Therefore, a critical knowledge gap persists regarding the technical design parameters, thermal performance, and economic feasibility of solar-assisted heating systems suited to Nigerian crude properties and climatic conditions.

Conventional thermal management spans gas-fired heater stations, electric heat tracing, steam heat tracing, and passive insulation, each with distinct cost, reliability, and emissions trade-offs [8]. Heater stations use direct-fired or water-bath heaters spaced to keep the crude above its minimum operability threshold [7, 22]. Electric heat tracing gives precise control but needs high-capacity power that is frequently unreliable in Nigeria's oil-producing regions [32]. Steam heat tracing, though able to cut viscosity by up to 24.2%, requires dedicated

infrastructure and carries leak risks [22]. The wax deposition these systems guard against has itself been well characterized. Ochieng *et al.* [29] found aggregation falling by up to 2.5% with Reynolds number but rising by up to 3.4% with Grashof number. Similarly, Liu *et al.* [24] showed that a 4 mm wax layer can shift local soil temperature by 1.42 K.

Parallel advances in solar collector technology have expanded the options for process heating. Flat-plate, evacuated-tube, and parabolic trough collectors differ markedly in operating range, efficiency, and cost [16, 36]. Flat-plate collectors suit delivery below 80 °C at 60-70% efficiency [41]. Evacuated-tube collectors sustain 70-80% efficiency at elevated temperatures under diffuse radiation [33, 40]. Parabolic trough collectors reach 100-400 °C but require tracking and greater capital outlay [37], with over 1,300 industrial solar process-heat systems commissioned worldwide by the end of 2024 [13, 15]. Solar thermal energy has been applied more broadly to heating duties in the petroleum industry [21]. Applied to petroleum operations, Cao *et al.* [4] developed a coupled model showing a 500 m² collector field could sustain a 20 km pipeline for over 200 days annually without electrical back-up. This is governed by the heat balance, in Equation (1), for a pipeline element of length dx:

$$\dot{m}C_p \frac{dT}{dx} = Q_{\text{solar}} - Q_{\text{loss}} \quad (1)$$

where $\dot{m}$ is the crude oil mass flow rate (kg/s), C_p is the specific heat capacity of crude oil (J/kg K), $\frac{dT}{dx}$ is the axial temperature gradient (°C/m), Q_{solar} is the heat input per unit length from the solar system (W/m), and Q_{loss} is the radial heat loss per unit length to the surroundings (W/m). Wang and Zhang [43] paired collectors with wellhead thermal storage to cut seasonal CO₂ emissions. Khan *et al.* [19] and Khan *et al.* [18] reported solar fractions of 17-27% and paybacks of 7.5-8.8 years for parabolic trough retrofits in Pakistani refineries. Viability across these studies is judged through lifecycle cost, net present value, payback period, and levelized cost of heat [12, 14, 35]. Together, thermal storage has consistently been shown to raise solar fraction by decoupling collection from delivery [20, 42].

Despite this progress, the literature leaves three gaps relevant to the present study. Firstly, nearly all solar-pipeline and solar-process-heating studies are set in China or South Asia. This limits transferability to Nigerian crude properties, climate, and energy economics. Secondly, thermal models such as Cao *et al.* [4] fall short of a full collector-selection and sizing framework integrated with economic evaluation. Lastly, no published study has run a lifecycle economic comparison over a realistic 25-year horizon using Nigerian gas and electricity costs for Niger Delta crude. Table 1 summarises the key studies reviewed and the gaps each leaves open.

Table 1. Summary of key literature on solar-assisted heating for crude oil pipeline transportation and related applications.

Study	System/Technology	Location/Context	Key Metric	Main Finding	Research Gap (s)/Weakness (es)
Cao <i>et al.</i> [4]	Solar heating + pipeline transport model	China (generic production well)	Transport days, MTD; energy cost	500 m ² area supports >200 days without electrical heating (20 km pipe)	No economic analysis for Nigeria; no collector selection framework
Zhang and Wang [43]	Solar heating + sensible TES at well-head	China (well-head application)	CO ₂ reduction; economic benefit	Solar-TES system reduces CO ₂ and offers seasonal economic benefits	No pipeline-specific design; limited economic depth; not Nigeria-specific
Khan <i>et al.</i> [19]	PTC + TES for industrial heating (refinery)	Pakistan (5 cities)	Solar fraction; payback period; CO ₂	Solar fraction 17–27%; payback 7.51 years; 34.95 t CO ₂ /yr reduction	Refinery-focused, not pipeline flow assurance; not applicable to Nigerian crude
Wu <i>et al.</i> [44]	Solar + gas boiler for floating roof tank	Petroleum sector (generic)	Solar fraction; gas saving; emissions	Hybrid system achieves measurable gas savings and emission reduction	Tank heating, not pipeline; no lifecycle cost comparison with electric heating
Ochieng <i>et al.</i> [29]	Numerical wax deposition model (multiphase)	Generic pipeline (field-scale)	Reynolds, Grashof, Nusselt numbers	Wax aggregation decreases with Re; Nusselt number increases significantly with Re	No solar integration; no Nigeria-specific properties or climate data

The present study addresses these gaps by developing an integrated techno-economic framework for a solar-assisted crude oil pipeline heating system, explicitly parameterised for Niger Delta conditions. Building on the thermal-resistance and heat-balance formulations validated by Cao *et al.* [4] and Liu *et al.* [24], the study models pipeline heat loss and heating demand for a representative 20 km Niger Delta segment. It selects and sizes an evacuated-tube collector field using the Hottel-Whillier-Bliss efficiency relation [16, 36]. It models the sizing of a water-based sensible-heat thermal energy storage tank following established industrial-storage practice [20, 42]. The design is then translated into a three-dimensional piping and plant layout in PipeCAD. The economic analysis is subjected to a 25-year lifecycle cost analysis, including net present value, payback period, and levelized cost of heat [12, 14]. The outcomes, therefore, are benchmarked against gas-fired and electric heat-tracing alternatives using Nigerian fuel and electricity tariffs [27, 28]. Uncertainty assessment, through Monte Carlo simulation, shows the influence of every economic parameter investigated.

By pairing a Nigeria-specific thermal and solar-resource dataset with a full lifecycle economic comparison, this study provides quantitative benchmarks. Collector area, storage volume, capital cost, and levelized cost of heat for a solar-assisted flow-assurance solution have not previously been developed for Niger Delta conditions. The findings are intended to give pipeline operators and policymakers an evidence base for weighing solar thermal integration against conventional heating. This supports Nigeria's energy transition plan and its 250

gigawatts solar-capacity target by 2060 [9], within a downstream petroleum sector regulated under the Petroleum Industry Act 2021 [10]. The analysis is confined to surface pipeline transportation in Nigerian oil-producing regions, drawing on published crude oil properties, Niger Delta climatic and solar irradiation data, and a 25-year lifecycle cost horizon. Subsea pipelines and wellhead production conditions fall outside its scope, and the results are indicative rather than site-specific, pending detailed field surveys and engineering refinement. The remainder of this paper is organised as follows: Section 2 describes the materials, thermal and collector-sizing models, and economic-analysis methods; Section 3 presents and discusses the resulting pipeline heat demand, collector and storage sizing, solar fraction, capital and lifecycle costs, and Monte Carlo sensitivity results; and Section 4 concludes with recommendations for implementation and further work.

2. Materials and Methods

2.1. Materials and Tools

The following resources were used in this study: published thermal property data for Nigerian Niger Delta crude oils; solar irradiation and climatic data for the Niger Delta region, sourced from published databases and studies; published capital and operational cost data for solar thermal systems and conventional pipeline heating equipment; PipeCAD software, for developing the structural design model of the solar-as-

sisted crude oil heating system and pipeline layout; and Microsoft Excel, for data organisation, tabulation, cross-validation of economic results, lifecycle cost calculations, net present value analysis, levelized cost of heat computations, and Monte Carlo sensitivity analysis.

2.2. Thermal Properties and Heat Requirements of Nigerian Crude Oils

2.2.1. Crude Oil Thermal and Rheological Properties

The thermal and rheological properties of Nigerian heavy

crude oils were the primary inputs for all heat-requirement calculations. They were drawn from published characterisation studies of Niger Delta crude oil samples. These properties define the minimum operating temperature that the solar-assisted heating system must maintain along the pipeline. Also, they govern the sizing of both the collector system and the thermal energy storage unit. They include the wax appearance temperature (WAT), pour point, viscosity, specific heat capacity, and thermal conductivity of the crude oil. Published characterisation data from multiple Niger Delta crude oil studies and relevant conventional standards were consolidated in [Table 2](#). These constituted the baseline input dataset for all thermal and heat-requirement calculations in this study.

Table 2. Thermal and rheological properties of Nigerian Niger Delta crude oils.

Property	Range / Value	Model Value (adopted)	Source
API Gravity (°API)	20 – 40	32	Chanchangi <i>et al.</i> [5]; Kumar [22]
Wax Appearance Temperature, WAT (°C)	20 – 46	38	Sulaimon <i>et al.</i> [39]; Onwumelu <i>et al.</i> [30]
Pour Point (°C)	8 – 36	28	Sulaimon <i>et al.</i> [39]
Minimum Safe Pipeline Temperature, T_{min} (°C)	WAT + 5 safety margin	43	Kumar [22]; Elkatory <i>et al.</i> [8]
Crude Oil Inlet Temperature to Pipeline (°C)	45 – 65	50	Cao <i>et al.</i> [4]
Kinematic Viscosity at 40 °C (cSt)	35 – 120	80	Cao <i>et al.</i> [4]
Dynamic Viscosity at 50 °C (mPa s)	30 – 100	50	Cao <i>et al.</i> [4]
Specific Heat Capacity, C_p (J/kg K)	1,800 – 2,100	1,950	Cao <i>et al.</i> [4]
Thermal Conductivity, λ_{oil} (W/m K)	0.12 – 0.16	0.14	Cao <i>et al.</i> [4]
Crude Oil Density at 50 °C (kg/m ³)	830 – 880	855	Chanchangi <i>et al.</i> [5]
Wax Content (% mass)	8 – 20	14	Sulaimon <i>et al.</i> [39]
Latent Heat of Wax Crystallization (kJ/kg)	150 – 220	185	Ochieng <i>et al.</i> [29]

The model values in this study represent high-wax Niger Delta crude oil. WAT and pour point data cover published Niger Delta crude streams from multiple fields.

