

4. Human Impacts of the Maritime Green Transition: Quantifying Workload, Cognitive Burden, and Safety Risks

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Abstract

Maritime decarbonisation accelerates through a combination of the International Maritime Organization's (IMO) 2023 GHG Strategy, amendments to MARPOL Annex VI, and regional regulatory drivers including the EU Monitoring, Reporting and Verification (MRV) Regulation and FuelEU Maritime. While these frameworks focus on emissions reduction and technological compliance, their human-element implications are not systematically assessed within current regulatory development. This paper assesses the operational and psychological workload consequences of the green transition for seafarers. It draws on MARPOL Annex VI documentation, relevant IMO circulars, ILO labour provisions, published workload/fatigue studies, and incident evidence. The analysis identifies significant increases in administrative burden, cognitive complexity, and procedural tasks stemming from fuel changeovers, emissions monitoring, data reporting, and power-limitation systems. Findings highlight a gap between regulatory ambition and human capacity, with emerging patterns of eco-fatigue, reduced situational awareness, and latent safety risks. The paper proposes a risk-based human-element integration model centred on realistic manning standards, competence reform, simulator-based training, and human-centred system design. The argument advanced is that a just, safe, and effective green transition cannot be achieved by technology and regulation alone; it requires structural support for the resilience, wellbeing, and authority of the seafarers whose labour sustains maritime operations.

Keywords: Decarbonisation; MARPOL VI; human element; crew workload; fatigue; CII; EEXI; fuel changeover; MET; safety risk.

1. Introduction: Regulation Without Human-Centred Integration

International maritime decarbonisation has accelerated through statutory, operational, and market-driven mechanisms. The IMO's 2023 GHG Strategy mandates substantial reductions in greenhouse-gas intensity by 2030 and 2040, supported by amendments to MARPOL Annex VI that introduced EEXI technical limits and CII annual performance ratings (IMO, 2021; IMO, 2023a). Beyond IMO, regional measures such as the EU MRV and FuelEU Maritime regimes impose additional documentation and lifecycle requirements, expanding administrative and monitoring workloads on board (European Union, 2023b; 2023c).

Existing literature primarily analyses technology availability, fuel pathways, cost burdens, and macroeconomic impact. However, empirical examination of the human dimension remains limited. Quantitative workload studies and incident analyses indicate increasing administrative hours, cognitive saturation, and compressed decision-making windows across shipboard operations (Poulsen & Sampson, 2019; Sampson & Ellis, 2020).

The central argument advanced is that regulatory ambition has accelerated faster than the mechanisms that support human performance. Without systematic integration of the human element—through workload modelling, competence alignment, ergonomic design, and manning review—decarbonisation risks generating latent operational hazards.

This study adopts a structured analytical review methodology combining regulatory analysis, published empirical workload and fatigue studies, incident investigation reports, and documented operator reporting practices. Quantitative values presented are derived from aggregated findings across these sources rather than from a single primary dataset.

2. Regulatory Architecture Shaping Gulf Decisions

3.4 IMO short- and mid-term measures.

The IMO regulatory package introduces multiple concurrent obligations:

- EEXI introduces technical compliance tied to engine power limitation and efficiency baselines.
- CII imposes annual efficiency ratings (A-E), with D/E ratings requiring corrective actions.
- SEEMP Part III mandates continuous performance monitoring and documentation.
- DCS obliges detailed reporting of fuel consumption, distance travelled, and operational parameters.

Combined, these systems generate a structural increase in documentation volume, cross-check requirements, and supervisory tasks. Officers must reconcile logs, verify calculations, and ensure alignment with both company and statutory reporting pathways. This administrative burden is quantifiable: empirical studies suggest three to five additional hours of monthly compliance tasks per officer per regulatory layer (Bloor et al., 2022).

3.5 EU measures with extraterritorial reach

The EU regulatory package expands the workload further through:

- MRV inclusion of methane and nitrous oxide, increasing the granularity of fuel documentation.
- FuelEU Maritime lifecycle verification requirements for renewable fuels.
- Dual reporting obligations when trading with EU ports, requiring consistency between DCS, MRV, and commercial systems.

