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Original Research Article

Energy-Efficient Transformation of Fuel Retail Stations in Saudi Arabia: A Strategic Framework for Vision 2030

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Abstract: Fuel retail stations in Saudi Arabia are positioned at the intersection of energy efficiency, distributed renewable energy, transport electrification, and service-sector modernization. This review develops a strategic framework for transforming conventional stations into energy-efficient mobility and service hubs aligned with Saudi Vision 2030. A structured integrative review synthesizes thirty verified peer-reviewed studies spanning Saudi energy policy, hot-climate building efficiency, photovoltaic performance, electric-vehicle charging, battery storage, and digital energy management. The synthesis indicates that transformation should follow an efficiency-first sequence: establish measured baselines, reduce avoidable cooling and auxiliary loads through weather- and season-responsive operation, deploy climate-adapted photovoltaic generation, integrate EV charging according to traffic demand and electrical hosting capacity, add storage only where it resolves a defined constraint, and coordinate assets through interoperable digital energy management. The review highlights that Saudi climatic conditions make cooling efficiency, seasonal thermostat control, photovoltaic soiling, thermal derating, and maintenance central to lifecycle performance. The framework therefore treats local weather as an operating input: during milder periods, particularly where central and eastern locations experience cooler winter conditions, convenience-retail HVAC should automatically reduce unnecessary cooling rather than continue summer-style operation. It also finds that unmanaged fast charging can create avoidable grid and transformer stress, whereas controlled charging, storage, and forecasting can improve flexibility. Two station archetypes and decision tables, together with two graphical frameworks, translate the evidence into implementation logic. Key research gaps concern station-specific benchmarks, monitored solar-canopy performance, charger utilization, battery economics, and field validation of digital controls. The paper concludes that scalable transformation requires outcome-based regulation, measurement and verification, interoperability, and staged portfolio learning rather than isolated technology deployment.

Keywords: Saudi Vision 2030; fuel retail stations; energy efficiency; photovoltaic systems; electric vehicle charging; battery energy storage; digital energy management; decarbonization; climate-responsive HVAC; seasonal energy management.

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1. INTRODUCTION

Saudi Arabia's fuel retail network sits at a strategic crossroads between the legacy hydrocarbon economy and the emerging low-carbon mobility system. Fuel stations are no longer only points for dispensing gasoline and diesel; they increasingly function as convenience-retail sites, distributed energy nodes, service hubs, and potential interfaces for electric mobility. This shift is especially relevant under Vision 2030, which links economic diversification, energy efficiency, renewable deployment, urban modernization, and transport transformation. Academic work on the Saudi transition shows that national decarbonization is not a single-technology project but a coordinated institutional process involving regulation, prices, infrastructure, investment, and consumer behavior (Alomari and Heffron, 2021; Al-Sinan *et al.,* 2023). Energy-price reforms have also strengthened the economic case for efficiency by reducing distortions that historically weakened incentives to conserve electricity and transport fuels (Aldubyan and Gasim, 2021). The station level deserves specific attention because it combines several energy-intensive functions within a compact commercial asset. Typical sites include illuminated forecourts, air-conditioned convenience stores, refrigeration, pumps, signage, compressed-air equipment, car-wash systems, offices, and increasingly electric-vehicle chargers. In Saudi Arabia's hot climate, cooling and envelope performance can materially influence electricity demand. Evidence from Saudi and Gulf buildings consistently identifies air-conditioning efficiency, thermal insulation, controls, and measured retrofit verification as central levers for reducing operational energy use (Al-Homoud and Krarti, 2021; Almasri and Alshitawi, 2022; Ahmed and Asif, 2021). A Saudi commercial retrofit case further demonstrates that auditable savings require both technical measures and post-retrofit measurement and verification rather than relying only on modeled expectations (Ahmed *et al.,* 2023). At the same time, forecourt geometry provides an opportunity for distributed solar generation.

Canopies and roof areas can host photovoltaic systems that offset daytime retail loads and support charging. Yet solar deployment in Saudi conditions is not a generic plug-and-play solution. High temperatures, dust, coastal aerosols, and cleaning requirements affect yield and lifecycle economics. Field evidence from Yanbu confirms that soiling and tilt materially influence photovoltaic output, making maintenance design a first-order operational issue rather than an afterthought (AlZahrani, 2023). These climate-specific constraints are important when translating global photovoltaic charging-station research to Saudi sites. The rise of electric vehicles creates a second transformation pathway. Saudi power-system studies indicate that EV adoption can alter load profiles and generation requirements, while charging infrastructure design affects reliability and investment needs (Almutairi, 2021; Almohaimeed, 2022; Almutairi, 2022). International research shows that photovoltaic generation, battery storage, managed charging, and real-time energy management can reduce grid stress and operating costs at charging stations (Wu *et al.,* 2020; Li *et al.,* 2020). For fuel retailers, the challenge is therefore not merely whether to install chargers, but how to integrate charging with existing electrical capacity, customer dwell time, solar resources, storage, and retail operations. The literature remains fragmented across building efficiency, renewable-energy integration, EV charging, energy policy, and transport decarbonization. Few studies treat the fuel retail station as an integrated socio-technical asset in the Saudi context. This review addresses that gap by synthesizing evidence into a strategic framework that prioritizes efficiency first, then renewable supply, flexible charging, digital energy management, and governance. The emphasis is on transformation pathways that are technically credible, commercially manageable, climate-adapted, and aligned with Vision 2030 rather than on speculative technology adoption.