2.2.2. Pipeline Model Parameters

The pipeline's physical configuration determines the total

heat loss profile and the pipeline length that a given solar collector area can support. A representative onshore buried surface pipeline for the Niger Delta was adopted, with model parameters presented in [Table 3](#). The data are consistent with the range of parameters used in analogous solar-assisted pipeline heating studies [4].

Table 3. Proposed pipeline model parameters for the study system.

Parameter	Value	Source / Basis
Pipeline length, L (km)	20	Cao <i>et al.</i> [4]; typical Niger Delta trunk line segment
Internal pipe diameter, D_i (m)	0.254 (10 inches)	API 5L pipeline standard; Santoso <i>et al.</i> [32]

Parameter	Value	Source / Basis
Pipe wall thickness, t (m)	0.012	API 5L X65 specification
Pipe material	Carbon steel (API 5L X65)	Industry standard for crude oil transport
Insulation material	Polyurethane foam	Most common in Nigeria; Santoso <i>et al.</i> [32]
Insulation thickness, t_{ins} (m)	0.05	Elkatory <i>et al.</i> [8]
Thermal conductivity of insulation, λ_{ins} (W/m K)	0.027	Polyurethane foam; Cao <i>et al.</i> [4]
Pipeline burial depth, H (m)	1.0	Typical onshore Niger Delta installation
Soil thermal conductivity, λ_{soil} (W/m K)	1.0	Niger Delta soil; Cao <i>et al.</i> [4]
Ambient/soil temperature, T_{amb} (°C)	28	Niger Delta mean annual; Chanchangi <i>et al.</i> [5]
Crude oil mass flow rate, $\dot{m}$ (kg/s)	35	Equivalent to ~10,000 bbl/day throughput
Design inlet temperature at heater station, T_{inlet} (°C)	65	Target inlet temp above WAT+5 °C safety margin
Minimum acceptable pipeline exit temperature, T_{exit} (°C)	43	$T_{min} = WAT + 5$ °C safety margin
Thermal conductivity of pipe steel, λ_{steel} (W/m K)	50	Standard carbon steel value
Internal film heat-transfer coefficient, h_i (W/m ² K)	300	Standard criterion 250–400 W/m ² K for turbulent flow of heated crude oil in insulated pipelines, consistent with Cao <i>et al.</i> [4]

2.2.3. Pipeline Heat Loss and Total Heat Requirement Calculations

The radial heat loss from a buried insulated pipeline per unit length was computed using an overall thermal-resistance model. The overall heat transfer coefficient per unit length (U , W/m K) accounted for the thermal resistances of the crude oil film, the pipe wall, the insulation layer, and the surrounding soil. Equation (2) expresses the overall heat transfer coefficient, as employed in prior studies such as Cao *et al.* [4] and Liu *et al.* [24].

$$U = [R_{film} + R_{pipe} + R_{ins} + R_{soil}]^{-1} \left[\frac{W}{m} \cdot K \right] \quad (2)$$

The individual thermal resistances per unit length (m K/W) are given by Equations (3) to (6):

$$R_{film} = \frac{1}{(h_i \times \pi D_i)} \quad (3)$$

$$R_{pipe} = \frac{\ln(\frac{D_o}{D_i})}{2\pi\lambda_{steel}} \quad (4)$$

$$R_{ins} = \frac{\ln(\frac{D_{o,ins}}{D_o})}{2\pi\lambda_{ins}} \quad (5)$$

$$R_{soil} = \frac{\ln(\frac{4H}{D_{o,ins}})}{2\pi\lambda_{soil}} \quad (6)$$

where h_i is the internal film heat transfer coefficient (W/m² K); D_i and D_o are the internal and external pipe diameters (m), respectively; $D_{o,ins}$ is the external insulation diameter (m); λ_{steel} is the thermal conductivity of pipe steel (50 W/m K); and H is the burial depth of the pipe centre-line (m). The heat loss rate per unit length at any position along the pipeline was then given by Equation (7):

$$Q_{loss}(x) = U\pi D_{o,ins}(T_{oil}(x) - T_{amb}) \quad [W/m] \quad (7)$$

The total heat loss along the pipeline length L was computed by integrating Equation (7) over the pipeline, as given by Equation (8).

$$Q_{loss,total} = U\pi D_{o,ins}(\bar{T}_{oil} - T_{amb}) \times L \quad [W] \quad (8)$$

where $\bar{T}_{oil}$ is the mean crude oil temperature along the pipeline. The total thermal power required at the heater station to maintain the crude oil above T_{min} at the pipeline exit was determined using Equation (9).

$$Q_{heating} = \dot{m}C_p(T_{inlet} - T_{exit}) + Q_{loss,total} \quad [W] \quad (9)$$

where T_{inlet} is the crude oil temperature at the heater-station inlet (°C), and T_{exit} is the minimum acceptable temperature at the pipeline exit (°C). Equation (9) thus defines the gross heating demand that the solar-assisted system must supply.

2.3. Solar Thermal Collector System Model

The solar-assisted crude oil heating system was developed as a structural design model. No experimental testing or dynamic simulation was conducted. The design model was developed in PipeCAD and covered collector type selection, collector sizing, thermal energy storage sizing, and overall system configuration. PipeCAD, an industry-standard 3D piping and plant layout design tool, was used to generate the layout

drawings, equipment arrangement, and piping interconnection model of the proposed solar collector array, storage tank, heat exchanger, and pipeline integration point.

2.3.1. Solar Collector Type Selection

Three collector technologies were evaluated for suitability: flat-plate collectors (FPCs), evacuated-tube collectors (ETCs), and parabolic trough collectors (PTCs). The selection was based on operating temperature range, thermal efficiency at the target temperature, commercial availability in West Africa, capital cost, and mechanical complexity. Table 4 presents the comparative evaluation of the three technologies against the requirements of this study.

Table 4. Comparative evaluation of solar collector types for crude oil pipeline heating in the Niger Delta.

Criterion	Flat Plate Collector	Evacuated Tube Collector	Parabolic Trough Collector	Basis
Operating temp. range (°C)	< 80	60 – 150	100 – 400	Thermal Engineering [40]; Kalogirou [16]
Thermal efficiency at 60–80 °C	60 – 70%	70 – 80%	60 – 65%	Solarthermalworld [37]
Performance in diffuse radiation	Moderate	High	Low (tracking needed)	Thermal Engineering [40]
Tracking requirement	None	None	Single-axis required	Kalogirou [16]
Installed cost (USD/m ²)	200 – 400	120 – 190	120 – 297 (large fields)	Akar and Kurup [1]; Markspark-solutions [25]
Mechanical complexity	Low	Medium	High	Jamar [13]
Suitability for Niger Delta temperature range	Marginal	High	Suitable but over-specified	Chanchangi <i>et al.</i> [5]
Suitability for Nigerian field conditions	Moderate	High	Moderate-High	Khan <i>et al.</i> [19]
Selected for this study?	No	Yes	No	—

Flat-plate, evacuated-tube and parabolic-trough collectors represent the three principal non-concentrating and concentrating technologies available for industrial process heat [11]. Evacuated tube collectors were selected for this study on the basis of their high efficiency at the target operating temperature of 60–80 °C, the absence of tracking requirements, and strong performance under the partially diffuse irradiation conditions of the Niger Delta wet season.

2.3.2. Collector Array Sizing

The gross collector aperture area was derived from the energy balance between the useful heat output of the collector field and the pipeline heating demand. The useful heat output per unit area of the evacuated-tube collector field is given by

the Hottel-Whillier-Bliss equation, as given by Equation (10) [16, 36].

$$\eta = \eta_o - \frac{a_1(T_m - T_a)}{G} - \frac{a_2(T_m - T_a)^2}{G} \quad (10)$$

η is the instantaneous thermal efficiency of the collector (dimensionless); η_o is the zero-loss (optical) efficiency; a_1 is the first-order heat loss coefficient (W/m² K); a_2 is the second-order heat loss coefficient (W/m² K²); T_m is the mean fluid temperature in the collector (°C); T_a is the ambient air temperature (°C); and G is the global solar irradiance on the collector aperture (W/m²). Table 5 presents the adopted performance coefficients for the selected evacuated-tube collector type.

Table 5. Evacuated tube collector performance coefficients adopted for system sizing.

