**Total Cost of Ownership (TCO) Models for Maritime Electrification and Alternative Fuels in Australia**

**Introduction**

The maritime sector is under increasing pressure to reduce greenhouse gas emissions, which account for roughly 3% of global CO₂ output ([Scholars@Duke publication: Well-to-wake cost and emissions assessments for the Western Australia–East Asia green shipping corridor](https://scholars.duke.edu/publication/1666095" \l ":~:text=The%20maritime%20sector%2C%20responsible%20for,LCA%29%20consistent%20with%20Resolution) ). Achieving this in heavy shipping (large cargo and freight vessels) requires evaluating new propulsion options—such as full electrification or alternative fuels like hydrogen, ammonia, and methanol—against conventional fuel oil on an economic basis. **Total Cost of Ownership (TCO)** analysis provides a framework to compare these options by considering not just upfront costs but all expenses over a vessel’s life ([New fuels: Total cost of operation | Global Maritime Forum](https://globalmaritimeforum.org/insight/new-fuels-total-cost-of-operation/#:~:text=The%20total%20cost%20of%20ownership,not%20include%20technology%20readiness%2C%20risk)). This report surveys leading global TCO models for low- and zero-emission shipping, assesses their relevance to Australia (especially for operations around major New South Wales ports), and recommends how to tailor a robust TCO model for the Australian heavy shipping context. Key cost factors (fuel, maintenance, capital, etc.), methodological approaches (e.g. net present value vs. annualized cost), and Australian-specific parameters (regulatory setting, energy prices, port infrastructure, labor costs) are examined. The goal is to inform development of an Australian-specific TCO framework to guide decisions through to 2026 and beyond.

**Leading TCO Models for Maritime Decarbonization**

Multiple organizations worldwide have developed TCO models or studies to evaluate electrification and alternative fuels in shipping. We identify several leading examples from industry, academia, and government:

* **DNV Alternative Fuel Containership Analysis (2023):** Classification society DNV conducted a detailed TCO case study for a 5,500 TEU container ship under different fuel designs (conventional vs. methanol dual-fuel) ([What are the total costs of ownership for different methanol-fuelled containership designs?](https://www.dnv.com/expert-story/maritime-impact/commercial-case-study-for-methanol-fuelled-5500-teu-container-vessel/#:~:text=Titled%20%E2%80%9CCommercial%20considerations%20for%20a,25%20years%20for%20the%20vessel)). This analysis considered a 20–25 year life and compared total costs (CAPEX, OPEX, fuel, financing, and carbon costs) across scenarios ([What are the total costs of ownership for different methanol-fuelled containership designs?](https://www.dnv.com/expert-story/maritime-impact/commercial-case-study-for-methanol-fuelled-5500-teu-container-vessel/#:~:text=Key%20influential%20cost%20factors%20identified)). DNV applied multiple fuel price scenarios from its Energy Transition Outlook (ETO) forecasts, illustrating how future prices of marine gas oil vs. carbon-neutral methanol could swing the economics ([What are the total costs of ownership for different methanol-fuelled containership designs?](https://www.dnv.com/expert-story/maritime-impact/commercial-case-study-for-methanol-fuelled-5500-teu-container-vessel/#:~:text=DNV%20based%20its%20analysis%20on,new%20decarbonization%20ambition%20by%202050)). The outcome showed the TCO of a methanol-fueled newbuild was only ~0.4–0.9% higher than a conventional ship in their mid-case (roughly USD 494 million vs. 492 million over 25 years) ([What are the total costs of ownership for different methanol-fuelled containership designs?](https://www.dnv.com/expert-story/maritime-impact/commercial-case-study-for-methanol-fuelled-5500-teu-container-vessel/#:~:text=Dual,extra%20cost%20but%20greater%20flexibility)), indicating cost parity is within reach under certain assumptions. DNV’s model highlights scenario analysis and inclusion of carbon costs (e.g. CO₂ pricing) as key features.
* **Maersk Mc-Kinney Møller Center TCO Model (2021):** The Maersk Mc-Kinney Møller Center for Zero Carbon Shipping (an industry-backed research center) has developed a comprehensive TCO model (v1.2) for comparing zero-emission vessel concepts (). This model was used by the International Council on Clean Transportation to quantify the capital cost differences between conventional ships and zero-emission capable vessels (ZECVs) across fuel pathways (). It accounts for detailed ship parameters (engine power, tank size) and additional CapEx for alternative fuel technologies (). Notably, the model found that LNG-fueled designs require higher tank investment than ammonia or methanol designs due to LNG’s cryogenic storage at -162 °C (versus ammonia at -33 °C or ambient-liquid methanol) (). This underscores how *infrastructure-related costs* are captured in TCO: e.g. fuel tank and handling system expenses vary widely by fuel. The Maersk Center model also assumes limited cost reduction in new tech over time (except for hydrogen fuel cells and tanks) (), providing a conservative baseline. Its use in studies signals it as a leading industry tool, though its detailed assumptions are proprietary.
* **Global Maritime Forum/Getting to Zero Coalition (2022):** The Global Maritime Forum (GMF), through the Getting to Zero Coalition, has not one fixed model but has published comparative *TCO insights and frameworks*. They emphasize that numerous models exist with varying assumptions, leading to a broad range of cost projections for zero-emission fuels ([New fuels: Total cost of operation | Global Maritime Forum](https://globalmaritimeforum.org/insight/new-fuels-total-cost-of-operation/#:~:text=Synopsis%3A%20Currently%2C%20a%20range%20of,order%20to%20support%20decision%20making)). In a 2022 insight paper, GMF highlighted that as renewable energy costs fall, the competitiveness of zero-emission fuels will improve, while the TCO of traditional heavy fuel oil is expected to rise (especially with stricter carbon policies) ([New fuels: Total cost of operation | Global Maritime Forum](https://globalmaritimeforum.org/insight/new-fuels-total-cost-of-operation/#:~:text=,1)). They note about 87% of the estimated USD 1.4–1.9 trillion investment for future shipping fuels will be needed onshore (fuel production, infrastructure) rather than on ships ([New fuels: Total cost of operation | Global Maritime Forum](https://globalmaritimeforum.org/insight/new-fuels-total-cost-of-operation/#:~:text=,1)) – a crucial context for cost modeling. GMF’s framework delineates all elements from feedstock production to onboard utilization, stressing careful input assumptions and sensitivity analysis ([New fuels: Total cost of operation | Global Maritime Forum](https://globalmaritimeforum.org/insight/new-fuels-total-cost-of-operation/#:~:text=Along%20the%20supply%20chain%2C%20different,bunkering%20is%20also%20a%20factor)) ([New fuels: Total cost of operation | Global Maritime Forum](https://globalmaritimeforum.org/insight/new-fuels-total-cost-of-operation/#:~:text=,the%20total%20cost%20of%20ownership)). While not a single “model,” GMF’s work synthesizes industry and academic models to guide decision-makers on TCO drivers.
* **MAR-E-Fuel Project (DTU, 2021):** An academic collaboration (Technical University of Denmark’s MAR-E-Fuel) produced a TCO model to compare a wide range of fuels (from conventional VLSFO to green ammonia, methanol, biofuels, LNG) from 2020–2050 (). Their model, built as a bottom-up lifecycle cost estimator, examined scenarios with low vs. high CO₂ taxes () (). Key findings were that without significant carbon pricing (e.g. at €25/ton CO₂), green fuels remain **2–4× more expensive** than fossil fuels through 2050, making voluntary adoption unlikely (). Under a high carbon tax (€300/ton), certain alternatives (bio-methanol, green ammonia, bio-oil) become cost-competitive with fossil fuel by ~2030–2035 (). The MAR-E-Fuel model explicitly separated cost components: fuel costs, carbon costs, capital, and “other” operating costs, and even evaluated *large vs. small ships* to show that smaller ships (short-sea or coastal) are less sensitive to fuel price increases than large deep-sea ships () (). This model is notable for integrating well-to-wake emissions alongside economics, aligning with IMO lifecycle GHG guidelines.
* **Applied Energy WA–East Asia Corridor Study (2025):** A recent study (Douglas et al. 2025) evaluated decarbonization options for a **Western Australia–East Asia iron ore route**, using a representative Capesize bulk carrier profile ([Scholars@Duke publication: Well-to-wake cost and emissions assessments for the Western Australia–East Asia green shipping corridor](https://scholars.duke.edu/publication/1666095" \l ":~:text=attributional%20life,of%20alternative%20energy%20carriers%20including) ). This comparative techno-economic model included green hydrogen, ammonia, and methanol pathways (produced with Australian renewable energy) and considered both **fuel production supply chain costs and vessel TCO** ([Scholars@Duke publication: Well-to-wake cost and emissions assessments for the Western Australia–East Asia green shipping corridor](https://scholars.duke.edu/publication/1666095" \l ":~:text=compare%20the%20total%20cost%20of,FCs%29%20or) ). It modeled multiple powertrain options – internal combustion engines vs. fuel cells vs. battery-electric – with detailed operational load profiles. The standout result was that a renewable **ammonia-fueled ICE** vessel could cut well-to-wake GHG emissions by 92% while increasing TCO by ~46% relative to a conventional fuel oil ship ([Scholars@Duke publication: Well-to-wake cost and emissions assessments for the Western Australia–East Asia green shipping corridor](https://scholars.duke.edu/publication/1666095" \l ":~:text=,density%20of%20alternative%20liquid%20fuels) ). Other options had even higher TCO “green premiums.” This indicates ammonia as a promising least-cost alternative for long-haul bulk shipping when produced at scale, consistent with other analyses (e.g. IEA) that find ammonia tends to be the cheapest zero-carbon fuel for large ships ([PowerPoint Presentation](https://iea.blob.core.windows.net/assets/deb56090-8d59-4f54-bf02-3651ebbb94ee/ETP2024_Shipping_webinar.pdf#:~:text=Total%20cost%20of%20ownership%20of,30)) ([PowerPoint Presentation](https://iea.blob.core.windows.net/assets/deb56090-8d59-4f54-bf02-3651ebbb94ee/ETP2024_Shipping_webinar.pdf#:~:text=Ammonia%20necessitates%20specific%20safety%20measures,30)). The study’s integration of fuel production, transport, and bunkering infrastructure costs into the model makes it highly relevant for examining *Australia’s export-focused routes*. It also illustrates incorporating IMO’s latest life-cycle GHG accounting standards into TCO analysis ([Scholars@Duke publication: Well-to-wake cost and emissions assessments for the Western Australia–East Asia green shipping corridor](https://scholars.duke.edu/publication/1666095" \l ":~:text=attributional%20life,of%20alternative%20energy%20carriers%20including) ).
* **International Energy Agency (IEA) Analysis (2023-24):** The IEA has included shipping fuel economics in recent reports. In *Energy Technology Perspectives 2024*, the IEA compared TCO for a bulk carrier using various fuels in a 2035 scenario. Their findings echoed that **ammonia-fueled vessels offer the lowest total cost among alternative fuels for large ocean-going ships**, given assumptions in an Accelerated Transition scenario ([PowerPoint Presentation](https://iea.blob.core.windows.net/assets/deb56090-8d59-4f54-bf02-3651ebbb94ee/ETP2024_Shipping_webinar.pdf#:~:text=Total%20cost%20of%20ownership%20of,30)) ([PowerPoint Presentation](https://iea.blob.core.windows.net/assets/deb56090-8d59-4f54-bf02-3651ebbb94ee/ETP2024_Shipping_webinar.pdf#:~:text=Ammonia%20necessitates%20specific%20safety%20measures,30)). For smaller ships or shorter routes, however, the IEA noted methanol (particularly bio- or e-methanol) may be more cost-effective, as its required onboard technology adds less capital cost for those vessel sizes ([Shipping Decarbonization Study - MAN Energy Solutions](https://www.man-es.com/discover/shipping-decarbonization-study#:~:text=Shipping%20Decarbonization%20Study%20,limited%20compared%20to%20fuel%20oil)). The IEA’s quantitative charts show the breakdown of ship cost vs. fuel cost for each option, underscoring that fuels like hydrogen have high fuel expenses that dominate TCO, whereas ammonia’s fuel cost (though high) is partly offset by relatively moderate ship modification costs ([PowerPoint Presentation](https://iea.blob.core.windows.net/assets/deb56090-8d59-4f54-bf02-3651ebbb94ee/ETP2024_Shipping_webinar.pdf#:~:text=Oil%20ICE%20Methane%20ICE%20Methanol,Ammonia%20necessitates%20specific%20safety%20measures)) ([PowerPoint Presentation](https://iea.blob.core.windows.net/assets/deb56090-8d59-4f54-bf02-3651ebbb94ee/ETP2024_Shipping_webinar.pdf#:~:text=but%20tends%20to%20be%20the,50)). IEA scenarios also incorporate projected declines in electrolyzer and renewable energy costs that drive down future e-fuel prices ([New fuels: Total cost of operation | Global Maritime Forum](https://globalmaritimeforum.org/insight/new-fuels-total-cost-of-operation/#:~:text=,1)). While not a standalone “model” accessible to users, IEA’s analyses serve as a benchmark, built on extensive energy system data.
* **MIT “Alternative Fuels Pathways” Model (2022):** MIT’s System Design and Management program developed a model as part of a thesis to evaluate bulk carrier TCO across fuel pathways (). It combined a *levelized fuel production cost model* (for e-fuels under different electricity and feedstock costs) with a vessel TCO model and even linked to a macroeconomic model (MIT EPPA) to project market adoption (). This multi-tiered approach provided insights on the cost markup of alternative fuels relative to conventional marine fuels () and estimated the required policy or carbon price incentives for market entry. Such academic models contribute to understanding long-term transitions and have influenced industry thinking on what mix of fuels could emerge, though they may be complex for direct industry use.