2. Aim of the Study

This review aims to develop an evidence-based strategic framework for transforming fuel retail stations in Saudi Arabia into energy-efficient, low-carbon, digitally managed mobility and service hubs that support Vision 2030. The study integrates research on commercial-building efficiency, weather- and season-responsive HVAC operation, photovoltaic systems in arid climates, electric-vehicle charging, battery storage, energy management, and Saudi energy policy to identify a practical sequencing of interventions, decision criteria, and governance requirements. The review does not attempt to forecast a single national technology mix. Instead, it establishes how station operators, regulators, utilities, and investors can evaluate site-specific transformation choices while preserving safety, service reliability, and commercial viability.

3. Research Objectives

Five objectives guide the review. First, it evaluates the principal electricity-demand sources and efficiency opportunities within fuel retail stations, with particular attention to cooling, lighting, refrigeration, building envelopes, controls, and weather-responsive seasonal operation. Second, it assesses the role of photovoltaic generation, battery energy storage, and climate-adapted maintenance in reducing grid dependence and carbon intensity. Third, it examines how EV charging can be integrated into existing fuel-station assets without creating avoidable peak-demand, transformer, or reliability problems. Fourth, it identifies digital energy-management capabilities needed to coordinate loads, generation, storage, tariffs, and customer-service requirements. Fifth, it develops managerial and policy priorities, including a government-enabled seasonal operating framework for cooling setpoints, weather normalization, monitoring, and compliance, that can support scalable station transformation under Saudi Vision 2030 while recognizing differences among urban, highway, and remote sites.

4. Research Questions

The review addresses five questions. What operational measures, including weather- and season-responsive cooling controls in convenience retail, can reduce energy demand at Saudi fuel retail stations before new generation capacity is added? Which combinations of solar photovoltaic systems, battery storage, and grid supply are most defensible under hot, dusty operating conditions? How should EV charging be sized and controlled to protect distribution assets while supporting mobility growth? What data, control, and measurement architecture is required for continuous energy-performance management? Finally, which regulatory, seasonal-operating, financial, and organizational mechanisms can move station transformation from isolated projects to a repeatable national program aligned with Vision 2030?

5. REVIEW METHODOLOGY

A structured integrative review design was adopted to address a research problem spanning engineering, building science, transport, economics, and public policy. The methodological aim was to connect evidence across different system levels rather than to conduct a meta-analysis of a narrowly defined intervention. The review utilized Scopus and Web of Science journal coverage, supplemented by publisher platforms and Crossref-style DOI verification. Searches were conceptually organized around combinations of terms such as “Saudi Arabia”, “fuel station”, “petrol station”, “service station”, “energy efficiency”, “commercial building retrofit”, “photovoltaic”, “solar canopy”, “electric vehicle charging station”, “battery energy storage”, “energy management system”, “smart charging”, “transport decarbonization”, and “Vision 2030”. Backward and forward relevance checking was applied when a high-value paper identified an adjacent technical stream. Inclusion criteria prioritized peer-reviewed journal articles published primarily from 2020 to 2025, with earlier material considered only when necessary to establish a technical baseline. Studies were included if they contributed directly to at least one of five analytical domains: Saudi energy-transition governance, hot-climate commercial-building efficiency, arid-region solar performance, EV-charging planning and control, or integrated renewable-storage charging systems.

We excluded research on unrelated vehicle technologies, non-energy retail topics, purely mechanical fuel dispensing, or contexts with little transferability to hot-climate station operations. The review did not use conference papers, company announcements, news reports, or unverified consultancy claims as its evidentiary core. Screening was performed in stages by title relevance, abstract relevance, methodological usefulness, and fit with the review questions. Because the review was assembled through iterative cross-database searching rather than a single exported bibliographic dataset, no article-flow counts are reported; retrospective counts would imply a level of reproducibility not preserved during discovery. This choice avoids fabricated precision. We checked each retained source for a genuine DOI using publisher or bibliographic records. We limited the final reference set to thirty peer-reviewed works so every source could be substantively integrated rather than merely listed. Quality assessment considered five dimensions: clarity of research design, transparency of assumptions or data, appropriateness of analytical method, relevance to Saudi or comparable hot-climate conditions, and usefulness for decision-making at station level. Empirical Saudi studies received particular weight for climate, policy, and demand assumptions, while international optimization studies were used primarily to establish transferable system-design principles. The synthesis followed a thematic configuration approach. Findings were coded into demand reduction, on-site renewable supply, storage and flexibility, charging integration, digital control, economics, and governance. We interpreted contradictory findings through differences in climate, tariff structure, system boundary, load profile, and optimization objective rather than averaging them indiscriminately. The methodology has limitations. Fuel retail stations are underrepresented as a distinct building and infrastructure category in peer-reviewed Saudi literature, so evidence from commercial buildings and EV charging facilities had to be translated cautiously. Optimization studies often assume ideal forecasts, rational charging behavior, or simplified tariffs that may not hold in practice. Likewise, measured Saudi retrofit evidence remains limited compared with simulation studies. These constraints are treated as research gaps rather than concealed by numerical aggregation. Table 1 clearly summarizes the evidence domains and their station-level decision implications.

