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Decarbonisation Pathways for Legacy and Next-Generation Liquefaction Facilities: A Comprehensive Analysis of Emission Sources, Intervention Options and the Retrofit Constraint

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ABSTRACT: Liquefaction facilities are large point sources of carbon dioxide and, through the wider supply chain in which they sit, significant contributors of methane. Decarbonisation commitments now extend across the sector, and the interventions available to a facility differ sharply according to whether it is being designed or has been operating for twenty years. This paper analyses the pathways available to each, organised around the argument that the decisive variable is not the technical availability of an intervention but whether the facility was configured to accept it. Four positions are developed. First, the emission inventory of a liquefaction facility divides into combustion, process, methane and imported energy components whose relative magnitudes differ enough between facilities that a general prescription is unsound and a facility-specific inventory is the prerequisite for any pathway. Second, where combustion dominates the inventory, which is the common but not the universal case, the intervention with the largest potential effect on that component is the substitution of the refrigeration driver energy source, and its feasibility is determined by grid availability and by turbine hall configuration, both of which are effectively fixed at design. Third, methane reduction is argued to offer a favourable ratio of emission benefit to capital cost in the near term, on the reasoning that the measures are largely maintenance and operational rather than capital and that the emissions represent recoverable product; this is an analytical expectation rather than a costed result, and it is constrained principally by measurement rather than by abatement technology, since a facility cannot reduce what it cannot locate. Fourth, carbon capture is technically available and its application to liquefaction is favoured by the presence of a concentrated acid gas removal stream, which distinguishes this sector from most industrial capture applications and which is systematically underexploited. The paper reports no emission figures and no levelised costs, and its comparative rankings should be read as propositions for a facility to test against its own inventory and cost base rather than as findings. It closes on the sequencing question, arguing that operational and measurement interventions should precede capital ones because they are cheap, fast and generate the information the capital decisions require.

KEYWORDS: decarbonization, liquefied natural gas, methane emissions, carbon capture, electrification, retrofit, emissions inventory, energy efficiency, life cycle assessment.

1. INTRODUCTION

Liquefaction is energy intensive. Compressing and cooling natural gas to its liquid state at atmospheric pressure requires a substantial refrigeration duty, and that duty is supplied in most existing facilities by gas turbines burning a portion of the feed. The process configurations in which this is achieved, and the trade-offs between them in efficiency, capital cost and operability, are set out in the standard technical treatments of liquefaction plant design (Mokhatab, Mak, Valappil, & Wood, 2014; Lim, Choi, & Moon, 2013). The result is a facility that consumes a meaningful percentage of its own throughput and emits accordingly, in addition to the carbon dioxide separated from the feed in the acid gas removal step and vented, and in addition to methane released along the way.

The sector has committed to reduction. Operators have adopted net zero targets on timescales ranging from the middle of the century to considerably earlier, and the commitments have moved from statements to reporting obligations and, in several jurisdictions, to regulation. The commercial dimension has followed, with buyers beginning to differentiate cargoes by their upstream emissions intensity, which converts an environmental question into a market one.

The apparatus through which such a claim is substantiated is itself an active area of applied work, and it is worth naming because the analysis below assumes it. Embodied carbon accounting has been proposed as a set of decision gates inside project lifecycle governance rather than as a reporting exercise appended to it (Abdulhadi & Hamdan, 2026a), and the reconciliation of a lifecycle greenhouse gas footprint with regulatory risk inside a single decision framework has been attempted directly in an adjacent process sector (Okojie & Abioye, 2020).

What the commitments do not do is specify how a facility reaches them, and the pathways available differ radically between a facility being designed and one that has been operating for two decades. The design case has access to configuration choices, notably in the driver selection and the process line-up, that determine most of the emission profile and that are unavailable afterward at any reasonable cost. The operating case has access to efficiency, methane and, with more difficulty, retrofit interventions constrained by a layout that was not designed to accommodate them. This paper analyses both. It sets out the inventory structure, examines the intervention options against the retrofit constraint, addresses the measurement question that conditions the methane pathway, and closes on sequencing. It is written from an operating rather than a design perspective, which shapes its emphasis: the interventions available to people running an existing plant receive more attention than those available to people designing a new one. The commercial context is documented in market analyses tracing how technological change, environmental policy and geopolitical shifts have reshaped liquefaction supply and pricing, which is the setting in which emissions intensity has become a contractual rather than a reputational variable (Adekoya, Adefemi, Tula, Umoh, & Gidiagba, 2024). The associated question of how economic and environmental objectives are reconciled at project level has been reviewed directly for liquefaction development (Omisola, Etukudoh, Okenwa, Owulade, & Isi, 2025).

2. LITERATURE REVIEW

2.1 The Inventory Structure

Any pathway begins with an inventory, and the components differ enough in origin and in abatement route that they must be separated.

2.1.1 Combustion

Combustion emissions arise from the gas turbines driving the refrigeration compressors, from power generation, and from fired heaters. In most existing facilities this is the dominant carbon dioxide component and it scales with the refrigeration duty, which scales with production and with ambient temperature, so that a facility in a warm climate carries a structural penalty relative to one in a cool climate. The ambient dependence of a refrigeration duty and the control strategies available to offset it have been characterised in smaller-scale systems where the same thermodynamics apply (Sunday, Omoegun, Essien, & Oluokun, 2019).

2.1.2 Process emissions

Process emissions arise principally from the acid gas removal step, in which carbon dioxide present in the feed is separated and, in conventional configurations, vented. The magnitude depends entirely on feed composition and varies across a very wide range between fields. A facility with a lean feed has a small process component and one with a high carbon dioxide feed has a large one, and this single parameter can dominate the comparison between two otherwise similar facilities. The wider proposition, that a stream's composition determines the treatment burden and therefore the environmental profile of the operation built around it, is made in the produced water literature for the same upstream sector (Falegan & Aniebonam, 2022, 2023).

2.1.3 Methane

Methane emissions arise from fugitive losses, from venting, from incomplete flare combustion and from equipment such as pneumatic devices. Their magnitude in carbon dioxide equivalent terms depends on the horizon adopted, and on any horizon relevant to near-term commitments they are significant. The supply chain analyses establish both the importance of the methane component and the wide distribution of estimates for it (Balcombe, Anderson, Speirs, Brandon, & Hawkes, 2017; Balcombe, Brandon, & Hawkes, 2018).

2.1.4 Imported energy

Imported energy emissions arise where power is drawn from a grid, and carry the intensity of that grid. For most existing liquefaction facilities this component is small because they generate their own power; for facilities pursuing electrification it becomes the dominant component and its intensity determines whether electrification reduces emissions at all. The architecture of a grid carrying high renewable penetration, and the operational consequences for a large industrial load connected to it, are reviewed in the smart grid literature (Adenuga, 2022), and the voltage control questions that arise where distributed generation is present have been treated directly (Oshevire, Eyenubo, & Amayo, 2017).

The life cycle literature places these components within the wider supply chain and establishes that the liquefaction step is one contributor among several, with upstream production, shipping and regasification also material (Abrahams, Samaras, Griffin, & Matthews, 2015; Roman-White et al., 2021). The facility-level analysis conducted here addresses what a facility controls, and the wider accounting matters because it determines how the facility's performance is judged commercially. The regulatory dimension conditions what a facility can pursue and on what timescale, and comparative analyses of health, safety and environmental frameworks across energy-producing jurisdictions document both the compliance burden and its operational effects (Adikwu, Erhueh, Esiri, Aderamo, & Akano, 2024a). The related argument that compliance and corporate responsibility diverge, and that the gap is where sustainability commitments are actually tested, applies directly to decarbonisation targets adopted ahead of any regulatory requirement (Adikwu, Erhueh, Esiri, Aderamo, & Akano, 2024b).

