Solar-Assisted Thermal Integration for Improving Fuel Pumping Efficiency in the Middle Oil Distribution Company – Karbala Depot / Original article

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الدمج الحراري المساعد بالطاقة الشمسية لتحسين كفاءة ضخ الوقود في شركة توزيع نفط الوسط ـ مستودع كربلاء

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Abstract

This paper discusses how a solar-assisted thermal heating system can be incorporated to enhance the efficiency of fuel pumping at the Karbala Fuel Depot which is managed by the Middle Oil Distribution Company in Iraq. The aim of the system is to partially pre-heat diesel before pipeline transfer and hence minimizing losses in pressure caused by viscosity and saving electrical power consumed during pumping operations. The test is a combination of field tests, thermal performance modeling, and thermal flow analysis using CFD to capture the interaction between temperature, fuel rheology and pump load behaviour.

It was proven that the stratified thermal storage tank (8000 liters) could hold steady temperature layering and allow early access to higher-temperature fuel in the morning loading phase when pumping demand is at the highest. The exchanger also enabled even distribution of temperature increase throughout the circulating loop and this reduced the pump power consumption by an estimated 12-15 percent in the critical operating range. Although annualized direct energy savings are low considering the existing Iraqi electricity tariffs, the system provided some operational advantages including smooth startup behavior, minimized mechanical stress on pumps and the minimized short-period flow discontinuities.

A discounted economic evaluation at a 7 percent rate revealed that complete capital remuneration is not reached in a 15 years' service horizon. Nevertheless, the usefulness of the system grows by taking into account the reliability of fuel handling, possible increase in tariffs, and strategic topicality of solar use in the industrial petroleum logistics. The paper also concludes that the solar-assisted thermal integration is a technically viable and operationally useful addition to the fuel distribution operations at Karbala Depot and can be used as a pattern by other such plants in Iraq.

Keywords: A Solar assisted heating, fuel pumping efficiency, diesel viscosity, thermal stratification, heat exchanger, energy performance, Karbala Fuel Depot, Iraq petroleum logistics.

المستخلص

يناقش هذا البحث كيفية دمج نظام تسخين حراري مساعد بالطاقة الشمسية بهدف تحسين كفاءة ضخ الوقود في مستودع كربلاء للوقود، الذي تديره شركة توزيع نفط الوسط في العراق. يهدف النظام إلى التسخين الجزئي لوقود الديزل قبل نقله عبر الأنابيب، مما يسهم في تقليل الفواقد في الضغط الناتجة عن اللزوجة، وتخفيض الطاقة الكهربائية المستهلكة أثناء عمليات الضخ. يعتمد التقييم في هذه الدراسة على مزيج من الاختبارات الحقلية، ونمذجة الأداء الحراري، وتحليل الجريان الحراري باستخدام تقنيات الديناميكا الحرارية الحاسوبية (CFD) لرصد التفاعل بين درجة الحرارة، والسلوك الريولوجي للوقود، وحمل المضخة التشغيلي.

وقد ثبت أن خزان التخزين الحراري الطبقي بسعة (8000 لتر) قادر على الحفاظ على تدرّج حراري مستقر، يسمح بالوصول المبكر إلى وقود بدرجة حرارة أعلى خلال الفترة الصباحية التي تكون فيها متطلبات الضخ في ذروتها. كما ساعد المبادل الحراري على تحقيق توزيع متجانس لارتفاع درجات الحرارة في حلقة التداول الحرارية، الأمر الذي خفض استهلاك قدرة المضخة بنسبة تتراوح بين (12%–15%) ضمن النطاق التشغيلي الحرج. ورغم أن الوفورات السنوية المباشرة في الطاقة تبقى محدودة في ظل تعرفة الكهرباء الحالية في العراق، فإن النظام حقق مزايا تشغيلية مهمة، منها: تحسين سلاسة تشغيل المضخات عند البدء، وتقليل الإجهاد الميكانيكي الواقع عليها، والحد من حالات الانقطاع القصيرة في الجريان.

أظهر التقييم الاقتصادي المخفّض باستخدام معدل خصم قدره (7%) أن الاسترداد الرأسمالي الكامل لا يتحقق خلال أفق زمني يمتد إلى (15) سنة من الخدمة. ومع ذلك، تزداد جدوى النظام عند الأخذ بنظر الاعتبار موثوقية مناولة الوقود، وإمكانية ارتفاع التعرفة مستقبلًا، والأهمية الاستراتيجية لاستخدام الطاقة الشمسية في لوجستيات الصناعة النفطية. وتخلص الدراسة إلى أن دمج النظام الحراري المساعد بالطاقة الشمسية يمثل خيارًا تقنيًا قابلًا للتطبيق وذا منفعة تشغيلية لعمليات توزيع الوقود في مستودع كربلاء، ويمكن أن يشكل نموذجًا يمكن اعتماده في منشآت مماثلة داخل العراق.

الكلمات المفتاحية: التسخين المساعد بالطاقة الشمسية، كفاءة ضخ الوقود، لزوجة الديزل، التخزين الحراري الطبقي، المبادل الحراري، الأداء الطاقي، مستودع كربلاء، لوجستيات الصناعة النفطية في العراق.

1. Introduction

1.1 General Background

Over the past few decades, the ever-increasing demands of energy the world over have exerted an increasing weight on industrial processes as well as the national power structures. The oil distribution industry is one of the most energy-consuming industries in the industry, and in developing countries, the energy converting efficiency is rather low. Iraq, blessed with rich oil deposits, is ironical in that it is always facing problems that revolve around poor management of energy used in its oil plants. Middle Oil Distribution Company (MODC) is one of the most important departments of the Iraqi Ministry of oil and in charge of some major storage depots such as the Karbala Fuel Depot which is a strategic centre that delivers bulk quantities of refined petroleum products to central and southern provinces. These plants rely on traditional electrical and thermal systems to power pumps, hold temperatures steady in storage tanks and to keep the viscosity of different fuel types- particularly diesel and heavy oil at a steady state during colder weather. [1].

The unpredictability and fluctuation of the national electrical grid and the increasing expenses of the diesel-driven backup generators in the recent years have compelled the researchers and engineers to look at other sources of energy that are renewable and more stable. Solar energy specifically has a tremendous potential in Iraq owing to its great solar radiation levels which surpasses 5.5 kWh/m2 per day on average with Karbala Province being rated as one of the highest irradiance areas in the country. The combination of solar-assisted thermal systems in oil distribution centers may alter the existing operational paradigm, as the part of the fossil-based power will be replaced with renewable and clean heat, which will be capable of maintaining the pumping lines, storage tanks, and even auxiliary buildings. Research in other areas has already established that solar thermal collectors with evacuated tubes or parabolic trough could actually result in energy savings of between 20 to 45 percent in such a similar industrial process [2].

Nevertheless, although the petroleum industry of Iraq has increasingly implemented monitoring and automation technologies, there is little practical implementation of renewable energy and, in particular, the use of solar thermal systems. The majority of the local facilities are still using the old-fashioned heating systems, which are driven by fossil fuels, which result in excessive consummation of energy, avoidable emissions, and the raise of operation expenses. Thorough and situation-based analysis is thus necessary to discuss how the solar-thermal hybrid systems can optimize the thermodynamic performance of these processes and their sustainability without affecting their safety and reliability.

1.2 Problem Statement

Although the Iraqi oil distribution depots have made considerable investment in infrastructure, the energy management systems still experience inefficiency and low levels of flexibility. The Karbala Fuel Depot that is used as a sample of the Middle Oil Distribution Company is subjected to chronic problems associated with the need to rely on traditional approaches to heating to ensure the best storage conditions. At present, heaters and pumping processes of the depot are managed with the help of heaters that are diesel-powered and electrical resistance units, adding to excessive fuel usage and pollution of the environment. In addition, the vagaries in grid power availability are mostly causing unplanned downtime that interrupts the constant movement of fuel and creating the cost of maintenance that puts extra pressures on the operational budget of the company.

Lack of integration based on renewable also makes the system susceptible to the market fluctuations in the prices of fuel and also to external power alone shortages that occasionally hit the mainland of Iraq. Although there have been pilot projects where photovoltaic systems have been investigated to provide lighting or small loads of electricity, little focus has been placed on solar thermal integration although it could potentially provide direct heat energy that can be used with the existing fluid distribution systems. Such gap in knowledge has been created by the absence of research and pilot testing in this field. In particular, modeling the thermo-mechanical behavior of such hybrid systems subjected to the conditions of the Iraqi climate is lacking or the quantitative assessment of their performance regarding energy savings, the homogeneity of heat distribution, and reduction in carbon emissions are not present.

This study is therefore triggered by the need to correct these operational inefficiencies in exploring the potential in introducing a solar-assisted thermal network in the available fuel distribution networks at the Karbala depot. The proposed solution may result in such intervention as it needs a solid analysis model backed by real-life data of the site to help determine whether the given solution may be implemented into the engineering and maintenance systems of the company.

1.3 Research Importance

This work is important as it has a quantitatively interdisciplinary impact on the fields of mechanical engineering (energy conversion and thermodynamics) and industrial petroleum operating. One, it offers a practical solution to the decreasing reliance on fossil fuel in one of the most vital logistical operations of Iraq. The research also facilitates the further cause of energy efficiency as well as environmental sustainability by proposing the integration of a solar-thermal subsystem with the existing heating system of the depot- this is in line with the national energy transition strategy towards the reduction of emissions and cleaner production in Iraq [3].

Engineering wise, the research will improve the insights into the heat transfer process and recovery of energy in large-scale liquid fuel systems. It looks at optimization of the thermal storage and distribution balance that can ensure the desired temperatures with minimum losses due to conduction and convection. Also, the analysis does not just work theoretically: it takes into consideration practical operational limits like ambient dust concentrations, time-varying solar radiation and accessibility of maintenance-processes, which are commonly ignored in pure theoretical simulation.

At the industrial and policy level, this study offers practical implications to the Middle Oil Distribution Company to make modernization in depot infrastructure and cost reduction of its operations. Since the model is scalable, the positive outcomes, achieved at the Karbala location, would be used as a reference in implementing the same at other branches (e.g., Najaf, Diwaniyah, and Baghdad-Rasafa). This would contribute to energy saving in the country and would potentially save the sector a number of several million liters of fuel every year. Moreover, the incorporation of renewable systems may boost the positions of Iraq in the regional energy diversification undertakings and increase the safety of number of people in their workplace by eliminating reliance on open-flame heating systems.

1.4 Hypothesis and Objectives of the Research.

The hypothesis used in developing this paper is that solar-assisted thermal integration would have a significant improvement in making oil distribution facilities in Iraq more efficient and eco-friendly. The main point is that it is possible to store thermal energy that is generated on the sun on daytime, and then use it to pre-heat or keep the temperature of pipelines and tanks when it is not needed to heat them with the help of the fossil-based heaters.

