

Strategic Optimization of Industrial Lubricants for Energy Efficiency and Asset Reliability in Saudi Arabia's Oil and Gas Sector: A Vision 2030 Framework

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Abstract- Industrial lubrication is usually regarded as a maintenance item rather than as a means of achieving energy efficiency, asset reliability, and lifecycle value. This difference is important in Saudi Arabia's oil and gas industry, since pumps, compressors, turbines, gearboxes, hydraulic systems and auxiliary equipment have to operate under heavy loads, thermal stress, a risk of contamination and strict availability requirements. This study brings together peer-reviewed evidence published between 2020 and 2025 in order to look at how lubricant selection, application engineering, contamination control, condition monitoring, predictive analytics and sustainable formulation can be incorporated into a strategic lubrication framework that is in line with Saudi Vision 2030. To do this, a structured integrative approach is applied drawing on the fields of tribology, reliability engineering, condition monitoring, digital transformation and the literature on Saudi energy transition. The evidence shows that lubricant optimisation improves efficiency by reducing friction and churning losses, enhances reliability by ensuring good film integrity and controlling wear, and has an impact on maintenance costs by enabling earlier detection of degradation and allowing for better timing of interventions. Yet value is sacrificed when lubricant decisions are left scattered among the procurement, operations, laboratories and maintenance departments. It is therefore suggested that a framework geared towards Saudi Vision 2030 should be based on five interconnected capabilities: asset criticality, application-specific lubricant engineering, condition-based surveillance, data-driven decision support, and circular resource management. The review concludes that the greatest opportunity does not lie in simply using higher-performance oils, but in treating lubrication as an asset-management system that delivers measurable results in the areas of energy, reliability, environment and localisation.

I. INTRODUCTION

The oil and gas sector in Saudi Arabia brings together on a global scale hydrocarbon infrastructure and at the same time is carrying out a national programme aimed

at improving efficiency, promoting localisation, achieving digitalisation and enhancing environmental performance. In this context, the reliability of equipment is closely linked to energy productivity. Equipment which is rotating or reciprocating uses energy not only to carry out useful work but also to counter friction, fluid drag, churning and the losses caused by deteriorated interfaces. As a result, modern tribology treats lubrication as an engineering factor which affects mechanical efficiency, wear, temperature, the life of components and the need for maintenance rather than as a simple routine activity (Meng et al., 2020; Luo and Zhou, 2020). This view is particularly applicable to pumps, compressors, turbines, bearings, gears and hydraulic equipment that work continuously in the production, processing and utility systems.

Recent studies indicate that the lubrication performance is determined by a number of interacting factors such as the base-oil chemistry, viscosity, additive package, contamination, temperature, load, speed, surface condition, the method of replenishment and the quality of the maintenance decisions. In the case of gear research, it has been shown that the lubrication method and the amount used can have a significant effect on power losses and on thermal behaviour, while more general reviews in the field of tribology reveal that effective control of friction and wear can lead to important energy and lifecycle savings (Liu et al., 2020; Yilmaz et al., 2022). The practical result is that energy efficiency cannot be obtained simply by choosing a nominal viscosity grade; it is necessary to match the lubricant's rheology and chemistry to the operating conditions, to control degradation, and to make sure that the lubricant still meets its required purpose during use.

The reliability aspect is just as important. The state of the lubricant provides information on both the fluid and the machine; changes in viscosity, oxidation, water content, particle concentration, elemental wear debris or the depletion of additives can show that faults are developing before there is functional failure. Nowadays, the literature on predictive maintenance more and more combines this type of data with vibration, temperature, pressure and process signals, thus providing a route from regular oil testing to an integrated health assessment (Olesen and Shaker, 2020; Wen et al., 2022). In the oil and gas industry, condition monitoring is especially useful since failures can stop production, raise safety risks and lead to additional damage. Therefore, reviews of pumps, rotating equipment and asset integrity stress early detection, risk-based prioritization and data quality as the main reliability requirements (Lakal et al., 2022; Almazrouei et al., 2023).

The Saudi Vision 2030 programme includes a strategic element in relation to these technical matters. Studies into Saudi energy policy stress the need for energy efficiency, economic diversification, the adoption of technology and lower-carbon operations (Amran et al., 2020; Alomari and Heffron, 2021; Belaïd and Massié, 2023). More up-to-date research on the oil and gas sector in the Gulf has shown that digital transformation, operational efficiency and circular-economy practices are becoming increasingly important as factors promoting sustainable competitiveness (Al-Hajri et al., 2024; Alsuhaybany, 2025). Industrial lubrication is at the point where these priorities meet since it can help to reduce avoidable losses, lengthen the life of equipment, improve the accuracy of maintenance, assist in building local technical capacity and cut down on lubricant waste.