Table 1: Evidence domains and station-level decision implications.

Domain	Evidence focus	Station-level implication	Illustrative KPI
Demand reduction	Cooling, envelope, lighting, refrigeration, commissioning, weather-responsive controls	Reduce avoidable load before sizing generation or storage; reset cooling operation to actual outdoor conditions and season	kWh/site; kWh/m^2; peak kW; weather-normalized kWh; cooling runtime; verified savings
On-site PV	Canopy/roof generation; arid-climate soiling and thermal effects	Size to revised daytime load; design cleaning and monitoring	PV yield; self-consumption; availability; cleaning intensity
EV charging	Variable high-power load; utilization and grid-hosting constraints	Match charger mix to dwell time, traffic, and connection capacity	Sessions/day; kWh/session; uptime; coincident peak
Storage/flexibility	Peak shaving, renewable smoothing, resilience	Deploy only against quantified operational/economic constraint	Peak reduction; cycles; round-trip efficiency; avoided upgrades
Digital M&V	Forecasting, submetering, coordinated control	Use interoperable data for verification, fault detection, optimization	Data completeness; fault response; baseline variance
Governance	Safety, interconnection, standards, finance, seasonal operating requirements	Standardize interfaces while allowing site-specific engineering and climate-zone operating rules	Approval time; compliance; weather-normalized performance; verified portfolio outcomes

6. Thematic Literature Review and Critical Analysis

6.1 Efficiency first: reducing the station's underlying load

The strongest cross-cutting finding is that demand reduction should precede renewable oversizing. Saudi building research shows that cooling dominates electricity use in many building types and that envelope and equipment improvements can materially reduce required electrical capacity (Al-Homoud and Krarti, 2021; Al-Tamimi, 2022). Gulf-wide evidence similarly prioritizes efficient air-conditioning and thermal insulation (Almasri and Alshitawi, 2022). Although a fuel station convenience store is smaller than an office or residence, it often operates long hours, has frequent door openings, refrigeration loads, high lighting levels, and exposed glazing. This makes operational controls, high-efficiency packaged cooling, calibrated thermostat schedules, door management, LED lighting, efficient refrigeration, and shading highly relevant. Thermal-comfort research in the Middle East also cautions against overcooling based on imported comfort assumptions. Elnaklah *et al.,* (2021) found that conventional comfort models can poorly reflect regional occupant responses, implying that setpoint policies should be evidence-based rather than automatically conservative. For station operators, this supports a commissioning approach: measure indoor temperature, humidity, occupancy, and equipment duty cycles, then tune controls without degrading customer experience. The most important management principle is to verify savings. Ahmed *et al.,* (2023) demonstrate the value of measurement and verification in a Saudi commercial retrofit, while Ahmed and Asif (2021) identify limited post-retrofit verification as a persistent weakness in GCC research. Consequently, any station retrofit program should build in submetering and baseline normalization. A further operational issue is the persistence of fixed cooling practices across seasons. Convenience-retail operators may continue low thermostat setpoints and high cooling duty even when outdoor conditions become materially milder, which can preserve avoidable electricity consumption during winter and shoulder periods. This is especially relevant for portfolios spanning central and eastern regions, where seasonal conditions can provide meaningful opportunities to reduce compressor runtime while maintaining acceptable indoor comfort. A climate-responsive operating model should therefore link thermostat setpoints, operating schedules, ventilation, door management, and equipment staging to measured outdoor temperature and humidity rather than to a year-round fixed setting. Site performance should also be weather-normalized so that managers can distinguish genuine efficiency improvement from changes caused simply by a cooler or hotter season. At policy level, a national framework could require or incentivize regional seasonal HVAC operating plans for convenience-retail premises, including minimum control capabilities, approved comfort bands, automatic setpoint reset, submetered cooling data, and documented exceptions for food safety, humidity control, or other operational needs. The intent would not be to compromise comfort or product protection, but to prevent unnecessary cooling when weather conditions permit lower energy use.

