



Energy Efficiency Optimization of Heat Exchanger Networks in Saudi Arabia's Oil and Gas Facilities under Vision 2030

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Abstract: Heat exchanger networks (HENs) play a key role in energy recovery in refineries, gas-processing plants and integrated petrochemical complexes since they decide how much process heat is reused internally before outside heating and cooling utilities have to be bought. This review looks at the developments published between 2020 and 2025 and uses them to formulate an optimisation programme specific to oil and gas facilities that are operating in accordance with Vision 2030. The evidence shows that the most effective retrofit approaches no longer regard pinch targets, network topology, exchanger design, fouling, pressure drop, maintenance and operability as independent issues; on the contrary, recent research has progressively combined thermodynamic targeting with mathematical programming, detailed thermal-hydraulic models, asset-life planning, real-time performance monitoring and the selection of retrofit measures within budgetary limitations. Refinery case studies show that significant reductions in utility and operating costs can be obtained through both low-disruption measures and more extensive reconfiguration of the network, although the outcomes depend heavily on the existing topology, the stream temperatures, the current state of fouling and the execution constraints. For Saudi facilities, the best approach therefore is not a single, universal HEN design but rather a step-by-step decision framework: first diagnose the actual losses in heat recovery, set realistic targets, rank the various retrofit options according to their energy and carbon value, take into account the hydraulic and fouling penalties, and then maintain the savings by means of digital monitoring and coordinated maintenance. The review suggests an implementation framework for Vision 2030 that connects HEN optimisation to fuel displacement, carbon-intensity reduction, reliability and capital discipline. It also points out gaps in dynamic optimisation, the treatment of uncertainty, site-wide integration, carbon-aware objective functions and validation based on data from Saudi plants. The main manuscript contains 4,400 words (from the Abstract to the Conclusion; excluding the title, headings, keywords, tables, figure captions and references).

Keywords: Heat Exchanger Networks (HENs); Energy Recovery; Process Integration; Pinch Analysis; Network Optimization; Heat Exchanger Fouling; Retrofit Optimization.

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1. INTRODUCTION

The oil, gas and petrochemical industries in Saudi Arabia involve large heat loads and operate

continuously with high asset utilisation and a heavy reliance on fired heating, steam and cooling systems. In these types of facilities, a heat exchanger network

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is not simply a set of individual exchangers; it is instead the thermal infrastructure covering the whole plant and decides whether recoverable heat is reused at the right temperature or is instead lost to the cooling systems, with extra fuel being used elsewhere. Because of this, the performance of the heat exchanger network has a direct bearing on operating expenditure, furnace duty, steam demand, cooling-water load, production resilience plus carbon intensity. According to recent research into Saudi energy policy, energy efficiency is considered, together with fuel switching and the deployment of renewables, as a practical means of decarbonisation, and Vision 2030 has sped up the overall move toward more efficient use of the country's energy resources (Al-Saidi, 2022; Belaid and Massie, 2023; Matar *et al.*, 2024).

The technical basis upon which HEN optimisation is based is well developed, yet the practical problem is still challenging. Pinch Analysis is capable of determining the minimum heating and cooling requirements and of spotting thermodynamic bottlenecks; mathematical programming can explore large structural spaces; models at the exchanger level can take into account pressure drop, the heat-transfer area, baffle layout and fouling; and monitoring techniques can pick up any deterioration in performance as the plant is running. A thermodynamically attractive network could entail a great deal of piping or could call for a lot of shutdown work. The advantage of an optimum obtained under clean conditions may disappear once fouling has occurred. A cheap topology may prove hard to control when there are changes in the feed or in the throughput. Klemes *et al.*, (2020) have therefore claimed that the field should go past theoretical energy targets and instead concentrate on practical solutions which take into account the life cycle and operability. Later studies have progressively adopted this approach by combining network retrofit with asset planning, integrating detailed thermal-hydraulic considerations, managing fouling and using computationally effective optimisation.

This issue is particularly pertinent to the Saudi refineries and gas plants currently in operation, since brownfield limitations play a decisive role. When designing new process units, it is possible to base them on an optimal energy layout, but existing plants have to work with fixed plot space, existing equipment, pipe racks, material properties, pressure ratings, control systems and turnaround periods. Any retrofitting has to ensure that both operational safety and production continuity are maintained while having to compete for capital investment with other projects relating to reliability, capacity and product quality. Graphical studies of refineries show that fairly simple temperature-related diagnoses can

identify high-value opportunities with a short payback period, and further benefits are found in advanced optimization studies when the topology, the type of equipment and the operating variables are taken into account (Alhajri *et al.*, 2021; Wang *et al.*, 2021; Teng *et al.*, 2023; Zhi *et al.*, 2024).

Fouling in crude preheat trains leads to a gradual decrease in heat transfer, changes the hydraulic resistance and causes a redistribution of the duties throughout the network. It therefore follows that cleaning, operating by bypassing, and the sequencing of exchangers can result in a change to the economic optimum during a run. Studies based on plant data and employing Kalman filtering together with network-level thermal-hydraulic indicators show how monitoring can help to make better decisions regarding cleaning and operation (Kansha *et al.*, 2022; Apio *et al.*, 2023; Patil *et al.*, 2023). Since, in the case of Saudi operations, long campaigns and high throughput can increase the cost of thermal degradation, optimisation there should include the capability to maintain and verify the benefits after the project has been commissioned.