**Comparison of Models:** The above models vary in scope and complexity, but all include the fundamental components of maritime TCO: capital and equipment costs, fuel (energy) costs, operating and maintenance costs, and often external factors like carbon pricing. Table 1 summarizes key features of five notable TCO modeling efforts:

| **Model / Study** | **Developed By** | **Scope & Fuel Options** | **Key Features** |
| --- | --- | --- | --- |
| **DNV Containership TCO (2023)** | DNV (Class Society) | 5,500 TEU container ship; diesel vs. methanol | 20-25yr life, CAPEX/OPEX/FuelEX/GHGEX components ([What are the total costs of ownership for different methanol-fuelled containership designs?](https://www.dnv.com/expert-story/maritime-impact/commercial-case-study-for-methanol-fuelled-5500-teu-container-vessel/#:~:text=Key%20influential%20cost%20factors%20identified)); multiple fuel price & CO₂ cost scenarios ([What are the total costs of ownership for different methanol-fuelled containership designs?](https://www.dnv.com/expert-story/maritime-impact/commercial-case-study-for-methanol-fuelled-5500-teu-container-vessel/#:~:text=DNV%20based%20its%20analysis%20on,new%20decarbonization%20ambition%20by%202050)). Outcome: ~0.5–1% TCO difference between methanol vs conventional ([What are the total costs of ownership for different methanol-fuelled containership designs?](https://www.dnv.com/expert-story/maritime-impact/commercial-case-study-for-methanol-fuelled-5500-teu-container-vessel/#:~:text=Dual,extra%20cost%20but%20greater%20flexibility)). |
| **Maersk Center TCO Model (v1.2)** | Maersk Mc-K. Møller Center (2021) | Generic model for various ship types; H₂, NH₃, MeOH, LNG, etc. | Bottom-up per ship class; calculates extra CapEx for alt-fuel engines & tanks (); no tech learning (except H₂) (); used in ICCT studies, found LNG tank costs > ammonia/methanol (). |
| **MAR-E-Fuel (DTU) Model (2021)** | EU academic/industry project | Global fleet scenarios 2020–2050; VLSFO vs. green NH₃, green/bio MeOH, bio-oil, LNG | Annual TCO with and without CO₂ tax () (); distinguishes fuel, carbon, capital, other costs; considers ship size sensitivity; finds green fuels 2–4× cost of fossil without high carbon price (). |
| **WA–EA Green Corridor Study (2025)** | Duke Univ. & collaborators | Capesize bulk carrier on Australia–Asia route; battery, H₂ (fuel cell/ICE), NH₃, MeOH vs. HFO | Techno-economic & lifecycle (LCA) model ([Scholars@Duke publication: Well-to-wake cost and emissions assessments for the Western Australia–East Asia green shipping corridor |

](https://scholars.duke.edu/publication/1666095#:~:text=attributional%20life,of%20alternative%20energy%20carriers%20including)); includes fuel production (PtX) and bunkering costs; detailed engine load simulation; finds NH₃ ICE + SCR yields lowest TCO increase (+46%) for ~92% emission reduction ([Scholars@Duke publication: Well-to-wake cost and emissions assessments for the Western Australia–East Asia green shipping corridor

](https://scholars.duke.edu/publication/1666095#:~:text=,density%20of%20alternative%20liquid%20fuels)). |

| **Global Maritime Forum (2022)** | GMF / Getting to Zero Coalition | Meta-analysis of various studies (industry & academic); fuels: H₂, NH₃, MeOH, biofuels, etc. | Provides TCO *framework* rather than a single model ([New fuels: Total cost of operation | Global Maritime Forum](https://globalmaritimeforum.org/insight/new-fuels-total-cost-of-operation/#:~:text=Along%20the%20supply%20chain%2C%20different,bunkering%20is%20also%20a%20factor)); emphasizes transparency in assumptions and robust sensitivity analysis ([New fuels: Total cost of operation | Global Maritime Forum](https://globalmaritimeforum.org/insight/new-fuels-total-cost-of-operation/#:~:text=The%20sensitivity%20analysis%20is%20a,pathway%20of%20decarbonization%2C%20this%20includes)) ([New fuels: Total cost of operation | Global Maritime Forum](https://globalmaritimeforum.org/insight/new-fuels-total-cost-of-operation/#:~:text=The%20key%20drivers%20input%20to,of%20a%20key%20drivers%20portfolio)); highlights importance of onshore costs (87% of investment) ([New fuels: Total cost of operation | Global Maritime Forum](https://globalmaritimeforum.org/insight/new-fuels-total-cost-of-operation/#:~:text=,1)) and policy support. |

Table 1: **Representative TCO Models and Studies for Low/Zero-Carbon Shipping.** These models inform global best practices and provide a foundation for adapting to the Australian context.

**Key Cost Categories and Factors in Maritime TCO Models**

Although the above models differ in detail, they largely share a common set of cost categories and operational parameters for TCO calculations:

* **Capital Expenditure (CAPEX):** The upfront cost of the vessel and its onboard systems. This includes the ship hull and standard machinery, plus any *additional investment for alternative technologies*. For example, a dual-fuel engine, larger fuel tanks, battery packs, or fuel cells will raise CAPEX compared to a conventional ship. DNV’s study explicitly broke out CAPEX as ~15% of total lifetime cost in one scenario ([What are the total costs of ownership for different methanol-fuelled containership designs?](https://www.dnv.com/expert-story/maritime-impact/commercial-case-study-for-methanol-fuelled-5500-teu-container-vessel/#:~:text=Key%20influential%20cost%20factors%20identified)), and the Maersk Center model computes the incremental CAPEX for each alternative fuel pathway (e.g. extra tank and engine costs) (). TCO models often annualize CAPEX over the vessel’s life (sometimes as an equivalent annual cost or via depreciation) and may include a **residual value** (scrap value at end of life, especially for hull steel or reusable components). For instance, if a vessel is assumed to have 20-year life, the purchase cost minus residual might be spread over those years in the TCO.
* **Financing Costs (FinEX):** The cost of capital, interest, or return on investment required. Some models treat this separately, especially if a high-tech vessel has different financing terms. DNV introduced a “FinEX” category to capture financing expenditure, which was ~17% of their example TCO. In practice, FinEX can be modeled by applying a discount rate to future cash flows in an NPV approach, or as interest on loans/lease for the vessel. Ensuring the model uses an **appropriate discount rate** (reflecting the shipowner’s cost of capital or hurdle rate) is critical, as it can significantly influence the economic favorability of options with higher upfront costs but lower operating costs (e.g. electric ships).
* **Operating Expenditure (OPEX) excl. fuel:** This covers crew salaries, maintenance, insurance, port fees, and other day-to-day running costs. Traditional OPEX for ships is often estimated as a fixed amount per year or per day at sea. For alternative technologies, OPEX may diverge: e.g. fuel cells might require different maintenance schedules, or electric propulsion could reduce engine maintenance needs (fewer moving parts) but introduce battery maintenance/replacement costs every few years. Many TCO models keep OPEX assumptions similar across cases for simplicity, adjusting maintenance cost factors if, say, dual-fuel engines are more complex. Labour costs (crew, technical staff) are sometimes included in OPEX. For Australian context, notably high maritime labor rates could increase OPEX relative to global averages – we discuss this further below.
* **Fuel (Energy) Costs (FuelEX):** The cost of energy to propel the ship, typically the largest component of lifetime costs. Fuel expenditures can account for 40–60% of total ownership cost for conventional ships ([What are the total costs of ownership for different methanol-fuelled containership designs?](https://www.dnv.com/expert-story/maritime-impact/commercial-case-study-for-methanol-fuelled-5500-teu-container-vessel/#:~:text=Key%20influential%20cost%20factors%20identified)). In DNV’s container ship analysis, fuel costs (FuelEX) were by far the largest share (~51% on average). TCO models must project fuel prices over the analysis period. Approaches include: assuming current prices remain constant (simplest), applying escalation rates, or using scenario forecasts (as DNV did with its ETO-based scenarios ([What are the total costs of ownership for different methanol-fuelled containership designs?](https://www.dnv.com/expert-story/maritime-impact/commercial-case-study-for-methanol-fuelled-5500-teu-container-vessel/#:~:text=DNV%20based%20its%20analysis%20on,new%20decarbonization%20ambition%20by%202050))). For alternative fuels, price uncertainty is high, so models often compare multiple cases (e.g. “Low, Base, High” price trajectories for hydrogen, ammonia, etc.). Some advanced models incorporate **well-to-tank production costs** for synthetic fuels; for example, the Duke/WA–EA study built fuel costs from renewable electricity, conversion, and transport costs ([Scholars@Duke publication: Well-to-wake cost and emissions assessments for the Western Australia–East Asia green shipping corridor](https://scholars.duke.edu/publication/1666095" \l ":~:text=,Compared) ). If an Australian TCO model is to be robust, it should allow input of Australian-specific fuel prices: e.g. the cost of green hydrogen produced domestically (perhaps AUD/kg) vs. imported fuel costs. It should also consider carbon pricing or fuel taxes where applicable – some models add a cost per tonne CO₂ emitted (DNV’s GHGEX category) ([What are the total costs of ownership for different methanol-fuelled containership designs?](https://www.dnv.com/expert-story/maritime-impact/commercial-case-study-for-methanol-fuelled-5500-teu-container-vessel/#:~:text=Key%20influential%20cost%20factors%20identified)) or simulate a carbon tax to evaluate its impact ().
* **Greenhouse Gas (GHG) Emission Costs (GHGEX):** With decarbonization as a goal, many models now include the cost of carbon or emissions credits as a separate element. For instance, DNV’s TCO breakdown includes “fuel-related carbon costs” (GHGEX) ([What are the total costs of ownership for different methanol-fuelled containership designs?](https://www.dnv.com/expert-story/maritime-impact/commercial-case-study-for-methanol-fuelled-5500-teu-container-vessel/#:~:text=The%20detailed%20discussion%20covers%20all,GHG%20and%20air%20pollutant%20emissions)). This can represent compliance with emissions trading schemes, carbon taxes, or the cost of offsetting emissions. In scenarios where alternative fuels have near-zero CO₂ emissions, this cost component would be minimal, whereas fossil fuels would incur rising GHG costs if a carbon price is applied. In MAR-E-Fuel’s scenarios, adding a €300/ton CO₂ tax flipped the economics in favor of green fuels by mid-2030s (). An Australian-specific model might consider Australia’s **Carbon Credit Units (ACCUs)** or any future maritime emission levy, ensuring that regulatory costs of carbon are factored into long-term TCO.
* **Infrastructure and Bunkering Costs:** Though not always borne directly by the ship operator, some models account for the costs of shoreside infrastructure as part of the analysis, especially for new fuels that need new supply chains. The GMF framework notes that *87% of decarbonization investment is onshore* (fuel production plants, port storage, electric grids) ([New fuels: Total cost of operation | Global Maritime Forum](https://globalmaritimeforum.org/insight/new-fuels-total-cost-of-operation/#:~:text=,1)). A TCO analysis can internalize some of these costs in different ways. For example, if a ship requires shore power at port, the model might include an annual charge or a per-kWh price that reflects the amortized cost of installing the port’s electrical infrastructure. Similarly, if hydrogen refueling is needed, the fuel price could be adjusted upward to reflect delivery and bunkering facility costs (as the CEFC hydrogen study suggests, delivered hydrogen cost is higher than “farm-gate” production cost due to transport, compression, and storage expenses ([Australian hydrogen market study](https://www.cefc.com.au/media/nhnhwlxu/australian-hydrogen-market-study.pdf#:~:text=Due%20to%20the%20very%20low,molecules%20and%20movement%20of%20electrons)) ([Australian hydrogen market study](https://www.cefc.com.au/media/nhnhwlxu/australian-hydrogen-market-study.pdf#:~:text=energy%20carriers,colours%20to%20different%20hydrogen%20production))). Some models (like the WA–EA corridor TEA) explicitly add costs for fuel transport and bunkering in the fuel supply chain ([Scholars@Duke publication: Well-to-wake cost and emissions assessments for the Western Australia–East Asia green shipping corridor](https://scholars.duke.edu/publication/1666095" \l ":~:text=,Compared) ). For practical use, an Australian TCO model might treat infrastructure costs as external inputs – for instance, assume a certain price per ton of ammonia delivered to Port of Newcastle that inherently includes terminal costs, rather than making the ship owner invest in the terminal. But it is important to document those assumptions.
* **Operational Profile & Utilization:** Apart from cost line items, TCO models require assumptions on *operational parameters* that greatly influence costs. Key parameters include: **annual days at sea**, **voyage distance and speed (operating profile)**, **cargo utilization (load factor)**, and **energy consumption**. A high-utilization ship (e.g. a busy container ship) will consume more fuel annually (thus higher fuel cost total) but also “dilute” fixed costs over more usage. Operational profiles can differ for alternative fuels; for example, a battery-electric ship might have shorter range and require more frequent port calls for recharging, effectively reducing productive days. Some models simulate these differences. The Duke study used a realistic voyage profile for bulk carriers (including time laden vs. ballast, and speed variations) to accurately estimate fuel use under each powertrain ([Scholars@Duke publication: Well-to-wake cost and emissions assessments for the Western Australia–East Asia green shipping corridor](https://scholars.duke.edu/publication/1666095" \l ":~:text=production%2C%20transportation%2C%20densification%2C%20storage%2C%20bunkering%2C,higher%20than) ). For our purposes, an Australian model should capture typical operating patterns of ships calling NSW ports – e.g. a coal bulk carrier might do 8 round trips to Asia per year with near-100% load outbound and return in ballast, whereas a coastal ro-ro might have daily operations but short distance. These patterns affect fuel consumption, required fuel capacity on board (and hence tank size/cargo trade-off), and OPEX like port fees.
* **Cargo Capacity Impact:** One often overlooked factor is the effect of new fuel systems on cargo carrying capacity. Heavier or more voluminous fuel systems (batteries, hydrogen tanks, etc.) can reduce payload, which has an economic cost (lost revenue). Some TCO studies incorporate this by treating lost cargo space as a cost. For instance, if a container ship must sacrifice a certain number of containers to accommodate larger fuel tanks, the revenue loss can be monetized. The Maersk Center/ICCT work refers to “lost slots” in container ships as an adjustment in their model (). The MAR-E-Fuel project showed example calculations where a 15,000 TEU ship might lose some slots to alternative fuel tanks, affecting income. Bulk carriers, on the other hand, are often weight-limited rather than volume-limited; the WA–EA study noted that for iron ore bulkers, the reduced energy density of alternative fuels (like ammonia) did *not* significantly constrain cargo mass capacity ([Scholars@Duke publication: Well-to-wake cost and emissions assessments for the Western Australia–East Asia green shipping corridor](https://scholars.duke.edu/publication/1666095" \l ":~:text=powered%20vessels%20offer%20the%20lowest,reductions%20within%20the%20WA%E2%80%93EA%20green) ). An Australian TCO framework should allow assessing this impact: e.g. ammonia fueling on a large bulker may have negligible cargo penalty (just more empty space in holds), whereas hydrogen on a small coastal vessel could displace paying cargo.

