Energy-Efficient Design and Performance Optimization of Pressure Vessels and Process Equipment in Saudi Oil and Gas Facilities

Abstract:

The oil and gas infrastructure in Saudi Arabia includes a large number of pressure vessels, separators, heat exchangers, columns, pumps and compressors, and it is the way in which their design and operation interact that has an effect on both the reliability of production and the level of energy demand. However, energy-efficiency programmes often prioritise rotating equipment and treat pressure equipment as passive hardware. This study contends that such a separation is technically incomplete. Although a pressure vessel does not usually use shaft power directly, its shape, thermal boundaries, internal components, maximum allowable pressure loss, separation performance, condition of degradation, and operating set point can influence subsequent heating, cooling, pumping, and compression tasks. The review brings together evidence from peer-reviewed publications between 2020 and 2025 relating to the optimisation of mechanical design, process integration, heat-transfer management, fouling control, the operation of rotating equipment and digital condition assessment, and then applies this evidence to the case of Saudi hydrocarbon facilities. The literature shows a shift from single-variable design to restricted multi-objective optimisation, in which mass, stress, fatigue life, pressure drop, heat loss, reliability, cost and emissions are all taken into account. For existing plants, the opportunities with the highest level of confidence are integrated management of pressure drop, insulation renewal, retrofitting of exchanger networks and cleaning, the configuration of compressors and pumps, and the use of operating envelopes that are based on condition assessments. For new facilities, structural optimisation, high-resolution simulation and lifecycle decision criteria should be incorporated before the equipment specifications are finalised. Studies on composite vessels show that there are effective optimisation methods but these require specific qualification for the type of service before they can be applied to hydrocarbon operations. A framework for implementation in Saudi Arabia is suggested which connects integrity constraints alongside energy key performance indicators and includes a physics-informed digital feedback loop. The review concludes that energy-efficient design of pressure equipment should be seen as a plant-wide lifecycle issue rather than as a separate exercise focused on minimising individual components.

1. Introduction

Energy efficiency in the oil and gas processing industry is usually regarded as a matter relating to utilities or rotating equipment, whereas in fact the thermodynamic performance of the whole facility is influenced by the geometry, layout and state of the static equipment. The literature on process integration now sees cleaner production as a systems issue in which equipment choices, resource recovery and operational optimisation have to be assessed together. For the Kingdom, industrial transition studies regard energy use, technology selection and carbon constraints as closely linked strategic variables rather than as separate policy issues.

The title of this review combines "design" and "performance optimisation" intentionally. There is a difference between the two. Design decisions are taken taking into account allowable stress, corrosion allowance, fatigue, fabrication, inspection, maintainability and compliance with codes. Performance decisions, on the other hand, are based on throughput, product quality, pressure, temperature, fouling, availability and control requirements. In order for an energy-efficient plant to be achieved, these two kinds of decision must agree. A shell that is thinner, a vessel that is smaller or an exchanger that costs less is not always more energy efficient if it results in an excessive pressure drop, speeds up degradation, calls for more frequent shutdowns and means shifting the duty to the compressors and heaters. Recent research into pressure vessels shows this new approach to design, this shift being from conventional dimensional selection to geometry optimisation, finite-element verification, reliability analysis and multi-objective search.

The situation in Saudi Arabia makes it more important to adopt a lifecycle approach. The high ambient temperatures make cooling more difficult and can affect the performance of compressors, air coolers, and insulation; dust from the desert increases the difficulty of external heat transfer and filtration; and the constant high level of operation raises the economic impact of pressure losses, fouling and unforeseen outages. This does not provide a reason for reducing integrity margins. On the contrary, it shows that integrity should be included, not excluded, from the energy optimisation process. National mapping of industrial pollution shows that refining and petrochemical activities are major stationary sources within the country's emissions inventory, and economy-wide analysis proves that energy efficiency remains a significant means of achieving decarbonisation. The actual issue then is not whether pressure equipment should be 'lightened' in order to save energy, but rather how its structural, thermal and hydraulic design can be coordinated with the operating strategy so that safe equipment carries out the required process function with the least lifecycle energy burden.

The relevant literature is spread out over the areas of pressure-vessel mechanics, composite structures, heat exchanger networks, petroleum process intensification, production optimisation and digital twins. Research involving composite pressure vessels looks at mass, winding angle, burst pressure and fatigue, while studies relating to refineries focus on heat recovery, fouling and crude-distillation energy. In the case of oil and gas production, pumping and compression are identified as the main powered loads, and digital-twin research places emphasis on monitoring and condition assessment. The aim of this review is to bring together these different areas around one engineering idea: static pressure equipment establishes boundary conditions for active energy consumers, and those boundary conditions can be optimised.

