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From Green Measures to a Port-Region Transition Platform: A Digital–Energy–Governance Framework for Northern Taiwan's 2050 Net-Zero Pathway

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ABSTRACT- Electrifying berths and cargo-handling equipment removes combustion from the quay, but it also moves part of the problem onto the local distribution feeder and into the hands of organizations that do not share data or budgets. We address this coordination gap for the ports of Keelung, Taipei and Suao in Northern Taiwan by proposing the Northern Taiwan Port-Region Transition Platform (N-TIP), which links emissions measurement, a federated energy digital twin, investment mechanisms and port-region governance. To test how the framework ranks options, we built a reduced-order scenario model in which every parameter is listed. Four pathways (incremental efficiency, accelerated electrification, balanced integration and alternative-fuel dominance) are compared from a 2025 baseline index of 100 using activity-segment shares, carrier shares, grid-factor trajectories, feeder peak loads, a 48-hour outage balance and a five-dimension Transition Readiness Index (TRI). In the central case the balanced pathway reaches a 2050 emissions index of 13.7, against 17.7 for accelerated electrification, keeps the feeder loading ratio at 0.94 (1.44 for accelerated electrification) and scores a TRI of 0.84. Analytical checks reproduce the baseline exactly. The balanced pathway stays below accelerated electrification in all 5,000 Monte Carlo draws, has the lowest emissions in 62 of 64 factorial cases, and has the lowest weighted multi-objective score for 91% of random weight sets. A decomposition shows, however, that most of its advantage comes from on-site solar, efficiency and drop-in fuels rather than from its carrier mix, and accelerated electrification would emit less only if the 2050 grid factor fell below about 3% of its 2025 value. The results are illustrative and need metered port data before they can support investment decisions.

KEYWORDS- Port Decarbonization; Energy Governance; Scenario Analysis; Digital Twin Architecture; Transition Readiness.

I. INTRODUCTION

Most port decarbonization plans are written as lists of projects: shore power, electric cargo-handling equipment, rooftop solar, building retrofits, cleaner bunker fuels and smoother gate operations [1]. Each item is useful, yet treating them one at a time ignores the fact that a port is a coupled technical and institutional system [2]. Its loads do not simply add up [3]. Vessel arrivals are irregular and crane cycles create short, high electrical peaks, while reefer stacks draw power around the clock, so berth-side and onboard energy use have to be coordinated [4]. Emission reports must also decide which activities belong inside the port boundary [5], and on-site solar and batteries have to be shared between tariff arbitrage, equipment charging and backup reserve.

Decision rights and data are spread across the port authority, city governments, the electric utility, terminal operators, shipping lines, customs, dock labor and nearby residents. Choices about alternative marine fuels [6] and about the bunkering chains needed to supply them [7] add further technical uncertainty. Net zero in a port therefore cannot be solved inside the terminal fence. It is a regional socio-technical problem, close to what nearly zero-energy port frameworks describe [8], in which grid reliability, energy security, throughput, public health and institutional legitimacy must be weighed together.

Northern Taiwan illustrates the problem well. The ports of Keelung, Taipei and Suao are all operated by the Taiwan International Ports Corporation, but their roles differ. Keelung is a tight urban harbor with cruise and passenger traffic; Taipei is a large industrial port handling containers, offshore wind components and fuels; and Suao serves bulk cargo and regional energy uses. Taiwan's 2050 Net-Zero Pathway [9] and its twelve key strategies set targets for renewable integration, grid resilience and a just transition. They say little, however, about how a group of ports with shared feeders and separate operators should turn those targets into projects.

Current green-port practice usually starts from a backward-looking greenhouse-gas inventory and then funds projects one by one. An inventory cannot show that shore power will raise the feeder peak, trigger a substation upgrade or shift emissions to the power sector. Reviews of digital-twin and hydrogen applications in ports [10] also suggest that dashboards alone do not settle who decides or who pays. Building on infrastructure reviews such as [11], we argue that a regional transition mechanism needs four capabilities: auditable data with clear provenance; a federated digital twin that simulates at several time scales; a direct link from model outputs to procurement, tariffs and investment order;

and equity indicators (local air quality, worker certification and protection of small firms) inside the optimization itself. This paper develops the Northern Taiwan Port-Region Transition Platform (N-TIP) to provide these capabilities. N-TIP is not one central software system. It is a federated arrangement of data, models and governance bodies working on three time scales: real-time dispatch and shore-power coordination (seconds to hours); maintenance, berth planning and charging schedules (days to months); and infrastructure investment aligned with national policy revisions (years to decades). Four research questions guide the work: (1) which institutional and engineering capabilities are needed to move a multi-port region from separate projects to a common 2050 net-zero platform; (2) how a federated energy digital twin can couple logistics, distribution constraints and emissions accounting while remaining a decision tool rather than a reporting screen; (3) how multi-objective optimization can rank investments under regulatory uncertainty while protecting feeder stability and equity; and (4) which phased sequence suits the Keelung–Taipei–Suao triad.

This paper makes three contributions:

- Architecture: the N-TIP design, which combines emissions monitoring, reporting and verification (MRV), a physics-informed digital twin, transition-finance mechanisms and polycentric governance in one interoperable framework.
- Analytical model: a normalized multi-objective portfolio formulation and a five-dimension Transition Readiness Index (TRI) that make technical, financial and equity trade-offs explicit.
- Roadmap and quantitative test: a staged 2026–2050 roadmap and a reproducible scenario calculation with listed parameters, verification checks, uncertainty propagation and sensitivity analysis.

The study follows a design-science approach. Its scenario results test the decision logic of the platform under stated assumptions; they are not a forecast for the three ports, and they indicate which field data a pilot should collect first.

II. BACKGROUND AND LITERATURE

A. Taiwan's Net-Zero Policy Context and Seaport Governance

Taiwan announced its 2050 Net-Zero pathway in 2022. The pathway rests on four transitions (energy, industry, lifestyle and society) and is supported by climate legislation and research funding. Studies of how ports have digitalized show that technical modernization has to move together with regulation [12]; in Taiwan, the relevant regulation follows the global net-zero roadmap for the energy sector [13] and the international targets for greenhouse-gas emissions from ships [14]. The national plan calls for investment in renewable energy, green hydrogen, smart distribution grids, energy storage, carbon capture, transport electrification, green finance and a just transition. The National Development Council has also raised Taiwan's 2030 reduction target to 24% ± 1% below the 2005 level, tying industrial decarbonization to grid resilience and to support for small and medium-sized enterprises.

For commercial ports, these policies matter in three ways:

- Ports are dense electrical loads. Shore power at high and low voltage, automated cranes, straddle carriers, cold-chain warehouses, automated gates and workshops all replace on-site fuel combustion, but they also add demand to the local distribution feeders, which makes energy-efficiency management part of the same problem [15].
- Ports import, store and bunker energy carriers. Handling LNG as a transition fuel, and later ammonia or hydrogen, requires containment, separation distances, hazard monitoring and emergency plans on waterfront land that is already scarce; at the same time, it creates links with offshore energy activities [16].
- Ports are local centers of transport and employment. A clean-energy project that cuts emissions but raises occupational risk, imposes electricity tariffs that small contractors cannot pay, or increases local trucking costs without compensation is likely to lose public support and may disrupt operations.

In Northern Taiwan these policies are applied through the Keelung Branch of the Taiwan International Ports Corporation (TIPC), which manages the ports of Keelung, Taipei and Suao. The three ports differ. Keelung sits inside the city and handles cruise and Ro-Ro traffic; Taipei is a deep-water port with automated container handling, offshore wind assembly and liquid fuel logistics; and Suao handles regional industrial bulk cargo and hosts new marine and distributed-energy projects. National policy sets carbon targets and financing tools, but it does not specify how several ports should share feeder capacity, cope with irregular vessel calls or handle effects that cross city boundaries. N-TIP is intended to fill this gap as a coordination framework that works with the existing authorities, reporting systems, power-market rules and terminal operating systems, without taking over any of their legal responsibilities.