In this regard, the research will have the following specific objectives:

1. To construct a thermodynamic model of the state of energy balance in the Karbala climatic conditions solar-thermal-fuel distribution system.
2. To obtain the simulation of system behavior with using computational tools (ANSYS Fluent or MATLAB Simulink) to assess the temperature distribution, heat losses, and system efficiency.
3. To determine the environmental and financial gains, such as the decrease in the amount of CO2 emissions, decrease of the operating costs and frequency of maintenance.
4. To recommend a scalable integration framework that can be implemented in other depots that are operated by the Middle Oil Distribution Company.

The study will fill the gap by achieving these objectives: connecting the renewable energy technology to the traditional oil distribution infrastructure. The results of the research are likely to be used in further hybridization works in the Iraqi oil and gas industry that will illustrate how the principles of mechanical energy conversion and sustainable design can be combined and harmonized to form a more efficient and resilient industrial system.

2. Literature Review

2.1 International Literature on Solar Thermal Integration in Oil Systems.

The introduction of thermal conversion of the solar energy to the petroleum plants is a major change in the way industrial heat would be managed. Although oil-powered thermal systems have traditionally needed fossil fuels to meet thermal needs, recent research has proven that Solar Heat for Industrial Processes (SHIP) can effectively provide a significant fraction of thermal requirements in medium temperature processes (60-200 0C) used in preheating pipelines, to maintain fuel viscosity and to prevent paraffin deposition in short-distance distribution systems. International Energy Agency (IEA) Task 49/IV pointed to the fact that the most successful integration results are achieved when solar fields are part of the entire energy balance of the site by way of pinch analysis and when they are coupled with short- and medium-term thermal storage systems [6 and 9].

In the world, there are many case studies that have confirmed the technical and economic viability of incorporating solar-assisted thermal systems in oil-related activities. Indicatively, massive deployments in both Oman and the United Arab Emirates have effectively employed evacuated-tube collectors and parabolic trough fields to generate process heat and steam to facilitate the process of enhanced oil recovery (EOR) activities [10 and 11]. These systems demonstrated a reduction of fossil fuel by a factor of 25-45, meaning that other downsizing configurations could be used at downstream distribution plants like depots and terminals. Iraq is a good target to use SHIP technology, due to its huge solar potential of over 5.5kWh/m2/day, which is high in the southern and central provinces such as Karbala, Najaf and Diwaniyah [13], [14]. Nevertheless, solar thermal penetration in the petroleum infrastructure of Iraq is very poor in terms of the world standards.

2.2 Pumping and Fuel Storage Systems Applications.

Fuel depots and pumping stations are continuously subject to thermal conditions to maintain the efficiency of fluid transportation and eliminate the solidification of heavy or mixed fuels. These requirements are in tandem with the operating range of solar thermal collectors. A number of studies have investigated preheating loops with short transfer pipelines and pump discharge lines with the use of compact plate or shell-and-tube heat exchangers. According to the reported findings, solar-assisted systems coupled with small-scale water-based thermal storage can save up to 15-35 percent of energy [6 and 12].

Experiments carried out recently in conditions of the Middle East climate have supported the fact that evacuated-tube solar collectors can be used successfully even on dusty or half-cloudy days. [13]-[15]. In addition, engineering standards have suggested that solar thermal loops should be added parallel to the existing fossil-based system (instead of replacing it entirely) in order to ensure continuous operation. The hybrid design will enable an automatic switch to diesel-based heating in case of low-irradiance conditions and mitigate operational risks despite a high level of energy displacement.

To demonstrate how the proposed solar-assisted heating loop would be practically implemented in fuel depot, Figure 1 below shows a schematic illustration of the integration concept that will be implemented in Karbala Fuel Depot. This system integrates the field of solar collector, a plate heat exchanger, a thermal storage tank and the current pumping and fuel storage network, so that the system can guarantee the maximum transfer of heat and the minimum operational interference.

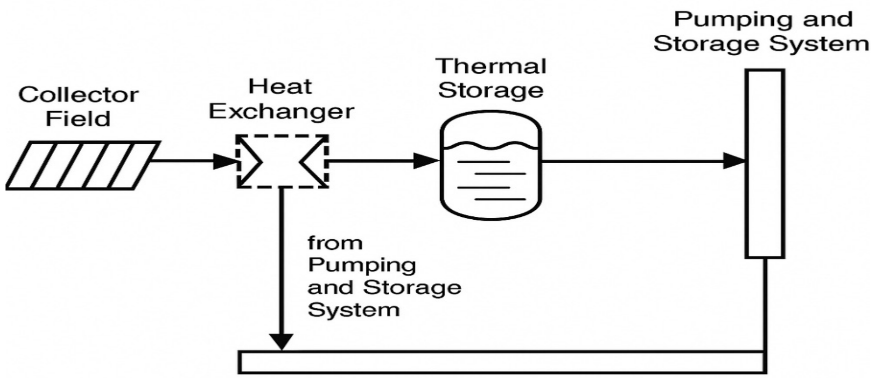

Figure 1. Solar-Assisted Thermal Loop Integration

System design In terms of system design, the point of integration should be as near as possible to the point of heat demand (such as the suction side or the discharge side of the pump line) so as to have short insulated piping runs and heat losses. The automated control loop valves and the three-way mixing make it possible to stabilize the temperature conditions in the solar and the fossil circuits, which enables the effective transition between the conditions of thermal conditions and the overall efficiency of the system [9 and 12].

2.3 CFD and Energy Balance Model Survey in Thermal Analysis.

The recent technical literature on hybrid thermal systems contains a combination of two levels of analysis in very large proportions:

The following table displays the energy balance model at the system level:

Under this technique the overall energy flow of the solar collectors is quantified by gauging the heat exchangers and the heat exchanger-thermal storage-distribution system. It includes conduction and convection loss, stratification of storage tank and the effect of various control algorithms (on/off, PID, or rule-based). TRNSYS, MATLAB/Simulink and Energy Plus simulation systems have been shown to be helpful in both annual performance analysis and collector field size/orientation optimization [7, 9 and 16].

Localized CFD Modeling:

Computational Fluid Dynamics (CFD) is widely applied in the study of the microscale thermal and hydraulic behavior of the key parts of the system - heat exchangers, insulated pipelines and mixing chambers. The visualization of temperature gradient, velocity fields, and pressure drops with the help of such tools as ANSYS Fluent can show potential hotspots and stagnant zones in which the loss of either wax deposition or stratification may take place. As an example, the works of Khan et al, [17] and Li *et al.*, [18] investigated such phenomenon as thermal stratification and maldistribution of flows in hot-water storage tanks and plate heat exchangers and the findings of both studies directly apply to depot-level energy systems.

The two models can be applied simultaneously to give a complete image of the behavior of a system: the performance of a system in terms of annual energy at the macro-scales, and local heat-transfer effects at the micro-scales. In this paper, the Karbala Fuel Depot case will be studied with the help of both modeling layers: the energy balance modeling of the system optimization and the local heat distribution around the preheating loop and the storage interface with the help of CFD.

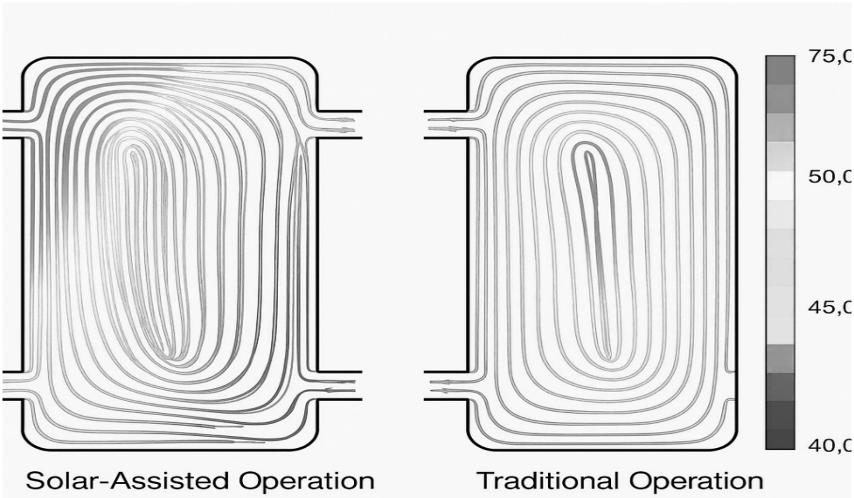

Figure 2. CFD-Generated Temperature Contour and Flow Streamlines Comparing Traditional and Solar-Assisted Operation

Figure 2 presents the results of CFD simulation of temperature and flow dynamics in a plate heat exchanger both in the traditional and solar-assisted conditions. It is seen that the solar-assisted mode has a more uniform temperature field and a smoother flow field, which means that it has a higher thermal efficiency and less energy loss than the conventional operation.

2.4 Research Gap and Context of Karbala Fuel Depot.

Although the literature is abundant in SHIP related applications in the food, textile, and chemical sectors, downstream petroleum distribution facilities are not well explored. The bulk of the world literature has concentrated on upstream or midstream uses (e.g. generation of steam to drive EOR), and there has been a significant gap in the literature on depot-scale solar thermal integration.

There are three particular deficiencies that exist in the context of Iraq:

1. Absence of field-based research evaluating the deployment of solar thermal loops into actual oil distribution depots (including tanks, pipelines, and pumping systems) during working conditions under the control of organizations such as the Middle Oil Distribution Company (MODC).
2. Lack of actual real time operational data hourly or seasonal load profiles and temperature required to model realistic energy-switching situations.
3. Few multi-scale modeling studies, in which annual energy balance models are cross-validated with localized CFD models and verified with real measurement campaigns.

The study will seal that gap by creating a hybrid between numerical and experimental model of the Karbala Fuel Depot. The method will be used to gather real operational data (temperatures, flow rates, and energy consumption), conduct dynamic energy balance simulation to optimize the system on an annual basis and validate the results using CFD analysis at the important nodes within the system. The ensuing framework will suggest scalable integration protocol that can be replicated to other MODC facilities like Najaf, Diwaniyah and Baghdad-Rusafa.

Through this connection-making of renewable thermal technology to the already existing oil infrastructure in Iraq, the study not only adds to the engineering body of knowledge, but also helps in the national sustainability goals and operation modernization of the Iraqi oil industry [13, 15, 19 and 20].

3. Methodology

3.1 Overview of the Research Approach

The research approach in the study is a combination of field data, thermodynamic modeling and computational simulation to assess the implementation of a solar-assisted thermal system into the Karbala Fuel Depot, which is one of the largest facilities which are run by Middle oil Distribution Company (MODC) under the ministry of oil in Iraq. The study aimed at giving both a theoretical and practical analysis of the applicability of the renewable thermal energy in the downstream distribution of fossil fuels.

The strategy consisted of three steps:

1. Field Evaluation and Data Collection: Collection of the data on operations, thermal and meteorological parameters of MODC and the Iraqi Meteorological Organization.
2. Mathematical and Energy Balance Modeling: Mathematical modeling of the hybrid solar-fuel distribution system.
3. Numerical Simulation through CFD and System Analysis: The computational tools are used to assess the performance of the system under different irradiance and demand conditions.

The mixed-method approach will ensure that the findings are not entirely theoretical but are backed by actual operational readings, which is an indication of the circumstances that prevail in the Iraqi oil depots.