Even though there is strategic importance involved, the existing literature is still fragmented. Tribology studies generally concentrate on friction mechanisms or on formulation science; maintenance studies concentrate on diagnostics; asset-integrity studies stress risk and inspection; and research into sustainability in Saudi Arabia is carried out at either the policy or sector level. The missing element is a comprehensive explanation of how lubrication can be treated as a measurable operational system in the oil and gas facilities of Saudi Arabia. This review tackles

that gap by linking lubricant engineering with reliability, digital maintenance, and the outcomes of Vision 2030, and at the same time distinguishing between technologies that are ready for implementation and those that still need field validation.

II. AIM, OBJECTIVES AND RESEARCH QUESTIONS

This review seeks to establish a framework for industrial lubrication that is based on evidence and is aimed at enhancing energy efficiency, asset reliability, and sustainable operational performance within Saudi Arabia's oil and gas industry. The analysis is guided by four objectives: to identify the lubrication mechanisms that affect mechanical and energy performance; to evaluate the condition-monitoring and predictive-maintenance methods applicable to assets that depend on lubricants; to assess sustainable and circular lubrication options without sacrificing reliability; and to turn the evidence obtained into an implementation framework that is in line with Vision 2030. Three research questions are examined: How does the lubrication strategy impact the energy and reliability outcomes of machinery used in the oil and gas sector? Which monitoring and decision-making practices offer the greatest operational value? And how can lubrication governance be connected with Saudi objectives relating to efficiency, digitalisation, localisation and sustainability?

III. REVIEW METHODOLOGY

A structured integrative review was chosen since the research problem involves various fields including tribology, lubricant chemistry, reliability engineering, predictive maintenance, oil and gas asset integrity and Saudi energy policy. The approach was developed with the aim of maintaining a high level of technical detail while allowing for the integration of findings from different disciplines that employ diverse experimental methods and outcome measures. The searches were concentrated on peer-reviewed publications from the period 2020 to 2025, giving priority to literature in Scopus-indexed journals and also making use of major engineering and multidisciplinary databases where appropriate. The search combinations comprised terms such as

"industrial lubrication", "tribology", "energy efficiency", "lubricant condition monitoring", "oil analysis", "predictive maintenance", "rotating equipment", "oil and gas", "asset reliability", "biolubricants", "digital twin", "Saudi Arabia", "Vision 2030", "energy efficiency" and "circular economy".

Eligibility was assessed on the basis of a study's relevance to at least one of the four analytical areas—lubricant-performance mechanisms, machinery reliability and condition monitoring, the sustainability of lubricant systems, or the Saudi oil and gas transformation. Any studies that dealt with unrelated biological lubrication, those that focused solely on automotive consumer applications without involving transferable industrial mechanisms, or non-engineering policy issues lacking a link to energy or industrial operations were excluded. Since the aim was critical synthesis and not a meta-analysis, the studies were not combined statistically. Rather, the evidence was coded according to asset type, mechanism, monitoring approach, operational outcome, and implementation constraint.

The evaluation of quality focused on methodological transparency, the peer-reviewed nature of the work, the clear connection between the measurements and the conclusions drawn, and the relevance of the findings to industrial equipment. In order to ascertain the current state of knowledge, review papers were consulted, whereas experimental and data-driven

studies were employed to determine whether the proposed mechanisms had operational support. Special care was taken when it came to claims regarding substantial energy savings since the tribological improvements measured at a single contact point may not correspond to overall savings at the machine or plant level. Likewise, predictive models were interpreted in light of the quality of the data, the extent to which they could be transferred to other situations, and the frequency of failure rather than solely on accuracy measures.

The study was based on a logic that moved from mechanism to outcome. Initially, the evidence relating to friction, film formation, viscosity and lubricant delivery was looked at in order to understand how energy losses occur. Then, the evidence concerning degradation, contamination and wear was analysed in relation to the development of failure. Next, the literature on monitoring and analytics was evaluated to see whether it could turn lubricant data into maintenance decisions. After that, the sustainability and those pertaining to Saudi Arabia studies were reviewed in order to detect any strategic constraints and to ensure policy alignment. Since there was no prospective recording of the number of records in each database, a numerical screening process is not reported because inventing such figures would lead to a false sense of precision. The framework that results from this is therefore an open and integrative synthesis rather than a quantitative systematic review.