6.2 Solar photovoltaic systems as an operational asset.

Saudi Arabia's renewable-energy trajectory and solar resource make on-site photovoltaics an obvious component of station transformation. Still, the business case depends on site geometry and operating discipline, not resource abundance alone. Al-Gahtani (2024) situates solar expansion within the broader national energy transition, while Al-Sinan *et al.,* (2023) emphasize the need to connect renewable deployment with credible pathways toward long-term emissions reduction. Fuel-station canopies are attractive because they can generate electricity without competing with retail floor area and may provide additional shading benefits. However, PV yield in arid conditions is sensitive to soiling. AlZahrani's (2023) two-year Yanbu study shows that module technology, tilt, dust, and local environmental conditions materially affect output. Therefore, transformed stations should treat cleaning frequency, water use, access design, and performance monitoring as part of the energy system. A nominally large array that is poorly maintained may underperform a smaller, well-monitored system. This consideration is especially important for distributed portfolios because hundreds of small sites can create hidden maintenance liabilities.

6.3 EV charging, storage, and grid interaction.

EV charging introduces a new load whose timing and power are more variable than most legacy station loads. Saudi studies show that EV deployment can affect generation adequacy and that infrastructure configurations influence service reliability (Almutairi, 2021; Almutairi, 2022). Almohaimeed (2022) argues that EV integration requires coordinated planning with the Saudi electric power system rather than treating charging as an isolated transport service. For retailers, this implies that charger counts should not be based on marketing targets alone. It should follow an electrical hosting-capacity assessment, expected dwell time, traffic profile, utilization forecast, and upgrade cost. International station research offers useful operating principles. Li *et al.,* (2020) show that renewable generation, storage, and scheduled charging can be coordinated to manage congestion and uncertainty. Datta *et al.,* (2020) demonstrate that battery storage can reduce transformer overloading while smoothing photovoltaic output. Nishimwe and Yoon (2021) link charging-station planning with operational scheduling, showing that capacity decisions and daily dispatch should be solved together rather than sequentially. Shafiei and Ghasemi-Marzbali (2023) further show how renewable uncertainty, demand response, and storage can be incorporated into fast-charging design. These models differ in assumptions and market structures. Still, they converge on one conclusion: unmanaged high-power charging can create avoidable infrastructure costs, whereas flexible charging and storage can convert part of that risk into controllable demand. Photovoltaic-assisted charging also changes the value of daytime energy. Kouka *et al.,* (2020) coordinate PV, storage, and EV charging according to vehicle requirements, while Wu *et al.,* (2020) use a Markov decision process to respond to uncertain user behavior. Cabrera-Tobar *et al.,* (2022) demonstrate real-time model-predictive control under uncertainty in PV output, battery state, price, EV demand, and emissions. These approaches are more sophisticated than most current retail energy systems, yet they identify a practical digital roadmap: forecast, measure, optimize, and revise continuously. A station does not need an advanced research controller on day one, but it should avoid installing disconnected chargers, PV inverters, and batteries that cannot exchange data.

6.4 Portfolio economics and location differentiation.

Not every Saudi fuel station should receive the same package. Urban sites may have stronger convenience retail, shorter dwell times, high charger utilization potential, and constrained electrical capacity. Highway stations may need fewer but higher-power chargers, larger waiting areas, stronger reliability provisions, and potentially more storage to reduce demand spikes. Remote stations may prioritize energy resilience, on-site solar, efficient cooling, and communications before large charging investments. Table 2 differentiates recommended priorities across urban, highway, and remote station archetypes. This differentiation is consistent with charging-infrastructure research showing that location, user behavior, network constraints, and pricing jointly determine system value. Luo *et al.,* (2020) demonstrate that charging and photovoltaic infrastructure planning should consider transport and power networks together rather than as separate assets. Economic evaluation should therefore move beyond simple payback. It should include avoided electricity consumption, demand-related costs where applicable, transformer or connection upgrades, maintenance, charger utilization, battery degradation, lost sales during outages, and additional retail revenue associated with customer dwell time. Minh *et al.,* (2021) show that solar-powered charging economics vary with irradiation and system configuration, while Rehman *et al.,* (2023) connect load management with economic and environmental outcomes. These findings support scenario-based portfolio appraisal rather than a single national template. In addition to urban, highway, and remote archetypes, portfolio planning should apply a climate-region overlay. Stations with similar commercial formats can have different seasonal cooling opportunities depending on local temperature and humidity patterns. Central and eastern portfolios, for example, should be assessed for winter and shoulder-season HVAC reset potential rather than being operated under a uniform summer cooling logic throughout the year. This climate overlay should influence energy baselines, retrofit priorities, operating schedules, and expected savings.

Table 2: Station archetypes and differentiated transformation priorities.

Archetype	Typical context	PV priority	EV charging approach	Storage rationale	Management focus
Urban	High retail load; constrained sites; frequent short visits	Medium–high; canopy/roof constrained by geometry	Destination/fast mix; utilization-led expansion	Targeted for peak control or connection deferral	Customer dwell, charger uptime, retail conversion
Highway	Large forecourt; long-distance travel; high service criticality	High where land/canopy allows	Fewer high-power chargers; redundancy important	Potentially valuable for peak smoothing/resilience	Power availability, queueing, reliability, amenities
Remote/peripheral	Lower traffic; possible grid limitations; resilience priority	Often high resource potential	Modular deployment tied to observed demand	Case-dependent; stronger resilience rationale	Energy autonomy, remote diagnostics, maintenance logistics