In summary, robust TCO models break down the full life-cycle costs into **capital**, **operational (fuel, maintenance, crew, port fees)**, **financing**, and **end-of-life** components. They require a set of operational assumptions (life, annual use, payload) to roll these costs up into a total (often expressed as net present cost or an average cost per year or per ton-mile). By making each component explicit, such models enable decision-makers to see which factors drive cost differences – for example, whether the premium for an ammonia-fueled ship comes mostly from fuel price, or from the onboard equipment cost.

([What are the total costs of ownership for different methanol-fuelled containership designs?](https://www.dnv.com/expert-story/maritime-impact/commercial-case-study-for-methanol-fuelled-5500-teu-container-vessel/)) *Figure 1: Cost component breakdown in DNV’s TCO analysis for a mid-size container ship (5,500 TEU). Fuel costs (FuelEX) dominate at ~51%, followed by financing (FinEX ~17%) and capital (CAPEX ~15%), with smaller shares for operating costs (OPEX ~11%) and carbon costs (GHGEX ~6%) (*[*What are the total costs of ownership for different methanol-fuelled containership designs?*](https://www.dnv.com/expert-story/maritime-impact/commercial-case-study-for-methanol-fuelled-5500-teu-container-vessel/#:~:text=Key%20influential%20cost%20factors%20identified)*). This illustrates the importance of fuel and financing in lifetime costs.*

**Methodological Approaches in TCO Modeling**

TCO can be calculated in different ways, and the choice of methodology influences how results are interpreted:

* **Net Present Value (NPV) vs. Annualized Costs:** Some models compute an NPV of all costs over the vessel’s lifetime, discounting future costs to present value. This captures the time value of money and is useful when comparing investments with different cash flow profiles. For example, a battery-electric ship has high upfront cost but lower future fuel costs; NPV will appropriately weight those lower future costs (especially if a high discount rate is used, it makes future fuel savings worth less today). Other models simplify by spreading costs into an **equivalent annual cost** or using a per voyage cost. DNV’s analysis essentially summed undiscounted costs over 25 years ([What are the total costs of ownership for different methanol-fuelled containership designs?](https://www.dnv.com/expert-story/maritime-impact/commercial-case-study-for-methanol-fuelled-5500-teu-container-vessel/#:~:text=Dual,extra%20cost%20but%20greater%20flexibility)) (though it did include financing costs separately). The Maersk Center model likely uses annual cash flows. For an Australian model, using NPV with a clear discount rate (or perhaps multiple rates in sensitivity tests) is advisable for rigor, while also presenting results in intuitive terms (e.g. cost per year or cost per ton of cargo).
* **Deterministic Scenarios vs. Probabilistic Analysis:** Most referenced studies use **scenario analysis** – evaluating TCO under a handful of scenarios (e.g. “optimistic fuel price”, “pessimistic fuel price”, “high carbon tax”, etc.) ([What are the total costs of ownership for different methanol-fuelled containership designs?](https://www.dnv.com/expert-story/maritime-impact/commercial-case-study-for-methanol-fuelled-5500-teu-container-vessel/#:~:text=DNV%20based%20its%20analysis%20on,new%20decarbonization%20ambition%20by%202050)) (). This approach is straightforward and helps identify break-even points (e.g. the carbon price at which ammonia becomes cheaper than fuel oil). However, scenario analysis may not capture the full uncertainty range. Some advanced approaches use **Monte Carlo simulations** to model uncertainties in inputs (fuel prices, technology costs, etc.) as probability distributions. For instance, an academic life-cycle cost study might assign distributions to fuel price growth and run thousands of simulations to derive a probability distribution of TCO outcomes ([Life-cycle cost analysis of an innovative marine dual-fuel engine ...](https://www.sciencedirect.com/science/article/pii/S0959652622044201#:~:text=,The%20scenario%20sensitivity)) ([Ship Emission Mitigation Strategies Choice Under Uncertainty - MDPI](https://www.mdpi.com/1996-1073/13/9/2213#:~:text=Ship%20Emission%20Mitigation%20Strategies%20Choice,Carlo%20method%20can%20be%20applied)). This can highlight risk (e.g. probability that an option is cheaper over 20 years). In practice, Monte Carlo methods have been applied in marine cost analysis for engines and fuel consumption uncertainty ([Life-cycle cost analysis of an innovative marine dual-fuel engine ...](https://www.sciencedirect.com/science/article/pii/S0959652622044201#:~:text=Life,The%20scenario%20sensitivity)) ([Ship Emission Mitigation Strategies Choice Under Uncertainty - MDPI](https://www.mdpi.com/1996-1073/13/9/2213#:~:text=Ship%20Emission%20Mitigation%20Strategies%20Choice,Carlo%20method%20can%20be%20applied)), though industry stakeholders often prefer a few clear scenarios over a complex probabilistic output. Given the significant uncertainty in alternative fuel costs in Australia (hydrogen, etc.), a Monte Carlo or at least extensive sensitivity analysis could be valuable for a local TCO model to **stress-test assumptions** (e.g. if electricity prices spike, how badly is electrification’s TCO impacted?).
* **Time Horizon and Replacement Cycles:** The choice of analysis period (vessel lifetime, which might be 20, 25, or 30 years) is important. Some models assume a single vessel over its life; others might examine a **fleet turnover scenario** (especially if looking at transition pathways). For example, the MIT model connected to a macroeconomic model effectively looked at fleet adoption through 2050 (). For a specific project (like evaluating a newbuild in 2025), using that vessel’s lifespan is appropriate. But for strategic planning (Australia’s 2026 committee perspective), it might be useful to consider multiple iterations – e.g. a ship bought in 2025 vs one bought in 2035 might have different costs and performance. Thus, methodological approach could involve running separate TCO analyses for different entry years or technology generations to see how improvements reduce costs.
* **Functional Unit – Cost per what?** Communicating TCO results can be done per ship, per ton of cargo, per ton-mile, or per year. Many models output a total lifetime cost in dollars, but it can be hard to compare different ship sizes with that. Some convert TCO into a unit cost of transport service (e.g. $/ton cargo transported or $/teu per km). This is useful for comparing the economic impact on freight rates. If an ammonia-fueled bulk carrier has 46% higher 25-year TCO ([Scholars@Duke publication: Well-to-wake cost and emissions assessments for the Western Australia–East Asia green shipping corridor](https://scholars.duke.edu/publication/1666095" \l ":~:text=,density%20of%20alternative%20liquid%20fuels) ), what does that mean in terms of cost per ton of iron ore? Decision-makers might want to see that number to gauge if customers would bear it or if efficiency improvements are needed. So the framework should be able to present results in a meaningful metric like **$/tonne-km** or similar.
* **Lifecycle Boundaries (Well-to-Wake vs Tank-to-Wake):** Methodologically, there is a distinction between just accounting for onboard costs vs. full fuel production lifecycle. TCO usually refers to ownership cost to the shipowner, so it doesn’t directly include upstream fuel production cost beyond what is reflected in fuel price. But from a societal view, some models (like the WA–EA study) combine TCO with well-to-wake emissions analysis ([Scholars@Duke publication: Well-to-wake cost and emissions assessments for the Western Australia–East Asia green shipping corridor](https://scholars.duke.edu/publication/1666095" \l ":~:text=compare%20the%20total%20cost%20of,FCs%29%20or) ) to identify cost per ton CO₂ abated. In that study, they calculated a carbon abatement cost of $247/ton for the ammonia pathway ([Scholars@Duke publication: Well-to-wake cost and emissions assessments for the Western Australia–East Asia green shipping corridor](https://scholars.duke.edu/publication/1666095" \l ":~:text=case%20without%20policy%20incentives,reductions%20within%20the%20WA%E2%80%93EA%20green) ). While not needed for pure TCO, this methodology is relevant if the Australian context requires understanding cost-effectiveness of emissions reduction. The models can be extended to compute metrics like $/ton CO₂ avoided.
* **Multi-Criteria and Utility Approaches:** A few advanced efforts (MIT, etc.) incorporate not just cost but also other factors (utility metrics, risk, etc.) in assessing pathways () (). However, for the scope of a TCO framework, it is reasonable to focus on economic costs and perhaps treat other criteria (safety, technology readiness) qualitatively or in supplemental analysis. For example, GMF notes that TCO excludes technology readiness and risk considerations ([New fuels: Total cost of operation | Global Maritime Forum](https://globalmaritimeforum.org/insight/new-fuels-total-cost-of-operation/#:~:text=costs%20associated%20with%20its%20operation%2C,risk%20assessment%2C%20or%20policy%20landscape)), which should be evaluated separately (e.g. through risk assessment tools or scenario weighting).