2. Review aim, objectives and methodology

This review seeks to critically combine the evidence from 2020 to 2025 on the coupling of mechanical design for pressure vessels and the operational optimisation of process equipment in order to lower energy intensity without jeopardizing integrity, throughput, or service life in Saudi oil and gas facilities. The analysis is guided by four objectives. The first is to identify the main energy-loss pathways and design factors among pressure vessels, separators, heat exchangers, pumps and compressors. The second entails assessing the various methods of structural, material, thermal and reliability optimisation for pressure vessels and examining whether these can be applied to service in hydrocarbon environments. The third looks at the operational measures that affect the plant's energy performance, such as pressure management, exchanger-network retrofitting, fouling control, the configuration of rotating equipment and digital condition assessment. The fourth is to develop a decision-making framework that is specific to Saudi conditions and which incorporates safety, lifecycle energy use, emissions and business constraints, rather than viewing energy reduction as a single objective.

A targeted and structured review was chosen since the research question involves both mechanical design and process operations rather than focusing on a single clinical or laboratory intervention. The searches, which ran from January 2020 to December 2025, used structured queries on scholarly web sites, publisher databases, the ASME Digital Collection and the IEEE Xplore records, and were also supported by verification of Crossref-compatible DOIs and metadata. The search terms included "pressure vessel", "design optimisation", "finite element", "fatigue", "composite pressure vessel", "heat exchanger network", "fouling", "compressor efficiency", "pump efficiency", "process integration", "digital twin", "oil and gas", "refinery", "Saudi Arabia" and "GCC", and different Boolean combinations were used to ensure that papers on pressure equipment were not eclipsed by the larger body of general energy-efficiency literature.

The sources that were eligible had to be peer-reviewed journal articles written in English and published between 2020 and 2025, with a direct connection to mechanical design, structural reliability, thermal management, process-energy optimisation or condition-informed operation, and must have carried a verifiable DOI. Studies that did not focus on the oil and gas sector were only included if the methods they used could be directly applied to the design of pressure equipment, for example in the case of multi-objective composite-vessel optimisation or fatigue assessment. Records that were based solely on conference proceedings, duplicate entries, sources lacking a verifiable DOI and studies that had no significant relationship to pressure-containing or process equipment were excluded. The final core body of evidence consisted of 30 studies. The evidence was arranged in a synthesis matrix according to equipment class, design variable, energy mechanism, integrity constraint, optimisation method and level of implementation maturity.

The effect sizes are not combined since the studies included have incompatible objectives, equipment scales and boundary conditions. In their place, a mechanism-based narrative synthesis is applied. The findings are examined at three levels: that of direct evidence, which involves the study citing the relevant equipment or process; transferable evidence, which refers to an optimisation method being credible even if the service is different; and engineering inference, which entails deriving the plant-level consequences from well-established thermodynamic relationships. This stratified approach means, for example, that a result obtained from a hydrogen or water composite vessel cannot be treated as direct evidence when it comes to sour hydrocarbon service. It also permits a more defensible framework to be developed for use in Saudi Arabia since the recommendations are based on the maturity of the evidence rather than on novelty alone.

3. Energy-efficiency problem framing in Saudi process equipment

In an electrical context pressure vessels are passive but in a thermodynamic one they are active. A separator produces a pressure drop and a residence time; a knockout drum affects the amount of liquid carried over to the compressor; a suction scrubber ensures the effectiveness and dependability of compression; a flash vessel alters the amount of vapour generated and the downstream recompression requirement; and the exchanger shell sets the maximum allowable pressure loss, the heat-transfer area and the fouling behaviour. It therefore follows that the energy importance of a pressure vessel should be assessed in terms of the duties it imposes or avoids elsewhere. The most proper boundary to use is thus the process system and not the vessel wall. This is in accordance with the general process-integration principle that local changes can transfer energy and material loads between units rather than eliminate them.

Conceptually, a practical lifecycle energy balance can be described as the total of the energy required for the initial fabrication, the thermal losses during operation, the energy needed to overcome pressure losses through pumping or compression, the energy used for maintenance and cleaning, the energy loss due to degradation, and the energy associated with replacement or repair. In the case of most hydrocarbon plants, the energy used in operation is the most significant; yet when evaluating different design alternatives that have similar process performance, the material mass and the frequency of repairs become important factors. The aim of optimisation therefore ought to be to minimise lifecycle energy or cost, taking into account the necessary constraints relating to pressure integrity, corrosion, fatigue, operability, product quality and availability.

The Saudi industrial situation increases the value of this more general measure. As Alshammari shows, the industrial transition routes in the country are determined by the costs of technology and the assumptions regarding the energy system, and Hamieh et al. identify the main stationary carbon sources, comprising refining and petrochemical operations. Belaid and Massieconclude that energy efficiency can have a significant contribution to Saudi decarbonisation, and Sanfilippo et al.claim that efficiency should be given greater importance in the transition programmes of the Gulf states.

