

Low-Carbon Smart GIS Substations for Saudi Arabia Under Vision 2030: Integrating SF6 Leakage Detection, Gas Recovery, Predictive Maintenance, and Asset-Life Extension

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Article History

Received: 27.07.2026

Accepted: 19.09.2026

Published: 22.09.2026

Abstract: Gas-insulated substations and switchgear (GIS) offer compactness, reliability and environmental protection, but the continued use of sulphur hexafluoride (SF₆) creates a material climate-management obligation because small losses can dominate the greenhouse-gas footprint of otherwise efficient high-voltage assets. This review develops an integrated low-carbon operating framework for Saudi GIS portfolios by connecting four practices that are commonly managed separately: leakage detection, gas recovery and inventory control, predictive condition assessment, and risk-based asset-life extension. A structured integrative review of peer-reviewed research published from 2020 to 2025 was conducted across recent SF₆-alternative, leakage-monitoring, partial-discharge, digital-twin, health-index and lifecycle studies. The evidence indicates that decarbonisation cannot be reduced to replacing the insulating gas. Existing fleets require accurate leak localisation, closed-loop gas handling, condition-informed interventions and disciplined decisions about refurbishment versus replacement. Infrared and multi-channel optical methods improve non-contact leak identification, while decomposition sensing, vibration analysis, partial-discharge diagnostics and data-driven models broaden the observable condition state. Health-index and condition-based risk-management methods then translate heterogeneous evidence into maintenance priorities and life-extension decisions. For Saudi Arabia, the proposed architecture is designed for hot, dusty, geographically dispersed and rapidly modernising grid environments, where outage avoidance, technician capability, spare-parts strategy and emissions stewardship must be considered together. The review concludes that smart GIS should be governed as a coupled carbon-reliability system in which gas balance, defect evidence, intervention history and remaining-life decisions continuously update one another.

Keywords: Gas-insulated switchgear; SF₆ leakage; gas recovery; predictive maintenance; partial discharge; health index; asset-life extension; Saudi Arabia; Vision 2030; low-carbon substations.

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1. INTRODUCTION

Gas-insulated substations and switchgear are strategically important where high reliability,

compact footprint and protection from external contamination are required. In this paper, GIS denotes gas-insulated switchgear/substation

Citation: Aleem, F. (2026). Low-Carbon Smart GIS Substations for Saudi Arabia Under Vision 2030: Integrating SF₆ Leakage Detection, Gas Recovery, Predictive Maintenance, and Asset-Life Extension; *Glob Acad J Econ Buss*, 8(5), 1300-1310.
<https://doi.org/10.36348/gajeb.2026.v08i05.022>

equipment rather than Geographic Information Systems. The distinction is important because the attached reference article uses the same acronym for spatial analysis, whereas the present review concerns high-voltage electrical assets. The engineering case for GIS remains strong, yet its traditional dependence on SF6 presents a disproportionate climate burden. Recent literature describes SF6 as an exceptionally persistent, high-global-warming-potential dielectric and arc-quenching medium and has accelerated the search for lower-impact alternatives [1,2].

For existing fleets, however, a binary choice between retaining SF6 and replacing every asset is technically and economically inadequate. A substation that is replaced early may avoid future gas losses but can incur substantial embodied impacts, capital expenditure, outage risk and material consumption. Conversely, retaining poorly sealed or deteriorating equipment without effective monitoring allows repeated leakage, emergent failures and avoidable gas top-ups. A low-carbon strategy therefore depends on controlling the full asset cycle: identify loss, recover and reuse gas where feasible, detect incipient defects, quantify health, plan interventions and extend life only when risk remains acceptable. The lifecycle comparison of switchgear designs reinforces the need to consider both equipment manufacture and use-phase emissions rather than focusing on one stage [2,30].

Leakage control is the first operational barrier. Computational and early-warning work has shown that SF6 released in substations can disperse in ways that affect both environmental inventory and occupational safety [3]. Non-contact infrared methods can detect weak gas plumes without de-energising equipment, but low contrast, background noise, viewing geometry and atmospheric conditions complicate reliable interpretation [10,27]. Field-scale approaches are moving from point inspection toward persistent, image-based or multi-sensor surveillance, making it possible to connect a leak event with a specific compartment and maintenance work order rather than treating annual gas consumption as an unexplained aggregate.