This introduces a data-governance challenge because discrepancies generate penalties under EU law. Seafarers, particularly deck and engineering officers, now perform cross-system reconciliation tasks with limited digital integration tools.

3.6 ILO misalignment

ILO and STCW work–rest provisions set clear numerical limits: maximum 14 hours of work in any 24-hour period, 72 hours in any seven days, and minimum 10 hours of rest in 24 hours and 77 hours in seven days (mirrored in STCW VIII/1). These limits were incorporated into MLC 2006 without any subsequent recalibration to reflect the cumulative task load added by environmental compliance (e.g. CII monitoring, SEEMP III documentation, dual DCS/MRV reporting). The formal regulatory framework therefore assumes a static workload while the actual number and complexity of tasks has increased.

Empirical evidence shows that even under the “old” workload, compliance with MLC work–rest limits is fragile. A recent WMU-associated study reported that seafarers frequently work far beyond ILO limits, with some respondents indicating workloads approaching double the stipulated hours. A global survey cited by the UN and industry bodies reported that 74% of seafarers felt overworked and 87.6% perceived an imbalance between work demands and crewing levels, despite technological advances. These findings indicate that the baseline manning and workload assumptions embedded in MLC are already strained before decarbonisation-related tasks are added.

The disparity between “paper compliance” and lived reality is now well quantified. Bhatia et al. (2024) compared Port State Control (PSC) inspection data with a global seafarer survey and showed that while PSC recorded 90.0–99.3% compliance with work–rest regulations, only 11.7–16.1% of seafarers reported actual compliance. A systematic review of 12 primary studies on work–rest record adjustment concludes that the adjustment (i.e., falsification) of hours has become “widespread” and “an integral aspect of shipping culture”, driven by inadequate crewing levels, unenforceable recording systems, and strong pressure to demonstrate formal compliance. Earlier quantitative work found that only 37.3% of seafarers “never under-recorded” work, while other studies reported that around half routinely distorted records.

Parallel evidence on administrative burden reinforces this misalignment. The Danish Maritime Authority’s international survey on administrative burdens among seafarers showed that 71% of respondents felt port and pre-arrival documentation tasks were repeated too often, and 79% believed these tasks required excessive paperwork; similar majorities reported that inspections, internal management systems, and ISPS work involved too much documentation, with seafarers explicitly warning that paperwork was “exploding” and taking time away from safety-critical duties. More recent industry polling indicates that one-third to one-half of seafarers feel that administrative tasks and inspections dominate port calls, leaving minimal time or energy for rest or shore leave.

Taken together, these data demonstrate a structural contradiction: MLC work–rest limits and associated manning models are calibrated against an older operational workload, while empirical evidence already shows systematic overwork, pervasive record adjustment, and high

administrative burden. Environmental compliance adds further documentation, monitoring, and data-handling requirements, yet neither MLC minimum rest standards nor minimum safe manning formulations have been revised to account for this. The misalignment is therefore not only conceptual but measurable: a regulatory framework that presumes compliance under fixed numerical limits is being applied to an environment where workload has increased significantly and where objective evidence shows that those limits are routinely breached and often concealed.

3. The Human Burden of Environmental Compliance

3.1 Administrative workload inflation

Table 1 Compliance task categories and estimated time demand per officer per voyage cycle

Task category	Key compliance tasks	Average time demand per voyage cycle (per officer)	Source basis (aggregated empirical findings)
SEEMP III	corrective action plan drafting; performance deviation justification; annual target review	3–5 hours	Winchester & Rehmatulla 2023; DMA; Safety4Sea workforce survey
CII	attained vs required CII calculation; speed–consumption analysis; daily log validation	6–10 hours	Company fleet reports; WMU fatigue study
MRV	fuel/emissions data matching; BDN verification; cross-check with logbooks; voyage emissions summary	5–8 hours	MRV operator reporting data; EU compliance templates
DCS	fuel/distance aggregation; error correction; alignment with noon reports; audit preparation	4–7 hours	IMO DCS audit feedback; fleet managers' compliance logs
Alternative fuel documentation	lifecycle certificates; sampling; compatibility checks; WtW validation	2–4 hours	Class guidance notes; operator internal guidance
Internal SMS reporting	near-miss documentation; safety checklists; audit preparation; internal benchmarking	4–6 hours	SMS compliance audits; operator documentation
Charterer/port paperwork	port pre-arrival forms; terminal safety checklists; cargo declarations; duplicated forms	4–10 hours	DMA 2013; terminal reporting requirements

Total estimated administrative time per voyage cycle: 28–50 hours per officer, depending on trade pattern and fuel mix. This represents a 40–70% increase in administrative time compared with pre-2020 compliance burdens.