For facility engineers this means there is a hierarchy of measures. At the first level, avoidable losses are eliminated without altering the process function itself, for example by repairing damaged insulation, reducing excessive exchanger fouling, eliminating unnecessary recirculation, avoiding throttling and improving the way pumps or compressors are loaded. At the second level the way the system is operated is changed while still within the limits of the existing mechanical setup: this entails selecting parallel units, rationalising the pressure set-point, controlling exchanger bypasses, setting cleaning schedules and redistributing duties. At the third level modifications are made to the internal components, surface area or hydraulic arrangement of the equipment during a planned shutdown. At the fourth level the design of the equipment is changed when it is being replaced or as part of a new project.

Figure 1 shows the main causal sequence. The mechanical design determines the geometry, the materials, the nozzles, the internals and the thermal boundary conditions. These features in turn influence pressure loss, heat transfer, separation efficiency, sensitivity to fouling and degradation. The process effects then manifest themselves as the duties of the heater, cooler, pump and compressor. The most compelling business case in terms of energy therefore arises when an alteration that preserves integrity eliminates a persistent systemic drawback. Although a thicker shell might have a negligible effect on operating energy, a poorly chosen demister, an undersized nozzle or a fouled exchanger can result in a continuous power or fuel penalty. Energy reviews should thus assess the mechanisms according to their annual duty impact rather than on the basis of component visibility.

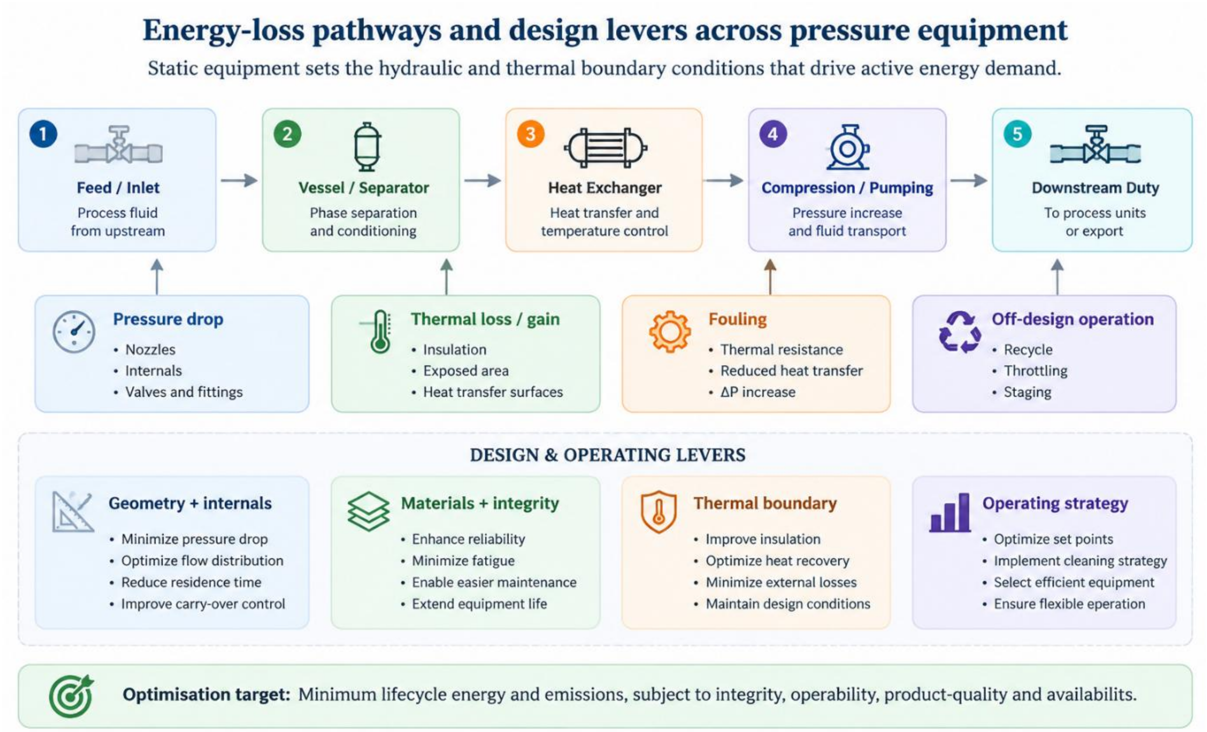

Figure 1. Energy-loss pathways and design levers linking pressure equipment to plant energy demand.

4. Pressure vessel design improvement: structure, materials, and lifecycle performance

The latest literature on pressure vessels indicates a clear shift from sizing that merely complies with codes to optimisation within the design space that is limited by those same codes. Arunkumar et al. applied analysis-based optimisation to a horizontal vessel, focusing on the co-ordinated choice of the heads, nozzles and supports rather than treating each of these as separate features. In their work, Hajmohammad et al. developed an analytical method of optimisation for fibre-reinforced vessels in which buckling, weight, failure criteria, thickness, number of layers and fibre angle were all considered together. Abdalla et al. showed how shape optimisation can be carried out for a naturally closed metallic pressure vessel with the aim of either reducing mass or increasing volume while at the same time satisfying the structural constraints. Salins et al. further show how finite-element analysis can reveal structural-load effects which simplified sizing methods do not represent adequately. Together, these studies support an optimisation process in which compliance is treated as a constraint and performance as the objective.

