CBA OF SUSTAINABLE PROPULSION OPTIONS FOR VANCOUVER ISLAND'S PASSENGER RAIL CORRIDOR (DIESEL, HYBRID, HYDROGEN)

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Abstract – Vancouver Island's 225 km rail corridor presents an opportunity to reintroduce passenger service with modern, sustainable propulsion. This report evaluates three options – conventional diesel, diesel-hybrid, and hydrogen fuel cell trains – comparing capital costs, operating costs, emissions, and lifecycle economics over 30 years. Prior cost modeling is integrated with fleet scaling scenarios (6, 12, 20 trains) to project capital expenditure (CAPEX) needs for rolling stock and infrastructure. A detailed emissions analysis quantifies *well-to-wheel* CO_2, NO_x, and PM for each technology per km and per year, monetizing externalities via social carbon costs and health impact valuations. We then synthesize total lifecycle costs (TCO) combining CAPEX and operational expenditure (OPEX), including scenario analysis for fuel prices, maintenance schedules, and technology improvements. Finally, phased adoption strategies (diesel → hybrid → hydrogen) are presented with investment timing and infrastructure staging aligned to CleanBC 2030 and Canada's 2050 net-zero goals. The analysis finds that diesel traction offers lowest upfront cost but highest emissions; hydrogen trains achieve zero on-board emissions and deep GHG reductions, though with high initial investment; and hybrid diesel-battery systems provide an interim solution with moderate cost and emissions benefits. A phased approach is recommended: near-term diesel/hybrid service to kickstart operations and build ridership, followed by transition to hydrogen propulsion as technology matures and costs decline, positioning the Island rail for long-term sustainability and policy alignment.

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Introduction

The former VIA Rail Malahat (Budd RDC diesel railcar) at Parksville in 2006. Passenger service on Vancouver Island's 225 km rail line from Victoria to Courtenay ended in 2011 due to track disrepair[1][2]. Revitalization plans envision new rolling stock and infrastructure upgrades to reintroduce regional rail service.

Rail transportation is integral to sustainable mobility, and Vancouver Island's dormant Esquimalt & Nanaimo (E&N) corridor offers a prime candidate for low-carbon transit revival. The corridor spans 225 km from the capital Victoria in the south to Courtenay in the north (with a branch to Port Alberni), connecting major communities along the Island. Service was discontinued in 2011 amid safety concerns over the aging track, leaving the Island without passenger rail[1][2]. Recent proposals highlight both the demand and challenges of restoration: the Island Corridor Foundation's 2022 business case estimated **C$431 million** total investment (C$381 M in track rehabilitation and C$50 M in trains) to relaunch combined passenger and freight service, aiming for operating cost breakeven around $12.8 M per year[3]. This plan assumed conventional diesel rolling stock (e.g. refurbished or new diesel multiple units), which represents the most straightforward and lowest-cost path to service resumption. However, diesel propulsion runs counter to British Columbia's CleanBC climate strategy and Canada's net-zero 2050 commitments, due to diesel's greenhouse gas (GHG) emissions and air pollution.

To future-proof the Island rail project, stakeholders are considering **sustainable propulsion alternatives**. Two prominent options are **hydrogen fuel cell trains** – which use on-board hydrogen to produce electricity with zero tailpipe emissions – and **diesel hybrid trains** – which augment a diesel engine with battery storage for regenerative braking and peak shaving. These technologies promise environmental benefits: hydrogen trains eliminate on-board CO_2, NO_x, and particulate emissions, and hybrids can significantly cut fuel consumption and pollution. Yet they also involve higher upfront costs and new infrastructure (especially for hydrogen). Decision-makers face a complex trade-off between short-term capital efficiency and long-term sustainability.

This report provides a comprehensive analysis of **diesel vs. hybrid vs. hydrogen propulsion** for Vancouver Island's rail corridor. We evaluate each option across key dimensions:

- **Capital Expenditure (CAPEX):** Vehicle procurement costs for each technology and required infrastructure investments (from diesel fueling tanks to hydrogen refueling stations), including scaling of costs for different fleet sizes (6, 12, 20 trains) to meet various service levels. Quantitative cost tables are presented for rolling stock and infrastructure under each scenario.

- **Operational Expenditure (OPEX):** Ongoing costs of fuel/energy and maintenance for diesel, hybrid, and hydrogen trains. We compare fuel prices (diesel vs. hydrogen per energy unit) and consumption, relative efficiency (e.g. fuel cell efficiency vs. diesel engine), and maintenance differences (routine servicing, overhauls, component lifetimes). This section incorporates uncertainty in fuel price trajectories and potential cost reductions in emerging technologies.

- **Emissions Analysis:** A detailed breakdown of **tailpipe and life-cycle emissions** for each propulsion system – including carbon dioxide (CO_2), nitrogen oxides (NO_x), and particulate matter (PM). We calculate emissions per km and per year for typical operations on the Island corridor. Critically, we monetize these emissions' externalities using a **social cost of carbon** (for CO_2) and health damage costs for NO_x and PM pollution, to illustrate the societal impact of each option in dollar terms. This provides an "external cost" perspective to complement the direct financial costs.

- **Lifecycle Cost Analysis (Total Cost of Ownership):** A 30-year total cost of ownership comparison, integrating CAPEX and discounted OPEX (fuel + maintenance) for each option. We examine net present costs under baseline assumptions, then perform scenario analysis: e.g. a high fuel price scenario (reflecting potential carbon taxes or oil price spikes), accelerated technology improvement scenario (lower hydrogen costs, longer fuel cell life), and varying maintenance schedules. This illustrates which technology minimizes long-term costs under different futures.

- **Deployment Scenarios and Phased Adoption:** Given the differing readiness levels, we outline possible *phased implementation strategies*. One scenario is an initial diesel or hybrid fleet to start service by the late 2020s, followed by gradual adoption of hydrogen trains in the 2030s as costs fall – aligning with CleanBC goals to decarbonize transport by 2040. We consider infrastructure staging (e.g. building a hydrogen fueling facility in phases, starting with a pilot project on a portion of the line[4]) and fleet replacement timing to minimize stranded assets. Policy drivers such as CleanBC's Low Carbon Fuel Standard and federal clean fuel incentives are noted in shaping the transition schedule.

