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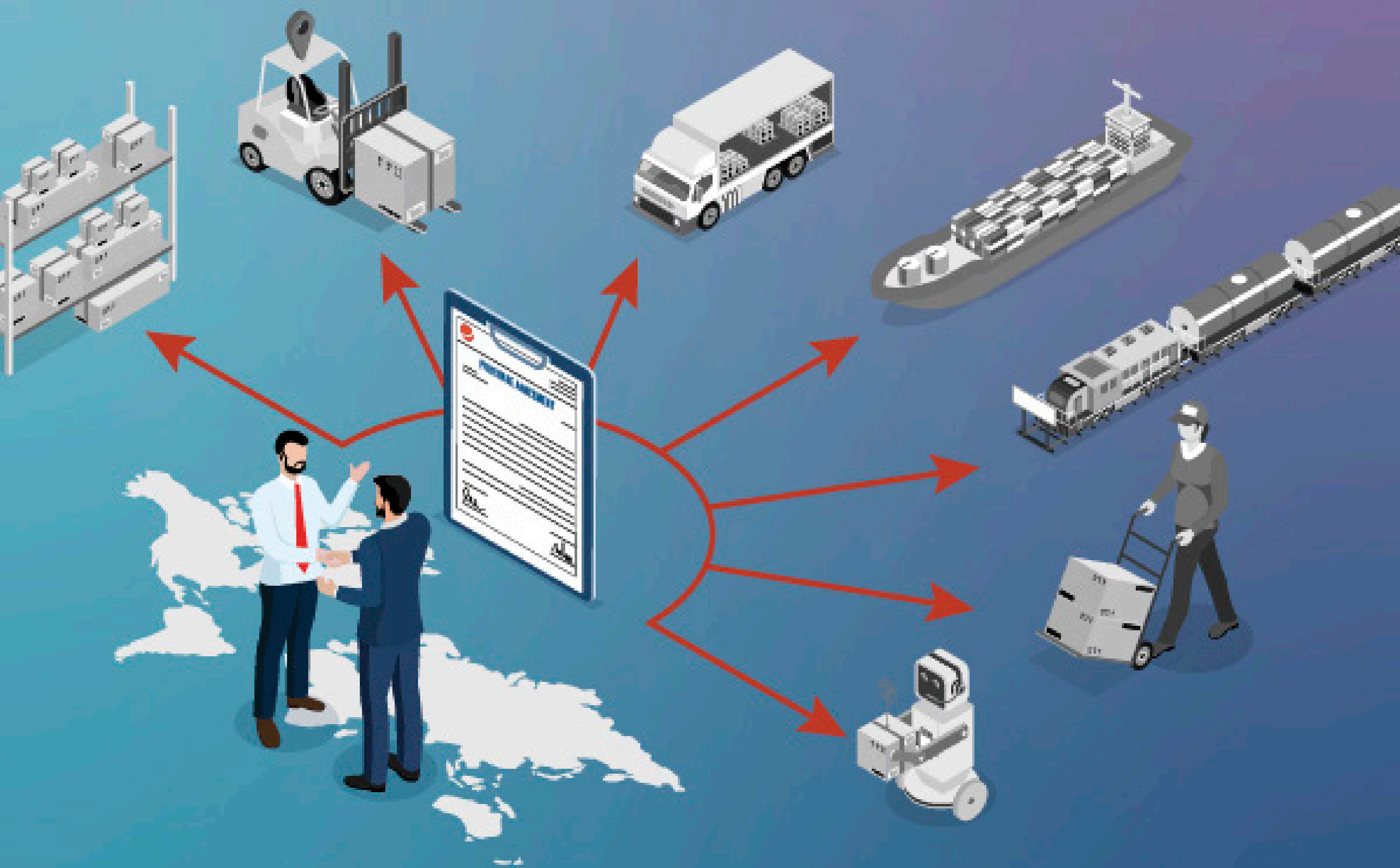

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A Roadmap for Optimizing Energy Consumption in Warehousing Operations: A Review and Strategic Directions for the Vietnamese Market

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ABSTRACT

Warehousing is a growing share of logistics energy use as e-commerce, automation, and service- level pressures rise. This paper synthesises peer-reviewed evidence on energy-saving measures inside warehouses spanning material handling, storage systems, building services, and digital optimisation. Drawing on recent studies, we highlight (i) operational levers such as energy-aware order picking and workforce/activity scheduling; (ii) technology levers including high-density automated storage, regenerative drives, and LED/controls; and (iii) strategic pathways to Net-Zero logistics facilities via on-site renewables and self-consumption strategies. Using a structured methodology (2015–2025 focus) and examples that translate to Vietnam, we quantify impacts where available, discuss costs and payback qualitatively, and propose a phased roadmap distinguishing quick wins and CAPEX-intensive upgrades. Limitations include uneven regional evidence and scarce primary metered data in the literature; we therefore note assumptions explicitly and prioritise sources with transparent methods.

INTRODUCTION

Warehouses are critical nodes in contemporary supply chains, concentrating inventory, information, and value-adding services close to production and consumption points. They alsoconcentrate energy use: within the four walls, electricity and fuels power lighting and controls, heating ventilation air-conditioning (HVAC) and dehumidification, material-handling equipment (MHE) such as forklifts and conveyors, and, increasingly, automation (e.g., shuttle-based storage and retrieval, robotic picking) and digital infrastructure. As e-commerce and omnichannel fulfilment drive higher order volumes with smaller average order sizes, the intensity of picking, travel, and sortation per unit shipped tends to rise unless countered by better slotting, batching, and routing policies (Bartolini, Bottani, & Grosse, 2019). In Vietnam, rapid logistics growth and hot-humid climates magnify both baseline energy demand and the opportunity for meaningful efficiency improvements at scale.

