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Conceptual Framework for Sustainable Gas Processing and Dehydration Efficiency in Offshore Facilities

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Abstract
Offshore gas processing and dehydration must deliver high reliability, low emissions, and cost effectiveness under harsh, variable conditions. This paper proposes a conceptual framework that integrates thermodynamic analysis, process intensification, digital monitoring, and sustainability assessment to optimize dehydration efficiency in offshore facilities handling associated and non-associated gas streams. The framework links multi-scale energy and exergy evaluation with equipment selection, heat recovery, control strategy design, and lifecycle decision making. Core elements include: (1) a digital twin that fuses first-principles models with data-driven surrogates for rapid scenario testing; (2) a decision matrix for selecting between triethylene glycol, molecular sieves, membranes, or hybrid layouts based on dew-point targets, footprint, energy intensity, corrosion risk, and hydrate propensity; (3) an exergy-based heat-integration plan that recovers waste heat from compression and power generation; and (4) reliability-centered maintenance informed by condition monitoring and failure-mode analysis. Methodologically, the framework applies pinch and exergy analyses to quantify avoidable losses, Monte Carlo propagation to treat metocean-driven feed variability, and multi-criteria decision analysis to balance efficiency, operability, safety, and environmental impacts. A cyber-physical layer enables closed-loop optimization using soft sensors and model predictive control to stabilize regenerator duty, lean-solvent purity, adsorber cycling, and membrane stage cuts under turndown, slugging, and fluids compositional shifts. Sustainability is embedded through lifecycle KPIs, including water-removal efficiency, specific energy consumption, methane and CO_2 intensity, solvent make-up, corrosion index, and hydrate-incident frequency. These indicators aggregate into a Dehydration Sustainability Index that supports explicit trade-offs across technical, economic, and ESG dimensions. Implementation proceeds via baseline auditing and data cleansing; model calibration and uncertainty quantification; KPI benchmarking against best available techniques; pilot trials of heat recovery and hybrid units; and phased roll-out with operator training, cybersecurity, and governance. Expected outcomes include 10–25% energy reduction from heat recovery and advanced control, 30–50% solvent-loss reduction via optimized regeneration and mist elimination, fewer hydrate-related upsets, and verifiable cuts in venting and flaring, subject to site constraints. The framework is adaptable to brownfield tie-backs and greenfield topsides, and scalable across asset classes. By aligning rigorous thermodynamics with pragmatic operability and sustainability metrics, it enables resilient, low-carbon, high-efficiency offshore dehydration and gas processing.

Keywords: Offshore Gas Processing, Dehydration Efficiency, Thermodynamics, Exergy, Digital Twin, Heat Integration, Model Predictive Control, Sustainability Metrics

1. Introduction

Offshore gas processing operates under acute constraints limited footprint, harsh metocean variability, stringent emissions targets, and high reliability demands making dehydration a pivotal function for flow assurance, corrosion control, and product specification. Persistent challenges such as hydrate formation, solvent losses, energy-intensive regeneration, and frequent turndown conditions underscore the need for a coherent approach that unites thermodynamics, advanced control, reliability engineering, and sustainability metrics. This introduction presents a conceptual framework to align dehydration efficiency with broader environmental and operational goals in offshore facilities (Asata, Nyangoma & Okolo, 2020, Bukhari, *et al*., 2020, Essien, *et al*., 2020).

The objective is to develop an integrated decision and optimization framework that improves water removal at minimum energy and emissions cost while maintaining safety, uptime, and product quality. Specifically, the framework seeks to quantify avoidable losses via energy–exergy analysis; rationalize technology choices among triethylene glycol, molecular sieves, membranes, and hybrid trains; embed model predictive control and soft sensing for dynamic stability; and define lifecycle indicators that transparently balance technical performance with ESG requirements. The scope spans greenfield and brownfield topsides handling associated and non-associated gas, covering steady-state and transient operations, including slugging, turndown, and compositional shifts (Abass, Balogun & Didi, 2020, Amatare & Ojo, 2020, Imediegwu & Elebe, 2020).

The research questions guiding this work are: How can multi-scale thermodynamic insight be translated into actionable dehydration setpoints and heat-integration schemes under offshore constraints? Which technology or hybrid configurations deliver superior dew-point control per unit energy, mass, and space at varying feed compositions and pressures? What digital and control architectures best stabilize regenerator duty, lean-solvent quality, and adsorber cycling in the presence of uncertainty? Which sustainability key performance indicators credibly capture trade-offs among energy use, solvent make-up, methane and CO_2 intensity, hydrate-incident frequency, and corrosion risk, and how should they be aggregated for governance?

Sustainability and dehydration efficiency are jointly motivated by regulatory pressure to reduce flaring and venting, escalating fuel and carbon costs, and the operational risk of hydrate-induced outages. By integrating rigorous thermodynamics with process intensification, digital twins, and reliability-centered maintenance, the proposed framework enables verifiable reductions in energy consumption and emissions while enhancing resilience and operability. The anticipated contribution is a practical blueprint that connects model-based diagnostics to real-time decisions, accelerating continuous improvement in offshore gas processing (Adesanya, *et al*., 2020, Oziri, Seyi-Lande & Arowogbadamu, 2020).

2. Methodology

The study adopts a mixed, systems-engineering methodology that blends thermodynamic/exergy analysis, multi-criteria decision analytics, and digitally enabled operations borrowing predictive-analytics, dashboarding, and risk-governance patterns from the cited business/analytics frameworks. First, an offshore context pack is assembled from PVT assays (H_2S/CO_2/water), metocean and power-availability profiles, space/weight limits, corrosion and hydrate histories, and on-board sensor streams (T, P, flow, dew point). These data are fused in a digital-twin historian with soft sensors for water content and lean-TEG estimation, adopting data-quality checks and reconciliation routines akin to CRM/finance analytics pipelines to ensure trustworthy inputs. Second, an energy/exergy and pinch study quantifies avoidable losses across contactors, regenerators, reboilers, compressors, and coolers; compression heat recovery and cold-utility targets are screened to size heat-integration options and to compute dew-point control margins. In parallel, a reliability baseline (RCM/FMEA) ranks critical equipment and single-point failures, integrating "zero-trust" style safeguards for alarms, trips, and bypasses in line with cyber-reliability patterns from resilient multi-cloud literature. Third, dehydration technology pathways are compared: conventional TEG trains (circulation, lean loading, flash/strip gas), molecular sieves (isotherms, bed sizing, regeneration strategy), membranes, and hybrids. A multi-criteria decision matrix evaluates alternatives against energy intensity, footprint/weight, operability and safety, CAPEX/OPEX, hydrate and corrosion exposure, solvent losses, and emissions/fugitive risks; weights are set with stakeholder workshops and subjected to sensitivity checks as in portfolio governance works. Fourth, an optimization engine builds Pareto fronts (efficiency–emissions–cost) with operational constraints (ramp limits, protection logic, campaign windows), stress-testing metocean extremes and feed variability. The selected option is translated into execution via model predictive control that coordinates dew-point targets, anti-surge protection, recycle valves, and regenerator duty while respecting constraints; standard operating playbooks for start-up, upset, and energy-aware shutdown are codified, and a condition-based maintenance plan addresses solvent quality, sieve bed integrity, foaming, and corrosion.

Fifth, measurement and verification instantiate sustainability KPIs: specific energy (kWh/MSm^3), glycol loss (kg/MSm^3), CH_4/CO_2 intensity, venting/flaring rate, hydrate incident frequency, and corrosion index. A dashboard patterned after performance dashboards and revenue-assurance architectures presents near-real-time KPIs, CUSUM drift, and control limit breaches, with automated triggers for retraining soft sensors, re-weighting the decision matrix, or updating MPC constraints. Governance aligns with ESG and safety compliance, adds audit trails and management-of-change gates, and schedules quarterly lessons-learned reviews. Throughout, predictive analytics from the marketing/finance sources inform anomaly detection (e.g., unexpected solvent-loss spikes), segmentation (duty-cycle clustering across sea states), and campaign planning, while digital-twin practices from supply-chain twin literature guide versioning and scenario libraries. The loop closes with continuous improvement: KPI deltas and events feed back into the thermodynamics, reliability model, and controller tuning, sustaining dehydration efficiency within offshore constraints.