By structuring the analysis in this way, the report aims to inform decision-makers of the **trade-offs** involved: Diesel is a proven, low-cost baseline but with high climate and health costs; hydrogen offers transformative emissions benefits but at high upfront expense; hybrids serve as a near-term bridge, mitigating emissions while leveraging existing infrastructure. The overarching goal is to identify a **pathway for Vancouver Island rail** that balances economic viability with environmental stewardship, ultimately supporting regional and national decarbonization commitments.

Capital Expenditure (CAPEX)

Capital costs encompass the procurement of rolling stock (trains) and the construction of any new supporting infrastructure. We compare the upfront costs for diesel, hybrid, and hydrogen options, including how costs scale with fleet size. Vancouver Island's corridor will likely require multiple train sets to provide daily service (the exact number depends on frequency and schedule; we examine 6, 12, and 20 train scenarios for illustration). Table 1 summarizes the *order-of-magnitude* CAPEX for each technology at these fleet sizes, based on current industry data:

Table 1 – Estimated Capital Costs by Fleet Size and Propulsion Option (in millions of Canadian dollars, CAD)

Fleet Size	**Diesel** (baseline) – Diesel multiple units or locomotives + minimal infra	**Hybrid** (diesel-battery) – Vehicles + minimal infra	**Hydrogen Fuel Cell** – Vehicles + H_2 fueling infra
6 trains	~\$30 M vehicles (6× ~\$5 M each) + ~\$2 M fueling depot = **\$32 M**	~\$36 M vehicles (6× ~\$6 M) + ~\$2 M = **\$38 M**	~\$60 M vehicles (6× ~\$10 M) + ~\$15 M H_2 station = **\$75 M**
12 trains	~\$60 M vehicles + ~\$2 M = **\$62 M**	~\$72 M vehicles + ~\$2 M = **\$74 M**	~\$120 M vehicles + ~\$15 M = **\$135 M**
20 trains	~\$100 M vehicles + ~\$2 M = **\$102 M**	~\$120 M vehicles + ~\$2 M = **\$122 M**	~\$200 M vehicles + ~\$15 M = **\$215 M**

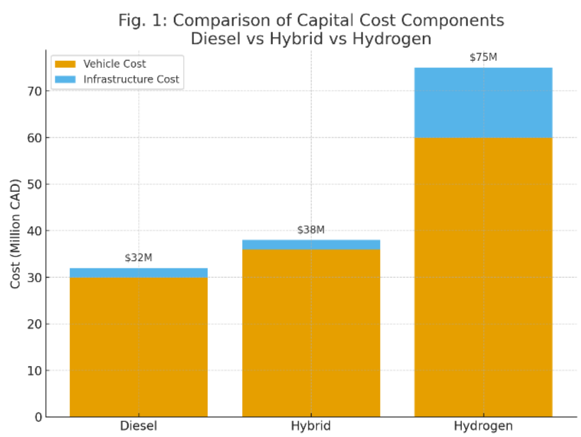
Assumptions: Diesel unit cost ~\$5 M (modern passenger DMU or locomotive+coaches)[5]; Hybrid unit cost ~20% higher (battery system adds cost)[6][7]; Hydrogen unit cost ~2× diesel in early market[8][9]. Hydrogen infrastructure (electrolyzer, storage, dispenser) is a significant fixed cost (assumed ~\$15 M for one fueling station adequate for the fleet)[10][11]. Diesel/hybrid assume existing or low-cost fueling facilities (~\$2 M allowance for diesel fuel tanks/pumps or minor charging setup). These estimates are illustrative for comparison; actual costs would be refined by detailed engineering studies and procurement.

As Table 1 indicates, **diesel has the lowest upfront cost**: it is a **mature technology with established supply chains** and requires virtually no new infrastructure beyond track rehabilitation. A new diesel multiple-unit (or locomotive) for passenger service typically costs on the order of \$5 – 6 million, though prices vary by specifications[5]. For example, recent North American passenger diesel locomotives (e.g. Tier 4 compliant, ~3200 HP) can be in the \$5 M+ range each, and self-propelled diesel train units similarly range in the high single-digit millions. In the Island Corridor Foundation plan, ~\$50 M was budgeted for rolling stock to cover the initial service[3], consistent with acquiring roughly 6–8 diesel railcars or locomotives. Because diesel rolling stock can use **existing fuel infrastructure**, additional capital for fueling is minimal – typically just on-site fuel storage tanks or using tanker trucks for refueling, which are relatively inexpensive (on the order of 1–2% of rolling stock cost)[10][11]. Thus, the diesel option benefits from economies of scale and decades of industry experience, yielding the **lowest CAPEX per train** of the three options[12].

Hydrogen fuel cell trains require the highest CAPEX due to both **vehicle cost premiums and new infrastructure**. Hydrogen rail technology is in early commercialization; initial units (such as Alstom's Coradia iLint) have been sold at significantly higher prices than diesel equivalents due to small production volumes and complex components (fuel cells, high-pressure H_2 tanks, battery buffers)[13][14]. First-of-a-kind orders in Europe have indicated unit costs easily 50–100% above diesel. For instance, one European tender came in at ~€66 M for four hydrogen trains plus a fueling station[15][16], implying perhaps ~€15 M per train when infrastructure is included – several times the cost of a diesel unit. While costs are expected to come down with scale (industry roadmaps target <50% premium, e.g. a hydrogen train for ~\$4.5 M if a diesel is \$3 M)[17], current hydrogen rolling stock is **approximately double the cost of diesel** on a per-unit basis. In Table 1 we assumed ~$10 M per train as a representative figure. Moreover, adopting hydrogen propulsion necessitates building fueling infrastructure from scratch: compressing or liquefying equipment, storage tanks, and dispensers at a minimum, and possibly an on-site hydrogen production facility (electrolyzer) if delivering hydrogen by truck is not viable[10][18]. These **infrastructure costs are substantial**, often in the tens of millions even for a single station[19]. For example, the €66 M project above explicitly included one hydrogen refueling station[19]. In Canada, recent hydrogen rail and bus pilots have similarly required multi-million-dollar investments in fueling sites. Notably, infrastructure costs do not scale linearly with fleet size – a single station can often fuel multiple trains – so larger fleets improve the per-train cost efficiency of hydrogen. This is reflected in Table 1: the 6-train hydrogen scenario costs ~2.3× the diesel scenario, whereas the 20-train scenario is ~2.1×, slightly narrowing the gap as the fixed station cost is spread out. Still, **hydrogen remains the highest-CAPEX choice** for any given fleet size in today's terms. Decision-makers must plan for a significant upfront investment if pursuing hydrogen, potentially seeking government funding or public-private partnerships (as has been done in Europe) to share the infrastructure cost burden[19].