In view of this, the current paper provides an in-depth study of research carried out between 2020 and 2025 on HEN synthesis, retrofitting, fouling, monitoring and oil-refinery heat integration, linking the technical evidence to Saudi Arabia's energy-efficiency objectives. Unlike a review that is arranged solely according to algorithm type, the analysis is based on the decisions which a working facility has to take: how to identify losses, establish targets, choose the level of retrofit, take into account equipment and fouling, assess the economic and carbon values, and sustain performance.

2. Objectives and Review Objectives

This review seeks to find out how modern HEN optimisation techniques can be combined in order to form an achievable energy-efficiency strategy for the oil and gas facilities in Saudi Arabia in accordance with Vision 2030. The study is not aiming at designing a new optimal network for a single plant; rather, it critically reviews the various methods and evidence available so that retrofit decisions can be aligned with the constraints of brownfield sites, operational risk and the nation's decarbonisation goals.

The review is based on five objectives. The first of these is to classify the recent research into five areas: thermodynamic targeting, mathematical programming, exchanger-level design, fouling and asset management, and operational monitoring. The second objective is to compare the advantages and pragmatic limitations of these methods in relation to their use in refineries and in gas processing. Thirdly,

the review looks at how capital cost, pressure drop, fouling, maintainability, network complexity and process variability affect the concept of an 'optimal' design. Fourthly, it converts the evidence into a step-by-step implementation framework for use in Saudi Arabia, with the framework relating to fuel, emissions, reliability and economic value. Fifthly, it points out the research gaps in dynamic, uncertainty-aware and carbon-aware HEN optimisation which should be filled using data from Saudi operations.

3. REVIEW METHODOLOGY

A methodology based on critical review was used, one that took the transparency guidelines of PRISMA 2020 into account even though the aim of the study was an engineering synthesis, not a clinical-type meta-analysis (Page *et al.*, 2021). The searches were designed using combinations of the following terms: 'heat exchanger network', 'HEN retrofit', 'pinch analysis', 'crude preheat train', 'refinery heat integration', 'fouling', 'cleaning optimisation', 'thermal-hydraulic performance', 'mathematical programming', 'Saudi Arabia', 'energy efficiency' and 'Vision 2030'. In order to check the bibliographic details and to give priority to peer-reviewed papers, the records were verified via publisher platforms, DOI-indexed entries and scholarly indexing services.

The criteria for inclusion required that the article had to be published in a peer-reviewed journal or in a conference journal between 2020 and 2025, must have a valid DOI, and had to be directly relevant to at least one of the following review areas: HEN synthesis or retrofit, heat-transfer enhancement inside networks, exchanger selection, pressure-drop or thermal-hydraulic design, fouling and cleaning, operational monitoring, refinery heat integration, or Saudi energy-efficiency policy. Papers which concentrated solely on individual heat exchangers without any consequences for the network were excluded unless the method in question specifically concerned HEN performance. Since the two papers attached here were published outside the specified time frame, they were used only as references for structure and presentation, whereas the attached 2024 paper on the Saudi microgrid was acceptable for contextual citation (Abusaq and Zohdy, 2024).

Evidence was entered into a qualitative matrix which included information on the application context, the optimisation method, the main decision variables, the reported direction of performance, the implementation implications and the limitations. Special attention was paid to whether or not a study had focused on an existing network rather than on a network designed from the ground up, since relevance to brownfield situations is of decisive importance for Saudi operating assets. Examples of this are graphical pinch retrofits of crude preheat

trains, mathematical computation carried out on refinery cases, and monitoring or cleaning methods tested on actual crude-distillation exchanger networks (Alhajri *et al.*, 2021; Trafczynski *et al.*, 2023; Teng *et al.*, 2023; Zhi *et al.*, 2024).

A decision-layer approach was used in the synthesis. The various methods were categorised depending on the questions they address: thermodynamic targeting calculates the amount of recovery that is theoretically possible; network optimisation decides where and how heat should be matched; equipment-level models examine whether the proposed matches are hydraulically and mechanically feasible; fouling and maintenance models estimate how performance changes over time; and monitoring methods check that the actual operation corresponds to the expected performance. The Saudi policy sources were then used to understand how these technical decisions add to the broader energy and carbon objectives (Belaïd and Massie, 2023; Islam and Ali, 2024; Matar *et al.*, 2024).

There was no pooled effect size calculated since the studies that were reviewed involve heterogeneous processes, utility prices, stream data, network sizes, objective functions, and retrofit boundaries. The quantitative results are employed merely as illustrations of potential for specific cases, and the principal conclusions are derived from the recurring mechanisms and trade-offs found throughout the evidence base.