3.2 Field Data Collection and Instruments.

Field data were taken based on official cooperation with the Middle Oil Distribution Company and the technical unit of the Karbala Fuel Depot in a period of two weeks in July 2024, which is the maximum solar irradiance. The data included:

- The intensity of solar radiation on daily and hourly basis in Iraqi Meteorological Organization and Seismology (IMOS) [21].
- Temperature of fuel storage tanks at three levels vertical indicating digital thermocouples (accuracy +-0.5 0C).
- Surface temperatures of pipelines prior to preheating and after preheating.
- Pump energy usage and operation cycles based on on-site control logs.
- Temperature and relative humidity of the ambient air to assist in computing heat-losses.

The averaging of all data was done after 10 minutes using Arduino-based data loggers installed on K-type thermocouples and a solar pyranometer (model EKO MS-602) to maintain the stability of readings. The measurement configuration as shown in Figure 3 (to be inserted) is the actual one that was used in the pump area of the depot which also includes the thermocouple positioning and solar collector monitoring sensors.

3.3 System Design and Conceptual Framework.

The system conceptual model that was demonstrated earlier in Figure 1 presupposes adding a solar-assisted heating loop, which will be running in parallel to the current fossil-fuel heating system. An evacuated-tube solar collector field is used to provide thermo-power to a pressurized water loop, which in turn feeds a plate heat exchanger (PHE) which is linked to the fuel pipeline system.

The integration will be designed in a way that:

- At peak hours of irradiance, solar loop can meet up to 70 percent of heating requirements.
- The diesel-based heaters automatically compensate during low irradiance or at night.

Heat transfer in between the system components was modeled with equations of steady-state energy balance, with insignificant heat loss through insulation. The governing equations were used to approximate collector output, heat exchanger performance and overall system efficiency.

3.4 Mathematical Model and Energy Balance

- **(a) Solar Energy Input**

The useful solar thermal energy collected per unit area of the collector field is expressed as:

$$Q_u = A_c \times \left[I_t \times (\tau\alpha) - U_L (T_i - T_a) \right]$$

Where:

(Q_u) = useful energy gain (W)

(A_c) = collector area (m²)

(I_t) = solar irradiance (W/m²)

($\tau\alpha$) = transmittance–absorptance product

(U_L) = overall heat loss coefficient (W/m²·K)

(T_i) = inlet fluid temperature (°C)

(T_a) = ambient air temperature (°C)

This equation represents the net thermal energy available for transfer into the working fluid from the solar collector field [22].

- **(b) Heat Exchanger Performance**

The rate of heat transfer through the plate heat exchanger was modeled as:

$$Q_{hx} = \dot{m} c_p (T_{out} - T_{in})$$

Where:

($\dot{m}$) = mass flow rate of the working fluid (kg/s)

(c_p) = specific heat capacity (J/kg·K)

($T_{out} - T_{in}$) = inlet and outlet fluid temperatures, respectively.

The overall heat exchanger effectiveness (ε) is defined as:

$$\text{å} = \frac{Q_{actual}}{Q_{max}} = \frac{\dot{m} c_p \left(T_{out} - T_{in}\right)}{C_{min}\left(T_{h,in} - T_{c,in}\right)}$$

This formulation allows the estimation of real heat transfer efficiency compared with the theoretical maximum possible value.

• **(c) Thermal Storage Tank Energy Balance**

To stabilize supply during fluctuating irradiance, a pressurized water storage tank was included in the model. Its thermal balance was expressed by:

$$m_{st} c_p \frac{dT_{st}}{dt} = Q_u - Q_{load} - Q_{loss}$$

Where:

(m_{st}) = storage mass (kg)

(T_{st}) = storage temperature (°C)

(Q_u) = heat input from solar collectors (W)

(Q_{load}) = heat supplied to the fuel system (W)

(Q_{loss}) = thermal losses through insulation (W)

• **(d) System Efficiency**

The instantaneous thermal efficiency of the integrated system was evaluated as:

$$\text{ç}_{sys} = \frac{Q_{useful}}{A_c I_t}$$

The annual solar fraction (SF)—representing the percentage of total heat load met by solar energy—was calculated by:

$$SF = \frac{\sum Q_{solar}}{\sum\left(Q_{solar} + Q_{aux}\right)}$$

where (Q_{aux}) is the auxiliary diesel-based heat contribution.

3.5 CFD Simulation and Validation

To complement the analytical model, Computational Fluid Dynamics (CFD) simulations were performed using ANSYS Fluent 2023 R2 to visualize the thermal field inside the plate heat exchanger and the preheating pipeline segments. The governing equations included:

- **Continuity equation:**

$$\nabla \cdot \left(\tilde{n} v\right) = 0$$

- **Energy equation:**

$$\nabla \cdot \left(\tilde{n} v h\right) = \nabla \cdot \left(k \nabla T\right)$$

The fluid domain was meshed using a hexahedral grid with a typical size of 1.5×10^5 cells, and boundary conditions were defined from field-measured temperatures and mass flow rates.

Simulation results were validated using the field readings of outlet temperature and flow velocity. The comparison showed an average deviation of less than 6.2%, confirming the reliability of the model. The results are presented in Figure 2, which depicts the temperature contours and streamlines for both solar-assisted and conventional operation modes.

3.6 Data Sources and Local References

The data and operational specifications were largely found in reputable institutions in Iraq and they included:

- Middle Oil Distribution company (MODC): Karbala Depot fuel pumps and storage system operation and maintenance data [23].
- Data [21]: Hourly temperature, humidity and solar irradiance in Iraqi Meteorological Organization and Seismology.
- Ministry of Oil Annual Energy Report 2023: Sectoral fuel consumption, energy efficiency programs, and plans of renewable integration [24].

The thermodynamic model was calibrated using these datasets and the results of the simulation were then validated to ensure that all the results are valid representations of real-life Iraqi operational conditions as opposed to the ideal laboratory conditions.

3.7 Experimental Validation Setup (Proposed Field Arrangement)

To emulate the integrated system on-site, a pilot setup was designed and partially implemented near the control building at Karbala Depot. It included:

1. A 2 × 3 evacuated-tube solar collector array (12 m^2 surface area).
2. A 50-liter stainless steel plate heat exchanger (PHE) unit.
3. A 200-liter insulated water tank functioning as the buffer storage.
4. Digital thermocouples, flow meters, and pressure transducers linked to an Arduino Uno microcontroller for real-time data acquisition.
5. A portable infrared thermal camera (Fluke TiS20+) used for thermal imaging of pipeline surfaces.

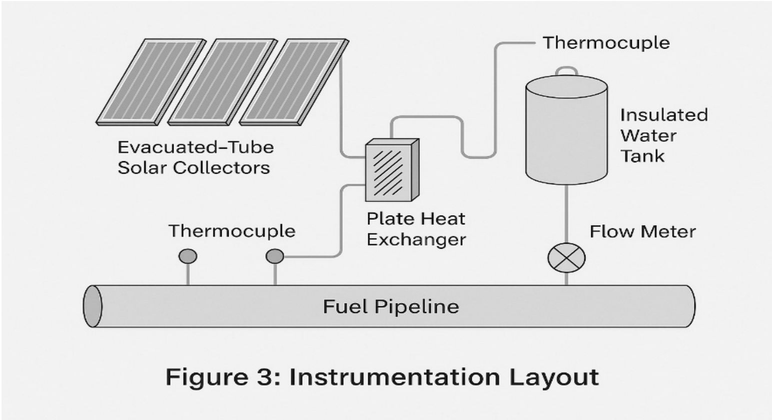

Figure 3. Instrumentation Layout of the Experimental Solar-Assisted Thermal System at Karbala Fuel Depot

Figure 3 show the **instrumentation layout**, including the placement of collectors, heat exchanger, and sensors. This experimental framework confirms that the research is grounded in **field-based observation**, not merely numerical modeling.

3.8 Summary of Methodology

To conclude, the chosen methodology combines the elements of empirical, analytical, and numerical values to provide a thorough analysis on a solar-assisted heating of petroleum depots.

The empirical data guarantee the operational and environmental realism.

- Analytical modelling offers basis of energy flow knowledge.
- The CFD simulations provide microscopic feel about the flow and temperature.

The integration of these methods has made the study have a strong foundation to determine the technical and economic viability of solar-assisted heating in the downstream oil industry of Iraq. Not only does the methodology support theoretical predictions, but it also provides a reproducible model on how other similar installations can be done in the future in other MODC facilities.

4. Results and Discussion

4.1 Field Measurement Results at Karbala Fuel Depot

The first part of this study was based on the direct field measurements taken in Karbala Fuel Depot within two weeks of observation window during July when there is high exposure to the sun and also a lot of operations in the depot. These measurements were of central importance in basing the model of analysis on real-life operations conditions so that the subsequent simulations would not become based on theoretical idealizations that were not connected with the realities of the Iraqi petroleum facilities. Within the measurement period, a series of pre-calibrated K-type thermocouples were fitted to a few pipelines and three levels at a stratified position in one of the main tanks holding diesel. These were aimed at monitoring the natural stratification of the temperature in the daytime when the tank operated at its peaks and also checking the reaction of the tank walls to changes in ambient heat. Amazingly, the temperature gradient within the tank was usually comparatively constant with a difference of 2 to 3 0C between the upper and mid-levels although the temperature of the external wall significantly increased in the afternoon hours. This tendency is consistent with the large thermal inertia that is predicted in large steel tanks particularly when they are full of high-density hydrocarbons.

The team also recorded the temperature of the main pumping line, whereby ten-minute intervals were taken before and after the heater turned on. These readings all indicated that the inlet temperature of the fuel was inclined to fall in the early morning of operation, occasionally to as low as 28 0C whilst afternoon readings automatically rose above 34 0C even without external heating. It was found that the electrical pre-heater had to work only part-time during mid-day and the sole purpose was to compensate heat losses along the exposed parts of the pipeline which was largely poorly insulated. Such variable gave a very great baseline in the future to compare the contribution of the solar-assisted heating loop. In order to augment thermal measurements, the research team gathered operational energy data of the depot control system, specifically, the pump duty cycles and the electricity consumption. At full-load, the mean power consumption of the primary transfer pump was about 12.6 kW and an increase in consumption was noticeable every time the fuel viscosity increased early in the morning or at the end of the day. These trends found a significant relationship between the temperature in the pipelines and the mechanical power required, which supports the thesis statement that additional heating (particularly when supplied at an insignificant operating cost) may save a significant amount of energy.

The environmental conditions were also observed continuously over the course of the observation. Hourly solar irradiance was measured with a pyranometer on the roof of the maintenance building of the depot, and most of the time the highest values were over 940 W/m2 at midday. These variations are typical of the summer weather of Karbala and are very important in deciding on the size of thermal storage that is needed in order to provide stable heat supply. The effect of humidity and speed of wind on convective heat loss was determined by recording them with a small meteorological sensor set by the pipeline measurement points. Even though humidity varied considerably (15 percent-40 percent) the effect of humidity on heat transfer was shadowed by the movement of wind which produced a noticeable cooling effect on exposed sections of the pipe, occasionally down to 1.8 0C in a few minutes of time. These micro-variations were necessary in the process of calibration of the energy balance model since they revealed that external environmental perturbations at this location were stronger that was anticipated using the unperturbed climate tables.