Hybrid diesel-battery trains fall in between diesel and hydrogen on CAPEX. A hybrid locomotive or train set is essentially a diesel-electric vehicle with an added high-capacity battery and power electronics. This yields a moderately higher vehicle cost – roughly **10–30% premium over a standard diesel** according to industry examples[6][7]. The premium depends on the size of the battery (which drives cost) and whether the unit is a new purpose-built hybrid or a retrofit. Some hybrid retrofits have been achieved cost-effectively by repurposing older locomotives and adding battery modules, leveraging the sunk cost of the existing vehicle[6]. For planning purposes we assumed ~\$6 M per hybrid unit vs \$5 M for diesel (i.e. ~20% more). Importantly, **infrastructure needs for hybrids are minimal** – they continue to use diesel fuel, so they can refuel at the same diesel infrastructure (no new fuel type). If a hybrid design is "plug-in" (able to recharge batteries from the electrical grid when idle), there would be some cost to install charging stations at depots, but these are relatively minor (e.g. installing industrial power outlets or small charging pads, likely a few hundred thousand dollars, not tens of millions)[20][11]. In many cases, hybrids recharge on-board via the diesel engine and regenerative braking, avoiding even that requirement[21]. Thus, the **incremental CAPEX for hybrids is limited to the vehicle premium**, making it an attractive lower-risk investment. In Table 1, the hybrid option is only ~20–25% costlier than diesel for equivalent fleet sizes – a meaningful difference, but far less than the hydrogen jump. This middle-ground cost profile is a key reason hybrids are seen as a transitional step: they require **much less upfront investment** than hydrogen to achieve some emissions benefit, which can be crucial for budget-constrained projects.

To summarize CAPEX findings: Diesel is cheapest and leveraged by existing infrastructure (the Island corridor's restoration would predominantly be civil works on track rather than new tech infrastructure). Hydrogen demands the largest capital outlay – new high-tech trains plus fueling facilities – although costs are projected to decline with commercialization. Hybrids offer a compromise, with only modest cost increase over diesel and no major infrastructure build-out needed. Figure 1 illustrates the CAPEX comparison by option, normalized for a common fleet size, showing the vehicle and infrastructure components:



Notes: The Island rail revival also incurs large capital costs common to all options – notably **track and structure upgrades** (e.g. replacing rails, bridges, signaling) which in the ICF proposal were estimated at \$381 M[3]. These costs are independent of propulsion choice and thus omitted in the above comparison, which focuses only on the differential costs attributable to diesel vs hybrid vs hydrogen trains. In practice, a decision to pursue hydrogen might slightly increase project scope (for example, constructing an electrolyzer plant on Vancouver Island, or reinforcing electric supply for it), whereas diesel or hybrid would not. Such considerations would be part of a detailed implementation plan.

Operational Expenditure (OPEX)

Operational costs include **fuel/energy consumption and maintenance** over the system's life. These costs ultimately determine economic sustainability – a train that is cheap to buy but very expensive to run may be less attractive in the long term. We compare OPEX for diesel, hybrid, and hydrogen trains, highlighting how fuel price volatility and efficiency differences impact each option, as well as maintenance routines and their costs.

Fuel and Energy Costs

Fuel is typically the largest component of train OPEX. Diesel fuel has been the standard: it's widely available and energy-dense, but its price can fluctuate with global oil markets. Hydrogen as a fuel is currently more expensive per unit energy, but fuel cell trains are more efficient at converting energy to motion, partially offsetting the price gap[25][26]. Hybrid trains still use diesel but at a reduced rate, translating directly into fuel cost savings proportional to the fuel economy improvement.

Diesel Fuel Costs: For context, a typical diesel passenger train might consume on the order of **2–4 liters of diesel per km** (exact consumption depends on train weight, speed profile, and stops). At a diesel price of, say, \$1.00 per liter (roughly \$3.78/US gallon), that equates to \$2–\$4 per km in fuel cost. Over a 225 km one-way trip, fuel expense would be around \$500–\$900. If a train runs a round-trip daily (450 km), annual fuel costs can exceed \$150,000 per train (assuming ~330 operating days). In a multi-train operation, this scales up quickly – e.g., a fleet of 6 trains each running ~150,000 km per year could incur on the order of **\$0.9 million/year** in diesel fuel costs at these prices. Notably, fuel can represent **~70–80% of total OPEX** for diesel rail operations[27]. For instance, U.S. freight rail studies found fuel was ~80% of life-cycle operating cost for locomotives running ~150,000 miles/year[27]. Diesel prices in BC and Canada are also rising with carbon taxes; the federal carbon price is set to reach \$170/tonne by 2030, adding roughly 45¢ per liter to diesel by that time. Thus, while diesel fuel has historically been affordable, future policy and market shifts could significantly increase diesel OPEX.