4. The Development of HEN Optimisation Methods from 2020 to 2025

The HEN research carried out recently may be seen as having evolved from a focus on energy targeting to one involving the optimisation of all assets. But the major innovation since 2020 has been the combination of these thermodynamic findings with computer-based search methods and with practical retrofit guidelines. Wang *et al.*, (2020) linked a modified retrofit thermodynamic grid diagram with mixed-integer linear programming and particle-swarm optimisation, showing how insights from the diagram can be used to carry out a more thorough search for changes that are economically attractive. Lo *et al.*, (2020) applied retrofit considerations to multi-plant systems together with the question of how to allocate benefits, while Chin *et al.*, (2020) incorporated long-term investment and maintenance planning so as to take into account exchanger replacement, enhancement and service life over a number of periods.

Mathematical programming is useful in cases where there are interactions among multiple heat matches, stream splits, utility levels, and equipment decisions. Angsutorntorn and others (2021) created a

modified stage-wise model with the aim of obtaining feasible industrial retrofit solutions while keeping the computational effort under control. Zhao and colleagues (2024) accelerated the synthesis of large-scale HENs by combining multiple initialisations, automatic topology generation, and the use of a reduced nonlinear model, including applications involving industrial cases. Teng and co-authors (2023) employed a P-graph framework which is able to retain the existing units, take account of positional swapping, and yield several near-optimal retrofit configurations instead of a single unclear optimum. This approach is beneficial in the context of brownfield engineering since project teams usually need a number of technically viable alternatives which can then be evaluated against shutdown, piping, and constructability constraints.

Network models which assume a general cost per unit area may not account for significant effects resulting from pressure drop, the type of exchanger, the materials used and the geometry. Wang *et al.*, (2021) included both heat-exchanger design and material selection in their retrofit analysis, whereas Li *et al.*, (2022a) examined how detailed thermal-hydraulic performance, covering fouling and pressure drop, affects network synthesis. Li *et al.*, (2022b) introduced various shell-side flow arrangements into a mixed-integer nonlinear formulation, showing that the exchanger configuration can alter the trade-off between the investment in area and pumping cost. Wang *et al.*, (2022) did the same by combining an advanced grid-diagram method with a detailed plate heat exchanger design. This approach is especially important for facilities in Saudi Arabia because high crude-oil viscosity, pressure limitations, metallurgical considerations, and existing equipment standards can make a purely temperature-based optimum unfeasible.

Heat-transfer enhancement offers a middle-ground retrofit approach between operating adjustments and major network reconstruction. Li *et al.*, (2021) developed a method for evaluating targets which allows one to find exchangers at which an improvement in heat transfer can boost recovery without altering the network's topology. This basic idea is appealing for heavily congested brownfield facilities since, if a thermodynamic bottleneck is due to the exchangers having insufficient effectiveness rather than to a fundamentally bad match, it may be

cheaper and simpler to improve the exchangers than to fit in a new cross-pinch connection. However, enhancement can lead to a greater pressure drop, and its worth depends on how the network responds. For this reason, the existing literature recommends that evaluation should be based on both thermal and hydraulic performance rather than on the heat-transfer coefficient alone (Klemes *et al.*, 2020; Li *et al.*, 2022a).

Fouling is no longer regarded as a design factor that can be taken for granted, but has become a variable that can be optimised dynamically. Hang *et al.*, (2022) carried out an optimisation of the HEN design throughout an operating cycle, taking into account fouling, the area margin, the location of the bypass and the operational decisions. Kansha *et al.*, (2022) stressed the importance of managing fouling in crude-oil exchangers on the basis of plant data, while Trafczynski *et al.*, (2023) optimised the cleaning schedules for a real 26-exchanger refinery network by comparing the energy recovered after cleaning with the cleaning cost. These studies alter the financial justification of retrofitting. A network which has excellent cleaning performance but degrades rapidly may in fact yield a lower annual benefit than one with a slightly less aggressive design that is easier to clean, monitor and control. Hence, in crude preheat service, design, operation, and maintenance should be optimised as a coupled life-cycle problem.

The last stage needed to maintain the benefits is operational monitoring. Apio and colleagues (2023) used a constrained extended Kalman filter combined with smoothing in order to monitor fouling in a real crude-distillation HEN. Patil and co-authors (2023) created network-level indicators of excess thermal and hydraulic load that are able to tell the difference between exchanger degradation and changes in the inlet conditions and network interactions. Since these methods are related to digital transformation, they enable ordinary process measurements to be turned into performance diagnostics. With an HEN that is under monitoring, it is possible to determine whether an apparent loss is due to fouling, flow redistribution, a control action, or a change in the operating envelope, so that engineers can decide on cleaning, adjusting the bypass or retuning rather than having to accept a higher furnace duty as something that cannot be avoided.