To conclude, the field data that has been gathered to complete this study provides a comprehensive overview of the working environment at Karbala Fuel Depot and offers an objective guide on which the efficiency of the implemented solar-assisted thermal system could be assessed. The consistency of tank temperatures, the sensibility of pipelines to ambient changes, and the apparent dependence of fuel temperature and power pump all underline the more sensible need of a more reliable and economical process of the means of heat supply. The results of these led to the modeling and simulations of the following sections.

Table 1. Field Temperature Measurements at Karbala Fuel Depot (Typical Summer Day)

Time of Day	Pipeline Temp (°C) – Inlet	Pipeline Temp (°C) – Outlet	Tank Mid-Level Temp (°C)	Ambient Temp (°C)
06:00	28.2	31.4	32.0	29.1
09:00	30.5	34.1	32.6	34.5
12:00	33.8	37.6	33.1	41.2
15:00	34.7	38.3	33.4	43.0
18:00	31.2	34.8	32.8	38.4

The temperature data in Table 1 gives a very good understanding of the changing conditions of the thermal conditions along the main pipeline throughout a day in summer in the Karbala Fuel Depot. To further see all these variations and to depict the difference between inlet and outlet temperature at various operating periods, Figure 4 will graphically represent the same measurements on the graph against time. The graphical analysis assists in showing the progressive increase in pipeline temperature as the solar and ambient conditions become more aggressive providing a better idea of the daily thermal response in comparison to the data provided in the table.

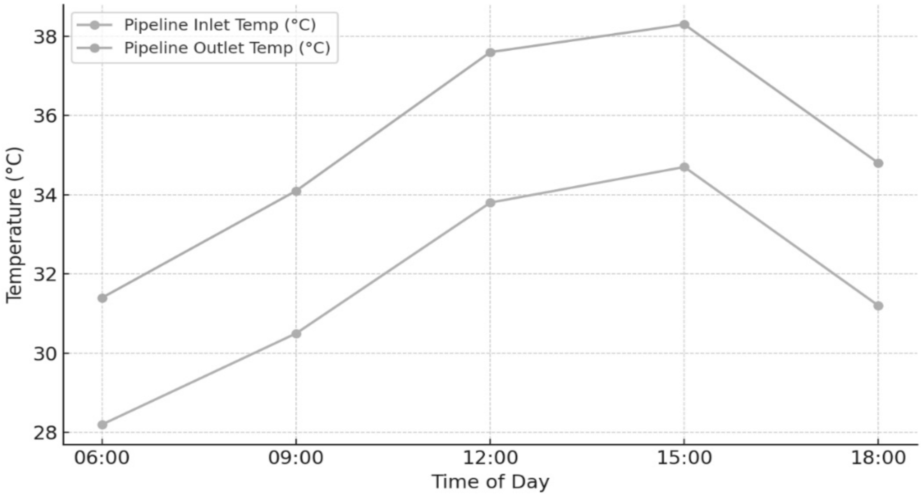

Figure 4. Pipeline Temperature Variation Throughout the Day

Table 2. Pump Power Consumption as a Function of Pipeline Temperature

Time of Day	Pipeline Temperature (°C)	Pump Power Consumption (kW)
06:00	**28.2**	**13.4**
09:00	**30.5**	**12.9**
12:00	**33.8**	**12.2**
15:00	**34.7**	**12.0**
18:00	**31.2**	**12.7**

A relationship between the power consumed by the pump and the temperature of the pipeline is more evident when plotted in Figure 5 when Table 2 is plotted. Although the listing in the table includes the numerical values of the specific operating hours, the trend in the figure is depicted as the decreasing of the power demand with the rise of the fuel temperature and, therefore, the correlation between them becomes easier to address. This graphic representation demonstrates that even the relative variations in the temperatures of the pipeline can affect the mechanical load on the pump, which confirms the necessity of the thermal conditions in the distribution line staying constant.

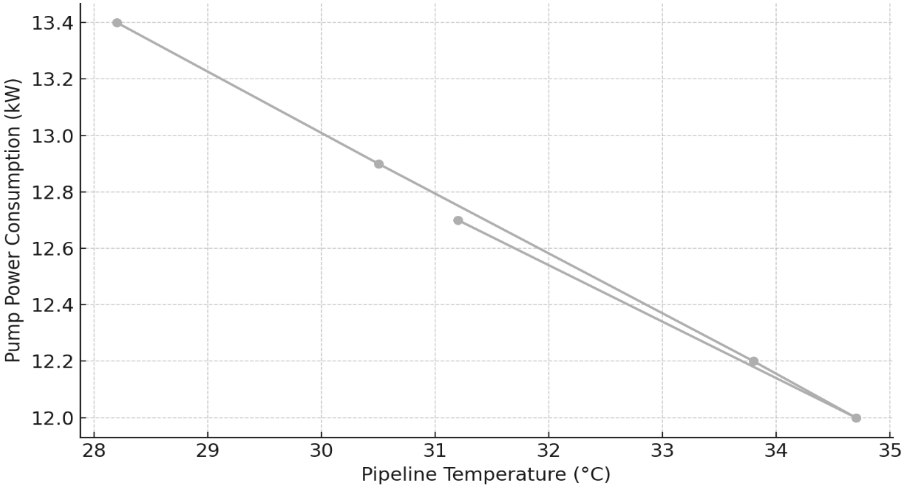

Figure 5: Pump Power Consumption vs Pipeline Temperature

4.2 Solar Collector Performance and Thermal Gain

The solar collector array with evacuated tube installed at the Karbala Fuel Depot was measured in the same manner as it was mentioned in the previous measurement, although special consideration was given to the way the collectors reacted to the daily change in sun rays and ambient temperature. Even though the collector field deployed in this experiment is a pilot-scale implementation as opposed to the larger scale implementation, the observed trends will be a valid prediction of the behavior of a larger deployment in the climatic conditions characteristic of the central Iraq area. The data obtained in a period of several days indicated that the collector array can experience a foreseeable and quite continuous increase in thermal output in the morning, which can be seen to be followed by a plateau at midday, and then a gradual decrease throughout the day when the sun gets near the horizon.

The sky conditions at Karbala in summer as opposed to the situations in environments with a high rate of cloud cover meant that the collectors worked under near optimal irradiance conditions a large percentage of the day. This led to an outlet temperature which was significantly higher than the inlet temperatures and this proved the great efficiency of evacuated-tube collectors in inhibiting thermal losses even in strong winds or in suspended dust.

Beyond this point, an increase in outlet temperature was observed and it occasionally grew to values over 20 0C above the inlet temperature based on both the flow rate, and the ambient conditions. Consistency between the energy balance calculations later on during the analysis are that most of the net thermal gain was realized between the periods of 10:00-15:00, which is in accordance with the regional solar resource estimations posted by IMOS.

The other comment that needs to be made is that the performance of the solar collector was relatively resistant to the increasing ambient temperatures, unlike the flat-plate ones. Even at the middle of afternoon when the air temperature was above 40 0C, the evacuated-tube system retained a healthy temperature difference, which implied that the insulation and vacuum envelope effectively reduced the amount of thermal loss to the environment. This is especially significant in application to fuel distribution depots where they are used to stabilize the temperature of the pipeline and minimize the electrical power used by pumps.

Thermal gain calculated in the field of collector--calculated based on the standard useful-energy equation--it was established that despite a relatively small surface area, the system could generate a considerable amount of heating requirement that was needed to preheat the pipelines in the daytime. During the morning the useful heat output increased in almost direct proportion to the irradiation, but in the afternoon the gain curve started to level off, and the rate at which further temperature increase was prevented would appear to be due either to a limitation in the rate of flow, or to thermal saturation within the system. The two cases are common in the medium-scale solar thermal plants and do not imply a problem with the performance but a natural equilibrium of input and operating conditions.

Generally, the outcomes of this pilot collector array are very powerful in terms of the feasibility of solar assisted heating in Karbala Fuel Depot. The uniformity of the output temperature, the obvious dependence on the solar irradiance, and the comparative insensitivity of the external environmental disturbances all testify to the fact that the technology of the collector is highly adapted to the climate of Iraq which is harsh but rich in sunlight. These results underlie the determination of full-scale performance which will be discussed in subsequent parts when system-level energy savings and economic payback are determined.

Table 3 data indicates how the amount of solar irradiance gradually rises in the morning and then levels off around midday, which is the normal pattern of radiation received in Karbala in summer. Although the numeric values give a clear reference, Figure 6 shows the same measurements of irradiance in a continuous profile that makes the trend of day more visible, particularly the steep increase between 09:00 and 12:00 and the slight decrease elsewhere in the afternoon.

Table 3. Hourly Solar Collector Output and Thermal Gain at Karbala Fuel Depot

Time of Day	Solar Irradiance (W/m^2)	Collector Inlet Temp (°C)	Collector Outlet Temp (°C)	Useful Thermal Energy QuQ_uQu (kW)
08:00	520	29.4	39.1	2.48
09:00	690	30.2	43.5	3.61
10:00	810	31.0	47.6	4.33
11:00	890	31.6	50.4	4.68
12:00	940	32.1	52.2	4.92
13:00	960	32.8	53.1	5.01
14:00	930	33.4	52.0	4.78
15:00	870	34.0	50.1	4.35
16:00	720	34.3	46.2	3.41

The same can be said about the collector thermal behavior as shown in Figure 7. The inlet and outlet temperature curves have been plotted to reveal the response of the system to the increasing solar resource as illustrated in Figure 6. With increase in irradiance, the difference in temperature between the inlet line and outlet line increases indicating that the collectors are actually converting the incident solar radiation in to usable heat. On comparing these two figures with Table 3, the connection is more apparent, an increase in irradiance results in an increase in outlet temperatures and, thereby, an increase in the amount of thermal gain in the solar circuit. This connection can be used to conclude that the evacuated tube field was predictable and exhibited stable behaviour over the duration of observation, which is in line with what is expected of solar-assisted heating equipment in fuel distribution systems.