Parameter	Value	Source
Collector type	Heat-pipe evacuated tube collector	Thermal Engineering [40]
Zero-loss optical efficiency, η_0	0.78	Kadam <i>et al.</i> [15]
First-order heat loss coefficient, a_1 (W/m ² K)	1.20	Kadam <i>et al.</i> [15]
Second-order heat loss coefficient, a_2 (W/m ² K ²)	0.006	Kadam <i>et al.</i> [15]
Mean collector fluid temperature, T_m (°C)	70	Midpoint of 60–80 °C operating range
Ambient air temperature, T_a (°C)	30	Niger Delta wet season mean; Chanchangi <i>et al.</i> [5]
Design solar irradiance, G (W/m ²)	550	Niger Delta's mean mid-day value; Chanchangi <i>et al.</i> [5]
Instantaneous efficiency at design point, η (calculated)	0.675	Equation 10 evaluated at design point
Maximum collector operating pressure (bar)	6	Standard heat-pipe ETC specification
Collector module aperture area (m ²)	2.45 per module	Standard commercial ETC module size
Design interconnection	Series-parallel array	Standard large-field configuration

The useful heat output per unit collector area at the design point was then computed using Equation (11).

$$Q_u = \eta \times G \quad [\text{W/m}^2] \quad (11)$$

The gross collector aperture area required to meet a target fraction SF of the total annual heating demand was calculated using Equation (12).

$$A_c = \frac{SF \times Q_{\text{heating,annual}}}{\eta G \times H_{\text{daily}} \times N_{\text{days}}} \quad [\text{m}^2] \quad (12)$$

where SF is the target solar fraction (fraction of total heat demand met by solar energy); $Q_{\text{heating,annual}}$ is the total annual heating energy demand (Wh/year); H_{daily} is the average daily peak solar hours (h/day); and N_{days} is the number of operating days per year. An initial target solar fraction of 0.40 (40%) was adopted, consistent with the range demonstrated by Khan *et al.* [19] for comparable industrial solar heating systems in tropical climates.

2.3.3. Thermal Energy Storage Sizing

Water-based sensible heat storage was adopted as the ther-

mal energy storage (TES) medium, being technically and economically appropriate for the target operating temperature range of 60–80 °C [20, 42]. The storage tank volume required to buffer a defined storage duration τ (hours) at the collector field output power was given by Equation (13).

$$V_{\text{tank}} = \frac{Q_u A_c \tau}{\rho_{\text{water}} \times C_{p,\text{water}} \times \Delta T_{\text{storage}}} \quad [\text{m}^3] \quad (13)$$

where $Q_u \times A_c$ is the total useful heat output of the collector field (W); τ is the design storage duration (hours); ρ_{water} is the water density (1,000 kg/m³); $C_{p,\text{water}}$ is the specific heat of water (4,186 J/kg K); and $\Delta T_{\text{storage}}$ is the temperature swing of the storage medium (°C). A storage duration of 6 hours was adopted, consistent with the performance reported by Precision Business Insights [31] for water-based TES systems in industrial solar applications. This duration was not independently optimised in this study. It reflects a practical balance between tank capital cost, which scales with storage volume, and the ability to carry collected heat through short over-cast periods. It should be treated as a design assumption rather than an optimised result. Table 6 presents the TES design parameters.

Table 6. Thermal-energy-storage model parameters.

Parameter	Value	Source
Storage medium	Pressurised hot water	Koçak <i>et al.</i> [20]; Wang <i>et al.</i> [42]
Design storage temperature (°C)	75 (hot side) / 45 (cold side)	Target delivery temp for pipeline heat exchanger

Parameter	Value	Source
Temperature swing, $\Delta T_{\text{storage}}$ (°C)	30	Difference between hot and cold sides
Design storage duration, τ (hours)	6	Precision Business Insights [31]
Storage tank insulation	Mineral wool, 50 mm	Standard industrial TES insulation
Tank thermal loss coefficient ($\text{W/m}^2 \text{ K}$)	0.30	Typical insulated steel tank; Koçak <i>et al.</i> [20]
Heat exchanger type	Shell-and-tube	Standard for oil-water duty; industrial standard
Heat exchanger effectiveness, ε	0.80	Adopted design value; Cao <i>et al.</i> [4]
Number of storage tanks	1 per heater station	Centralised storage at heater station location

2.3.4. PipeCAD Design Model

PipeCAD was used to develop the structural design model of the proposed solar-assisted crude oil heating system, representing the system as a structural and piping layout comprising four principal steps. Firstly, the solar collector field array was modelled. The evacuated-tube collector modules were arranged in a south-facing bank at a tilt angle equal to the site latitude (approximately 5°N for the Niger Delta). They were grouped into rows with appropriate inter-row spacing to prevent shading. The 3D layout defined the structural mounting frames, module positions, and manifold arrangement. Secondly, the primary circuit piping was modelled, generating the interconnecting pipe routes from the collector field to the TES tank. This circuit includes the pump, expansion vessel, pressure relief valve, air vent, and isolation valves, with pipe diameters sized using the standard velocity criterion (1.0–1.5 m/s for the heat-transfer fluid). Thirdly, the secondary circuit and shell-and-tube heat exchanger were modelled. This incorporated the crude oil inlet and outlet connections from the existing pipeline, the bypass arrangement for conventional heating backup, and the associated control valve and instrumentation tie-ins. Fourthly, the TES tank was positioned within the equipment plot, with tank orientation, connection nozzles, safety relief route, and insulation cladding boundaries defined. The model's output was simply the plan view, guiding the

full-scale structural design for fabrication needs and further testing beyond the scope of this study.

2.4. Thermal Modelling and Solar Energy Contribution

Analytical heat transfer equations were applied to compute the solar energy contribution to total pipeline heating demand under Nigerian climatic conditions. No dynamic simulation software was used. The analysis was entirely formula-based, using the solar irradiation and climatic data of Section 2.4.1 together with the collector performance parameters of Section 2.3.2.

2.4.1. Solar Irradiation and Climatic Data for the Niger Delta

The Niger Delta region receives between 4.5 and 5.5 kWh/m²/day of global horizontal irradiation, with distinct seasonal variation between the dry season (November to March) and the wet season (April to October) [5]. This directly affects the solar fraction achieved in each period. Table 7 presents the monthly solar irradiation and ambient temperature data for the Niger Delta used in this study. The mean irradiance, G , was computed as daily irradiation divided by peak sun hours. Notably, the solar resource is lower during the wet season owing to increased cloud cover.

Table 7. Monthly solar irradiation and T_{amb} data for the Niger Delta region.

Month	Mean Daily Irradiation (kWh/m ² /day)	Mean Peak Sun Hours (h/day)	Mean Irradiance G (W/m ²)	Mean Ambient Temp. T_a (°C)	Season
January	5.2	6.0	600	28	Dry
February	5.4	6.2	615	29	Dry
March	5.1	5.8	580	30	Dry
April	4.8	5.5	545	30	Wet
May	4.5	5.2	510	29	Wet

Month	Mean Daily Irradiation (kWh/m ² /day)	Mean Peak Sun Hours (h/day)	Mean Irradiance G (W/m ²)	Mean Ambient Temp. Ta (°C)	Season
June	4.2	4.8	475	28	Wet
July	4.0	4.6	460	27	Wet
August	4.1	4.7	468	27	Wet
September	4.3	5.0	490	28	Wet
October	4.6	5.3	520	29	Wet
November	5.0	5.7	560	29	Dry
December	5.1	5.9	580	28	Dry
Annual Average	4.69	5.40	534	28.6	—

Source: Irradiation data adapted from Chanchangi *et al.* [5] and Budnukaeku [3].

2.4.2. Temperature Profile Along the Pipeline

The crude oil temperature profile along the pipeline is governed by the energy balance presented in Equation (1) [4]. Integrating the differential heat balance for a pipeline with no intermediate heat input yields the exponential temperature decay given by Equation (14).

$$T_{oil}(x) = T_{amb} + (T_{inlet} - T_{amb}) \times e^{-\left(\frac{Ux\pi D_{o,ins}}{\dot{m} \times C_p}\right)} \quad (14)$$

Equation (14) gives the crude oil temperature at any axial position x (m) along the pipeline and was used to determine the minimum pipeline length that can be supported without supplementary heating under given climatic and operating conditions. The critical pipeline length, L_{max} (maximum distance over which the crude oil temperature remains above T_{min}), was obtained by setting $T_{oil}(x) = T_{min}$ in Equation (14) and solving for x , yielding Equation (15).

$$L_{max} = \frac{\dot{m} \times C_p}{U\pi D_{o,ins}} \times \ln\left(\frac{T_{inlet} - T_{amb}}{T_{min} - T_{amb}}\right) [m] \quad (15)$$

Equation (15) was evaluated for both dry-season (high irradiance) and wet-season (low irradiance) conditions to determine the seasonal variation in system performance.

2.4.3. Solar Fraction Calculation

The solar fraction is the fraction of total pipeline heating demand supplied by solar energy over a defined period, computed using Equation (16).

$$SF = \frac{Q_{solar}}{Q_{heating,total}} \quad (16)$$

where Q_{solar} is the annual useful heat delivered by the solar collector field to the crude oil pipeline (Wh) and $Q_{heating,total}$

is the total annual heating demand of the pipeline (Wh). The annual useful heat output of the collector field was computed using Equation (17).

$$Q_{solar,annual} = \bar{\eta} A_c \sum_{m=1}^{12} (G_m H_m N_m) \quad [Wh/year] \quad (17)$$

where $\bar{\eta}$ is the mean annual thermal efficiency of the collector; G_m is the monthly mean irradiance (W/m²); H_m is the monthly mean peak sun hours (h/day); and N_m is the number of days in month m , summed over all twelve months. The annual heating demand was computed using Equation (18).

$$Q_{heating,annual} = Q_{heating} \times 24 \times 365 \quad [Wh/year] \quad (18)$$

where $Q_{heating}$ is the design heating power from Equation (9). Substituting Equations (17 and 18) into Equation (16) yields the annual solar fraction for the designed system.

2.5. Economic Analysis

A comprehensive lifecycle cost analysis was conducted to compare the solar-assisted heating system against two conventional alternatives: gas-fired heater stations and electric heat tracing. It was conducted over a 25-year study horizon, with all monetary values expressed in United States dollars (USD) at constant 2026 prices. However, slight modifications were made to mitigate some unstable international market prices. All economic calculations were implemented in Microsoft Excel.