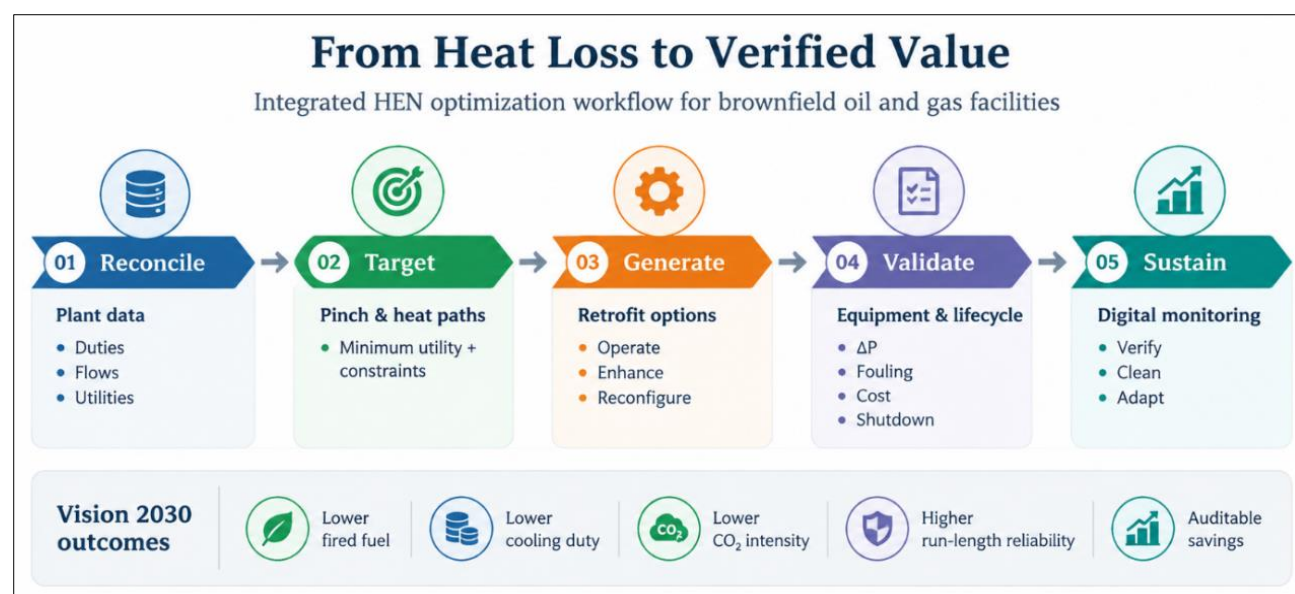


Figure 1: Integrated HEN optimization workflow for brownfield oil and gas facilities

Table 1: Representative 2020–2025 evidence and implications for Saudi HEN retrofit

Study	Method / application	Key contribution	Saudi relevance
Wang <i>et al.</i> , (2020)	Retrofit grid + MILP/PSO Existing HEN	Balances utility/capital; reduces payback	Useful for structured brownfield screening
Chin <i>et al.</i> , (2020)	MILP + asset-life planning Retrofit lifecycle	Links retrofit, replacement and maintenance	Supports turnaround-aligned investment
Alhajri <i>et al.</i> , (2021)	Graphical Pinch Analysis Crude refinery	Practical visual retrofit; short-payback case	Strong analogue for Saudi refineries
Li <i>et al.</i> , (2021)	Heat-transfer enhancement targeting Fixed-topology HEN	Adds recovery with limited topology change	Attractive where piping changes are difficult
Li <i>et al.</i> , (2022a)	Thermal-hydraulic synthesis review Industrial HEN	Highlights pressure drop, fouling and design detail	Prevents thermodynamic-only optimization
Hang <i>et al.</i> , (2022)	Cycle-wide fouling optimization HEN operation/design	Optimizes bypass, area margin and fouling effects	Relevant to crude preheat run-length
Trafczynski <i>et al.</i> , (2023)	Cleaning-schedule optimization 26-exchanger refinery HEN	Values cleaning through avoided operating cost	Connects maintenance to energy economics
Patil <i>et al.</i> , (2023)	Thermal/hydraulic performance monitoring HEN monitoring	Separates fouling effects from inlet-condition changes	Enables sustained digital performance
Teng <i>et al.</i> , (2023)	P-graph retrofit optimization Real refinery cases	Returns multiple practical topologies	Useful for constructability trade-offs
Zhi <i>et al.</i> , (2024)	Graphical pinch + T-hot/T-cold Residuum hydrogenation	High-value industrial retrofit with short payback	Relevant to heavy hydrocarbon services
Zhao <i>et al.</i> , (2024)	Multi-start + reduced NLP Large-scale industrial HEN	Accelerates near-optimal synthesis	Supports large Saudi networks
Yang <i>et al.</i> , (2025)	MINLP + GCC + multiple utilities Waste heat / utility integration	Co-optimizes waste heat and hot utilities	Useful for evolving utility systems

5. Evidence Obtained from the Use of the Refinery and Petrochemical Applications

The situation in refineries is the best example when considering Saudi oil-processing facilities since the crude preheat trains involve large heat duties, severe fouling and a strong linkage to furnace consumption. Alhajri *et al.*, (2021) used a

graphical pinch method on an operating crude-distillation network in Kuwait and found retrofit changes which led to significant heat recovery and reductions in operating costs with a payback period of less than one year. The significance of this finding is not merely in the numerical result; it demonstrates that a visual analysis of the temperature driving force

can identify practical retrofit options before a complex optimization model is developed. Osman and Mirghani (2022), who worked at Najran University, carried out a similar study on a crude preheat HEN by combining various heat paths with different heat-recovery approach temperatures, thus confirming the value of structured load shifting for reducing utility usage.