Hydrogen Fuel Costs: Hydrogen contains plenty of energy (1 kg H_2 ≈ 1 U.S. gallon of diesel in energy content), but today's hydrogen fuel (especially "green" hydrogen from renewables) costs anywhere from \$5 to \$15 per kg in most regions – much higher than the equivalent cost of diesel per energy unit[28][26]. However, hydrogen trains can use energy more efficiently: a fuel cell-electric drivetrain can achieve **50% or higher efficiency** from fuel to wheel, compared to a diesel engine's ~35–40% thermal efficiency[25]. This means **less fuel energy is needed** for the same work. If a diesel train uses 1 gallon to go a certain distance, a hydrogen train might use only ~0.8 kg H_2 to cover that distance[26]. In cost terms, if diesel is \$1/L (\$3.78/gal) and hydrogen is \$10/kg, the diesel costs \$3.78 for that distance while hydrogen costs \$8 – still over 2× more. Clearly, at today's prices hydrogen fuel would significantly raise OPEX. But future projections are optimistic: the Hydrogen Council forecasts bulk green hydrogen costs as low as \$1.5–\$2/kg in favorable markets by 2030[29]. If realized, hydrogen fuel cost per km could **drop below diesel's**. Another important factor is carbon pricing: diesel's effective cost per liter will rise with carbon taxes, whereas green hydrogen (zero-carbon) would not incur those costs. A European analysis found hydrogen trains become economically favorable if diesel prices exceed ~€1.35/L (~\$5.75/gal) and electricity for H_2 is cheap (~€50/MWh)[30]. In other words, **in a scenario of high diesel prices (or taxes) and declining hydrogen costs, hydrogen train**

OPEX can beat diesel[31][32]. Regions with aggressive carbon policy and cheap renewable power are approaching that crossover. British Columbia is a relevant case: BC's hydroelectricity is low-cost and low-carbon, and the province's Low Carbon Fuel Standard and carbon pricing make conventional diesel more costly over time. By the mid-2030s, hydrogen fuel in BC could be much cheaper than today, especially if produced with abundant off-peak hydro or wind power. For planning, it's prudent to consider **two hydrogen OPEX scenarios** – a high scenario (H_2 \$10/kg) where fuel cost per km is ~2× diesel's, and a low scenario (H_2 \$3/kg with policy support) where hydrogen OPEX could be on par or lower than diesel's. In any case, fueling a hydrogen train requires ensuring supply: either on-site production (with electricity costs) or delivered hydrogen (with supplier margins). These logistics need to be built into operating plans.

Hybrid Fuel Costs: A hybrid diesel-battery train uses the same diesel fuel but more frugally. By regenerating braking energy and optimizing engine usage, hybrids can **cut fuel consumption by 20–50%** depending on service patterns[33][34]. For example, in stop-and-go commuter service with many braking opportunities, fuel savings at the upper end (~50%) have been observed[35]. On a more moderate intercity route like Victoria–Courtenay with fewer stops, savings might be around 20–30%. Even a 30% reduction in fuel use means a 30% reduction in fuel cost – effectively if diesel was \$1/L, the hybrid's net fuel cost is like paying \$0.70/L for the same work[36][37]. This is a significant operating advantage. Moreover, **hybrids reduce exposure to fuel price volatility** – if prices spike, the absolute increase in cost is less when you're burning less fuel. In our earlier example (6 trains, \$0.9 M/year diesel cost), a 30% savings would save about \$270k per year. In fact, one can compute a simple payback on the hybrid investment: if each hybrid unit costs \$1 M more upfront than diesel and saves \$0.27 M/year in fuel, the payback is ~4 years; if it saves \$0.45 M/year (50% fuel cut), payback is ~2 years. These are rough numbers, but they illustrate why **hybridization can be economically attractive** even aside from environmental benefits[38]. It should be noted that if a hybrid train requires electricity from the grid (some can optionally plug in), the cost of that electricity is much lower per energy unit than diesel fuel, further reducing OPEX. For instance, charging with BC Hydro's clean electricity at say \$0.10/kWh would cost only \$2.78 per equivalent gallon of diesel (since 1 gal diesel ~37 kWh energy). In practice, most hybrids would use self-charging, but the option exists for further OPEX optimization if infrastructure is added.

In summary, **diesel OPEX is dominated by fuel cost**, which is moderate now but expected to rise, **hydrogen OPEX is currently higher** but could decline drastically with technology and policy (potentially undercutting diesel in a decade or two), and **hybrid OPEX is essentially a discounted diesel cost** thanks to fuel savings. Figure 2 shows an illustrative comparison of per-km fuel costs under different price assumptions:

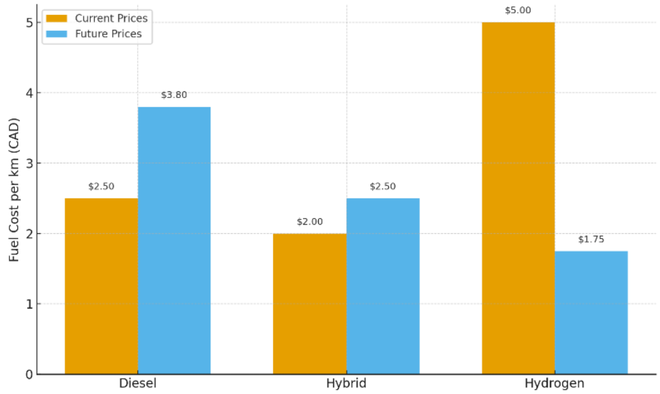


Fig. 2: Fuel Cost per Kilometer by Propulsion Type
Current vs Future Scenarios

Maintenance Costs

Maintaining trains is the other key OPEX element. It includes routine servicing (inspections, oil changes for diesel engines, etc.), corrective repairs, and major overhauls or component replacements over the life of the train. The maintenance profile differs significantly between diesel, hybrid, and hydrogen technologies:

- **Diesel:** A conventional diesel locomotive or DMU has a well-understood maintenance regime. This typically involves **frequent engine maintenance** – e.g. oil and filter changes every few weeks, engine inspections, and periodic heavy overhauls (a diesel engine might be rebuilt or replaced after, say, 20,000–30,000 hours of operation). Other mechanical systems (cooling, turbochargers) and the electrical transmission (generators, traction motors) also require upkeep. For budgeting, a common rule of thumb for North American diesel locomotives is maintenance costs around **\$0.20–\$0.30 per km** (or per mile, some sources say \$0.50–\$0.80 per mile)[39][40]. For a passenger DMU running ~100,000 km/year, that would be on the order of \$20k–\$30k per year in parts and labor (not including fuel). In practice, maintenance cost scales with usage and the complexity of the machinery. Modern diesel engines with emissions aftertreatment (catalysts, diesel exhaust fluid systems, etc.) require additional care to keep those systems functioning (e.g. replacing catalyst elements, refilling urea). Overall, diesel maintenance is a steady, significant cost, but the industry is experienced in managing it and parts/skills are readily available[41].