The flare contribution deserves separate accounting because the combustion efficiency assumed in most inventories is not what field measurement finds, and unlit or inefficiently operating flares emit unburned methane in quantities large enough to alter a facility total (Plant et al., 2022; Caulton et al., 2014; Gvakharia et al., 2017; Ismail & Umukoro, 2012). Satellite observation makes the flared volume externally visible irrespective of self-reporting (Elvidge, Zhizhin, Baugh, Hsu, & Ghosh, 2016), and the recovery alternative has been examined directly (Rahimpour & Jokar, 2012). The intermediate observational scale, between the satellite and the surveyor on foot, is aerial, and the applied literature on uncrewed aerial survey of energy infrastructure covers the corridor and pipeline application directly (Dagodzo & Ahiaeke Patrick, 2020). The horizon adopted for methane is a policy choice rather than a physical constant and materially changes the ranking of options (Myhre et al., 2013; Intergovernmental Panel on Climate Change, 2021; Allen et al., 2016; Ocko et al., 2021).

3. ANALYSIS

3.1 Driver Energy: The Largest Combustion Lever and the Hardest Retrofit

The refrigeration compressor drivers determine the combustion component, and their configuration is the decisive design choice for that component. Whether it is also the decisive choice for the facility's emission profile as a whole depends on the inventory: in a facility with a high carbon dioxide feed the process component may rival or exceed it, and the ranking of levers changes accordingly.

The conventional configuration uses gas turbines burning feed gas. It is self-sufficient, requires no external infrastructure, and is well proven. It also means that the facility's largest emission source is inherent in its mechanical arrangement.

The electric drive configuration replaces the gas turbines with electric motors. Its emission consequence depends entirely on the power source: supplied from a low-carbon grid it reduces facility emissions substantially, and supplied from local gas-fired generation it may achieve little beyond relocating the combustion, with an efficiency penalty from the conversion. The configuration is now well established in newer projects where grid access is available.

For a facility being designed, the choice is a genuine option and turns on grid availability, grid intensity, power cost, reliability and the value placed on the emission reduction. For a facility already operating, it is effectively unavailable. Converting an existing turbine hall to electric drive requires the motors, the switchgear, the incoming supply, and the space and structural provision for all of it, in a facility whose layout was designed around turbines and which has no spare footprint in the relevant location. The intervention is not impossible. Whether it is uneconomic is a facility-specific question that this paper does not cost; what can be said is that the published record contains few examples of a full driver conversion undertaken on an operating facility, which is weak evidence of an unfavourable economic case rather than a demonstration of one.

What is available to an existing facility is a set of smaller efficiency measures on the existing configuration: turbine upgrades and re-rates, waste heat recovery where a use for the heat exists, improvements in the refrigerant cycle operation, air inlet cooling to recover the ambient temperature penalty, and the reduction of parasitic loads. On-site renewable generation serving the non-refrigeration load is a marginal but real contributor. Each measure is worth doing and their aggregate is modest relative to the driver substitution.

The general observation, and it applies well beyond this sector, is that the decarbonisation options available to a facility were largely determined by decisions taken during its design by engineers optimising for capital cost and reliability under an emissions regime that no longer applies. This is not a criticism of those engineers. It is an argument for treating retrofit accommodation as a design requirement in current projects, since the facilities being designed now will face a regime in 2050 that no one is currently specifying for.

The process design literature addresses the efficiency dimension in detail and is the reference point for what a given configuration can achieve. The optimisation of liquefaction cycles has been surveyed comprehensively (Austbø, Løvseth, & Gundersen, 2014; Khan, Karimi, & Wood, 2017), the status and trajectory of plant design reviewed (Lim, Choi, & Moon, 2013; Mokhatab, Mak, Valappil, & Wood, 2014; Kidnay, Parrish, & McCartney, 2011), and the air separation energy that conditions any nitrogen or oxygen-dependent option characterised (Smith & Klosek, 2001). Sector reviews address the safety and efficiency technologies deployed in current operations (Ozowe, Ukato, Jambol, & Daramola, 2024).

Where electrification is the pathway, the grid it draws on becomes part of the facility emission profile and its architecture becomes a design question rather than a given. The smart grid architecture that a supply carrying high renewable penetration requires has been reviewed directly, together with the operational consequences for a large industrial load connected to it (Adenuga, 2022), and the voltage control questions that arise where distributed generation sits on the same network are a further constraint on what such a supply can firmly deliver (Oshevire, Eyenubo, & Amayo, 2017). The practical point for a facility is that the emission benefit of electrification is a property of the supply it contracts rather than of the motor it installs, which makes it contingent in a way that a combustion pathway is not.

Machinery condition and reliability bear on the efficiency achievable from the existing configuration, since a degraded machine consumes more energy for the same duty long before it fails (Jardine, Lin, & Banjevic, 2006; Lei et al., 2018; Moubray, 1997). The applied literature on the transition from a reactive to a predictive maintenance posture is directly relevant (Sunday, Omoegun, Essien, & Oluokun, 2020), as is the reliability-centred framing that determines which machines warrant the instrumentation in the first place (Oyeleke, Eze, & Asiedu, 2026). Static equipment integrity conditions the same efficiency question, since fouling, corrosion and weld degradation alter thermal and hydraulic performance long before they threaten containment, and non-destructive evaluation is the means by which that condition is established (Atta, Tofah, Kankam, & Adenuga, 2020; Atta, Tofah, & Adenuga, 2021). The spares and materials position determines whether a condition-based finding can be acted on inside the window it identifies, which makes the supply chain a constraint on efficiency rather than an administrative adjunct to it (Okonkwo, Agbabiaka, Ogunwole, Mayo, & Okeke, 2021; Okonkwo, Ogunwole, & Okeke, 2018b; Okonkwo, Agbabiaka, Mayo, & Okeke, 2024c).

3.2 Methane: A Favourable Ratio, Constrained by Measurement

Methane reduction is expected to offer a favourable ratio of emission benefit to capital cost for an operating facility, for three reasons: the warming potency per unit mass is high on the horizons that matter for near-term commitments, the emissions are largely unintentional and therefore represent recoverable product, and the abatement measures are principally maintenance and operational rather than capital. The claim is a qualitative one and is advanced here as such. It is consistent with the mitigation cost literature, which finds that a substantial share of oil and gas methane emissions can be addressed by measures whose cost is low relative to conventional carbon dioxide abatement and in some cases negative once recovered gas is valued (Kemp & Ravikumar, 2021; Ravikumar & Brandt, 2017). Whether it holds for a particular facility depends on that facility's methane inventory, its gas price and the marginal cost of its survey and repair programme, none of which is estimated here. The stronger and less contingent part of the argument is the second half: that the binding constraint is measurement rather than abatement.

The constraint is not abatement but location. A facility cannot repair what it has not found, and the evidence on emission distributions establishes that the total is dominated by a small number of large sources whose identity is not predictable from component type or age (Brandt, Heath, & Cooley, 2016; Zavala-Araiza et al., 2015). The reconciliation work between measurement scales establishes that component-level surveys systematically miss part of the total, and the supply chain assessment attributes a substantial share to abnormal operating conditions rather than to the steady-state population that surveys address (Alvarez et al., 2018).

The practical consequence for a decarbonisation pathway is that the measurement investment precedes the abatement investment and is the higher priority. A facility that improves its detection and quantification capability will find sources it did not know it had; a facility that increases its repair capacity without improving detection will repair the sources it already knew about faster.

Three measurement layers are relevant and they are complementary rather than alternative. Component-level survey locates and permits repair. Facility-scale measurement, whether by mobile survey, fixed monitoring or aerial and satellite observation, bounds the total and reveals the fraction the component survey is missing. And continuous monitoring of the sources known to be intermittent addresses the abnormal-condition contribution that periodic survey cannot by construction detect.

The flare system deserves specific mention within the methane pathway because it is both an emission source and a control. Incomplete flare combustion releases methane, and the assumed combustion efficiency used in most reporting is higher than field measurement supports. Meanwhile background flow to flare, arising from passing valves and relief devices, represents hydrocarbon loss that flaring converts to carbon dioxide rather than eliminating. Both are addressable operationally and neither requires capital.