Jabbar and colleagues in 2023 carried out a combination of refinery process simulation, heat integration and a techno-economic analysis, demonstrating that the selection of the feed and operating conditions can affect the possibilities for heat integration. Zhi and co-authors in 2024 applied graphical pinch analysis and a hot-against-cold temperature diagram to a real residuum-hydrogenation process and presented a retrofit which included additional heat recovery and had a short payback period. The crude oil mix, the throughput of the unit, the product specifications, the hydrogenation severity, the constraints relating to the compressor or the furnace and the seasonal cooling conditions can all influence the temperatures of the streams and the value of the utilities.

The evidence from the refinery also explains why it is not possible to pass savings directly from one plant to another since the existing exchanger area, the approach temperatures, the fouling factors, the bypass arrangements, the utility pressure levels, the furnace efficiency and the local project costs are very different. In some plants a new exchanger may be needed if the same pinch target is adopted whereas in others it will be sufficient to redistribute the duty. It therefore follows that the percentages obtained in the case studies should be understood as showing the mechanisms at work and not as guarantees of Saudi performance. What can be transferred is the workflow: that is, quantify the current heat recovery, identify the thermodynamic bottlenecks, generate a number of possible ways of making modifications, evaluate the hydraulic and fouling implications, and rank the alternatives on the basis of annualised economic and carbon criteria.

6. Saudi Arabia: Turning HEN Optimization into Vision 2030 Value

The Vision 2030 policy alters the decision-making environment for HEN projects since energy savings now have strategic importance in addition to their ability to reduce utility costs. In Saudi literature on energy transition, efficiency, fuel diversification and emissions reduction are seen as complementary approaches rather than as competing priorities (Al-Saidi, 2022; Islam and Ali, 2024). Belaid and Massie (2023) discovered that energy efficiency can make a significant contribution to long-term decarbonization in Saudi Arabia, and Matar *et al.*, (2024)

demonstrated that the national energy system could achieve considerable emissions reductions under different policy scenarios. At the level of individual plants, HEN optimization helps to achieve these aims by decreasing the amount of thermal energy that has to be provided by fired heaters or steam systems and, in certain cases, by reducing cooling demand and the associated electricity consumption.

The performance metric that is appropriate is therefore more extensive than simply the percentage of heat recovered. A project involving a HEN in Saudi Arabia should provide at least five related results: a decrease in the amount of fired fuel or steam required; a reduction in the demand for cooling utilities; an annual benefit to operating costs; avoided carbon emissions based on a clear fuel and electricity basis; and an impact on availability or the level of maintenance needed. These indicators ensure that a project is not regarded as efficient if it simply shifts energy use to pumping or if it results in excessive maintenance. It is important to use detailed exchanger models in cases where greater heat recovery causes an increase in pressure drop or when new equipment brings about metallurgy and inspection requirements (Li *et al.*, 2022a; Li *et al.*, 2022b).

The implementation should also identify three different depths of retrofit. The first of these is operational optimisation, which involves adjusting bypass settings, modifying flow distribution, changing the control set points and correcting maldistribution caused by fouling as well as preventing the misuse of utilities all by means of the existing equipment. The second level consists of targeted hardware improvements, such as cleaning, altering the bundle, improving the exchanger, adding more area or replacing a small number of bottleneck units. The third level is that of a structural network retrofit and includes the introduction of new matches, resequencing, repiping, the addition of further exchangers and changes to the utility systems. The literature indicates that these stages should be examined in sequence since the least disruptive approach can capture some of the value while at the same time keeping the possibility of carrying out a more extensive retrofit later (Li *et al.*, 2021; Teng *et al.*, 2023). This step-by-step approach is in line with Saudi turnaround planning and helps to reduce the risk of choosing a network that is theoretically optimal but operationally unfeasible.

Digitalization offers the means of keeping the result. Even though Abusaq and Zohdy (2024) concentrated on a Saudi hybrid microgrid rather than HENs, they do show the broader national tendency towards optimization based on technical, economic and resilience considerations. In process plants, the

corresponding HEN function serves as a performance layer which constantly checks and adjusts the exchanger temperatures, the flows, the pressure drops, fuel consumption and the cleaning history. The methods suggested by Apio *et al.*, (2023) and Patil *et al.*, (2023) demonstrate how data from the plant can be converted into indicators of fouling and of network performance. When this kind of monitoring is combined with a steady-state process model, it is possible to establish an energy-performance baseline, to detect any drift and to measure the value of taking corrective action.

7. Suggested Integrated Optimisation Framework

In view of the evidence examined, an optimisation framework tailored for use in Saudi Arabia should include six decision stages rather than depend on a single algorithm. The first stage involves data reconciliation and the establishment of a baseline. Stream temperatures, flow rates, heat capacities, exchanger duties, utility conditions, pressure drops, bypass arrangements and the amount of fuel used in the furnaces or boilers should all be reconciled over typical operating periods. The condition of the fouling and the quality of the measurements should be recorded since they influence the apparent heat-recovery gap. When the instrumentation is poor, it is better to use uncertainty ranges rather than give false precision.