The literature indicates three broad families of levers for intra-warehouse energy efficiency. First are operational and digital levers, which alter how work is organised without major capital expenditure. Second are technology and building-services levers. Lighting is often a dominant electrical load in ambient warehouses; studies on smart lighting systems show substantial savings when LED fixtures are combined with intelligent controls (e.g., occupancy and daylight sensing) and policy changes (e.g., zoning, task-tuned illuminance), including in order-picking contexts (Füchtenhans *et al.*, 2021; Füchtenhans *et al.*, 2023). Third are strategic and site-level pathways that pair demand reduction with supply-side decarbonisation. Emerging roadmaps for Net-Zero logistics facilities articulate sequences that begin with load minimisation (operations, lighting, HVAC, automation settings), proceed to on-site renewables (e.g., rooftop photovoltaics), and then increase self-consumption via measures such as battery energy storage and smart charging for electric MHE fleets (Cannava & Perotti, 2025).

Against this backdrop, the aim of this paper is fourfold: (i) to consolidate recent peer-reviewed evidence on intra-warehouse energy efficiency across operational/digital, technology/building services, and strategic/site-level levers (Atashi Khoei *et al.*, 2023; Bortolini *et al.*, 2017; Ene *et al.*, 2016; Füchtenhans *et al.*, 2021, 2023; Galgaro *et al.*, 2020; Popović *et al.*, 2021); (ii) to present a transparent review methodology that documents sources, inclusion/exclusion criteria; (iii) to analyse current practices and gaps with a focus on applicability to Vietnam, distinguishing where international findings are readily transferable and where adaptation is required; and (iv) to offer an actionable roadmap that separates no/low-cost "quick wins" from CAPEX-intensive upgrades and sequences measures over short, medium, and long-term horizons in line with Net- Zero facility trajectories (Cannava & Perotti, 2025).

LITERATURE REVIEW

Framing warehouse energy use and the role of operations

Energy demand within warehouses arises from a blend of building services (lighting, ventilation/air-conditioning, and, in some cases, refrigeration) and intralogistics (material-handling equipment, order picking, storage/retrieval motions, and controls). While end-use shares vary by climate, operating hours, layout and automation level, lighting frequently represents a dominant electrical load in conventional facilities, especially where large aisles

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and high-bay racking require broad illumination footprints across long shifts. In a detailed case perspective reported in the order- picking lighting literature, illumination accounted for about a third of total electricity, underscoring the importance of technology choice (e.g., LED) and control strategies (e.g., occupancy and daylight harvesting) to overall performance (Füchtenhans *et al.*, 2021).

At the same time, intralogistics motions forklift horizontal travel, vertical lifting, starts and stops, and acceleration/ deceleration patterns are the heart of energy use in manual picker-to-part environments. Recent modelling work explicitly treats energy, rather than distance or time alone, as the objective for routing and storage assignment. That shift in objective function often alters the "optimal" movement patterns and yields non-trivial reductions in traction and lifting energy without compromising cycle times meaningfully (Atashi Khoei *et al.*, 2023; Ene *et al.*, 2016).

Energy-aware picking, routing, and slotting

A stream of research replaces classic distance-minimising heuristics with energy-minimising formulations that incorporate payload mass, vertical lifts, aisle geometry, kinematics (acceleration/deceleration), and frictional losses. The Energy-Minimising Forklift Routing Problem (EMFRP) is one such formulation: by proxying forklift physics and separating horizontal/vertical components, the model can choose tours that reduce joule consumption even if distance is similar to a traditional tour (Atashi Khoei *et al.*, 2023). In a representative instance, the energy-aware tour decreased total energy versus a distance-based benchmark (e.g., ~571,818 J vs ~588,879 J), largely via ~16% lower vertical energy, and even delivered ~10% faster completion time illustrating that energy and service can be co-optimised rather than traded off (Atashi Khoei *et al.*, 2023).

Beyond routing, storage assignment ("slotting") determines how often and how far pickers must drive and lift. Ene *et al.* (2016) develop a genetic algorithm (GA) that jointly optimises order batching and routing with an energy-based objective in a picker-to-part warehouse. The GA consistently found lower-energy solutions across order set sizes, and sensitivity tests show that batch size materially affects energy: in their numerical experiments, a batch size of two minimised energy for the illustrated dataset (e.g., 2.261 kWh vs. 3.249 kWh at batch size one; higher batch sizes increased energy due to additional detours and handling) (Ene *et al.*, 2016). This reinforces that "bigger batches" are not always greener; the optimum depends on layout and demand mix.

The GA study also emphasises that energy-centred objectives can be embedded within mainstream warehouse decision variables (chromosome encodings of routes/ batches), enabling practical "drop in" optimisation that many WMS/TMS stacks can absorb (Ene *et al.*, 2016). In sum, energy-aware routing and slotting research indicates (i) physics-based costs alter tour choice; (ii) batching must be tuned for energy, not only labour time; and (iii) moderate re-slotting of high-turn SKUs nearer to docks or at lower elevations can save both vertical and horizontal energy, particularly in high- lift environments.

Finally, workforce/activities scheduling intersects with energy-aware operations when staffing patterns drive when and how equipment runs. Studies compiling green warehousing indicators also note that coordinated scheduling of mobile electrical equipment (e.g., forklifts) with tariff structures can flatten peaks and reduce both energy and CO_2 impacts (cited within Popović *et al.*,2021). While these scheduling models primarily target labour cost and service, they open a path to energy-conscious dispatching (e.g., consolidating energy-intensive lifts into off-peak windows where feasible).