6.5 Digital energy management and performance governance.

The transformed station should be managed as a small multi-energy system. At minimum, this requires interval metering for grid import, PV output, EV charging, convenience-store demand, major cooling loads, and battery flows. The management layer should identify abnormal consumption, compare similar sites, forecast peaks, schedule flexible assets, and provide auditable energy and emissions indicators. Hao *et al.,* (2020) demonstrate the value of forecasting for coordinating photovoltaic generation and charging, while Cabrera-Tobar *et al.,* (2022) show how explicit control laws can respond quickly to uncertainty. Digitalization is therefore not a decorative “smart station” feature; it is the mechanism that converts installed hardware into sustained performance. Cybersecurity, interoperability, and data ownership should be addressed from procurement. Retailers can become locked into proprietary charger or inverter platforms that fragment data and increase lifecycle costs. Open communication protocols, exportable interval data, clear asset identifiers, remote diagnostics, and performance-service requirements can reduce this risk. The objective is a practical digital architecture supporting verification and portfolio benchmarking. The same digital layer should ingest basic weather variables and use them in cooling control and performance analysis. Outdoor temperature and humidity, indoor conditions, HVAC runtime, and convenience-store electricity should be trended together so that fixed-setpoint operation during mild weather can be identified and corrected. Weather-normalized benchmarks would also allow fair comparison among stations in different Saudi regions and across seasons.

6.6 Resilience, safety, and climate adaptation.

Energy efficiency cannot be separated from operational resilience at sites that handle combustible fuels, electrical equipment, and high customer turnover. Add new electrical assets through disciplined zoning, protection coordination, ventilation, fire-safety review, and emergency-isolation design. Batteries and chargers introduce heat rejection, power-electronics, and fault-management requirements that differ from conventional station equipment. In the Saudi climate, outdoor electrical enclosures, cables, connectors, cooling systems, and communication equipment must be selected for high ambient temperatures, dust ingress, and solar exposure. Resilience planning should therefore evaluate not only annual energy savings but also equipment derating, charger availability, inverter trips, battery thermal management, and recovery after grid interruptions (Alsharif *et al.,* 2021). A useful distinction is between efficiency resilience and supply resilience. Efficiency resilience reduces the load that must be served during stress, while supply resilience concerns the ability of PV, storage, backup systems, and the grid connection to maintain critical functions. These objectives can reinforce one another. A highly efficient convenience store requires less backup capacity, and a well-controlled charger can curtail noncritical demand during constrained periods. Conversely, oversized batteries used only for rare outages may be uneconomic. The appropriate design depends on the critical-load definition, outage exposure, customer-service requirements, and the cost of unavailable retail operations.

6.7 From individual assets to a repeatable transformation framework.

The literature indicates that the central management problem is integration across technologies with different lifetimes and decision rules. Building measures are often evaluated through energy audits; PV through yield and lifecycle cost; charging through utilization and power capacity; and batteries through cycling economics. A station program needs a common decision framework that compares these interventions using shared metrics. Recommended metrics include annual grid electricity reduction, peak-demand reduction, verified renewable generation, charging-service availability, lifecycle cost, avoided network upgrades, emissions reduction, and operational complexity. The framework should also recognize option value. Conduits, switchgear space, spare communication ports, structural allowance for PV, and modular charger foundations can make later expansion cheaper even when immediate installation is not justified. This matters in a rapidly changing mobility market. Designing for expandability allows operators to respond to EV uptake without prematurely committing to full-scale charging capacity. Similarly, a digital platform that initially monitors electricity can later coordinate storage, chargers, refrigeration, and utility signals.