Condition monitoring is the second barrier. Gas quantity alone cannot indicate whether an old bay is safe to retain. Mechanical vibration, partial discharge, gas decomposition, contact overheating and switching history provide complementary evidence about deterioration [4,9,12-17]. Recent learning methods address practical problems such as domain shift, scarce labels and the difference between laboratory and field distributions [9,12,18-20,24-26]. The asset-management challenge is to convert these signals into decisions. Health-index and

conditional-factor methods demonstrate how observable defects, age, operations, obsolescence and duty can be integrated into maintenance prioritisation [14, 21], while condition-based risk-management approaches support extension beyond rigid time-based replacement [29].

Saudi Arabia adds a distinctive operating and strategic context. High ambient temperatures, dust, long transmission corridors, rapid capacity expansion and increasingly digital operations place a premium on robust monitoring and disciplined outage planning. Vision 2030 also strengthens the case for efficiency, localisation and technology-enabled infrastructure. The contribution of this review is therefore an integrated framework that treats SF6 stewardship, reliability and asset life as one decision system. Rather than assuming that decarbonisation is achieved only through new gas technology, it asks how the existing GIS fleet can become measurably lower carbon while new assets transition toward lower-impact designs.

2. Aim, Objectives and Review Questions

The aim of this review is to formulate a low-carbon smart-GIS operating framework for Saudi substations that links SF6 containment with predictive condition management and defensible life-extension decisions. The framework is intended for both legacy SF6 assets and transition portfolios in which alternative gases or SF6-free designs are gradually introduced.

Five objectives structure the analysis. First, the review evaluates recent SF6 leakage-detection approaches, distinguishing concentration monitoring, optical imaging and localisation methods by their operational value rather than by sensor novelty alone. Second, it examines gas recovery, inventory discipline and sealing compatibility as lifecycle controls that can reduce avoidable emissions from existing equipment. Third, it synthesises electrical, mechanical and chemical condition-monitoring evidence that can support predictive maintenance. Fourth, it evaluates health-index, digital-twin and risk-based methods for converting condition evidence into repair, refurbishment, life-extension or replacement decisions. Fifth, it translates these findings into an implementation roadmap suitable for Saudi grid operators seeking simultaneous reliability, carbon and capability outcomes.

Three review questions follow. RQ1 asks which sensing and gas-management practices most effectively convert SF6 leakage from an inventory uncertainty into an actionable maintenance event. RQ2 asks how partial-discharge, vibration, decomposition and operational data should be fused

to estimate condition without over-relying on a single diagnostic. RQ3 asks how Saudi asset owners can use condition evidence to extend GIS life without shifting environmental or reliability risk into the future.

3. REVIEW METHODOLOGY

A structured integrative review was selected because the problem spans dielectric materials, gas handling, optical sensing, high-voltage diagnostics, machine learning, lifecycle assessment and asset management. A conventional meta-analysis would be inappropriate because the underlying studies report fundamentally different outcomes, from gas-concentration fields and imaging accuracy to partial-discharge classification, health indices and lifecycle carbon effects. The methodology therefore emphasised traceable selection, technical comparability and decision-oriented synthesis.

Searches covered literature published from 2020 to 2025 using combinations of the terms gas-insulated switchgear, gas-insulated substation, SF6 leakage, infrared gas imaging, gas recovery, insulating gas alternatives, decomposition products, partial discharge, vibration diagnosis, health index, digital twin, predictive maintenance, condition-based risk management and asset life. Records were sought in major engineering and multidisciplinary databases. To keep the technical evidence auditable, the final reference set was restricted to peer-reviewed publications with resolvable DOI records and direct relevance to at least one of the four review domains. Papers using GIS only to mean Geographic Information System were excluded from the technical evidence base.

Screening proceeded in three stages. Title and abstract screening removed sources concerned primarily with unrelated gases or non-switchgear applications. Full-text relevance screening retained studies that reported a transferable sensing principle, material mechanism, diagnostic method, lifecycle result or asset-management framework. Quality appraisal considered methodological transparency, clarity of test conditions, relevance to operating equipment, treatment of uncertainty and the extent to which laboratory findings could reasonably inform field practice. No study was treated as universally generalisable; instead, conclusions were weighted according to the operational maturity of the evidence.