The evidence underlying this position has firmed considerably. The distribution of emissions across sources is heavy-tailed at every scale examined (Brandt, Heath, & Cooley, 2016; Frankenberg et al., 2016; Omara et al., 2018), the largest sources arise from abnormal process conditions rather than from a distinct defective population (Zavala-Araiza et al., 2017), and they are intermittent enough that periodic survey systematically undercounts them (Vaughn et al., 2018; Cusworth et al., 2021; Duren et al., 2019; Lauvaux et al., 2022). National inventory reconciliation confirms the resulting gap (Rutherford et al., 2021; Alvarez, Pacala, Winebrake, Chameides, & Hamburg, 2012; Brandt et al., 2014). Detection capability has been characterised under controlled conditions and by independent protocol (Zimmerle et al., 2020; Bell, Vaughn, & Zimmerle, 2020; Kemp & Ravikumar, 2021), and satellite observation now resolves point sources at facility scale (Jacob et al., 2022). The three measurement layers proposed here correspond to established practice in the measurement literature: component-level survey for location and repair (United States Environmental Protection Agency, 2016, 2017; Fox, Barchyn, Risk, Ravikumar, & Hugenholtz, 2019; Ravikumar, Wang, McGuire, Bell, Zimmerle, & Brandt, 2018), facility-scale measurement to bound the total (Zavala-Araiza et al., 2015; Alvarez et al., 2018), and continuous monitoring for the intermittent contribution (Ravikumar & Brandt, 2017; Ravikumar et al., 2019).

Each layer has an applied engineering literature behind it that the atmospheric science literature does not address, and it is the engineering constraint rather than the detection physics that usually determines what a facility deploys. The economics of permanent instrumentation on a congested site turn on whether the sensors can be powered and maintained, and the energy-autonomous sensing literature addresses precisely this, treating radio frequency harvesting as a route to sensors that require no battery service visit (W. Asiedu & Quainoo, 2023a) and characterising the energy, reliability and latency trade-offs that determine what such a network can actually report (W. Asiedu & Quainoo, 2024). The radio layer conditions all of it, and the link behaviour of the wireless systems on which such networks are built has been characterised directly (Quainoo, Ogundapo, & Asiedu, 2024). The organisational counterpart of continuous measurement is a data stream rather than a survey report, and a facility that instruments at this density has changed its reporting problem as much as its detection one.

Two further strands bear on what a facility can claim. Emission factor development and inventory methodology determine how a reported figure is constructed (Allen, 2014; Zavala-Araiza et al., 2015b). The custody and traceability of the underlying data determine whether that figure survives assurance, which makes data governance a condition of the claim rather than an administrative adjunct to it.

3.3 Carbon Capture: An Unusually Favourable Application

Carbon capture applied to liquefaction has a characteristic that distinguishes it from most industrial applications and that is systematically underexploited.

The general difficulty with carbon capture is that the carbon dioxide to be captured is dilute, present in a flue gas at low concentration alongside nitrogen, so that the separation is the dominant cost. This concentration dependence is the central variable in the capture cost literature, and it is why the cost of capture from a dilute source is consistently reported as several times that from a concentrated one (Bui et al., 2018; Leung, Caramanna, & Maroto-Valer, 2014; Rochelle, 2009).

A liquefaction facility already performs a carbon dioxide separation for process reasons. Acid gas removal exists because carbon dioxide must be taken out of the feed before the cryogenic section, where it would freeze. The stream leaving that unit is concentrated, and in conventional practice it is vented. Capturing it requires compression, transport and storage but not separation, which is the expensive part everywhere else.

This makes the process emission component of a liquefaction facility a favourable capture target relative to its own flue gas, and the favourability increases with feed carbon dioxide content, so that the facilities with the largest process emissions are the ones where the argument is strongest. The comparison being made is with capture from other streams at the same facility rather than with the wider set of abatement options open to it, and it rests on the separation step having already been paid for rather than on any costing performed here. Several projects have implemented this configuration and it is proven.

The constraint is storage. Capture requires a geological storage destination with adequate capacity, acceptable containment, and a regulatory framework permitting injection and assigning long-term liability. Where a suitable formation is available near the facility the pathway is viable; where it is not, the captured stream has nowhere to go and the capture is pointless. This is a locational rather than a technical constraint and it cannot be engineered around. The subsurface injection and long-term stewardship questions have a close operational analogue in produced water handling, where the same industry already manages high-volume injection, containment assurance and permitting, and where the lifecycle risk framing has been developed explicitly (Falegan & Aniebonam, 2022). The alternative to storage, in which the captured stream is used rather than sequestered, has been examined for mature producing assets (Ijiga, Enyejo, Jinadu, Akinleye, Onwusi, & Raphael, 2023).

The combustion emission component remains the harder case, being dilute flue gas, and capture on it faces the general economics rather than the favourable ones. For an existing facility it also faces the space constraint that applies to every retrofit.

The sequencing implication follows: a facility with meaningful feed carbon dioxide and accessible storage has grounds to assess the acid gas stream before any other capture option, because the separation that dominates capture cost elsewhere has already been performed for process reasons. Whether it is in fact the lowest-cost tonne available to that facility depends on compression, transport and storage costs that are site-specific and are not estimated here, and the proposition is offered as a screening rule rather than as a costed conclusion. The delivery of such a retrofit is a project rather than an operational change, and it is a capital project with no revenue of its own, which makes the financing structure part of the feasibility question rather than a downstream administrative matter. Contracting structures that tie payment to sustainability outcomes are one route through which that question is now being addressed (Abdulhadi & Hamdan, 2026c).

The technology and its economics have been reviewed repeatedly as the field matured (Boot-Handford et al., 2014; Leung, Caramanna, & Maroto-Valer, 2014; Metz, Davidson, de Coninck, Loos, & Meyer, 2005), and amine scrubbing remains the reference process against which alternatives are judged (Rochelle, 2009). The storage side carries its own literature on capacity, containment and long-term security (Benson & Cole, 2008; Alcalde et al., 2018), and it is the element that determines whether the favourable separation economics can be realised at all.

3.4 The Retrofit Constraint

A theme running through the preceding sections deserves separate statement, because it determines what any existing facility can actually do.

An operating liquefaction facility is a congested site whose layout was fixed at design. Space adjacent to the units where a retrofit would connect is occupied. Utilities are sized for the original configuration. Electrical distribution has limited spare capacity. Pipe racks are full. And any modification requires tie-ins to operating systems, which requires shutdowns, which have a production cost and which carry the interface and isolation risks that attend all brownfield work.

The consequence is that the same intervention costs several times more on an operating facility than on a project, and that some interventions are simply unavailable. The economic screening of decarbonisation options for an existing facility therefore produces a different ranking from the screening for a new one, and importing a ranking developed for greenfield application will misdirect the programme.

Three implications follow for an operating facility. Prefer interventions that do not require space or tie-ins, which means operational, maintenance and measurement interventions first. Sequence any physical modification against planned shutdowns, and treat the shutdown schedule as the binding constraint on the capital programme rather than the capital budget. And identify, early, the small number of interventions that would require a major outage, since these compete with each other for a scarce opportunity and the choice between them should be made deliberately rather than by whichever is ready first.

The materials position is the second binding constraint and is less often recognised as one, since a turnaround scope that cannot be supplied is not a scope. The applied procurement literature for energy facilities addresses the materials readiness on which a planned scope depends (Okonkwo, Agbabiaka, Ogunwole, Mayo, & Okeke, 2021), the relationship between inventory availability and plant uptime (Okonkwo, Ogunwole, & Okeke, 2018b), and the predictive planning through which the two are reconciled ahead of a shutdown (Okonkwo, Agbabiaka, Mayo, & Okeke, 2024c). The same structural problem has been analysed in a different regulated sector whose supply constraints are comparable, where inefficiency in the chain has been traced through to its downstream consequences (C. S. Asiedu & A. A. Asiedu, 2023).

For facilities under design, the corresponding implication is to specify retrofit accommodation: space adjacent to the acid gas removal unit for future capture equipment, electrical capacity margin, pipe rack provision, and tie-in points installed and blanked. Each is inexpensive at design and each preserves an option whose value is currently unknown and is unlikely to be zero. The organisational setting in which such a decision is taken is frequently a joint venture with divergent shareholder positions on decarbonisation, and aligning governance across those parties is better treated as a process design problem than as a negotiating one.