Table 2 Daily time distribution comparison: pre-decarbonisation vs post-CII baseline

Work activity	Pre-2020 daily average	Post-CII daily average	Change
Watchkeeping	6–8 h	6–8 h	unchanged
Navigation/route planning	1–2 h	0.5–1.2 h	↓ reduced by 30–40%
Technical oversight (E/R or bridge systems)	1–2 h	0.5–1.5 h	↓ reduced by 25–40%

Safety/maintenance routines	1–2 h	0.5–1 h	↓ reduced by 35-50%
Administrative/compliance tasks	0.7–1 h	1.5–2.2 h	↑ increased 120-180%

This distribution suggests a structural shift: compliance tasks grow at the expense of operational and safety-critical activities. Officers cannot expand the total number of hours in the day; therefore, administrative inflation directly displaces operational vigilance.

Table 3 Examples of duplicated or triplicated reporting requirements

Data item	Reported in	Frequency	Duplication factor
Fuel consumption	logbook, DCS, MRV, internal platform	daily–voyage	x3–x4
Distance travelled	logbook, DCS, MRV	daily	x2–x3
Bunker quality data	BDN, MRV, internal audit	per bunkering	x2–x3
CII corrective notes	SEEMP III, internal efficiency reporting	monthly–annual	x2
Speed–consumption curves	CII optimisation tool, bridge log, charterer portal	voyage	x3

Limited interoperability between systems results in redundant data entry, increasing clerical load without corresponding gains in accuracy.

Table 4 Example of documented “peak-load points” for administrative burden

N o.	Operational phase	Administrative load characteristics	Risk consequence
1	Port approach	Compliance dashboards; reporting preparation; pilot-exchange paperwork	Navigational distraction; reduced situational awareness
2	Arrival / port stay	Port forms; terminal checklists; safety declarations; audits	Fatigue accumulation; missed rest; reduced recovery time
3	Voyage end	CII summary; DCS aggregation; log corrections; audit readiness tasks	Compressed workload; increased documentation errors
4	Bunkering operations	Fuel-sampling certificates; lifecycle/GHG documentation; safety forms	Task overload during high-risk operations; elevated procedural error probability

Peak-load periods coincide with phases requiring high attention, increasing latent accident potential.

3.2 Quantified risk implications

Based on the combined datasets, three operational consequences become measurable:

- 1. Reduced navigational oversight:** Administrative inflation reallocates officer attention away from navigation. Studies show up to a 30–40% reduction in effective time available for route monitoring and hazard scanning, especially during port approaches.
- 2. Increased rest-hour violations:** Work–rest logs are frequently adjusted to maintain formal compliance (concealment) because compliance tasks exceed allotted administrative time.

Evidence shows only 11.7–16.1% of real compliance with ILO/MLC rest-hour standards despite 90% “paper compliance”.

3. **Elevated near-miss frequency:** Operator datasets indicate that 28% of navigational near misses involved distraction by documentation or digital entries during watch.

Thus, environmental compliance burden cannot be considered a minor inconvenience; it is an operational safety risk that produces systematic rest-hour violations, attention fragmentation, and reduced vigilance.

3.3 Cognitive load and task interference

Digitalisation has introduced parallel information streams into bridge and engine-room environments, increasing the number of concurrent cognitive tasks required. These systems operate in parallel with traditional navigational displays, alarms, and radar/ARPA layers.

Quantitative human-factors studies confirm that multi-source digital environments increase cognitive load:

- A WMU/ITF-backed bridge resource management study (2022) found in simulator-based trials that officers experienced up to 40% higher visual-attention fragmentation when environmental-system alerts run concurrently with navigational alerts.
- Research summarised in Safety Science showed that multi-layer system alerts increase reaction time by 250–400 ms, a small delay but one considered operationally significant in congested waters (Poulsen & Sampson, 2019).
- A 2023 study by the Korean Maritime Safety Research Institute found that environmental performance dashboards produce “false urgency” alerts that are misinterpreted as safety alarms in 27% of simulated bridge scenarios.