The synthesis used six thematic codes: climate and alternative-gas context; leak detection and localisation; gas recovery and sealing integrity; electrical and mechanical condition sensing; predictive analytics and digital twins; and health-index/life-extension governance. Cross-coding was used where a study connected domains, for example when decomposition products were interpreted as

an insulation-condition indicator [15] or when a digital twin supplied simulated data for partial-discharge localisation [24]. Conflicting evidence was retained, particularly where alternative gases may reduce climate impact but introduce new questions about stability, decomposition, low-temperature performance or material compatibility [1,6-8,11,16,22].

The final step translated evidence into a closed-loop architecture and a staged Saudi implementation roadmap. The review does not invent field failure rates or claim a single optimal replacement age. Instead, it identifies the information relationships that a utility would need to measure locally: compartment gas balance, confirmed leak rate, recovery efficiency, defect severity, health index, probability of failure, outage consequence, intervention cost and avoided replacement. This approach preserves the review nature of the paper while producing an implementable decision framework.

4. SF6, Low-Carbon Transition and Material Integrity

The environmental case for improved SF6 governance is clear, but the technical pathway is more nuanced than substitution. Reviews of alternative gases show that dielectric strength, arc interruption, thermophysical behaviour, decomposition chemistry and practical operating temperature must be assessed together [1,6]. Life-cycle analysis further shows that greenhouse benefits depend on actual leakage, equipment design and manufacturing burdens [2,30]. A Saudi transition strategy should therefore distinguish three asset classes: legacy SF6 equipment requiring strong containment; retrofit or replacement candidates where condition or leakage no longer justifies retention; and new equipment where lower-impact technologies can be specified without compromising system duty.

Material compatibility is central to all three classes. Seals age under temperature, pressure cycling, mechanical assembly and chemical exposure. Research on C4F7N mixtures and EPDM demonstrates that alternative media can interact differently with elastomer formulations, affecting gas decomposition and seal performance [8]. Diffusion studies similarly show that new gas mixtures do not behave as simple drop-in replacements; mixing, concentration stability and transport need to be characterised [11]. The practical implication is that low-carbon procurement should not evaluate gases separately from gaskets, enclosures, filling procedures and monitoring thresholds.

Decomposition chemistry provides a second link between carbon management and reliability. Alternative-gas studies have identified degradation products under electrical stress and evaluated stability and toxicity under switching and dielectric tests [7,22]. For SF₆ equipment, temperature-related decomposition and diffusion modelling indicates that local overheating can alter gas composition in ways that may reveal insulation or contact problems [15]. Thus, gas analysis has value beyond environmental inventory: it can become an input to condition assessment. A gas-management programme that merely records kilograms added misses this diagnostic opportunity.

A low-carbon GIS strategy should therefore use a hierarchy of controls. Avoid unnecessary emissions through sealed handling and recovery; detect abnormal losses early; diagnose the cause before refilling; decide whether repair restores containment; and use replacement only when condition, obsolescence or recurrent loss makes continued operation unjustifiable. This hierarchy protects against two weak approaches: repeated top-up without root-cause correction and premature fleet replacement justified by carbon concerns alone.

5. Leakage Detection, Localisation and Gas Recovery

Leakage detection becomes operationally valuable when it answers three questions: whether gas is escaping, where the escape originates, and whether the measured loss is significant enough to change maintenance priority. Fixed concentration sensors can provide continuous warning but may struggle to localise a small source in ventilated or spatially complex rooms. Dispersion modelling demonstrates why monitor position matters and why alarm interpretation should consider room geometry and flow [3]. A smart substation should therefore treat fixed sensors as one layer rather than as the complete solution.

Optical gas imaging adds spatial information. Low-contrast infrared detection methods improve

the visibility of weak SF₆ plumes by separating gas signatures from noise and background variation [10]. More recent binocular approaches use paired spectral channels to suppress background and system noise and have reported very high experimental detection accuracy [27]. Field deployment still requires controls for viewing angle, thermal background, weather, distance and calibration. The benefit is not the image alone but the ability to tag a flange, bushing, density monitor, valve or enclosure joint as a probable source and link that evidence to a work order.

Gas recovery closes the environmental loop. Every intervention that opens a compartment should begin with a planned gas balance: initial inventory, quantity recovered, quantity treated or recycled, quantity returned, make-up gas, and any residual loss. The literature on alternative gases and diffusion underscores the need for contamination control and composition verification [7,11,22]. For SF₆, the same discipline prevents maintenance from becoming an unmeasured emissions event. Portable recovery carts, vacuum procedures, sealed cylinders and calibrated weighing should be integrated with the digital asset record rather than maintained as paper-only workshop practice.