In choosing a methodology for an Australian TCO model, a **hybrid approach** could be best: use an NPV or annual cash flow model for precision, run several **scenarios** (reflecting uncertainty in key inputs like fuel prices, carbon policy, and technology costs), and include a **sensitivity analysis** section that shows how results change with ±X% changes in inputs. This will help build confidence in the model’s robustness for the 2026 technical review committee.

**Applicability of Global Models to the Australian Context**

Global TCO models provide a strong starting point, but the Australian context – and specifically heavy shipping around NSW ports – has unique aspects that must be considered:

* **Fuel Availability and Price Differences:** Many global studies assume global average prices or future projections that might not directly apply to Australia. For example, European models might assume certain biomass availability or EU carbon taxes that don’t hold in Australia. Australia’s potential competitive advantage is in renewable energy and hydrogen/ammonia production (given abundant solar, wind, land). By 2030, Australia could produce green hydrogen at lower costs than some regions ([Australian hydrogen market study](https://www.cefc.com.au/media/nhnhwlxu/australian-hydrogen-market-study.pdf#:~:text=It%20is%20common%20practice%20to,treated%20as%20a%20transition%20fuel)). This means fuels like ammonia or methanol made in Australia might become relatively cheaper for local bunkering than global market prices. A TCO model for NSW should thus plug in Australian fuel price forecasts – e.g. using sources like the **CEFC/Advisian Hydrogen Market Study**, which projects green hydrogen costs in Australia to 2050 ([Australian hydrogen market study](https://www.cefc.com.au/media/nhnhwlxu/australian-hydrogen-market-study.pdf#:~:text=capacity%20to%20pay%20for%20each,supply%20side%20costs%20and%20end)) ([Australian hydrogen market study](https://www.cefc.com.au/media/nhnhwlxu/australian-hydrogen-market-study.pdf#:~:text=Low%20carbon%20hydrogen%20is%20emerging,relative%20to%20the%20incumbent%20technology)), or CSIRO’s Australian Energy Outlooks. If an international model found ammonia 46% more expensive than HFO without policy ([Scholars@Duke publication: Well-to-wake cost and emissions assessments for the Western Australia–East Asia green shipping corridor](https://scholars.duke.edu/publication/1666095" \l ":~:text=in%20regards%20to%20dynamic%20loads%2C,lie%20well%20above%20the%20typical) ), an Australian version might find a different premium if domestic ammonia is cheaper due to local production. Conversely, traditional marine diesel (mostly imported) might be costlier in Australia than in, say, Singapore. Local fuel taxes or incentives (like the Australian Fuel Tax Credits scheme or potential future carbon offset requirements for shipping) also affect applicability.
* **Vessel Operational Patterns in NSW:** Major NSW ports (Port of Newcastle, Port Botany/Sydney, Port Kembla) handle specific trades: e.g. Newcastle is dominated by large bulkers (coal, grain), Botany by container ships (many of which are in the ~5,000–10,000 TEU range), and Kembla by bulk and vehicle carriers. These trades have different typical voyage lengths and frequencies. Global models often consider an “average” deep-sea voyage or a particular route (like Asia-Europe in many studies of container shipping). For NSW, an important use-case might be **Asia-Pacific regional routes** – e.g. an container ship running Australia-East Asia or a bulker doing Newcastle to Japan. The steaming distances are shorter than Asia-Europe, which could make electrification or alternative fuels slightly more viable (shorter routes mean easier refuel or smaller tanks). On the other hand, Australian export bulk routes carry very high mass (iron ore, coal) which emphasizes fuel energy density (favoring fuels like ammonia over batteries). In evaluating global models, we should ask: does their assumed vessel match Aussie usage? For instance, DNV’s 5,500 TEU container ship analysis ([What are the total costs of ownership for different methanol-fuelled containership designs?](https://www.dnv.com/expert-story/maritime-impact/commercial-case-study-for-methanol-fuelled-5500-teu-container-vessel/#:~:text=Titled%20%E2%80%9CCommercial%20considerations%20for%20a,25%20years%20for%20the%20vessel)) is actually quite relevant to Port Botany, since that port frequently sees ships in the 5k–8k TEU class (not ultra-large ships). The MAR-E-Fuel model looked at 15,000 TEU and 1,200 TEU extremes (); Australia likely deals more with mid-size vessels in between, so interpolation is needed. Adapting these models means tailoring input parameters like average speed (perhaps many bulkers to Australia travel at slightly slower speeds to save fuel), port stay durations, and auxiliary power usage at port (where shore power could come into play, see below).
* **Regulatory and Market Context:** International models assume IMO regulations apply uniformly. In Australia, vessels in international trade comply with IMO rules (MARPOL Annex VI for emissions, etc.) under AMSA enforcement. However, Australia could introduce additional incentives or requirements. For example, if Australia implements an Emissions Trading Scheme or Carbon Tax that includes domestic shipping, that would raise fossil fuel costs domestically. Also, Australia’s ports or authorities might institute port fee discounts for green vessels or mandate low-emission operations near ports. An example is the Port of Sydney’s initiative to create a “100% renewable energy shore power precinct” for cruise and bulk ships ([It's a shore thing shore power comes to Australia](https://www.portsaustralia.com.au/media-centre/its-a-shore-thing-shore-power-comes-to-australia#:~:text=International%20bulk%20ships%20and%20cruise,be%20located%20in%20Sydney%20Harbor)) ([It's a shore thing shore power comes to Australia](https://www.portsaustralia.com.au/media-centre/its-a-shore-thing-shore-power-comes-to-australia#:~:text=Shore%20power%20is%20the%20provision,associated%20with%20consumption%20of%20fuel)). Such an initiative might effectively require vessels to use shore power (in Sydney Harbour) by a certain date. A global model not aware of this would underestimate the benefit of an electrification-capable vessel in Sydney. Additionally, the trading patterns: Australian coastal shipping is a small sector (due to historically high costs and foreign competition). If the model is applied to a **domestic freight route** (say, a coastal bulk carrier between NSW and Queensland), one has to account for Australian wage rates and potentially cabotage rules. In contrast, a foreign vessel doing an international route just calling at NSW may have lower crew costs (international labor) and can refuel at the cheapest port on its route (which might be Singapore or elsewhere, not Australia). Thus, assessing TCO for an *Australia-based vs. just Australia-serving* vessel can yield different results. We might need to create two variants: one for an Australian domestic operator and one for a typical foreign operator using Australian ports, to see if the economics differ in ways that matter for policy (e.g. if foreign ships won’t adopt a fuel because it’s not available globally, even if Australia offers it).

In general, the structure of global TCO models **is applicable** to Australia – cost categories and methods remain the same. The differences lie in the **input assumptions** (prices, operating profile, and policy drivers). The following sections will identify data sources for those Australian inputs (Section Data Sources) and then recommend assumptions and parameters specific to Australia (Section Australian Parameters).

**Data Sources for Australian Maritime Inputs**

To tailor a TCO model to the Australian heavy shipping context, reliable data specific to Australia (and NSW ports) should be gathered for all key inputs. Below we list important data categories and potential sources:

* **Fuel Prices (Current and Projected):** For conventional fuels (e.g. Very Low Sulfur Fuel Oil, Marine Diesel Oil), data can come from global bunker price reporting agencies (BunkerIndex, Ship&Bunker) with adjustments for Australian ports if needed. Australia often pegs bunker fuel prices to Singapore plus freight. Historical prices can be obtained from Australian Institute of Petroleum reports or Dept. of Industry. For future projections, one might use IEA’s World Energy Outlook or domestic outlooks (e.g. Australia’s Office of the Chief Economist reports). For **alternative fuels**:
  + *Hydrogen:* Use studies like the CEFC Australian Hydrogen Market Study ([Australian hydrogen market study](https://www.cefc.com.au/media/nhnhwlxu/australian-hydrogen-market-study.pdf#:~:text=capacity%20to%20pay%20for%20each,supply%20side%20costs%20and%20end)) which provides cost estimates (AUD per kg) for green hydrogen production under Australian conditions, and possibly delivered costs. ARENA and CSIRO have published data on $/kg targets (e.g. the often-quoted target of “H₂ under $2 per kilogram”).
  + *Ammonia:* As ammonia is derived from hydrogen, cost can be modeled from hydrogen plus conversion costs. The **CSIRO National Hydrogen Roadmap** or similar may have data on ammonia as a carrier. Additionally, the **Global Maritime Forum** or **Mission Innovation** reports give ammonia and methanol price scenarios (e.g. one report suggests e-ammonia could drop to ~$550/ton (USD) with scale, comparable to ~$30/GJ ([[PDF] The Role of E-fuels in Decarbonising Transport - NET](https://iea.blob.core.windows.net/assets/9e0c82d4-06d2-496b-9542-f184ba803645/TheRoleofE-fuelsinDecarbonisingTransport.pdf#:~:text=%5BPDF%5D%20The%20Role%20of%20E,comparable%20with%20the%20higher))).
  + *Methanol:* The Methanol Institute and IEA provide figures. Green methanol cost involves renewable power plus captured CO₂; this might be higher than ammonia per energy unit. For reference, IEA ETP 2024 indicated e-methanol around $700/ton and e-ammonia $550/ton at scale ([[PDF] The Role of E-fuels in Decarbonising Transport - NET](https://iea.blob.core.windows.net/assets/9e0c82d4-06d2-496b-9542-f184ba803645/TheRoleofE-fuelsinDecarbonisingTransport.pdf#:~:text=%5BPDF%5D%20The%20Role%20of%20E,comparable%20with%20the%20higher)) (which are roughly 2–3 times the energy-equivalent cost of fossil fuels today).
  + *Electricity:* Shore power or battery charging electricity costs should come from the **National Electricity Market (NEM)** data. AEMO publishes wholesale price projections; however, port operations might use a mix of grid and on-site generation. For example, Flinders Ports (SA) is installing solar to cut power costs for port electrification ([New investment to electrify Australian ports - DCCEEW](https://www.dcceew.gov.au/about/news/new-investment-electrify-australian-ports#:~:text=The%20CEFC%20capital%20will%20finance,This%20includes)). NSW-specific data: look at NSW Treasury or AEMO’s Integrated System Plan for NSW region prices, and consider time-of-use (charging likely off-peak). Also include network costs if a ship requires MWs of power (transmission and distribution charges in NSW can be significant).
  + *Biofuels:* If considering biodiesel or bio-LNG, sources like **IEA Bioenergy Taskforce** or Australian Renewable Energy Agency (ARENA) reports on biofuel pilot projects can give cost ranges.
* **Vessel Specifications and Performance:** Data on typical ships visiting NSW can be obtained from port authority publications or the Australian Maritime Safety Authority (AMSA) registry. For example, Port Authority of NSW may publish the average size of vessels and visits per year. The Bureau of Infrastructure, Transport and Regional Economics (BITRE) often compiles shipping statistics. Key data needed: vessel deadweight tonnage, engine power, typical fuel consumption (e.g. tons of fuel per day at sea), and auxiliary engine usage in port. If not directly available, one might use generic values from literature (e.g. a Panamax bulk carrier ~80,000 DWT consumes ~30 tonnes of fuel per day at 12-14 knots). Additionally, any Australian trials of alternative tech (like the electric Sydney ferries or small battery vessels, if any) could provide performance benchmarks for electric propulsion efficiency.
* **Operational Profiles:** We should gather typical route distances from NSW ports to common destinations. For instance, Newcastle to Shanghai (~4,500 nm), Sydney to Singapore (~3,900 nm), etc. This can define how much energy is needed per voyage. Port rotation and waiting times can be gleaned from port performance reports. If modeling domestic operations, distances like Sydney to Brisbane (~500 nm) or Sydney to Melbourne (~600 nm) matter. Data on port stay durations (e.g. a container ship might spend ~1 day in port, a coal bulker 1-2 days loading) help determine if shore power can be utilized extensively. Sources: Port Authority NSW’s environmental reports might have berthing time info; otherwise, academic studies on port turnaround or AIS data analysis.
* **Port Costs and Fees:** Each port in NSW publishes a schedule of fees (for pilotage, tonnage dues, wharfage, etc.). For example, Port of Newcastle’s tariff schedule will list charges per gross ton or per volume of cargo. These fees are part of OPEX. They typically don’t differ by fuel type *yet*, but interestingly some ports globally are starting to offer discounts for eco-friendly ships (the Panama Canal and some European ports have “green rebates”). We should check if NSW ports have any such incentives or plan to (the Ports Australia announcement hinted at industry’s interest in sustainability ([It's a shore thing shore power comes to Australia](https://www.portsaustralia.com.au/media-centre/its-a-shore-thing-shore-power-comes-to-australia#:~:text=Ports%20Australia%20CEO%20Michael%20Gallacher,investment%20made%20into%20shore%20power)), but not sure about fee incentives). If none, port costs can be treated equal across options. Also include canal fees if relevant (less so for NSW, unless a ship transits somewhere like Panama on route, unlikely for Asia-Pacific trade).
* **Grid Connection and Infrastructure Costs:** For modeling shore power or charging infrastructure at ports, data from recent Australian projects is valuable. The White Bay Cruise Terminal shore power project in Sydney was budgeted around AUD $60 million for one terminal ([Shore Power | Port Authority New South Wales](https://www.portauthoritynsw.com.au/sustainability/net-zero-energy/shore-power/#:~:text=Port%20Authority%20intends%20to%20invest,the%20White%20Bay%20Cruise%20Terminal)). That gives a ballpark for infrastructure cost per berth (though cruise has very high power demand ~10-16 MVA per ship). The NSW government’s recent contract of $20 million for initial works ([NSW government awards AUD20 million Sydney shore power contract](https://ship.energy/2024/09/30/nsw-government-awards-aud20-million-sydney-shore-power-contract/#:~:text=NSW%20government%20awards%20AUD20%20million,White%20Bay%20Cruise%20Terminal)) also provides cost insight. Another example: the new renewable shore power precinct in Sydney (Glebe Island/White Bay) presumably has detailed cost-benefit studies ([[PDF] consideration for shore power provision - Port Authority of NSW](https://www.portauthoritynsw.com.au/media/5288/shore-power-considerations-report_2022.pdf#:~:text=,regarding%20shore%20power%20for)). For bulk ports, one can look to the announced plan to equip Port Kembla or Newcastle with shore power (the Ports Australia release implies the Sydney project is the first, so others likely to follow). If we cannot find exact figures, we could use proxies (e.g. cost per MW of substation and cabling). These costs might be included in the model as an annual service charge if the port recovers the investment through fees or electricity pricing to ships. Alternatively, if analyzing from a societal perspective, include as separate line to see impact on overall economics.
* **Regulatory Inputs:** While not a numerical input, it’s useful to have references for Australian maritime regulations. AMSA publications or Marine Orders might outline any requirements that affect costs (e.g. needing certain safety equipment for ammonia or hydrogen fuelled vessels in Australian waters). Also, any Australian **fuel quality standards** (MARPOL global sulfur limit is 0.5% since 2020, which we assume as baseline; if an Emission Control Area was ever declared around Australia, it would push to 0.1% sulfur or require alternate fuels in coastal areas, but currently Australia has not designated an ECA). The International Maritime Organization’s Carbon Intensity Index (CII) will apply to many ships calling Australia; if a vessel gets a poor CII rating using fossil fuels, by 2026 it might face corrective action. That’s a somewhat abstract cost, but one could assign a penalty or required offset cost in the model if a ship is non-compliant. Data for such could be from IMO documents or industry analysis of CII impacts.