Regarding oil and gas services in Saudi Arabia, structural optimisation should start with steel vessels since carbon and low-alloy steels are still widely used in separators, drums and process columns. Optimising the geometry will reduce excess mass and the amount of work needed for fabrication, and more significantly it will help in controlling local stress concentrations which, in other cases, would call for conservative reinforcement, frequent inspection or early repair. The position of nozzles, the spacing of the supports, the shape of the saddles and the form of the head all affect both the structural response and the process layout. When a compact arrangement shortens the high-pressure piping without causing unacceptable nozzle loads, it is possible to reduce both hydraulic loss and thermal surface area at the same time.

The reliability analysis improves this method by substituting the simple 'safe/unsafe' interpretation with an explicit consideration of variability. Solazzi and Vaccari examined the reliability behaviour of composite, steel and aluminium pressure vessels and found that deterministic safety factors do not show a linear relationship with reliability. A more defensible approach is to achieve an efficient design at a specified reliability level, taking the uncertainty through the structural model.

Fatigue and repeated cycling are just as important since improvements in efficiency can change the way the equipment is operated. Kim and Yoshikawa combined numerical fatigue-life assessments with experimental data for pressure accumulators, and Yoo et al. measured the conservatism of various low-cycle-fatigue evaluation rules by using notched specimens. Ma et al.looked at crack propagation and fatigue life in a large austenitic pressure vessel operating under hydrogen conditions, pointing out how sensitive the life is to both pressure and to the areas around the nozzles. A power-saving control strategy which results in more starts, stops or pressure fluctuations may offset fuel savings by causing faster damage.

Machine-learning surrogates are now being used more and more in order to make high-dimensional structural optimisation computationally feasible. In their study, Sun and colleagues combined an artificial-neural-network surrogate with multi-objective particle-swarm optimisation in order to improve vessel sealing performance, this greatly cutting down the cost of carrying out repeated finite-element evaluations. Similarly, Wang and co-authors linked automated finite-element simulation with machine learning in order to predict failure factors throughout the design space of composite vessels. A validated surrogate can then quickly screen out thousands of different combinations of thickness, reinforcement geometry, support parameters and operating loads, after which high-fidelity analysis is only carried out on the designs that have been shortlisted.

Studies with multiple objectives show the importance of identifying trade-offs rather than prematurely combining them into a single weighted score. Rozova et al. optimised the parameters of composite vessels with regard to several mechanical objectives, while Vondracek et al.used thermoelastic analysis, evolutionary techniques and data-driven modelling to look at filament-wound vessels. Warkina and Regassa looked into the effects of winding and lay-up in hybrid overwrapped vessels. For the Saudi projects, a similar Pareto front could involve vessel mass, the level of stress utilisation allowed, fatigue life, heat loss, pressure drop, inspection burden, capital cost and lifecycle carbon. The final choice would then be based on the priorities specific to the service rather than on an arbitrary overall optimum.

The results relating to composite vessels need to be handled with care. Although the weight savings achieved with composite storage vessels are appealing, the requirements associated with use in hydrocarbon processes—such as temperature effects, fire exposure, chemical compatibility, permeation, impact, inspection and repair—differ from those applying to the storage of water or hydrogen. The value that can be transferred is the fact that composite research has developed matured optimisation tools, namely layerwise modelling, uncertainty treatment, surrogate-assisted search and failure-constrained design—for the optimisation of metallic pressure equipment.

Brownfield integrity results in a different optimisation problem — that of maintaining safe service while minimising the lifecycle penalty. Mihaljec et al. carried out a combination of failure analysis, finite-element optimisation and experimental verification concerning a composite repair patch for a corroded steel pressure vessel. When it comes to making repair-or-replacement decisions in operating facilities, the remaining life, the length of the outage, energy performance, inspection frequency and future degradation should all be taken into account. A repair which recovers pressure integrity but still leaves severe thermal loss, maldistribution or internal fouling unaddressed might be technically safe but operationally suboptimal.

Thermal design is also a factor that is not being used enough. Afra et al. found that better insulation is more effective at reducing heat loss in steam-injection systems than just raising the temperature or increasing the flow rate. Rong and Zhu combined thermal analysis with the design of insulation thickness for subsea production equipment, showing how insulation requirements should take into account transient operating conditions. Although for Saudi surface facilities the direction of heat flow may vary depending on the service, the principle is still that insulation should be designed based on its duty, the ambient exposure, the shutdown requirements and the lifecycle economics, rather than on a fixed thickness that is carried over from one project to another. Hot vessels and pipes lose useful energy while cold equipment can absorb unwanted heat and thus increase the load on refrigeration or compression. Insulation that has degraded should therefore be considered not only as a personnel-protection problem but also as an energy-performance defect.