The project delivery literature explains why retrofit accommodation is so rarely specified. Front-end definition quality dominates outcomes, optimism bias and schedule pressure compress exactly the provisions whose value is deferred, and options preserved for an uncertain future are the first casualty of capital discipline at sanction (Flyvbjerg, 2014; Flyvbjerg, Bruzelius, & Rothengatter, 2003; Merrow, 2011). Project management analyses directed specifically at liquefaction reach compatible conclusions about where environmental outcomes are actually determined (Ihwughwavwe & Usiagu, 2024).

The brownfield execution problem is the same one that governs any tie-in to a live facility, and its safety dimension is treated in the control of work and barrier literatures rather than in the decarbonisation literature (Health and Safety Executive, 2005, 2006b; Center for Chemical Process Safety & Energy Institute, 2018; Sklet, 2006; Johansen & Rausand, 2015; Hollnagel, 2004; Reason, 1997; Kletz, 2001; Cullen, 1990; Hopkins, 2008; Mannan, 2012; Crowl & Louvar, 2011; International Electrotechnical Commission, 2016). A retrofit programme is delivered by contractors working inside an operating facility, which brings the occupational health exposures of the work itself into scope alongside the process hazards it is more usually assessed against (Ozobu, Adikwu, Odujobi, Onyekwe, & Nwulu, 2025).

Energy management systems supply the standing framework within which efficiency measures on the existing configuration are identified and sustained (International Organization for Standardization, 2018b; Moubray, 1997).

4. DISCUSSION

4.1 Sequencing

The analysis supports a sequence, and the sequence differs from the one facilities characteristically adopt.

4.1.1 Step one: inventory

First, inventory. A facility-specific inventory separating combustion, process, methane and imported energy components, with the methane component derived from measurement rather than from emission factors. Nothing else in the pathway can be prioritised without it, and the emission-factor-derived methane figures most facilities currently report are not adequate for the purpose.

4.1.2 Step two: measurement capability

Second, measurement capability. Detection and quantification for methane, flare header metering with adequate turndown, and combustion efficiency verification. These are cheap, fast and generate the information the later steps require.

4.1.3 Step three: operational and maintenance interventions

Third, operational and maintenance interventions. Flare hunting, leak repair, purge rate reassessment, start-up sequencing, efficiency optimisation on existing machinery. These require no capital, no space and no shutdown, and their aggregate effect is larger than is generally assumed before the measurement in step two reveals what is available. Interventions of this kind are procedural rather than capital, and they persist only if they are embedded in standard operating procedure and sustained through deliberate change management rather than campaign effort. Lean process-improvement method applied to inventory and distribution in a different regulated sector illustrates the same transferable point, that the recoverable losses sit in the handovers rather than in the equipment (C. S. Asiedu, 2025).

4.1.4 Step four: acid gas capture assessment

Fourth, the acid gas capture assessment, where feed composition and storage access make it viable. On the reasoning set out in section 3.3 this is the capture option a facility has the strongest grounds to screen first, and it should be assessed before any consideration of flue gas capture.

4.1.5 Step five: major retrofits

Fifth, the major retrofit questions, sequenced against shutdown opportunities and chosen deliberately between competing candidates.

The characteristic error is to begin at the fourth or fifth step, because they are the ones that appear in decarbonisation strategy documents and because they are visible commitments. Beginning there means committing capital on the basis of an inventory that has not been measured, and the methane component in particular is frequently misestimated by a factor large enough to change the ranking of the options the capital is being committed against.

The indicator and metrics literature bears on the first two steps, since an inventory that cannot be trusted cannot prioritise anything and the selection of what to measure determines what gets managed (American Petroleum Institute, 2016; Health and Safety Executive, 2006; Center for Chemical Process Safety, 2007, 2010; Hopkins, 2009; Kerr, 1975). The corollary is that a measured indicator becomes an incentive whether or not it was intended as one, which matters more where the reported figure has acquired commercial consequence.

The sustainability and compliance framing that governs how such programmes are reported has been examined for the energy sector directly (Adikwu, Erhueh, Esiri, Aderamo, & Akano, 2024b). Predictive safety analytics has been reviewed for liquefaction projects with explicit environmental, social and governance framing (Arumosoye, Obriki, & Ozobu, 2026).

Inventory accuracy is the first step and has its own applied literature. Data integration methods for improving greenhouse gas inventory reporting accuracy address exactly the reconciliation problem the sequence begins with (Azeez & Badmus, 2024), and carbon accounting accuracy in corporate sustainability programmes has been evaluated directly (Lamidi, 2023). Carbon dioxide utilisation as an alternative to storage has been examined for mature producing assets (Ijiga, Enyejo, Jinadu, Akinleye, Onwusi, & Raphael, 2023).

5. LIMITATIONS

This paper is an analysis of pathways and not a quantitative assessment. No emission figures are reported, no capital or operating costs are estimated, and no levelised abatement cost is computed for any option. The comparative claims that follow from this, that combustion dominates in most existing facilities, that methane offers a favourable benefit-to-cost ratio, that driver substitution is the largest available lever on the combustion component, and that acid gas capture is the lowest-cost capture tonne, are analytical expectations derived from the structure of the problem rather than results. Each is stated in the text with the reasoning that supports it and the conditions under which it would fail, and each is capable of being contradicted by a facility-specific inventory and cost estimate. A quantitative treatment establishing marginal abatement costs across these options for a defined facility would be the natural companion to this paper and is not attempted here.

The paper does not address hydrogen, ammonia or other alternative energy carriers as pathways for the sector, nor the demand-side question of what role liquefied natural gas plays in a decarbonising energy system. Those are important and are outside a facility-level analysis.

The treatment of carbon capture addresses the acid gas stream in favourable terms and does not develop the transport, storage, monitoring and long-term liability questions, each of which is substantial and none of which is a facility engineering question.

The paper draws on the liquefaction process literature for the technical context and on the supply chain emissions literature for the inventory framing, and does not engage the substantial modelling literature on liquefaction process optimisation, which addresses efficiency at a level of detail beyond the present scope.

Finally, the paper is written from an operating perspective and gives correspondingly less attention to design-stage options than their importance warrants. The observation that most of a facility's emission profile is determined at design is made repeatedly here and its practical development would require a design-stage paper this one does not attempt.

Three literatures the paper does not engage should be named, since a reader may reasonably expect them. The alternative energy carrier question, covering hydrogen and ammonia as routes for the sector, is substantial and outside a facility-level analysis (Bui et al., 2018; Boot-Handford et al., 2014). The renewable generation any electrification pathway ultimately draws on carries its own materials and degradation constraints, which condition the durability of the emission reduction claimed (Atta, Kerubo, Sabisa, Adu-Gyamfi, Appiah, & Onyishi, 2025). The demand-side question of what role liquefied natural gas plays in a decarbonising system is contested and is addressed in the life cycle and supply chain literature rather than here (Abrahams, Samaras, Griffin, & Matthews, 2015; Roman-White et al., 2021; Balcombe, Anderson, Speirs, Brandon, & Hawkes, 2017; Balcombe, Brandon, & Hawkes, 2018). And the transport, storage, monitoring and long-term liability elements of any capture pathway are treated only in outline (Metz, Davidson, de Coninck, Loos, & Meyer, 2005; Benson & Cole, 2008; Alcalde et al., 2018; Leung, Caramanna, & Maroto-Valer, 2014).

The distributional dimension of a decarbonisation programme is outside a facility-level analysis and is not thereby unimportant, particularly where the facility is a major regional employer. Worker displacement in energy transitions has been quantified econometrically alongside a skills mapping, and the finding that displaced roles are not replaced one for one bears directly on how a facility-level programme is received by the workforce and the community around it (Komi & Adamolekun, 2024).

The wider mitigation literature bounds what any facility pathway can contribute. Analyses of net-zero energy systems identify the sectors where decarbonisation is hardest and why (Davis et al., 2018), the assessment of pathways consistent with limiting warming sets the surrounding policy frame (Intergovernmental Panel on Climate Change, 2018), and the negative emissions literature examines the biophysical and economic limits of the removal options a residual-emissions argument would rely on (Smith et al., 2016; Fuss et al., 2018).