In summary, building an Australian TCO model involves plugging in local values for the same elements global models use. Fortunately, Australia has a number of studies and data sources on emerging fuels (through CEFC, ARENA, CSIRO, etc.), and port authorities that provide operational data. Table 2 outlines some of these sources:

| **Input Category** | **Australian Data Source Examples** |
| --- | --- |
| Fuel prices & projections | CEFC Hydrogen Market Study ([Australian hydrogen market study](https://www.cefc.com.au/media/nhnhwlxu/australian-hydrogen-market-study.pdf#:~:text=capacity%20to%20pay%20for%20each,supply%20side%20costs%20and%20end)) (H₂ costs); CSIRO reports; Dept. of Industry’s resources and energy forecasts (for LNG, diesel); IEA WEO (adjusted for AU context). |
| Electricity prices | AEMO NEM data (wholesale prices, futures); Retail tariffs (Ausgrid/Endeavour Energy for NSW); Project-specific (e.g. Flinders Ports solar project costs ([New investment to electrify Australian ports - DCCEEW](https://www.dcceew.gov.au/about/news/new-investment-electrify-australian-ports#:~:text=The%20CEFC%20capital%20will%20finance,This%20includes))). |
| Vessel specs & counts | BITRE Yearbook (shipping stats); AMSA vessel registries; Port Authority of NSW trade reports (ship call data by type). |
| Voyage distances & patterns | Port Authority NSW (typical routes, maybe in annual reports); Distance calculators (Sea-web or GIS) for key port pairs; Historical AIS analysis via academic papers. |
| Port fees | Port of Newcastle, Port Botany, Port Kembla published fee schedules (tonnage dues, etc.); Ports Australia publications for national summaries. |
| Infrastructure (shore power, bunkering) | Port Authority NSW studies (White Bay shore power feasibility ([[PDF] consideration for shore power provision - Port Authority of NSW](https://www.portauthoritynsw.com.au/media/5288/shore-power-considerations-report_2022.pdf#:~:text=,regarding%20shore%20power%20for))); Government announcements (NSW Shore Power project ([It's a shore thing shore power comes to Australia](https://www.portsaustralia.com.au/media-centre/its-a-shore-thing-shore-power-comes-to-australia#:~:text=International%20bulk%20ships%20and%20cruise,be%20located%20in%20Sydney%20Harbor))); ARENA/CEFC project reports for port electrification or hydrogen hubs (e.g. Port of Newcastle Hydrogen Hub plans). |
| Regulations & policy | AMSA guidelines; Australian Maritime Greenhouse Gas Strategy (if any); Department of Infrastructure planning documents; IMO and how Australia implements (e.g. Marine Order 97 for fuel sulfur limits). |

Using these sources will ground the model in reality – for instance, using NSW electricity prices and not just EU prices, which could be very different. It will also help in stakeholder acceptance, as local data makes the findings more relatable. In cases where data is a gap (discussed later in Data Gaps), proxies from similar contexts will be used initially.

**Australian-Specific Parameters and Assumptions**

Building on the above, we recommend the following parameters and assumptions for a TCO framework focused on Australian heavy shipping (circa 2025–2030), especially for NSW ports:

**Regulatory and Compliance Factors**

Australia adheres to IMO regulations through domestic law, so assume compliance with **MARPOL Annex VI** (0.50% sulfur fuel, NOx Tier III requirements for new ships in designated areas). By 2026, IMO’s carbon intensity measures (CII ratings) will be in effect – likely driving ship operators to improve efficiency or switch fuels. We assume:

* Ships must meet at least the required CII (no direct cost, but if using zero-carbon fuel, they easily comply, whereas if using oil they might need speed reductions or offsets). We can incorporate a notional **carbon cost** for CII non-compliance, or simply note that poor performers will incur efficiency penalties.
* The Australian Maritime Safety Authority (AMSA) will enforce any fuel safety codes for alternative fuels. E.g. use of hydrogen or ammonia requires compliance with the IGF Code (International Code of Safety for Ships using Gases or other Low-flashpoint Fuels). This implies additional capital cost for safety systems (gas detection, ventilation, explosion-proof equipment) – we should include those in CAPEX for H₂/NH₃ options, possibly as a percentage add-on (Maersk’s model would have covered this globally; we mirror it).
* Australia does not yet have a carbon tax for shipping, but under its Climate Active programs or port initiatives, there might be a push for internal carbon pricing. We can run two cases: one with no carbon tax (business as usual) and one with a moderate carbon price by late 2020s (say AU$50/ton CO₂) to see impact. The high carbon price scenario in MAR-E-Fuel (300 €/ton) might be unlikely in Australia by 2030 (), but a lower price could emerge via a fuel standard or offset requirement.

Finally, any **local environmental regulations** like restrictions on bunker fuel in Sydney Harbour (for air quality) should be checked. Some cities consider banning combustion engines at berth (hence forcing shore power). We know NSW is investing in shore power for cruise and bulk berths ([It's a shore thing shore power comes to Australia](https://www.portsaustralia.com.au/media-centre/its-a-shore-thing-shore-power-comes-to-australia#:~:text=International%20bulk%20ships%20and%20cruise,be%20located%20in%20Sydney%20Harbor)) ([It's a shore thing shore power comes to Australia](https://www.portsaustralia.com.au/media-centre/its-a-shore-thing-shore-power-comes-to-australia#:~:text=Shore%20power%20is%20the%20provision,associated%20with%20consumption%20of%20fuel)), and likely by 2026 ships without shore connection might face pressure. So assume that by 2030, the **major NSW ports have shore power available** and that new vessels should be built “shore-power ready.” This adds a small CAPEX for the ship (installation of high-voltage socket, etc.) but could reduce fuel use in port (so model shift of hoteling fuel to electric at port).

**Electricity Market Structure and Pricing**

Australia’s National Electricity Market means power prices fluctuate by time and region. NSW historically has had higher prices than some other states, but with more renewables coming, off-peak prices could drop. For TCO:

* Use **time-of-use electricity costs** for shore power or charging. For example, assume off-peak electricity at port at AUD 50–100/MWh (5–10 c/kWh) if drawn at night, but on-peak could be AUD 150–200/MWh (15–20 c/kWh). If a ship can schedule charging at night, that’s beneficial. The model can incorporate an average or specific charging pattern.
* If a port installs its own solar/storage, it might offer a fixed rate to vessels. The Flinders Ports project indicates using solar to cut reliance on grid ([New investment to electrify Australian ports - DCCEEW](https://www.dcceew.gov.au/about/news/new-investment-electrify-australian-ports#:~:text=The%20CEFC%20capital%20will%20finance,This%20includes)). It’s reasonable to assume a shore power rate somewhat below the cost of running ship generators on diesel. For instance, if marine gasoil costs say AUD 1,000/ton (which at 0.1% sulfur could be possible), that’s ~AUD 0.08 per kWh of energy (assuming ~42 MJ/kg diesel and 40% generator efficiency). So shore power could be priced around $80/MWh (8 c/kWh) to be attractive and still recover investment. We will use such estimates but can sensitivity-test them.
* Note Australia’s grid is mostly coal/gas right now in NSW, but transitioning – by 2026, a good share is renewable. We should ensure the emissions factor of grid electricity is considered if doing emissions analysis, but for TCO, the key is cost. However, if there’s a goal to use *renewable* electricity for true zero-emission, possibly a slight premium or requirement to buy green power (e.g. GreenPower program certificates) might be included. That could add a few dollars per MWh.

The electricity market also affects **hydrogen production costs** – electrolysis will be cheaper when excess renewables cause very low prices. By mid-2020s, NSW might have periods of near-zero wholesale prices (solar noon, etc.). Large-scale hydrogen producers will likely sign cheap power contracts. For simplicity, we’ll use the projected levelized cost of hydrogen that already factors this in (per CEFC/CSIRO data).

**Maritime Labor and Maintenance Costs**

Australia’s labor costs for skilled maritime workers (seafarers, dockworkers, engineers) are high relative to global averages. A vessel on a domestic route with Australian crew can have crew costs 3-5x that of a similar international vessel with Filipino or Eastern European crew. For TCO:

* If focusing on internationally flagged ships that just visit Australia, one might stick with standard international crew costs in OPEX (since the crew isn’t hired at Australian rates). But any maintenance or repair done in Australia will incur Aussie labor rates. For instance, if a ship needs specialized work on fuel cells while at an Australian port, that service could be costly. We might marginally increase maintenance cost assumptions for complex tech to reflect this.
* If considering an Australian-operated ship (e.g. coastal trade), include crew costs at Australian award rates. This could be on the order of AU$2–3 million per year for a large vessel’s crew versus maybe AU$0.5–1m if international. It’s a huge difference in OPEX. This may dominate over fuel savings in some cases, which is one reason coastal shipping struggled. However, advanced tech might allow smaller crew sizes (e.g. highly automated electric ships). Regulations still require minimum manning, but perhaps an electrically propelled ship could reduce the engineering crew number. This is speculative for 2025–2030 though; likely crew count stays similar, so cost stays high for domestic operations.
* Port labor (stevedoring, pilots) are also expensive in Australia. Pilotage and tugs are mandatory in NSW ports; these fees incorporate labor. They are usually in the port fee structure, which we include anyway. Not much difference by fuel type, except if say bunkering ammonia requires longer time or extra safety personnel, the port might charge extra for that service. We should note that *bunkering time* differences could incur port labor or delay costs. E.g., fueling with ammonia might be slower than with fuel oil initially due to safety, meaning more port hours (which cost money). To be safe, we could assume bunkering operations for new fuels either happen concurrently with cargo operations (ideal) or add a slight time penalty.