Table 1. Analytical domains used in the integrative review.

Domain	Evidence focus	Operational relevance	Principal caution
Tribology and lubricant engineering	Viscosity, friction, film formation, additives, delivery	Energy loss, wear control, thermal behaviour	Contact-level gains may not equal whole-asset savings
Condition monitoring and prognostics	Oil analysis, vibration, sensors, AI/ML	Early fault detection and maintenance timing	Data quality and transferability govern model value
Asset integrity and reliability	Criticality, failure consequence, inspection and maintenance	Availability, safety and lifecycle cost	Generic thresholds can misclassify asset-specific risk
Sustainability and Saudi transformation	Energy efficiency, circularity, digitalization, localization	Vision 2030 alignment and resource productivity	Environmental substitution must preserve reliability

IV. THEMATIC SYNTHESIS

4.1 Lubrication as an Energy-Efficiency Lever

The argument in favour of strategic lubrication starts by looking at frictional and hydrodynamic losses. When boundary and mixed lubrication are involved, inadequate film strength leads to greater interaction between asperities, higher local temperatures and increased wear; in the case of full-film lubrication, using a viscosity that is unnecessarily high results in greater viscous shear and higher pumping losses. It is therefore necessary to adopt an operating-window approach rather than simply assuming that thicker oil always offers better protection. Reviews of tribology and gear lubrication regularly demonstrate that it is the combination of load, speed, temperature and surface interaction which determines the balance between friction reduction and film adequacy (Meng et al., 2020; Liu et al., 2020).

The method of lubricant delivery is also important. Yilmaz et al. (2022) showed that decreasing the amount of lubricant can reduce the losses in gears and bearings when there is no load, although thermal limitations become more significant since there is less oil available for removing heat. This result shows a key principle relating to oil and gas equipment: efficiency improvements must be assessed in conjunction with temperature control and reliability margins. For instance, a gearbox might have lower churning losses when the oil level is reduced or when lubricant is injected in a targeted way, but the intervention is only advantageous if the tooth contacts, bearings and seals stay within safe thermal and lubrication limits.

In terms of formulation, current research into lubricants is looking at low-friction additives, ionic liquids, nanoparticles and a number of other advanced chemical solutions. Cai et al. (2020) explain that ionic-liquid chemistry is capable of promoting low-friction tribofilms, and Zhao et al. (2021) examine nanoadditives which reduce friction and wear by means such as the formation of a protective film, polishing and mending. Research into liquid superlubricity takes this a step further by investigating situations involving extremely low friction, but industrial use is still limited by problems relating to compatibility, durability, tolerance to contamination and the need to scale up (Luo and Zhou, 2020). As a result, the operators in Saudi Arabia should make a distinction between the proven optimisation of viscosity, cleanliness and delivery, which can currently be put into practice, and the newer types of formulation that require specific equipment qualification.

Energy performance must therefore be assessed at the asset level. Appropriate indicators are motor power under comparable load conditions, bearing temperature, gearbox losses, pump efficiency, compressor specific energy and lubricant temperature stability. The aim is not to state a general percentage reduction, but rather to set up a controlled baseline and to check whether a lubrication intervention leads to a reduction in energy input without causing an increase in wear or maintenance risk. This approach transforms tribological improvements into tangible, auditable operational benefits.

Lubrication value chain: mechanism to operational outcome



Figure 1. Lubrication value chain linking application engineering to energy and reliability outcomes.

4.2 Lubricant Selection, Degradation and Contamination Control

The choice of lubricant involves a consideration of reliability since the fluid has to keep its required viscosity, film strength, oxidation resistance, demulsibility, air release properties, corrosion protection, and additive functionality throughout the entire service period. Mistakes in selection are usually not detected at first; the machine may keep running even though the film thickness is decreasing, oxidation is speeding up or deposits are forming. The effects are then seen later in the form of higher temperatures, noise, deterioration of seals, bearing problems or a shorter lifespan of the oil. It is therefore better to have application-specific specifications than to rely on brand-based standardization.