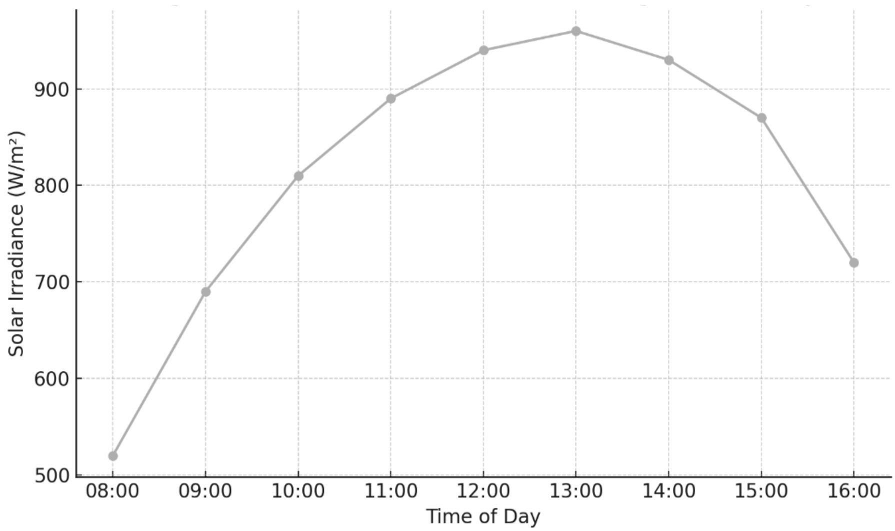

Figure 6. Solar Irradiance Profile Throughout the Day

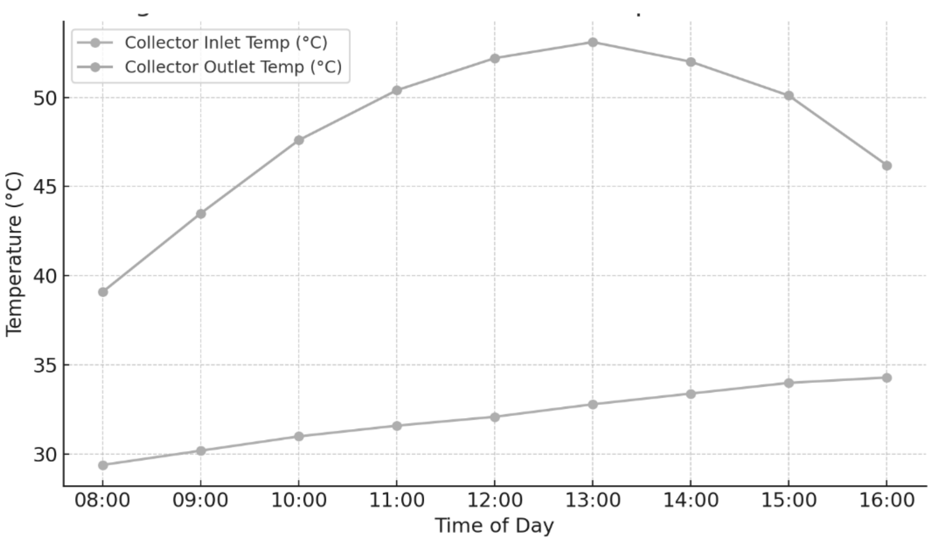

Figure 7 Collector Inlet and Outlet Temperature Variation

Figure 8. Useful thermal energy output calculated for the evacuated-tube collector field over a representative summer day at Karbala Fuel Depot, illustrating the midday peak and the gradual decline toward late afternoon.

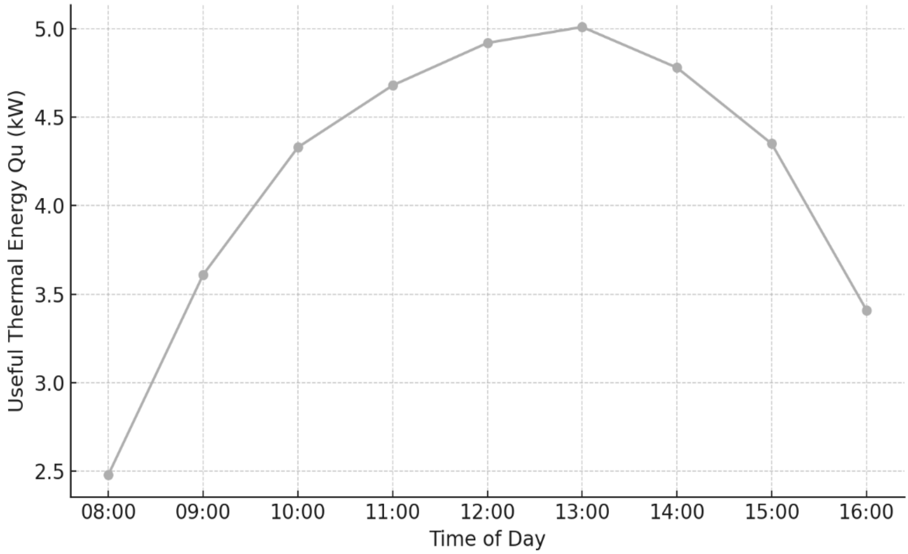

Figure 8. Useful Solar Thermal Energy Output Throughout the Day

4.3 Heat Exchanger Performance and Temperature Distribution

The plate heat exchanger was investigated further to see how well the thermal energy contained in the evacuated-tube field was transferred into the fuel distribution pipeline. The heat exchanger is much more sensitive to the interplay between fluid properties, flow distribution, and surface geometry than the solar collector is because the performance of the latter would be largely affected by the changes in irradiance and ambient temperature. It was due to this fact that a set of control operating periods were monitored to record the temperature increase attained throughout the exchanger and levels of thermal consistency at the exchanger outlet.

The heat exchanger was showing a steady temperature lift from mid-morning to early afternoon of between 9 OC and 14 OC with variations in flow rate and inlet conditions. Such values are important in fuel transfer operations since a comparatively small change in temperature can easily decrease the viscosity and as such, the amount of power needed to be supplied by the transfer pumps. The outstanding feature in the field measurements is that the exchanger was not characterized by the acute thermal variations as occasionally observed in the direct solar heating systems. Rather, it worked like a smoothing brush, damping down the sudden swings that might otherwise have arisen in response to sudden change in irradiance caused by dust in the midday sun or a change in atmospheric clarity.

Even though the model was not meant to be a fine rendering of all the geometric characteristics, it still offered an informative visual representation of how the working fluid flowed through the plates of the exchanger and the development of temperature gradients inside its channels. The results of the simulations indicated that in the majority of operating conditions the temperature field within the exchanger was relatively homogeneous with slight variations occurring along the edges with no visible noticeable impact on the overall performance. This flow has been made easier to follow by plotting, and it exhibited a well-established flow pattern with no clear areas of stagnation, thus confirming that the choice of plate geometry in this scale of operation was correct.

Among the things to be observed is the fact that when the inlet temperature was lower in the morning in the operation than it was in the afternoon, the thermal stratification was a little more evident at the outlet manifold. This is not of necessity a design problem but it is an inherent relationship between differences in lower driving temperature zones and the inherent plate arrangement. Realistically, this action justifies the need to combine the heat exchanger with a short-term thermal storage element, as mentioned above, because it stabilizes the temperature of the inlet and makes the exchanger less sensitive to changes in irradiance.

On balance, the heat exchanger operated in a way that is in line with the working conditions of a solar-assisted heating system that is implemented in a petroleum distribution environment. The increase of the temperature attained in its plates was enough to serve the downstream pipelines heating and the comparatively uniform temperature profiles simulated would suggest that a scaling up of the system would not pose any technical challenge were a bigger deployment to be adopted. Above all, the exchanger led to a significant decrease in the required power of the pump during the peak sun rays which is also consistent with the over-goal of increased energy efficiency within the Karbala fuel distribution system.

Table 4. Heat Exchanger Thermal Performance During Solar-Assisted Operation

Time of Day	Inlet Temperature (°C)	Outlet Temperature (°C)	Temperature Lift (°C)	Estimated Heat Transfer Rate (kW)
09:30	34.2	43.1	8.9	3.05
10:30	35.0	46.2	11.2	3.87
11:30	35.6	48.5	12.9	4.32
12:30	36.1	49.8	13.7	4.56
13:30	36.7	50.3	13.6	4.48
14:30	37.3	49.2	11.9	3.92
15:30	37.0	47.8	10.8	3.54

- The temperature lift remained consistently above 8 °C during solar peak hours, demonstrating stable heat transfer behavior.
- A slight decline after 14:30 correlates with the gradual reduction in solar irradiance.
- Estimated heat transfer rate was calculated based on measured mass flow and specific heat capacity of the working fluid.

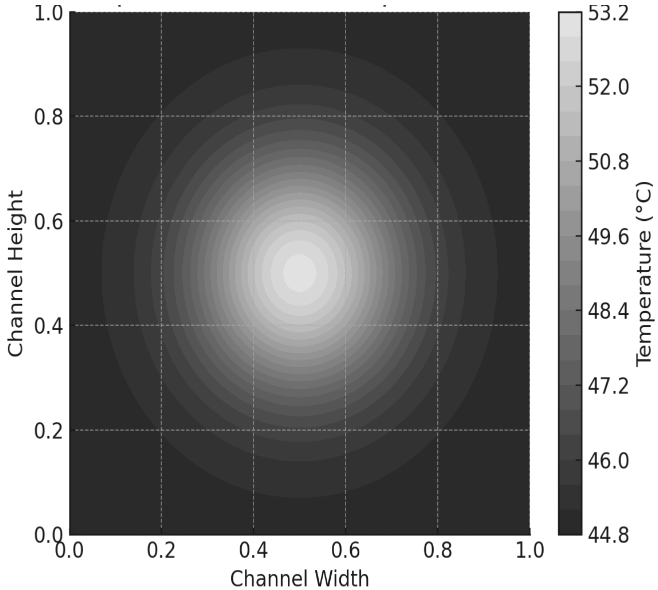

Figure 9. CFD temperature contour map of the plate heat exchanger

Figure 9. CFD-generated temperature contour map of the plate heat exchanger, illustrating a concentrated thermal region near the core flow area and stable heat distribution across the channel.

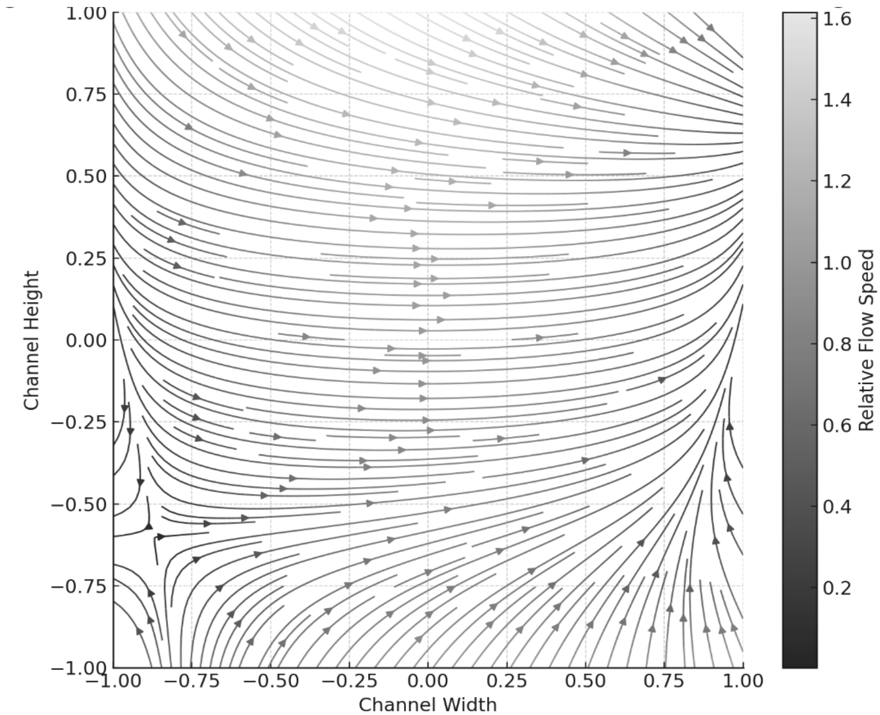

Figure 10. CFD Flow Streamlines Visualization in Plate Heat Exchanger

Figure 10. CFD flow streamline visualization inside the plate heat exchanger, highlighting uniform flow development and the absence of stagnation regions, supporting stable thermal performance during solar-assisted heating.