B. Seaports as Integrated Energy and Cyber-Physical Systems

The maritime engineering literature shows that port emissions come from many activities that cannot be optimized separately from berth scheduling, yard logistics, gate operations and hinterland transport, and that energy planning must allow for renewable uncertainty [17]. Commercial success also depends on linking these improvements to the way a green port positions itself in the market [18]. Shore power cuts auxiliary-engine exhaust at berth, but large connections can produce coincident peaks on medium-voltage networks. Electric yard cranes, automated guided vehicles and terminal tractors reduce local particulate emissions, but they bring charging logistics and battery-ageing limits. Rooftop PV and battery energy storage systems (BESS) lower peaks only if their dispatch copes with weather variability. Zero- and near-zero-carbon fuels are an option for deep-sea ships that cannot run on batteries, but they involve lifecycle conversion losses, bunkering investment and hazardous-material handling.

Recent work describes ports as Integrated Port Energy Systems (IPES), in which energy supply, conversion between carriers, industrial loads, logistics and social value are linked both physically and through information flows, supported by industrial cyber-physical integration [19]. In

this view a port acts as a regional energy hub rather than a passive consumer, which calls for decarbonization models that cross disciplines [20]. Ports are also national infrastructure exposed to extreme weather, equipment failure, cyber intrusion, interruptions in energy supply and economic shocks, as reviews of global supply chains and maritime chokepoints show [21]. Cargo decisions change energy flows directly: a delayed ship or a changed berth moves megawatts of shore-power demand, an unmanaged charging schedule can slow terminal work, and a voltage sag caused by a large load can disturb both logistics and the city grid.

Digital twins offer a way to model and test these interactions, in line with national industrial transition roadmaps [22] and with joint strategies for air-pollution control and carbon reduction in ports [23]. Yu et al. propose an IPES digital twin built on physical, information and value layers, two-way real-time data and hybrid data–mechanism models [24]. Other green-port studies use digital twins for interoperability, predictive maintenance, microgrid dispatch and bunkering safety across maritime sectors [25]. Reviews of critical energy infrastructure, however, report recurring barriers: fragmented system integration, uneven digital maturity among operators, skills shortages, unclear cost recovery and cybersecurity weaknesses in operational technology (OT) [26].

These findings suggest that the usefulness of a digital twin depends more on institutional design than on model sophistication. A detailed simulation without clear data ownership, common data formats, independent verification and a defined decision authority remains a demonstration. A simpler model tied to concession agreements, grid-connection rules, procurement terms and daily routines can be far more useful. N-TIP therefore treats the digital twin as an analysis engine inside a multi-stakeholder governance structure, not as a standalone software product.

C. *Infrastructure Resilience, Governance Boundaries, and Just Transition*

Decarbonization can reduce local environmental burdens while creating new weak points. Large-scale quay electrification removes local combustion but makes the port more dependent on the regional grid. Hydrogen and ammonia bunkering widen the fuel mix but add toxicity and explosion hazards. Distributed generation and microgrid islanding can keep a port running through a typhoon or blackout, yet they make fault protection and power-quality control harder. A transition platform therefore has to look beyond annual greenhouse-gas totals and also track resilience, recovery time, safety margins and long-term adaptability.

The platform must also work within a fragmented set of authorities. State-owned port companies administer terminal land and berths; city governments manage roads, environmental monitoring and land-use planning; the utility controls feeders, substation capacity and tariffs; private concessionaires operate cargo equipment; shipping lines decide on retrofits and fuels; and dockworkers and residents bear many of the local effects. Because decision rights, money and expertise are unevenly spread across these actors, the governance design cannot assume that any one of them can direct the others.

The just-transition principle embedded within Taiwan's climate statutory framework requires that emission cuts be shared fairly and decided with the people affected. In a commercial port-region setting, the principle can be expressed as five auditable criteria: occupational workforce reskilling for high-voltage and alternative-fuel handling; dockside worker and community safety protection; verified mitigation of criteria air pollutants (NO_x, SO_x, $PM_{2.5}$) and acoustic noise in adjacent urban districts; economic viability and tariff safeguards for small-to-medium logistics operators; and institutionalized procedural participation for local municipal stakeholders. These criteria work as practical constraints: they affect how quickly projects are permitted, how fast operators adopt them and whether the regional pathway can be sustained.

III. RESEARCH DESIGN AND SYSTEM BOUNDARY

A. *Design-Science Research Framework and Evaluation Criteria*

This study follows a design-science research (DSR) approach to develop and evaluate N-TIP as a socio-technical artifact for port decarbonization involving many stakeholders. Because the artifact connects national net-zero policy with port engineering practice, it is assessed against four criteria:

1. Completeness: the platform covers logistics, medium-voltage network limits, low-carbon fuel supply, investment sequencing, grid resilience and equity.
2. Internal coherence: there is a traceable path from measured data through simulation and optimization to the body that is accountable for each decision.
3. Measurability: each technical, environmental, financial and equity indicator can be calculated from auditable field data.
4. Staged implementability: the platform can be commissioned in phases and delivers value before the whole port is instrumented.

The design draws on policy documents of Taiwan's Climate Change Administration and National Development Council, TIPC master plans, and established standards for cyber-physical infrastructure and microgrid modeling. Harmonized and verified operational data covering all terminal operators in Northern Taiwan are not publicly available, so the study does not impute missing data. Instead, it defines data-governance rules and model equations, and tests the decision logic with the reduced-order scenario model presented in Section VI.

B. *Spatial, Functional, and Jurisdictional Boundaries*

The study area consists of the three ports administered by the TIPC Keelung Branch (Keelung, Taipei and Suao), together with adjacent logistics zones and utility connections. The boundary defines a coordination zone for shared energy dispatch, emissions monitoring and investment planning; it does not change any statutory jurisdiction.

Twelve operational domains fall within the functional boundary:

- Commercial vessel hoteling, maneuvering, and shore-power coupling at berth.
- Heavy yard-handling machinery, including rail-mounted and rubber-tired gantry cranes, reach stackers, and automated guided vehicles.
- Terminal building electrical baseloads, cold-chain

refrigerated container blocks, and administrative facilities.

- Heavy drayage truck queues, optical character recognition container gates, and internal terminal tractors.
- Distributed renewable generation (rooftop solar PV), battery energy storage systems (BESS), and fast-charging depots.
- Marine bunkering infrastructure, hazardous material containment, and low-carbon alternative fuel supply chains.
- Port maintenance workshops, floating plant operations, and harbor tug servicing.
- Solid waste recovery, graywater management, and circular resource processing.
- Stack emissions accounting for Scope 1 direct fuel combustion, Scope 2 purchased electricity, and bounded Scope 3 logistics operations.
- High-resolution fence-line monitoring of criteria air pollutants (NO_x , SO_x , $PM_{2.5}$, PM_{10}) and acoustic contours in adjacent neighborhoods.
- Critical infrastructure exposure to typhoons, seismic events, storm surges, and utility supply disruptions.
- Institutional mechanisms linking green tariffs, concession renewal benchmarks, carbon pricing, and workforce reskilling programs.

C. System Design Requirements

Based on international maritime decarbonization standards and national net-zero policy, the platform is designed to meet eight requirements:

- R1—Auditability: every reported record carries a provenance trail with asset ID, calibrated meter timestamp, boundary class, units, emission factor, uncertainty and data owner.
- R2—Interoperability: terminal operating systems (TOS), vessel automation, utility SCADA and municipal traffic platforms exchange data through common schemas and versioned APIs.
- R3—Cyber-physical coupling: the model represents the links between vessel and yard schedules, feeder loads, local emissions, battery ageing and fault resilience.
- R4—Decision relevance: model outputs feed specific actions such as berth allocation, demand-response dispatch, investment priority, differentiated port dues and concession reviews.
- R5—Uncertainty: results are reported as ranges from scenarios and sensitivity tests rather than as single-point forecasts.
- R6—OT security and confidentiality: control loops and utility interfaces use network segmentation under IEC 62443, role-based access, cryptographic verification and tamper-evident logs to protect commercial data.
- R7—Justice: effects on nearby communities, occupational health, worker reskilling and the compliance burden on small carriers enter the model as constraints or objectives.
- R8—Scalability: the platform is useful from the first pilot berth or terminal and does not require instrumentation of the whole harbor at the start.