Leakage response should also be risk based. A minor, stable leak from a non-critical bay may justify a planned seal repair during the next outage; a rapid loss from a high-consequence bay may require immediate intervention. Repeated leakage after repair is an escalation signal because it can indicate flange distortion, seal ageing, enclosure movement or unsuitable maintenance practice. In hot Saudi conditions, thermal cycling and seal condition deserve particular attention. The appropriate KPI is therefore not simply annual gas purchased. Better indicators include confirmed leak events per compartment-year, time from detection to localisation, recovery percentage during intervention, repeat-leak rate, unexplained gas-balance variance and emissions intensity per installed GIS bay.

Table 1: Evidence-to-decision synthesis for low-carbon GIS management

Control domain	Evidence from 2020-2025 literature	Primary decision	Failure if managed alone	Representative KPI
SF ₆ containment	Dispersion, low-contrast infrared and binocular imaging improve detection and localisation [3,10,27].	Locate and prioritise leak repair.	Annual gas purchase hides source, recurrence and response delay.	Repeat-leak rate; time to localisation
Gas handling	Alternative-gas diffusion and degradation studies emphasise composition and contamination control [7,11,22].	Recover, weigh, treat and reconcile gas during intervention.	Top-up restores pressure without proving containment.	Recovery %; unexplained gas variance

Control domain	Evidence from 2020-2025 literature	Primary decision	Failure if managed alone	Representative KPI
Condition sensing	Vibration, PD, decomposition and multisensor methods expose mechanical/electrical degradation [4,12,15,17,28].	Verify incipient defect and severity.	Single sensors create false confidence or false alarms.	Confirmed defects; diagnostic lead time
Predictive analytics	Transfer, federated, semi-supervised and digital-twin methods address scarce or shifted field data [9,18-20,24-26].	Rank bays for additional testing or outage.	Model score is mistaken for physical diagnosis.	Precision on confirmed events; model drift
Life extension	Health-index, fuzzy and CBRM methods combine condition, age and consequence [14,21,29].	Continue, repair, refurbish or replace.	Calendar age dominates despite actual condition.	Risk-adjusted life extension; forced outage

6. Predictive Condition Monitoring

Predictive maintenance requires a broader condition picture than gas pressure. Mechanical, electrical and chemical deterioration can develop before protection trips or conventional inspection reveals a problem. Vibration-based work demonstrates that circuit-breaker operation can excite signatures useful for identifying mechanical defects in assembled GIS [4]. Such methods are attractive because they can be non-invasive and can compare operating events over time. Their principal challenge is establishing stable baselines across equipment models and separating true degradation from normal variations in operating mechanism, mounting and ambient condition.

Partial discharge is a particularly rich indicator of insulation defects. Recent research has progressed from conventional pattern recognition toward transfer learning, federated learning, multi-information ensembles, time-reversal localisation and joint diagnosis-localisation models [9,12,13,17-20]. The shift matters because field data rarely match laboratory distributions. Domain-adaptive models attempt to reduce performance loss when operating conditions differ from the training set [9,18,19], while semi-supervised methods exploit large quantities of unlabelled data where expert-labelled fault examples are scarce [26]. Multi-information approaches combine UHF and acoustic evidence to reduce dependence on one sensor channel [17].

Digital twins strengthen this direction by providing a physics-informed source of synthetic or simulated data. Meta-learning work has used a GIS digital twin to support partial-discharge localisation when only limited target samples are available [24]. This is promising for Saudi utilities with large but heterogeneous fleets: a twin can represent geometry, sensor positions and propagation paths, while field

events calibrate the model. However, a digital twin should not be treated as a decorative three-dimensional model. Its value depends on parameter traceability, data quality, uncertainty bounds and demonstrated improvement in a maintenance decision.

Chemical sensing offers another predictive layer. SF₆ decomposition products can indicate electrical or thermal stress, and compact gas-sensor arrays are being developed to detect characteristic products without relying exclusively on laboratory instruments [28]. Numerical decomposition-diffusion studies further connect contact overheating with local gas chemistry [15]. A practical architecture can therefore combine density and gas-balance trends, optical leak evidence, partial-discharge severity, vibration features, decomposition markers, switching counts and thermal observations.