5. Process-equipment performance optimisation

The best evidence showing energy savings comes from the way in which equipment interacts rather than from the design of the vessel walls. This is clearly shown in the case of petroleum separation and fractionation. Cui et al. suggested using internal partial condensation as a replacement for the conventional pump-around process in petroleum fractionators, achieving a lower pressure drop together with more effective heat and mass transfer. In their case study they found an 11.88% reduction in energy consumption for an existing fractionator, alongside an improvement in product yield. Although that specific figure cannot be applied to every crude oil unit in Saudi Arabia, it does show that reconsidering the internals can at the same time alter the thermal duty, the hydraulic resistance and the separation performance. Process-equipment optimisation is thus most beneficial when it eliminates a thermodynamic irreversibility rather than simply improving the efficiency of one component.

In many production facilities rotating equipment is still the main electrical load. According to Sutoyo et al.gas compression and pumping are major users of energy in hydrocarbon production and they demonstrate that the way in which equipment is configured and the settings at which it operates can make a significant difference to the amount of power needed. When it comes to the design of pressure vessels, this result has important implications for the decisions made in the hydraulic area. If there is an excessive pressure drop across inlet fittings, demisters, control valves, exchangers or if the nozzles are too small, then more compression or pumping work will be needed to achieve the same process aim. It is therefore useful to assign to each avoidable kilopascal of pressure loss at the relevant flow conditions an annual energy cost and then compare that cost with the capital cost or layout penalty of reducing the resistance.

Compressor optimisation must take into account suction pressure, stage matching, recycle, anti-surge margin, cooler performance and liquid exclusion as a unified approach. A suction scrubber which permits carry-over poses a reliability risk, but if the inlet device is too restrictive it will reduce suction pressure and raise the compression ratio. In the same way, running several compressors at a poor load can be less efficient than choosing a smaller number of compressors to operate, as long as the requirements for availability and turndown are met. The pressure vessels located around a compressor train should therefore be incorporated into compressor energy models and should not be shown as fixed pressure losses. Only in this way can the performance of the internals or the set points be assessed on the same basis as changes to compressor control.

Pump systems exhibit the same kind of interaction. Although throttling is a convenient method, it turns pressure directly into loss. When process conditions allow it, power consumption can be reduced more effectively by using variable-speed operation, selecting the appropriate impeller, scheduling the use of pumps in parallel, and by lowering the resistance of the network. The set points for the liquid level in the vessel and for downstream pressure have an effect on the static head and on the position of the control valve, so that apparently small changes in operation can lead to a change in pump duty. The right optimisation variable is not simply 'pump efficiency' but the total system curve for the representative operating cases. This is particularly important when the production rate, the fluid density and the viscosity vary over time.

Heat exchanger networks provide a well-established means of reducing the need for fuel and cooling. Teng et al. created a graph-theoretical approach for retrofitting which takes into account the existing structure of the network and is able to identify several feasible retrofit options, a valuable asset for brownfield projects that are subject to constraints. Instead of aiming for a theoretical maximum level of heat recovery which would involve considerable changes to the piping, the method presents alternative solutions that differ in terms of the extent of the modifications required. Yang et al.have extended this concept to include multi-period and multi-objective heat exchanger network synthesis for an industrial crude-distillation system, explicitly taking into account decarbonisation and variable operating periods. These advances are directly applicable to the Saudi refineries since the crude slates, throughput and utility conditions vary, which means that a single design-point optimum could be fragile.

Fouling has to be taken into account when optimising exchangers since the performance of a clean design is seldom maintained indefinitely. Trafczynski et al. applied measurement-aided fouling monitoring and optimised the cleaning schedules in a refinery network. Their main contribution is a decision rule: cleaning should be carried out when the energy recovered and the operating costs avoided are greater than the cleaning costs, taking the operational constraints into account. This is an improvement on fixed-interval cleaning since different exchangers foul at different rates and have different degrees of influence within the network. For facilities in Saudi Arabia, a fouling programme should rank the exchangers according to the marginal fuel or cooling penalty, not just on the basis of the observed pressure drop or the amount of time they have been in operation. The most valuable cleaning target could be an exchanger whose reduced duty causes a furnace or a compressor to have to compensate.

When considering debottlenecking, pressure vessels and exchangers should be looked at together. Increasing the throughput will result in higher velocity, a greater pressure drop and higher heat-transfer coefficients, but it may also make entrainment, vibration, erosion and fouling worse. It is possible that the energy optimum will therefore be below the hydraulic maximum. Multi-period optimisation can determine whether a revamp should add area, change the network topology, modify the internals or alter the operating pressure. This avoids a typical brownfield situation in which one bottleneck is eliminated only for the energy demand or reliability risk to be passed on to the next unit.

Table 1 brings together these mechanisms according to equipment class. This synthesis allows for economic normalisation in that each intervention can be measured in terms of the electricity, fuel, cooling, emissions and risk of lost production that it avoids each year.

Table 1. Evidence-to-design synthesis across major equipment domains.