- **Hybrid:** A hybrid diesel-battery train still contains a diesel engine, so it inherits much of the maintenance requirements of a diesel – but with an important caveat: if the hybrid strategy reduces engine run hours and stress, **engine wear-and-tear is reduced**[42][43]. For example, hybrids can shut the engine off during idle or low-power coasting and use battery power, meaning the engine accumulates fewer hours. Over a year, a hybrid locomotive might see, say, 30% fewer engine hours for the same mileage. This can extend the time between major overhauls. Additionally, hybrids experience less brake wear since regenerative braking takes some load – savings on brake pads and wheel maintenance have been noted in hybrid pilot programs[44][45]. On the flip side, hybrids introduce **battery maintenance**: while batteries generally need little day-to-day servicing, they have a finite life (perhaps 5–8 years in heavy rail use). Eventually, battery modules will need refurbishment or replacement, which is a sizeable expense (though battery costs are dropping over time). One might treat battery replacements as a periodic CAPEX rather than annual OPEX. Some studies have suggested overall maintenance cost for hybrids is similar to diesel, or slightly lower, if fuel savings do not come at the expense of frequent battery issues[46][47]. Real-world data is still limited, but early results show **no major maintenance penalty for hybrids** – they may even save on engine and brake maintenance. Rail operators would need to train maintenance staff on high-voltage battery systems and take safety precautions, but those are manageable steps (battery-electric buses and trains provide a precedent).

- **Hydrogen:** A hydrogen fuel cell train has a **drastically different maintenance profile**. It eliminates the diesel engine and its complex mechanical subsystems (no oil changes, no pistons, no emissions aftertreatment), relying instead on fuel cell stacks, electric motors, and electronic controls[48][49]. Electric traction systems (motors, inverters) are generally low-maintenance compared to diesel engines, since they have few moving parts and no combustion. The main new component is the **fuel cell stack**, which slowly degrades and will require replacement or refurbishment after a certain lifespan (measured in operating hours). Current fuel cell lifetimes for rail are improving; targets are around **30,000 hours by 2030** for fuel cell stacks[50]. If a train operates, say, 8 hours a day on average, that's ~3,000 hours/year, meaning a stack might last ~10 years before needing replacement. Replacing fuel cell stacks is a major expense akin to an engine overhaul on a diesel – although one advantage is that it might be done incrementally (e.g. swapping modules) rather than rebuilding an engine. Hydrogen trains also have **additional systems**: high-pressure H_2 storage tanks (which require periodic inspection for integrity), hydrogen sensors and safety systems (checked regularly), and compressors/pumps if on-board (some designs use onboard compressors for the fuel cell). Early assessments in the 2010s projected higher maintenance costs for hydrogen – even double that of diesel – due to unfamiliarity and low component maturity[51]. However, recent experience is more optimistic: the fuel cell train fleet in Germany (Alstom iLint) has achieved high reliability with no major mechanical failures reported, suggesting maintenance can be kept under control as teething issues are resolved[52]. A U.S. Federal Railroad Administration study noted that non-diesel technologies *may require less regular maintenance* because of fewer moving parts[49], but they also caution that new tech has a learning curve[51]. For budgeting, one might assume hydrogen train maintenance is **comparable to diesel** in cost, with some costs shifting (less engine work, more stack replacement) and the potential for cost reduction as fuel cell longevity improves. If anything, by the 2030s hydrogen train maintenance could even dip below diesel's if fuel cells and batteries (yes, hydrogen trains also have small batteries for dynamic support) prove very robust. Manufacturer warranties and support contracts (e.g. Alstom offering maintenance included for X years in their hydrogen train deals) can also mitigate uncertainty in the early years.

In summary, **diesel and hybrid share similar maintenance costs**, with hybrids potentially saving on certain items (engine, brakes) but adding battery renewal costs. **Hydrogen shifts maintenance to a more electrical paradigm**, potentially simplifying some tasks while introducing new ones like fuel cell care. Given Vancouver Island's moderate service intensity (not a 24/7 operation), we do not expect maintenance to be a deciding factor between these options – it will be in the same ballpark for all, perhaps 5–10% of total lifecycle cost. However, it is worth noting that **maintenance staff training and facilities** are factors: diesel is familiar; hydrogen and high-voltage systems would require new training, hazard protocols (for hydrogen safety), and possibly new maintenance facility investments (e.g. ventilation for hydrogen in the shop). These "softer" costs are hard to quantify but need consideration in implementation.

Emissions Analysis

One of the most critical comparisons between diesel, hybrid, and hydrogen technologies lies in their **environmental emissions**. We examine both **direct (tailpipe) emissions** and **indirect (well-to-wheel) emissions**, focusing on greenhouse gases (CO_2) and air pollutants (NO_x, PM). We then evaluate the societal impacts by monetizing these emissions – essentially putting a dollar value on the environmental and health damages to illustrate the external cost of each option. This section demonstrates how drastically the choices diverge in terms of sustainability:

Tailpipe Emissions and Air Quality

- **Diesel:** Diesel engines emit a suite of pollutants from combustion. Chief among them: carbon dioxide (CO_2), which is the end product of burning hydrocarbon fuel and a major greenhouse gas; **nitrogen oxides (NO_x)**, which form in the high-temperature combustion and contribute to smog and respiratory issues; and **particulate matter (PM)** or soot, which are tiny black carbon particles harmful to lungs and classified as carcinogenic. Modern diesel locomotives are much cleaner than older ones due to stringent emissions standards (Tier 4 in the US, Stage V in EU) that require advanced aftertreatment (e.g. urea SCR to cut NO_x, diesel particulate filters to trap soot). Even so, **diesel traction produces significant emissions**. CO_2 is directly proportional to fuel burned – about **2.7 kg CO_2 per liter** of diesel consumed[53]. For perspective, a busy commuter rail line running diesel trains (with multiple trips daily) can emit on the order of **tens of thousands of tonnes of CO_2 per year**; one study estimated ~27,000 t/year for a heavily used line[53]. A more moderate service like the Island corridor (e.g. a few round-trips per day) would emit on the order of a few hundred to a few thousand tonnes CO_2 annually, depending on frequency. NO_x emissions from diesel locomotives, even Tier 4, are not negligible – Tier 4 standards allow roughly 1.3 g/bhp-hr of NO_x, which might equate to ~5–8 g of NO_x per liter of fuel burned (and older engines emit more). Over many kilometers, this accumulates into local pollution that can affect air quality along the corridor. Diesel PM is small but potent; Tier 4 limits PM to ~0.03 g/bhp-hr, which might be ~0.1 g per liter fuel. In absence of aftertreatment (older engines), PM could be ~0.5–1 g/L or higher. In summary, a single diesel train can emit **kilograms of NO_x and hundreds of grams of PM per day** into the local air. These pollutants are of particular concern in populated or enclosed areas – e.g. in downtown Victoria or Nanaimo stations, or if trains idle near communities. Diesel exhaust PM has known health impacts (aggravating asthma, heart and lung disease, and contributing to premature deaths). While improved engine tech reduces emissions per liter, **diesel remains the worst of the three options in tailpipe emissions**.