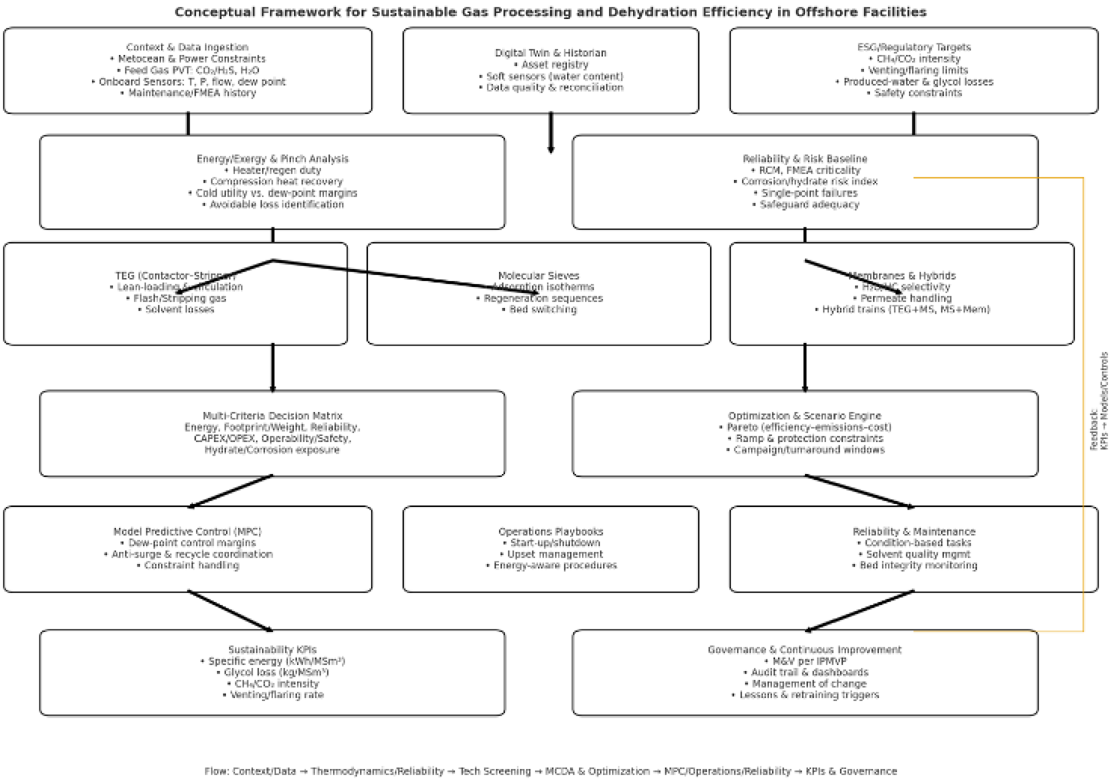

Fig 1: Flowchart of the study methodology

3. Offshore Context and Challenges

Offshore gas processing unfolds in a uniquely constrained environment where the sea and atmosphere impose forces that land-based plants rarely confront. Meteocean variability an interplay of wind, waves, currents, temperature, and humidity drives platform motions that influence separation efficiency, heat transfer, and the mechanical integrity of columns and piping. Heave, roll, and pitch modulate liquid residence times in separators, aggravate foaming in contactors, and destabilize control loops tuned for steady conditions. Wave-induced vibration and vortex shedding can excite structural modes, affecting instrument readings and leading to nuisance trips when alarms are set without motion-aware deadbands. Seasonal changes in seawater temperature shift cooling duties, altering dew-point margins and solvent regeneration demands; tropical cyclones and winter storms compress maintenance windows and force pre-emptive shutdowns that must be executed without compromising hydrate safety or corrosion control. Marine growth and biofouling progressively reduce heat-exchanger performance, elevating approach temperatures and power consumption for compression and dehydration (Akinrinoye, *et al*. 2015, Bukhari, *et al*., 2019, Erigha, *et al*., 2019).

Space and weight limits define the geometry of every process choice offshore. Topsides modules are bounded by crane capacities, deck loading, center of gravity constraints, and blast and fire zoning, forcing designers to favor compact, low-mass equipment and to trade thermodynamic ideality for footprint. Triethylene glycol contactors compete with molecular sieve vessels and membrane skids not only on energy and operability but also on diameter, height, and dry weight metrics. Column internals must be selected with anti-motion performance in mind; structured packing may offer lower pressure drop and height but demands robust liquid distribution tolerant to tilt and sloshing (Adesanya, *et al*., 2020, Seyi-Lande, Arowogbadamu & Oziri, 2020). Adsorber beds must resist settling and channeling under vibration. MEG regeneration and reclamation units, attractive for hydrate management, introduce thermal and solids-handling equipment with significant mass and layout implications. Every additional exchanger or knockout vessel exacts penalties in weight, structural reinforcement, and escape-route congestion; redundancy philosophies (N+1) are therefore calibrated carefully to reliability targets rather than replicated wholesale from onshore practice.

Hydrate risk is an omnipresent threat in wet-gas systems exposed to high pressures and low temperatures typical of subsea tiebacks and risers. The hydrate equilibrium curve often intersects normal operating envelopes during start-up, ramp-down, or unexpected pressure drops across restrictions, valves, and coolers. Dehydration is the primary structural mitigation, but offshore lines frequently still require kinetic inhibitors or thermodynamic agents, particularly during transients. Methanol and MEG injection strategies must be harmonized with dehydration trains to prevent solvent contamination, foaming, and increased reboiler duty (Asata, Nyangoma & Okolo, 2020, Essien, *et al*., 2020, Imediegwu & Elebe, 2020).

Slugging from terrain-induced accumulations or transient operations can overwhelm contactors, dilute lean solvent, and entrain liquids into compressors, compounding hydrate hazard downstream. The control philosophy must coordinate anti-surge, temperature control, and inhibitor dosing to maintain a safe distance from hydrate onset while minimizing chemical consumption and energy use. Because ambient seawater often provides the cold sink, sudden drops in seawater temperature can reduce overhead temperatures enough to push water content toward specification limits unless regenerator duty and reflux are adjusted rapidly. Figure 2 shows simplified scheme of the FPSO processes presented by Sánchez & de Oliveira Junior, 2015.

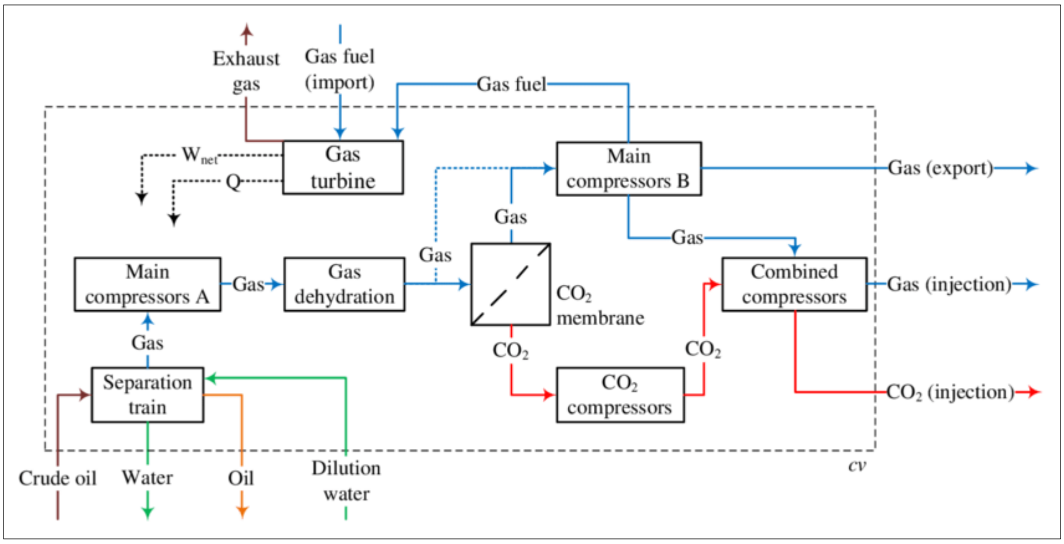

Fig 2: Simplified scheme of the FPSO processes (Sánchez & de Oliveira Junior, 2015).

Corrosion challenges in offshore gas processing arise from carbon dioxide, hydrogen sulfide, liquid water, organic acids, oxygen ingress, and microbially influenced mechanisms. CO_2 corrosion (sweet corrosion) produces carbonic acid, and the protective $FeCO_3$ films that sometimes form can be unstable under high shear or temperature fluctuations, leading to localized attacks. H_2S introduces sour corrosion, sulfide stress cracking, and hydrogen-induced cracking risks that demand careful materials selection, hardness control, and inhibition programs. Chloride-rich seawater used in cooling systems exacerbates pitting and crevice corrosion, and under-deposit corrosion can flourish where solids and biofilms accumulate. Oxygen ingress during start-up or maintenance aerates systems and accelerates corrosion of carbon steel, while amine- or glycol-rich environments can enable degradation pathways that generate heat-stable salts, elevate corrosion rates, and impair solvent quality (Ajayi, *et al*., 2018, Bukhari, *et al*., 2018, Essien, *et al*., 2019). Corrosion management offshore must combine robust metallurgy carbon steel with corrosion allowance, CRAs in critical sections, and lined vessels with inhibitor dosing, oxygen control, solids management, and online monitoring (ER/LPR probes, UT thickness trending) tuned to motion and access constraints.

Feed-gas characteristics determine dehydration choices and operating envelopes. High CO_2 partial pressure not only elevates corrosion risk but also shifts phase behavior, modifies hydrocarbon dew points, and influences membrane selectivity if membranes are part of the scheme. Hydrogen sulfide above threshold partial pressures triggers sour-service requirements, limits material options, and raises safety case complexity. Water content at inlet conditions, often expressed in mg/Nm³ or lb/MMscf, can vary with reservoir conditions, choke settings, and line heat exchange with seawater; compositional shifts from new wells or commingled fields alter solubility in hydrocarbons and lean solvent requirements (Akinrinoye, *et al*. 2020, Essien, *et al*., 2020, Imediegwu & Elebe, 2020). Heavy hydrocarbon and BTEX content can cause glycol losses through absorption and increase emissions from regenerators, which are further constrained by offgas handling and environmental permits. Sand and fines from the reservoir introduce erosion risk and foster foaming and maldistribution in packed sections, demanding robust filtration and solids removal before dehydration stages. Figure 3 shows theoretical framework for the sustainable development of the natural gas industry presented by Dong, *et al*., 2015.