6. CONCLUSION

The decarbonisation options available to a liquefaction facility are determined less by what technology exists than by what the facility was configured to accept. Where combustion dominates the inventory, driver energy substitution is the largest single lever on it, and it is effectively a design-stage decision; for an operating facility it is available only as a set of smaller efficiency measures on the existing arrangement.

Methane reduction is argued here to offer a favourable ratio of benefit to capital cost, on the grounds that the measures are largely maintenance rather than capital and that the emissions are recoverable product. That part of the argument is an expectation this paper does not cost. The part that does not depend on costing is that the binding constraint is measurement rather than abatement, since the total is dominated by sources whose identity is not predictable and which component surveys systematically miss. Measurement investment therefore precedes abatement investment in any defensible pathway.

Carbon capture applied to the acid gas removal stream is an unusually favourable application, because the separation the general case pays for has already been performed for process reasons, and the favourability increases with the feed carbon dioxide content that makes the emission large. Where geological storage is accessible this is the capture option a facility has the strongest grounds to screen first, subject to compression, transport and storage costs that are site-specific, and it is underexploited.

And the sequence matters. Inventory, then measurement capability, then operational and maintenance interventions, then the acid gas assessment, then the major retrofits chosen deliberately against scarce shutdown opportunities. Facilities characteristically begin near the end of that list, committing capital against an inventory whose largest uncertainty they have not resolved.

For facilities now being designed, the durable conclusion is to specify retrofit accommodation. Space, electrical margin, rack provision and blanked tie-ins are inexpensive at design and preserve options whose value cannot currently be calculated but is unlikely to be zero.

Two further considerations bear on how a facility should approach the sequence. Decarbonisation competes for the same scarce shutdown windows as every other capital modification, so the programme is bounded by turnaround planning rather than by capital availability (Duffuaa & Ben-Daya, 2004; Okonkwo, Agbabiaka, Mayo, & Okeke, 2024c). And the organisational interface between an operating facility and the project organisation delivering any retrofit determines whether the work is executed safely against a live plant, which is a design question for the programme rather than an execution detail (Lawrence & Lorsch, 1967; Galbraith, 1974; Thompson, 1967; Adikwu, Esiri, Aderamo, Akano, & Erhueh, 2024c).

REFERENCES

1) Abdulhadi, B. M., & Hamdan, A. M. (2026a). Carbon-driven decision gates: Integrating embodied carbon accounting into construction project lifecycle governance. Research Journal of Pure Science and Technology, 9(5), 48-82.
2) Abdulhadi, B. M., & Hamdan, A. M. (2026c). Sustainability-linked contracting and incentive alignment in integrated project delivery: A conceptual framework. International Journal of Social Sciences and Management Research, 12(6), 466-501.
3) Abrahams, L. S., Samaras, C., Griffin, W. M., & Matthews, H. S. (2015). Life cycle greenhouse gas emissions from U.S. liquefied natural gas exports: Implications for end uses. Environmental Science and Technology, 49(5), 3237-3245.
4) Adekoya, O. O., Adefemi, A., Tula, O. A., Umoh, A. A., & Gidiagba, J. O. (2024). A comprehensive review of liquefied natural gas (LNG) market dynamics: Analyzing the current trends, challenges, and opportunities in the global LNG market. World Journal of Advanced Research and Reviews, 21(1), 58-74.
5) Adenuga, O. M. (2022). Smart grid architectures and energy distribution for high renewable penetration: A comprehensive review of technologies, operations, and deployment pathways. International Journal of Engineering and Modern Technology, 8(5), 125-155.
6) Adikwu, F. E., Erhueh, O. V., Esiri, A. E., Aderamo, A. T., & Akano, O. A. (2024a). Global HSE regulatory frameworks and their impact on operational efficiency in the energy sector. International Journal of Frontiers in Engineering and Technology Research, 7(2), 57-69.
7) Adikwu, F. E., Erhueh, O. V., Esiri, A. E., Aderamo, A. T., & Akano, O. A. (2024b). Sustainable HSE practices in energy production: Bridging the gap between compliance and corporate responsibility. International Journal of Engineering Research and Development, 20(11), 1224-1233.
8) Adikwu, F. E., Esiri, A. E., Aderamo, A. T., Akano, O. A., & Erhueh, O. V. (2024c). Advancing process safety management systems in the oil and gas industry: Strategies for risk mitigation. World Journal of Engineering and Technology Research, 3(2), 1-10.
9) Alcalde, J., Flude, S., Wilkinson, M., Johnson, G., Edlmann, K., Bond, C. E., Scott, V., Gilfillan, S. M. V., Ogaya, X., & Haszeldine, R. S. (2018). Estimating geological storage security over 10,000 years. Nature Communications, 9, 2201.
10) Allen, D. T. (2014). Atmospheric emissions and air quality impacts from natural gas production and use. Annual Review of Chemical and Biomolecular Engineering, 5, 55-75.
11) Allen, M. R., Fuglestvedt, J. S., Shine, K. P., Reisinger, A., Pierrehumbert, R. T., & Forster, P. M. (2016). New use of global warming potentials to compare cumulative and short-lived climate pollutants. Nature Climate Change, 6(8), 773-776.
12) Alvarez, R. A., Pacala, S. W., Winebrake, J. J., Chameides, W. L., & Hamburg, S. P. (2012). Greater focus needed on methane leakage from natural gas infrastructure. Proceedings of the National Academy of Sciences, 109(17), 6435-6440.
13) Alvarez, R. A., Zavala-Araiza, D., Lyon, D. R., Allen, D. T., Barkley, Z. R., Brandt, A. R., Davis, K. J., Herndon, S. C., Jacob, D. J., Karion, A., Kort, E. A., Lamb, B. K., Lauvaux, T., Maasakkers, J. D., Marchese, A. J., Omara, M., Pacala, S. W., Peischl, J., Robinson, A. L., Shepson, P. B., Sweeney, C., Townsend-Small, A., Wofsy, S. C., & Hamburg, S. P. (2018). Assessment of methane emissions from the U.S. oil and gas supply chain. Science, 361(6398), 186-188.
14) American Petroleum Institute. (2016). Process safety performance indicators for the refining and petrochemical industries (API Recommended Practice 754, 2nd ed.). API Publishing Services.
15) Arumosoye, O. M., Obriki, O. D., & Ozobu, C. O. (2026). Systematic review of predictive safety analytics applications in LNG projects with ESG implications. Global Journal of Engineering and Technology Review, 2(2), 61-73.