- **Hydrogen:** A hydrogen fuel cell electric train has **zero tailpipe emissions** in operation. The fuel cell combines hydrogen with oxygen from the air to produce electricity, and the only byproduct is water vapor (H_2O)[54][55]. That means **no CO_2, NO_x, or PM** coming out of the train at all[54][56]. This is a massive benefit for air quality and climate –

essentially equivalent to an electric train. It's important to clarify: this is true for *fuel cell* hydrogen usage. If one were to burn hydrogen in a combustion engine (an alternative concept being tested elsewhere), there would be no CO_2 but still some NO_x produced by the high-temp combustion of hydrogen in air[57]. However, hydrogen combustion is not our focus (fuel cells are far more efficient and produce no NO_x because the reaction is electrochemical). So, assuming fuel cells, a hydrogen train emits nothing harmful on-site. This yields **immediate air quality improvements**: no diesel smell or soot at stations, no contribution to urban NO_2 levels, and very low noise (hydrogen trains are much quieter, as the only noise is the hum of motors and compressors). For communities along the Island corridor, hydrogen trains would eliminate the local pollution that diesel trains would otherwise introduce – an important consideration given the route goes through populated areas and pristine natural environments that benefit from zero-emission transport. The tailpipe GHG advantage is obvious too: a hydrogen train emits **0 grams of CO_2** from its operations[58][59]. This gives it the potential to essentially eliminate operational emissions if the hydrogen is produced cleanly.

- **Hybrid:** A hybrid diesel train **still has a diesel engine**, so it **still emits CO_2, NO_x, and PM**, but in proportion to its reduced fuel consumption. If a hybrid achieves 30% fuel savings, it will emit ~30% less of each pollutant compared to an equivalent conventional diesel[60][61]. In many cases, emissions reductions can be even a bit better than the fuel percentage, because hybrids can avoid running the engine in regimes that produce disproportionately high emissions (like idling and abrupt accelerations). For example, shutting off the engine at idle not only saves fuel but also avoids the situation where NO_x aftertreatment might not work well (diesel catalysts need high exhaust temperature) – thus hybrids prevent those "gross" emissions during idle[62][63]. Some hybrid locomotives in yard service demonstrated >40% NO_x reduction and >70% PM reduction thanks to eliminating idle and smoothing engine loads[64][65]. For a hybrid on the Island passenger route, similar benefits would apply whenever the train is coasting or at stations – the engine can turn off, meaning zero emissions during those periods. During acceleration or climbing hills, the engine works in tandem with the battery, potentially operating in a more efficient (and cleaner) regime than a sole diesel would. Overall, one can expect a **hybrid to cut NO_x/PM roughly in line with its fuel reduction** (e.g. 30–50% cuts)[66]. This is a **significant improvement** but obviously not as good as zero. Hybrids *mitigate* local pollution but do not eliminate it. They are particularly beneficial in sensitive areas like city centers – the battery can propel the train out of a station without firing the engine, reducing the puff of smoke that a diesel would normally eject upon departure. In a place like Victoria, this could be valuable for air quality. Still, a hybrid is an **interim solution** on emissions: it can halve them, but cannot reach zero without either external electrification or eventually switching to a zero-carbon fuel.

Table 2 summarizes the operational (tailpipe) emissions profile of each option:

Table 2 – Operational (Tailpipe) Emissions Comparison (per train)

Emission & Pollutant	Diesel	Hydrogen Fuel Cell	Diesel Hybrid
CO_2	Yes – **High.** ~2.7 kg	**Zero.** No CO_2 emitted	**Reduced.** Proportional to

Emission & Pollutant	Diesel	Hydrogen Fuel Cell	Diesel Hybrid
(Carbon Dioxide)	CO_2 per liter of diesel burned; thousands of tonnes per year for a busy train line[53][67]. Baseline for GHG emissions.	during operation (water is the only byproduct)[54][56]. Huge advantage for climate if H_2 is produced cleanly.	fuel savings – e.g. 30–50% less CO_2 than diesel by burning less fuel[60][61]. Still emits carbon, so not zero-carbon.
NO_x (Nitrogen Oxides)	Yes – **Significant.** Even Tier 4 diesels emit some NO_x (grams per liter fuel). Contributes to smog, respiratory problems. Hotspots near tracks/stations possible.	**Zero.** No NO_x from fuel cell reaction[54]. Big air quality benefit, especially in urban or enclosed areas (stations, tunnels). *(Hydrogen combustion engine would emit NO_x, but fuel cells do not.)*	**Reduced.** Roughly proportional to fuel reduction (30–50% less NO_x)[60][61]. Plus hybrids avoid high-NO_x situations (idle, transient spikes)[62], improving low-speed urban emissions.
PM (Particulate Matter)	Yes – **Notable.** Diesel exhaust soot (black carbon) is emitted, though filters can cut it. Diesel PM is carcinogenic; even small amounts matter for health. Visible smoke under load for older units.	**Zero.** No particulate emissions at all (no combustion)[54]. Eliminates soot – good for lungs and cleanliness (no soiling of structures).	**Reduced.** Like NO_x, PM is lowered ~30–50% with fuel savings[60]. Also, hybrids prevent a lot of idling (where incomplete combustion can produce more PM)[62], so PM reductions could be high in practice (>50%). Not zero, but a cleaner diesel.
Other (CO, HC, noise)	**CO/HC:** Small amounts of carbon monoxide, unburned hydrocarbons from engine. **Noise:** Loud engine noise, vibration, especially under load.	**CO/HC:** None from vehicle. **Noise:** Much quieter – only a low hum from electric motors and slight noise from air compressor and cooling fans.	**CO/HC:** Reduced with less fuel burned. **Noise:** Quieter than diesel – engine off at idle and low power, battery can move train in stations, etc. Still some engine noise under heavy load, but overall noise pollution is lower.