IV. THE N-TIP FRAMEWORK ARCHITECTURE

N-TIP organizes regional decarbonization as five linked processes supported by four layers. Figure 1 shows how the processes and layers fit together.

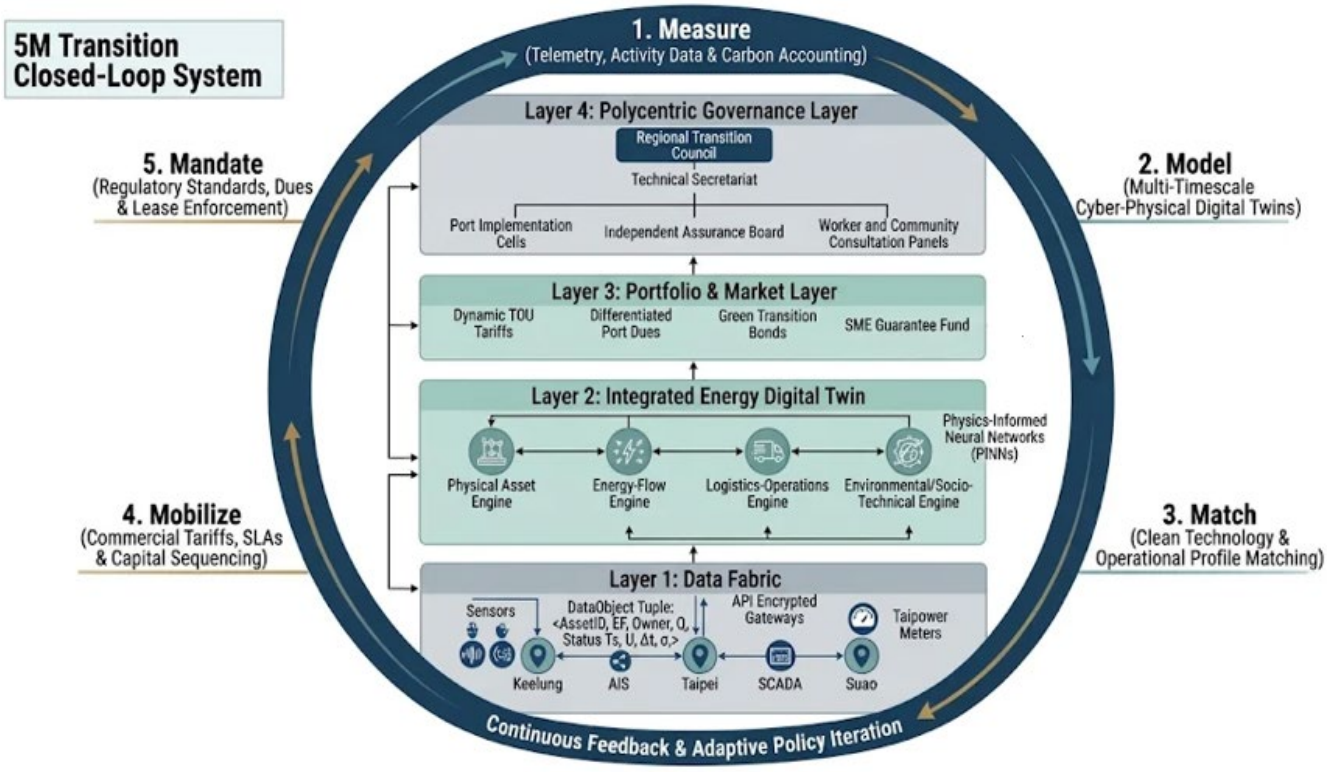


Figure 1: The N-TIP framework architecture, illustrating the five iterative transition loops and four interoperable layers across the Keelung–Taipei–Suao port triad.

A. The Five Iterative Transition Loops

The five processes form a feedback cycle rather than a one-way administrative sequence:

- Measure: builds an auditable baseline for the three ports from equipment telemetry, interval utility bills, bunkering records, Automatic Identification System (AIS) tracks, feeder power-quality data and fence-line air monitoring. Scope 1 combustion and Scope 2 purchased electricity are calculated directly, while upstream fuel, chartered logistics and external trucking are added step by step under Scope 3. Measured values are kept separate from estimates.
- Model: maintains a multi-timescale digital twin of assets, energy conversion, terminal logistics, feeder limits and bunkering safety distances. It runs dispatch and stress scenarios and reports sensitivity ranges and error margins with every result.
- Match: compares candidate technologies with the profile of each port. It identifies berths where shore power is technically feasible and cheaper than auxiliary-engine operation, sites where rooftop PV and BESS can cut peaks, and machinery that is better served by drop-in fuels, subject to substation headroom and concession periods.
- Mobilize: turns selected measures into contracts and commercial tools, including investment schedules, green procurement specifications, time-of-use (TOU) tariffs, carrier service-level agreements (SLAs) and training plans.
- Mandate: links verified results to the decisions of the responsible authorities. Audited data go to the Maritime and Port Bureau, TIPC and the city environmental bureaus, where they inform lease renewals, differentiated harbor dues, environmental permits and public disclosure. Large deviations from expected performance trigger a review of the project portfolio.

B. Four Interoperable Structural Layers

- Trusted Transition Data Fabric-
  The data fabric is a federated, secured communication layer connecting terminal operators, Taipower, shipping lines and city environmental regulators. To protect commercial data and limit OT exposure, cargo manifests and contracts stay on each operator's own servers. Organizations exchange information through encrypted, versioned application programming interfaces (APIs) and federated queries that return only aggregated values.

Every data object exchanged on the fabric uses the same structure:

$$\text{DataObject} = \langle \text{ID}, \text{Context}, \text{Telemetry}, \text{Emission}, \text{Audit} \rangle \quad (1)$$

where:

$$\text{ID} = \{\text{AssetID}, \text{Owner}\},$$
$$\text{Context} = \{\text{GeoLocation}, \text{ProcessType}\},$$
$$\text{Telemetry} = \{\Delta t, Q, U\},$$
$$\text{Emission} = \{\text{Boundary}, EF, \sigma, \text{Source}\}, \text{ and}$$
$$\text{Audit} = \{T_s, \text{Status}\}.$$

where Δt is the measurement interval, Q is measured quantity, U denotes engineering units, EF is the applied emission factor, σ represents the calculated measurement uncertainty, T_s is the calibrated timestamp, and Status indicates third-party audit verification. Data-sharing agreements set query permissions, retention periods and verification rules, and are administered by the Technical Secretariat.

- Port-Region Integrated Energy Digital Twin-
  The analysis core links four simulation engines covering Keelung, Taipei and Suao:
  - Physical asset engine: electrical, thermal and mechanical models of substations, crane drives, gate equipment, reefer stacks, PV arrays, batteries and fuel tanks.
  - Energy-flow engine: power-flow calculations, cryogenic fuel handling and conversion efficiencies across distribution lines, gas pipelines and bunkering systems.
  - Logistics engine: terminal operations, including berth allocation, automated guided vehicle (AGV) routes, rubber-tired gantry (RTG) crane moves, truck queues and container handling times.
  - Environmental and social impact engine: converts dispatch results into local air-pollutant footprints (NO_x , SO_x , $PM_{2.5}$), equivalent greenhouse gas balances, acoustic decibel contours, and worker hazard exposures.

In a full implementation the engines can use hybrid physics-informed neural networks (PINNs), in which data-driven predictions are bounded by physical limits such as battery state of charge and transformer thermal ratings, with error margins reported. The scenario model in Section VI is a much simpler reduced-order version used only to test the decision logic.