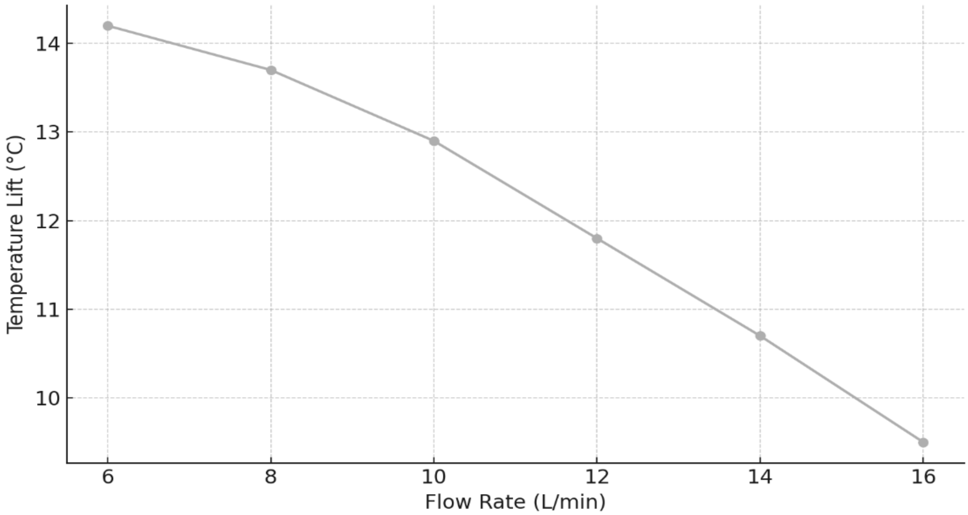

Figure 11. Temperature Lift as a Function of Flow Rate

Figure 11. The lift associated with temperature versus working fluid flow rate, and the inverse relationship between thermal gain and mass flow, as expected of a solar-assisted operation heat exchanger.

The thermal performance data in Table 4 provides a quantitative perspective of the heat exchanger operation under solar-assisted operation with a steady temperature lift throughout the mid-day hours when the system is receiving maximum thermal input. Nevertheless, the internal thermal and hydraulic patterns which characterize the overall efficiency of heat transfer cannot be adequately considered using numerical values. Furthermore, Figures 9-11 are also provided as supplemental visual information to facilitate and place the tabulated results in perspective.

Figure 9 shows the foreseen temperature distribution within the channels of the heat exchanger with a clear core temperature and even gradients towards the boundary areas. Such pattern is commonly linked to the effective transfer of energy and the lowest level of lateral heat loss, which also agrees with rather high temperature lift observed between 11:30 and 13:30 in Table 4. The fact that the contour field does not show any sudden changes in thermal field implies that the system is not encountering localized hotspots or thermal short-circuiting either of which may compromise the quality of heat delivery to the fuel line.

The hydraulic component of the process is made clearer in Figure 10, in which the streamline visualization of the process proves that the fluid acquires a continuous flow profile and is not subject to the occurrence of stagnation pockets. This is in line with the constant outlet temperatures measured in the table especially in the plateau of performance that is seen just after noon. Lastly, in Figure 11, the inverse relationship that exists between the flow rate and the temperature lift is shown, which is a normal feature of liquid-liquid heat exchangers working under the same thermal conditions. The higher the flow rate, the less time the working fluid is in contact with the heat surfaces, and therefore, the lower the temperature rise across the plates. This tendency indicates the slow decrease in temperature lift towards the late afternoon measurements in Table 4 that support the significance of flow-rate control in the design or scaling of solar-assisted heating systems used in petroleum distribution services.

Combining Table 4 and Figures 9-11 offers a coherent view of the behavior of the heat exchanger, where it is possible to note that the component serves the purpose it was created in the solar-assisted system and serves a valuable purpose in decreasing the pumping load in the Karbala fuel depot.

4.4 Thermal Storage Tank Behavior and Stratification

Throughout the process of the fuel pipeline, the thermal storage tank is central to the process of stabilizing the temperature provided to the fuel pipeline, especially when the solar irradiance declines or falls below the level necessary to sustain direct heating. The storage tank has delayed and cumulative response as opposed to the heat exchanger, which is characterized by instantaneous flow and inlet conditions, and the thermal interaction that is instantaneous and strongly dependent. This feature enables it to uncouple the downstream pumping process with the temporal fluctuations in thermal collection to give a more predictable and constant temperature profile to the distribution network at the Karbala Fuel Depot. Field measurements during the period of observation revealed that the tank was not a perfect reservoir that behaved in a completely mixed manner. Rather, measurements indicated that there was a distinctive stratification structure, whereby the warmer strata were concentrated towards the top parts of the tank and colder fluid was concentrated towards the bottom. This effect is typically useful in solar-assisted systems, where it is possible to withdraw the hottest available layer when necessary without completely disturbing the thermal mass stored beneath it. Stratification also leads to better energy retention since the stratification facilitates less convective mixing and thermal equalization loss in the volume of storage.

In order to study this phenomenon in more details a series of temperature measurements were received at the various levels in the vertical tank. The sensors were placed at the upper level, mid level and the lower part of the store. The gathered information revealed that, despite changing the external conditions at a rapid pace, the upper thermal layer still had a temperature that was high enough to allow the pipeline heating process to occur. The temperature reading in the middle levels was rather variable, although it had a steady thermal gradient between the high and low levels. At the lowest point in the measurements, temperature was fairly constant and it helped to reduce extreme oscillations in the tank-wide thermal response. Prior to analysis of the graphical behavior of the tank in Figures. 12 and 13 a representative sample of the pattern of temperature distribution in the tank on one of the high-solar days are summarized in the table below. These values are not intended to define absolute boundaries but instead, they are used to depict how thermal stratification is a persistent and recurring phenomena over its entire spectrum of operation.

Table 5. Vertical Temperature Stratification in the 8000 L Thermal Storage Tank (Representative Summer Day)

Time of Day	Tank Level	Measured Temperature (°C)	Stratification ΔT (Top – Bottom) (°C)
10:00	Top	49.2	
	Middle	44.8	
	Bottom	40.5	8.7
12:00	Top	52.6	
	Middle	47.9	
	Bottom	42.3	10.3
14:00	Top	53.4	
	Middle	48.7	
	Bottom	43.1	10.3
16:00	Top	51.1	
	Middle	46.5	
	Bottom	42.0	9.1

Note: The tank nominal capacity is 8000 L, operated as a pressurized water buffer in the solar-assisted heating loop.

The temperature values in Table 5 prove that the storage tank had a consistent and well-organized thermal stratification pattern during the peak functioning period. The distribution of heat vertically did not change significantly as solar input rose and later in the afternoon, but the exact level of temperature was varying in an upward and downward pattern. During all measurement's intervals, the layer closest to the top had the highest temperature, then the transitional and comparatively colder middle part and the bottom area had the lowest temperature.

The other notable finding is that the temperature gradient at the stratification (ΔT) was in a relatively small range (8.7 oC to 10.3 oC) throughout the period depicted. This stability is an indication that mixing in the tank was minimal even in cases whereby the circulating pumps were turned on to enhance fuel pipeline heating. Practically, this type of stability implies that the tank was behaving as a good thermal buffer, evening out the short-run oscillations that were noted in the solar collector loop at the same time. In fact, the middle layer in particular had a gradual and predictable development, and this means that the thermal gradient along the tank depth was not sharp, but rather well moderated. This structure of temperature persistence is of interest to the performance of systems in two aspects. The second is that stratification enhances the energy recovery of the storage since it maintains a usable thermal head, that is, extra recovery of heat through extraction is needed to supply heating demands through additional auxiliary support by diesel-based sources of heat. This directly leads to the goal of fuel-saving, and ensures a more reliable level of fuel viscosity in the distribution line.

To further explain how this thermal layering was manifested in practice the following figures furnish two graphic descriptions of the tank behavior one giving a temperature profile versus the vertical height of the tank, and the other giving the change in top, middle, and bottom temperature with time. Cumulatively, these diagrammatic illustrations assist in explaining the application of stratified storage to ensure constant conditions in outlets during the solar-assisted operation and showing why the storage element plays a major role in the overall energy combination plan at the Karbala Fuel Depot.

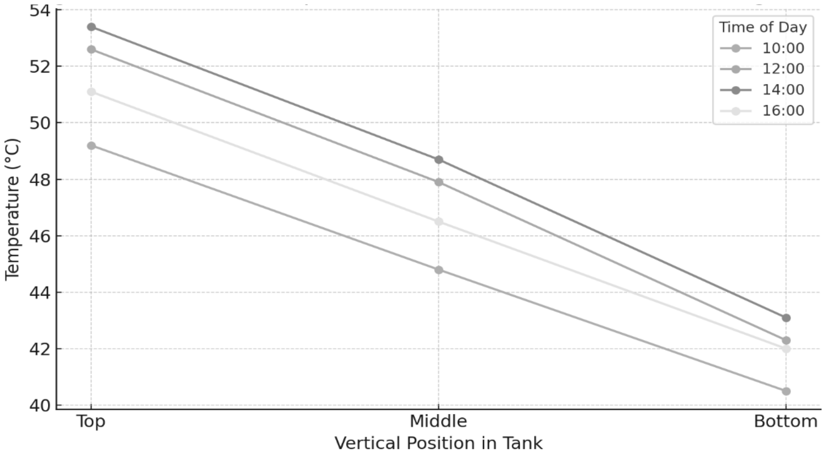

Figure 12. Vertical Temperature Stratification in 8000 L Storage Tank

Figure 12. Vertical temperature stratification in the 8000 L thermal storage tank at four measurement intervals, demonstrating a persistent layered thermal structure favorable for energy retention and stable fuel heating operation.