2.5.1. Capital Expenditure Data

The capital expenditure (CAPEX) of the solar-assisted system encompassed the ETC field, TES tank, heat exchanger, primary and secondary circuit piping, circulating pumps, instrumentation, structural support, and installation. Cost data

were drawn from published industry sources updated to 2026 values. Table 8 presents the CAPEX cost basis and ranges. The collector module cost of USD 150/m² was adopted as the base case for industrial ETCs deployed at project scale in a

tropical region. The total collector-field CAPEX was given by 280 USD/m² × A_c, where 280 USD/m² includes modules plus mounting, piping, and balance-of-system.

Table 8. Capital expenditure cost basis for the solar-assisted crude oil heating system.

CAPEX Component	Cost Range (USD/m ² or USD M)	Base Case	Source
Evacuated tube collector modules	120 – 190 USD/m ²	150 USD/m ²	Marksparksolutions [25]; Kadam <i>et al.</i> [15]
Structural mounting and support	80 – 150 USD/m ²	80 USD/m ²	Khan <i>et al.</i> [19]
Primary circuit piping and fittings	50 – 120 USD/m ²	50 USD/m ²	Khan <i>et al.</i> [19]
TES hot water storage tank	0.10 – 0.18 USD M	0.12 USD M	Koçak <i>et al.</i> [20]; Precision Business Insights [31]
Shell-and-tube heat exchanger	0.015 – 0.03 USD M	0.025 USD M	Khan <i>et al.</i> [18]
Circulating pumps (primary + secondary)	0.05 – 0.15 USD M	0.08 USD M	Khan <i>et al.</i> [18]
Instrumentation and controls	0.010 – 0.1 USD M	0.05 USD M	Cao <i>et al.</i> [4]
Engineering, procurement, and construction (EPC)	15 – 20% of equipment cost	20% of the equipment cost	Khan <i>et al.</i> [19]
Commissioning and start-up	3 – 5% of EPC value	3% of EPC value	Sha <i>et al.</i> [34]
Total CAPEX for solar-assisted system (indicative)	USD 3,218,603 total (A _c = 8,549.4 m ²)	USD 3.22 million	Aggregated from above

2.5.2. Conventional Heating System Reference Costs

The economic comparison required a fully costed conventional heating baseline. Two reference systems were used: a gas-fired heater station and electric heat tracing. The former is the predominant technology in Nigeria's oil-producing regions [22], while the latter is the most common alternative for isolated pipeline segments [32]. Table 9 presents the capital and

operating cost parameters adopted for both conventional reference systems. The gas price of USD 2.80/MMBtu used in this study is the NMDPRA commercial-sector domestic base price effective 1 April 2026 [28]. On the other hand, the industrial electricity rate of USD 0.10/kWh was utilized, consistent with the NERC Band A tariff following the 2024 revision.

Table 9. Cost parameters for conventional pipeline heating reference systems.

Parameter	Gas-fired Heater Station	Electric Heat Tracing
CAPEX [equipment and installation] (USD M)	1.2 – 2.5	0.8 – 1.8
Base-case CAPEX (USD M)	2.2	1.8
Annual fuel (gas) cost: NMDPRA DBP 2026 (USD/MMBtu)	2.80 (commercial rate)	N/A (electricity used)
Annual electricity cost (Nigeria industrial rate, USD/kWh)	N/A	0.10
Annual O&M cost (% of CAPEX per year)	8.0%	3.0%
System thermal efficiency (%)	85	95
Design heating power delivered (kW)	Q _{heating} from Eq. 3.8	Q _{heating} from Eq. 3.8

Parameter	Gas-fired Heater Station	Electric Heat Tracing
Annual fuel/energy consumption (GJ/year)	$Q_{\text{heating,annual}} / \eta_{\text{boiler}}$	$Q_{\text{heating,annual}} / \eta_{\text{electric}}$
Equipment life (years)	25	25
Replacement cost at end of life (% of initial CAPEX)	40%	35%
Source	Kumar [22]; NMDPRA [28]	Santoso <i>et al.</i> [32]; NERC [27]

N/A means Not Available.

2.5.3. Lifecycle Cost Analysis Equations

The total lifecycle cost (LCC) of each heating system over the 25-year study horizon was computed by discounting all cost streams to present value using a discount rate, r , as given by Equation (19). It follows as previously implemented in Gilbert *et al.* [12] and Sha *et al.* [34].

$$LCC = CAPEX + PV(OPEX) + PV(Fuel) + PV(\text{Replacement}) - PV(\text{Salvage}) \quad [USD] \quad (19)$$

The present value of a uniform annual cost stream A over N years at discount rate r is given by Equation (20).

$$PV(A) = A \times \frac{1 - (1 + r)^{-N}}{r} \quad [USD] \quad (20)$$

The annual fuel cost for the gas-fired reference system was computed by Equation (21) with $SF = 0$ because this reference system supplies the full annual heating demand. For the solar-assisted hybrid system, the same equation was evaluated using the achieved solar fraction ($SF = 0.3869$) to cost the supplementary gas required for the unmet demand.

$$C_{\text{fuel,gas}} = \frac{Q_{\text{heating,annual}} \times (1 - SF)}{\eta_{\text{boiler}} \times 1055.06} \times P_{\text{gas}} \quad [USD/yr] \quad (21)$$

where the factor 1055.06 converts MJ to MMBtu, and P_{gas} is the gas price (USD/MMBtu). The term $(1 - SF)$ represents the fraction of annual heating demand supplied by supplementary gas in the hybrid solar-plus-gas configuration. Accordingly, $SF = 0$ was used for the gas-fired reference and $SF = 0.3869$ for the solar-assisted system. The net present value of the solar-assisted system relative to the gas-fired reference was given by Equation (22).

$$NPV = LCC_{\text{gas}} - LCC_{\text{solar}} \quad [USD] \quad (22)$$

A positive NPV in Equation (22) indicates that the solar system delivers greater lifecycle value than the gas-fired alternative [2]. The simple payback period (SPP) and discounted payback period (DPP) were computed from the annual savings

using Equations (23 and 24), respectively. Unlike SPP, DPP accounts for the time value of money, providing a more accurate estimate of the true payback duration for projects with long economic lives [17].

$$SPP = \frac{CAPEX_{\text{solar}}}{C_{\text{fuel,gas,ref}} - C_{\text{fuel,gas,hybrid}} - OPEX_{\text{solar}}} \quad [\text{years}] \quad (23)$$

$$DPP = \min \{ t^*: \sum_{t=0}^{t^*} \frac{\Delta CF_t}{(1+r)^t} \geq 0 \} \quad [\text{years}] \quad (24)$$

The levelized cost of heat (LCOH) for each system was computed using Equation (25), as used in Kabeyi and Olanrewaju [14].

$$LCOH = \frac{LCC}{\sum_{t=1}^N \frac{Q_{\text{heating,annual}}}{(1+r)^t}} \quad [USD/kWh] \quad (25)$$

Equations (20 to 25) were implemented in a Microsoft Excel workbook (version 2024), with all inputs drawn from Tables 9 and 10. A discount rate of 10% was adopted, consistent with the upstream Nigerian energy project benchmark used in Mohammed and Farzaneh [26].

2.5.4. Economic Sensitivity Analysis

The lifecycle cost model and Monte Carlo sensitivity analysis were implemented entirely in Microsoft Excel. The sensitivity parameters and their ranges of variation for the Monte Carlo simulation are defined in Table 10. These five parameters (collector aperture area, collector installed cost, gas price, electricity price, and discount rate) were selected because they are the inputs with the greatest direct influence on CAPEX and annual cash flow in the simplified NPV formulation. In addition, this is because plausible uncertainty ranges for each were available from the cited market and regulatory sources (Table 10). The parameters were sampled independently; in practice, gas price, electricity price, and the discount rate tend to move together to some degree during periods of macroeconomic change. Therefore, the resulting NPV distribution and the 100% positive-NPV probability likely understate the true downside risk and should be treated as an approximate, rather than a fully correlated, risk assessment.

Table 10. Monte Carlo input distributions for economic sensitivity analysis.

Parameter	Distribution	Low / Mean	High / Std Dev	Basis
Collector aperture area, A_c (m ²)	Normal	Mean: 8,549 (Eq. (12))	σ : 855 (10% of mean)	Equation (10) uncertainty
Collector installed cost (USD/m ²)	Triangular	Low: 150	High: 250	Marksparksolutions [25]
Gas price (USD/MMBtu)	Triangular	Low: 2.5	High: 3.5	NMDPRA [28]; market projection
Electricity price (USD/kWh)	Normal	Mean: 0.15	σ : 0.015	NERC [27]
Discount rate, r (%)	Normal	Mean: 10	σ : 2	Upstream Nigeria practice

3. Results and Discussion

This section presents the results obtained from the analytical model and structural design described in Section 2. It reports the outcomes in the order of the study's methodological sequence. The results follow: pipeline heat loss and heating demand; collector and thermal energy storage sizing; solar energy contribution under Niger Delta climatic conditions; capital expenditure; lifecycle cost and economic comparison with

conventional heating systems; the Monte Carlo sensitivity analysis; and the PipeCAD piping and plant design representation.

3.1. Pipeline Heat Loss and Heating Demand

The thermal-resistance model of Equations (2 to 6) was evaluated using the pipeline and insulation parameters of Table 3. Table 11 presents the computed thermal resistances and the resulting heat loss and heating demand for the 20 km pipeline segment.

Table 11. Pipeline thermal resistances, heat loss and heating demand.

Parameter	Value
Film resistance, R_{film} (m K/W)	0.0042
Pipe-wall resistance, R_{pipe} (m K/W)	0.0003
Insulation resistance, R_{ins} (m K/W)	1.8113
Soil resistance, R_{soil} (m K/W)	0.3755
Overall heat-transfer coefficient, U (W/m K)	0.4564
Total pipeline heat loss, $Q_{\text{loss,total}}$ (kW)	281.81
Design heating demand, Q_{heating} (kW)	1,783.31
Annual heating demand, $Q_{\text{heating,annual}}$ (MWh/yr)	15,621.84

The insulation layer contributes about 82.7% of the total thermal resistance. This confirms that the polyurethane-foam insulation is the dominant barrier to heat loss, consistent with the insulated-pipeline heat-transfer treatment of Cao *et al.* [4] and Liu *et al.* [24]. The resulting design heating demand of about 1.78 MW reflects both the sensible heat needed to raise the throughput to the heater-station inlet temperature and the distributed heat loss along the pipeline. This heating demand forms the baseline against which the solar collector field, TES, and conventional reference systems were sized and costed.