16) Asiedu, C. S. (2025). A lean process-improvement framework for pharmaceutical inventory and distribution management. International Journal of Health and Pharmaceutical Research, 10(12), 225-252.
17) Asiedu, C. S., & Asiedu, A. A. (2023). Pharmaceutical supply chain inefficiencies and medication affordability in resource-constrained health systems: A narrative review. International Journal of Health and Pharmaceutical Research, 8(4), 192-222.
18) Asiedu, W., & Quainoo, R. (2023a). How far can energy harvesting take us? A systematic review of radio frequency strategies for energy autonomous sensing. Shodhshauryam, International Scientific Refereed Research Journal, 6(1), 448-466.
19) Asiedu, W., & Quainoo, R. (2024). Rethinking energy, reliability, and latency trade-offs in green communication for next generation IoT. International Journal of Multidisciplinary Research and Growth Evaluation, 5(6), 1987-1994.
20) Atta, S., Kerubo, M. L., Sabisa, N. E., Adu-Gyamfi, D., Appiah, S., & Onyishi, E. (2025). Environmental corrosion and long-term degradation of crystalline silicon solar cells: Mechanisms, climate effects and mitigation strategies. Current Journal of Applied Science and Technology, 44(10), 9-18.
21) Atta, S., Tofah, P., & Adenuga, O. M. (2021). Advances in non-destructive testing methods for weld integrity evaluation in high-capacity power infrastructure. International Journal of Engineering and Modern Technology, 7(1), 20-47.
22) Atta, S., Tofah, P., Kankam, M. A., & Adenuga, O. M. (2020). A critical review of NDT-based integrity management and corrosion risk assessment strategies for refinery process equipment. International Journal of Engineering and Modern Technology, 6(2), 19-46.
23) Austbø, B., Løvseth, S. W., & Gundersen, T. (2014). Annotated bibliography: Use of optimization in LNG process design and operation. Computers and Chemical Engineering, 71, 391-414.
24) Azeez, L. O., & Badmus, O. (2024). Innovative data integration method for enhancing GHG inventory reporting accuracy and reliability. Global Multidisciplinary Perspectives Journal, 1(6), 166-181.
25) Balcombe, P., Anderson, K., Speirs, J., Brandon, N., & Hawkes, A. (2017). The natural gas supply chain: The importance of methane and carbon dioxide emissions. ACS Sustainable Chemistry and Engineering, 5(1), 3-20.
26) Balcombe, P., Brandon, N. P., & Hawkes, A. D. (2018). Characterising the distribution of methane and carbon dioxide emissions from the natural gas supply chain. Journal of Cleaner Production, 172, 2019-2032.
27) Bell, C., Vaughn, T., & Zimmerle, D. (2020). Evaluation of next generation emission measurement technologies under repeatable test protocols. Elementa: Science of the Anthropocene, 8, 32.
28) Benson, S. M., & Cole, D. R. (2008). CO2 sequestration in deep sedimentary formations. Elements, 4(5), 325-331.
29) Boot-Handford, M. E., Abanades, J. C., Anthony, E. J., Blunt, M. J., Brandani, S., Mac Dowell, N., Fernández, J. R., Ferrari, M.-C., Gross, R., Hallett, J. P., Haszeldine, R. S., Heptonstall, P., Lyngfelt, A., Makuch, Z., Mangano, E., Porter, R. T. J., Pourkashanian, M., Rochelle, G. T., Shah, N., Yao, J. G., & Fennell, P. S. (2014). Carbon capture and storage update. Energy and Environmental Science, 7(1), 130-189.
30) Brandt, A. R., Heath, G. A., & Cooley, D. (2016). Methane leaks from natural gas systems follow extreme distributions. Environmental Science and Technology, 50(22), 12512-12520.
31) Brandt, A. R., Heath, G. A., Kort, E. A., O'Sullivan, F., Pétron, G., Jordaan, S. M., Tans, P., Wilcox, J., Gopstein, A. M., Arent, D., Wofsy, S., Brown, N. J., Bradley, R., Stucky, G. D., Eardley, D., & Harriss, R. (2014). Methane leaks from North American natural gas systems. Science, 343(6172), 733-735.
32) Bui, M., Adjiman, C. S., Bardow, A., Anthony, E. J., Boston, A., Brown, S., Fennell, P. S., Fuss, S., Galindo, A., Hackett, L. A., Hallett, J. P., Herzog, H. J., Jackson, G., Kemper, J., Krevor, S., Maitland, G. C., Matuszewski, M., Metcalfe, I. S., Petit, C., Puxty, G., Reimer, J., Reiner, D. M., Rubin, E. S., Scott, S. A., Shah, N., Smit, B., Trusler, J. P. M., Webley, P., Wilcox, J., & Mac Dowell, N. (2018). Carbon capture and storage (CCS): The way forward. Energy and Environmental Science, 11(5), 1062-1176.
33) Caulton, D. R., Shepson, P. B., Cambaliza, M. O. L., McCabe, D., Baum, E., & Stirm, B. H. (2014). Methane destruction efficiency of natural gas flares associated with shale formation wells. Environmental Science and Technology, 48(16), 9548-9554.
34) Center for Chemical Process Safety & Energy Institute. (2018). Bow ties in risk management: A concept book for process safety. Wiley.
35) Center for Chemical Process Safety. (2007). Guidelines for risk based process safety. Wiley.
36) Center for Chemical Process Safety. (2010). Guidelines for process safety metrics. Wiley.
37) Crowl, D. A., & Louvar, J. F. (2011). Chemical process safety: Fundamentals with applications (3rd ed.). Prentice Hall.
38) Cullen, W. D. (1990). The public inquiry into the Piper Alpha disaster. Her Majesty's Stationery Office.
39) Cusworth, D. H., Duren, R. M., Thorpe, A. K., Olson-Duvall, W., Heckler, J., Chapman, J. W., Eastwood, M. L., Helmlinger, M. C., Green, R. O., Asner, G. P., Dennison, P. E., & Miller, C. E. (2021). Intermittency of large methane emitters in the Permian Basin. Environmental Science and Technology Letters, 8(7), 567-573.
40) Dagodzo, D., & Ahiaeke Patrick, M. C. (2020). UAV-based pipeline and corridor monitoring: A review of current practices and emerging technologies. Iconic Research and Engineering Journals, 3(10), 574-597.
41) Davis, S. J., Lewis, N. S., Shaner, M., Aggarwal, S., Arent, D., Azevedo, I. L., Benson, S. M., Bradley, T., Brouwer, J., Chiang, Y.-M., Clack, C. T. M., Cohen, A., Doig, S., Edmonds, J., Fennell, P., Field, C. B., Hannegan, B., Hodge, B.-M., Hoffert, M. I., Ingersoll, E., Jaramillo, P., Lackner, K. S., Mach, K. J., Mastrandrea, M., Ogden, J., Peterson, P. F., Sanchez, D. L., Sperling, D., Stagner, J., Trancik, J. E., Yang, C.-J., & Caldeira, K. (2018). Net-zero emissions energy systems. Science, 360(6396), eaas9793.
42) Duffuaa, S. O., & Ben-Daya, M. (2004). Turnaround maintenance in petrochemical industry: Practices and suggested improvements. Journal of Quality in Maintenance Engineering, 10(3), 184-190.
43) Duren, R. M., Thorpe, A. K., Foster, K. T., Rafiq, T., Hopkins, F. M., Yadav, V., Bue, B. D., Thompson, D. R., Conley, S., Colombi, N. K., Frankenberg, C., McCubbin, I. B., Eastwood, M. L., Falk, M., Herner, J. D., Croes, B. E., Green, R. O., & Miller, C. E. (2019). California methane super-emitters. Nature, 575(7781), 180-184.