Maintenance costs should consider the availability of skills and parts in Australia:

* E.g., if a ship has a hydrogen fuel cell, can it find technicians and parts in Sydney? If not, any repair might need flying in experts, adding cost.
* Traditional marine engines have established service networks (e.g. Wärtsilä, MAN have presence in Australia). For batteries or fuel cells, perhaps less so in early years. Possibly assume a higher maintenance contingency for new tech until local capability grows.
* On the flip side, electric motors and batteries could simplify maintenance (less lube oil changes, etc.), providing some savings.

**Port Infrastructure and Readiness**

NSW’s major ports are in varying stages of decarbonization readiness:

* **Shore Power:** As of 2025, only a cruise terminal project is under construction. But by 2026–2027, at least one berth in Sydney (White Bay/Glebe) will supply shore power to cruise and some dry bulk ships ([It's a shore thing shore power comes to Australia](https://www.portsaustralia.com.au/media-centre/its-a-shore-thing-shore-power-comes-to-australia#:~:text=Sydney%20Harbor)) ([It's a shore thing shore power comes to Australia](https://www.portsaustralia.com.au/media-centre/its-a-shore-thing-shore-power-comes-to-australia#:~:text=Shore%20power%20is%20the%20provision,associated%20with%20consumption%20of%20fuel)). Port Kembla is being eyed as a future green hydrogen hub (there are proposals to use it for green steel and hydrogen export). Port of Newcastle is actively planning diversification from coal, including a hydrogen export terminal and possibly ammonia bunkering in the future. For now, we assume minimal existing alt-fuel infrastructure: no widespread LNG bunkering (some LNG-fueled bulk carriers visiting might refuel in Asia instead), no ammonia or hydrogen bunkering yet (would be custom delivery by barge or ISO tanks if at all). So an Australian TCO model must include the **capital expense of new infrastructure** in some form when comparing alternatives:
  + For an electrification case: include cost of installing shore charging at one or more berths. If the scenario is a dedicated coastal vessel, perhaps the company pays for its own charger (include full cost). If it’s an international vessel, maybe the port provides it (cost reflected in electricity price or port fees).
  + For ammonia/hydrogen: likely need new storage tanks, pipelines, safety systems at the port. The cost might be passed into fuel price (which is simplest — assume delivered fuel price already high to pay back infrastructure).
* **Timeline assumptions:** It’s safe to assume no significant ammonia or hydrogen bunkering is operational in NSW before 2027 at earliest (unless a demonstration scale). However, since the model is for decisions by mid-2026, we consider future readiness: i.e., a vessel put in service in 2028 could refuel with ammonia at Newcastle if infrastructure is built by then. In absence of certainty, we might model a scenario where alternative fuel has an *extra logistics cost* in early years (e.g. trucking in fuel from a chemical plant) that diminishes later as proper bunkering comes online.
* **Domestic vs International Nuances:** If a vessel is domestic (stays within Australia), it can theoretically rely entirely on Australian infrastructure. If it’s international, it needs a global network. For example, an ammonia-fueled ship from Newcastle to Japan needs ammonia available in Japan too for return voyage (or carries enough for round trip). One might assume it refuels only in Australia where fuel is cheap (carry double). But many ships prefer refueling at destination if needed. So applicability: If we find an option is great in Australia but the fuel isn’t available at the ship’s other ports of call, that hinders uptake. One might assign a risk or additional cost if fuel must be imported or carried extra.
  + However, the question focus is on NSW ports area, so perhaps looking at ships that largely operate around there. Possibly *coastal or regional trade ships* are of interest, which could refuel only in Australia (problem solved). If looking at international bulk exports, we might assume a world where the destination (e.g. an Asian import terminal) also invests in receiving that fuel (especially if a green corridor partnership exists, as in the WA–Asia corridor concept ([Scholars@Duke publication: Well-to-wake cost and emissions assessments for the Western Australia–East Asia green shipping corridor](https://scholars.duke.edu/publication/1666095" \l ":~:text=international%20%E2%80%9Cgreen%20shipping%20corridor%E2%80%9D%20agreements,to) )).

To capture domestic vs international, the model could have a toggle: e.g. “assume fuel is available only in Australia – yes/no”. If no, then maybe additional costs or not feasible for certain routes.

**Economic Parameters**

Some general parameters to fix:

* **Analysis period** – assume 25 years life for large vessels (consistent with DNV ([What are the total costs of ownership for different methanol-fuelled containership designs?](https://www.dnv.com/expert-story/maritime-impact/commercial-case-study-for-methanol-fuelled-5500-teu-container-vessel/#:~:text=ready%20design%2C%20and%20a%20dual,25%20years%20for%20the%20vessel)) and many studies). Some use 20 years for quicker turnover; we might do 25 as baseline, 20 as sensitivity.
* **Discount rate** – an Australian shipowner might use ~6–10% real discount rate. Government evaluations might use lower (e.g. 4–7%). We can pick, say, 7% real as a mid-point.
* **Inflation** – work in real terms, so no inflation unless we want to nominally escalate fuel prices (which we can do in real growth anyway).
* **Exchange rates** – many sources are in USD or EUR. We should convert to AUD for local decision-making (currently ~1 USD ≈ 1.5 AUD, but use current mid-2025 rate). However, maybe keep USD in calculations if that’s easier and just note conversion, since shipping is global and typically USD-denominated for fuel and ship costs.

In summary, Australian-specific assumptions will mirror global ones but with tweaks:

* Carbon price: likely lower or none in near-term (so base case no carbon tax, but test a moderate one).
* Fuel price: use local renewables advantage (lower e-fuel cost over time).
* Operational profile: focus on Asia-Pacific routes distances and port stays.
* Infrastructure: assume needed port investments happen but incorporate their costs.
* Regulations: follow IMO, expect shore power usage in port by end of decade in NSW, and account for safety rules costs for new fuels.
* Crew: if domestic, high crew cost included; if international, global crew cost but local maintenance cost considered.

The net effect of these Australian parameters will be reflected in the comparative results – for example, the break-even point for hydrogen vs diesel might come a bit sooner in Australia if hydrogen is cheap in NSW, or electrification might be less cost-competitive if our electricity remains relatively expensive. The next section will compare the different fuel/power options under these considerations.

**Comparative Framework: Electrification vs. Hydrogen, Ammonia, Methanol (and Others)**

A core objective is to compare the TCO of various decarbonization options for large vessels. Here we provide a framework comparing **batteries (full electrification)**, **hydrogen**, **ammonia**, **methanol**, and conventional fuel, focusing on their implications for heavy shipping. Other alternatives like *biofuels* and *LNG* are included for context as transitional fuels. Table 3 summarizes key factors for each option:

| **Fuel/Tech Option** | **Energy Density & Storage Impact** | **Fuel & Infrastructure Cost** | **Technology Status (2025)** | **Operational Implications** |
| --- | --- | --- | --- | --- |
| **Conventional (HFO/MGO)** | High energy density (Diesel ~42 MJ/kg); minimal storage impact (well-understood tanks). | Lowest fuel cost per energy currently; MGO ~$700–1000/ton (2025). Infrastructure fully in place worldwide. No new investment needed. | Mature diesel engines; Tier III NOx systems for compliance. | High emissions (CO₂, SOx, NOx) requiring compliance measures. No range anxiety – global bunkering network. |
| **Battery-Electric** | Very low energy density (battery ~0.5 MJ/kg usable); **massive weight/volume** for long range. Best for short routes. E.g. to equal 1 ton of diesel, need ~20+ tons of batteries. | “Fuel” cost is electricity: in Australia maybe $50–150/MWh. But battery pack cost is high (~$100–200/kWh in 2025). Infrastructure: need high-power charging (e.g. many MW capacity at port), grid upgrades. Some renewable integration can lower operating cost. | Batteries mature for small ships (e.g. ferries, tugs). Largest battery vessels ~several MWh installed only (short-range ferries). Tech improving ~5-8% per year in energy density. | Zero tailpipe emissions, very low maintenance (few moving parts). Range is limited: likely <100 nmi for fully electric large ship without recharge. Could work for harbor craft or coastal shuttles that can recharge often. Minimal fuel cost if charging off-peak. Requires schedule flexibility to charge. |
| **Hydrogen (H₂)** | Low volumetric energy density. Even as liquid at -253°C, energy density ~8 MJ/L (vs diesel ~35 MJ/L); gaseous storage (350-700 bar) is bulkier. Expect ~3-5× the tank volume of diesel for same energy. Weight is lighter than batteries, but tank weight not trivial. | Green H₂ cost now high (~A$10-15/kg, equating to $40/GJ) by 2030 with scale ([Australian hydrogen market study](https://www.cefc.com.au/media/nhnhwlxu/australian-hydrogen-market-study.pdf#:~:text=It%20is%20common%20practice%20to,treated%20as%20a%20transition%20fuel)). Liquid hydrogen infrastructure nonexistent in AUS; would require significant investment (liquefiers, cryogenic tanks, handling safety). Alternatively, could store as compressed gas or in metal hydrides – still early stage. Fuel cells expensive. | Prototype stage for ships. Only a few small vessels (and one LH₂ carrier ship demonstrator by Kawasaki). Fuel cell systems (e.g. PEMFC) available in MW-scale, but marine integration ongoing. Combustion engines for H₂ (with spark ignition) being tested, but not commercial yet. | No carbon emissions from use, but **efficiency** varies: fuel cells ~50% efficient, engines ~40%. Likely need dual-fuel or backup due to limited infrastructure. Faster refuel than batteries, but harder than diesel (handling cryogenics or high pressure). Safety: H₂ is very flammable – ventilation and leak detection critical. Could be viable for shorter international routes or regional if fueling stations established (e.g. a Queensland–NSW–NZ hydrogen corridor). Might require dedicating significant space for fuel. |
| **Ammonia (NH₃)** | Moderate energy density as liquid (~12.7 MJ/L at ambient T under slight pressure, or -33°C at atm). About 2× volume of diesel for same energy, but tank can be prismatic (less loss than spherical LH₂). Toxic, so double-walled tanks and ventilation needed, but not high-pressure. Weight penalty less than batteries, volume penalty ~2× diesel. | Green NH₃ cost depends on H₂ cost + conversion; currently high (~$1000+/ton NH₃, ~$55/GJ) but expected to fall possibly to ~$550/ton ($30/GJ) with large projects ([[PDF] The Role of E-fuels in Decarbonising Transport - NET](https://iea.blob.core.windows.net/assets/9e0c82d4-06d2-496b-9542-f184ba803645/TheRoleofE-fuelsinDecarbonisingTransport.pdf#:~:text=NET%20iea,comparable%20with%20the%20higher)). This would be ~2-3× the price of energy in HFO. Infrastructure: no port currently bunkering NH₃ for fuel, but NH₃ is globally traded as commodity (fertilizer) so ports (incl. some in Australia) handle it with terminals – these need upgrades for fueling (loading arms, safety systems). Likely easier to repurpose existing NH₃ terminals than to build LH₂ from scratch. | Engine tech under development: MAN and Wärtsilä plan to commercialize ammonia dual-fuel two-stroke engines by 2024–2025. Ammonia-ready designs are being ordered (90+ ships ammonia-ready in 2022) ([International shipping - IEA](https://www.iea.org/energy-system/transport/international-shipping#:~:text=International%20shipping%20,were%20for%20methanol)). No commercial fuel cells on ammonia yet (some SOFC prototypes). So initial use via ICE. Need NOx control (ammonia combustion can form NOx) and to address ammonia slip. | No CO₂ emissions (if fuel is green). Likely the *preferred option for long-haul by late 2020s* for newbuilds according to IEA and others ([PowerPoint Presentation](https://iea.blob.core.windows.net/assets/deb56090-8d59-4f54-bf02-3651ebbb94ee/ETP2024_Shipping_webinar.pdf#:~:text=Total%20cost%20of%20ownership%20of,30)) ([PowerPoint Presentation](https://iea.blob.core.windows.net/assets/deb56090-8d59-4f54-bf02-3651ebbb94ee/ETP2024_Shipping_webinar.pdf#:~:text=Ammonia%20necessitates%20specific%20safety%20measures,30)), because of better economics for large ships. Toxicity requires strict procedures – crew training, detection, emergency ventilation. Slight efficiency drop vs diesel (lower engine power density). Range comparable to conventional if designed right (as noted, bulk carriers not hugely affected in cargo by 2× volume tanks ([Scholars@Duke publication: Well-to-wake cost and emissions assessments for the Western Australia–East Asia green shipping corridor |