The key governance principle is evidence fusion rather than algorithm competition. A single high anomaly score should trigger verification, not automatic replacement. Predictive maintenance becomes defensible when several independent indicators converge or when one high-severity diagnostic has a well-understood failure mechanism. This reduces false positives and helps scarce outage windows focus on the bays with the highest combination of defect probability and consequence.

7. Health Index, Risk and Asset-Life Extension

Condition data only creates value when translated into an asset decision. Health-index methods provide a practical bridge by normalising inspection and diagnostic results into comparable condition scores. A conditional-factor approach has been applied to GIS by combining visible or measurable degradation with age, number of operations, satisfactory service, obsolescence and

interrupting adequacy [14]. Fuzzy logic has also been used to reduce some of the subjectivity of conventional weighting and scoring [21]. Neither method removes engineering judgement, but both make assumptions visible and repeatable.

Life extension should be framed as a risk decision rather than an age concession. Research on condition-based risk management argues that rigid time-based replacement can retire serviceable GIS well before the end of useful life and that inspection, monitoring, health indices and probability-of-failure reasoning can support longer operation [29]. This is particularly relevant where replacement requires lengthy procurement, major outages, civil modification or imported specialist support. Extending life can also avoid embodied materials and project emissions, but only if recurrent SF₆ loss and failure risk remain controlled.

A Saudi decision model should therefore separate condition, consequence and carbon. Condition estimates the probability that an asset will fail or leak materially; consequence captures system criticality, safety, outage duration and repair complexity; carbon captures expected gas loss plus the lifecycle effect of repair, refurbishment or replacement. An old but tight, diagnostically stable GIS bay may be a good life-extension candidate. A younger bay with repeat SF₆ leakage, increasing partial discharge and obsolete spares may not be. This logic prevents chronological age from dominating the decision.

Uncertainty must be explicit. Health indices can create false precision if all inputs are treated as equally reliable. Sensor confidence, missing inspections, unverified alarms and model drift should reduce decision confidence. A useful practice is to attach an evidence-quality grade to each health score and require higher-quality evidence before approving major life extension. Where uncertainty is high and consequence is severe, additional testing is preferable to optimistic scoring.

The asset-life decision should culminate in one of four actions: continue with routine monitoring; targeted repair with enhanced surveillance; refurbishment or component replacement; or full bay replacement. The decision should then feed back into the model. If a seal replacement stops loss, the result validates the diagnosis. If partial discharge persists, the health state should not reset merely because maintenance occurred. This closed learning loop is essential for developing local failure knowledge rather than

repeatedly relying on generic manufacturer assumptions.

8. Integrated Low-Carbon Smart GIS Framework

The proposed framework connects the four review domains in a closed operational loop. Layer one is the physical asset and gas inventory: each compartment has a controlled identifier, gas type, nominal mass, fill history, seal history and design information. Layer two is observation, combining density monitoring, fixed concentration sensors, optical leak surveys, UHF/acoustic partial discharge, vibration, temperature and gas decomposition. Layer three is data quality and context, where measurements are time synchronised, associated with the correct bay, screened for sensor health and enriched with loading, switching and ambient conditions.

Layer four is analytics. Leak-rate trends and gas balance estimate containment performance; diagnostic models classify or localise defects; digital twins test whether observed signals are physically plausible; and health-index models combine condition with invisible ageing factors [14,21,24]. Layer five is risk and carbon decision support. The model compares maintenance options using probability of failure, consequence, SF₆ emissions exposure, recovery feasibility, outage constraints, spare availability and expected remaining life. Layer six is controlled intervention: leak repair, gas recovery, component overhaul, monitoring escalation, refurbishment or replacement.

The final layer is learning. Confirmed failure causes, recovered gas mass, repair effectiveness, post-maintenance diagnostics and actual outage outcomes update component rules and model parameters. Figure 1 represents this architecture, while Table 1 summarises the evidence-to-decision relationships. The architecture is deliberately modular because not every Saudi substation requires the same sensor density. High-consequence urban or industrial GIS may justify continuous multi-sensor monitoring; lower-consequence sites may use periodic optical and diagnostic campaigns supported by disciplined gas inventory.

A defining feature is that carbon and reliability share the same asset record. This avoids parallel environmental and maintenance databases that disagree about the identity or history of equipment. When a leak is detected, the system can show previous top-ups, prior seal work, condition anomalies and planned outages. When life extension is proposed, decision-makers can see whether the asset has remained gas-tight and diagnostically stable rather than considering age alone.