Stage 2 involves thermodynamic targeting. In order to set minimum heating and cooling targets and to detect any cross-pinch violations or constrained heat paths, composite curves, problem-table methods, grid diagrams or other similar tools should be used. The targets must be calculated for more than one operating case when there are substantial changes in the feed or in the throughput. Graphical methods are still valuable at this stage since they make the available opportunities clear to the operations and project teams and can point out promising modifications before detailed optimization (Wang *et al.*, 2020; Alhajri *et al.*, 2021).

In stage 3, the process involves generating retrofit options. The various alternatives should include operating changes, improvements in heat transfer, replacement of equipment, the addition of new exchangers, resequencing of streams and changes to utilities. Mathematical programming or graph-based methods can then be used to examine combinations, keeping the existing equipment in place where this is advantageous. It is not sufficient merely to minimize utility costs. A practical way of formulating the objective is to minimize a composite annual value $J = \text{TAC} + \alpha(\text{CO}_2) + \beta(\text{Roper}) + \gamma(\text{Ccomplex})$, where TAC stands for total annualized cost, CO₂ is the annual emission level, Roper is a measure of operability or reliability

penalty, Ccomplex is the level of implementation complexity, and alpha, beta and gamma are decision weights. This kind of objective captures the approach taken by recent multi-criteria and complexity-aware HEN research without suggesting any specific weight values.

At stage 4, equipment and hydraulic validation is carried out and the candidate solutions must be examined with regard to exchanger area, allowable pressure drop, velocity, vibration risk, materials compatibility, tendency to foul, cleanability and control performance. If network optimization omits these checks it can lead to costly rework at the front-end engineering stage. As shown in the detailed-design literature, the type of exchanger, the baffle arrangement and the pressure drop can affect the total annual cost and even the preferred topology (Wang *et al.*, 2021; Wang *et al.*, 2022; Li *et al.*, 2022b). When dealing with Saudi crude and heavy hydrocarbon services, this stage should specifically take into account the expected fouling rate and the ability to isolate or clean the equipment over the intended run length.

In stage 5, life-cycle and turnaround planning is carried out; capital expenditure, the timing of installation, lost production, maintenance costs and exchanger reliability should all be annualised over the expected duration of the project. Chin *et al.*, (2020) demonstrated that retrofitting and maintenance decisions are interdependent over long time periods. For the operating facilities in Saudi Arabia, the practical best course of action might be to carry out a modification that aligns with an already scheduled turnaround rather than to choose a more energy-saving option which would require an extra shutdown. Cleaning schedules should also be optimised on the basis of the value of the recovered heat and not just according to fixed time intervals (Trafczynski *et al.*, 2023).

Stage 6 involves measurement and continuous improvement. The performance after the startup should be compared with the reconciled baseline when the operating conditions are the same. The thermal and hydraulic indicators should be tracked in order to detect fouling, maldistribution or changes in network interactions (Patil *et al.*, 2023). The benefits must be reported in terms of fuel, steam, cooling, electricity, cost and emissions so that the energy performance can be incorporated into corporate sustainability and operational dashboards. This completes the link between project design and the actual performance achieved, something that is necessary if HEN optimisation is to make a genuine contribution to Vision 2030 rather than just stay as a one-off engineering study.