The conditions under which oil and gas facilities operate make the problem more difficult. Because of the high ambient temperatures, the presence of process heat, dusty conditions, exposure to wash-downs and intermittent contamination, there are simultaneous requirements regarding oxidation stability and cleanliness. Water has the effect of reducing the strength of the film and causing corrosion; solid

particles can lead to three-body abrasion; if incompatible top-up oils are used this can cause the additive systems to become unstable; and with excessive heat chemical degradation occurs more rapidly. As a result, the lubrication programme regards storage, transfer, filtration, the use of breathers, sampling points and the exclusion of contamination as engineering controls not as housekeeping tasks.

It is better to base oil changes on the condition of the oil rather than stick to a calendar schedule when it is possible to sample the oil and have the analytical facilities available. The choice should take into account the condition of the fluid, the level of contamination and the indications of machine wear. Trends are more informative than a single laboratory test since the rate of change can show abnormal deterioration even if a parameter is still within a general limit. In the case of important assets, alarm limits should be set according to the type of equipment, the chemistry of the lubricant and the historical performance rather than just using general laboratory warning flags.

Sustainable formulations provide an extra factor when making selections. Reviews published from 2022

onwards indicate quick advances in vegetable-oil derivatives, synthetic esters, ionic liquids and nanoparticle-enhanced biolubricants (Teh et al., 2022; Pawar et al., 2022; Pichler et al., 2023). The benefits of these can be biodegradability, a high viscosity index and good lubricity, but limitations such as oxidation stability, hydrolytic sensitivity, low-temperature performance, seal compatibility and additive interactions are still dependent on the particular application. Substitution for oil and gas facilities in Saudi Arabia should therefore be approached on a risk basis: environmentally sensitive and moderate-severity applications might be suitable for early adoption, while high-temperature turbines, critical compressors or long-drain systems will need thorough qualification before being converted.

4.3 Condition Monitoring and Predictive Maintenance

Value is obtained from lubricant condition monitoring when the analytical information causes maintenance decisions to change. The most useful approach brings together three kinds of evidence: the condition of the lubricant, the level of contamination and the extent of machine wear. Indicators such as viscosity, oxidation and acid-base content show the degradation of the fluid; measurements of water and particles show external or process contamination; whereas elemental spectroscopy, ferrous debris and particle morphology give evidence of component wear. When these different signals are interpreted together, the risk of treating the lubricant and the machine as if they were separate systems is reduced.

Predictive-maintenance research is now combining oil data with that from vibration, temperature, pressure and process variables. Olesen and Shaker (2020) demonstrate that improved pump maintenance can be achieved by using information from multiple sources, and Wen et al. (2022) point out that data-driven prognostics is a key area for maintenance planning. With regard to oil and gas pumps, the severe operating conditions make it difficult to select sensors, carry out calibration and ensure their survivability, so that the design of the measurement system is just as important as the choice of algorithm (Lakal et al., 2022). The above findings suggest that analytics should not be put into use until reliable sampling, sensor governance and data context have been established.

As long as there is an adequate amount of representative data, machine-learning techniques can be used for predicting trends and detecting anomalies. For instance, Li et al. (2023) combined a long short-term memory prediction method with support-vector data description in order to identify abnormal lubricant wear conditions. What is important here is not the particular algorithm but rather the change of approach from retrospective laboratory analysis to forward-looking detection. The same kind of reasoning can be seen in research on oil and gas pumps, in which AI-based models are being used to predict faults and to optimise the timing of maintenance (Almazrouei et al., 2023). Nevertheless, the accuracy obtained from research datasets should not be taken to mean that it will automatically apply to entire fleets; differences in sensor position, lubricant type, operating conditions, maintenance history and the frequency of faults can have a substantial effect on model performance.

A reasonable way of implementing this is to have several layers. For basic assets route-based inspections and periodic oil analysis are sufficient; for more important assets oil analysis should be combined with vibration and thermography; and for critical assets online particle, moisture, dielectric or viscosity-related sensing together with advanced analytics should be added. The decision regarding maintenance should also take into account the importance of the asset and the consequences of its failure. A small anomaly on a production-critical compressor should lead to earlier investigation than a greater deviation on redundant auxiliary equipment. By associating condition data with consequences, lubrication monitoring becomes an element of risk-based asset management rather than remaining a separate laboratory service.