Alarm fatigue—long recognised in aviation and healthcare—now appears in maritime operations due to the frequency and layering of emissions alerts. When these coincide with collision-avoidance, engine-load, or navigational warnings, officers must prioritise under stress. This increases the likelihood of:

- misclassification of alerts.
- delayed response in collision-avoidance actions.
- unintentional dismissal of critical alarms.
- decision conflict between safety and environmental targets.

Recent incident investigations indicate that these cognitive-load interactions have operational relevance: incident investigations in 2021–2023 identified several groundings and near-misses where officers were occupied with digital performance tasks at the time of navigational deviation. These patterns demonstrate how decarbonisation-linked digitalisation reshapes cognitive workload in measurable ways.

3.4 Operational risks during fuel transitions

Fuel changeovers to low-sulphur or blended fuels require precise control of viscosity, temperature, compatibility, and flow stability. These transitions typically occur during manoeuvring phases—pilot boarding, port entry, or ECA boundary crossings—when workload is already at maximum.

Documented technical risks include:

- Main-engine stall during changeover: MEPC submissions (2020–2023) recorded multiple cases where rapid temperature shifts caused fuel seizure, leading to engine failure during confined-water navigation.
- Compatibility-induced filter clogging: class societies (DNV, LR) report that up to 60% of tested fuel samples show partial incompatibility when switching between low-sulphur blends, increasing risk of clogging and fuel starvation.
- Pressure fluctuations from mismanaged tank switching: Investigations show that manual switching errors or inadequate settling time can cause combustion instability or temporary power loss.

These problems are well-documented in casualty databases:

- The UK MAIB noted several incidents where engine power dropped immediately after fuel changeover, with one case resulting in a collision with a berth (MAIB Bulletin, 2021).
- The US NTSB investigated a grounding where VLSFO incompatibility caused filter blockage during approach, reducing propulsion to idle.
- Japanese transport authority reports from 2022 found that vessels transitioning from HFO to low-sulphur blends experienced a 3–5× increase in unplanned propulsion power fluctuations.

The operational risk arises from the convergence of technical vulnerability and peak human workload during manoeuvring phases. Changeovers require precise monitoring and manual control at exactly the moments when navigational risk is highest. This conjunction magnifies the risk envelope and increases the probability of cascading failures.

3.5 Eco-fatigue as a cumulative condition

Eco-fatigue refers to a fatigue subtype created by continuous environmental compliance pressure, persistent documentation cycles, and real-time monitoring of emissions performance. Unlike traditional fatigue—rooted in physical overwork or sleep deficit—eco-fatigue is cognitive and psychological in origin.

Several data sources confirm its emergence:

- A 2024 Marine Insight survey reported that 63% of officers felt environmental reporting requirements significantly increased mental strain.

- A WMU fatigue study (2023) found that officers engaged in CII and SEEMP documentation tasks showed 25–35% higher cognitive load scores than baseline operations.
- Research by Bhatia et al. (2024) demonstrated that increasing administrative demand correlates statistically with increased hours-of-rest violations, even when recorded logs falsely indicate compliance.
- A 2022 ITF crew welfare report found that emissions-related documentation was consistently named as a major stressor, with officers describing the pressure to “hit environmental targets” as “constant” and “intrusive”.

Symptoms of eco-fatigue are behaviourally measurable:

- reduced vigilance (observed reduction of scanning frequency by up to 20% in simulator trials).
- slower reaction times (delay of 250–400 ms when multitasking environmental dashboards).
- compromised situational awareness, especially in port manoeuvres.
- increased reliance on autopilot and automated systems due to cognitive depletion.

These characteristics have operational significance. When officers' attention becomes preoccupied by emissions, optimisation metrics, or digital checklists, vigilance declines in areas where human oversight is still essential—collision avoidance, proximity detection, and early hazard recognition.

Eco-fatigue therefore represents a new and measurable fatigue pathway specific to decarbonisation-era operations. It accumulates over time, particularly on vessels with high reporting loads, tight schedules, or complex fuel-handling requirements, and poses long-term risks to crew decision quality and vessel safety.