Equipment domain	Dominant mechanism	Priority variables	Design / operating implication
Pressure vessels / separators	Pressure loss, entrainment, thermal exposure, local stress	Nozzle size; internals; residence time; head/support geometry; insulation	Optimise process function and integrity together; quantify downstream pumping/compression penalty.
Composite-vessel methods	Mass and stress concentration; burst/fatigue uncertainty	Lay-up; fibre angle; thickness; polar geometry; surrogate variables	Powerful optimisation methods are transferable, but material substitution needs service-specific qualification.
Thermal boundary	Heat loss/gain and shutdown thermal transients	Insulation material and thickness; exposed area; shutdown criterion	Size insulation from duty and lifecycle economics rather than fixed legacy thickness.
Heat exchanger networks	Lost heat recovery; utility demand; hydraulic resistance	Network topology; added area; stream matches; multi-period operation	Use retrofit options that respect brownfield constraints and variable operating cases.
Exchanger fouling	Increasing thermal resistance and pressure drop	Condition index; cleaning frequency; cleaning timing	Prioritise cleaning by avoided utility cost and network leverage, not elapsed time alone.
Compressors and pumps	Shaft power, recycle, throttling, off-design operation	Unit configuration; speed; staging; suction pressure; system resistance	Optimise the complete system curve and pressure boundary, not equipment efficiency in isolation.
Digital condition	Hidden degradation	Sensors; reconciled	Use physics-informed

Equipment domain	Dominant mechanism	Priority variables	Design / operating implication
layer	and model drift	parameters; uncertainty; feasible operating envelope	monitoring to update constraints before optimisation recommendations are implemented .

6. Optimising digitally and operating in a way that takes account of the condition

Digital twins are able to reduce the gap between the original design intentions and the actual operating conditions. Knebel et al. look at the implementation of digital twins in the oil and gas industry and highlight real-time monitoring, state prediction, cloud-edge architecture and the practical issues relating to security and data governance. Ren et al. show an example of a dig, using for natural-gas triebehavioral,col dehydration ein which geometric, process, behavioural and rule models are employed in the evaluation of the condition. Soesanto et al. offer a digital twin on an industrial scale which has been verified against plant data and is used for control and optimisation studies. Taken together, these papers illustrate a move from static design models to operational models that are continuously brought into agreement with measurements.

The most useful digital twin for pressure equipment is not a three-dimensional visualisation but a decision model which is able to estimate unmeasured performance and the remaining constraints. The inputs can be pressure, temperature, flow rate, valve position, vibration, the temperatures in the exchanger, compressor power, and the results from corrosion monitoring and inspections. A core based on physical principles maintains the conservation laws and the relationships between pieces of equipment, while the data-driven layers compensate for bias or estimate parameters such as fouling resistance. The twin can then compute the energy key performance indicators under production conditions that match those in practice, thus stopping the plant from claiming an improvement just because the throughput or the properties of the feed have changed.

Information on the condition also helps to maintain integrity when optimising. A vessel which is experiencing increasing wall loss, greater fatigue usage or an unstable separation should not be driven towards a nominal energy optimum that would reduce its remaining margin; rather, the range of feasible operation should become narrower as the condition worsens. In this way, data obtained from inspections is turned into a constraint for the optimisation process. The same reasoning applies to exchangers: a measured level of fouling alters both the heat-transfer efficiency and the pressure loss, and as a result changes the optimal time for cleaning and the way in which the utilities should be allocated. Digitalisation is thus most valuable in so far as it makes the constraints dynamic.

The greatest risk in terms of implementation is model confidence. Although surrogate models can greatly reduce computation, a quick and incorrect model is still going to be incorrect. Every digital optimisation layer must have a specified validation domain, an uncertainty band and a fallback rule. Actions with high consequences must be kept within approved control and integrity boundaries. Cybersecurity, the quality of the sensors, time synchronisation and the completeness of the historian have to be regarded as engineering requirements, not as afterthoughts of information technology. For pressure-containing systems, a step-by-step deployment — starting with advisory calculations, then operator confirmation, and only afterwards carrying out closed-loop optimisation — is more defensible than immediate autonomous control.