4.4 Asset Reliability in Pumps, Compressors, Turbines and Gear Systems

The reliability advantages from optimising lubrication vary depending on the type of asset. For pumps, these advantages relate to the condition of the bearings and seals, the hydraulic state and the control of contamination. In the case of water-injection and process pumps, predictive maintenance studies highlight the importance of identifying degradation before it leads to a loss of capacity or an unexpected shutdown (Almazrouei et al., 2023). Lubricant signals

are especially useful when they are considered together with changes in vibration and operating point since mechanical wear and hydraulic instability can cause similar symptoms.

The lubrication of the bearings in compressors is coupled with a high level of thermal and process sensitivity. In the case of reciprocating machines, cylinder lubrication, valve performance and pulsation effects also have to be taken into account, whereas centrifugal compressors can be equipped with complex lube-oil systems which provide support for both journal and thrust bearings. Studies using machine learning on rotating and reciprocating equipment indicate that intelligent fault diagnosis is progressing, although the robustness of the models is dependent on the quality of the features and on having representative failure data (Manikandan and Duraivelu, 2021). For operators the main concern is to make sure that the pressure, temperature, filtration, the condition of the reservoir and the contamination indicators of the oil system are recorded with sufficient context so as to be able to tell the difference between lubricant problems and process disturbances.

Turbines need outstanding oxidation stability, together with good air release and deposit control since varnish and degradation products may affect the bearings, servo systems and the reliability of the control mechanisms. The gear systems must have a viscosity and additive performance that enables them to maintain film strength under high contact stress while at the same time reducing churning and sliding losses. As shown in the gear literature, the same lubricant selection has an impact on efficiency, scuffing resistance, contact fatigue and temperature, so it is unsafe to optimise any one of these factors alone (Liu et al., 2020).

In every class, the improvement in reliability results from standardising the decision process rather than forcing the use of a single lubricant. The asset register should list the lubrication points, the specification of the lubricant, the sump volume, the contamination target, the location for sampling, the alarm limits, the method of replenishment and the critical failure modes. With this information, repeatable audits become possible, root-cause analysis is supported and the need for relying on individual memory is reduced.

Moreover, it provides the data base necessary for digital twins and advanced asset analytics, both of which are still promising but are currently only unevenly implemented in the oil and gas industry (Wanasinghe et al., 2020).

4.5 Sustainable Lubrication and Circular Resource Management

Sustainable lubrication must be assessed on the basis of its lifecycle performance and not just its biodegradability. A lubricant that is renewable but needs to be replaced frequently or causes deposits and reduces the life of components might in fact have a greater total environmental impact than a conventional formulation with a longer service life. For this reason, existing evaluations stress the need to assess tribological performance, toxicity, renewability, oxidation stability and service life all at the same time (Khadem et al., 2023; Silva-Álvarez et al., 2024). This approach, which takes a systemic view, is especially important in relation to the oil and gas facilities in Saudi Arabia since reliability failures there can have serious implications for production and the environment.

Circularity starts by extending the useful life of the oil through control of contamination and by replacing it according to the condition of the equipment. It then involves separating out the used oils, preventing cross-contamination, providing recovery or re-refining options where it is both technically and legally feasible, and reducing the need for unnecessary flushing or disposal. Improved control of inventory also helps to cut down on stock that has expired and on the use of incompatible products. The implementation of these measures does not require any change to the lubricant chemistry and often brings about immediate operational advantages.

When alternative formulations are being considered, the qualification process should involve bench testing, meet the original-equipment requirements, ensure elastomer compatibility, exhibit thermal stability and include controlled field trials. Pichler et al. (2023) indicate that the development of sustainable lubricants is growing in the areas of bio-based, bio-derived and other low-impact components, although performance must still be tailored to the specific application.

Strategic procurement can help to establish local capabilities in formulation, testing and analysis, thus linking environmental goals with industrial localization. The most compelling sustainability argument therefore follows a priority hierarchy: first avoid consumption where it is avoidable, then extend the life of the oil and the assets, then recover value from used lubricant, and finally substitute the formulations only when the overall lifecycle performance has clearly been improved.

4.6 Alignment with Saudi Vision 2030

The Vision 2030 framework should link decisions regarding lubrication at the plant level with wider national objectives. Research into Saudi Arabia's energy transition identifies efficiency as a key factor in reducing emissions and enhancing economic resilience, and policy studies highlight the importance of diversification, technological capability and improved environmental governance (Alomari and Heffron, 2021; Belaïd and Massié, 2023). Unlike large capital projects, lubrication optimisation makes a contribution by increasing the productivity of existing assets through the reduction of avoidable friction, by preventing degradation and by extending their service life.