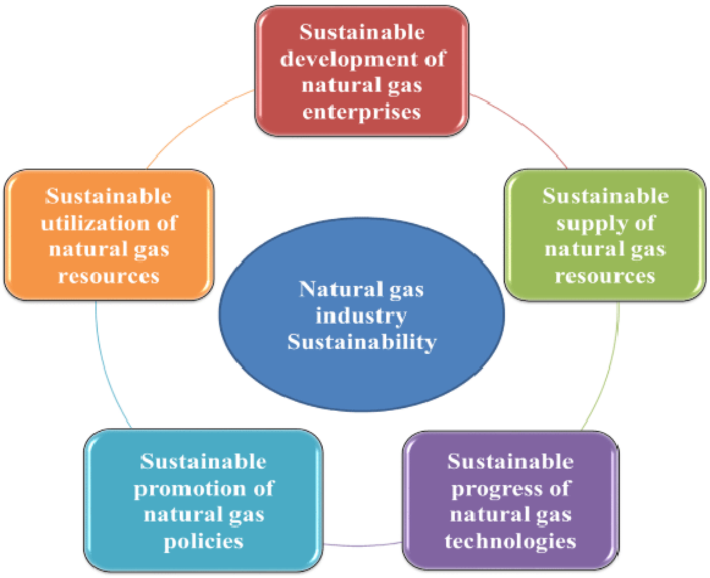

Fig 3: Theoretical framework for the sustainable development of the natural gas industry (Dong, *et al*., 2015).

Operating constraints offshore integrate safety, regulation, energy balance, and manning. Flaring and venting consents limit the use of traditional upset management techniques; flare minimization strategies require high reliability in compression and dehydration to avoid routine depressurizations. Power is often generated by gas turbines whose efficiency depends on ambient and load; parasitic loads from heat medium pumps, seawater lift pumps, and large blowers must be balanced against production targets. Reboiler duty for glycol or MEG units competes with other thermal demands, making heat integration with turbine exhaust or compressor aftercoolers attractive yet operationally complex when load fluctuates. Hazardous-area classification governs equipment selection and maintenance practices, constraining sensor options and the adoption of certain control elements (Akinrinoye, *et al*. 2020, Bukhari, *et al*., 2020, Elebe & Imediegwu, 2020). Crew size and logistics limit maintenance frequency; equipment must be accessible, modular, and maintainable within tight lifting envelopes and short weather windows. Cybersecurity and safety instrumented systems must be integrated without adding operational brittleness during storms, black starts, or subsea trips.

Dynamic operations turndown, start-up, hot restarts after trips, and frequent rate changes from market dispatch or reservoir management stress dehydration units that were sized for nameplate flows. At turndown, contactor mass transfer deteriorates, regenerator stripping becomes inefficient, and temperature profiles collapse unless control strategies adjust reflux, stripping gas, and circulation rates in concert. At ramp-up, solvent carryover and misting can increase without adequate demisting and filtration, contaminating downstream equipment (Ajayi, *et al*., 2019, Bukhari, *et al*., 2019, Oguntegbe, Farounbi & Okafor, 2019). Membranes are sensitive to liquid breakthrough and aromatic plasticization; molecular sieves can suffer premature breakthrough and thermal stress if cycle times and regeneration temperatures are not adapted to motion and feed variations. Instrumentation drift in saline, humid, and vibrating environments introduces uncertainty that must be acknowledged in setpoints and safeguards.

Finally, environmental and social expectations are rising. Methane intensity metrics and regional emissions trading schemes push operators to document and reduce solvent losses, heater fuel consumption, and fugitive emissions from valves and seals. Produced-water handling interacts with dehydration through entrainment and mist capture, while waste streams from solvent reclaimer operations require careful disposition within offshore waste management plans (Ajayi, *et al*., 2019, Bayeroju, *et al*., 2019, Sanusi, *et al*., 2019). Any conceptual framework for sustainable dehydration must weave these realities together: the sea's variability, the platform's physical limits, the chemistry of hydrates and corrosion, the variability of feed-gas composition, and a lattice of operating constraints that prioritize safety and emissions alongside uptime and quality. Only by explicitly acknowledging and modeling these offshore-specific challenges can technology selection, control design, and lifecycle governance deliver dehydration efficiency that is resilient, compliant, and credibly sustainable.

4. Framework Architecture

The framework architecture is organized as a set of interoperable layers that together convert raw offshore operating data into resilient, low-emission dehydration and gas-processing decisions. At its base lies a thermodynamics and exergy layer, which expresses every major unit separator, compressors, coolers, contactors, regenerators, molecular sieve beds, membrane stages, and MEG systems in terms of mass and energy conservation, phase equilibrium, and exergy accounting. This layer quantifies real losses against theoretical minima and partitions them into avoidable and unavoidable components, providing a rigorous baseline for improvement (Asata, Nyangoma & Okolo, 2020, Essien, *et al*., 2020, Elebe & Imediegwu, 2020). Flash calculations, equation-of-state models, electrolytic and activity-coefficient routines for water and glycols, and transport correlations for pressure drop and heat transfer are coupled with hydrate equilibrium predictions and corrosion thermochemistry. Exergy destruction maps identify where mixing, throttling, heat leakage, and finite-temperature transfers erode efficiency; for dehydration specifically, the maps reveal penalties from over-stripping, excessive reflux, suboptimal solvent circulation, and undersized mist elimination. By rendering losses in a common currency, this layer aligns operations, maintenance, and sustainability teams on where each incremental kilowatt and kilogram of solvent matters most.

Building on this foundation, a technology selection layer encodes the decision logic for choosing and configuring process pathways. It implements a multi-criteria decision structure that evaluates triethylene glycol contactors, molecular sieves, membranes, and hybrid topologies against site-specific constraints of footprint, weight, power availability, dew-point targets, sour service, and turndown. The layer hosts parametric templates packing and tray hydraulics for TEG columns, cycle times and bed sizing for sieves, stage-cut and selectivity envelopes for membranes, and heat-integration options for regenerators to simulate candidate configurations rapidly under varying feeds and metocean conditions (Asata, Nyangoma & Okolo, 2020, Essien, *et al*., 2019, Elebe & Imediegwu, 2020). A scoring engine aggregates metrics such as specific energy consumption, solvent losses, methane and CO_2 intensity, corrosion index, hydrate proximity margin, reliability block-diagram availability, and life-cycle cost. Uncertainty treatments propagate ranges for reservoir composition, seawater temperature, inhibitor contamination, and motion-induced maldistribution so that the final recommendation reflects robust performance rather than nominal point estimates. The outcome of this layer is a shortlist of viable designs and operating envelopes, each annotated with risk controls, expected efficiency, and requirements for control and monitoring. Figure 4 shows the conceptual framework presented by Jangsawang, 2019.

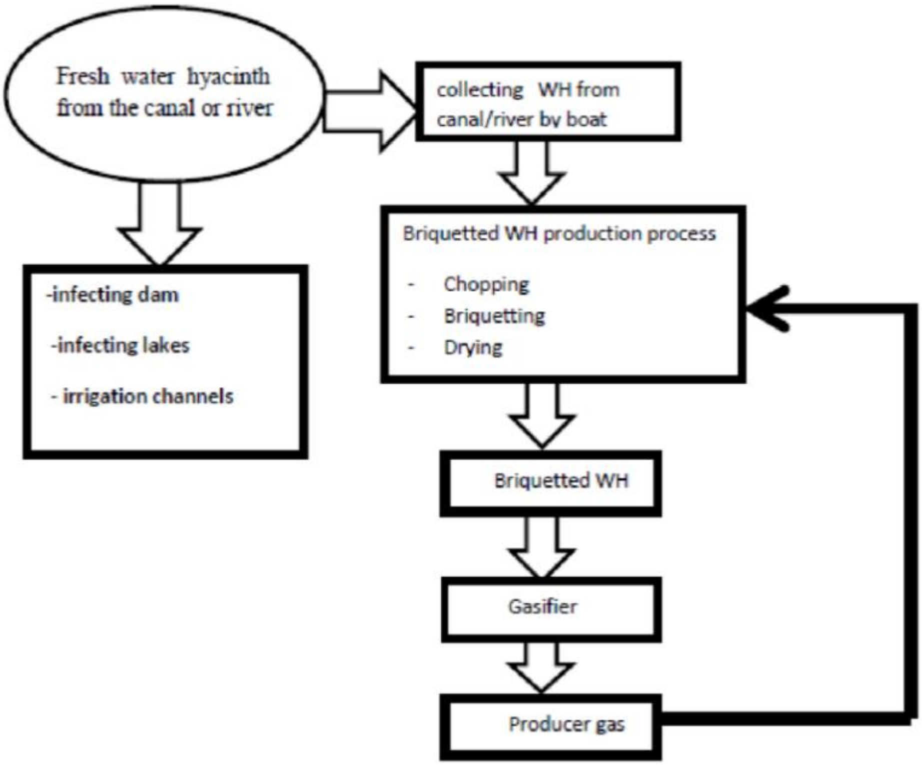

Fig 4: The conceptual framework (Jangsawang, 2019).