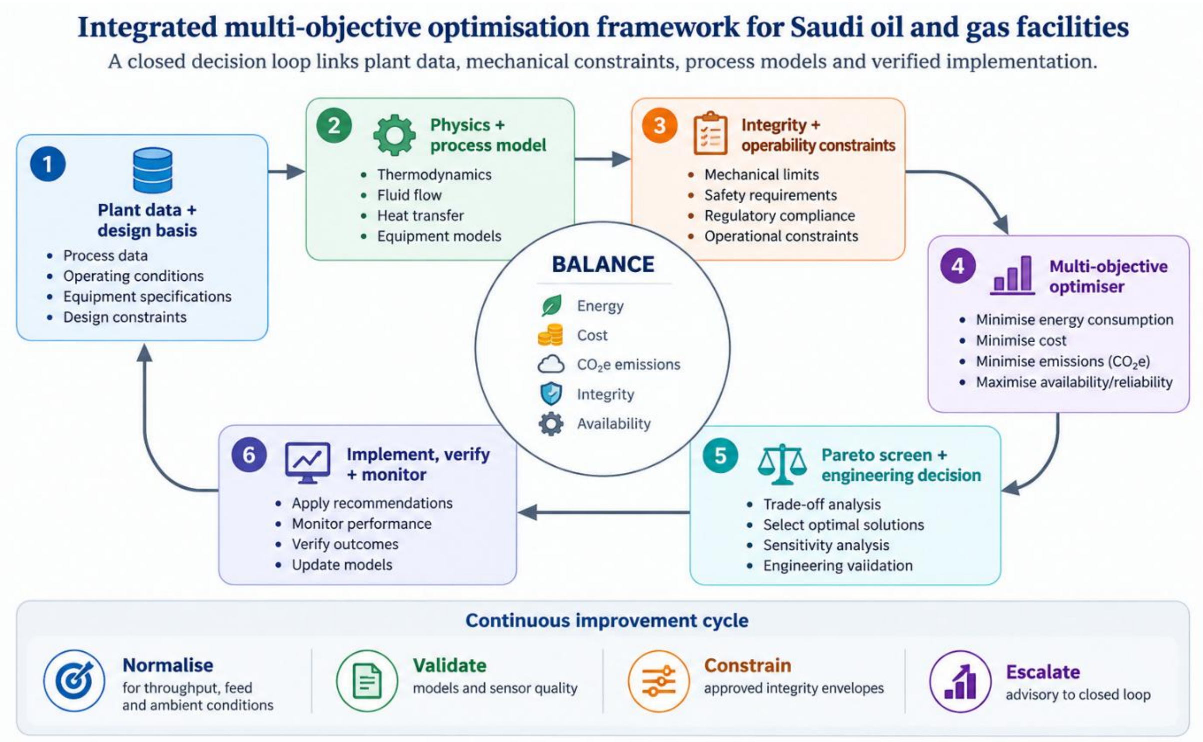

Figure 2. Integrated multi-objective optimization and verification loop for Saudi oil and gas facilities.

7. The framework relating to Saudi Arabia's deployment, the research gaps and the priorities regarding implementation

The framework for the deployment that Saudi Arabia is using must start by dividing the plants into sections. When establishing new facilities, multi-objective optimisation should be carried out before procurement takes place, since at that stage the vessel geometry, the exchanger area, the choice of compressor and the arrangement of the site are still flexible. In the case of existing facilities, the procedure should first involve preparing an energy and pressure map which has been based on data from normal operation; the major vessels and exchangers should then each be allocated their respective amounts of thermal loss, pressure drop, separation quality and the duty imposed on the downstream units. The rotating equipment should also be assessed under the same operating conditions so that the interactions within the system can be observed.

The following stage is that of setting up absolute constraints. Such constraints involve the requirements concerning pressure design codes, material compatibility, corrosion allowance, relief-system capacity, fatigue, vibration, operability, adherence to product specifications and the necessity of having a safe shutdown. Within these constraints, the criteria to be optimised should be annual energy output, lifecycle cost, emissions, availability and integrity margin. As Rostamian et al.have shown, even though their study focuses on field-development optimisation, they provide a useful methodological insight in that the decisions taken in the oil and gas industry involve conflicting objectives and are thus more appropriately described through the use of multi-objective optimisation than by depending on a single economic criterion. A Pareto front allows the various trade-offs to be seen by asset owners and prevents any unspoken weighting assumptions from affecting the design.

The following step involves intervention sequencing. The no-regret actions include restoring the insulation, getting rid of unnecessary bypasses, correcting sensor bias, keeping the exchanger clean and optimising the operating set-points or configuration. Next come adjustments to the operating set-points and control reconfiguration, followed by modifications to the internals or network carried out during the planned turnaround. A decision matrix is provided in Table 2 that associates the type of intervention with the key performance indicators and constraints. The sequence deliberately concentrates on measurable operating losses before proceeding to structurally innovative solutions.

Table 2. Saudi implementation matrix for energy-efficient pressure and process equipment.