Digital transformation enhances this aspect. Studies looking at the digitalisation of oil and gas in the Gulf have shown a growing use of analytics, connected sensing and integrated decision systems, even though organisational, data and interoperability obstacles still exist (Al-Hajri et al., 2024). Research focused on Saudi Arabia also points out barriers connected with implementation, organisational readiness and the particular complexity of the sector (Alshibani et al., 2024). A lubrication programme offers a practical example of digital transformation since the data are directly linked to physical deterioration and maintenance activities. Moisture, particle, temperature and vibration signals obtained online can be combined with laboratory results, work orders and operating data to establish a traceable record of asset health.

There is also a strategic opportunity in the area of localization. The sector of industrial lubrication calls for application engineers, laboratory analysts, reliability specialists, knowledge of filtration, field-

service abilities and the capacity to interpret data. By building these capabilities locally it is possible to decrease reliance on external troubleshooting and at the same time create technical knowledge that can be applied in the fields of refining, petrochemicals, mining, power generation and manufacturing. In addition, local qualified laboratories and controlled field trials can assist in the development of lubricants and additives in Saudi Arabia without putting the equipment warranties or reliability at risk.

Circular-economy principles can be put into practice by means of extending the life of lubricants, recovering used oil and using resource-efficiency performance indicators. Alsuhaybany (2025) states that digital innovation and circular-economy practices together contribute to sustainability in the oil and gas operations of Saudi Arabia. By adopting a strategic approach to lubrication, this connection is put into action at the level of equipment: digital monitoring identifies when it is actually necessary to intervene with the oil, and the application of circular economy practices reduces unnecessary use and waste. Vision 2030 is therefore best aligned when the indicators relating to energy, reliability, localization and the environment are coordinated and managed as a whole rather than being presented as individual initiatives.

V. INTEGRATED VISION 2030 LUBRICATION OPTIMIZATION FRAMEWORK

The synthesis proposes a five-layer approach. In the first layer, asset criticality is considered and equipment should be ranked on the basis of its production consequence, safety exposure, redundancy, repair lead time and environmental impact. This avoids the need for expensive monitoring being carried out uniformly and makes it possible to apply stronger controls to those lubrication points which have a high consequence. The second layer relates to application engineering: for each critical lubrication point there should be a documented specification which includes details on viscosity, base-oil type, performance class, compatibility, cleanliness and the method of delivery. Procurement should enforce the specification rather than replace the product simply on the grounds of price.

The third level concerns contamination and conditions control, and storage rooms, transfer containers, breathers, filtration equipment, sampling ports and flushing procedures should all be incorporated as part of the lubrication system. Laboratory and online monitoring then need to be organised according to criticality. The fourth level is decision intelligence, and trend rules, alarm logic and analytical models should transform the measurements into actions such as filtration, dehydration, resampling, inspection, review of the load or carrying out a planned oil change. Advanced analytics should support engineering judgement rather than conceal it, and the asset histories must include the reason for each intervention so that the thresholds can be improved over time.

The fifth level is that of performance governance. Instead of relying on a single measure of oil consumption, a strategic programme should use a balanced scorecard. The energy indicators can be things such as normalized kWh per unit of output or verified reductions in power following an intervention. For reliability, indicators might be the number of bearing distress events, lubrication-related failures, the mean time between failures and the amount of unplanned downtime that has been avoided. With regard to lubricants, the indicators could be compliance with contamination standards, the extension of oil life and the percentage of critical assets that have representative samples. The sustainability indicators should include lubricant consumption per operating hour, used-oil recovery and the amount of disposal that has been avoided. As for capability indicators, they may be the laboratory's turnaround time, technician certification and the percentage of assets covered by digital health records.

Figure 1 sets out the chain of mechanisms running from lubricant engineering to the actual operational results, whereas Figure 2 converts this chain into a closed-loop implementation model suitable for use in Saudi Arabia. The key managerial principle is that benefits build up when the various stages support and reinforce one another; if better lubricant selection is made without at the same time controlling contamination, performance will not be maintained; data will be generated but not reliability if sensors are in place without having associated decision rules; and setting sustainability targets which fail to take into

account the life of the equipment will result in misleading cost savings. The framework thus views lubrication as a socio-technical management system involving engineering standards, people, data, suppliers and continuous improvement.