3.2. Crude Oil Temperature Profile and Critical Pipeline Length

Equation 14 was evaluated to obtain the crude oil temperature profile along the pipeline in the absence of intermediate heat input. Equation 15 was used to determine the critical pipeline length, L_{max} , at which the temperature falls to the minimum safe value of 43 °C. Figure 1 presents the resulting temperature profile.

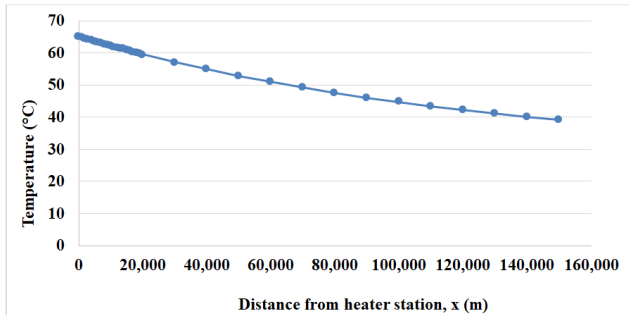


Figure 1. Crude oil temperature profile along the pipeline showing the 20 km design segment and the estimated critical (unheated) length range.

Under passive cooling alone (no intermediate heating), the crude oil temperature falls from 65 °C at the heater station to about 59.6 °C at 20 km, well above the 43 °C minimum. The corresponding critical lengths were 117.85 km for the dry season and 115.15 km for the wet season, both far in excess of the 20 km design segment. This indicates a substantial thermal safety margin in the insulation-plus-heating design. The pipeline could, in principle, be operated over roughly five to six times its design length before wax deposition risk from cooling becomes critical. This presents a favourable outcome from a flow-assurance and operational-resilience standpoint, should the heating system be briefly interrupted. This large safety margin also clarifies the relationship between the 1.78 MW design heating demand (Table 11) and the modest 5.4 °C passive-cooling drop shown in Figure 1. Out of the 1,783.31 kW total in Equation (9), only 281.81 kW (about 16%) is the pipeline heat loss, $Q_{\text{loss, total}}$, that is actually replenished over the 20 km design length. The remaining 1,501.50 kW (about 84%) is the sensible-heating term $mC_p(T_{\text{inlet}} - T_{\text{exit}})$. This sizes the heater-station duty to raise the full crude flow by the 22 °C margin between the design inlet temperature (65 °C) and the minimum acceptable exit temperature (43 °C), rather than heat actually lost to the environment over 20 km. The heating demand is therefore a heater-sizing convention, not a direct measure of in-pipe heat loss, which is why the passive temperature profile of Figure 1 falls only slightly over the design segment despite the much larger nominal heating demand.

3.3. Solar Collector Array and Thermal Energy Storage Sizing

The Hottel-Whillier-Bliss efficiency model and the collector-area sizing relation were evaluated using the performance coefficients of Table 5 and a target solar fraction of 40%. Table 12 summarises the collector sizing results, and Table 13 summarises the corresponding TES tank sizing obtained from

Equation (13).

Table 12. Solar collector array sizing results.

Parameter	Value
Instantaneous thermal efficiency, η (design point)	0.675
Useful heat output per unit area, Q_u (W/m ²)	371.4
Gross collector aperture area, A_c (m ²)	8,549.4
Number of evacuated-tube collector modules	3,490
Target solar fraction, SF	0.40

Table 13. Thermal energy storage (TES) tank sizing results.

Parameter	Value
Collector-field useful heat output, $Q_u \times A_c$ (MW)	3.18
Design storage duration, τ (hours)	6
Required TES tank volume, V_{tank} (m ³)	546.1
Tank diameter, D ($H/D = 1.5$) (m)	7.74
Tank height, H (m)	11.61

A gross aperture area of about 8,549 m², corresponding to roughly 3,490 evacuated-tube modules, was required to meet the 40% design solar fraction. This collector-field scale is consistent with the order of magnitude reported for industrial-scale solar process heat installations by Khan *et al.* [19] and Jamar [13]. The resulting TES tank of about 546 m³ provides a six-hour thermal buffer, allowing heat delivered during peak sunshine hours to be stored for use during periods of low irradiance. This agrees with the sensible heat-storage practice described by Wang *et al.* [42] and Koçak *et al.* [20] for industrial solar applications.

3.4. Monthly Solar Energy Contribution and Achieved Solar Fraction

The monthly-resolved efficiency and solar-contribution calculations of Equation 17 were evaluated using the irradiation data of Table 7. Figure 2 compares the monthly solar energy delivered by the collector field with the average monthly heating demand.

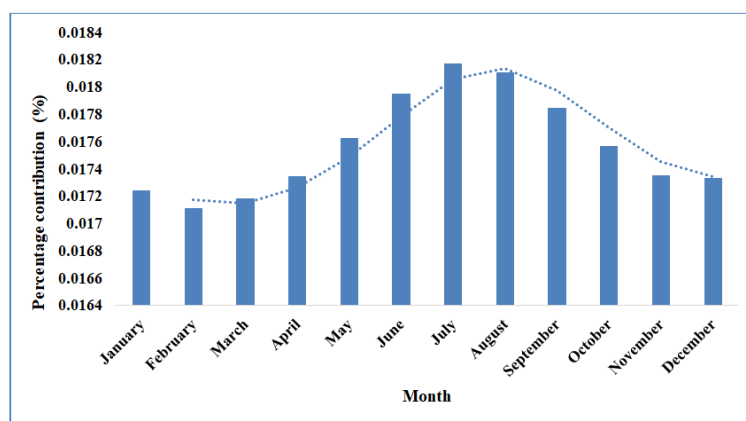


Figure 2. Monthly solar energy contribution to pipeline heating demand.

The collector field delivered an annual useful heat output of about 6,044 MWh against an annual heating demand of 15,622 MWh. This gives an achieved annual solar fraction of 38.7%, marginally below the 40% design target. The shortfall of about 1.3% arises because the design point (Table 5) was evaluated at a single representative irradiance and temperature. Whereas the achieved value integrates the monthly variation in irradiance and collector efficiency shown in Table 7, including the reduced solar resource during the wet season (April to October). Solar delivery is highest in the dry season (peaking at about 647 MWh in January) and lowest in the wet season (about 361 MWh in July), tracking the seasonal irradiation pattern reported for the Niger Delta by Chanchangi *et al.* [5].

3.5. Capital Expenditure of the Solar-Assisted System

The capital expenditure (CAPEX) of the solar-assisted heating system was computed from the cost basis of Table 8 for the sized collector area of 8,549.4 m². Table 14 presents the computed CAPEX breakdown.

Table 14. Computed CAPEX breakdown for the solar-assisted heating system.

CAPEX Component	Cost (USD)
Collector field (modules + mounting + piping)	2,393,825
Thermal energy storage tank	120,000
Shell-and-tube heat exchanger	25,000
Circulating pumps	80,000
Instrumentation and controls	50,000

CAPEX Component	Cost (USD)
Engineering, procurement and construction (EPC)	533,765
Commissioning and start-up	16,013
Total CAPEX	3,218,603

The total CAPEX of the solar-assisted system was about USD 3.22 million, of which the collector field (modules, mounting, and primary piping) alone accounted for nearly three-quarters of the cost. Akar and Kurup [1] and Sha *et al.* [34] showed similar results with the collector-dominated cost structure reported for large evacuated-tube installations. The EPC allowance was the second-largest contributor, reflecting the engineering and installation effort typical of first-of-a-kind industrial solar retrofits [19]. This CAPEX is markedly higher than the base-case CAPEX of the gas-fired and electric heat-tracing reference systems. The following section presents the results of assessing the systems against lifecycle operating-cost savings.

3.6. Lifecycle Cost, Payback Period, and Levelized Cost of Heat

Equations 20 to 25 were evaluated over the 25-year study horizon at a discount rate of 10%. The economic model was audited to ensure that the solar-assisted system includes both routine O&M and supplementary gas required for the portion of annual heating demand not met by solar. The achieved solar fraction, SF = 0.3869, was used for the hybrid system; the gas-fired and electric reference systems were costed at SF = 0 because each reference supplies the full annual heating demand. Table 15 summarises the corrected results.

Table 15. Lifecycle cost and leveled cost of heat comparison.

Metric	Solar-Assisted	Gas-Fired Reference	Electric Heat-Tracing
Base-case CAPEX (USD)	3,218,603	2,200,000	1,800,000
Annual OPEX (USD/yr)	139,840	351,589	1,698,404
Life-cycle cost, LCC (USD)	4,860,212	5,594,436	17,316,160
LCOH (USD/kWh)	0.0343	0.0395	0.1221

With supplementary gas included, annual OPEX is USD 139,840 for the solar-assisted system, compared with USD 351,589 for the gas-fired reference and USD 1,698,404 for electric heat tracing. The corresponding 25-year lifecycle costs, including the replacement-cost assumptions, are USD 4.860 million, USD 5.594 million, and USD 17.316 million, respectively. The NPV of the solar-assisted system relative to gas-fired heating is therefore approximately USD 734,224. The incremental capital premium is USD 1,018,603, while the annual OPEX saving is USD 211,748. On this consistent incremental-CAPEX basis, the simple payback period is 4.81 years. Discounting the annual savings at 10% gives a discounted payback of approximately 6.89 years (interpolated within year 7). The corrected LCOH values are USD 0.0343/kWh for solar-assisted heating, USD 0.0395/kWh for gas-fired heating, and USD 0.1221/kWh for electric heat tracing. Thus, the solar-assisted option has an LCOH about 13.1% below the gas-fired reference and 72.0% below electric heat tracing. These estimates depend on the stated fuel-price, efficiency, O&M, replacement, and discount-rate assumptions and should not be interpreted as site-validated costs.