Smart lighting systems in warehouses

Lighting is a tractable and often high-return lever. A comprehensive "state-of-the-art" review of smart lighting for order-picking areas finds that sensor driven controls presence detection, zoning, and daylight harvesting paired with LEDs can cut lighting energy substantially while preserving visual ergonomics for picking accuracy (Füchtenhans *et al.*, 2021). Case evidence within that stream shows illumination representing ~36% of electricity demand in a referenced warehouse, highlighting the large technical potential (Füchtenhans *et al.*, 2021).

A dedicated simulation of smart lighting in warehousing settings stresses that savings scale with how aggressively lights are dimmed or switched off when aisles are unoccupied; in high-share lighting cases, smart control strategies achieved very large reductions relative to a "fully on" baseline, with the study reporting up to 87% energy savings under strong control assumptions (simulation model) (Füchtenhansc *et al.*,2023). The authors caution that actual outcomes depend on occupancy patterns, zoning granularity, and sensor placement. Nevertheless, the direction is unambiguous: LEDs + controls beat legacy fluorescent/HID with static switching by wide margins, and dynamic set-points (e.g., task-tuned illuminance for order-picking aisles) avoid over-lighting.

From a Southeast Asia perspective where many warehouses operate long hours and where skylights/ daylight apertures are feasible the combination of high-efficacy luminaires (LED) and controls is particularly compelling. In climates like Vietnam's, daylighting must be balanced against heat gain; hence, controls that weight daylight contribution without adding cooling loads are beneficial. The literature also flags human-factors constraints (glare, colour rendering for label reading), which modern LEDs can satisfy while keeping watts/□ low (Füchtenhans *et al.*, 2021).

Automated storage/retrieval (AS/RS) and energy–time trade-offs

In automated environments, cranes/shuttles' movements dominate intralogistics electricity. Research on bi-objective storage assignment shows that modest increases in cycle time can unlock non-trivial energy reductions, guiding "balanced" policies rather than pure time-minimisation. In an AS/RS context, unit-load assignment that shortens heavy-lift profiles or reduces vertical travel yields meaningful energy savings; importantly, the Pareto frontier between time and energy is often shallow near the optimum, enabling small throughput concessions for outsized kilowatt-hour gains (Bortolini *et al.*,2017).

These insights align with earlier energy-focused storage assignment work (e.g., Meneghetti & Monti, as cited by Ene *et al.*, (2016), which proposed energy-based dwell-point and slotting policies for automated warehouses. Collectively, they support tiered policies: (i) energy-aware placement of heavy or frequently handled loads; (ii) regenerative drives and braking on cranes/shuttles; and (iii) speed profiles that avoid energy-intensive accelerations where time buffers exist. Workforce and activities scheduling as a sustainability lever

Sustainable warehouse management extends beyond equipment to how work is sequenced and staffed. Popović *et al.* (2021) propose an integer-programming approach that co-schedules workforce and activity execution, motivated by the real-world variability of labour demand across the day. By permitting certain activities to be deferred within allowable windows and enabling substitution among workers during shifts, the model reduces workforce costs and smooths resource utilisation; in 61% of instances, costs fell by >20% when co-scheduling activities with staff compared to conventional shift plans (Popović *et al.*, 2021). Although the paper centres on economic/social outcomes, the same smoothing can cut peak power draw (e.g., battery charging, simultaneous MHE use) and thereby lower both tariffs and stress on electrical systems an environmental co-benefit the authors acknowledge in discussion.

The literature review within Popović *et al.* also consolidates green-warehouse indicators and frameworks (e.g., Bank & Murphy, 2013; Torabizadeh *et al.*, 2020) that situate scheduling alongside facility design, layout, mechanical handling equipment and WMS as levers for sustainability. Notably, studies on scheduling mobile electrical equipment against electricity price signals (Carli *et al.*, 2020) demonstrate how operational planning can directly influence energy and CO_2 footprints by shifting high-draw tasks out of peak windows (cited therein). For Vietnam, where many distribution centres face time-of-use tariffs and rapid e-commerce cycles, these models are applicable, provided process owners identify deferrable activities (e.g., non-urgent replenishment) and codify them in the WMS.

Alternative building concepts: underground and thermally advantaged designs

An emerging thread explores how unconventional siting can cut space-conditioning loads. A case study on underground warehouses for food storage in the Dolomites argues that thermal stability and reduced exposure to ambient temperature swings can lower cooling energy compared with surface structures. While site-specific economics (excavation, waterproofing) and logistics constraints (access/egress, safety) are non-trivial, the analysis highlights a physical pathway using the ground as a thermal buffer to reduce mechanical cooling demands (Galgaro *et al.*, 2020). For hot-humid regions, partial earth-sheltering of cold rooms or using semi-buried annexes could achieve similar effects where geology permits.