To put this into practice, facilities should first carry out a baseline audit covering the variety of lubricants, the way they are stored, the critical machinery, the failure history, performance regarding contamination, the quality of sampling and the energy data. A pilot project should then focus on a small number of high-value assets since it will be possible to measure both the technical and economic outcomes. The successful practices should then be standardised and expanded upon using site procedures, digital templates and the development of competency. This step-by-step method reduces the risks involved in implementation and produces local evidence which can be used to justify further investment.

The implementation should also take account of the incentives within the organization since those involved in operations are rewarded for being available, those in the procurement department are rewarded for controlling costs, and those responsible for maintenance are rewarded for carrying out their work, even though lubrication performance affects all three areas.

A shared governance approach can help reduce such conflicts by setting common targets relating to compliance with contamination requirements, verified energy performance, avoidance of failure, and lubricant lifecycle cost. This is important since local optimization might otherwise result in system-wide losses, for example by buying a cheaper fluid which reduces the length of time between drains or by lowering oil flow without keeping an eye on the thermal margin. Decision-making powers should therefore be clearly defined, with engineering approval needed whenever lubricant substitutions are made on critical assets and with a properly documented management of change when there is a change to the viscosity, chemistry, filtration or delivery method.

Baseline data quality is just as important since unreliable nameplate information, inconsistent

sampling points and incomplete work histories can weaken both traditional trend analysis and advanced analytics; the same discipline also helps to improve supplier collaboration since performance claims can

be checked against agreed baselines rather than being accepted as general product advantages.

Closed-loop Vision 2030 lubrication optimization framework

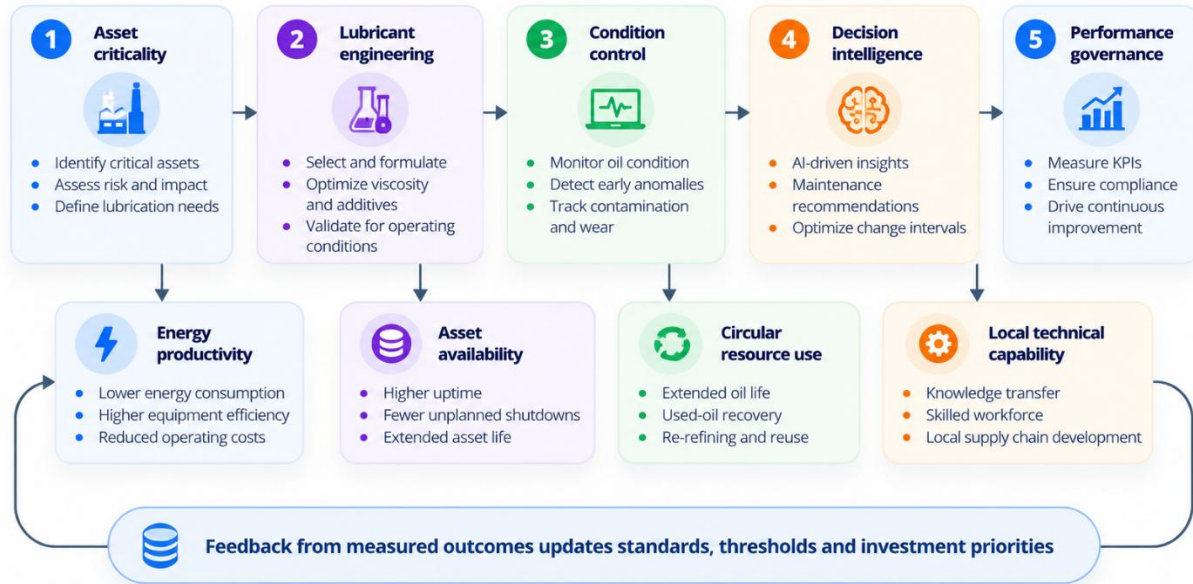


Figure 2. Closed-loop implementation framework for Vision 2030-oriented lubrication optimization.

Table 2. Proposed balanced KPI architecture for strategic lubrication.