- Transition Portfolio and Market Mechanisms Layer-
  This layer lists candidate investments and the market mechanisms used to pay for them. Projects—spanning high-voltage shore power ($6.6\ \text{kV}/11\ \text{kV}$), automated battery-swapping stations, crane electrification kits, and warehouse rooftop PV—are evaluated by capital cost, operational expenditure, localized feeder impact, footprint, and lead time.

Four market mechanisms connect model results with financing:

- Time-of-use (TOU) and green pricing: shifts reefer loads and BESS charging toward solar hours to avoid maximum-demand charges.
- Differentiated harbor dues: discounts for carriers with verified shore-power use or certified low-carbon fuel.
- Transition finance: links audited projects to green bonds and sustainability-linked loans, with additionality checked by the assurance board.
- Regional transition fund and SME support: sets aside part of green-port revenue and public grants for low-interest equipment loans, vehicle conversion subsidies and safety certification for small trucking firms and coastal service craft, so that compliance costs do not fall mainly on them.
- Polycentric Governance, Assurance, and Subsidiarity-
  The governance structure coordinates the main stakeholders in Northern Taiwan without replacing existing legal authorities. It has five bodies:
- Regional Transition Council: the steering body, made up of TIPC and its Keelung Branch, the Keelung, New Taipei and Yilan local governments, Taipower and the transport ministry. It approves regional carbon

budgets, shared infrastructure and grid-connection investments.
- Technical Secretariat: runs the data-fabric catalog, API security and the multi-port digital-twin simulations.
- Port Implementation Cells: engineering teams at Keelung, Taipei and Suao that turn council decisions into berth schedules, maintenance plans and substation management.
- Independent Assurance Board: accredited third-party auditors who check Scope 1–3 boundaries, green-finance additionality and IEC 62443 compliance.
- Worker and Community Panels: forums for dock unions and nearby residents to review high-voltage safety procedures, reskilling plans and fence-line noise and air-quality results.

Decisions are taken at the lowest level that can handle them. Routine logistics, berth dispatch and crane operations stay with each terminal operator and go to the Regional Council only when they involve shared utility capacity, effects across city boundaries or joint investment.

V. MODELS AND INDICATORS

A. Multi-Tier Greenhouse Gas and Environmental Accounting

Operational emissions across the Keelung–Taipei–Suao port triad are calculated within defined time and space boundaries. For activity category i at discrete time interval t across port facility $p \in$ {Keelung,Taipei,Suao}, direct and indirect operational emissions $E_{p,t}$ are evaluated as:

$$E_{p,t} = \sum_{i\in\mathcal{S}_1}\left[A_{p,i,t} \times \mathrm{EF}_{i,t} \times \left(1 - R_{p,i,t}\right)\right] + \sum_{j\in\mathcal{S}_2}\left[E^{\mathrm{grid}}_{p,j,t} \times \mathrm{EF}^{\mathrm{grid}}_{j,t}\right] + E^{\mathrm{proc}}_{p,t} - E^{\mathrm{rem}}_{p,t} \quad (2)$$

where $\mathcal{S}_1$ denotes Scope 1 combustion sources (e.g., yard tractors, diesel generators, mobile harbor cranes), $\mathcal{S}_2$ represents Scope 2 purchased electricity, $A_{p,i,t}$ is metered operational activity (fuel consumption in metric tons or operating hours), $\mathrm{EF}_{i,t}$ is the validated fuel emission factor (tCO_2e/unit), and $R_{p,i,t} \in [0,1]$ is the measured abatement efficiency of installed retrofits. For purchased electricity, $E^{\mathrm{grid}}_{p,j,t}$ denotes metered electrical energy (MWh), and $\mathrm{EF}^{\mathrm{grid}}_{j,t}$ is recorded in two parallel ledgers: location-based factors representing the national utility average, and market-based factors reflecting certified power purchase agreements (PPAs) or on-site renewable generation. The term $E^{\mathrm{proc}}_{p,t}$ accounts for industrial process emissions, while $E^{\mathrm{rem}}_{p,t}$ represents certified permanent carbon removals.

Boundaries are kept separate: avoided emissions achieved via cold-ironing connections are accounted for separately under vessel-operator Scope 3 categories or shared maritime corridor balance sheets, preventing double-counting within the port authority's Scope 1 and 2 compliance boundaries. For any candidate transition portfolio x, the computational engine calculates annual gross emissions, cumulative carbon budgets, localized air pollution totals (NO_x, SO_x, $PM_{2.5}$), and net energy import balances. Residual hard-to-abate emissions are listed alongside permanence durations, technological barriers, and continuous monitoring requirements.

B. Multi-Objective Portfolio Optimization Formulation

Let $x_j \in [0,1]$ denote the deployment scale or binary selection of clean-energy engineering project $j \in \mathcal{J}$ (e.g., high-voltage shore power, automated terminal electrification, rooftop solar PV arrays, battery storage installations, or alternative fuel bunkering facilities). Because individual evaluation criteria differ in physical dimensions and numerical scales, all objective components are normalized against baseline reference values. The multi-objective scalarized optimization problem is formulated as:

$$\min_x F(x) = w_1\frac{C(x)}{C_0} + w_2\frac{E(x)}{E_0} + w_3\frac{Q(x)}{Q_0} + w_4\frac{H(x)}{H_0} + w_5\frac{J(x)}{J_0} \quad (3)$$

subject to the parameter constraints:

$$\sum_{k=1}^{5} w_k = 1, \quad \forall w_k \geq 0 \quad (4)$$

where $C(x)$ is the discounted net present lifecycle cost; $E(x)$ represents aggregate greenhouse gas emissions; $Q(x)$ models population-weighted exposure to criteria air pollutants (NO_x, SO_x, $PM_{2.5}$); $H(x)$ quantifies system reliability and technological failure risks; and $J(x)$ evaluates procedural and distributive equity risks across vulnerable dockworker and port-adjacent community cohorts. The denominators C_0, E_0, Q_0, H_0, J_0 represent reference values under a business-as-usual trajectory. The weights w_k are varied to trace a Pareto frontier, allowing stakeholders to examine trade-offs under competing policy priorities.

The portfolio is subject to physical, electrical, and operational system constraints across all time steps t:

$$P^{\mathrm{ren}}_{p,t}(x) + G_{p,t} + D_{p,t} - L_{p,t} - P^{\mathrm{ch}}_{p,t} + P^{\mathrm{dis}}_{p,t} \geq R_{p,t}, \quad \forall p, \forall t \quad (5)$$

where $P^{\mathrm{ren}}_{p,t}(x)$ is local dispatchable and intermittent renewable generation (e.g., rooftop solar arrays on warehouse roofs), $G_{p,t}$ is purchased utility grid import, $D_{p,t}$ is certified demand-response flexibility, $L_{p,t}$ denotes uncontrollable baseline terminal and cold-chain loads, $P^{\mathrm{ch}}_{p,t}$ is battery storage and electric equipment charging power, $P^{\mathrm{dis}}_{p,t}$ is battery storage discharge power, and $R_{p,t}$ is the minimum spinning reserve margin needed to keep the port-city feeder stable.

To capture physical storage dynamics and degradation kinetics, battery energy storage systems (BESS) are governed by discrete-time state-of-charge (SOC) formulations:

$$\mathrm{SOC}_{p,t+1} = \mathrm{SOC}_{p,t} + \left(\eta_c P^{\mathrm{ch}}_{p,t} - \frac{1}{\eta_d}P^{\mathrm{dis}}_{p,t}\right)\frac{\Delta t}{C^{\mathrm{batt}}_p} \quad (6)$$

$$\mathrm{SOC}_{p,\min} \leq \mathrm{SOC}_{p,t} \leq \mathrm{SOC}_{p,\max}, \quad \forall t \quad (7)$$

$$0 \leq P^{\mathrm{ch}}_{p,t} \leq P^{\mathrm{ch}}_{p,\max}u_{p,t}, \quad 0 \leq P^{\mathrm{dis}}_{p,t} \leq P^{\mathrm{dis}}_{p,\max}\left(1 - u_{p,t}\right), \quad u_{p,t} \in \{0,1\} \quad (8)$$

where C^{batt}_p represents the installed battery capacity (MWh), η_c and η_d are charging and discharging efficiencies, $\mathrm{SOC}_{p,\min}$ and $\mathrm{SOC}_{p,\max}$ enforce operational cycle limits to prevent accelerated cell degradation, and binary variable $u_{p,t}$ prevents simultaneous charging and discharging.