Closed-loop low-carbon smart GIS architecture

Containment, condition evidence and asset decisions operate as one feedback system

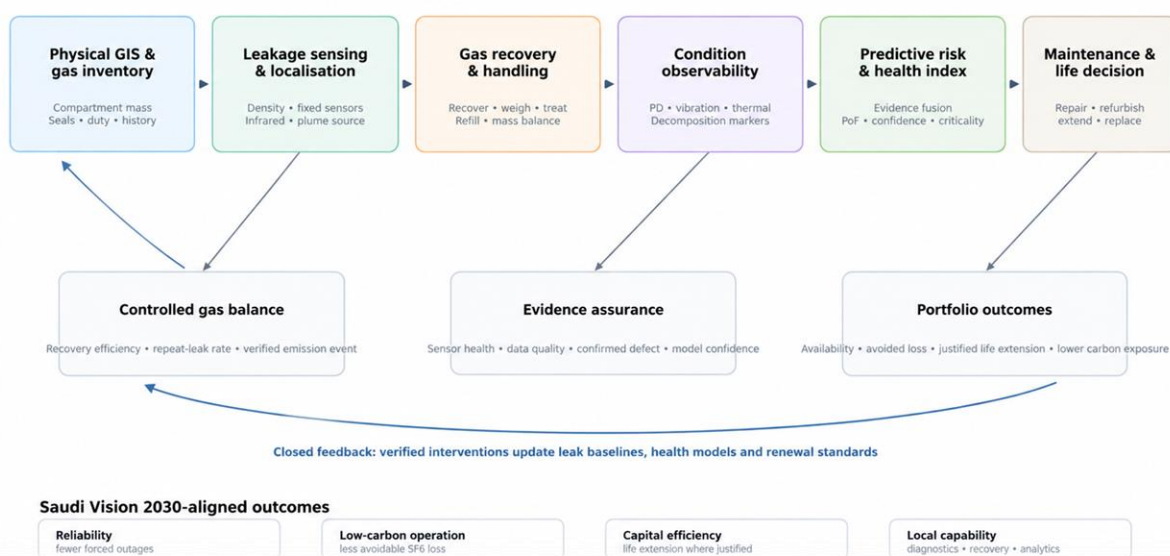


Figure 1: Closed-loop low-carbon smart GIS architecture linking containment, condition, risk and asset intervention

9. Saudi Vision 2030 Implementation Roadmap

Implementation should begin with data discipline rather than sophisticated analytics. Stage one establishes a verified GIS register, compartment-level SF₆ inventory, leakage history, criticality ranking and consistent failure taxonomy. Without these foundations, advanced models can only automate uncertainty. The initial outcome is a trustworthy baseline for both emissions and reliability.

Stage two instruments leakage control. Critical rooms receive appropriate fixed detection, periodic optical surveys are standardised, recovery equipment is calibrated, and every gas-handling intervention records mass balance. Staff competence is important because a recovery cart or camera does not guarantee correct use. Training should include leak localisation, sealed handling, cylinder management, contamination control and digital work-order closure. Metrics include unexplained gas variance, repeat-leak rate and recovery efficiency.

Stage three integrates condition monitoring. Existing protection and monitoring data are supplemented where justified with UHF/acoustic partial-discharge sensing, vibration, thermal or gas-decomposition measurements. Analytics should first be validated on known defects and maintenance outcomes. Domain-adaptive and semi-supervised approaches are relevant because utilities cannot wait for large labelled failure datasets before using condition information [9,18,19,26]. This stage should

also develop a common evidence-quality scale so that models and human inspections can be compared transparently.

Stage four introduces health-index and risk-based life management. A cross-functional team agrees component weights, conditional factors, consequence categories and escalation thresholds. The aim is not to maximise average asset age; it is to retain low-risk assets and replace high-risk ones at the economically and environmentally appropriate time. CBRM-style reasoning can support this transition from calendar replacement to evidence-based renewal [29].

Stage five creates portfolio governance. Environmental, maintenance, planning and procurement teams use the same dashboard to review SF₆ intensity, high-risk bays, recovery performance, life-extension approvals and replacement pipeline. Procurement specifications increasingly favour proven lower-impact technologies where duty permits, while legacy equipment receives stricter containment and end-of-life recovery controls. Local engineering capability can be strengthened through diagnostic laboratories, calibration routines, model validation, seal-failure analysis and technician certification.