Synthesis and implications for Vietnam

Taken together, the literature suggests a hierarchy of intra-warehouse measures:

- Operational/digital optimisation: Energy-aware routing and slotting (EMFRP, GA-based batching/routing) that explicitly model lifting and acceleration; WMS-enabled co- scheduling of activities and labour to smooth peaks and align high-draw tasks with lower- tariff periods (Atashi Khoei *et al.*, 2023; Ene *et al.*, 2016; Popović *et al.*, 2021). These are largely low-capex, software-first changes that can be piloted quickly.
- Technology retrofits: LEDs plus sensor-based controls in aisles and staging areas; for automated sites, regenerative drives and energy-aware dwell-point policies; for manual sites, right-sized chargers and managed charging windows. Evidence points to large lighting savings potential up to very high percentages in simulation under aggressive control logic and meaningful, often low-trade-off energy reductions in AS/RS when energy is co- optimised with time (Füchtenhans *et al.*, 2021; Füchtenhans *et al.*, 2023; Bortolini *et al.*, 2017).
- Strategic facility choices: Where brownfield constraints allow, thermal-advantaged designs (e.g., partial earth-sheltering of cold rooms) can moderate HVAC loads. However, these are site-dependent and capital-intensive; the literature advises careful feasibility studies (Galgaro *et al.*, 2020).

For Vietnam, three contextual points emerge. First, hot-humid climates increase the marginal value of reducing lighting heat and optimising ventilation/AC further strengthening the LED-plus-controls case (by reducing both kWh for lighting and sensible heat gains). Second, demand peaks (e-commerce cut-offs, evening inbound flows) make workforce/activity scheduling models particularly relevant; smoothing work and aligning charging to off-peak windows is feasible because many warehouse tasks are deferrable within short windows (Popović *et al.*, 2021). Third, manual picker-to-part operations remain prevalent across SMEs; therefore, energy-aware routing/slotting via lightweight optimisation is a near-term "quick win" with minimal equipment change (Ene *et al.*, 2016; Atashi Khoei *et al.*, 2023).

MATERIALS AND METHODS

Design and scope

This study adopts a structured narrative review focused on evidence published between 2015 and 2025, complemented by seminal antecedents where they established core modelling assumptions or measurement practices that remain influential (e.g., early energy-centred treatments of material- handling dynamics) (Makris *et al.*, 2006). A narrative design is appropriate because the warehousing energy literature spans heterogeneous methods analytical models, discrete-event simulations, optimisation heuristics, laboratory tests, and field case studies which are not readily combined in a single meta-analytic effect size without strong assumptions about comparability. To maintain rigour, we impose a protocol for search, screening, appraisal, and synthesis that preserves original metrics and reflects engineering-ready insights.

The unit of analysis is the intra-warehouse system: lighting and controls, HVAC/dehumidification, storage and retrieval (manual/automated), material-handling equipment (MHE), and digital/operational policies affecting energy use. We treat both ambient and temperature-controlled facilities; cross-docking is included only when it materially alters the energy profile. Transport energy (road/air/maritime) is out of scope except where warehouse choices have direct, evidenced implications for outbound efficiency (not modelled here). Geographic emphasis is on Vietnam; when local studies are sparse, we include international benchmarks and then assess transferability to hot-humid climates and regional operating conditions (Bartolini *et al.*, 2019; Galgaro *et al.*, 2020; Cannava & Perotti, 2025).

Conceptually, our scope spans three complementary levers that recur across the literature: Operational/digital optimisation (e.g., energy-minimising order picking, slotting, batching, workforce/activity scheduling), which can reduce energy without major CAPEX (Ene *et al.*, 2016; Atashi Khoei *et al.*,2023; Popović *et al.*, 2021).

- Technology/infrastructure (e.g., LEDs with intelligent controls; AS/RS with energy-aware policies; regenerative drives), which re-shape the energy/time trade-off at the equipment or system level (Bortolini *et al.*, 2017; Füchtenhans *et al.*, 2021; Füchtenhans *et al.*, 2023).
- Strategic/site-level pathways (e.g., on-site PV and self-consumption), which situate warehouse energy efficiency within decarbonisation plans for logistics facilities (Cannava & Perotti, 2025).
- This triangulation allows us to compare software-driven quick wins with CAPEX-intensive upgrades, a distinction that is particularly salient for brownfield Vietnamese facilities with constrained budgets and data (Bartolini *et al.*, 2019).

Data sources and search strategy

We used a multi-stage search strategy. First, we examined seed articles from the provided attachments, selected to represent each lever: (i) energy-aware routing/slotting and metaheuristics (Ene *et al.*, 2016); (ii) order-picker routing with physical energy modelling (Atashi Khoei *et al.*, 2023); (iii) workforce and activities scheduling as a managerial complement to technical measures (Popović *et al.*, 2021); (iv) smart lighting both a state-of-the-art review and a warehouse simulation study (Füchtenhans *et al.*, 2023; Füchtenhans *et al.*, 2021); (v) AS/RS energy–time slotting (Bortolini *et al.*, 2017); (vi) underground warehousing as an alternative concept with thermal advantages (Galgaro *et al.*, 2020); (vii) a systematic review of green warehousing framing dominant themes and gaps (Bartolini *et al.*, 2019); and (viii) a simulation-based Net-Zero roadmap for logistics facilities (Cannava & Perotti, 2025).