The control and automation layer translate thermodynamic insight and technology choices into stable, real-time action. Its core is a digital twin that fuses first-principles models with data-driven surrogates calibrated to plant historians. The twin runs faster than real time, providing setpoint advisories for regenerator duty, circulation rate, reflux ratio, stripping gas flow, membrane stage cut, and sieve cycle timing. Around the twin sits a hierarchy of control: regulatory loops maintain temperatures, levels, pressures, and flows with motion-robust tuning; supervisory model predictive control coordinates multivariable interactions to minimize energy use and solvent losses while enforcing safety and equipment constraints; and optimization routines periodically re-solve for best operating points as feed quality or ambient conditions shift (Adeniyi Ajonbadi, *et al*., 2015, Didi, Abass & Balogun, 2019, Umoren, *et al*., 2019). Soft sensors estimate hard-to-measure variables like lean-solvent purity, contactor approach to equilibrium, droplet carryover risk, hydrocarbon absorption into glycol, and incipient hydrate margin from easily measured temperatures, pressures, and compositions. Fault detection and diagnostics monitor signatures of foaming, mist eliminator flooding, tray weeping, adsorbent degradation, membrane wet-out, exchanger fouling, and valve stiction, triggering automated de-rates or maintenance work orders before efficiency collapses into an upset. The layer also embeds inhibitor coordination logic so that methanol or MEG dosing respects dehydration limits and avoids contaminant loading that would inflate reboiler duty or poison adsorbents.

The sustainability layer institutionalizes measurement, governance, and continuous improvement. It hosts a curated catalog of key performance indicators spanning energy, emissions, water removal, reliability, and integrity. Representative metrics include water-removal efficiency relative to specification, specific thermal and electrical energy per unit of water removed, methane intensity, CO_2 per dehydrated volume, solvent make-up and degradation rates, reboiler off-gas composition, hydrate-incident frequency, corrosion rate trends, and flare volumes attributed to dehydration upsets. These indicators are consolidated into a Dehydration Sustainability Index that communicates performance and trade-offs in a single score for operational reviews and board-level reporting (Ajonbadi, Mojeed-Sanni

& Otokiti, 2015, Evans-Uzosike & Okatta, 2019, Oguntegbe, Farounbi & Okafor, 2019). The layer codifies measurement and verification protocols so that claimed efficiency gains and emission reductions are reproducible: baselining against comparable ambient and flow conditions, CUSUM tracking to detect drift, and statistical adjustments for turndown and reservoir transitions. It aligns with environmental permits and corporate ESG commitments, generating auditable records and root-cause narratives for deviations, while feeding improvement backlogs prioritized by exergy and emissions impact.

Data flows bind these layers into a living system. At the edge, sensors deliver temperatures, pressures, levels, flows, valve positions, vibration, composition surrogates, and ambient data. Gas chromatographs, moisture analyzers, and corrosion probes provide slower but higher-value streams; subsea and topside flow assurance sensors contribute line temperatures and pressures relevant to hydrate margins. A data acquisition and historian tier, with time-synchronization and quality flags, ingests these signals. Data quality services apply plausibility checks, reconciliation, and motion compensation to mitigate bias from heave and sloshing. Preprocessed data feed two branches simultaneously: the digital twin for state estimation and control optimization, and the analytics warehouse for performance accounting, reliability trending, and sustainability dashboards (Akinbola, *et al*., 2020, Balogun, Abass & Didi, 2020). Feedback from the twin optimal setpoints, constraint advisories, and predicted deviations travels to the advanced process controllers, which implement moves subject to safety interlocks and rate limits. Concurrently, diagnostic insights flow to computerized maintenance management systems as condition-based tasks with spare parts and lifting plans tailored to offshore constraints.

Model development and upkeep circulate through a governed loop. Operating campaigns and planned test sequences perturb the system within safe bounds to excite dynamics and refresh model parameters. Bayesian updating and transfer-learning routines adjust surrogate models when feed composition drifts or equipment is overhauled. When anomalies arise such as unexpected glycol losses or adsorber breakthrough the framework opens a structured investigation: the thermodynamics layer checks consistency with phase equilibria; the technology layer re-scores configuration options under the new conditions; the control layer proposes interim setpoint shifts; and the sustainability layer quantifies the emissions and energy implications to prioritize actions (Akinrinoye, *et al*., 2020, Farounbi, Ibrahim & Abdulsalam, 2020). Decision support sits on top of these flows as an operator-facing cockpit that shows the current hydrate margin, dew-point approach, exergy loss map, energy and solvent KPIs, corrosion risk, and recommended next best action, along with confidence intervals and safety justifications. Management views aggregate multi-asset performance, highlighting modules with the highest avoidable exergy destruction and largest sustainability leverage.

Cyber-physical integrity is treated as an architectural property rather than an add-on. Role-based access, digital signatures on model versions, and tamper-evident data pipelines protect the provenance of numbers that ultimately drive sustainability disclosures. Simulation-in-the-loop testing allows control logic and alarm rationalization to be validated against realistic metocean disturbances and transient operations before deployment. Because offshore bandwidth can be intermittent, the architecture supports local autonomy: edge compute maintains essential estimation and control if the backhaul link is lost, buffering data for later synchronization (Ajonbadi, Otokiti & Adebayo, 2016, Didi, Abass & Balogun, 20219). Conversely, cloud resources provide elasticity for scenario studies, global benchmarking, and fleet-wide model updates, with differential deployment so that changes are rolled out gradually and reverted if anomalies appear.

Heat integration is operationalized through this architecture. The thermodynamics layer evaluates exchanger networks that reclaim compressor discharge heat or turbine exhaust for reboiler duty; the control layer coordinates valves and bypasses to keep regenerator temperatures stable as machine loads fluctuate; the sustainability layer records the realized fuel and emissions savings; and the decision cockpit visualizes the trade-off between recovery gains and pressure-drop penalties under current ambient conditions. Similar cross-layer logic governs solvent quality management: the models compute the equilibrium purity required for target dew point, the control layer adjusts stripping gas and reflux, diagnostics watch for heat-stable salt buildup, and the sustainability layer monetizes the reduction in solvent make-up and flare risk (Balogun, Abass & Didi, 2019, Otokiti, 2018, Oguntegbe, Farounbi & Okafor, 2019).

In this architecture, modularity ensures that improvements in one layer propagate coherently. A better hydrate equilibrium correlation immediately sharpens the control layer's margin estimation; a new membrane module with updated plasticization kinetics updates the technology layer's rankings; and a refined emissions factor recalibrates the sustainability index. The result is a cohesive system that turns noisy, motion-affected offshore data into transparent, defensible, and efficient dehydration decisions, continually learning from operations while honoring safety and environmental constraints (Ajonbadi, *et al*., 2014, Didi, Balogun & Abass, 2019, Farounbi, *et al*., 2019).

5. Technology Pathways and Decision Matrix

Technology pathways for offshore gas dehydration are determined by the balance between thermodynamic performance, operational reliability, physical footprint, and environmental constraints. The conceptual framework treats each pathway triethylene glycol (TEG) systems, molecular sieves, membranes, and hybrid combinations not as mutually exclusive technologies but as building blocks whose integration can be tuned to site conditions and dew-point targets. Each technology embodies a different compromise between water removal efficiency, energy demand, complexity, and resilience to feed-gas variability, and the decision matrix embedded in the framework provides a quantitative, transparent method for selection and optimization (Akinrinoye, *et al*. 2020, Balogun, Abass & Didi, 2020, Oguntegbe, Farounbi & Okafor, 2020).

TEG absorption remains the industry standard for offshore dehydration due to its relative simplicity, adaptability, and the ease with which it can be integrated into conventional process trains. A well-designed TEG unit can consistently achieve outlet water contents of 10–30 mg/m³ (corresponding to hydrocarbon dew points of –5 to –15 °C), sufficient for most transmission or liquefaction feed requirements. However, pushing TEG systems to ultra-dry specifications (<5 mg/m³) requires high reboiler temperatures, vacuum regeneration, or stripping gas, all of which impose penalties on energy efficiency and solvent degradation (Seyi-Lande, Oziri & Arowogbadamu, 2018). In addition, mist elimination, foaming control, and oxygen exclusion become critical to maintaining reliability offshore, where maintenance opportunities are limited. The decision matrix treats TEG units as favorable where medium dryness is required, power availability is constrained, and modular, lightweight construction is essential. Energy consumption per unit of water removed, solvent losses, and emissions from still vents form the core performance indicators for TEG pathways.

Molecular sieve adsorption represents the next step in dryness capability, typically achieving outlet water contents below 1 ppm v/v well suited for cryogenic processing, LNG feed, or subsea tie-backs with long cool lines. The trade-off lies in high capital cost, significant vessel weight, and the need for cyclic regeneration using hot dry gas, which increases complexity and operational risk. Bed cycling and temperature swings impose stresses that must be monitored with thermocouples and predictive control to prevent channeling and thermal fatigue (Akinbola & Otokiti, 2012, Dako, *et al*., 2019, Oziri, Seyi-Lande & Arowogbadamu, 2019). The framework positions molecular sieves as optimal where ultra-low dew-points and hydrocarbon dew-point control are paramount, but space and power are available to support their auxiliary systems. The matrix assigns heavy weighting to reliability metrics mean time between bed failures, valve cycle life, and regeneration gas ratio alongside the energy cost per kilogram of water removed.