7. DISCUSSION

The synthesis suggests that the most defensible transformation pathway is sequential rather than technology-led. First, establish a measured energy baseline and remove avoidable demand. Second, add on-site renewable generation sized against the revised load profile. Third, introduce EV charging according to traffic demand and electrical hosting capacity. Fourth, use batteries and managed charging where they solve a defined constraint such as peak demand, limited connection capacity, resilience, or renewable self-consumption. Fifth, connect all assets through a digital energy-management layer and verify performance over time. This order prevents the common error of using capital-intensive generation or storage to compensate for inefficient loads. The framework also reframes the station's business role. Under a petroleum-only model, throughput centers on rapid refueling. Under a mixed-mobility model, charging can increase dwell time, which changes the economics of convenience retail, food service, seating, shade, and digital customer services. Energy strategy and retail strategy therefore become interdependent. Charger utilization affects electrical economics, while the quality of the customer environment affects whether longer dwell time creates additional revenue. Saudi policy conditions strengthen the case for integrated action. Energy-price reform improves the signal for efficiency, while Vision 2030 and net-zero-oriented policy create a broader rationale for renewable and transport transformation (Aldubyan and Gasim, 2021; Alomari and Heffron, 2021). Yet policy effectiveness depends on coordination. Alajmi (2021) identifies energy consumption as a major driver of Saudi emissions, and Shannak *et al.,* (2024) show that transport emissions respond only modestly to fuel-price reform. This means that price signals alone are insufficient. Infrastructure, technology standards, investment mechanisms, and operating capabilities must move together. The strategic framework therefore has five layers: efficient demand, clean on-site supply, flexible mobility load, digital coordination, and enabling governance. Figure 1 visualizes this staged transformation logic and its feedback structure. Each layer has a different decision horizon. LEDs, controls, and commissioning can be rapid; envelope retrofits and electrical upgrades require capital planning; PV and storage need lifecycle maintenance; EV charging needs utilization growth; and regulation must provide consistency across many assets. Treating all measures as one "green station" project obscures these different risk profiles. A staged portfolio program lets quick savings finance later investments and builds operational evidence before full-scale rollout. A further implication concerns transition timing. Operators should distinguish measures that are mature and broadly applicable from measures whose value depends on future demand. Efficient lighting, cooling controls, refrigeration maintenance, submetering, and basic photovoltaic feasibility are low-regret actions because they improve current operations. High-power charging, large batteries, and complex market-responsive controls are more contingent on vehicle adoption, tariffs, network capacity, and service strategy. Portfolio governance should therefore use stage gates: diagnose, pilot, verify, standardize, and scale. Figure 2 converts the framework into a stage-gated implementation roadmap. Each gate should specify evidence required before capital advances to the next stage. This staged approach also improves organizational learning. A small group of representative pilot stations can reveal climate-related equipment failures, cleaning costs, charger utilization, customer dwell patterns, and data-integration problems that desktop models cannot fully anticipate. Results should then be translated into standard designs with controlled variants for different station archetypes. This learning reduces procurement fragmentation and lets technical specifications evolve from measured performance. Finally, evaluate transformation against counterfactual performance. Reporting renewable capacity alone can obscure simultaneous load growth from refrigeration, expanded retail, or EV charging. Managers should track normalized energy intensity, peak demand, renewable contribution, and service output together. This prevents a station from appearing greener merely because it installed visible technology while its underlying energy productivity deteriorated. Outcome-based evaluation is therefore essential to align commercial modernization with genuine Vision 2030 energy-efficiency objectives. It also creates a stronger evidence base for regulators, utilities, and investors. Climate-responsive retail operation should be treated as part of the efficiency-first stage rather than as a secondary optimization. Before sizing PV, storage, or new electrical capacity, operators should test whether seasonal thermostat reset and weather-linked HVAC schedules can reduce the convenience-store base load. A national rollout would be stronger if government guidance translated this principle into regionally differentiated seasonal requirements and reporting rules, supported by measured indoor comfort and weather-normalized energy data.