Figure 2 presents the maturity pathway and Table 2 defines representative measures. Alignment with Vision 2030 is expressed through outcomes rather than slogans: more reliable electricity

infrastructure, lower avoidable greenhouse-gas emissions, better use of installed capital, digitally enabled maintenance, and deeper local capability in high-voltage asset management. The framework also

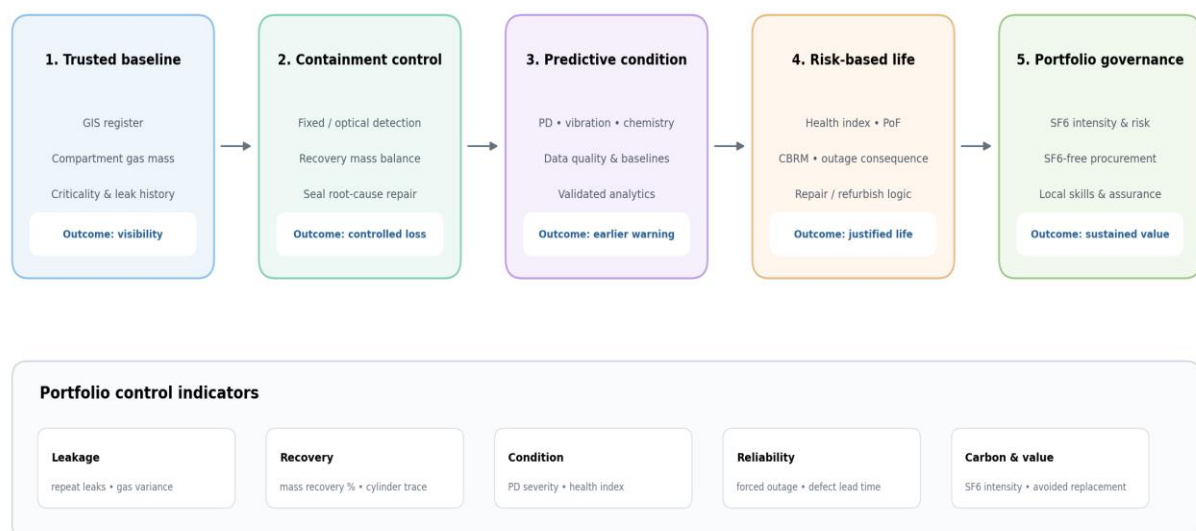
supports resilient planning because asset replacement is based on evidence, making future capital requirements more predictable.

Table 2: Implementation maturity stages and representative portfolio controls

Maturity stage	Priority actions	Decision gate	Core measures	Expected Saudi outcome
1. Trusted baseline	Verify GIS register, compartment inventory, criticality and leak history.	Asset identity and baseline gas balance are complete.	Inventory completeness; unresolved variance.	Comparable carbon and reliability baseline.
2. Containment control	Standardise fixed/optical detection, recovery equipment and seal root-cause repair.	Leak can be localised and intervention mass is reconciled.	Leak recurrence; recovery efficiency; response time.	Lower avoidable SF6 loss.
3. Predictive condition	Integrate PD, vibration, thermal and decomposition evidence with data quality.	Anomaly is verified by physical evidence or repeatable trend.	Defect lead time; false alarm rate; evidence grade.	Earlier, better-targeted maintenance.
4. Risk-based life	Apply health index, conditional factors, consequence and carbon exposure.	Life extension supported by adequate evidence quality.	PoF band; HI trend; avoided replacement.	Capital efficiency without hidden risk.
5. Portfolio governance	Link environmental, maintenance, planning and procurement decisions.	Renewal and low-impact procurement follow portfolio risk.	SF6 intensity; high-risk bays; local capability.	Sustained reliability and decarbonisation.

Low-carbon smart GIS maturity roadmap

A staged path from inventory discipline to portfolio-level carbon and reliability governance



Strategic alignment: reliable electricity • reduced avoidable emissions • efficient capital • digitally enabled maintenance • local engineering capability

Figure 2: Maturity roadmap for low-carbon smart GIS implementation in Saudi substation portfolios

10. DISCUSSION AND RESEARCH GAPS

The reviewed evidence shows that the technologies needed for low-carbon GIS management are advancing faster than their integration. Leakage imaging, decomposition sensing, partial-discharge learning and health-index methods are often demonstrated as separate research problems. Utilities, by contrast, need an end-to-end decision chain. A detected plume is valuable only if it triggers repair; a high partial-discharge score is useful only if the defect can be verified and prioritised; a health index is useful only if it changes maintenance or renewal. Future research should therefore evaluate decision performance, not just sensor or classifier accuracy.