Membrane dehydration introduces a compact, low-maintenance alternative that relies on selective permeation of water vapor through polymeric or composite membranes. It provides moderate dew-point depression (5–15 °C) with minimal moving parts, making it attractive for unmanned or remotely operated platforms. Yet membrane performance is sensitive to condensate carry-over, aromatic swelling, and pressure-ratio limitations. Flux declines as membranes foul or plasticize, and high feed-gas pressure is required to maintain driving force, leading to recompression penalties if permeate is vented or flared. In the decision matrix, membranes score well in footprint and weight, moderately in OPEX, and lower in ultimate dryness and long-term reliability under hydrocarbon exposure. The matrix emphasizes compatibility with feed composition, tolerance to methanol or MEG, and the potential for modular replacement rather than overhaul (Akinrinoye, *et al*. 2019, Didi, Abass & Balogun, 2019, Otokiti & Akorede, 2018).

Hybrid trains combine these technologies to capitalize on their complementary strengths. A TEG contactor followed by a molecular sieve unit provides efficient bulk water removal and final polishing with reduced adsorbent duty and extended cycle life. A TEG-membrane hybrid achieves similar benefits in lighter configurations, where membranes handle final dew-point trimming after absorption. The decision matrix treats hybrids as optimization outcomes rather than initial assumptions, assigning composite scores that reflect combined energy efficiency, redundancy, and resilience to upset (Abass, Balogun & Didi, 2020, Didi, Abass & Balogun, 2020, Oshomegie, Farounbi & Ibrahim, 2020). The hybrid option is often superior in brownfield retrofits, where partial upgrades can meet new specifications without full system replacement. It can also improve heat integration: regenerated gas from a sieve stage can serve as stripping gas for TEG, while low-grade heat recovered from TEG regeneration can pre-heat sieve regeneration gas, closing energy loops and reducing total exergy destruction.

The framework's decision matrix is structured as a multi-criteria screening tool combining quantitative and qualitative factors. Core criteria include energy efficiency, footprint and weight, reliability, OPEX/CAPEX balance, and safety/environmental compliance. Energy efficiency captures thermal duty per kilogram of water removed, compressor power for regeneration or recompression, and potential for heat recovery. Each technology's energy profile is normalized against equivalent dehydration performance to ensure fair comparison. Footprint and weight account for equipment size, module integration, and support-structure reinforcement needs critical parameters in topside design where lifting limits and center-of-gravity constraints dominate feasibility (Akinola, *et al*., 2020, Akinrinoye, *et al*. 2020, Balogun, Abass & Didi, 2020). Reliability incorporates both intrinsic equipment availability and maintainability under offshore access limitations; it penalizes systems requiring frequent bed change-outs, solvent reclaiming, or delicate membrane handling.

The economic dimension of the matrix distinguishes between capital intensity and operating expenditure. TEG units have the lowest CAPEX per unit throughput but rising OPEX with solvent losses, vented hydrocarbons, and periodic filter replacement. Molecular sieves carry high CAPEX due to pressure-vessel design and insulation requirements but lower OPEX once installed, provided feed-gas filtration is effective (Seyi-Lande, Oziri & Arowogbadamu, 2019). Membranes exhibit moderate CAPEX but uncertain long-term OPEX as module replacement costs accumulate. Hybrids spread CAPEX across simpler subsystems and reduce lifecycle cost through energy integration. The framework assigns weighted scores reflecting project drivers if power is scarce, energy receives highest weighting; if deck load is constrained, footprint dominates; if autonomy is prioritized, reliability and maintenance frequency gain importance.

Safety and environmental performance are integral rather than peripheral considerations. The matrix evaluates flammable inventories, potential hydrocarbon or glycol emissions, explosion-proofing requirements, and toxicity of regeneration offgas. Molecular sieves eliminate liquid inventories but introduce hot-gas cycles with burn risk; TEG units involve flammable solvent and potential VOC releases; membranes have minimal hazard but rely on high-pressure operation. Each technology's safety score is benchmarked to applicable offshore regulations and quantified through a qualitative–quantitative hybrid risk index. Environmental indicators include methane slip, CO_2 from heating fuel, and waste generation from solvent reclamation or adsorbent disposal. These feed into the sustainability layer of the overarching framework, ensuring technology selection aligns with carbon-reduction targets and ESG commitments (Abass, Balogun & Didi, 2019, Ogunsola, Oshomegie & Ibrahim, 2019, Seyi-Lande, Arowogbadamu & Oziri, 2018).

To operationalize the decision process, the matrix employs a weighted-sum or analytic hierarchy process (AHP) algorithm calibrated through expert judgment and empirical data. Inputs include process-simulation results, reliability data, vendor specifications, and lifecycle cost analyses. Sensitivity analysis explores the impact of uncertainties in feed-gas composition, ambient temperature, and energy prices on the ranking of alternatives. The output is not a single verdict but a Pareto frontier of options showing trade-offs among efficiency, cost, and risk. Visualization tools display how a small relaxation in dew-point target may yield disproportionate savings in energy or weight, allowing decision makers to calibrate specifications to strategic priorities rather than historical convention (Ayanbode, *et al*., 2019, Onalaja, *et al*., 2019).

A key innovation in the framework is dynamic linkage between the decision matrix and the digital-twin environment described in the control layer. Performance data from operating facilities continuously update the criteria weights and expected values. For example, measured solvent losses, adsorbent lifetimes, or membrane flux declines feed back into the model, refining OPEX projections and reliability distributions. This learning loop ensures that technology decisions evolve with actual performance rather than static design-stage assumptions. As global regulatory pressures tighten on emissions and venting, the sustainability metrics within the matrix adjust automatically to elevate low-carbon options even when they carry higher initial CAPEX, thereby embedding policy alignment into engineering decision logic (Eyinade, Ezeilo & Ogundeji, 2020, Fasasi, *et al*., 2020).

By treating dehydration technologies as adaptable modules rather than fixed packages, the conceptual framework promotes lifecycle optimization. Early design stages use the matrix for screening; detailed engineering refines the chosen pathway with thermodynamic and exergy models; operations teams use the same structure for continuous benchmarking and retrofit justification. The ultimate goal is a transparent, auditable selection process that balances energy, footprint, reliability, cost, and safety to deliver sustainable dehydration under offshore constraints. In such a system, TEG remains the versatile workhorse, molecular sieves the precision tool for ultra-dry service, membranes the minimalist solution for remote assets, and hybrids the bridge toward integrated, low-carbon gas processing (Pamela, *et al*., 2020, Patrick & Samuel, 2020). Together they form a spectrum of technology pathways that, when filtered through a disciplined multi-criteria decision matrix, enable offshore operators to meet dew-point targets efficiently, safely, and sustainably across the full range of environmental and economic conditions.

6. Thermodynamic & Heat-Integration Analysis

Thermodynamic and heat-integration analysis provides the quantitative backbone of a sustainable dehydration strategy by converting noisy offshore operating realities into clear targets for avoidable-loss reduction and practical recovery options. The approach begins with simultaneous energy and exergy balances around each equipment item and the overall dehydration system. Energy balances identify where heat and work are consumed, but exergy balances reveal the quality of those energy streams and the irreversibilities mixing, finite temperature heat transfer, throttling, pressure drops, and chemical disequilibria that destroy useful potential (Bankole, *et al*., 2020, Dako, *et al*., 2020). For a TEG train, exergy destruction typically concentrates in the regenerator reboiler and still column, where water–glycol separation proceeds at finite driving forces, and in contactor sections with maldistributed liquid, foaming, or over-circulation. For molecular sieves, the largest penalties arise during thermal swing regeneration, particularly when hot dry gas is produced at temperatures well above what the beds require, or when purge rates exceed the minimum to displace desorbed water. Membrane units exhibit exergy losses when high-pressure feed is expanded or when permeate is vented rather than recompressed or used constructively. These maps convert intuition into ranked opportunities: reduce regenerator temperature approach, lower stripping-gas rates, tighten reflux matching to overhead composition, extend adsorber cycles with better inlet drying, and repurpose warm permeate or hot compressor discharge to replace purchased utilities.

Pinch analysis translates these opportunities into network-level design moves. Composite and grand composite curves are constructed using measured or rigorously simulated stream data over representative operating windows (turndown, shoulder, and nameplate). Hot streams include compressor aftercoolers, turbine exhaust, hot separator liquids, and regenerator overheads; cold streams include feed gas preheats, lean-solvent preheat, sieve purge-gas preheats, and space heating. The minimum temperature approach (ΔTmin) is selected to reflect compact exchanger hardware and seawater fouling realities offshore; values of 8–15 °C are typical, but sensitivity to 6–10 °C is examined for hybrid trains that exploit high-effectiveness plate-fin or printed-circuit exchangers. The pinch location identifies the utility targets: the minimum hot utility for the reboiler and the minimum cold utility for gas cooling (Atobatele, Hungbo & Adeyemi, 2019, Hungbo & Adeyemi, 2019). Once the pinch is fixed, network synthesis prioritizes matches that shift duty from fired heaters to recovered heat. For example, compressor stage discharge at 110–160 °C can preheat lean TEG from 60 to 100 °C, trimming fired reboiler duty by 10–20%. Likewise, a portion of turbine exhaust can be ducted through a compact waste-heat recovery unit to provide stable base-load reboiling, leaving only peak trim to auxiliary burners. The grand composite curve reveals whether integrating MEG regeneration or a sieve heater into the same thermal ladder yields additional savings or creates cross-coupling that complicates control during rate changes.