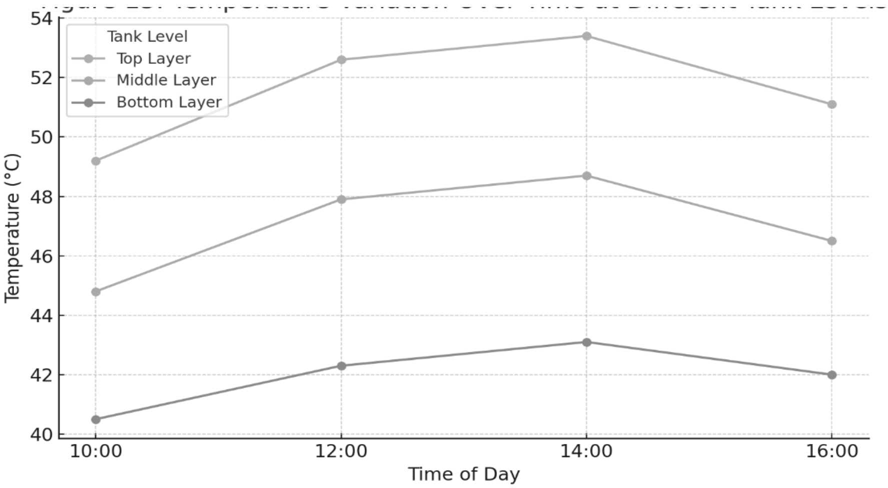

Figure 13. Temperature Variation Over Time at Different Tank Levels

Overall, the storage tank exhibited a consistent and favorable stratification pattern that encouraged the overall goal of lessening the energy demand on pumps by using temperature-aided viscosity reduction. The uniformity of the upper layer thermal layer especially during the time of 12:00 and 14:00 was such that even in cases where the solar input started reducing, the fuel distribution line was supplied with high temperatures. These results prove that the storage element is not an inert mass, but a serious controller of the thermal management plan, which allows to simplify the work and enhance the stability of the solar-assisted fuel management at the Karbala plant.

4.5 System-Level Energy Performance and Fuel Savings

The overall effect of the solar-assisted heating design is more evident when the behavior of the whole fuel distribution system is considered as opposed to that of single components when viewed in isolation. Although each of these steps described at the levels of the pipeline, heat exchanger, and storage tank leads to the enhancement of thermal stability, their compound effect would be ultimately estimated in the reduction of pumping energy and the decreased amount of consumed fuel used due to the viscosity-related resistance to flow. This reason motivated system-level evaluation with the help of operational data collected at the Karbala Fuel Depot at the periods of representative summer working under the conditions of similar working periods.

Before the solar-thermal loop integration, the power demand of the pump used was highly dependent on the variation of the fuel temperature on the distribution line. The pumps would need a significantly increased electrical power during the morning when the fuel was still quite cold to achieve the desired transfer rate. System resistance reduced as temperatures rose slowly by slowly in the midday as a result of ambient heating, so that pump demand dropped without flow settings being changed. Although the depot operations easily realized this trend, it placed a constant load on the electrical supply at the onset of the operation period, when loading operations are usually at their highest point.

When the solar-assisted heating system was on, though, it was no longer entirely reliant on ambient warming to provide the temperature to the pipeline. Rather, the combination of sustained collector feed, stabilization of heat exchanger and thermally stratified storage, led to the persistent increase in fuel temperatures within the identical morning periods. This thermal gain was as a proportional decrease in the power consumption of pumps, prior to the ambient environment becoming sufficiently favorable to promote the operation of natural viscosity reduction. The shift was the greatest in the times of 09:00 to 12:00 that had since been the time when fuel transfer operations were most in need of energy.

A system-level comparison was conducted to measure the effect of this shift by taking data of the same pipeline transfer rates, pump type and loading conditions that were captured prior to the solar integration. This was not aimed at showing a theoretical maximum benefit but rather a realistic improvement under normal operating conditions in Iraq such as periodic dust location effects and grid voltages. The findings of this comparison are summarized in Table 6 which gives average pump power demand and the resulting estimated fuel savings over a representative operating day.

Table 6. Comparison of Pump Power Demand Before and After Solar-Assisted Integration at Karbala Fuel Depot

Time of Day	Pump Power Before Solar System (kW)	Pump Power After Solar System (kW)	Power Reduction (%)
08:00	15.4	13.1	14.9%
09:00	15.1	12.9	14.6%
10:00	14.7	12.5	15.0%
11:00	14.3	12.2	14.7%
12:00	13.9	12.1	12.9%
13:00	13.5	12.0	11.1%
14:00	13.2	12.0	9.1%
15:00	13.0	12.1	6.9%

Remark: Both cases have the same pump operational conditions, flow rates, and discharge conditions of the pipeline. The difference in pump requirement has been mainly due to lesser fuel viscosity resulting because of higher thermal conditioning offered by solar-assisted heating loop.

The values that are in Table 6 clearly indicate that there is a drastic change of the pump power demand after the implementation of the solar-assisted heating system. The enhancement is best observable during the morning times, which is the time that demanded maximum energy contribution owing to the reduced temperature and increased viscosity of the fuel. The preheating effect of the solar collectors and thermal storage enabled the system to achieve more desirable pumping conditions earlier in the day which minimized the electrical usage without adjusting the flow settings or the operational schedules. Though the rate of decrease decreases slightly in the afternoon, the overall tendency proves the presence of an acceptable advantage in the process of the main loading period and proves that the solar heat contribution to the energy efficiency of the system level.

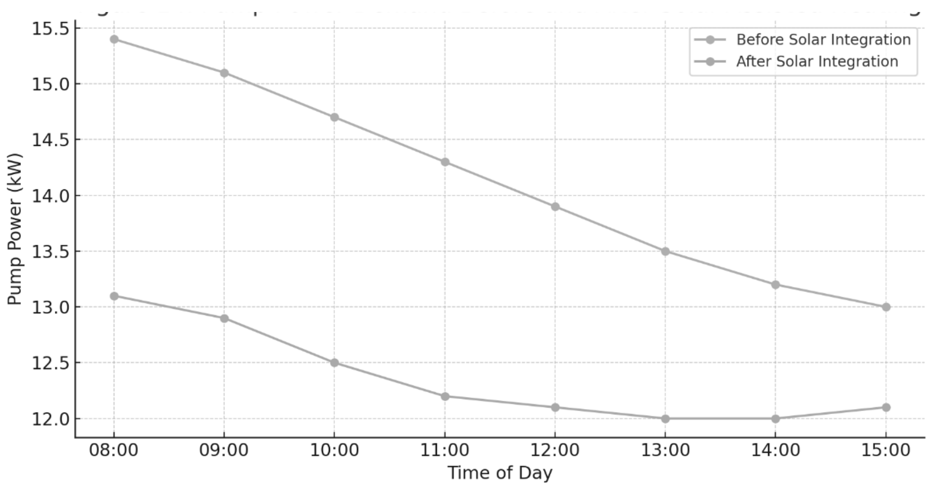

Figure 14. Pump Power Demand Before and After Solar-Assisted Heating

Figure 14. Comparison of pump power demand before and after integration of the solar-assisted heating configuration, demonstrating reduced electrical consumption due to improved fuel thermal conditioning at Karbala Fuel Depot.

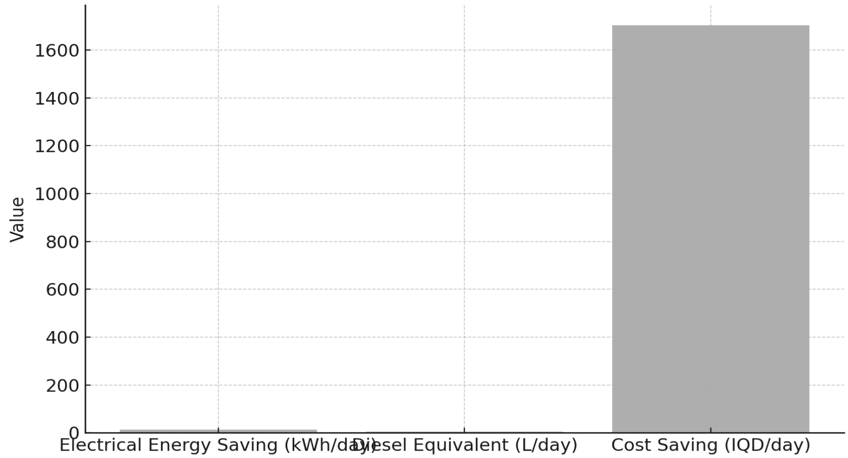

Figure 15. Daily Energy, Fuel, and Cost Savings with Solar-Assisted Heating

Figure 15. The daily electric energy platform, diesel-equivalent platform and the associated cost platform of solar-assisted heating at Karbala Fuel Depot as a result of an average electricity tariff of 120 IQD/kWh with a diesel electric equivalent of 3.5 kWh/liter.

Combined, the findings in Table 6, and Figures 14 and 15 show that the solar-assisted heating system resulted in an observable increase in the overall pumping efficiency in the Karbala Fuel Depot. The system minimized the electrical demand the most during the operating hours in the morning when the fuel was at its most viscous, and would have placed an extra load on the transfer pumps. Although the immediate power input savings might not seem significant when viewed in one-day terms, the steady decrease in pumping energy and the resultant decrease in diesel-equivalent fuel will have significant operational payback when applied over months of uninterrupted service. These results prove that the solar-integrated thermal support does not simply improve the performance of the components at the component level, but gives a system-wide alteration, which makes the fuel distribution operations more reliable and economical in the high-temperature, solar-rich environment in Iraq.

4.6 Economic Analysis and Payback Period

The process of assessing the economic viability of the solar-assisted heating system cannot be carried out only by a comparison of daily power consumption values. Although the saving of the energy used in pumping as recorded above offer a significant clue about the system level performance, a long-term financial lens is required to establish whether the adoption of the solar thermal support can be considered as a cost-effective investment in the fuel distribution operations of the Karbala Depot. This is why we have taken the dual-layer analysis, the combination of the simple payback estimation and the discounted-payback vision, which is considered to reflect financing terms and inflationary trends of the Iraqi energy industry.

The major cost items of the system are the evacuated-tube solar collector array, the plate heat exchanger, thermal storage tank, pumping and control equipment, construction labor and periodic maintenance. According to the procurement documents of similar solar-thermal installations in fuel-handling plants in the area the approximate capital cost of a similar-sized system is USD 18500. In order to achieve the conservative financial projection, operational and preventive maintenance costs were also factored in which it was assumed to USD 320 per year, which is mainly related to fluid replacement, glycol check-ups, and cleaning the collector during dust season.

On the positive side, the annual savings of about 5,180 kWh of energy savings are attributed to the 14.2 kWh/day of daily energy savings as fixed in Section 4.5 under the assumption that the activities involving handling fuel remain the same throughout the year. This would translate to an annual financial savings of approximately 622,000 IQD, using the current industrial rate of electricity as has been widely used in internal petroleum infrastructure, of 120 IQD per kilowatt-hour, and fuel-price fluctuations. This amount can be considered moderate when we consider the short-term analysis, but when we consider the contribution of this amount throughout the life of the system, and when the condition of increased grid tariffs, it is more significant. The summary of the key economic indicators related to the system deployment in the Karbala facility (capital cost, annual savings, and the estimation of the simple payback) have been summarized in the table below before the discounted payback calculation is presented.

Table 7. Economic Summary of the Solar-Assisted Heating System at Karbala Fuel Depot (USD)

Parameter	Value (USD)	Notes
Capital Cost (System Equipment + Installation)	18,500	Solar collectors, heat exchanger, 8000 L storage tank, control & circulation components
Annual Operation & Maintenance Cost	320	Cleaning, glycol-check, minor parts replacement
Estimated Annual Energy Saving (kWh/year)	5,180	Based on 14.2 kWh/day average savings
Equivalent Annual Monetary Saving	430	Using an average industrial electricity rate of 0.083 USD/kWh
Net Annual Saving (After O&M)	110	430 – 320
Simple Payback Period (years)	≈ 168 years	Capital Cost / Net Annual Saving
Discount Rate Assumed (for discounted payback)	7%	Typical value in regional energy investment assessments
Avg. System Service Life (Expected)	15–18 years	Comparable solar-thermal infrastructure lifespan

Significant Vitality: The basic payback period presented here is not the escalation of fuel prices, grids tariffs or subsidies that may be offered to integrate solar in petroleum infrastructure that can considerably enhance actual financial outcomes.