A second gap is the weak integration of gas recovery into smart-asset research. Leakage detection studies usually end at identification, while lifecycle studies quantify environmental impact at a higher level. Field research should measure the complete intervention balance: quantity removed, recovery losses, purification yield, refill mass and recurrence after repair. These data would allow utilities to distinguish an apparent reduction in purchased SF₆ from a real reduction in emissions.

A third gap concerns transferability to severe climates. Material compatibility, seal ageing, sensor enclosures and optical performance may behave differently under high temperatures, dust and strong solar loading. Saudi field trials should therefore test sensors and seals across representative seasonal conditions. The same principle applies to machine learning. Domain adaptation helps, but local labels from confirmed defects remain essential for credible validation.

A fourth gap is carbon-aware life extension. Existing health indices focus primarily on technical condition and failure risk [14,21,29]. Future models should add a carbon term that estimates expected SF₆ loss under continued operation and compares it with refurbishment or replacement pathways. Such a model must avoid simplistic assumptions: the lowest short-term emissions option may not be the lowest lifecycle-risk option if it preserves an unreliable asset.

Finally, the sector needs clearer evidence on alternative-gas transition at high voltage. Promising mixtures demonstrate strong dielectric and interruption performance, yet material compatibility, decomposition, toxicity, low-temperature behaviour and long-term service experience remain part of the qualification problem [1,6-8,11,16,22]. Saudi procurement should therefore remain technology-neutral but evidence demanding, rewarding verified

lifecycle performance rather than nominal gas substitution alone.

11. Limitations

This review is limited by the heterogeneity of the underlying evidence. Many studies use laboratory GIS sections, controlled defects or specific voltage classes, so reported accuracy cannot be assumed for all field installations. The literature also contains more research on partial discharge and alternative gases than on measured gas-recovery efficiency and long-term post-repair leakage. The proposed framework is therefore conceptual and requires calibration with utility data before thresholds are used for operational decisions.

The 2020-2025 window intentionally prioritises recent sensing, analytics and environmental developments but excludes earlier foundational work. Saudi-specific peer-reviewed evidence on integrated SF₆ management is limited; consequently, the Saudi implementation discussion is an engineering transfer of international evidence rather than a claim that all methods have been validated locally. Future research should publish field datasets that connect confirmed GIS defects, leakage, maintenance actions, emissions and remaining life under regional operating conditions.

A further priority is interoperability between environmental and maintenance records. Compartment identifiers, sensor timestamps, cylinder transactions and work orders should use consistent asset keys. Without this discipline, utilities may detect a leak yet fail to connect it accurately to recovery history, defect recurrence or the replacement business case.

12. CONCLUSION

Low-carbon GIS management is not a single-technology problem. For Saudi substations, the strongest strategy is to connect containment, recovery, condition sensing, predictive analytics and asset-life decisions in one governed loop. Leakage detection must lead to localisation and repair; gas handling must produce a verifiable mass balance; diagnostic models must be checked against physical evidence; and life extension must be approved only when technical risk and emissions exposure remain acceptable.

Recent research provides the components of this approach. Infrared and binocular imaging improve SF₆ leak detection [10,27]; decomposition and material studies strengthen gas-condition understanding [7,8,15,22,28]; partial-discharge and digital-twin methods improve defect diagnosis and localisation [9,12,13,17-20,24-26]; and health-index and CBRM methods translate evidence into

maintenance and renewal priorities [14,21,29]. The remaining challenge is institutional integration.

Under Vision 2030, an integrated smart-GIS programme can reduce avoidable emissions while protecting reliability and installed capital. Its maturity should be judged by measurable outcomes: fewer recurrent leaks, higher gas-recovery accountability, earlier defect detection, better targeted outages, defensible life-extension decisions and a controlled transition toward lower-impact switchgear. The central principle is simple: every environmental observation should inform asset risk, and every asset intervention should update environmental performance. That feedback relationship turns the GIS portfolio from a collection of sealed high-voltage compartments into a learning, low-carbon infrastructure system.

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