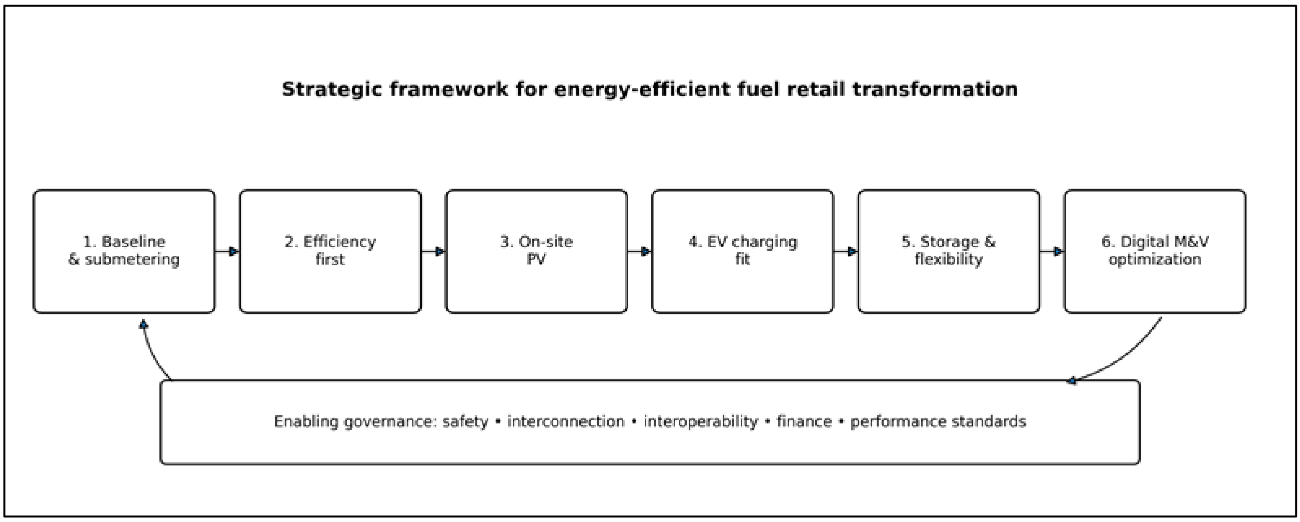

Figure 1: Strategic framework for energy-efficient fuel retail transformation

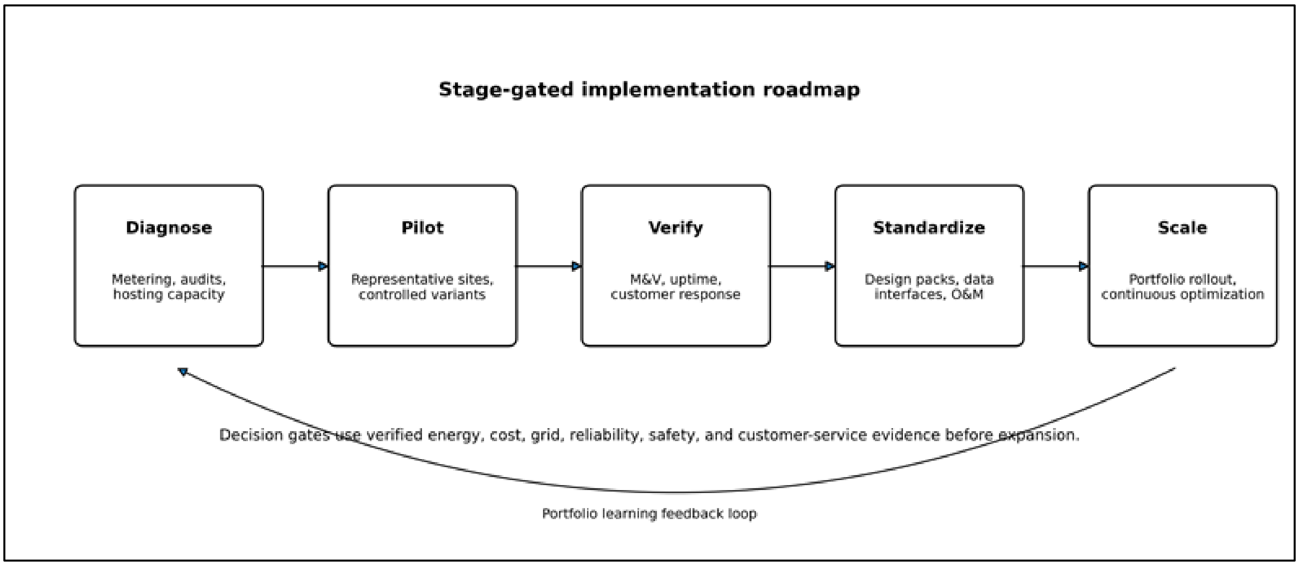

Figure 2: Stage-gated implementation roadmap for portfolio transformation

8. Research Gaps and Future Research

The first gap is the absence of station-specific Saudi energy benchmarks. Future studies should collect hourly end-use data across representative urban, highway, and remote stations, separating cooling, lighting, refrigeration, pumps, signage, car wash, EV charging, and ancillary services. Without such benchmarks, retrofit design relies too heavily on evidence from other commercial buildings. The second gap is limited field evidence on PV canopy performance at retail sites under Saudi dust, heat, cleaning, shading, and safety constraints. Longitudinal studies should combine energy yield, cleaning cost, water consumption, degradation, and maintenance downtime. Third, EV charging research needs a closer link to actual fuel-retail traffic and dwell-time patterns. Saudi studies should model charger utilization using observed station arrivals rather than generic mobility assumptions and should test how charging affects retail spending, queueing, parking, and customer satisfaction. Fourth, battery economics need site-specific investigation under realistic degradation, ambient temperature, warranty, and utility-connection conditions. Fifth, digital energy-management research should move from simulation to monitored pilots that compare rule-based control, predictive optimization, and simpler tariff-responsive strategies. A final gap concerns governance. Research should examine which combinations of minimum energy-performance requirements, charger-readiness rules, solar-ready design, financing, portfolio disclosure, and utility interconnection procedures create the lowest transaction cost for operators. Riyadh transport modeling illustrates the importance of linking transport-energy demand with urban policy (Oakil *et al.,* 2022). Future station studies should similarly connect local mobility patterns, distribution-network capacity, land use, and commercial service models rather than optimizing a station in isolation. A further research gap is the lack of station-level evidence on seasonal cooling behavior. Future field studies should compare fixed thermostat operation with weather-responsive controls across Saudi climate regions, especially during winter and shoulder periods, and quantify impacts on electricity use, indoor comfort, humidity, refrigeration interaction, and equipment cycling. This evidence would support defensible regional thresholds and seasonal operating requirements rather than relying on a single national thermostat assumption.