Second, we performed forward and backward snowballing from these seeds screening reference lists and citing works to surface adjacent studies (e.g., shuttle-based AS/RS design and regenerative braking; lighting control policies in order picking). Third, we executed keyword queries in multidisciplinary databases (e.g., Scopus, Web of Science) and publisher platforms (e.g., ScienceDirect) using Boolean strings combining topic, method, and context terms, for example:

- "warehouse" AND ("energy" OR "electricity") AND ("order picking" OR "routing" OR "slotting")
- "smart lighting" AND (warehouse OR intralogistics) AND (LED OR occupancy OR daylight)"

To avoid over-reliance on any single method genre, we sought method balance: optimisation and simulation papers (Ene *et al.*, 2016; Atashi Khoei *et al.*, 2023; Bortolini *et al.*, 2017; Füchtenhans *et al.*, 2023) were paired with reviews (Füchtenhans *et al.*, 2021; Bartolini *et al.*, 2019) and design/roadmap contributions (Cannava & Perotti, 2025; Galgaro *et al.*, 2020). This balance reflects practical decision-making: managers need both what works in principle (models/simulations) and what transfers in context (reviews/case-informed syntheses). Inclusion, exclusion, and appraisal

Inclusion criteria. We included studies that:

- Address intra-warehouse energy use or credible proxies (e.g., crane energy, picker work, lighting kWh), rather than generic sustainability.
- Report quantitative outcomes (e.g., kWh reduction, energy per pick, energy–time trade- offs) or sufficiently specified models to infer directional energy effects (Ene *et al.*, 2016; Bortolini *et al.*, 2017; Atashi Khoei *et al.*, 2023).
- Provide transparent methods (e.g., objective functions, constraints, parameter values, scenario definitions) enabling critical appraisal (Füchtenhans *et al.*, 2023; Popović *et al.*, 2021).
- Offer contextual relevance to Vietnam, either directly (climate, operating conditions) or via clearly adaptable mechanisms (Bartolini *et al.*, 2019; Galgaro *et al.*, 2020; Cannava & Perotti, 2025).

Exclusion criteria. We excluded sources that:

- Treated transport energy without an intra-warehouse link;
- Reported sustainability outcomes without energy relevance;
- Lacked methodological transparency or insufficient detail to interpret energy impacts;
- Were purely opinion/trade pieces without data or reproducible models. Appraisal rubric. Each included study was appraised on:

• Internal validity (e.g., physical realism of energy models, calibration, sensitivity analysis) (Atashi Khoei *et al.*, 2023; Bortolini *et al.*, 2017).

• External validity/transferability (e.g., facility type, climate, workload; whether assumptions align with hot-humid operations and brownfield constraints) (Bartolini *et al.*, 2019; Galgaro *et al.*, 2020).

• Measurement quality (e.g., sub-metering for lighting/ HVAC/MHE; clear baselines; treatment of occupant behaviour) (Füchtenhans *et al.*, 2023);

• Decision usefulness (e.g., are outputs expressed in managerial metrics like kWh/m²/year, kWh per pick, or payback windows?) (Cannava & Perotti, 2025; Popović *et al.*, 2021).

We flagged risk-of-bias patterns typical of this domain: (i) dependence on simulation parameters that may not reflect tropical facilities; (ii) single-site case studies with limited generalisability; (iii) objective misalignment minimising travel time rather than energy when the two diverge (hence our emphasis on explicitly energy-aware formulations) (Atashi Khoei *et al.*, 2023; Ene *et al.*, 2016). To mitigate these, we privilege studies that either model energy directly or report energy-centred outcomes, and we discuss transferability caveats rather than assuming equivalence across climates and technologies (Bartolini *et al.*, 2019).

Synthesis and metrics

We synthesised findings using a theory-informed typology with three clusters operational/digital, technology/ infrastructure, and strategic/site-level chosen because they map to distinct budget lines, time horizons, and implementation risks in warehouse projects (Popović *et al.*, 2021; Bortolini *et al.*, 2017; Cannava & Perotti, 2025). Within each cluster, we report (a) the mechanism (why a measure saves energy), (b) the conditions under which it works best (e.g., order profile, climate, duty cycles), and (c) quantitative impacts where available.

To preserve comparability, we retain original units and, where necessary, convert to commonly used normalised metrics:

• kWh/m²/year (building services such as lighting and HVAC),

• kWh per pick / per tour / per pallet move (intralogistics activities),

• peak-to-average load ratios (demand management relevance), and

• qualitative cost/payback ranges when studies provide cost but not full financials.

When studies provide site-specific or climate-sensitive results e.g., thermal benefits in underground warehousing we interpret the direction and mechanism (reduced cooling loads due to ground temperature stability) and flag feasibility/shock costs (civil works, site constraints) that condition transferability to Vietnam (Galgaro *et al.*, 2020). For facility-level Net-Zero roadmaps, we treat on-site PV and self-consumption strategies as supply-side complements to demand-side efficiency, reporting them qualitatively where warehouse load profiles (e.g., MHE charging) create alignment opportunities (Cannava & Perotti, 2025).

Because measurement conventions differ, we avoid synthesising into a single pooled effect. Instead, we provide a weight-of-evidence narrative, highlighting convergent findings across methods and boundary conditions where results diverge. Where the Vietnam evidence base is thin (as also noted by prior reviews), we explicitly label assumptions and evidence gaps rather than extrapolating beyond the data (Bartolini *et al.*, 2019).

Research Findings

Operational levers

Energy-aware routing, batching, and slotting. Order picking is typically the most energy-intensive in-warehouse activity, and its energy footprint depends not only on distance but also on vertical movements, accelerations/decelerations, rolling resistance and carried mass. Recent models that directly minimise energy rather than distance demonstrate that substantial savings are achievable without degrading service levels (e.g., meeting due times or route feasibility). Specifically, the Energy-Minimising Order-Picker Forklift Routing Problem (EMFRP) computes forklift energy for both horizontal and vertical motions while accounting for friction and dynamic effects; exact formulations (MIP, dynamic programming) and scalable tour- construction/ improvement heuristics show that "significant energy savings" are realised when routing by energy instead of the classic distance objective (Atashi Khoei *et al.*, 2023). In practice, this benefit becomes more pronounced as the number of items grows, average item weight increases, and pick-heights vary across levels conditions common in modern, tall-bay facilities. (Atashi Khoei *et al.*, 2023).