Additional operational constraints enforce utility substation feeder capacities ($G_{p,t} \leq G_{p,\max}$), dockside physical footprint limitations, blast-safety exclusion zones for alternative marine fuels, vessel cold-ironing cable reach boundaries, dockworker certification availability, and

engineering project delivery lead times. Safety is treated as a hard constraint: any configuration that raises toxic or explosion risk above the accepted limit ($\text{Risk}_j \geq \text{Risk}_{\text{threshold}}$) is removed from the feasible set, whatever its carbon benefit.

C. Regional Transition Readiness Index (TRI)

To track implementation progress across heterogeneous port facilities without obscuring operational trade-offs, the platform establishes the composite Transition Readiness Index (TRI). The TRI evaluates five normalized, auditable dimensions scaled from 0.0 to 1.0:

$$\text{TRI} = 0.25M + 0.25I + 0.20D + 0.15J + 0.15R \qquad (9)$$

where:

- M (Measurement and MRV Maturity): Evaluates single-port boundary definitions, automated sub-metering coverage across high-consumption assets, independent third-party audit status, and empirical telemetry verification frequencies.
- I (Infrastructure and Physical Energy Integration): Quantifies shore-power connection capacity at berths, terminal handling equipment electrification ratios, distributed rooftop solar penetration, microgrid BESS deployment, and utility interconnection feeder headrooms.
- D (Decision and Digital Governance Maturity): Measures data interoperability across terminal operating systems (TOS), deployment of closed-loop energy management systems (SEMS), predictive simulation capabilities, and automated tariff-clearing execution.
- J (Just-Transition Performance): Evaluates high-voltage and alternative-fuel labor technical certifications, occupational lost-time safety rates, ambient air quality improvements within adjacent urban boundaries, and tariff protections for small-to-medium logistics contractors.
- R (System Resilience and Cyber-Physical Assurance): Assesses autonomous microgrid islanding runtimes during utility outages, natural hazard mitigation infrastructure (typhoon and seismic hardening), and operational technology (OT) cybersecurity conformance.

In operation, the sub-indicators are computed from engineering logs, utility bills, air-quality sensors and administrative records; Section VI.B shows how they are computed in the scenario model. The main use of the TRI is to reveal bottlenecks: a port can score low overall if investment in electrical hardware (I) is undermined by unverified emission boundaries (M) or the exclusion of workforce reskilling programs (J).

D. System Assurance and Operational Technology (OT) Cybersecurity Metrics

Electrification and digital control loops make port operations more interdependent, so N-TIP adds a separate assurance index with six indicators:

- Data Availability (A_d): Uptime ratio of operational telemetry feeds and calibrated energy sub-meters across all berths.
- Model Drift Factor (δ_m): Mean absolute percentage error (MAPE) between simulated digital-twin state projections and observed field telemetry over rolling 30-day windows.
- Access Anomaly Rate (N_{sec}): Frequency of unauthorized access attempts, protocol violations, or anomalous telemetric injections detected along industrial communication buses.
- Mean Time to Recovery (MTTR): Operational duration required to isolate compromised digital nodes and restore automated dispatch control following a system fault.
- Cryptographic Ledger Integrity (I_{crypt}): Verification rate of immutable audit logs recording energy transactions, berth connections, and emissions baselines.
- Degraded-Mode Operational Continuity (T_{manual}): Verified time for which essential harbor equipment—including shore-power breakers, gantry cranes, and vessel traffic dispatch—operates safely via manual mechanical interlocks and fail-safe hardware overrides during complete network or SCADA isolation.

A project whose emission reduction depends on an OT control loop without certified fail-safe isolation or fast recovery is classed as incomplete and is not commissioned until this is fixed.

VI. ILLUSTRATIVE STRESS TEST AND RESULTS

A. Purpose, System Boundary, and Scenario Parameters

This section applies the indicators of Section V to four stylized pathways for the Keelung–Taipei–Suao triad. The aim is to show how N-TIP ranks options and where the ranking is fragile, not to estimate the actual inventory of the three ports, for which harmonized terminal-level data have not been published. The calculation is a reduced-order model with annual time points (2025, 2030, 2040 and 2050) written in Python and supplied as supplementary material, so that every number reported below can be regenerated. Emissions are expressed as an index in which the combined 2025 emissions of the three ports equal 100 ($B_0 = 100$). The index uses a geographic boundary that includes at-berth vessel emissions; the ledger split described in Section V.A can be applied afterwards without changing the totals.

The baseline is divided into four activity segments (Table 1): at-berth vessel hoteling (s1, 38), cargo-handling equipment (s2, 27), buildings, reefers and lighting already supplied from the grid (s3, 25), and harbor craft and in-port drayage (s4, 10). These shares are planning assumptions chosen to represent a mixed container and cruise port, and a pilot should replace them with metered values. Service demand grows by the same factor in every pathway, so differences between pathways come only from technology, carrier and efficiency choices.

When a fossil-fuelled service is electrified, its emissions per unit of service are multiplied by a conversion ratio k_s, which combines the efficiency gain of the electric drive with the ratio of grid and fuel emission factors. For berth hoteling, an auxiliary-engine efficiency of about 40% and a diesel factor of 0.267 kg CO_2 per kWh of fuel give 0.667 kg CO_2 per kWh generated on board. Shore supply at the 2025 grid factor of 0.474 kg CO_2e/kWh, with 5% network losses, gives 0.50 kg, so $k_1 \approx 0.75$. For yard equipment, a diesel-drive efficiency of about 30% against 85% for an electric drive gives $k_2 = (0.30/0.85)(0.474/0.267) \approx 0.63$; $k_4 = 0.65$ is used for the mixed craft and truck segment. The grid factor is assumed to fall to 0.80, 0.45 and 0.20 of its 2025 value by 2030, 2040

and 2050. Alternative fuels carry a lifecycle factor φ relative to diesel: 0.85, 0.50 and 0.25 for the LNG-to-hydrogen/ammonia sequence of P3, and 0.40, 0.30 and 0.20 for the drop-in biofuels used by P2 in non-electrifiable machinery.

Table 1: Common Model Parameters

Parameter	Symbol	2030 / 2040 / 2050 or value	Basis
Baseline segment shares (s1 / s2 / s3 / s4)	B_s	38 / 27 / 25 / 10	Planning assumption; sum = 100
Service-demand growth	G_y	1.04 / 1.10 / 1.15	Common to all pathways
Grid factor relative to 2025	g_y	0.80 / 0.45 / 0.20	Assumed path; 2025 = 0.474 kg CO_2e/kWh
Electric-to-fossil conversion ratio (s1 / s2 / s4)	k_s	0.75 / 0.63 / 0.65	Derived from drive efficiencies
Exposure weights (s1 / s2 / s4)	w_s	1.5 / 1.0 / 1.2	Distance to residents
Added peak at full electrification (s1 / s2 / s4)	λ_s	2.2 / 0.9 / 0.4	× 2025 feeder peak
Firm feeder capacity in 2050	P^{firm}	3.0	× 2025 peak, after reinforcement
Capital index (BAU / P0 / P1 / P2 / P3)	K_p	0.40 / 0.55 / 0.85 / 0.90 / 1.00	Relative, assumed
Carbon-fee and fuel-cost weight	Λ	0.45	Cost index

Year-dependent entries are listed as 2030 / 2040 / 2050. All values are normalized and are intended to be replaced by metered data in a pilot.

The four pathways cover the 2026–2050 horizon. Their carrier shares and other settings are given in Table 2.