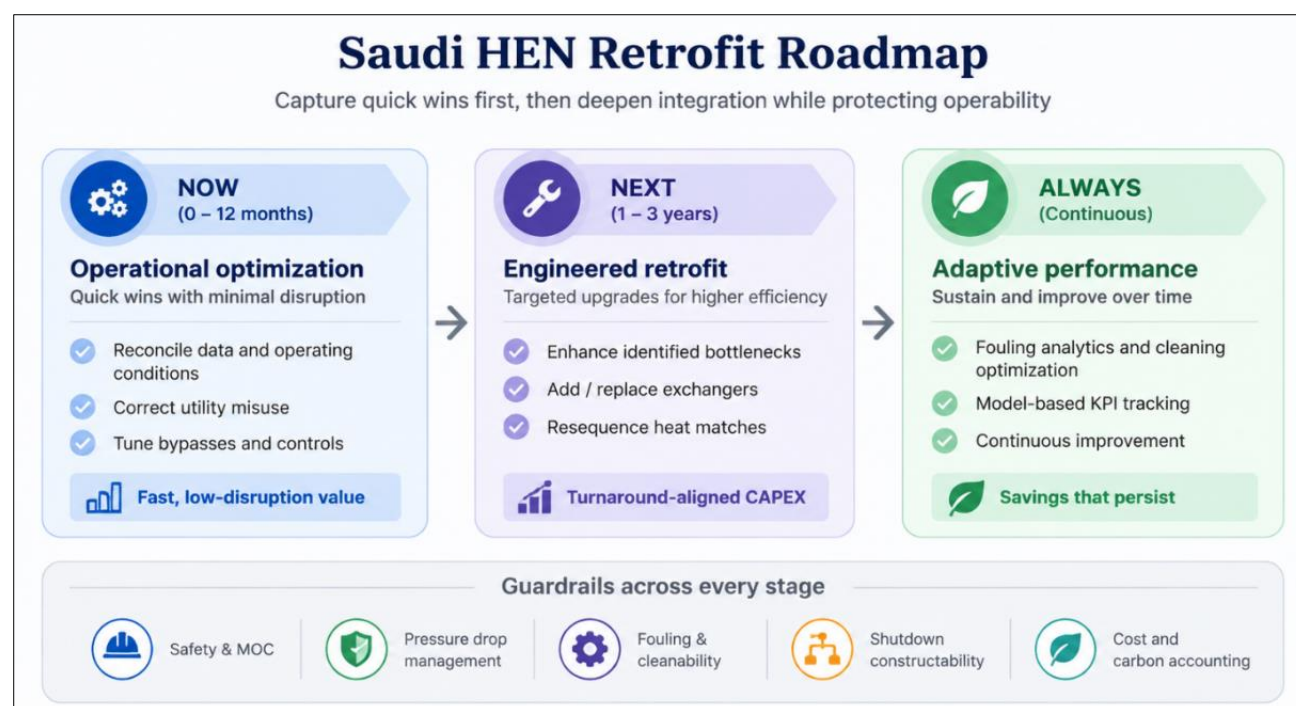


Figure 2: Saudi HEN retrofit roadmap aligned with staged Vision 2030 value delivery.

Source: authors' synthesis

Table 2: Vision 2030-oriented HEN implementation and governance matrix

Decision layer	Primary KPI	Horizon	Main risk	Control / evidence
Baseline & diagnostics	Reconciled duties; furnace/steam/cooling use; exchanger U and dP	0-6 months	False baselines; poor instrumentation	Data reconciliation; uncertainty bands
Operational optimization	Utility duty; bypass loss; heat-recovery ratio	0-12 months	Control interaction; operator acceptance	MOC, control-loop review, matched-condition testing
Targeted enhancement	Fuel saved per retrofit cost; pressure-drop penalty	Turnaround / 1-2 years	Hydraulic penalty; fouling; material limits	Thermal-hydraulic design and maintainability check
Structural HEN retrofit	TAC; NPV; heat recovery; tie-ins; shutdown hours	1-3 years	Constructability and production loss	Multiple near-optimal options + constructability screening
Fouling & cleaning optimization	Recovered duty after cleaning; run-length economics	Continuous	Cleaning cost; access; uncertain fouling rate	Plant-data fouling models and optimized schedules
Digital performance layer	Normalized thermal/hydraulic indicators; drift alarms	Continuous	Sensor bias; model mismatch	Routine model reconciliation and KPI governance
Vision 2030 reporting	Fuel, electricity, cost and tCO ₂ e avoided	Annual	Double counting; inconsistent baselines	Transparent conversion factors and auditable baselines

8. DISCUSSION: WHAT IS THE BEST RETROFIT STRATEGY?

There is no one best HEN method that applies to all Saudi facilities. Pinch Analysis is most effective for transparent thermodynamic targeting and for quick diagnosis; mathematical programming is most suitable in cases where a large number of

matches and constraints are involved; graph methods are helpful when it is necessary to evaluate alternative topologies and when existing units have to be kept; exchanger-level optimisation is necessary whenever pressure drop and the way the equipment is arranged are important; and data-based monitoring is required when fouling and variations in

operation are the main factors. The different methods are complementary in nature. A sound workflow involves using a simple method to identify the energy opportunity, a rigorous method to examine alternative options, detailed engineering to eliminate unrealistic solutions, and monitoring to maintain the final design.

There is a continual balance to be struck between achieving the greatest possible heat recovery and causing the least amount of disruption. Although major changes to the structure can get close to the thermodynamic goals, they might result in congested piping, the need for new foundations, extra control valves, and a great deal of shutdown work. On the other hand, methods that do not involve changing the topology reduce the risks associated with implementation even if they mean that some of the available energy is not taken advantage of. Li *et al.*, (2021) show the potential of improving heat transfer for obtaining further savings without having to make major changes to the system's topology, while Teng *et al.*, (2023) show how a graph-driven retrofit search can make use of the existing assets while at the same time considering possible changes in position. It therefore makes sense to use the thermodynamic maximum as a benchmark rather than as a automatic design aim.

The other area of tension lies between clean-design performance and run-length performance, since crude-service exchangers slowly move away from their designed heat-transfer coefficient and the resulting changes in duty are passed on through the preheat train. As Hang *et al.*, (2022) and Trafczynski *et al.*, (2023) have shown, fouling and cleaning decisions can be incorporated into network economics, and Apio *et al.*, (2023) and Patil *et al.*, (2023) have demonstrated monitoring methods which allow the degree of deterioration to be quantified. In the case of facilities suffering from severe fouling, the annual fuel savings should be based on a realistic performance trajectory rather than on the assumption of a permanently clean network; this in turn may lead to a different preferred exchanger arrangement, a different area margin, a changed bypass policy and a revised cleaning schedule.