9. Practical, Managerial, and Policy Implications

For station operators, the immediate priority is to create a portfolio energy register that includes site type, floor area, operating hours, monthly electricity use, peak demand (where available), major equipment, electrical connection capacity, roof and canopy area, and charger status. No-cost controls, low-cost retrofits, PV suitability, electrical constraints, and mobility demand can then rank sites. Procurement should require measurable performance outcomes, not simply equipment specifications. Energy service contracts should define baselines, data access, commissioning, maintenance response, and verification procedures. For managers, link investment gates to evidence. A station should not receive battery storage merely because storage is strategically attractive; the asset should solve a quantified peak, resilience, renewable-curtailment, or connection problem. Likewise, fast charging should follow utilization and capacity studies. Where chargers are initially underused, modular electrical design can preserve expansion options without locking capital into oversized equipment. Maintenance teams need capabilities in PV cleaning, inverter diagnostics, charger uptime, thermal management, and data quality because operational discipline determines whether modeled benefits persist. For policymakers and utilities, harmonized technical requirements can reduce project friction. Standardized interconnection processes, charger interoperability, metering rules, safety requirements, and transparent connection-capacity information would make investment more predictable. Building and station codes can encourage efficient cooling, solar-ready canopies, and EV-ready electrical pathways in new sites while allowing retrofit flexibility for existing stations. Policy should also distinguish between urban and corridor needs rather than imposing uniform charger configurations. Finally, national progress should be evaluated through outcome indicators such as energy intensity, verified savings, renewable self-consumption, charger uptime, peak-load reduction, and emissions intensity per service unit. These indicators are more informative than counting installed panels or chargers. The Saudi transition literature stresses integrated governance and implementation capacity (Alomari and Heffron, 2021; Al-Gahtani, 2024). Fuel retail transformation can operationalize that principle across national portfolios. Weather and seasonality should also be embedded explicitly in operating governance. For convenience-retail areas, operators should maintain region-specific seasonal HVAC schedules, reset thermostat targets when outdoor conditions are favorable, and use automatic controls that prevent cooling systems from continuing at summer intensity during mild periods. Government and utility bodies could support this through a sustainable-operations framework with four elements: published climate-zone guidance for seasonal cooling operation; minimum requirements for programmable or networked thermostat control in new and substantially refurbished sites; weather-normalized energy-performance reporting for larger fuel-retail portfolios; and periodic verification that cooling schedules, setpoints, sensors, and overrides are functioning as intended. Requirements should preserve indoor comfort, food safety, humidity control, and equipment reliability, while allowing documented site-level exceptions. Such a framework would convert favorable seasonal weather into a measurable efficiency resource rather than leaving savings dependent on voluntary operator behavior.

10. Limitations

The scarcity of peer-reviewed studies limits this review, which focuses specifically on Saudi fuel retail stations. The review therefore used evidence from residential and commercial buildings, EV charging stations, and international microgrids where the underlying engineering mechanism was transferable. The review does not estimate national investment requirements, carbon savings, or charger demand because the reviewed literature did not provide reliable station-level datasets. It also does not rank individual fuel retailers or technologies. Finally, optimization studies frequently rely on assumptions about tariffs, forecasts, user behavior, and storage degradation that may differ from Saudi operating conditions. The proposed framework should therefore be treated as a structured decision architecture to be validated through field pilots, not as a substitute for site engineering or financial due diligence.

11. CONCLUSION

Transforming Saudi fuel retail stations for Vision 2030 requires more than adding solar panels or EV chargers to conventional forecourts. The evidence supports an integrated pathway in which energy efficiency establishes a lower demand base, photovoltaic generation supplies part of the remaining daytime load, storage and managed charging provide flexibility where justified, and digital energy management sustains performance through measurement and control. Saudi building studies underline the importance of cooling efficiency, envelopes, commissioning, and verified retrofits, while Saudi EV research shows that charging expansion must be coordinated with the power system. International charging-station studies reinforce the value of joint planning across PV, storage, charging, and grid capacity. The proposed strategic framework is deliberately staged. It starts with metering and demand reduction, progresses to site-specific renewable generation, adds mobility services according to traffic and hosting capacity, and introduces storage only when a defined operational or economic constraint exists. A common digital architecture links these layers and enables portfolio-level learning. This sequencing reduces overinvestment risk, improves auditability, and allows different station archetypes to follow different transition pathways. For policymakers, the key requirement is an enabling environment that combines efficient building standards, predictable interconnection, interoperable charging, data transparency, and outcome-based performance indicators. For operators, the central capability is lifecycle energy management rather than one-time equipment procurement. The most successful future station will therefore be neither a traditional fuel outlet nor a technology showcase. It will be a measured, efficient, flexible, and commercially resilient mobility-energy hub, with investment decisions grounded in local demand, climate conditions, grid constraints, and customer value. Such a model can turn a mature retail asset class into a practical implementation platform for Saudi Arabia's broader energy and mobility transition. Portfolio reporting should separate efficiency gains from demand growth caused by new mobility services, ensuring that lower carbon intensity does not conceal rising absolute consumption. This distinction will help operators compare sites, prioritize investment, and demonstrate credible progress to regulators and investors. This sequencing protects service continuity, strengthens investment discipline, and creates measurable evidence for subsequent portfolio-scale decisions. The framework should also recognize weather as an active operating variable. In convenience retail, seasonal cooling practices can materially affect electricity demand; therefore, fixed year-round thermostat strategies should be replaced by climate-responsive controls where outdoor conditions permit. A government-supported, regionally differentiated framework for seasonal setpoints, automated HVAC reset, submetering, and weather-normalized verification would strengthen sustainable operations and make efficiency gains more consistent across national fuel-retail portfolios.

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