From Table 2, the clear winner in operational emissions is **hydrogen fuel cell**, which offers a true zero-emission vehicle (ZEV) experience. Hybrid improves over diesel but does not meet zero-emission goals, while diesel is the baseline emitting technology.

Life-Cycle GHG Emissions (Well-to-Wheel)

While tailpipe emissions are crucial for local air quality and immediate impacts, for climate change we must consider the **full life-cycle GHG emissions** (often called well-to-wheel, WTW, or "tank-to-wheel + upstream"). This accounts for emissions from producing and transporting the fuel, not just burning it in the train. For diesel, upstream emissions come from oil extraction, refining, and transport (which add roughly 20% on top of the tailpipe CO_2). For hydrogen, it depends entirely on how the hydrogen is made. We analyze a few cases:

- **Diesel WTW:** Each liter of diesel burned emits ~2.7 kg CO_2 directly, but producing that liter (refining petroleum) emits additional CO_2 – roughly 0.5 kg extra per liter on average. So WTW might be ~3.2 kg CO_2 per liter. Using low-carbon biofuels (renewable diesel or biodiesel) could lower WTW carbon intensity if adopted, but unless mandated by policy, we assume standard diesel. Over 30 years, a diesel train fleet could emit **hundreds of thousands of tonnes of CO_2**. (E.g. if one train emits 300 t/year, ten trains over 30 years would be 90,000 t CO_2.)

- **Hydrogen WTW:** Here we have a **wide range**:

- *Green Hydrogen:* Made by electrolyzing water using renewable electricity (or other near-zero-carbon energy). WTW emissions are minimal – essentially just the embodied emissions of building the equipment and any grid electricity overhead. Green H_2 can be considered ~zero-carbon fuel. Thus, a hydrogen train using BC Hydro power to electrolyze hydrogen would have **near-zero lifecycle GHG emissions** (BC's grid is ~95% renewable, ~10 g CO_2/kWh[68], which is negligible). This is the ideal scenario and aligns with CleanBC's vision of leveraging clean electricity.
- *Grey Hydrogen:* Made from natural gas via steam methane reforming (SMR) without carbon capture, which is the most common hydrogen today. This process emits CO_2 at the hydrogen plant. Approximately 9–10 kg CO_2 are emitted per 1 kg of H_2 produced from natural gas[69][70]. If a fuel cell train needs ~1 kg of H_2 to replace 1 gal of diesel, that's ~10 kg CO_2 upstream instead of the ~10 kg that burning a gallon of diesel would produce (interestingly similar order of magnitude). Studies indicate that even using grey hydrogen, there's often a reduction in total GHG: a Montreal commuter rail study found hydrogen (grey) could cut lifecycle GHG ~**55–75%** vs diesel[71][72]. Another analysis for a UK route suggested converting to hydrogen (with green H_2) could avoid **up to 187,000 tonnes CO_2 over 30 years** compared to diesel[73][74]. The key is that fuel cells are more efficient and diesel refining also has emissions, so grey H_2 is not as bad as one might think – but it's clearly not zero. It often yields ~25–50% GHG reduction relative to diesel[69][75].
- *Blue Hydrogen:* Made from natural gas but with carbon capture at the plant, reducing CO_2 emissions by ~50–90%. This would put H_2's footprint much lower, maybe ~1–4 kg CO_2 per kg H_2. Paired with a fuel cell train, this could achieve >80% GHG reduction vs diesel.
- *Hydrogen Delivery:* Transporting hydrogen (trucking liquid H_2, etc.) also uses energy. But given the scale of a rail operation, local production is likely (to avoid trucking costs).

In summary, **hydrogen trains can be anywhere from ~25% to ~100% cleaner than diesel in GHG terms**, depending on H_2 source[76][77]. The best case (green H_2) is essentially zero-carbon rail. The worst realistic case (grey H_2) still usually beats diesel on GHG, and in all cases the *tailpipe* is zero, which is great for local environment. Policymakers would almost certainly aim for green hydrogen for a project like this (to claim true zero-emission service). BC's electricity and interest in hydrogen suggest a green H_2 supply could be developed regionally.

- **Hybrid WTW:** A hybrid's WTW emissions are basically a fraction of diesel's, proportional to the fuel use reduction. If a hybrid cuts fuel by 30%, it also cuts lifecycle GHG by ~30%. If some grid electricity is used for charging, we must account for those emissions, but in BC the grid is very low-carbon (~10 g/kWh, as noted)[68], so even if 10% of the energy came from the grid, its CO_2 contribution would be trivial. Therefore, a hybrid running on standard diesel in BC might achieve ~30–50% lower GHG emissions than a pure diesel – a **good interim improvement** but still leaves significant emissions on the table[78][79]. Over decades, hybrids alone won't meet deep decarbonization targets, but they slow the growth of emissions. An important note: **Low-carbon fuels** could also help hybrids (and diesels) – e.g. blending biodiesel or renewable diesel into the fuel as mandated by BC's Renewable & Low Carbon Fuel Requirements. If by 2030 diesel fuel is, say, B20 (20% biodiesel), the effective CO_2 per liter would drop, benefitting both diesel and hybrid options somewhat. We do not specifically model that here, but it's a complementary decarbonization measure.