Complementing routing, storage assignment ("slotting") and order batching can be tuned for energy rather than time. Ene, Küçükoğlu, Aksoy and Öztürk (2016) formulate warehouse picking with an objective to minimise energy consumption via a genetic algorithm, demonstrating that storage policy materially affects the energy of tours and that the GA yields efficient solutions across test instances (Ene *et al.*, 2016). This reinforces a practical message for WMS configuration: when cycle-time buffers exist, energy-centred slotting and batching can shift demand to "energy-lighter" picks (e.g., lower lifts, fewer vertical transitions) with negligible service impact.

Workforce and activity scheduling. Variability in task arrivals (receiving, putaway, replenishment, picking, VAS) creates peaks and troughs that translate into idle MHE/ lighting during lulls and high coincident demand during peaks. A sustainable workforce-and-activity scheduling model tested on a real distribution warehouse and evaluated via integer programming shows lower workforce costs, time savings, and better utilisation of resources when execution of certain activities is deliberately deferred and coordinated, smoothing the daily profile (Popović *et al.*, 2021). While the study is cost-oriented, the same smoothing logic reduces peak electrical demand and non-productive runtime (e.g., lights or conveyors left on for sparse tasks), implying energy co-benefits particularly relevant to hot-humid Vietnam facilities operating long hours (Popović *et al.*, 2021).

Technology levers

Smart lighting (LEDs + controls). Lighting is often operated "fully on" during warehouse hours regardless of aisle occupancy or daylight ingress, a pattern singled out by both a simulation study and a state-of-the-art review as typical in logistics buildings. In response, Füchtenhans, Glock, Grosse, and Zanoni (2023) model smart lighting systems that adapt to process/aisle conditions and show great potential to reduce energy consumption compared with conventional (always-on) lighting, with supporting insights from an industrial case (Füchtenhans *et al.*, 2023). Their broader review (Füchtenhans *et al.*, 2021) notes that while smart lighting has been widely discussed in other sectors, industrial and logistics applications remain under-explored, strengthening the research and implementation case for warehouses. In hot-humid climates, pairing LEDs with occupancy sensing, task-tuned illuminance, and daylight harvesting avoids waste heat from legacy luminaires and reduces cooling loads. (Füchtenhans *et al.*, 2023; Füchtenhans *et al.*, 2021).

Automated storage/retrieval (AS/RS) and energy–time optimisation. In single-deep rack AS/RS, slotting for energy (not just time) can deliver double-digit energy reductions for cranes with only minor cycle-time penalties. In a beverage-industry case, choosing an assignment on the Pareto frontier achieved ~12.66% energy saving at the cost of ~2.52% longer single-command cycle time (Bortolini *et al.*, 2017). For managers, the "iso-energy" vs. "iso-time" contours imply different bay allocations, and the shift requires a managed transition to new locations but it is operationally feasible precisely because the system is automated. In Vietnam's dense urban nodes where footprint is constrained, AS/RS also concentrates throughput into smaller volumes, enabling lower lighting/HVAC intensities per unit of output a synergistic effect with smart lighting and demand management (Bortolini *et al.*, 2017).

Integration and measurement. To capture these benefits: Sub-meter lighting and AS/RS drives (or at least log controller power) to calculate kWh per line and kWh per crane cycle.

- Use the WMS to tag picks by aisle/level and correlate energy with vertical travel (a dominant driver in EMFRP and crane models).
- In tropical climates, couple lighting control zones with HVAC dehumidification schedules to avoid reheat penalties.

Strategic/site concepts

Thermal-advantaged warehouse designs. Site-specific designs most dramatically, underground warehouses can provide significant thermal stability, lower cooling loads, and resilience to power interruptions. A detailed case study from the Dolomites compares underground apple storage with an above-ground reference and reports:

- ~22% reduction in specific cooling energy over a full year of storage, attributed to a stable "cold buffer zone" in the surrounding rock mass once steady state is reached; and
- ~48% reduction in specific electrical energy consumption for cooling, assisted by groundwater at ~15 °C (yielding EER≈4.5) as a heat sink for refrigeration (Galgaro *et al.*, 2020).

These performance gains rely on several context-specific enablers: favourable geology and initial rock temperature, gas- and vapour-tight linings for controlled atmosphere storage, and access to stable groundwater temperatures (Galgaro *et al.*, 2020). For Vietnam, fully underground solutions will be rare due to geology, hydrology, permitting, and CAPEX but the principle transfers: leverage thermal mass and ground-coupled heat rejection where feasible (e.g., semi- buried cold rooms, shaded envelopes, evaporative pre-cooling of condenser air in dry seasons) and design docks/air-locks to minimise infiltration. As energy tariffs evolve, these strategies complement on-site PV and load-shifting by lowering the cooling baseline that PV/BESS must cover.

Synthesis across levers (what this means for Vietnam)

- Start with algorithms and policies. Deploy EMFRP-style routing and energy-aware slotting/batching in the WMS/WES; combine with activity scheduling to flatten peaks and align discretionary work with off-peak tariffs. These steps are low-disruption and low- CAPEX but require clear operating rules and KPIs (kWh per pick/pallet) (Atashi Khoei *et al.*, 2023; Ene *et al.*, 2016; Popović *et al.*, 2021).
- Retrofit lighting with intelligence. Move beyond lamp-for-lamp swaps by zoning aisles, adding occupancy/daylight controls, and tuning set-points to task needs. Expect material reductions vs. "always-on", with added comfort and safety (Füchtenhans *et al.*, 2023; Füchtenhans *et al.*, 2021). Use automation data to balance energy and time. Where AS/RS is present or planned, incorporate bi-objective slotting to trade small cycle-time penalties for double-digit energy savings, and verify with sub-metered crane drives (Bortolini *et al.*, 2017).
- Consider site-specific thermal strategies. Full underground warehouses will be rare, but semi-buried cold rooms, ground-coupled heat rejection, and tight docks/air-locks capture part of the underground advantage lower baselines that synergise with on-site PV and potential BESS. (Galgaro *et al.*, 2020).