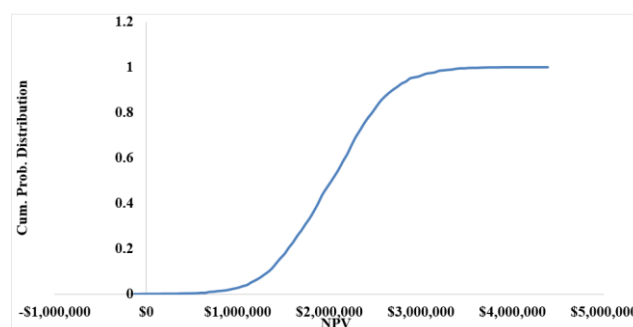
3.7. Monte Carlo Sensitivity Analysis

A 2,000-iteration Monte Carlo simulation was calculated using a simplified NPV formulation that includes full-demand gas cost for the gas-fired reference and supplementary gas cost for the solar-assisted system at the achieved SF. The sampled parameters remain collector aperture area, collector installed cost, gas price, electricity price, and discount rate. Table 16 reports the calculated distribution. Because this remains a simplified model and assumes independent parameter sampling, its probability estimate should be interpreted as indicative rather than as a fully correlated risk assessment.

Table 16. Monte Carlo simulation results for simplified NPV.

Statistic	Value
Mean simplified NPV (USD)	2,018,770
Standard deviation of NPV (USD)	539,727
5th percentile NPV (USD)	1,152,174

Statistic	Value
95th percentile NPV (USD)	2,878,382
Probability of positive NPV, P (NPV > 0)	100.0%
Minimum NPV (USD)	28,802
Maximum NPV (USD)	4,387,154

**Figure 3.** Monte Carlo cumulative probability distribution of simplified NPV.

The 2,000-draw simulation produced a mean simplified NPV of USD 2.019 million and a 100% frequency of positive NPV in the sampled draws. The 5th percentile was USD 1.152 million, and the minimum was approximately USD 28,802. These figures were generated by the workbook's simplified model and are not a substitute for a full probabilistic lifecycle model.

3.8. PipeCAD Piping and Plant Design Representation

To satisfy this study's objective of a structural design, the sized equipment and line data from Sections 3.1 to 3.6 were translated into a 3D piping and plant design, in Figure 4, using PipeCAD. The collector-field area, TES tank geometry, heat-exchanger effectiveness, pipeline bore, insulation thickness and burial depth, and the design heating duty and achieved solar fraction were carried across directly as equipment and line attributes. The produced drawing is parametrically consistent

with the analytical results reported above. The resulting general arrangement/plot plan lays out the ETC field (EQ-100, 8,549 m²), the shell-and-tube heat exchanger (E-101), the TES tank, the heater-station skid, the primary and secondary circulating pumps (P-101, P-102), and the tie-in to the buried 20

km, 10-inch API 5L X65 crude oil pipeline (L-201). Temperature, flow, and pressure instrumentation are shown at the heater-station tie-in and collector-field header. This specifically satisfies the process instrumentation implied by the heat-loss and demand model of Section 2.2.3.

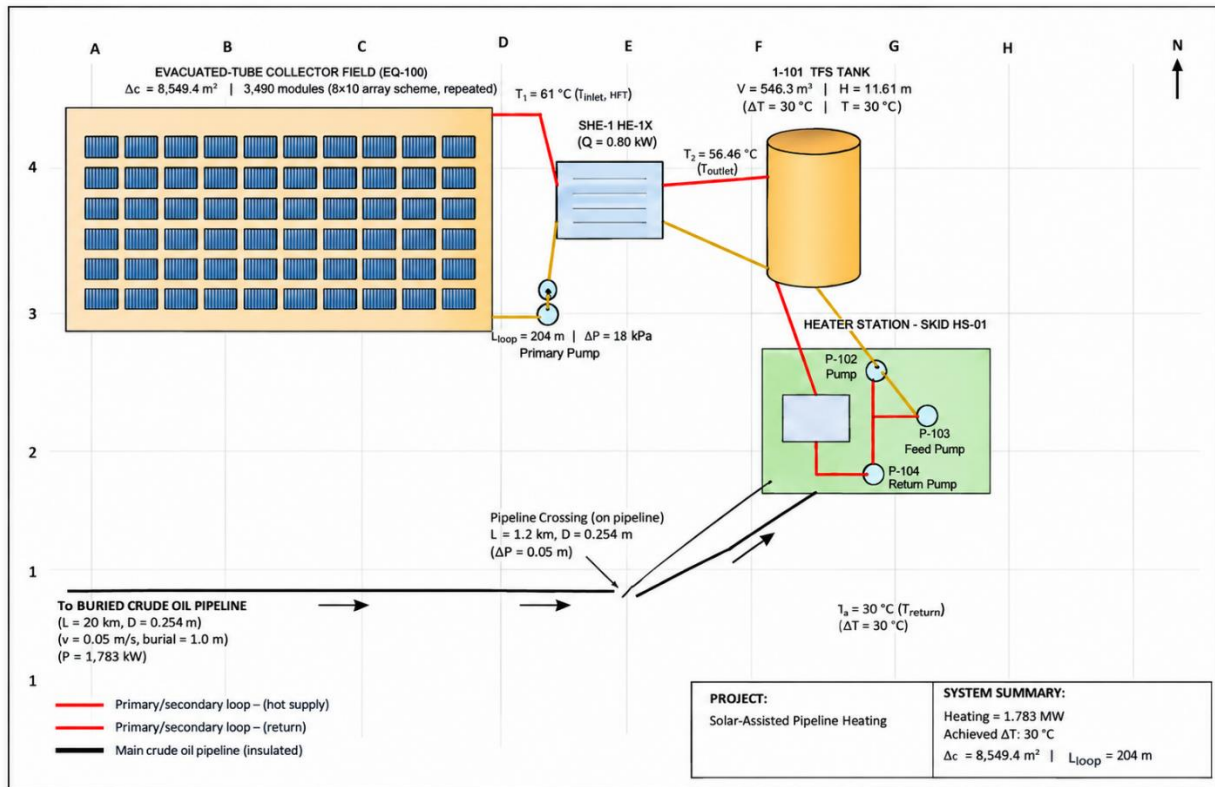


Figure 4. General Arrangement / Plot Plan of the solar-assisted crude oil pipeline heating system.

Finally, the PipeCAD representation demonstrates that the analytical design translates into a dimensionally consistent plant layout. Consistency between the drawing title block and the analytical model indicates that the technical and economic results are not merely theoretical. However, the full constructability of the analytical model would require detailed engineering design, equipment vendor data, and site-specific review beyond the scope of this study. Together, these findings show that a solar-assisted heating system can meet Nigerian pipeline flow-assurance requirements at a lower lifecycle cost than conventional alternatives. Nonetheless, the seasonal solar-fraction shortfall remains the principal limitation for future refinement.

4. Conclusions and Recommendations

4.1. Conclusions

This study developed and evaluated an analytical techno-economic model for a solar-assisted crude oil pipeline heating

system for a representative 20 km Niger Delta pipeline segment. The pipeline heat-loss and demand model showed that polyurethane-foam insulation accounts for about 82.7% of the total thermal resistance. This resulted in a design heating demand of about 15,622 MWh/yr for the 20 km target segment. The pipeline retained a substantial passive thermal margin, with a critical unheated length of 115–118 km compared with the 20 km design length. Some notable conclusions of this study include:

- 1) A collector field of about 8,549 m² (3,490 evacuated-tube modules) with a 546 m³ thermal energy storage tank was required to approach a 40% design solar fraction. The achieved annual solar fraction was 38.7%, with solar contribution strongly seasonal.
- 2) After explicitly including supplementary gas for the 61.3% of annual demand not met by solar and correcting the conventional reference costs to cover full demand, annual OPEX was USD 139,840 for solar-assisted heating, USD 351,589 for gas-fired heating, and USD 1.698 million for electric heat tracing.
- 3) The corrected 25-year lifecycle costs were USD 4.860

million, USD 5.594 million, and USD 17.316 million, respectively.

- 4) Relative to gas-fired heating, the solar-assisted system achieved an estimated positive NPV of USD 734,224, a simple payback of 4.8 years, and a discounted payback of 6.9 years on the incremental-CAPEX basis. Its LCOH of USD 0.0343/kWh was about 13.1% below the gas-fired reference and 72.0% below electric heat tracing.
- 5) The Monte Carlo analysis indicated a 100% frequency of positive NPV under the specified independent input distributions, but the simplified model and limited treatment of correlated uncertainty require caution. The sized collector field, TES tank, heat exchanger, pumps, and pipeline tie-in were translated into a PipeCAD general arrangement/plot plan. However, the physical constructability still requires detailed engineering and site-specific validation.

Overall, the analysis indicates that solar-assisted heating may be economically competitive with conventional systems under the assumptions modelled, even when the backup-fuel requirement is included. The LCOH advantage over gas-fired heating is marginal but still very significant. Results are based on an analytical, formula-based model using published inputs rather than field-measured or dynamically simulated performance and should be interpreted within that scope.

The study provides a reproducible spreadsheet-based workflow linking thermal sizing, solar contribution, lifecycle cost, and a PipeCAD design representation. The economic conclusions are conditional on the achieved solar fraction, the

adopted gas and electricity prices, equipment efficiencies, O&M and replacement assumptions, and the 10% discount rate. Further field validation and a more complete probabilistic assessment are required before investment decisions.