- Pathway 0 (P0: Incremental Efficiency): low-capital operational retrofits, gate-schedule smoothing, gradual replacement of yard tractors, and low-voltage shore connections limited to harbor craft and coastal vessels.
- Pathway 1 (P1: Accelerated Electrification): rapid electrification of all commercial berths, with high-voltage onshore power supply (HV-OPS, 6.6 kV/11 kV) at Keelung cruise wharves and Taipei container berths, electric RTG cranes and large charging plazas, but no local storage or microgrid.
- Pathway 2 (P2: Balanced Integration): somewhat lower electrification shares than P1, combined with warehouse rooftop PV, battery storage (BESS), demand-response contracts, rail and logistics optimization, workforce reskilling and drop-in biofuels for machinery that cannot be electrified.
- Pathway 3 (P3: Alternative-Fuel Dominant): investment centred on bunkering, storage and handling of low-carbon fuels (LNG as a transition fuel, followed by certified green hydrogen and e-ammonia) for vessels and heavy yard machinery, with limited grid reinforcement.

Table 2: Pathway-Specific Parameters

Parameter (2030 / 2040 / 2050)	P0	P1	P2	P3
Efficiency gain ε	.06/.10/.14	.04/.08/.10	.06/.12/.16	.04/.08/.10
On-site PV share π	.02/.04/.05	.02/.04/.05	.06/.15/.25	.02/.04/.05
Electrified share e, s1	.05/.15/.25	.30/.75/.95	.25/.65/.85	.10/.25/.35
Electrified share e, s2	.10/.25/.40	.40/.85/1.0	.35/.75/.90	.15/.30/.40
Electrified share e, s4	.10/.25/.40	.20/.60/.90	.20/.50/.70	.10/.20/.30
Alternative-fuel share a, s1	0	0	0/.05/.10	.15/.45/.60
Alternative-fuel share a, s2	0	0	.05/.10/.10	.15/.45/.55
Alternative-fuel share a, s4	0	0	.05/.20/.30	.15/.45/.60
Lifecycle fuel factor φ	–	–	.40/.30/.20	.85/.50/.25
Local NO_x/PM factor q	–	–	0.9	0.5
Coincidence factor c	0.85	0.85	0.65	0.85
BESS peak shaving β	0	0	.10/.25/.35	0
Backup generation $\bar{g}$ / endurance T (h)	0.60 / 48	0.30 / 48	0.35 / 48	0.70 / 36
BESS energy S (h) / islanding ι	0 / 0	0 / 0	16 / 1	0 / 0
Assigned TRI inputs: M / D	0.50 / 0.40	0.70 / 0.60	0.90 / 0.85	0.70 / 0.60
Assigned: certification / SME / OT	.40/.50/.50	.55/.40/.60	.85/.80/.85	.50/.45/.65

s1 = at-berth hoteling, s2 = cargo-handling equipment, s4 = harbor craft and in-port drayage. Backup generation and BESS energy are expressed relative to a critical load of 1.0. M, D, certification, SME support and OT conformance cannot be calculated without field audits and are assigned scenario scores.

Each pathway is tested under three operating conditions:

- Central conditions (S_1): the parameter values in Tables 1 and 2.
- Energy-market stress (S_2): purchased-electricity tariffs rise by 40% and renewable yields fall by 25% (PV share multiplied by 0.75).
- Critical infrastructure disruption (S_3): a 48-hour grid outage after typhoon damage or substation failure, with bunkering deliveries delayed. P3's on-site fuel endurance is limited to 36 h.

B. Calculation Procedure

For pathway p and year y, the emissions index is

$$E_{p,y} = G_y\left(1-\varepsilon_{p,y}\right)\left[\sum_{s\in\{1,2,4\}} B_s\left(f_{p,s,y} + k_s\gamma_{p,y}e_{p,s,y} + \varphi_{p,y}a_{p,s,y}\right) + B_3\gamma_{p,y}\right] \quad (10)$$

$$\gamma_{p,y} = g_y\left(1-\pi_{p,y}\right),\ f_{p,s,y} = 1 - e_{p,s,y} - a_{p,s,y} \quad (11)$$

where e and a are the electrified and alternative-fuel shares of segment s, f is the remaining fossil share, ε is the efficiency gain, and γ is the effective grid factor after the on-site PV share π. Eq. (10) is a reduced form of Eq. (2): the activity term becomes $B_sG_y(1-\varepsilon)$, the fuel factor becomes the carrier mix, and the grid term becomes γ. Cumulative 2025–2050 emissions are obtained by trapezoidal integration of the indices. A business-as-usual (BAU) reference without new measures, in which only the grid-supplied segment benefits from grid decarbonization, reaches 92.0 in 2050 and 2,400 index-years cumulatively.

Population-weighted local exposure to NO_x and PM, normalized to 100 in 2025, is

$$Q_{p,y} = 100G_y\left(1-\varepsilon_{p,y}\right)\frac{\sum_s w_sB_s\left(f_{p,s,y}+q_pa_{p,s,y}\right)}{\sum_s w_sB_s} \quad (12)$$

where w_s weights segments by their distance to residents and q_p is the local NO_x/PM factor of the alternative fuel (Table 2). The 2050 feeder peak and the feeder loading ratio (FLR) are

$$P^{\mathrm{pk}}_{p,y} = G_y\left(1-\varepsilon_{p,y}\right) + c_pG_y\sum_s\lambda_se_{p,s,y} - \beta_{p,y},\ \mathrm{FLR}_p = \frac{P^{\mathrm{pk}}_{p,2050}}{P^{\mathrm{firm}}} \quad (13)$$

where λ_s is the peak added by full electrification of segment s, c_p is the coincidence factor (0.85 for uncoordinated connection and charging, 0.65 with P2's demand response and smart charging) and β is battery peak shaving. Solar output is not credited at the peak because port peaks often occur at night. In the 48-hour outage, the unserved fraction of critical energy is

$$U_p = 1 - \frac{\min\left\{48,\bar{g}_p\min\left(T_p,48\right)+S_p+0.8\iota_pY_p\right\}}{48} \quad (14)$$

where $\bar{g}_p$ is backup generation capacity as a fraction of critical load, T_p is fuel endurance in hours, S_p is usable storage in critical-load hours, $\iota_p = 1$ if the microgrid can island, and Y_p is daily PV yield in critical-load hours, taken at 40% of normal over two storm days.

The TRI of Eq. (9) is built from sub-indicators scaled to [0, 1]. Three dimensions use model outputs. I is the mean of the electrified share, the clean-carrier share ($e + a$) and a feeder-headroom score $h = \min\{1, \max(0, 1.5 - \mathrm{FLR})\}$. J is the mean of workforce-certification coverage, SME support and the air-quality gain $1 - Q/100$. R is the mean of the served outage fraction $1 - U$ and OT-security conformance. M, D, certification, SME support and OT conformance are assigned scenario scores (Table 2) and should be read as targets rather than measurements.

To evaluate Eq. (3), the five objectives are calculated as

$$C = K_p + \Lambda\frac{E^{\mathrm{cum}}_p}{E^{\mathrm{cum}}_{\mathrm{BAU}}},\ H = 0.5\mathrm{FLR}_p + 0.5U_p \quad (15)$$

with E equal to the 2050 index, Q the 2050 exposure index and $J = 1$ minus the equity score. Each term is divided by its BAU value, as Eq. (3) requires. Weights are first set equal ($w_k = 0.2$) and then sampled from a uniform Dirichlet distribution (10,000 draws) to see how often each pathway minimizes F.

C. Simulation Results and Comparative Performance

Table 3 compares the pathways with the BAU reference. All four reduce cumulative emissions, from 18% (P0) to 44% (P2). P1 and P2 reach similar 2030 levels (83.3 and 80.7) because both rely on berth and yard electrification, whose benefit is small while the grid factor is still 0.8. The pathways separate after 2040 as the grid becomes cleaner.