Dimension	Illustrative KPI	Decision use	Vision 2030 contribution
Energy	Normalized power or specific energy before/after controlled intervention	Verify efficiency rather than assume it	Energy productivity and emissions intensity
Reliability	Lubrication-related failures, MTBF, avoided downtime	Prioritize reliability actions and critical assets	Industrial competitiveness and continuity
Lubricant health	Cleanliness compliance, oxidation trend, oil-life extension	Optimize filtration and replacement timing	Resource efficiency and lower waste
Digital	Critical assets with integrated oil/vibration/process history	Measure digital coverage and data completeness	Operational digitalization and analytics capability
Localization	Local laboratory turnaround, certified personnel, qualified local services	Track domestic technical capability	Human-capital and local-content development

VI. RESEARCH GAPS AND FUTURE RESEARCH

There are three areas that should be given priority. First, there is a lack of field data that quantifies the total asset energy savings resulting specifically from lubrication changes under operating conditions in Saudi Arabia. Controlled trials should therefore integrate tribological measurements with measurements of motor power, throughput, temperature and wear. Second, predictive models need to have better transferability between lubricant brands, types of asset and operating conditions. Future research should focus on using interpretable models, including uncertainty bounds, and should base its validation on actual fault development rather than on balanced laboratory datasets. Third, research into sustainable lubricants needs to include in its lifecycle analysis evidence relating to the longevity of the oil, the durability of the components, their compatibility and the methods available for recovery, not just friction data obtained in the laboratory or biodegradability.

A Saudi research programme could set up common testing procedures for turbines, compressors, pumps and gearboxes; produce anonymised condition-monitoring datasets; test locally developed lubricants under high-temperature and dusty conditions; and assess the economic aspects of extending the life of oil and using filtration. Digital-twin research should also include the lubricant's condition as a dynamic indicator of health rather than considering mechanical assets merely in terms of their geometry and vibration. This type of research would help to build up the evidence for localisation and reduce the gap between laboratory innovations and their acceptance in practice.

VII. PRACTICAL, MANAGERIAL AND POLICY IMPLICATIONS

Plant managers ought to have a responsible person in charge of lubrication who has the necessary authority covering maintenance, operations, procurement and the laboratories. Critical lubricant specifications must be kept from being replaced without control, and when assessing suppliers technical support, evidence of compatibility and real-world performance should be

taken into account. Reliability teams should combine oil analysis with vibration, process and work-order data so that warnings result in specific actions. Procurement teams should use total lifecycle cost rather than unit price as the main criterion for evaluating critical applications.

At the sector level, competency frameworks can assist certified lubrication technicians, analysts and reliability engineers. Local laboratories can be evaluated in terms of repeatability, turnaround time and the quality of their diagnostics. Policies and industrial-development programmes can promote local capabilities in filtration, testing, condition monitoring and lubricant formulation while at the same time keeping equipment standards. The resulting integrated ecosystem would turn a routine maintenance activity into a platform for energy productivity, workforce capability, circular use of resources and industrial localization.

VIII. LIMITATIONS

Since the review draws on evidence from a number of different engineering fields, a direct comparison is limited by the variations in the assets used, the test conditions, the lubricant chemistries, and the way the results are defined. Although some new technologies have strong support from laboratory studies they have only limited validation based on long-term use in oil and gas fields. The review also fails to include a meta-analytic estimate of the energy savings since consistent reports of the effect sizes at the plant level are not available. It is therefore appropriate for the framework to serve as a guide to structured implementation and measurement rather than be seen as guaranteeing a specific improvement in efficiency.

IX. CONCLUSION

Industrial lubrication is not only strategically important but is often inadequately regulated when it comes to improving energy efficiency and reliability in the oil and gas industry. Evidence released between 2020 and 2025 indicates that value is generated by the combination of proper lubricant specification, controlled delivery, exclusion of contamination, condition monitoring and decisions on maintenance based on risk assessment. Although advanced

additives, sustainable formulations and machine-learning analytics broaden the range of available tools, they do not cancel out the basic principles of application engineering and the need for disciplined data collection.

For Saudi Arabia, the closest link to Vision 2030 is achieved by treating lubrication as an integrated asset-performance system; energy losses can be reduced by optimising both viscosity and delivery; reliability can be enhanced by detecting degradation and wear at an early stage; environmental performance can be improved by extending the life of the oil and by implementing circular recovery; and localisation can be promoted by developing domestic capabilities in the fields of technical know-how, laboratories and digital technology. The proposed five-layer framework—comprising criticality, application engineering, condition control, decision intelligence and performance governance—offers a practical way of turning tribology into operational value.

The managerial conclusion is just as important as the technical one in that only when the overall system is able to select, protect, monitor and take action with respect to the lubricants can these be made to produce durable value. Oil and gas operators in Saudi Arabia who set up such a system can transform lubrication from an item which is a consumable expense into a factor which can be measured in terms of efficiency, availability, sustainability and industrial capability.

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