The third area of tension is that of carbon and cost. In the past, HEN optimization has aimed at cutting utility costs or total annual costs. However, in view of Saudi Arabia's decarbonisation goals, the marginal value of the fuel and emissions that are avoided could change as energy prices, carbon-accounting methods and corporate targets change. It is not necessary to impose an arbitrarily high carbon price in order to adopt a carbon-aware objective; at the very least, each alternative should be able to

provide an explicit statement of its emissions consequences together with the NPV or payback. Matar *et al.*, (2024) demonstrate the value of carrying out comparisons of policies at a system level, and this same principle applies within a single plant: decision-makers should consider whether the least-cost retrofit is also the lowest-carbon and most resilient one.

9. Zones Requiring Further Research and Future Lines of Inquiry

There are four research gaps that are important for use in Saudi Arabia. The first is that more studies should make use of data from Saudi refineries, gas-processing plants and petrochemical operations. Although international case studies provide methods, it is the local feed characteristics, the utility systems, the ambient conditions, the project costs and the operating practices that determine the actual value. The second point is that dynamic and multi-period optimization should be developed further. At present, most HEN models still only represent a limited number of steady states, while Saudi units might undergo changes in throughput, switches in crude oil, variations in seasonal cooling and progressive fouling. Performing optimisation amid these conditions would result in more resilient options for retrofitting.

Third, there should be the development of HEN models that take account of carbon emissions and electrification. Future facilities might make use of electric heating, heat pumps, renewable electricity, waste-heat power recovery or lower-carbon steam sources. A network which has been optimised solely in relation to the current utility hierarchy could become suboptimal when these technologies are introduced at the site. Yang *et al.*, (2025) show how waste heat recovery and multiple utilities can be incorporated into modern HEN synthesis; their Saudi extension should include emissions factors, utility flexibility and the changing opportunity cost of heat.

Fourthly, it is necessary to make implementation difficulty a more explicit factor in optimization. Although present models can express exchanger numbers, area and piping in simplified cost terms, constructability, the number of tie-ins, plot congestion, shutdown duration, control interactions, along with inspection requirements, have a major impact on the success of brownfield projects. Since methods such as that proposed by Teng *et al.*, (2023) are promising, they enable engineers to compare a number of near-optimal designs rather than having to accept just one mathematical solution. Subsequent research should use data from completed retrofit projects to formalise these practical penalties and should check the

predicted savings against the measurements taken after startup.

10. The Limitations of the Review

The review deliberately concentrates on studies published between 2020 and 2025 and thus does not include the earlier foundational pinch and HEN papers, even though these may still have a technical influence. Since the body of evidence is diverse and includes different network sizes, industries, utility prices and methods of reporting, the reported savings have not been combined into a single pooled percentage. Peer-reviewed HEN case studies that are specific to Saudi Arabia are still limited and for this reason refinery examples from other areas are used as a technical analogy, with careful interpretation. Lastly, the framework that is proposed serves as a synthesis for the purpose of supporting decision-making and should not be regarded as a replacement for plant-specific simulation, hazard review, mechanical design, operability testing or economic approval.

11. CONCLUSION

Heat exchanger network optimization provides Saudi oil and gas facilities with a practical means of reducing their fuel demand, utility consumption, operating costs and carbon intensity while making more effective use of the existing process heat. As shown by the literature from 2020 to 2025, the field is progressing from single-pinch targeting to integrated optimization which takes into account aspects such as topology, equipment design, pressure drop, fouling, asset life, maintenance and performance monitoring. This trend is pertinent to Saudi brownfield assets since, as with theoretical heat recovery, factors such as constructability, shutdown scheduling and sustained reliability are equally important.

The review concludes that the most reliable approach is to begin by reconciling the operating data and establishing realistic heat-recovery targets; afterwards, it is necessary to generate various options by making operational changes and carrying out structural retrofits; then the alternatives should be optimised and evaluated on the basis of economic, carbon, hydraulic, fouling and complexity criteria; and finally, the savings achieved should be verified by means of continuous monitoring. The use of graphical pinch methods assures transparency, mathematical and graph-oriented methods increase the solution space, detailed exchanger models guarantee engineering feasibility, and analytics-based monitoring makes certain that performance is maintained after commissioning.

Based on Vision 2030, HEN projects should be presented as measurable energy-productivity

projects, not simply as individual modifications to exchangers. The business case must link the recovered heat to lower furnace or steam requirements, to avoided emissions, to reduced cooling demand, to better run-length performance, and to more disciplined use of capital. The next step is local validation, which requires data from Saudi plants, multiple-period operating scenarios and measurements taken after the retrofit has been carried out in order to develop optimisation models that take into account the Kingdom's particular crude oil mix, gas-processing conditions, utility systems and project constraints. Once such evidence has been obtained, HEN optimisation can become a regular part of industrial energy management and a lasting contribution to the efficiency and decarbonisation goals of Vision 2030. Implementation can then begin.

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