Table 3: Emissions, Feeder Loading, Outage and Exposure Results (central case)

Pathway	*E* 2030	*E* 2040	*E* 2050	Cum. 2025–2050	FLR 2050	Unserved in S3 (%)	*Q* 2050
BAU reference	98.8	94.9	92.0	2400	0.38	40.0	115.0
P0: Incremental Efficiency	89.9	74.5	58.0	1959	0.68	40.0	68.1
P1: Accelerated Electrification	83.3	46.1	17.7	1424	1.44	70.0	4.4
P2: Balanced Integration	80.7	41.8	13.7	1342	0.94	25.0	13.7
P3: Alternative-Fuel Dominant	88.7	55.8	24.3	1595	0.75	47.5	36.1

E: emissions index (2025 = 100); Cum.: index-years 2025–2050; FLR: 2050 peak divided by firm feeder capacity; S3: 48-hour outage; Q: population-weighted NO_x/PM exposure index (2025 = 100).

P1 removes almost all local combustion ($Q = 4.4$ in 2050), but its feeder peak reaches 4.31 times the 2025 value, 44% above the assumed firm capacity. With no storage or islanding and part of the backup generation retired, it also leaves 70% of critical demand unserved during the outage. P2 has the lowest 2050 index (13.7) and keeps the FLR below 1.0 (0.94), helped by battery peak shaving and a lower coincidence factor. Even so, it leaves 25% of critical

demand unserved, which indicates that the 72-hour islanding target in Section VII.C needs more storage or backup capacity than assumed here. P3 keeps the feeder lightly loaded (FLR = 0.75), but its 2050 index (24.3) is held up by the 0.25 lifecycle factor applied to more than half of its non-electric service. P0 is the least costly option (C/C_0 = 1.08) and puts the least stress on the feeder, yet it stays at 58.0 in 2050, far from the net-zero target.

Table 4 reports the TRI and the multi-objective score. With equal weights, P2 has the lowest F (0.68), followed by P3 (0.87), P0 (0.91) and P1 (0.96). No pathway is best on every criterion: the normalized objectives show that P0 is best on cost (1.08) and reliability risk (1.38), P1 on local exposure (0.04), and P2 on emissions (0.15) and equity risk (0.23). Across 10,000 random weight vectors, P2 minimizes F in 90.7% of draws. P0 wins in 8.0%, almost all with high weights on cost and reliability, and P1 wins in 1.3%, mainly when local exposure receives the largest weight. The TRI ranks P2 first (0.84), then P3 (0.63), P1 (0.62) and P0 (0.47). P1 has the highest electrified share (0.96), but its TRI is pulled down by a feeder-headroom score of 0.06 and by its outage performance.

Table 4: TRI Dimensions and Multi-Objective Scores in 2050

Path	*M*	*I*	*D*	*J*	*R*	TRI	*F* (equal *w*)	Weight draws won (%)
P0	0.50	0.49	0.40	0.41	0.55	0.47	0.91	8.0
P1	0.70	0.66	0.60	0.64	0.45	0.62	0.96	1.3
P2	0.90	0.79	0.85	0.84	0.80	0.84	0.68	90.7
P3	0.70	0.68	0.60	0.53	0.59	0.63	0.87	0.0

TRI = 0.25M + 0.25I + 0.20D + 0.15J + 0.15R (Eq. 9). F is Eq. (3) with w_k = 0.2. The last column gives the share of 10,000 Dirichlet weight draws for which the pathway has the lowest F.

D. Verification, Uncertainty, and Sensitivity Analysis

Four checks were applied to the code. (i) With all carrier shares, efficiency gains and PV set to zero and $G = g = 1$, Eq. (10) returns exactly 100.00 for every pathway. (ii) A hand calculation of the P2 2050 value from its segment contributions (6.08 + 2.74 + 3.62 + 1.24 = 13.68) matches the coded result. (iii) Limiting cases behave as expected: with $e = a = 0$ the model returns the BAU path, and with $g = 0$ only the fuel and residual fossil terms remain. (iv) In the outage balance, served and unserved energy add up to 48 critical-load hours in every pathway. These checks show that the code implements the stated equations. They do not validate the parameter values, which requires metered port data.

Table 5 lists one-at-a-time changes of ±25% in the main inputs, the S_2 case and a Monte Carlo run (5,000 draws) in which k_s, g_{2050}, φ and demand growth vary independently and uniformly within ±20%. The grid factor is the most influential input for every electrified pathway, followed by the conversion ratio. The P2 < P1 ordering holds in every case and in all Monte Carlo draws.

Table 5: Sensitivity of the 2050 Emissions Index

Input varied	P1: 2050 index	P2: 2050 index	P3: 2050 index	P2 < P1 kept
Grid factor g_{2050} (±25%)	21.42 / 14.05	16.18 / 11.18	26.44 / 22.14	Yes
Conversion ratio k_s (±25%)	15.28 / 20.19	12.08 / 15.28	23.37 / 25.21	Yes
Demand growth G_{2050} (±25%)	17.16 / 18.32	13.23 / 14.13	23.50 / 25.08	Yes
Fuel factor φ (±25%)	17.74 / 17.74	13.22 / 14.14	21.47 / 27.12	Yes
Efficiency ε (±25%)	18.23 / 17.24	14.33 / 13.03	24.97 / 23.62	Yes
S2: PV yield −25%	17.93	14.52	24.41	Yes
Monte Carlo 5th–95th percentile	14.57–21.32	11.52–16.09	21.41–27.19	100% of draws
Central case	17.74	13.68	24.29	–

Paired values give the result at −25% / +25% of the input. Monte Carlo inputs vary uniformly within ±20%.

Solving $E_{P1} = E_{P2}$ for the 2050 grid factor gives a switching value of 0.028 (about 0.013 kg CO_2e/kWh). P1 would therefore emit less than P2 only on an almost carbon-free grid, where its higher electrified shares outweigh P2's residual fuel use. A 2^6 factorial sweep (grid factor 0.10 or 0.35, k_s ±15%, φ ±30%, P2 PV share 0.15 or 0.35, electrified shares ×0.85 or ×1.0, and 2050 growth 1.05 or 1.25) selects P2 as the lowest-emission pathway in 62 of 64 cases. P3 wins the remaining two, both combining a high grid factor, high k_s, low φ, low PV and reduced electrification.

To see where P2's advantage comes from, we re-ran P2 with P1's efficiency and PV values. Its 2050 index rises from 13.7 to 17.5, almost the same as P1 (17.7). Removing P2's drop-in fuels instead raises it to 21.0. P2's lower emissions therefore come from efficiency, on-site PV and drop-in fuels rather than from a better electrification mix, and these are the parameters a pilot should measure first.

Under S_2, lower PV yield raises P2's 2050 index by 0.8 (to 14.5) and the other indices by less than 0.2. The tariff rise matters more. If all carriers had similar unit costs, a 40% tariff increase would raise the energy bill by about 37% for P1, whose 2050 service is 93% grid-supplied, by 28% for P2, and by 17–18% for P0 and P3. Electrification-heavy pathways therefore need the tariff instruments described in

Section IV.B. Finally, sampling the TRI weights from a Dirichlet distribution centred on Eq. (9) (5,000 draws) keeps the full TRI ranking in 94% of draws. The 5th–95th percentile range for P2 is 0.83–0.85, and the only rank changes occur between P1 and P3, whose scores differ by about 0.01.

E. Adaptive Decision Gates

The sensitivity results translate into three threshold rules for the platform:

- Grid decarbonization lag: if the 2050 grid factor stays at 0.45 of its 2025 value (the central 2040 level), the 2050 indices rise to 36.2 for P1, 26.2 for P2 and 35.0 for P3, so P3 almost matches P1. In that case, capital should go first to on-site PV and efficiency rather than to further charging-depot expansion, while the local air-quality benefit of electrification is still counted.
- Underused shore power: if vessel connection rates fall below about 40% of eligible calls because fuel is cheaper than electricity, berth switchgear is underused. The platform would then use berth substations to supply nearby yard and reefer loads to avoid stranded assets. This rule is not represented in the present model and should be tested in a pilot.
- Alternative-fuel uncertainty: if certified lifecycle factors do not improve beyond the 2040 value (φ = 0.50), P3's 2050 index rises from 24.3 to 35.6. Large hydrogen or ammonia bunkering investment should remain at pilot scale until lifecycle accounting and bunkering safety rules are settled.