Overall, the evidence indicates that software-first optimisation (routing, slotting, scheduling) should be the immediate focus for Vietnam operators, followed by targeted building/automation upgrades verified with metered data. Where international findings are applied, differences in climate, tariff structure, and building stock should be explicitly noted and monitored to ensure benefits persist under local conditions.

RESULTS AND DISCUSSION

Vietnam roadmap by horizon

Purpose of the roadmap. The aim is to help Vietnamese warehouses reduce energy intensity while maintaining service levels, by sequencing low-disruption operational changes and targeted capital upgrades. The roadmap recognises (i) lighting can account for a large share of facility electricity (often cited up to ~65%), (ii) picking/slotting and workforce patterns drive when and where energy is used, and (iii) automation choices create time–energy trade-offs that can be tuned rather than treated as fixed (Füchtenhans *et al.*, 2023; Bortolini *et al.*, 2017).

Short term (0–2 years): operational and controls-first "quick wins."

1. Deploy energy-aware routing, batching, and slotting in the WMS. Energy-minimising approaches for order picking reduce the energy per tour by considering horizontal/vertical motion and acceleration not just distance. Where native WMS functions are limited, lightweight decision heuristics or metaheuristics (e.g., genetic algorithms) can be layered without layout changes (Ene *et al.*, 2016). In their study, optimising storage policy and batching with a GA specifically to minimise energy (rather than only time) yielded efficient solutions, demonstrating the feasibility of software-centric savings (Ene *et al.*, 2016).

2. Retrofit LEDs and activate 'smart' lighting strategies. Replace legacy luminaires with LEDs and, crucially, use control strategies (zoning, occupancy, adaptive set-points, daylight harvesting). A simulation study that varied warehouse and picking parameters shows smart lighting can substantially reduce energy consumption and operating costs relative to conventional "always-on" lighting; it also documents how lighting strategy interacts with process design important when sites operate extended shifts (Füchtenhans *et al.*, 2023). With lighting reported as up to ~65% of a warehouse's electricity, controls have outsized impact (Füchtenhans *et al.*, 2021).

3. Basic HVAC/dehumidification scheduling for hot-humid climates. Begin with time-of-day set-points, night setbacks, and demand-responsive ventilation. Prioritise dry-goods zones for controls first, then temperature-controlled spaces. (warehouses frequently face humidity peaks; even minimal scheduling avoids "always-on" operation when aisles are unoccupied.) Rationale link: lighting and HVAC are the dominant electrical loads in industrial buildings, so disciplined scheduling is foundational (Füchtenhans *et al.*, 2021).

4. Operator training for energy-aware material-handling equipment (MHE). Reinforce smooth acceleration/deceleration, coast where safe, minimise vertical mast moves, and adopt idle- power discipline at charging points. These behavioural levers complement algorithmic routing/slotting (Ene *et al.*, 2016).

5. Workforce & activity scheduling. Align discretionary tasks (e.g., non-urgent putaway, cycle counts, kitting) with off-peak windows to flatten load profiles. An integer-programming approach on a real DC showed lower workforce costs, time savings, and better resource utilisation, indicating that coordinated activity timing can reduce peaks that often drive energy and demand charges (Popović *et al.*, 2021).

Medium term (3–5 years): targeted retrofits and instrumentation.

1. Metering and dashboards. Install sub-meters for lighting, HVAC/dehumidification, and MHE charging to baseline and verify savings from software/controls. This enables energy- per-pick and energy-per-pallet KPIs and separates effects when multiple measures are deployed. Research gap note: industrial smart-lighting and energy studies are less prevalent than office/residential; metering helps build the local evidence base (Füchtenhans *et al.*, 2021).

2. Targeted envelope and dock upgrades. Address infiltration and sensible/latent loads where cost-effective: high-use doors with fast-acting curtains, dock seals, and vestibules; selective insulation on problem walls/roofs; destratification fans in tall bays. These measures are especially beneficial in hot-humid SEA climates, reducing the hours that HVAC/dehumidification must run (principle aligned with building-services dominance in industrial energy) (Füchtenhans *et al.*, 2021).

3. AS/RS or shuttle-based densification where justified. For high-volume nodes, evaluate goods-to-person or shuttle systems to concentrate throughput in smaller, controllable volumes. Critically, treat energy and time as co-objectives. A bi-objective unit-load assignment in automatic S/R warehouses achieved ~12.66% energy savings with only

~2.52% decrease in time efficiency evidence that modest cycle-time concessions unlock meaningful energy improvements (Bortolini *et al.*, 2017).

4. Smart lighting at scale. Extend pilots to full facilities: granular zoning per aisle/pick module; tunable illuminance targets by shift; integrate with the WMS to pre-light imminent pick zones. The simulation study shows strategy–process interactions matter, so settings should reflect SKU velocity and batching policy (Füchtenhans *et al.*, 2023).

Long term (5+ years): on-site generation and deeper system redesign.

1. Rooftop PV and (where justified) on-site storage to raise self-consumption. With LEDs, controls, and optimised operations in place, PV can offset a large fraction of remaining electricity. Battery energy storage (BESS) can align PV output with overnight MHE charging, increasing self-use and resilience (principle consistent with industrial load patterns and decarbonisation pathways).