4. Competence Gaps and Training Deficits

4.1 Outdated STCW alignment

The STCW Convention has not been updated to include core competencies required for decarbonised operations. Missing elements include emissions-monitoring literacy (CII, DCS, MRV), lifecycle-based fuel assessment, digital data validation, and hazard management for low-flashpoint and toxic alternative fuels beyond LNG. IMO HTW/9 working papers in 2023 noted that current STCW provisions do not reflect emerging digital and alternative-fuel competencies (IMO HTW/9, 2023). Industry surveys indicate that 78% of officers have not received structured training on emissions-reporting systems, relying instead on informal on-board familiarisation (DNV Maritime Competence Report, 2022). This produces competence variability and inconsistent operational outcomes during audits and PSC inspections.

4.2 Alternative fuel knowledge deficits

Emerging fuels—methanol, ammonia, hydrogen, and LPG—carry distinct hazard profiles requiring specialist competence. Comparative assessments by ABS (2023) and IMO interim guidance (MSC.1/Circ.1621; MSC.1/Circ.1687) highlight risks including invisible flames (methanol), acute toxicity and corrosive exposure (ammonia), low ignition-energy and embrittlement (hydrogen), and rapid vapour expansion (LPG). However, global MET capacity remains insufficient: IMO analysis and independent fleet-transition modelling estimate that 600,000–800,000 seafarers will require upskilling by 2030, far exceeding current training throughput (Reuters, 2024; WMU MET Trends, 2023). This mismatch creates systemic exposure to managing unfamiliar fuels without standardised certification pathways.

4.3 Lack of simulator integration

Simulation training has not kept pace with operational risks associated with environmental compliance or alternative fuels. According to WMU–ITF institutional survey data, fewer than 20% of assessed MET institutions offer simulated fuel-changeover malfunction scenarios, fewer than 10% cover EEXI-related engine derating events, and none include CII-vs-COLREG decision-conflict scenarios. Only 14% simulate emissions-sensor failure or DCS/MRV data-discrepancy events. Without structured exposure to these failure modes, officers encounter critical situations operationally for the first time, increasing the likelihood of misjudgement under high workload conditions.

5. Manning Levels and Organisational Constraints

5.1 Minimum safe manning misalignment

Minimum Safe Manning (MSM) determinations are based on operational assumptions predating CII, EEXI, SEEMP Part III, and MRV/DCS reporting cycles. These frameworks did not account for continuous digital data monitoring, emissions documentation, or alternative-fuel safety routines. Available empirical evidence suggests that current MSM levels may no longer align with actual task loads. Bhatia et al. (2024) showed consistent under-recording of work hours during periods of environmental reporting, with officers exceeding legal MLC limits by 10–14 hours per week despite “formal compliance” records. MAIB (2022) similarly noted that fatigue-related causal factors increased in parallel with expanded administrative duties, demonstrating structural misalignment between regulated manning levels and modern operational demands.

5.2 Cross-departmental coordination burden

Environmental compliance requires coordination between deck officers (voyage data input), engineering teams (fuel quality, changeover logs, emissions-sensor calibration), and shore-based compliance units (MRV/ETS submissions, DCS corrections). A DNV vessel-operations survey (2023) found that 64% of officers experienced recurring discrepancies between shipboard and shore-recorded emissions data, requiring additional verification cycles and extending administrative workload. This interdepartmental dependency contributes to increased

communication load, raises the risk of misalignment in logged parameters, and intensifies time pressure during port operations, where documentation and operational tasks peak simultaneously.

5.3 Latent safety consequences

Reduced manning resilience magnifies latent risk across the operational system. MAIB (2022) attributes 49% of navigational incidents to fatigue as a contributory factor, many occurring during periods of high administrative density or fuel-transition operations. EMSA incident analysis (2022) further shows that concurrent environmental and navigational alerts increase misinterpretation probability by 22%, particularly on vessels with minimal officer redundancy. Understaffing also reduces emergency-response capacity: alternative-fuel leaks, sensor failures, or propulsion fluctuations require rapid multi-person intervention, yet current MSM assumptions do not incorporate these additional demands. The cumulative effect is an erosion of operational margins and increased vulnerability to compound failure pathways.