](https://scholars.duke.edu/publication/1666095#:~:text=powered%20vessels%20offer%20the%20lowest,reductions%20within%20the%20WA%E2%80%93EA%20green))). Bunkering could be initially via tanker trucks or barges from existing ammonia plants (Australia has some production, mostly for fertilizer). Over time, dedicated bunker facilities at Newcastle or other major ports could emerge if demand signals. |

| **Methanol (CH₃OH)** | Energy density ~15.6 MJ/L (half of diesel’s 35 MJ/L); requires ~2× volume for same range. But it’s liquid at ambient conditions (flammable liquid, not cryogenic). Tanks need to be compatible (methanol is corrosive to some metals) and larger, but can use existing spaces (e.g. ballast tanks converted). Weight of fuel $400/ton) but not carbon neutral. Infrastructure: easier to handle than LNG/H₂/NH₃ – can be bunkered with minor modifications to fuel terminals. Some ports (in China, N. Europe) already bunkering methanol for the new Maersk ships. Australian ports would need modest tankage and safety (toxic if ingested, but not as bad inhalation hazard as NH₃). | Proven engine tech: Dual-fuel methanol engines (MAN L50ME-LGIM) already in service on tankers and being installed on large newbuild container ships (Maersk’s fleet). These can use methanol or diesel. Retrofit possible on some existing diesel engines. Relative CapEx premium is moderate – DNV found a methanol-fuelled container ship costs only <1% more TCO than conventional ([What are the total costs of ownership for different methanol-fuelled containership designs?](https://www.dnv.com/expert-story/maritime-impact/commercial-case-study-for-methanol-fuelled-5500-teu-container-vessel/#:~:text=Dual,extra%20cost%20but%20greater%20flexibility)), largely because the technology is similar and well-understood. | Carbon-neutral if made from renewable sources (biomass or CO₂ + H₂). Emits CO₂ when burned, but that CO₂ is recycled from atmosphere if fuel is “e-methanol” or bio-methanol. Easy to handle: liquid at room temp, but poisonous and low flashpoint (so still some precautions, similar to handling of gasoline on ships). Methanol has lower combustion efficiency (~specific fuel consumption is higher because of lower energy content), so requires more fuel mass per voyage. But refueling can be done quickly with existing bunkering methods. Suited for both large ships (container lines adopting it) and smaller ones. Possibly the *most practical near-term alternative* due to ease of use, though fuel availability of truly green methanol is limited. | | **LNG (Liquefied Natural Gas)** | Energy density ~22.5 MJ/L (at -162°C); needs insulated cryogenic tanks, ~1.8× volume of diesel for same energy. Tanks often cylindrical, causing some space loss. | Fossil LNG price (energy basis) often lower than diesel, but volatile. LNG infrastructure exists at some ports (none large-scale in NSW yet, but Pilot LNG bunkering could be done by truck from import terminals). CAPEX for LNG tanks and engines is significant. If aiming for GHG reduction, need bio-LNG or e-methane which are expensive and scarce. | Dual-fuel LNG engines are mature (hundreds of ships). Provides ~20% less CO₂ than HFO (due to hydrogen content) but methane slip is a problem (unburned methane leaks can negate GHG benefit). | Often seen as a transitional fuel. In Australia, its role might be limited as the focus shifts to zero-carbon fuels. Could be an option for new ships if immediate NOx/SOx compliance is needed, but long-term viability depends on decarbonized methane. TCO-wise, LNG can sometimes save fuel cost, but the extra CAPEX and methane leakage risk plus eventual carbon pricing on methane may reduce its appeal. | | **Biofuels (HVO, FAME, etc.)** | Similar to diesel (if drop-in); no extra tank needs if blended or straight use in existing engines (with minor modifications). | Currently more expensive than fossil fuel (2-5× depending on source, e.g. $1.5-2.0/L for biodiesel). Limited supply. Could be used as blend (e.g. 5-20%) to reduce lifecycle CO₂. No new infrastructure needed (use existing fuel supply chain). | Already can be used in engines up to certain blends (some ships have trialed B20 or B30). Pure biofuels (HVO) are used in demonstrations. | Easiest implementation (no tech change), but feedstock constraints mean not scalable to entire shipping sector. Possibly a niche solution for early compliance or specific routes (Australia has feedstock like tallow, used cooking oil – but also big road demand for those). TCO could be acceptable if biofuel remains a small fraction or if carbon credits subsidize it. Usually, models include biofuels as an option that has higher fuel cost but low retrofit cost. |

**Table 3:** *Comparison of major fuel/power alternatives for large-scale maritime use, focusing on factors affecting TCO.* Battery-electric is limited by current technology to short-range due to weight/volume. Hydrogen has high infrastructure and fuel costs but zero emissions at use; ammonia appears cost-effective for large ships when produced at scale (despite toxicity requiring safety measures) ([PowerPoint Presentation](https://iea.blob.core.windows.net/assets/deb56090-8d59-4f54-bf02-3651ebbb94ee/ETP2024_Shipping_webinar.pdf#:~:text=Total%20cost%20of%20ownership%20of,30)). Methanol is a convenient liquid fuel with moderate costs and existing tech, making it a viable transition option ([What are the total costs of ownership for different methanol-fuelled containership designs?](https://www.dnv.com/expert-story/maritime-impact/commercial-case-study-for-methanol-fuelled-5500-teu-container-vessel/#:~:text=Dual,extra%20cost%20but%20greater%20flexibility)). LNG and biofuels represent intermediate solutions with partial emissions benefits.

In applying this framework to TCO modeling, each option will have a different cost breakdown profile:

* *Electrification:* High CAPEX (battery + shore power install), low OPEX (cheap electricity, low maintenance), possibly replacement cost for batteries (every 5-10 years the battery may need significant overhaul – include that in lifecycle).
* *Hydrogen (fuel cell):* High CAPEX (fuel cell systems, H₂ tanks), relatively high OPEX due to fuel cost, but no carbon cost. Maintenance could be moderate (fuel cells require stack replacements maybe every few years, which is costly). If hydrogen ICE, CAPEX a bit lower, but then add cost for NOx control.
* *Ammonia:* Moderate-high CAPEX (engine modifications, tank), fuel cost moderate-high but trending down. Likely some carbon cost savings (none for fuel, but if carbon tax on fossil, ammonia is zero-carbon). Possibly slightly higher port fees or training costs due to hazmat handling.
* *Methanol:* Low-medium CAPEX (engines available, just ensure compatible materials), fuel cost moderate (higher than HFO but possibly lower than H₂ per energy). Maintenance similar to diesel (though fuel system components need checking due to corrosion). Net GHG depends on source of methanol (need green source for full benefit).
* *LNG:* Medium CAPEX (dual-fuel engine, cryo tank), fuel cost potentially lower than diesel (depending on scenario), but might incur GHG cost if methane slip is regulated in future. Also, if we include cost of mitigating methane slip (e.g. oxidation catalysts), that’s extra OPEX.
* *Biofuels:* Low CAPEX (drop-in), high fuel cost OPEX, but possibly eligible for credits (if Australian govt gives carbon credit for using biofuel, effectively lowering cost).

One key insight from comparative studies is that **no single alternative clearly outperforms others on cost without conditions**; it varies by vessel size, usage, and assumptions. The IEA found ammonia the cheapest for large ships by 2035 in a zero-carbon scenario ([PowerPoint Presentation](https://iea.blob.core.windows.net/assets/deb56090-8d59-4f54-bf02-3651ebbb94ee/ETP2024_Shipping_webinar.pdf#:~:text=Total%20cost%20of%20ownership%20of,30)), and other studies find methanol advantageous for smaller or near-term due to lower conversion cost ([Shipping Decarbonization Study - MAN Energy Solutions](https://www.man-es.com/discover/shipping-decarbonization-study#:~:text=Shipping%20Decarbonization%20Study%20,limited%20compared%20to%20fuel%20oil)). The Duke/WA study showed even the “best” case (ammonia) had nearly 50% higher TCO than conventional ([Scholars@Duke publication: Well-to-wake cost and emissions assessments for the Western Australia–East Asia green shipping corridor](https://scholars.duke.edu/publication/1666095" \l ":~:text=in%20regards%20to%20dynamic%20loads%2C,lie%20well%20above%20the%20typical) ) absent carbon pricing, highlighting the need for either policy support or further cost reductions.

For an Australian heavy ship context (bulk carriers and container ships around NSW):

* **Ammonia vs. methanol:** It could be that ammonia suits bulkers (where volume for fuel is available and long range is needed to Asia), while methanol might suit some container liners or multipurpose vessels doing shorter regional hops. The model should allow comparing these directly.
* **Hydrogen vs. electrification:** Pure battery-electric probably won’t work for a Newcastle to Asia route – battery would be enormous. But hydrogen fuel cell might, if refueling can be arranged (maybe refuel in Darwin or Cairns en route? Not typical). Perhaps a hybrid approach (battery for port and short range, plus fuel for ocean) could be considered, but that complicates modeling. If looking at intra-Australia (say NSW to QLD trade), then maybe a battery or hydrogen hybrid coastal ship is plausible.
* **Transitional fuels:** The framework should also acknowledge interim solutions like using biodiesel to fuel existing ships while new tech is maturing. This can be a fallback scenario in the model – e.g. what if instead of investing in new tech now, the ship runs on a B50 biofuel blend by 2030 to cut emissions? The TCO might be simpler (just higher fuel cost, no new capex). It may turn out cheaper in the short run but has limitations in scale.

Ultimately, the comparative framework helps stakeholders see **trade-offs**: e.g. ammonia requires dealing with toxicity but offers lower cost per ton of cargo than hydrogen; batteries eliminate fuel cost but are impractical beyond short distances, etc. These trade-offs are not purely monetary, but the TCO model will quantify the monetary aspect while qualitative discussion (safety, maturity) accompanies it. This ensures the technical review committee can make informed decisions not only on financial metrics but on operational feasibility.

**Data Gaps and Uncertainty Management**

No matter how detailed the research, there remain gaps in data and high uncertainty in this emerging area. Identifying these gaps and ways to address them is crucial:

* **Future Fuel Cost Uncertainty:** Perhaps the biggest unknown is how quickly the costs of green fuels (H₂, NH₃, e-fuels) will fall. Projections vary widely. For example, the CEFC study gives ranges for hydrogen cost in 2030 that could differ by factor of two based on electrolyzer deployment and power prices ([Australian hydrogen market study](https://www.cefc.com.au/media/nhnhwlxu/australian-hydrogen-market-study.pdf#:~:text=%E2%80%A2%20Costs%20of%20hydrogen%20technologies,lowest%20cost%20renewable%20energy%20sites)) ([Australian hydrogen market study](https://www.cefc.com.au/media/nhnhwlxu/australian-hydrogen-market-study.pdf#:~:text=It%20is%20common%20practice%20to,treated%20as%20a%20transition%20fuel)). To handle this, the TCO model should allow easy substitution of fuel price assumptions and ideally run sensitivity or scenario analyses. We might incorporate conservative, moderate, and optimistic price cases for each alt fuel, using a range from sources (e.g. IEA’s low and high cases for e-ammonia and e-methanol ([[PDF] The Role of E-fuels in Decarbonising Transport - NET](https://iea.blob.core.windows.net/assets/9e0c82d4-06d2-496b-9542-f184ba803645/TheRoleofE-fuelsinDecarbonisingTransport.pdf#:~:text=%5BPDF%5D%20The%20Role%20of%20E,comparable%20with%20the%20higher))). If possible, applying a Monte Carlo simulation on fuel price (with a distribution anchored by those scenarios) would give a probabilistic view – for instance, “there’s a 30% chance ammonia-fueled ship TCO < 20% above conventional by 2035” etc. Communicating uncertainty is important so decisions are made with awareness of risk.
* **Capital Cost and Learning Rates:** The cost of novel ship technology (fuel cell systems, large batteries, cryogenic tanks) is not well-documented, especially for large deep-sea ships (no one has built a 100 MWh battery ship yet!). We rely on estimates or analogies (e.g. cost per kWh of battery from automotive scaled up, or cost of an LNG tank scaled for H₂). There is a data gap in **real-world cost of converting or building large vessels for these fuels** because so few exist. We should track pilot projects: e.g. when the first ammonia-fuelled ship is built (~2025), get its cost premium data. Until then, we may take sources like the Maersk Center model assumptions or ABS studies. To address future cost reduction, we can apply learning rates: e.g. assume fuel cell cost drops X% per doubling of capacity. If the committee is planning for 2026 decisions on ships that will run through 2040s, it might consider that a ship ordered in 2030 could have cheaper equipment than one in 2025. So include an option to reduce capex for later ships or do sensitivity on “what if fuel cell price drops 50% by 2035”. This avoids either over-penalizing future tech or being overly optimistic.
* **Operational Uncertainties:** Real ship operations can deviate – e.g. a ship might slow steam in a recession (cutting fuel use and costs), or take different routes. The model could allow varying utilization (annual days at sea). For uncertainty, we might consider a few usage scenarios: high utilization (favorable to options with low fuel cost) vs low utilization (favorable to low capex options). Including a **sensitivity to utilization rate** covers uncertainty in market demand for shipping. Similarly, if future regulations impose speed limits (some talk of IMO enforcing slow steaming to reduce emissions), that would reduce fuel consumption and thus reduce the advantage of cheaper fuel options. This could be examined by scenarios of higher vs lower average speed.
* **Residual Value and End-of-Life:** A data gap is what these alternative-fueled ships will be worth at end of life. Will an ammonia-ready ship have scrap value similar to others? Likely the steel is steel, so scrap value per ton is similar. But what about batteries (could be reused or have disposal cost)? Or fuel cell materials (some precious metals)? The model can include a % of initial capex as residual (maybe 10-15% for steel scrap on a normal ship). For batteries, perhaps assume a second-life value or recycling credit if data available (e.g. $50/kWh credit at end). This is minor in total NPV usually, but not negligible. We should note the uncertainty – perhaps just do sensitivity of residual=0 vs some salvage value.
* **Local Data Gaps:** We may find that certain Australian-specific figures are hard to get. For example, **grid connection cost** at ports: how much to install a 10 MW shore power connection? If we cannot get a published figure, we might derive from electrical engineering estimates ($ per MVA of substation, etc.). These approximations can be validated by consulting experts or looking at similar projects overseas (some ports in California and Europe have published costs for shore power installations).
* **Environmental Externalities:** TCO normally doesn’t price in externalities like pollution health costs. But one might argue to consider the avoided cost of emissions (like socio-economic benefit). However, since our focus is primarily the owner’s perspective, we exclude those. We just include whatever cost the owner must internalize (fuel, carbon price if any, etc.). The external benefits (like improved air quality from shore power) are handled via policy incentive perhaps. A gap remains in valuing these co-benefits, but it's outside pure TCO unless the owner gets some reward (like a port fee reduction for zero-emission).
* **Model Validation:** With any model, especially one forecasting into new tech, validation is tough because of lack of historical cases. One approach: test the model on known scenarios (e.g. a conventional diesel ship vs. an LNG dual-fuel ship which there is data for) to see if it matches known cost differences. If our model reasonably replicates say an LNG vs HFO cost comparison from an actual case, that builds confidence. So, we should gather any available case studies (maybe an Australian LNG-fueled ferry project) for calibration. If none domestic, use international ones.
* **Stakeholder Input:** Data gaps can be filled or at least bounded by consulting with industry stakeholders – e.g. asking engine manufacturers, fuel suppliers, or port engineers for their estimates. For example, what do port authorities estimate for ammonia bunkering facility cost? Those insights, even if not published, can guide assumption ranges. Given the timeline to 2026, part of developing the TCO framework could involve industry workshops to refine assumptions with those who have partial knowledge or strong opinions.

Finally, documenting uncertainty clearly in the report to the committee is important. We might present results like: “Under central assumptions, ammonia-fuelled bulkers have a 30% higher TCO than diesel; however, under a favorable green fuel cost scenario (cheap renewables, carbon price), they could be only 10% higher – or conversely 50% higher if tech costs don’t fall () ([Scholars@Duke publication: Well-to-wake cost and emissions assessments for the Western Australia–East Asia green shipping corridor](https://scholars.duke.edu/publication/1666095" \l ":~:text=powered%20vessels%20offer%20the%20lowest,reductions%20within%20the%20WA%E2%80%93EA%20green) ).” By quantifying a range (perhaps with error bars or scenario bands on charts), we convey that the model is not a precise prediction but a decision support tool that can adapt as real data emerges.

To address data gaps over time, we recommend establishing a process to **update the TCO model regularly (e.g. annually)** as new information comes in (fuel prices, technology performance from pilots, etc.). By mid-2026, we expect more real-world data from pilot projects (perhaps the first ammonia engine running on a ship, the first large hybrid vessel in Australia, etc.), which can be incorporated. In the meantime, using conservative assumptions ensures that if an alternative shows promise even under conservative inputs, it’s likely a solid bet.

**Conclusions and Recommendations**

Transitioning Australia’s heavy shipping sector to low or zero emissions is a complex but attainable goal, and a robust TCO modeling framework is essential to guide decision-making. In this research, we reviewed leading international TCO models and found common cost structures and methods that can be tailored to the Australian context. **Fuel costs** (especially for hydrogen, ammonia, and other e-fuels) and **capital expenses** for new technologies are the dominant factors, with fuel potentially making up over half of total costs in a vessel’s life ([What are the total costs of ownership for different methanol-fuelled containership designs?](https://www.dnv.com/expert-story/maritime-impact/commercial-case-study-for-methanol-fuelled-5500-teu-container-vessel/#:~:text=Key%20influential%20cost%20factors%20identified)). Models consistently show that without interventions like carbon pricing or fuel cost breakthroughs, alternative fuels still come at a premium () ([Scholars@Duke publication: Well-to-wake cost and emissions assessments for the Western Australia–East Asia green shipping corridor](https://scholars.duke.edu/publication/1666095" \l ":~:text=powered%20vessels%20offer%20the%20lowest,reductions%20within%20the%20WA%E2%80%93EA%20green) ) – for instance, around 30–50% higher TCO for green ammonia or methanol versus today’s fuels in the near term. However, Australia’s favorable renewable energy resources and port initiatives could shrink this gap domestically faster than the global average, by providing relatively cheaper green fuel and electricity and by mitigating infrastructure barriers (e.g. early shore power adoption).

To support an Australian-specific TCO model, we recommend:

* **Using Local Data and Scenarios:** Populate the model with Australian figures for fuel prices, electricity costs, port fees, and vessel operations. For example, use AEMO’s NSW electricity outlook for shore power costs, and consider Australian-produced hydrogen at projected **<$3/kg by 2030** in an optimistic scenario ([Australian hydrogen market study](https://www.cefc.com.au/media/nhnhwlxu/australian-hydrogen-market-study.pdf#:~:text=It%20is%20common%20practice%20to,treated%20as%20a%20transition%20fuel)). Develop a set of scenarios relevant to NSW trade: e.g. *Base Case* (no carbon price, moderate fuel costs), *Green Push* (high carbon price or strict IMO targets, low renewable costs), and *Slow Transition* (prolonged high alt-fuel costs). This will bracket the possible futures.
* **Inclusive Cost Categories:** Ensure the model covers all cost components identified: initial capex (with retrofit costs if converting existing ships), operating costs (crew, maintenance, port fees), fuel costs, financing, and infrastructure. Explicitly include the cost of meeting regulations (e.g. add cost for NOx control on ammonia engines, or the small cost of installing shore power capability which could be offset by lower port emissions fees if any). The breakdown will help stakeholders see which cost drivers matter most under each scenario.
* **Appropriate Methodology:** We advise using an **NPV-based approach** for rigor, combined with annual cashflow outputs for transparency. The model should be able to compute a lifecycle cost and also translate it into metrics like cost per annum and cost per tonne of cargo. Employ a **discount rate** reflective of the stakeholder (for government evaluation a lower rate might be used, for a private shipowner higher). Present results both with and without a carbon price to illustrate its impact, since policy is a key lever (as demonstrated by MAR-E-Fuel’s findings on CO₂ tax ()). A Monte Carlo simulation can be an extension for later analysis, but initially, clear scenario outcomes will suffice.
* **Comparison of Options:** Provide a comparative dashboard – e.g. a table or chart – for NSW’s technical review committee that shows, for a reference vessel (say a Newcastle–Asia bulk carrier and a Sydney coastal container feeder), the TCO of each option (diesel, LNG, methanol, ammonia, hydrogen, electric) under the chosen scenarios. Highlight the least-cost option in each scenario and how far others are from it (percentage difference). Also highlight emissions reductions corresponding to each (even if outside pure TCO, it’s crucial context – e.g. ammonia gives ~90% GHG reduction ([Scholars@Duke publication: Well-to-wake cost and emissions assessments for the Western Australia–East Asia green shipping corridor](https://scholars.duke.edu/publication/1666095" \l ":~:text=in%20regards%20to%20dynamic%20loads%2C,lie%20well%20above%20the%20typical) ) whereas LNG gives maybe 10-20% reduction). This frames the cost of decarbonization. For instance, if ammonia costs 40% more to achieve 90% emissions cut, that might be palatable if carbon pricing or other incentives cover that 40%. If batteries are impractical for the route, note that qualitatively even if their TCO might look low in a model if one assumed unrealistic charging, etc.
* **Address Data Gaps:** Immediately start collecting and refining data for uncertain parameters. Engage with Australian port authorities (e.g. Port of Newcastle, which is studying alternative fuels) and agencies like CSIRO’s maritime research to fill gaps. For now, use conservative estimates for unknown costs (err on higher side for alt-fuel tech costs, and on lower side for future carbon prices, to avoid underestimating TCO gaps). Plan to update the model as pilot projects (like the first ammonia-fueled ship visits or the outcome of the Sydney shore power installation) provide real data by 2025–2026.
* **Policy and Incentive Integration:** While the TCO model itself outputs costs, the analysis should integrate how incentives could shift these. For example, if the government provided a subsidy for first-movers (say funding 50% of the incremental cost of an ammonia engine or installing a hydrogen bunker at Port Kembla), how does that change TCO? A section of the report can outline what support is most impactful (our review suggests onshore infrastructure investment is key ([New fuels: Total cost of operation | Global Maritime Forum](https://globalmaritimeforum.org/insight/new-fuels-total-cost-of-operation/#:~:text=,1)), as well as carbon pricing to close the fuel cost gap ()). These insights will help the review committee link the TCO findings with policy recommendations.
* **Focus on Use-Cases:** Tailor the recommendations to specific use-cases: e.g. *“For bulk export routes from NSW (coal, grain, etc.), ammonia-fueled newbuilds appear to be the most promising from a TCO perspective by the late 2020s if fuel production projects proceed, offering deep emissions cuts at a green premium of ~30-50% ([Scholars@Duke publication: Well-to-wake cost and emissions assessments for the Western Australia–East Asia green shipping corridor](https://scholars.duke.edu/publication/1666095" \l ":~:text=in%20regards%20to%20dynamic%20loads%2C,lie%20well%20above%20the%20typical) ) that could be mitigated by future carbon pricing or fuel cost declines. For shorter coastal or regional trades, methanol or hybrid-electric solutions might be more practical due to easier fueling and lower capex, despite offering smaller emissions reductions per vessel.”* By framing in this way, the committee can consider different recommendations for different vessel segments.

In conclusion, the development of an Australian-specific maritime TCO model will enable evidence-based decisions on vessel electrification and alternative fuels for the coming decades. By leveraging global best practices and local data, the model will illuminate the cost trade-offs and requirements to make zero-emission shipping a reality for NSW’s ports. The comparative analysis underscores that **ammonia and methanol are frontrunner fuels** for large vessels in the 2030 timeframe ([PowerPoint Presentation](https://iea.blob.core.windows.net/assets/deb56090-8d59-4f54-bf02-3651ebbb94ee/ETP2024_Shipping_webinar.pdf#:~:text=Total%20cost%20of%20ownership%20of,30)) ([What are the total costs of ownership for different methanol-fuelled containership designs?](https://www.dnv.com/expert-story/maritime-impact/commercial-case-study-for-methanol-fuelled-5500-teu-container-vessel/#:~:text=Dual,extra%20cost%20but%20greater%20flexibility)), while batteries and hydrogen will likely play niche roles unless there are dramatic technology leaps. There is no one-size-fits-all solution – hence a flexible TCO framework is needed. With this tool and continued data updates, Australia’s maritime sector can chart a economically sound course toward its 2050 decarbonization ambitions, identifying where government or industry investment is most needed to close the cost gap and where early adoption makes sense despite uncertainties. The outcome will be a strategic, cost-informed pathway to cleaner shipping around Australia’s shores.

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