N-TIP applies these rules through staged decision gates. A project moves from pilot to full procurement only when verified data show technical reliability (uptime ≥ 95%), audited additionality, OT cybersecurity certification (IEC 62443) and workforce safety accreditation. A project that fails a gate is paused and reviewed, while the rest of the roadmap continues. This limits the risk of lock-in to technologies whose performance has not yet been shown in the three ports.

VII. DISCUSSION AND ROADMAP

A. Systemic Insights: Governance, Electrification, and Just Transition

- Governance as part of the system: Cyber-physical port studies usually focus on dispatch algorithms or sensing. In practice, projects more often stall over data ownership, disputed terminal boundaries and unclear cost recovery. By building data-sharing charters, audit logs and a polycentric decision structure into the digital twin, N-TIP turns simulation from a dashboard into a coordination tool that several organizations can rely on.
- The Limits of Electrification Alone: The stress test shows that electrification without local flexibility is fragile. In P1, the coincident shore-power and charging peak reached 1.44 times the assumed firm feeder capacity, and only 30% of critical demand was served during the 48-hour outage. Deep-sea shipping and long-haul drayage also face battery weight limits. N-TIP therefore follows an electrification-first, not electrification-only, order: smooth logistics and electrify where feeder headroom exists, buffer the new load with PV and storage, and keep alternative fuels for assets that cannot be electrified.
- Data Governance as a Transition Asset: Sharing data between port organizations creates winners and losers. Shipping lines and terminal operators resist central data pools because manifests and cost structures are commercially sensitive. N-TIP's federated design separates data ownership from verification: privacy-preserving queries return audited carbon figures without exposing the underlying records.
- Operationalizing Distributive Equity: Putting just-transition indicators into the objective function addresses risks that often delay projects in practice. Ignoring worker safety, local pollution or the compliance burden on small trucking firms leads to regulatory delays and opposition. By quantifying verified training hours, fence-line ambient criteria pollutant levels (NO_x, SO_x, $PM_{2.5}$), and dedicated SME capital grants within the TRI, equity becomes a measurable operating requirement.

B. Risk Governance, Operational Safeguards, and Implementation RACI

Long-lived investments across the three ports need safeguards against four risks:

- Technology obsolescence and boundary shifting: modular switchgear is used, and well-to-wake boundaries are tracked so that compliance on paper does not simply move emissions upstream.
- Cyber-physical vulnerability: control links between terminal operating systems (TOS) and grid SCADA follow IEC 62443, with role-based access, cryptographic verification and mechanical fail-safe overrides that keep cranes and breakers operable if SCADA is isolated.
- Equity for small enterprises: a regional fund offers low-interest loans and vehicle conversion grants to small trucking firms and coastal service craft, protecting them from tariff shocks.
- Institutional accountability: Table 6 sets out the RACI (Responsible, Accountable, Consulted, Informed) assignments for the main stakeholders.

Table 6: Institutional RACI Matrix for Regional Transition Operations

Operational Domain	Regional Transition Council	TIPC Keelung Branch	Terminal Concessionaires	Taipower (Utility)	Municipalities & Labor Panels
Regional Carbon Budgets & Gating	A	R	C	C	C
OPS & Substation Capacity Dispatch	I	A	R	R	I
Federated Data Fabric & Cyber-Security	I	A	R	C	I
Fence-Line Air Quality & Workforce Reskilling	C	R	R	I	A

(R: Responsible for execution; A: Accountable for final outcome; C: Consulted for inputs; I: Informed of status)

C. Phased Implementation Roadmap (2026–2050) and Policy Priorities

The roadmap has three phases, each balancing investment against engineering readiness:

- Phase 1: Foundation (2026–2030): Charter Regional Transition Council and establish federated data fabric schemas; commission Keelung East Wharf No. 4 high-voltage cruise shore-power system; deploy SEMS Phase II sub-metering across Keelung, Taipei, and Suao ports; execute dockworker high-voltage electrical safety certification programs.
- Phase 2: Systemic Integration (2030–2040): Expand high-voltage shore power to high-throughput container berths in Taipei and Keelung; deploy utility-scale BESS and warehouse rooftop solar arrays for automated peak shaving; pilot heavy electric drayage depots and automated guided vehicle charging infrastructure; implement dynamic time-of-use industrial shore-power electricity tariffs with Taipower.
- Phase 3: Resilient Net-Zero Operations (2040–2050): Transition auxiliary service craft and yard fleets to zero-emission powertrains; operationalize autonomous port microgrid islanding (≥72-hour critical load runtime); enforce validated lifecycle bunkering protocols for certified green hydrogen and e-fuels; secure independent third-party verification for single-port net-zero carbon balance sheets.

Four policy steps are needed to put the roadmap into practice:

- TIPC Keelung Branch: manage energy as a portfolio and use concession renewals as checkpoints tied to audited carbon data, open-API compliance and worker certification.
- Taipower: Formulate dedicated industrial shore-power tariffs, shifting from static maximum-demand penalties to dynamic time-of-use schedules paired with capacity payments for port microgrid peak-shaving.
- Terminal Concessionaires: Integrate sub-metered telematics to qualify for sustainability-linked financing while automating Scope 1 and 2 regulatory disclosures.
- Municipalities (Keelung, New Taipei, Yilan): Coordinate urban freight corridors with container gate schedules and align metropolitan clean air zones with waterfront boundary monitoring networks.

VIII. CONCLUSION AND FUTURE SCOPE

This paper asked how the separate green measures of Keelung, Taipei and Suao could be managed as one regional transition. The proposed N-TIP framework answers by tying a federated data fabric and digital twin to investment rules, tariffs and a polycentric set of decision bodies, and by tracking progress with a five-dimension readiness index rather than with an emissions total alone.

The scenario model makes this logic testable. Under the central assumptions, balanced integration gave the lowest 2050 emissions index (13.7), kept the feeder within its assumed firm capacity and had the highest readiness score (0.84). Accelerated electrification gave the cleanest local air but overloaded the feeder by 44% and served only 30% of critical demand in a 48-hour outage. The ranking held in every Monte Carlo draw and in 62 of 64 factorial cases, and balanced integration had the lowest weighted score for 91% of random weight sets. Two findings qualify this result. Its emissions lead disappears when its efficiency and solar assumptions are set equal to those of accelerated electrification, so it depends on measures that still have to be proven on site. And even this pathway left a quarter of critical demand unmet in the outage, so the 72-hour islanding goal will need more storage or backup capacity.

The study has clear limits. Segment shares, conversion ratios and several readiness scores are planning assumptions; the model uses annual time points without a network power-flow solution; and the verification shows only that the code follows the equations. The next step is a pilot at a single berth group, such as the Keelung East Wharf No. 4 shore-power project, collecting metered fuel and electricity data, feeder measurements and independently audited readiness items. With those data, the parameters in Tables 1 and 2 can be replaced and the model calibrated before it is used for regional investment decisions.

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Data availability: The analysis relies on publicly accessible regulatory and institutional documents listed in the references, and all numerical inputs in this revision are synthetic and disclosed in the manuscript. The accompanying IJIR3239_Reproducibility_Package.zip (supplied as supplementary material and available upon reasonable request) contains the Python source code, scenario parameter tables, unrounded results, and verification outputs.

Ethics approval: This study did not involve human participants, personal data, or interventions; ethics approval was not required.

Originality: The manuscript is prepared as an original research article and is not under consideration elsewhere. The authors have reviewed and approved the final submitted manuscript.

AI assistance: AI-assisted tools supported language revision, document preparation, and development of the illustrative calculation and code. The calculations are reproducible from the disclosed synthetic inputs. Responsibility for verifying the scientific content, references, disclosures, and compliance with the journal's policy rests with the authors.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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