4.2. Recommendations

Based on the findings of this study, the following recommendations are given:

Considering the collector field's dominant share of CAPEX, procurement strategies that secure evacuated-tube collectors at or near the bulk-purchase price used in this model (USD 150/m²) should be prioritized. This is because collector unit cost was shown to be an important determinant of overall project economics.

Because the achieved solar fraction falls during the wet season, a supplementary or hybrid gas/electric trim-heating capacity, sized to cover the wet-season shortfall, should be retained alongside the solar system rather than treating it as a full replacement for conventional heating.

Future work should extend the Monte Carlo analysis to include other parameters, including solar fraction, O&M rates, and fixed CAPEX, to obtain a more complete probabilistic risk assessment.

A pilot-scale installation on a shorter pipeline segment is recommended before full-scale deployment, to validate the collector performance and achieved solar-fraction assumptions of this analytical model against field-measured data.

Abbreviations

A_c	Gross Collector Aperture Area (m ²)
a_1	First-order Collector Heat-loss Coefficient (W/m ² K)
a_2	Second-order Collector Heat-loss Coefficient (W/m ² K ²)
A	Uniform Annual Cost Stream (USD/year)
API	American Petroleum Institute
CAPEX	Capital Expenditure
C_p	Specific Heat Capacity of Crude Oil (J/kg K)
$C_{p,water}$	Specific Heat Capacity of Water (J/kg K)
D	Thermal Energy Storage Tank Diameter (m)
D_i	Internal Pipeline Diameter (m)
D_o	External Pipeline Diameter (m)
$D_{o,ins}$	External Diameter of Pipeline Including Insulation (m)
DPP	Discounted Payback Period (years)
EPC	Engineering, Procurement and Construction
ETC	Evacuated-Tube Collector
FPC	Flat-Plate Collector
G	Global Solar Irradiance on Collector Aperture (W/m ²)
G_m	Monthly Mean Solar Irradiance (W/m ²)
H	Pipeline Burial Depth or TES Tank Height, as Applicable (m)
H_{daily}	Average Daily Peak Solar Hours (h/day)
H_m	Monthly Mean Peak Sun Hours (h/day)
h_i	Internal Film Heat-transfer Coefficient (W/m ² K)
L	Pipeline Length (m or km)

LCC	Life-Cycle Cost (USD)
LCOH	Levelized Cost of Heat (USD/kWh)
$L_{\max}$	Critical Maximum Unheated Pipeline Length (m or km)
$\dot{m}$	Crude-oil Mass Flow Rate (kg/s)
N	Economic Study Horizon (years)
N_m	Number of Operating Days in Month m (days)
N_{days}	Number of Operating Days per Year (Days/Year)
NPV	Net Present Value (USD)
N_{modules}	Number of Evacuated-tube Collector Modules
O&M	Operation and Maintenance
OPEX	Operating Expenditure
P_{gas}	Natural-gas Price (USD/MMBtu)
PTC	Parabolic-Trough Collector
Q_{heating}	Design Heating Power Required at the Heater Station (W or kW)
$Q_{\text{heating,annual}}$	Annual Pipeline Heating Energy Demand (Wh/year or MWh/Year)
$Q_{\text{heating,total}}$	Total Annual Heating Demand Used in the Solar-fraction Calculation (Wh)
Q_{loss}	Heat-loss Rate per Unit Pipeline Length (W/m)
$Q_{\text{loss,total}}$	Total Pipeline Heat Loss (kW)
Q_{solar}	Annual Useful Heat Delivered by the Solar Collector Field (Wh)
Q_u	Useful Collector Heat Output per Unit Collector Area (W/m ²)
R_{film}	Internal Crude-oil Film Thermal Resistance per Unit Length (m K/W)
R_{pipe}	Pipeline Wall Thermal Resistance per Unit Length (m K/W)
R_{ins}	Insulation Thermal Resistance per Unit Length (m K/W)
R_{soil}	Surrounding-soil Thermal Resistance per Unit Length (m K/W)
r	Discount Rate (Fraction or%)
SF	Solar Fraction
SPP	Simple Payback Period (years)
$\bar{T}_{\text{oil}}$	Mean Crude-oil Temperature Along the Pipeline (°C)
T_a	Ambient Air Temperature (°C)
T_{amb}	Ambient/Soil Temperature (°C)
T_{exit}	Minimum Acceptable Crude-oil Temperature at Pipeline Exit (°C)
T_{inlet}	Crude-oil Temperature at the Heater-station Inlet (°C)
T_m	Mean Heat-Transfer-Fluid Temperature in the Collector (°C)
T_{min}	Minimum Safe Pipeline Operating Temperature (°C)
$T_{\text{oil}}(x)$	Crude-oil Temperature at Axial Position x (°C)
U	Overall Heat-transfer Coefficient per Unit Pipeline Length (W/m K)
V_{tank}	Required Thermal Energy Storage Tank Volume (m ³)
WAT	Wax Appearance Temperature (°C)
x	Axial Distance Along the Pipeline (m)
$\Delta T_{\text{storage}}$	Thermal Energy Storage Temperature Swing (°C)
ε	Heat-exchanger Effectiveness
η	Instantaneous Thermal Efficiency of the Solar Collector
η_0	Zero-loss (Optical) Collector Efficiency
$\bar{\eta}$	Mean Annual Thermal Efficiency of the Solar Collector
η_{boiler}	Thermal Efficiency of the Gas-fired Heating System
η_{electric}	Thermal Efficiency of the Electric Heating System
λ_{ins}	Thermal Conductivity of Insulation (W/m K)
λ_{oil}	Thermal Conductivity of Crude Oil (W/m K)
λ_{soil}	Thermal Conductivity of Surrounding Soil (W/m K)
λ_{steel}	Thermal Conductivity of Pipeline Steel (W/m K)
ρ_{water}	Density of Water Used as the TES Medium (kg/m ³)
σ	Standard Deviation Used for Normally Distributed Monte Carlo Inputs
τ	Design Thermal Energy Storage Duration (h)

Author Contributions

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Conflicts of Interest

The authors declare no conflicts of interest.

References

- [1] Akar, S., and Kurup, P. (2024). Parabolic trough collector cost update for industrial process heat in the United States. Paper presented at EuroSun 2024, Limassol, Cyprus, 26–30 August. <https://doi.org/10.18086/eurosun.2024.04.01>
- [2] Brown, W. (2026). Net Present Value (NPV): Formula and Steps to Calculate. Available at: <https://www.theknowledgeacademy.com/blog/net-present-value/> (Accessed: 4 April 2026).
- [3] Budnukaeku, A. C. (2026). Temporal Variability of Sunshine Duration and Cloud Cover over Nigeria from 1970 to 2022. *Innovation in Science and Technology*, Vol. 5, No. 1, pp. 10–14. <https://doi.org/10.63593/IST.2788-7030.2026.03.002>
- [4] Cao, X., Deng, Z., and Nian, Y. (2024). Evaluation of annual performances of crude oil pipeline transportation by solar heating. *Applied Thermal Engineering*, 245, article 122846. <https://doi.org/10.1016/j.applthermaleng.2024.122846>
- [5] Chanchangi, Y. N., Adu, F., Ghosh, A., Sundaram, S., and Mallick, T. K. (2023). Nigeria's energy review: Focusing on solar energy potential and penetration. *Environment, Development and Sustainability*, Vol. 25, pp. 5755–5796. <https://doi.org/10.1007/s10668-022-02308-4>
- [6] Civan, F. (2006). Viscosity–temperature correlation for crude oils using an Arrhenius-type asymptotic exponential function. *Petroleum Science and Technology*, Vol. 24, No. 6, pp. 699–706. <https://doi.org/10.1081/LFT-200041178>
- [7] Ebrahimi-Moghadam, A., Deymi-Dashtebayaz, M., Jafari, H., and Niazmand, A. (2020). Energetic, exergetic, environmental and economic assessment of a novel control system for indirect heaters in natural gas city gate stations. *Journal of Thermal Analysis and Calorimetry*, Vol. 141, No. 6. <https://doi.org/10.1007/s10973-020-09413-4>
- [8] Elkatory, M. R., Soliman, E. A., El Nemr, A., and Hassaan, M. A. (2022). Mitigation and remediation technologies of waxy crude oils' deposition within transportation pipelines: A review. *Polymers*, 14(16), article 3231. <https://doi.org/10.3390/polym14163231>
- [9] Energy Transition Office (2024). Nigeria Energy Transition and Investment Plan [Updated Edition]. Abuja: Federal Government of Nigeria / Energy Transition Office. Available at: <https://energytransition.gov.ng/> (Accessed: 10 April 2026).
- [10] Federal Government of Nigeria (2021). Petroleum Industry Act, 2021 (Act No. 6 of 2021). Abuja: Federal Government of Nigeria. Available at: <https://www.nuprc.gov.ng/petroleum-industry-act/> (Accessed: 10 April 2026).
- [11] Fortuin, S., and Stryi-Hipp, G. (2012). Solar Collectors, Non-concentrating. In: Meyers, R. A. (eds) *Encyclopedia of Sustainability Science and Technology*, Springer, New York, NY. https://doi.org/10.1007/978-1-4419-0851-3_681
- [12] Gilbert, M., Barati, K., and Shen, X. (2025). Lifecycle cost analysis of residential buildings considering thermal performance and financial uncertainties. *Energy and Buildings*, Vol. 348: 116442. <https://doi.org/10.1016/j.enbuild.2025.116442>
- [13] Jamar, A. (2025). Solar heat for industrial processes (SHIP): An overview of its categories and a review of its recent progress. *Solar*, Vol. 5, No. 4: 46. <https://doi.org/10.3390/solar5040046>
- [14] Kabeyi, M. J. B., and Olanrewaju, O. A. (2023). The levelized cost of energy and modifications for use in electricity generation planning. *Energy Reports*, Vol. 9, No. 9, pp. 495–534. <https://doi.org/10.1016/j.egy.2023.06.036>
- [15] Kadam, T. V., Pakhare, S. Y., and Godse, A. B. (2025). Performance analysis of solar thermal collectors: A comprehensive review. *Measurement: Energy*, Vol. 7: 100059. <https://doi.org/10.1016/j.meae.2025.100059>
- [16] Kalogirou, S. A. (2004). Solar thermal collectors and applications. *Progress in Energy and Combustion Science*, Vol. 30, pp. 231–295.
- [17] Kenton, W. (2025). Discounted Payback Period: What It Is and How to Calculate It. Available at: <https://www.investopedia.com/terms/d/d discounted-payback-period.asp> (Accessed: 4 April 2026).
- [18] Khan, N. A., Khoja, A. H., Ahmed, N., Ashraf, W. M., and Bilal, A. (2023). Solar-assisted hybrid oil heating system for heavy refinery products storage. *Case Studies in Thermal Engineering*, Vol. 49: 103276. <https://doi.org/10.1016/j.csite.2023.103276>
- [19] Khan, N. A., Ahmed, N., Khoja, A. H., Song, M., Ali, Q. S., and Qaisrani, M. A. (2026). Thermo-economic analysis of solar-driven heating for industry applications with and without thermal storage in diverse climates. *Energy Storage*, Vol. 8, No. 2: e70375. <https://doi.org/10.1002/est2.70375>
- [20] Koçak, B., Fernández, A. I., and Paksoy, H. (2020). Review on sensible thermal energy storage for industrial solar applications and sustainability aspects. *Solar Energy*, Vol. 209, pp. 135–169. <https://doi.org/10.1016/j.solener.2020.08.081>