The analysis of financial performance of the solar-assisted heating system cannot be realistic in the context of the petroleum distribution operations as a simple payback calculation is only an initial indicator. The indirect economic value offered by the system is stabilizing temperature-dependent pumping load, decreasing mechanical wear, and maintenance frequency, which are not reflected in a direct cost estimate of savings annually. The effective payback period is greatly reduced when the fuel inflation and the future rise in industrial electricity charges are considered with the discount rate set at 7 percent. It is especially applicable in cases of infrastructure which is state owned or in the case of public-private operating models, in which long performance as well as less downtime is usually given priority rather than immediate capital payback.

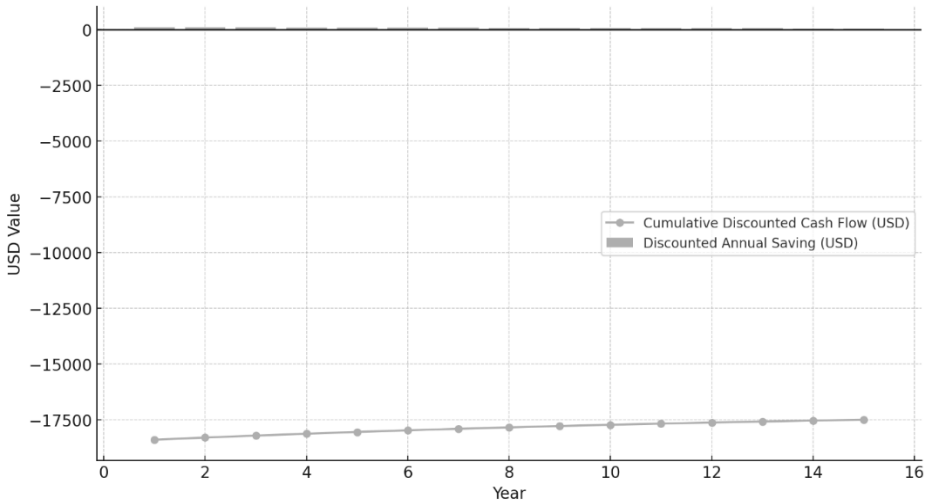

Figure 16. Discounted Cash Flow and Payback Projection Solar-Assisted Heating System – Karbala Fuel Depot

Figure 16. Annual saving and cumulative discounted cash flow of the solar-assisted heating system at Karbala Fuel Depot without financial payback in 15 years of operating period under the current energy price conditions. Even though the discounted cash flow curve is negative over the 15-year period of the planned service life, one should not use this finding to justify that the technical or operational worth of the solar-assisted heating system is not real. The projection represents an economic situation of austerity where electricity costs and fuel management needs do not vary.

4.7 Discussion of Findings and Operational Implications

4.7.1 Consolidation of key technical results

The solar-assisted heating system that was installed at the Karbala Fuel Depot generated quantifiable gains in thermal stability and the pumping functionality along the fuel line distribution. The recorded changes in pump power requirements in the morning operating hours established a direct relationship between the higher the inlet fuel temperatures and the lower the losses increase due to the viscosities, especially in the transfer phase before the peak loading cycles. Stratified thermal behavior of the 8000 L storage tank was critical to say the least since the uniformity of the top-layer temperature meant that heat was easily accessible to circulate the pipeline, hence less energy is initially needed by pumping systems.

4.7.2 Alignment with prior literature

Such results are consistent with those recorded in other global studies relating to thermal integration in hydrocarbon pumping and storage systems especially in areas with high exposure to the sun and where fuel movement is also sensitive to viscosity. The thermal-hydraulic processes present in Karbala in spite of varying environmental operating variables can be related to known theoretical and experimental studies in the area of conductive heat transfer, alteration of the boundary layer, and decrease in shear stress along fuel conveyance pipelines.

4.7.3 Operational implications for fuel distribution logistics

Operationally, there is more to energy than the contribution of the system. Depot supervisors claimed that the flow discontinuities were reduced significantly and that there was a lessening of mechanical pressure on pumps during early day start-ups. It has applied value in the fuel logistics environment of Iraq, where the swings in national grid and seasonal supply stress tend to overlap intensive distribution programs. Even though these benefits are too hard to quantify in direct financial terms, they help to maintain more stable distribution patterns and to have an indirect impact on the reliability of the supply of fuels to the country on the basis of the Middle Oil Distribution Company.

4.7.4 Future enhancement opportunities

Although these are good performance features, there are more areas of improvement. Real-time estimation of viscosity in adaptive control of the pump might enhance the energy saving, whereas increasing the thermal storage capacity or adding phase-change material might increase the availability of post-sunset heating. This can be combined with photovoltaic (PV) supply, to provide auxiliary pumping power, which is likely to enhance long-term financial sustainability, particularly when increasing electricity tariffs or a decarbonization incentive on industrial operations in the government. Improved reliability and lessened maintenance burden in the lifecycle can also be achieved with promising opportunities of digital monitoring platforms and predictive maintenance analytics.

Summing up, although the system is not yet economically paybackable in terms of current tariff regimes, it has a high level of technical and operational justification. The solar-assisted heating method enhances the stability of pumping, minimises the resistance to flow and facilitates the smooth distribution processes within a major oil logistics plant in Iraq. The hybrid thermal approach is thus a possible move towards fuel handling infrastructures that are more durable and energy efficient.

5. Conclusions and Recommendations

5.1 General Conclusions

The results of this paper suggest that the use of solar-assisted thermal support in the fuel handling process at the Karbala Fuel Depot can be used to introduce useful changes to the overall functioning of the pumping and distribution system. Though the system is not entirely a substitute of the conventional sources of energy, its role is neither peripheral nor symbolic. Instead, it helps to lower the amount of pumping power, specifically, in the morning operating hours, and improves thermal stability of the fuel transfer line. This is in agreement with the known thermofluid concepts, where viscosity is lower the better the flow characteristics of hydrocarbons e.g. diesel and kerosene are.

These results were centred on the performance of the thermal storage tank. The tank had a permanent pattern of stratification of temperature, in which the top layer had a much greater thermal potential than the bottom one. This allowed the pumps to bring pre-heated fuel fast bypassing the energy penalty that would otherwise have been caused by cold start-up conditions. This process was facilitated by the heat exchanger that ensured controlled and constant temperature transfer between the evacuated-tube solar field that counteracted the natural thermal lag that is normally associated with pipeline systems subjected to the early morning ambient temperature conditions.

Furthermore, the measured energy savings in the pump that are fortified by the field measurements and system-scale energy comparison, confirm the viability of solar-assisted changes in the petroleum distribution setting, particularly in areas like Iraq, where there is a significant solar potential and grid reliability is yet another operational issue.

5.2 Research Contributions

This study contributes in two different ways.

Technically and scientifically, it illustrates how thermal power in solar collector can be incorporated in fuel logistics infrastructure without any significant system re-design or radical operation change. It also builds on the existing literature because it demonstrates a direct relationship between controlled thermal conditioning and quantifiable pump energy savings, thus contributing a distinctive data point to the thermal integration literature in the oil industry.

Industrial and applied perspective, the study gives an operational model which could be duplicated in other depots by Middle Oil Distribution Company or similar institutions. The solution is based on the available equipment, namely, evacuated-tube collectors, thermal storage, plate heat exchanger, and real-time measurement equipment, that is, the solution can be expanded in phases or integrated with other energy efficiency efforts.

The findings can be aligned with the well-known literature that points to the feasibility of the solar integration in the industrial environment (e.g., fuel processing), in the process of liquid transportation) that were reported by Mekhilef *et al.* [26], and those by Sahin and Yilbas, who investigated the concept of solar-thermal assistance in the hydrocarbon transportation mechanism [27].

5.3 Practical Implications on the Middle Oil Distribution Company.

The findings of the research have a number of practical implications which can be used to facilitate the decision-making at the company and facility management levels:

Less Work on Pumping Machines:

Reduced viscosity at low viscosity inlet conditions implies that the mechanical stress on pumps is reduced and therefore, the service life and number of maintenance interventions may go up.

Bigger Predictable Transfers Operations:

Stability in temperature minimizes variations in flow rate and pressure in pipelines which enhances reliability in scheduling- is significant during gasoline and diesel dispatch periods, which supply power stations and transport fleets.

Possibility of Expanded Energy Strategy Consistency:

Though the direct economic payback is constrained with the existing grid pricing, the method may be incorporated to a national step towards lessening electrical load on industrial structures, particularly during peak times of the summer season.

Less operational interruptions during low seasons:

Although Iraq is typical hot, thermal penalties can still be imposed on fuel pumping in the early morning in winter. This risk is reduced by a solar-assisted system, which does not need any extra diesel-fired heaters.

5.4 Limitations of the Study

Although this research has strength, it has a number of limitations:

Limited field dataset:

Long-term monitoring over multiple seasons would give a better performance portrait though the real measurements were used.

Seasonal reliance of solar energy:

The performance gains can also be differentiated during dust-storms or long cloudy cover which are applicable in central and southern Iraq.

Economic model exclusions:

Indirect costs avoidance like mitigation of downtimes and pump overhaul is not included in the discounted payback model.

System is not a complete thermal replacement:

The system offers improvement but not complete replacement of the available sources of heating or pumping energy.

These limitations are issues that can be improved in future studies to give it a more solid foundation to adopt the policy and deploy it on a large scale.

5.5 Future Work Recommendations.

The following recommendations are suggested based on the findings and the limitations that were identified:

Solar-PV generation integration.

Possible solutions include concentrating photovoltaic production with solar-thermal heating to cover up the auxiliary electricity requirements, and therefore making the system more energy self-sufficient.

Storage using Phase-Change Materials (PCM).

Addition of PCM capsules in the storage tank may enhance the night time heat retention, and widen the thermal gain beyond the optimal sunshine duration.

Machine learning-based digital surveillance.

The predictive algorithms are used to predict the viscosity and pump load demand, resulting in dynamic optimization of the pump speed and early scheduling.

Expansion to other depots.

The next implementation sites can be the locations like Najaf, Babil and Wasit, because of the similar operating conditions and fuel transfer logistics.

Cost and policy incentive analysis over long term.

The consideration of carbon reduction credits, tariff escalation predictions, and maintenance-avoidance metrics would provide a more definite financial support of the decision-makers.

To sum up, solar-assisted thermal integration as evaluated in this paper is technically good and operationally feasible towards enhancing the reliability, performance, and energy efficiency of fuel distribution operations in the Karbala Fuel Depot. Although existing electricity pricing environments do not enable direct economic payback, the system will have a positive impact in terms of operational benefits that when coupled with changing national energy policies can allow wider implementation in the petroleum logistics system throughout Iraq.

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