Quantifying regenerator duty starts from first principles with a mass balance on the absorbed water and a stagewise or equilibrium model for solvent purification. For TEG, the duty Qreb approximates the sensible heat to raise rich solvent to reboiler temperature plus latent heat to strip absorbed water and any light hydrocarbons, adjusted for reflux ratio and column efficiency. A typical rule-of-thumb of 3.5–5.5 MJ per kilogram of water removed conceals large variability driven by lean-solvent purity targets and stripping-gas practices (Egemba, *et al*., 2020). Using exergy analysis, the target becomes not just minimizing Qreb but minimizing the destroyed exergy per kilogram of water, which pushes design toward narrower temperature approaches in the reboiler, better heat recovery upstream, and precise control of stripping gas to avoid overstripping. In molecular sieves, the regeneration duty depends on bed size (linked to breakthrough at target outlet ppmv), purge rate, and desorption temperature (often 250–300 °C). Here, pinch-guided integration of purge-gas preheat with compressor discharge or TEG lean-loop heat can cut heater fuel 10–25% while preserving cycle time, provided valves and controls maintain stable temperature ramp rates to protect adsorbent integrity. For membranes, the "duty" is largely electrical compression and recompression work which is minimized by optimizing stage cut and selectively recovering the permeate's pressure/enthalpy where feasible.

Compression heat recovery is quantified by matching hot composite segments from the compressor train to cold segments in the dehydration system. If a two-stage compressor delivers 4 MW of shaft power with isentropic efficiencies of 75–80%, roughly 2–2.5 MW emerges as reject heat after intercooling and aftercooling. With realistic overall heat-transfer coefficients and approach temperatures, 30–50% of that reject heat can be harnessed at useful temperatures (90–140 °C) to preheat lean solvent or purge gas, translating into 0.6–1.2 MW of displaced fired duty. When combined with turbine exhaust (which may provide 5–10 MW at 300–450 °C for a small offshore power package), a properly pinched network can cover base reboiler needs entirely in steady state. Exergy accounting ensures that high-temperature exhaust is used where its quality matters directly in reboiling or high-level preheats while lower-grade compressor heat is reserved for intermediate lifts, avoiding the common inefficiency of using premium heat for low-temperature tasks (Amuta, *et al*., 2020, Ezeanochie, Akomolafe & Adeyemi, 2022, Filani, Olajide & Osho, 2020).

Dew-point control margins must be expressed in thermodynamically consistent terms so that operations know both how close they are to specification and how robust that margin is to disturbances. For dehydration, the water content specification is often ≤ 7 lb/MMscf (≈ 112 mg/Nm³), but offshore gas headed to cryogenic processing or long cold lines may need ≤ 1 ppmv. The margin is the difference between current predicted outlet water content and the spec, adjusted for analyzer uncertainty, motion-induced measurement noise, and model bias. A control-oriented metric links that margin to manipulated variables: circulation rate, lean-solvent purity, contactor temperature, and regenerator duty for TEG; cycle time, bed temperature, and purge rate for sieves; stage cut and feed temperature for membranes (Giwah, *et al*., 2020, Ibrahim, Amini-Philips & Eyinade, 2020). Using sensitivity coefficients (∂Wout/∂u), the framework computes how much regenerator duty must increase to restore a 10 mg/Nm³ margin if seawater temperature drops 5 °C or feed rate surges 15%. In TEG systems, a 1 wt% loss in lean-solvent purity can degrade outlet dryness by tens of mg/Nm³; restoring purity may require incremental reboiler duty of 0.3–0.6 MJ/kg water and a temporary increase in stripping-gas flow, both visible as exergy costs. For sieves operating near breakthrough, the margin is cycle-time headroom; extending the cycle by 10–15% may demand a 5–10 °C higher regeneration temperature or improved purge preheat, which the pinch network should be configured to supply without new fuel firing.

Avoidable losses fall out naturally from this integrated analysis. Over-circulation in TEG elevates pump power and reboiler duty with diminishing returns on water removal; exergy maps flag this as a controllable penalty. Excess reflux or overly conservative stripping-gas rates emerge as heat loads that do not translate into dryness gain beyond the measurement noise band. In sieves, purge ratios above the desorption minimum translate into wasted hot gas that the grand composite curve could repurpose (Atobatele, Hungbo & Adeyemi, 2019, Hungbo & Adeyemi, 2019). In membranes, operating at stage cuts that drive excessive recompression work or accepting permeate venting rather than energy recovery are avoidable exergy sinks. Pinch synthesis then supplies concrete modifications: install a lean/rich exchanger with higher effectiveness to cut reboiler duty 5–8%; re-route a fraction of second-stage aftercooler duty to purge preheat; add a small trim condenser upstream of the contactor to reduce water load and stabilize dew-point margin during cold seawater transients; or include a permeate-to-feed heat exchanger to temper membrane cooling and improve selectivity.

Because offshore operations oscillate between turndown and ramp-up, the analysis is performed across operating envelopes, not just at the design point. Composite curves are generated for 60%, 80%, and 100% rates with ambient temperatures spanning seasonal extremes. The network is then stress-tested for controllability: heat-exchanger matches that look attractive at 100% may starve the reboiler at 60% unless variable bypasses and control valves maintain minimum driving forces. Exergy-based KPIs are normalized by dehydrated volume so that improvements remain visible even at low rates. The result is a set of operating recipes preferred matches, valve positions, and setpoint ranges that preserve dew-point margins with minimal additional duty under disturbances like 5 °C seawater shocks, 10% feed composition swings, or short slugging events (Bankole & Tewogbade, 2019, Fasasi, *et al*., 2019).

Finally, measurement and verification anchor claimed savings to reality. Baselines are defined by aligning historical operation with comparable ambient and throughput conditions, and CUSUM plots track cumulative deviations in fuel use and solvent duty after network changes. Where heat recovery displaces fired duty, stack O_2, fuel flow, and duty proxies corroborate modeled savings. Dew-point analyzers and calibrated moisture probes validate margin improvements and correlate with changes in regenerator duty or cycle parameters (Giwah, *et al*., 2020, Ibrahim, Amini-Philips & Eyinade, 2020). By uniting energy/exergy accounting, pinch-guided network design, and control-aware margin quantification, the framework turns thermodynamics into durable offshore practice: lower regenerator fuel, captured compression heat, and stable dew-point control that is robust to metocean variability each improvement measured, verified, and sustained over the asset life.

7. Digitalization, Control, and Reliability

Digitalization, control, and reliability are the execution engine of the conceptual framework, translating thermodynamic opportunity into stable, low-emission dehydration performance in the motion-prone, maintenance-constrained offshore environment. At the core is a physics-informed digital twin that mirrors the dehydration train and adjacent gas-processing units at multiple time scales. The twin couples first-principles models mass and energy balances, phase equilibrium with electrolytic effects for water and glycols, hydrate thermodynamics, adsorption kinetics, and compressor maps with data-driven surrogates calibrated on historian data (Atobatele, Hungbo & Adeyemi, 2019). These surrogates' approximate hard nonlinearities such as foaming thresholds, membrane flux decline under aromatic exposure, bed pressure drop evolution with fines loading, and reboiler response under variable heat-integration. The twin runs faster than real time, continuously assimilating process measurements with a state estimator that accounts for sensor bias, motion-induced noise, and drift. It outputs reconciled states lean-solvent purity, true contactor approach-to-equilibrium, adsorber loading fronts, incipient mist carryover risk, and hydrate margin that are otherwise unobservable, forming the basis for predictive control and reliability decisions.

Soft sensors extend observability by inferring key quality variables from robust, readily measured signals. A lean-purity estimator fuses regenerator top temperature, column differential pressure, reflux rate, and stripping-gas flow with feed composition to estimate water-in-glycol concentration and hydrocarbon absorption. A dew-point predictor blends contactor outlet temperature and pressure, analyzer lag, and solvent circulation to deliver a filtered outlet water-content estimate with confidence intervals. For molecular sieves, a breakthrough prognoser uses bed inlet humidity, cycle time, temperature profile propagation, and purge quality to anticipate end-of-cycle constraints and propose adjustments (Eyinade, Amini-Philips & Ibrahim, 2020, Tewogbade & Bankole, 2020). Membrane soft sensors estimate stage cut, permeance decay, and plasticization progression from pressure ratios, temperatures, and low-frequency lab checks. Each estimator is trained with domain constraints physical bounds, monotonicities, and mass balances so that machine learning augments rather than replaces physics. The result is a resilient measurement layer that sustains decision quality despite saline air, vibration, and periodic analyzer downtime.