2. Energy KPIs natively in the WMS/MES. Treat energy like time/service: expose kWh per pick/tour, heat-map "hot aisles," and include energy-aware routing/slotting modes as standard. GA-based models show this framing is feasible for day-to-day planning (Ene *et al.*, 2016).

3. Concept design options for new builds. Consider alternative building concepts that leverage thermal

advantages for instance, partially earth-sheltered or underground storage where geology and economics permit because stable subsurface temperatures can reduce cooling loads (Galgaro *et al.*, 2020). Such approaches are site-specific but illustrate the range of long-horizon levers.

Quick wins vs. CAPEX-intensive measures

Quick wins (no/low CAPEX; implement within weeks to months).

• Algorithmic changes to routing/batching/slotting. Start with rules-based changes (e.g., vertical-movement penalties; proximity clustering by energy cost) and iterate to metaheuristics (GA) for larger problems. Because these do not require hardware changes, they can deliver early energy reductions and productivity stability (Ene *et al.*, 2016).

• Lighting controls and set-points. Even before full LED upgrades, refine switch-on logic and aisle zoning; after LED retrofits, enable occupancy/daylight strategies and calibrate target lux by activity. Given lighting's large share, controls are disproportionately valuable (Füchtenhans *et al.*, 2021; Füchtenhans *et al.*, 2023).

• Maintenance for efficiency. Keep reflectors, sensors, and luminaires clean; maintain forklift tires, hydraulics, and chargers to spec; fix compressed-air leaks and set "sleep" modes for conveyors/MHE where available. These actions support the same mechanisms that algorithmic routing exploits reducing wasted motion and idle draw (logic aligned with Ene *et al.*, 2016).

• Sealing and scheduling at docks. Install/repair dock seals; schedule door openings; deploy air curtains on high-traffic doors. These mitigate infiltration, shrinking HVAC/dehumidification runtime especially salient in hot-humid Vietnam climates where latent loads are high (industrial-energy dominance by HVAC/lighting noted in Füchtenhans *et al.*, 2021). Workforce/activity timing. Use workforce models to shift discretionary tasks out of coincident peaks (e.g., avoid simultaneous peak picking and intensive replenishments). Evidence from an operational DC shows such scheduling improves utilisation and reduces cost, which typically correlates with smoother power profiles (Popović *et al.*, 2021).

CAPEX-intensive measures (evaluate via business case; stage over 3–7 years).

• High-density AS/RS (including shuttles). Benefits include smaller conditioned/illuminated volume per unit throughput, but success depends on bi-objective tuning that trades a small time penalty for double-digit energy gains (Bortolini *et al.*, 2017). Prior to investment, run scenario models that explicitly quantify energy vs. cycle time (Bortolini *et al.*, 2017).

• Comprehensive LED + smart-lighting systems. Go beyond lamp swaps to networked sensors, adaptive scenes, and WMS integration (pre-lighting imminent picks). Simulation evidence indicates strong potential; at the portfolio scale, standardising controls yields compounding benefits across sites (Füchtenhans *et al.*, 2023).

• Building envelope and HVAC upgrades. Add insulation where cost-effective in hot-boxes, adopt variable-speed fans/pumps, and right-size dehumidification with demand control. Sequence after metering so savings are verifiable (industrial-energy context: HVAC/lighting are principal loads; Füchtenhans *et al.*, 2021).

• Rooftop PV and optional BESS. Once loads are reduced and predictable, PV offsets purchased electricity; BESS can shift PV to night-time MHE charging, increasing self- consumption. Treat PV/BESS as the final layer after operational and controls measures have stabilised the load.

Research needs and proposed programme.

• Vietnam-specific field trials with telemetry. Pair sub-metering (lighting/HVAC/MHE) with controlled A/B tests of energy-aware routing/slotting and smart-lighting strategies; report kWh per pick, kWh per pallet move, and kWh/m²/year, with weather and workload normalisation. This would strengthen the external validity of algorithmic and controls interventions (Ene *et al.*, 2016; Füchtenhans *et al.*, 2023).

• Time–energy co-optimisation in automation design. Extend the bi-objective AS/RS assignment logic to shuttle systems and hybrid person-to-goods/goods-to-person operations, quantifying the service penalty threshold acceptable for given energy gains (Bortolini *et al.*, 2017).

• Human-centred scheduling studies. Build on workforce/activity scheduling models to test operator-centric rosters that improve morale while smoothing energy peaks an outcome already suggested by reductions in workforce cost and better utilisation (Popović *et al.*, 2021).

• Long-horizon concepts for tropical climates. Where feasible, explore earth- coupled/underground storage concepts for high-value products to exploit thermal stability and reduce cooling loads; validate economics with SEA geology and land-use constraints (Galgaro *et al.*, 2020).

CONCLUSIONS

A layered strategy can deliver credible, near-term results and set up deeper decarbonisation: start with software and controls (energy-aware routing/slotting, smart lighting, HVAC scheduling), instrument with sub-metering, then pursue targeted CAPEX (AS/RS with time energy co-optimisation, envelope fixes, PV/BESS). The cited studies show these levers are technically feasible and managerially tractable, with some reporting double-digit energy reductions for minimal service trade-offs (Bortolini *et al.*, 2017) and strong potential from smart lighting (Füchtenhans *et al.*, 2023). However, to maximise relevance for Vietnam, future work must provide metered, context-rich evidence so that business cases reflect local climate, shift structures, and technology baselines.

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