Equipment / context	Priority intervention	Primary KPI	Critical decision constraint
Separator / scrubber	Reduce avoidable inlet/internals pressure loss while preserving separation	kPa pressure drop; carry-over; downstream kW	Integrity, entrainment, relief and turndown limits
Heat exchanger train	Retrofit high-leverage matches; clean by measured fouling state	Approach temperature; fouling resistance; fuel/cooling duty	Plot space, outage scope, hydraulic limits, cleanability
Compression train	Select efficient unit combination; minimise recycle and suction losses	kWh per unit production; recycle fraction; compression ratio	Anti-surge margin, availability, liquid exclusion
Pump system	Reduce throttling and network resistance; optimise speed/staging	Specific pumping energy; valve loss; operating point	NPSH, minimum flow, hydraulic stability
Hot/cold vessels and piping	Restore or redesign insulation to service-specific duty	Surface loss/gain; downstream heating/cooling duty	CUI risk, fire protection, personnel protection, shutdown behaviour
Brownfield pressure equipment	Condition-informed operating envelope and repair/replace decision	Remaining life; energy penalty; inspection interval	Code compliance, corrosion/fatigue, turnaround window
New facilities	Multi-objective design before specification freeze	Lifecycle energy, CO2e, cost, integrity margin	Process specification, fabrication, maintainability, approved standards

There are still some research gaps. First, a great deal of the work carried out on the optimisation of pressure vessels has employed mass, stress or burst pressure as its objectives, while very little of it connects vessel geometry with the plant's overall operating energy. It is therefore essential that future research combines finite-element models with process simulation so that the sizing of the nozzles, the design of the internals, the arrangement of the supports and the thermal design can all be evaluated in terms of both integrity and their function in the following process steps. Second, even though the methodology applied in the optimisation of composite vessels is sophisticated, there is still a lack of direct evidence regarding their use in aggressive hydrocarbon processes. Before deciding on a general change of materials, research should focus on chemical compatibility, fire performance, inspectability, repair and ageing. Third, datasets specific to Saudi Arabia on exchanger fouling, insulation ageing, ambient effects and the degradation of pressure loss are rarely available in the open literature.

Fourth, energy projects need to undergo more thorough validation. The savings which are reported should be modified to consider the production rate, the make-up of the feed, the ambient conditions, and the availability of the equipment. Measurement and verification should consist of comparing similar periods of operation or involve the use of calibrated models together with uncertainty limits. This is particularly important in the case of compressor and exchanger projects since apparent savings may arise as a result of changes in throughput or weather conditions. Fifth, the connection between integrity management and energy optimisation is still not well established. Risk-based inspection, corrosion data and fatigue usage should be turned into explicit optimisation constraints so that energy savings can no longer be achieved by secretly using up equipment life.

The framework also contains suggestions concerning governance. The mechanical, process, reliability, operations and energy teams should all carry out a joint review of the optimisation proposals. Even if a process engineer suggests operating at a lower pressure, the mechanical engineers have to consider the effects of fatigue, relief and nozzle loads; the reliability engineers must examine degradation and inspection; and the operators have to check the controllability and start-up behaviour. A joint, cross-functional review is particularly important in relation to large assets in Saudi Arabia since changes could affect several units and in such cases the production value of availability becomes more important than the direct energy savings. For that reason, energy performance should be included in the management of change and not treated as a separate initiative.

The business case should be based on lifecycle value rather than just the energy payback; for example, a change that saves fuel but increases the length of the shutdown period may not be very appealing, whereas another that reduces energy use at the same time as extending the cleaning intervals or the life of the compressor might be worthwhile even if it has a longer direct payback. Where it is appropriate to do so, carbon intensity, the avoidance of maintenance, and production reliability should all be considered in monetary terms. This more thorough evaluation ties energy efficiency with asset integrity rather than treating the two as opposing factors, and it also favors durable design changes over short-term operating campaigns.

8. Conclusions

The evidence currently available shows that the energy-efficient operation of pressure equipment can be viewed in one way only, namely that the vessel boundary, the thermal boundary and the hydraulic boundary are all part of the plant's energy system. Even though pressure vessels usually need only a small amount of direct power, the shape of the vessel, the components inside it, the insulation, the extent of any degradation and the pressure at which they operate all have an effect on the amount of work required by heat exchangers, pumps, compressors and other utilities. Research into structural optimisation carried out between 2020 and 2025 has led to well-established methods in the areas of finite-element verification, reliability analysis, surrogate modelling and multi-objective search, but in the case of vessels used in hydrocarbon processes the transfer of these results from composite or hydrogen vessels must be based on hydrocarbon-service constraints. The process literature also provides more direct evidence of cost savings in existing installations as a result of managing pressure losses, retrofitting exchanger networks, adopting cleaning strategies according to the degree of fouling and choosing the configuration of the rotating equipment.

The most suitable method for Saudi oil and gas facilities is to apply a staged lifecycle approach, this involving the identification of the losses in various systems, establishing clear integrity constraints, optimising those operations which can be regarded as no-regret, making the necessary modifications during turnarounds, and holding on to innovative equipment ideas until it is possible to carry out service-specific qualification. Digital twins can support this approach by matching plant measurements with physical principles and by constantly updating the information regarding fouling, condition, and the feasible operating envelopes. Future research should clearly link the mechanical models of pressure vessels with process-energy simulations and should confirm the degradation and fouling behaviour specific to Saudi conditions. The key design principle is therefore not merely to reduce mass, pressure drop or heat recovery. Instead, it is to minimise the total energy and emissions over the facility's lifecycle for the given level of production, always remaining within well-defined integrity, operability and reliability constraints.

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