Model predictive control (MPC) coordinates multivariable interactions across the dehydration system to minimize energy and solvent losses while preserving safety margins. The MPC optimizes over a moving horizon, manipulating regenerator duty, circulation rate, reflux ratio, stripping gas, membrane stage cut, and sieve cycle timing subject to temperature, pressure, level, and composition constraints. Objective terms penalize specific energy per unit water removed, solvent make-up, and approach to hydrate onset while rewarding dew-point margin and stability (Amini-Philips, Ibrahim & Eyinade, 2020, Essien, *et al*., 2020). The controller enforces actuator rate and span limits, anti-surge and LOPA constraints, and hazardous-area interlocks so that no optimal move compromises protection layers. Because offshore disturbances arrive in packets cold seawater transients, slugging, step changes in export pressure the MPC uses scenario forecasts from the twin (e.g., expected cooling duty swing over the next hour) to stage proactive moves: preheating lean solvent before a predicted seawater dip, elongating an adsorber cycle when a warm spell boosts purge efficacy, or biasing inhibitor coordination to prevent solvent contamination when subsea temperature falls. Robust formulations handle model uncertainty by requiring feasibility across parameter sets that reflect composition drift, analyzer bias, and motion effects; tube-and-shell heat-transfer coefficients, for instance, are treated as interval parameters to avoid aggressive, brittle control.

Reliability is embedded through reliability-centered maintenance (RCM) and failure modes and effects analysis (FMEA) that are tightly integrated with the twin and soft sensors. The FMEA catalog enumerates failure modes for critical equipment TEG contactors and internals, mist eliminators, regenerator reboilers and burners, heat-stable salt reclaimers, circulation pumps, adsorber valves and beds, membrane modules and seals, lean/rich exchangers, and analyzer systems linking each mode to its precursors, detectable signatures, consequence severity, and mitigations (Bankole, Nwokediegwu & Okiye, 2020, Obuse, *et al*., 2020). Examples include tray weeping detected by simultaneous fall in column ΔP and rise in outlet water content at constant circulation; demister flooding indicated by high-frequency level oscillations and downstream compressor filter DP increase; adsorbent channeling inferred from asymmetric bed temperature profiles during regeneration; and membrane wet-out suggested by an abrupt rise in permeate hydrocarbon content at fixed pressure ratio. For each mode, the FMEA defines control responses (automatic de-rate, cycle extension, reflux adjustment), inspection tasks (borescope intervals, sample regimes), and spares strategy within lifting and storage limits.

RCM translates this knowledge into a living maintenance plan that prioritizes condition-based interventions over fixed intervals. Condition indicators from soft sensors and diagnostics feed a health index per asset, which is trended against environmental stressors and duty cycles. When a health index crosses a risk threshold with consequence-of-failure weighting for safety and flaring impact the system generates a work order with pre-defined scope, parts, tooling, permits, and expected lifting requirements (Aduwo & Nwachukwu, 2019, Erigha, *et al*., 2019). Because offshore windows are scarce, the plan groups tasks into weather-aligned campaigns and embeds “shadow kits” for high-criticality, low-weight spares to minimize mean time to repair. A feedback loop updates FMEA likelihoods and detection coverage based on actual findings if demister fouling emerges more frequently than predicted under new crude carryover, the likelihood is revised, soft-sensor thresholds are adapted, and MPC penalties for operating near flooding are sharpened.

Alarm rationalization and autonomy are designed to support operators in high-noise conditions. Diagnostic outputs are scored for confidence and presented as ranked “next best actions” with thermodynamic rationale “reduce circulation by 8% to restore exergy-efficient operation; predicted dew-point margin remains >20 mg/Nm³; solvent purity stable at 99.2 wt%±0.2.” Each recommendation includes the protection context SIS limits, interlock proximities, and hydrate margin to build operator trust. If communications to shore are interrupted, an edge runtime sustains essential estimation and MPC functions, buffering data and enforcing local cybersecurity policies. Simulation-in-the-loop testing validates new control strategies against recorded metocean scenarios before deployment, and digital signatures on model versions ensure traceable governance of any change that could affect emissions disclosures or safety arguments (Fasasi, *et al*., 2020, Giwah, *et al*., 2020).

Digitalization also orchestrates heat-integration and inhibitor coordination in real time. The twin continuously solves a pinch-consistent heat allocation, reassigning compressor discharge heat between lean-solvent preheat and sieve purge preheat as loads shift, while MPC modulates bypasses and valves to maintain minimum driving forces. Inhibitor dosing is coordinated with dehydration status: when lean-solvent purity dips, the optimizer prefers hydrate safety through temporary MEG increases over risking solvent contamination by methanol breakthrough; once purity recovers, dosing is trimmed to minimum hydrate margin targets. The energy and emissions impact of each decision is quantified and logged to a measurement and verification spine that uses CUSUM tracking to distinguish sustained improvements from noise, protecting claimed efficiency gains against rebound (Akinrinoye, *et al*., 2020, Alao, Nwokocha & Filani, 2020).

Cyber-physical resilience is treated as intrinsic. Role-based access control, network segmentation between safety and control, and whitelisting for controller code protect against unauthorized changes. Data provenance is preserved by cryptographically hashing historian blocks and model artifacts, enabling audits that tie board-level sustainability metrics to raw sensor evidence. Edge analytics perform plausibility checks first-law consistency over the column, reconciled compressor power vs. measured heat rejection flagging drifts that might indicate sensor bias or stealth faults. The integration of MPC and RCM yields tangible reliability gains that reinforce efficiency. By smoothing regenerator duty and circulation against predictable ambient swings, thermal fatigue in reboiler tubes is reduced, extending inspection intervals. By elongating sieve cycles only when purge quality and bed health permit, valve cycles decline, lowering failure probability in high-SIL service. By keeping membranes away from plasticization regions via temperature and pressure setpoint envelopes, module replacement frequency drops, stabilizing OPEX (Akintayo, *et al*., 2020, Dako, *et al*., 2020). Each reliability benefit is monetized in the same currency as energy: avoided flaring events, reduced solvent purchases, fewer helicopter trips, and lower burner fuel consumption. These savings feed a prioritization engine that recommends the next improvement project demister upgrade, analyzer redundancy, or lean/rich exchanger retrofit based on combined exergy and risk payback.

Finally, the human layer is central. Operators receive scenario-based training within the twin, practicing responses to seawater shocks, slug surges, analyzer failures, and compressor trips with MPC and diagnostics active. Shift handovers include a health and margin summary dew-point approach, hydrate distance, solvent quality, bed headroom so that intent carries across crews. Engineering, operations, and maintenance collaborate around a common, model-backed narrative rather than siloed KPIs, enabling faster consensus on trade-offs between energy, emissions, uptime, and safety. In this way, digitalization, control, and reliability cease to be parallel programs and become a single, cohesive capability that continuously turns offshore variability into predictable, efficient, and sustainable dehydration performance (Atobatele, *et al*., 2019, Filani, Nwokocha & Babatunde, 2019).

8. Sustainability Assessment and KPIs

Sustainability assessment in offshore dehydration must transform thermodynamic improvements into traceable environmental and social outcomes that withstand audit, regulation, and investor scrutiny. The conceptual framework treats sustainability as a lifecycle property of the dehydration function spanning design, construction, operation, maintenance, and decommissioning so that decisions on technology, setpoints, and maintenance can be expressed in comparable metrics and verified over time. The foundation is a compact set of key performance indicators that quantify energy use, material stewardship, atmospheric impact, operational integrity, and flow assurance, each normalized by a common activity basis such as "per standard cubic meter of gas dehydrated" or "per kilogram of water removed" to allow comparison across rates and seasons (Bankole, *et al*., 2019, Nwokediegwu, Bankole & Okiye, 2019).

Specific energy is the anchor metric because it couples directly to fuel consumption and emissions. For absorption systems, the thermal component is the reboiler duty and any stripping-gas compression; for adsorption, the heater duty for regeneration and purge compression; for membranes, electrical work for compression or recompression. The framework expresses specific energy as megajoules per kilogram of water removed and as megajoules per thousand standard cubic meters of dehydrated gas, both reported with ambient normalization using a rolling degree-day or seawater-temperature correction to ensure fair comparisons. Exergy-normalized variants capture quality loss and reward heat recovery that substitutes high-grade fuel with lower-grade compression heat (Ajayi, Onunka & Azah, 2020, Obuse, *et al*., 2020). A measurement and verification routine reconcile stack O_2, fuel flow, shaft power, and heat-recovery duty with moisture analyzers and production meters, producing confidence intervals that bound reported gains.

Solvent losses measure material circularity and latent emissions. In TEG and MEG systems, losses occur via vaporization in the contactor, entrainment past mist eliminators, absorption of hydrocarbons with subsequent venting, and liquid leaks. The KPI tracks kilograms of solvent make-up per million standard cubic meters dehydrated and partitions causes true loss to atmosphere, loss to produced water, and loss to contamination and reclaimer disposal. Where molecular sieves are used, the analogous metric is adsorbent consumption or deactivation rate expressed as kilograms per year normalized by throughput, with sub-indicators for cycle efficiency and purge-gas quality. Reductions in solvent loss improve VOC emissions, lower OPEX, and reduce shipping logistics, and they are tightly coupled to reliability actions such as demister upgrades and foaming control (Patrick, *et al*., 2019).

Methane and carbon dioxide intensity provide the link between energy performance and climate impact. Methane intensity aggregates measured and estimated fugitive emissions from valves, seals, contactor offgas, permeate vents, and regeneration releases, divided by dehydrated gas volume. CO_2 intensity accounts for combustion emissions from reboilers, heaters, and gas turbines allocated to the dehydration function, net of documented heat recovery. The framework distinguishes operational emissions from construction and decommissioning embodied carbon, reporting both operational intensity (kg CO_2e per thousand standard cubic meters) and lifecycle intensity (kg CO_2e per functional unit over asset life) for ESG comparability (Fasasi, *et al*., 2020, Giwah, *et al*., 2020, Hungbo, Adeyemi & Ajayi, 2020). Because methane's high short-term radiative forcing dominates climate risk, the framework includes a rapid-response protocol: when the digital twin detects conditions that likely elevate methane slip membrane permeate venting or still-column upsets the control system proposes immediate mitigation and logs the avoided emissions for later reconciliation.