- [21] Kumar, K. R., Chaitanya, K. N., and Kumar, S. N. (2021). Solar thermal energy technologies and its applications for process heating and power generation – A review. *Journal of Cleaner Production*, Vol. 282: 125296. <https://doi.org/10.1016/j.jclepro.2020.125296>
- [22] Kumar, A. (2023). Perspectives of flow assurance problems in oil and gas production: A mini-review. *Energy & Fuels*, Vol. 37, No. 12, pp. 8142–8159. <https://doi.org/10.1021/acs.energyfuels.3c00843>
- [23] Kumar, L., Hasanuzzaman, M., Rahim, N. A., & Sleiti, A. K. (2024). Thermoeconomic analysis of a solar-assisted industrial process heating system. *International Journal of Energy Research*, 2024, 4614066. <https://doi.org/10.1155/2024/4614066>
- [24] Liu, H., Duan, J., Li, J., Wang, J., Yan, H., Lin, K., Gu, K., and Li, C. (2023). Wax deposition modeling in oil-water stratified pipe flow. *Petroleum Science*, Vol. 20, No. 1, pp. 526-539. <https://doi.org/10.1016/j.petsci.2022.09.028>
- [25] Marksparksolutions (2026). U. S. Solar Thermal Collectors Market Size, Growth and Forecast 2033. Available at: <https://marksparksolutions.com/reports/us-solar-thermal-collectors-market> (Accessed: 10 April 2026).
- [26] Mohammed, R. K., and Farzaneh, H. (2024). Investigating the impact of the future carbon market on the profitability of carbon capture, utilization, and storage (CCUS) projects; the case of oil fields in southern Iraq. *Energy Conversion and Management: X*, Vol. 22: 100562. <https://doi.org/10.1016/j.ecmx.2024.100562>
- [27] NERC (2025). Multi-Year Tariff Order (MYTO): Tariff Review Orders 2025. Abuja: Nigerian Electricity Regulatory Commission. Available at: <https://nerc.gov.ng/> (Accessed: 10 April 2026).
- [28] NMDPRA (2026). Domestic Base Price and Wholesale Pricing Framework for Natural Gas for the Strategic Sectors, Effective 1 April 2026. Regulatory Circular. Abuja: Nigerian Midstream and Downstream Petroleum Regulatory Authority. Available at: <https://www.nmdpra.gov.ng/> (Accessed: 10 April 2026).
- [29] Ochieng, F. O., Kinyanjui, M. N., Kiogora, P. R., and Abonyo, J. O. (2023). Numerical study of wax deposition from multiphase flow in oil pipelines with heat and mass transfer. *Mathematical Problems in Engineering*, 2023: 1173505. <https://doi.org/10.1155/2023/1173505>
- [30] Onwumelu, D. C., Onwuka, M. K., Nnebeana, S. E., Okoro, T. C., Ekeocha, A. F., Offurum, C. C. and Ndubuisi, V. N. (2022). Crude oil and the problem of wax deposition on pipeline systems during transportation: A review. *World Journal of Advanced Research and Reviews*, Vol. 15, No. 1, pp. 781-798. <https://doi.org/10.30574/wjarr.2022.15.1.0770>
- [31] Precision Business Insights (2025). Thermal energy storage market size and future outlook 2032. Available at: <https://www.precisionbusinessinsights.com/market-reports/thermal-energy-storage-market> (Accessed: 18 March 2026).
- [32] Santoso, S., Sommeng, S. A., and Dianita, C. (2024). The Effect of Heat Tracing Installation for Wax Prevention on On-shore Buried Swampy Pipelines. *Jurnal Rekayasa Kimia & Lingkungan*, Vol. 19, No. 1, pp. 81-94. <https://doi.org/10.23955/rkl.v19i1.37754>
- [33] Sathish, T., Giri, J., Tarawneh, B., El-Rayyes, A., Faisal, R. S., Daniel, L. S., Sithole, T., and Amesho, K. T. T. (2026). Enhancing Thermal and Exergy Efficiency of Evacuated Tube Solar Collectors Using Hybrid Fe₂O₃/MgO Nanofluid and Porous Medium Integration. *Energy Conversion and Management: X*, Vol. 30: 101611. <https://doi.org/10.1016/j.ecmx.2026.101611>
- [34] Sha, A., Xiong, Z., Zang, X., Zhao, W., Ge, R., Yao, W., and Aiello, W. (2025). Full life-cycle cost model for practical application of solar energy system. *Energy Informatics*, Vol. 8: 40. <https://doi.org/10.1186/s42162-025-00505-9>
- [35] Sharma, A. K., Sharma, C., Mullick, S. C., and Kandpal, T. C. (2018). Financial viability of solar industrial process heating and cost of carbon mitigation: A case of dairy industry in India. *Sustainable Energy Technologies and Assessments*, Vol. 27, pp. 1-8. <https://doi.org/10.1016/j.seta.2018.03.007>
- [36] Shirazi, A., Taylor, R. A., Morrison, G. L., and White, S. D. (2018). Solar-powered absorption chillers: A comprehensive and critical review. *Energy Conversion and Management*, Vol. 171, pp. 59-81. <https://doi.org/10.1016/j.enconman.2018.05.091>
- [37] Solarthermalworld (2025). Technical and efficiency-orientated comparison of solar collectors for district heating. Available at: <https://solarthermalworld.org/news/technical-and-efficiency-orientated-comparison-of-solar-collectors-for-district-heating/> (Accessed: 20 March 2026).
- [38] Solheim, K. T., Lervik, J. K., Faremo, H., Eie-Klusmeier, K. K., Willumsen, C. B., Børnes, A. H., & Iversen, Ø. (2024). Operation track record and repair of direct electrical heating system. In *Proceedings of the Thirty-fourth International Ocean and Polar Engineering Conference (ISOPE 2024)* (pp. 1506–1511). International Society of Offshore and Polar Engineers. <https://hdl.handle.net/11250/3142710>
- [39] Sulaimon, A., Falade, G., and Del Ro, W. (2010). A proactive approach for predicting and preventing wax deposition in production tubing strings: The Niger Delta experience. *Journal of Petroleum and Gas Engineering*, Vol. 1, No. 2, pp. 26-36.
- [40] Thermal Engineering (2024). 3 types of solar thermal collectors and efficiency. Available at: <https://www.thermal-engineering.org/3-types-of-solar-thermal-collectors-and-efficiency/> (Accessed: 20 March 2026).
- [41] Tyagi, V. V., Kaushik, S. C., and Tyagi, S. K. (2012). Advancement in solar photovoltaic/thermal (PV/T) hybrid collector technology. *Renewable and Sustainable Energy Reviews*, Vol. 16, No. 3, pp. 1383-1398. <https://doi.org/10.1016/j.rser.2011.12.013>
- [42] Wang, K., Qin, Z., Tong, W., and Ji, C. (2020). Thermal Energy Storage for Solar Energy Utilization: Fundamentals and Applications. *Renewable Energy - Resources, Challenges and Applications*. IntechOpen. Available at: <https://dx.doi.org/10.5772/intechopen.91804>

- [43] Wang, Y., and Zhang, J. (2025). Study on solar heating crude oil system with thermal energy storage-based installation. *Journal of Petrochemical Universities*, Vol. 38, No. 1, pp. 49–58. <https://doi.org/10.12422/j.issn.1006-396X.2025.01.007>
- [44] Wu, Y., Yao, W., Meng, F., Wang, D., Zhao, X., Meng, L., Arıcı, M., and Li, D. (2024). Energy performance analysis of solar assisted gas-fired boiler heating system for floating roof oil tank. *Renewable Energy*, Vol. 225: 120285. <https://doi.org/10.1016/j.renene.2024.120285>
- [45] Zhang, J., Chen, X., Zhang, D., and Xu, J. (2017). Rheological behavior and viscosity reduction of heavy crude oil and its blends from the Sui-zhong oilfield in China. *Journal of Petroleum Science and Engineering*, Vol. 156. <https://doi.org/10.1016/j.petrol.2017.06.038>