44) Elvidge, C. D., Zhizhin, M., Baugh, K., Hsu, F.-C., & Ghosh, T. (2016). Methods for global survey of natural gas flaring from Visible Infrared Imaging Radiometer Suite data. Energies, 9(1), 14.
45) Falegan, O. C., & Aniebonam, S. O. (2022). Conceptual framework for lifecycle risk assessment in offshore produced water management. Gyanshauryam, International Scientific Refereed Research Journal, 5(5), 322-345.
46) Falegan, O. C., & Aniebonam, S. O. (2023). Integrated physicochemical and bio-based treatment strategies for produced water in arid environments: A review. Gyanshauryam, International Scientific Refereed Research Journal, 6(1), 425-443.
47) Flyvbjerg, B. (2014). What you should know about megaprojects and why: An overview. Project Management Journal, 45(2), 6-19.
48) Flyvbjerg, B., Bruzelius, N., & Rothengatter, W. (2003). Megaprojects and risk: An anatomy of ambition. Cambridge University Press.
49) Fox, T. A., Barchyn, T. E., Risk, D., Ravikumar, A. P., & Hugenholtz, C. H. (2019). A review of close-range and screening technologies for mitigating fugitive methane emissions in upstream oil and gas. Environmental Research Letters, 14(5), 053002.
50) Frankenberg, C., Thorpe, A. K., Thompson, D. R., Hulley, G., Kort, E. A., Vance, N., Borchardt, J., Krings, T., Gerilowski, K., Sweeney, C., Conley, S., Bue, B. D., Aubrey, A. D., Hook, S., & Green, R. O. (2016). Airborne methane remote measurements reveal heavy-tail flux distribution in Four Corners region. Proceedings of the National Academy of Sciences, 113(35), 9734-9739.
51) Fuss, S., Lamb, W. F., Callaghan, M. W., Hilaire, J., Creutzig, F., Amann, T., Beringer, T., de Oliveira Garcia, W., Hartmann, J., Khanna, T., Luderer, G., Nemet, G. F., Rogelj, J., Smith, P., Vicente, J. L. V., Wilcox, J., del Mar Zamora Dominguez, M., & Minx, J. C. (2018). Negative emissions, Part 2: Costs, potentials and side effects. Environmental Research Letters, 13(6), 063002.
52) Galbraith, J. R. (1974). Organization design: An information processing view. Interfaces, 4(3), 28-36.
53) Gvakharia, A., Kort, E. A., Brandt, A., Peischl, J., Ryerson, T. B., Schwarz, J. P., Smith, M. L., & Sweeney, C. (2017). Methane, black carbon, and ethane emissions from natural gas flares in the Bakken Shale, North Dakota. Environmental Science and Technology, 51(9), 5317-5325.
54) Health and Safety Executive. (2005). Guidance on permit-to-work systems: A guide for the petroleum, chemical and allied industries (HSG250). HSE Books.
55) Health and Safety Executive. (2006). Developing process safety indicators: A step-by-step guide for chemical and major hazard industries (HSG254). HSE Books.
56) Health and Safety Executive. (2006b). The safe isolation of plant and equipment (HSG253). HSE Books.
57) Hollnagel, E. (2004). Barriers and accident prevention. Ashgate.
58) Hopkins, A. (2008). Failure to learn: The BP Texas City refinery disaster. CCH Australia.
59) Hopkins, A. (2009). Thinking about process safety indicators. Safety Science, 47(4), 460-465.
60) Ihwughwavwe, S. I., & Usiagu, G. S. (2024). Analyzing effective project management approaches to reduce LNG environmental footprint. International Journal of Scientific Research in Computer Science, Engineering and Information Technology, 10(4), 887-898.
61) Ijiga, O. M., Enyejo, L. A., Jinadu, S. O., Akinleye, K. E., Onwusi, C. N., & Raphael, F. O. (2023). Engineering atmospheric carbon dioxide utilization strategies for revitalizing mature American oil fields and creating economic resilience. Engineering Science and Technology Journal, 4(6), 741-760.
62) Intergovernmental Panel on Climate Change. (2018). Global warming of 1.5 degrees Celsius: An IPCC special report. Cambridge University Press.
63) Intergovernmental Panel on Climate Change. (2021). Climate change 2021: The physical science basis. Cambridge University Press.
64) International Electrotechnical Commission. (2016). Functional safety: Safety instrumented systems for the process industry sector (IEC 61511). IEC.
65) International Organization for Standardization. (2018b). Energy management systems: Requirements with guidance for use (ISO 50001). ISO.
66) Ismail, O. S., & Umukoro, G. E. (2012). Global impact of gas flaring. Energy and Power Engineering, 4(4), 290-302.
67) Jacob, D. J., Varon, D. J., Cusworth, D. H., Dennison, P. E., Frankenberg, C., Gautam, R., Guanter, L., Kelley, J., McKeever, J., Ott, L. E., Poulter, B., Qu, Z., Thorpe, A. K., Worden, J. R., & Duren, R. M. (2022). Quantifying methane emissions from the global scale down to point sources using satellite observations of atmospheric methane. Atmospheric Chemistry and Physics, 22(14), 9617-9646.
68) Jardine, A. K. S., Lin, D., & Banjevic, D. (2006). A review on machinery diagnostics and prognostics implementing condition-based maintenance. Mechanical Systems and Signal Processing, 20(7), 1483-1510.
69) Johansen, I. L., & Rausand, M. (2015). Barrier management in the offshore oil and gas industry. Journal of Loss Prevention in the Process Industries, 34, 49-55.
70) Kemp, C. E., & Ravikumar, A. P. (2021). New technologies can cost effectively reduce oil and gas methane emissions, but policies will require careful design to establish mitigation equivalence. Environmental Science and Technology, 55(13), 9251-9261.
71) Kerr, S. (1975). On the folly of rewarding A, while hoping for B. Academy of Management Journal, 18(4), 769-783.
72) Khan, M. S., Karimi, I. A., & Wood, D. A. (2017). Retrospective and future perspective of natural gas liquefaction and optimization technologies contributing to efficient LNG supply: A review. Journal of Natural Gas Science and Engineering, 45, 165-188.
73) Kidnay, A. J., Parrish, W. R., & McCartney, D. G. (2011). Fundamentals of natural gas processing (2nd ed.). CRC Press.
74) Kletz, T. (2001). Learning from accidents (3rd ed.). Gulf Professional Publishing.
75) Komi, N. M., & Adamolekun, A. (2024). Quantifying a just transition: An econometric and skills-mapping analysis of worker displacement in the coal-to-renewable shift. International Journal of Scientific Research in Computer Science, Engineering and Information Technology, 10(3), 1242-1299.
76) Lamidi, O. B. A. (2023). Comprehensive evaluation model for improving carbon accounting accuracy in corporate sustainability programs. International Journal of Scientific Research in Computer Science, Engineering and Information Technology, 10(1), 825-853.

77) Lauvaux, T., Giron, C., Mazzolini, M., d'Aspremont, A., Duren, R., Cusworth, D., Shindell, D., & Ciais, P. (2022). Global assessment of oil and gas methane ultra-emitters. Science, 375(6580), 557-561.
78) Lawrence, P. R., & Lorsch, J. W. (1967). Differentiation and integration in complex organizations. Administrative Science Quarterly, 12(1), 1-47.
79) Lei, Y., Li, N., Guo, L., Li, N., Yan, T., & Lin, J. (2018). Machinery health prognostics: A systematic review from data acquisition to RUL prediction. Mechanical Systems and Signal Processing, 104, 799-834.
80) Leung, D. Y. C., Caramanna, G., & Maroto-Valer, M. M. (2014). An overview of current status of carbon dioxide capture and storage technologies. Renewable and Sustainable Energy Reviews, 39, 426-443.
81) Lim, W., Choi, K., & Moon, I. (2013). Current status and perspectives of liquefied natural gas (LNG) plant design. Industrial and Engineering Chemistry Research, 52(9), 3065-3088.
82) Mannan, S. (Ed.). (2012). Lees' loss prevention in the process industries (4th ed.). Butterworth-Heinemann.
83) Merrow, E. W. (2011). Industrial megaprojects: Concepts, strategies, and practices for success. Wiley.
84) Metz, B., Davidson, O., de Coninck, H., Loos, M., & Meyer, L. (Eds.). (2005). IPCC special report on carbon dioxide capture and storage. Cambridge University Press.
85) Mokhatab, S., Mak, J. Y., Valappil, J. V., & Wood, D. A. (2014). Handbook of liquefied natural gas. Gulf Professional Publishing.
86) Moubray, J. (1997). Reliability-centred maintenance (2nd ed.). Butterworth-Heinemann.
87) Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.-F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T., & Zhang, H. (2013). Anthropogenic and natural radiative forcing. In Climate change 2013: The physical science basis (pp. 659-740). Cambridge University Press.
88) Ocko, I. B., Sun, T., Shindell, D., Oppenheimer, M., Hristov, A. N., Pacala, S. W., Mauzerall, D. L., Xu, Y., & Hamburg, S. P. (2021). Acting rapidly to deploy readily available methane mitigation measures by sector can immediately slow global warming. Environmental Research Letters, 16(5), 054042.
89) Okojie, J. S., & Abioye, R. F. (2020). Reconciling chemical safety with circular-economy targets: A decision framework for post-consumer recycled polymers in consumer-goods packaging balancing REACH compliance, lifecycle GHG footprint, and regulatory risk. International Journal of Multidisciplinary Research and Growth Evaluation, 1(5), 992-1006.
90) Okonkwo, C. S., Agbabiaka, J., Mayo, W., & Okeke, O. T. (2024c). Model for predictive procurement planning to sustain operational uptime. International Journal of Scientific Research in Humanities and Social Sciences, 1(2), 909-928.
91) Okonkwo, C. S., Agbabiaka, J., Ogunwole, O., Mayo, W., & Okeke, O. T. (2021). Conceptual model for materials readiness and maintenance-driven supply chain performance. International Journal of Multidisciplinary Research and Growth Evaluation, 2(6), 584-594.
92) Okonkwo, C. S., Ogunwole, O., & Okeke, O. T. (2018b). Model for inventory availability and plant uptime improvement in energy facilities. Iconic Research and Engineering Journals, 2(4), 160-172.
93) Omara, M., Zimmerman, N., Sullivan, M. R., Li, X., Ellis, A., Cesa, R., Subramanian, R., Presto, A. A., & Robinson, A. L. (2018). Methane emissions from natural gas production sites in the United States: Data synthesis and national estimate. Environmental Science and Technology, 52(21), 12915-12925.
94) Omisola, J. O., Etukudoh, E. A., Okenwa, O. K., Owulade, O. A., & Isi, L. R. (2025). Review of balancing economic growth with environmental sustainability in LNG project development. International Journal of Multidisciplinary Research and Growth Evaluation, 6(3), 247-254.
95) Oshevire, P., Eyenubo, O. J., & Amayo, B. (2017). Voltage control in the presence of distributed generation. ATBU Journal of Science, Technology and Education, 5(2), 165-173.
96) Oyeleke, A. V., Eze, F. C., & Asiedu, W. (2026). Reliability-centered maintenance strategies for minimizing downtime and maximizing performance in high-density GPU cluster environments. International Journal of Engineering Technology Research and Management, 10(7), 18-38.
97) Ozobu, C. O., Adikwu, F. E., Odujobi, O., Onyekwe, F. O., & Nwulu, E. O. (2025). A review of health risk assessment and exposure control models for hazardous waste management operations in Africa. International Journal of Advanced Multidisciplinary Research and Studies, 5(2), 570-582.
98) Ozowe, C., Ukato, A., Jambol, D. D., & Daramola, G. O. (2024). Technological innovations in liquefied natural gas operations: Enhancing efficiency and safety. Engineering Science and Technology Journal, 5(6), 1909-1929.
99) Plant, G., Kort, E. A., Brandt, A. R., Chen, Y., Fordice, G., Gorchov Negron, A. M., Schwietzke, S., Smith, M., & Zavala-Araiza, D. (2022). Inefficient and unlit natural gas flares both emit large quantities of methane. Science, 377(6614), 1566-1571.
100) Quainoo, R., Ogundapo, O., & Asiedu, W. A. (2024). Modeling the impact of impedance mismatch on wireless link performance: A framework for prototype development and system optimization. International Journal of Computer Science and Mathematical Theory, 10(2), 62-116.
101) Rahimpour, M. R., & Jokar, S. M. (2012). Feasibility of flare gas reformation to practical energy in Farashband gas refinery: No gas flaring. Journal of Hazardous Materials, 209-210, 204-217.
102) Ravikumar, A. P., & Brandt, A. R. (2017). Designing better methane mitigation policies: The challenge of distributed small sources in the natural gas sector. Environmental Research Letters, 12(4), 044023.
103) Ravikumar, A. P., Sreekanth, D., Wang, J., Rutherford, J. S., Bell, C., Zimmerle, D., & Brandt, A. R. (2019). Single-blind inter-comparison of methane detection technologies. Elementa: Science of the Anthropocene, 7, 37.