Flaring and venting quantify waste and environmental burden during upsets and planned activities. The KPI family separates safety-critical depressurizations, operational flares tied to dehydration and compression upsets, and small continuous vents. Each volume is metered or estimated with event tagging and root-cause attribution, then normalized by dehydrated gas volume and operating hours. The objective is twofold: reduce frequency by strengthening reliability and control, and reduce magnitude by introducing high-integrity relief options and recompression or recovery schemes. Because offshore permits increasingly constrain routine flaring, the framework elevates flare-related KPIs to high weight in the composite sustainability score and requires explicit mitigation plans for top drivers (Awe, Akpan & Adekoya, 2017, Osabuohien, 2017).

Hydrate incident rate is a pragmatic flow-assurance proxy that bridges thermodynamics and operations. The KPI counts hydrate-related alarms, inhibitor overuse events, unplanned de-rates, and shutdowns attributable to hydration risk in a rolling period, weighted by severity and production impact. A related margin KPI expresses average and minimum distance to hydrate onset in °C or kPa under current composition, with analyzer uncertainty and model error bands. By tracking both rate and margin, the framework rewards strategies that achieve dryness efficiently without eroding safety buffers, discouraging short-term energy savings that raise incident risk (Akpan, Awe & Idowu, 2019, Ogundipe, *et al*., 2019).

Corrosion index captures the integrity dimension that, if neglected, turns efficiency into deferred risk. The index combines online corrosion probe trends, ultrasonic thickness surveys, coupon results, oxygen ingress frequency, and scaling or heat-stable salt indicators into a normalized score reflective of corrosion probability and consequence. Sub-indices distinguish sweet (CO_2) and sour (H_2S) mechanisms, chloride stressors in seawater circuits, and under-deposit corrosion in exchangers. The metric is linked to solvent quality KPIs because degraded solvents accelerate corrosion and to heat-integration strategies that may change temperature profiles and film stability. Target bands align with materials selection and inspection intervals so that gains in energy do not outpace integrity assurance (Awe & Akpan, 2017).

These KPIs flow into a Dehydration Sustainability Index, a single figure that communicates multidimensional performance without obscuring the drivers. The DSI is constructed by normalizing each KPI against a reference band defined by regulatory thresholds, corporate targets, and best-available-technology benchmarks. For metric i with value Vi, a normalized score Si is computed using piecewise-linear desirability functions: Si = 1 at the target, Si = 0 at a defined fail threshold, and smooth slopes in between (Akpan, *et al*., 2017, Oni, *et al*., 2018). Weights wi reflect stakeholder priorities and site constraints: wenergy high where fuel is scarce, wflare elevated where permits are tight, wCH4 prioritized for methane-sensitive ESG reporting, wcorrosion increased when sour service raises integrity risk. The DSI is the weighted sum ∑ wiSi, subject to a rule that any metric below a critical floor (e.g., a severe methane spike or corrosion breach) caps the overall index to prevent compensatory greenwashing. Confidence intervals accompany the index, propagated from measurement uncertainty and model error, so that boards and regulators see not only scores but their robustness.

ESG compliance checks turn the DSI and its components into auditable artifacts. The framework maps each KPI to disclosure standards and regulations, such as greenhouse gas protocols for Scope 1 accounting, methane reporting frameworks, flaring consent conditions, and marine discharge rules. It implements data lineage controls sensor provenance, calibration logs, digital signatures on model versions so that external auditors can trace reported reductions to raw evidence and approved algorithms (Akomea-Agyin & Asante, 2019, Awe, 2017, Osabuohien, 2019). Threshold alarms trigger governance workflows: exceeding methane intensity initiates a management-of-change review for vent sources; an uptick in solvent loss opens a root-cause analysis and temporary tightening of operating envelopes; corrosion index drift schedules accelerated inspection and inhibitor optimization. The compliance layer also evaluates supplier and waste-chain ESG: adsorbent sourcing certifications, solvent reclamation routes, and end-of-life handling for spent beds and contaminated liquids are recorded to ensure the dehydration function's footprint is not exported offsite.

Lifecycle thinking extends the assessment beyond day-to-day operations. Design choices receive embodied-carbon estimates, and vendors are required to provide environmental product declarations for major equipment. Construction logistics, module fabrication routes, and lift campaigns are costed in carbon terms and amortized over expected throughput. Decommissioning plans include solvent recovery, adsorbent disposal pathways, and emissions controls during blowdown. Because offshore assets evolve, the framework requires re-baselining after major tie-ins, technology swaps, or power-system changes so that KPI trajectories remain comparable (Asata, Nyangoma & Okolo, 2020, Bukhari, *et al*., 2020, Essien, *et al*., 2020).

To avoid metric gaming and rebound effects, the system incorporates statistical controls. CUSUM plots detect durable shifts in specific energy after heat-integration projects; drift diagnostics distinguish seasonal variability from genuine deterioration; and counterfactual modeling estimates what emissions and flaring would have been without an intervention, crediting only the delta attributable to the change. The digital twin enforces thermodynamic plausibility first-law reconciliations, dew-point consistency so that outliers trigger data-quality checks rather than misleading dashboards. Operator incentives are aligned with DSI improvements, but with safeguards that prevent sacrificing hydrate margin or corrosion health for short-term energy gains.

Decision support closes the loop by presenting sustainability and reliability in a single cockpit. Operators see real-time specific energy, solvent-loss rates, methane slip estimates, flare exposure, margin to hydrate onset, and corrosion health with recommended actions that move both energy and emissions in the right direction. Managers see weekly DSI trends with waterfall charts attributing changes to control tuning, maintenance fixes, or ambient shifts. Engineers use KPI decomposition to identify avoidable exergy pockets that offer the best sustainability payback. In this configuration, sustainability is not a parallel dashboard but the currency of daily decision-making, embedded in control objectives, maintenance priorities, and capital planning (Abass, Balogun & Didi, 2020, Amatare & Ojo, 2020, Imediegwu & Elebe, 2020).

By grounding assessment in lifecycle metrics, normalizing them into a transparent DSI, and binding them to ESG checks with auditable data lineage, the framework converts abstract sustainability goals into precise, controllable behaviors. Specific energy falls through heat recovery and MPC; solvent losses shrink via demisting and purity control; methane and CO_2 intensities decline with optimized duty and leak response; flaring events recede as reliability tightens; hydrate incidents become rarer under robust margin management; and corrosion risk is held in check through solvent governance and targeted inhibition. The outcome is dehydration performance that is not only efficient but provably sustainable measured, verified, and continuously improved across the offshore asset's life (Adesanya, *et al*., 2020, Oziri, Seyi-Lande & Arowogbadamu, 2020).

3. Conclusion

The conceptual framework presented aligns rigorous thermodynamics, modular technology selection, digital control, and lifecycle sustainability into a coherent pathway for offshore dehydration that is measurably efficient, resilient, and compliant. By coupling energy/exergy analysis with pinch-guided heat integration, the framework unlocks meaningful reductions in regenerator fuel and recompression work while preserving dew-point margins under metocean variability. Model predictive control, soft sensors, and a physics-informed digital twin convert those thermodynamic insights into real-time action, stabilizing circulation, reflux, regeneration, membrane stage cuts, and sieve cycles despite turndown, slugging, and compositional drift. Reliability-centered maintenance and FMEA further compress failure likelihood and consequence, translating to fewer hydrate-related upsets, lower solvent losses, reduced flaring during disturbances, and extended asset life. When aggregated through auditable KPIs and a Dehydration Sustainability Index, expected outcomes are sustained improvements in specific energy, verifiable cuts in CH_4/CO_2 intensity, and demonstrable risk reduction across hydrate formation and corrosion exposure.

Limitations remain. Performance claims depend on model quality, analyzer fidelity, and data governance; bias, drift, or sparse sensing can erode estimation accuracy and encourage overly conservative setpoints. Space/weight constraints may cap the extent of heat recovery or hybridization achievable on legacy topsides, and short weather windows limit retrofit depth. Human factors alarm load, training gaps, and change-management friction can blunt the benefits of advanced control. Cyber-physical risk is nontrivial: tighter integration between optimization and actuation increases the blast radius of misconfiguration or intrusion if segmentation, validation, and rollback procedures are weak.

Future work will prioritize pilot validation at representative assets to quantify baselines, measure avoided exergy, and calibrate uncertainty under real disturbances. Scalability pathways include templated twins, modular control libraries, and fleet-level benchmarking that propagate learnings across diverse platforms without bespoke reengineering. On cybersecurity, the roadmap advances zero-trust architectures, signed model artifacts, simulation-in-the-loop testing of changes, and tamper-evident data lineage to protect both safety and ESG claims. With disciplined pilots, standardized deployment kits, and hardened cyber controls, the framework can scale from promising concept to a repeatable, defensible operating standard for sustainable offshore gas processing and dehydration.

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