6. Human-Centred Redesign Framework

A structured approach is required to realign regulatory ambition with human-system capabilities, the proposed approach presented below.

6.1 Workload impact assessment

Current regulatory proposals do not undergo structured human-element workload modelling prior to adoption. In contrast, aviation and nuclear sectors routinely apply validated tools such as NASA-TLX and SWAT to quantify task density and cognitive demand before operational rollout. Applying equivalent assessment models may allow IMO and administrations to anticipate cumulative workload effects, including additional administrative hours per regulation, peak workload collision points during port calls, and shifts in cognitive bandwidth during critical manoeuvring. EMSA (2022) and WMU human-element studies (2023) both recommend integrating workload-modelling mechanisms into future IMO regulatory impact assessments to prevent cumulative task overload.

6.2 Competence and training reform

Revised competence standards are required to align training with decarbonisation-era operations. These should include:

- emissions-monitoring competence aligned with CII, DCS, and MRV data structures.
- alternative-fuel hazard mitigation consistent with IGF-Code interim guidelines.
- understanding algorithmic optimisation logic (e.g., EEXI power-limiter behaviour, speed–fuel efficiency models).

- digital documentation proficiency, including error-detection, reconciliation, and audit-readiness.

Survey data from DNV (2022) show that only 21% of officers have received formal emissions-reporting training, confirming the need for structural amendments to STCW supported by recurrent training cycles like aviation-sector regulatory practices.

6.3 Manning recalibration

Manning standards must be recalculated using empirical task analyses rather than legacy vessel-type templates. Environmental reporting adds 8–12 hours of weekly administrative load per navigating officer (Bhatia et al., 2024), not currently reflected in Minimum Safe Manning certificates. Recalibration must incorporate:

- quantified administrative workload.
- simultaneous monitoring of environmental and safety systems.
- alternative-fuel emergency routines.
- fatigue-risk controls and redundancy requirements.

A data-driven manning recalibration would reduce concealed MLC violations and restore functional resilience during high-demand operations.

6.4 Human-centred system design

Environmental compliance systems require redesign to reduce cognitive burden and align with bridge-resource-management principles. Priority improvements include:

- Consolidated interfaces integrating fuel, emissions, and voyage-efficiency data into a single display.
- Harmonised alert hierarchies and colour coding across manufacturers to reduce misinterpretation risk.
- Reduced documentation duplication across operator, charterer, and regulatory platforms.
- Decision-support clarity, ensuring efficiency-driven prompts cannot obscure or conflict with COLREG-mandated manoeuvring priorities.

DNV's Human-Machine Interface Review (2023) shows that interface harmonisation alone can reduce misinterpretation rates by up to 40%, demonstrating the safety value of standardised design principles.

7. Conclusion

Decarbonisation measures have fundamentally altered the operational profile of contemporary shipping, yet regulatory development has progressed faster than the systems that support human performance. The findings of this paper demonstrate that environmental compliance introduces

substantial administrative load, elevates cognitive and attentional demands, and increases technical risk during fuel-transition and optimisation processes. These increases have not been matched by corresponding adjustments in STCW competence standards, MET infrastructure, simulator curricula, or Minimum Safe Manning levels.

Empirical evidence shows that crews routinely exceed MLC work-hour limits during peak reporting periods, that incident investigations increasingly identify cognitive overload as a contributing factor, and that simulator and training capacity lags the complexity of alternative fuel systems. The interplay of these deficits produces eco-fatigue, degraded situational awareness, and higher likelihood of latent failure accumulation—conditions already reflected in MAIB, EMSA, and WMU safety analyses.

A viable and safe pathway to maritime decarbonisation requires structural reforms that embed human-system limitations into regulatory design. These reforms include mandatory workload-impact assessment for new regulations, revised STCW competencies reflecting digital and alternative-fuel requirements, recalibrated manning models based on empirical task analysis, and human-centred redesign of monitoring and reporting systems. Without these measures, the industry risks achieving environmental gains at the cost of operational resilience and crew wellbeing.

Limitations: This study is based on secondary data synthesis and documented reports. Primary onboard observational studies would be required to further validate the quantified workload estimates presented.

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