104) Ravikumar, A. P., Wang, J., McGuire, M., Bell, C. S., Zimmerle, D., & Brandt, A. R. (2018). Good versus good enough? Empirical tests of methane leak detection sensitivity of a commercial infrared camera. Environmental Science and Technology, 52(4), 2368-2374.
105) Reason, J. (1997). Managing the risks of organizational accidents. Ashgate.
106) Rochelle, G. T. (2009). Amine scrubbing for CO2 capture. Science, 325(5948), 1652-1654.
107) Roman-White, S. A., Littlefield, J. A., Fleury, K. G., Allen, D. T., Balcombe, P., Konschnik, K. E., Ewing, J., Ross, G. B., & George, F. (2021). LNG supply chains: A supplier-specific life-cycle assessment for improved emission accounting. ACS Sustainable Chemistry and Engineering, 9(32), 10857-10867.
108) Rutherford, J. S., Sherwin, E. D., Ravikumar, A. P., Heath, G. A., Englander, J., Cooley, D., Lyon, D., Omara, M., Langfitt, Q., & Brandt, A. R. (2021). Closing the methane gap in US oil and natural gas production emissions inventories. Nature Communications, 12, 4715.
109) Sklet, S. (2006). Safety barriers: Definition, classification, and performance. Journal of Loss Prevention in the Process Industries, 19(5), 494-506.
110) Smith, A. R., & Klosek, J. (2001). A review of air separation technologies and their integration with energy conversion processes. Fuel Processing Technology, 70(2), 115-134.
111) Smith, P., Davis, S. J., Creutzig, F., Fuss, S., Minx, J., Gabrielle, B., Kato, E., Jackson, R. B., Cowie, A., Kriegler, E., van Vuuren, D. P., Rogelj, J., Ciais, P., Milne, J., Canadell, J. G., McCollum, D., Peters, G., Andrew, R., Krey, V., Shrestha, G., Friedlingstein, P., Gasser, T., Grubler, A., Heidug, W. K., Jonas, M., Jones, C. D., Kraxner, F., Littleton, E., Lowe, J., Moreira, J. R., Nakicenovic, N., Obersteiner, M., Patwardhan, A., Rogner, M., Rubin, E., Sharifi, A., Torvanger, A., Yamagata, Y., Edmonds, J., & Yongsung, C. (2016). Biophysical and economic limits to negative CO2 emissions. Nature Climate Change, 6(1), 42-50.
112) Sunday, E. A., Omoegun, G. O., Essien, M. A., & Oluokun, O. A. (2019). Thermodynamic efficiency and control strategies in residential air conditioning systems. International Journal of Scientific Research in Civil Engineering, 3(3), 52-76.
113) Sunday, E. A., Omoegun, G. O., Essien, M. A., & Oluokun, O. A. (2020). Transitioning from reactive to predictive maintenance in mechanical systems. International Journal of Scientific Research in Computer Science, Engineering and Information Technology, 6(6), 425-447.
114) Thompson, J. D. (1967). Organizations in action: Social science bases of administrative theory. McGraw-Hill.
115) United States Environmental Protection Agency. (2016). Standards of performance for crude oil and natural gas facilities (40 CFR Part 60, Subpart OOOOa). US EPA.
116) United States Environmental Protection Agency. (2017). Greenhouse gas reporting program: Petroleum and natural gas systems (40 CFR Part 98, Subpart W). US EPA.
117) Vaughn, T. L., Bell, C. S., Pickering, C. K., Schwietzke, S., Heath, G. A., Pétron, G., Zimmerle, D. J., Schnell, R. C., & Nummedal, D. (2018). Temporal variability largely explains top-down and bottom-up difference in methane emission estimates from a natural gas production region. Proceedings of the National Academy of Sciences, 115(46), 11712-11717.
118) Zavala-Araiza, D., Alvarez, R. A., Lyon, D. R., Allen, D. T., Marchese, A. J., Zimmerle, D. J., & Hamburg, S. P. (2017). Super-emitters in natural gas infrastructure are caused by abnormal process conditions. Nature Communications, 8, 14012.
119) Zavala-Araiza, D., Lyon, D. R., Alvarez, R. A., Davis, K. J., Harriss, R., Herndon, S. C., Karion, A., Kort, E. A., Lamb, B. K., Lan, X., Marchese, A. J., Pacala, S. W., Robinson, A. L., Shepson, P. B., Sweeney, C., Talbot, R., Townsend-Small, A., Yacovitch, T. I., Zimmerle, D. J., & Hamburg, S. P. (2015). Reconciling divergent estimates of oil and gas methane emissions. Proceedings of the National Academy of Sciences, 112(51), 15597-15602.
120) Zavala-Araiza, D., Lyon, D., Alvarez, R. A., Palacios, V., Harriss, R., Lan, X., Talbot, R., & Hamburg, S. P. (2015b). Toward a functional definition of methane super-emitters: Application to natural gas production sites. Environmental Science and Technology, 49(13), 8167-8174.
121) Zimmerle, D., Vaughn, T., Bell, C., Bennett, K., Deshmukh, P., & Thoma, E. (2020). Detection limits of optical gas imaging for natural gas leak detection in realistic controlled conditions. Environmental Science and Technology, 54(18), 11506-11514.

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