Comparative Outcome: In terms of climate impact, **hydrogen (with green or blue H_2) is the only option that can approach near-zero lifecycle emissions**, truly aligning with 2050 net-zero goals[73][80]. Diesel-hybrids provide a partial reduction (important for the 2020s–2030s) but still rely on fossil fuel combustion, hence cannot get beyond ~50% emissions cuts. Conventional diesel obviously is the highest emitter and least sustainable long-term. Many studies conclude that for non-electrified rail lines, hydrogen fuel cell technology is among the most promising solutions to deeply cut GHG emissions[73][80] – provided the hydrogen is produced cleanly, which is a matter of energy policy and investment. If hydrogen were somehow produced from coal or other high-emission methods, it could negate benefits, but that scenario is unlikely in BC's context.

Monetized Externalities: Carbon and Health Costs

To grasp the broader impact of these emissions, we assign monetary values to them:

- **Social Cost of Carbon (SCC):** This represents the long-term damage caused by emitting a tonne of CO_2, in terms of climate change impacts (sea level, storms, agriculture, etc.). Estimates vary, but a common value used in policy is around **\$100 per tonne CO_2** (some use higher for more stringent climate economics, e.g. \$170/tonne as Canada's 2030 carbon tax, or ~$50/tonne as a lower bound). Using \$100/t for simplicity: a diesel train emitting 300 t CO_2/year imposes about **\$30,000/year** in climate damages. A fleet of 6 would be \$180,000/year. Over 30 years (discounting ignored), that's \$5.4 million in climate cost. For hydrogen with green H_2, CO_2 is near zero so negligible cost; with grey H_2 at 25% of diesel emissions, it'd be \$7,500/year per train instead of \$30,000. Hybrid at 50% diesel emissions would be \$15,000/year per train. These numbers give a sense of the hidden climate cost burden of continuing with diesel.

- **Health cost of air pollution:** NO_x and PM emissions translate into healthcare costs and mortality. Health Canada and other studies have calculated "benefit per tonne" values – essentially, how much society gains by removing 1 tonne of pollutant. These depend on population exposure (pollution in a city is worse than in a sparsely populated area). For a rough idea, estimates for **PM2.5** can be on the order of **\$100,000–\$500,000 per tonne** (PM is extremely damaging even in small amounts)[81]. **NO_x** (which contributes to ozone and secondary PM) has lower per-tonne costs, perhaps around **\$5,000–\$20,000 per tonne** in many analyses. Let's apply: If one diesel train emits, say, 1 tonne of NO_x and 0.05 tonnes of PM per year (just ballpark), the health damage might be about \$10,000 (NO_x) + \$15,000 (PM) = \$25,000/year per train. Six trains could thus cause ~$150k/year in health-related costs to society. If service intensifies (more trains or more frequency), these costs grow. Hydrogen trains, emitting zero NO_x/PM, essentially eliminate those local health costs. Hybrids would cut them roughly in half. Indeed, a Canadian study of highway traffic in Toronto found that **health costs of vehicle pollution far outweighed climate costs** – on the order of 8× higher[82][83]. In our example, health costs (~\$25k/train) exceeded climate costs (~\$7.5k/train at \$50/t carbon or \$15k at \$100/t). This underlines that *even if climate change wasn't a factor, reducing diesel pollution has economic merit in terms of public health*. Especially in regions aiming for improved air quality, electrified or hydrogen trains bring significant health benefits by **avoiding respiratory illness, heart disease, and premature deaths** associated with diesel exhaust. These benefits can be monetized as "avoided health care expenses and productivity losses." For instance, eliminating a tonne of NO_x might save a few thousand dollars in medical costs; eliminating a tonne of PM might save hundreds of thousands (because PM causes deaths at relatively low exposure).

In summary, factoring in externalities tilts the scales further in favor of cleaner technology. If one were to include carbon pricing and health damage costs in the economic analysis, diesel's apparent cost advantage shrinks. Governments often do this implicitly via carbon taxes (which BC already has) and environmental regulations. By adopting hydrogen or hybrid trains, **the Island rail project could avoid millions of dollars in societal costs over its lifetime**, strengthening the cost-benefit case beyond just the operator's balance sheet. Indeed, a recent cost–benefit analysis for a Battery-Electric retrofit of the Island corridor (a parallel concept) found that accounting for emissions and social impacts improved the benefit-cost ratio, and estimated **350 tonnes of CO_2 and significant pollution avoided annually** by going electric[84][85] – translating to quantifiable monetary and health gains.

Lifecycle Cost Analysis (30-Year TCO)

We now combine the capital and operating cost elements into a **Total Cost of Ownership (TCO)** evaluation over a 30-year horizon. This provides a holistic picture of which option might be most economical in the long run, accounting for upfront investment and cumulative OPEX. We also examine how results change under different future scenarios (fuel prices, technology improvements, utilization).

Baseline TCO Calculation: Let us first outline a baseline scenario for one train (we will later scale it up, but per-train is illustrative): - *Lifespan:* 30 years (2025–2055), with 3% real discount rate for NPV (standard for public infrastructure analysis[86][87]). - *Utilization:* ~100,000 km per year, which could correspond to ~1 round-trip per day on the 225 km line (actually 450 km round-trip × ~220 days = 99,000 km, allowing for some days off service or maintenance). - *Diesel fuel price:* \$1.20/L average (today around \$1.00–\$1.30 in BC after tax; future maybe higher but we'll use a moderate average). - *Hydrogen price:* \$6/kg average (assuming starts high, declines later; a mid-point scenario). - *Maintenance:* assume \$30k/year for diesel, \$33k for hybrid (slightly higher due to battery replacement reserve), \$30k for hydrogen (assuming simplified maintenance offsets fuel cell replacement cost). - *Efficiency:* Diesel 0.25 L/km (4 km per L, just an example giving ~25,000 L/year). Hybrid 0.175 L/km (30% saving). Hydrogen 0.20 kg/km (fuel cell uses ~0.8 kg per diesel gallon equivalent; so ~20,000 kg/year for 100k km).

Now, present value costs (30-year sum): - **Diesel:** CAPEX \$5 M. Fuel 25k L/yr * \$1.2 = \$30k/yr; NPV of that over 30yr ≈ \$600k (not discounting year by year for simplicity, just total \$900k undiscounted minus some discount factor ~0.67). Maintenance \$30k/yr, 30yr NPV ~\$600k. Total ≈ \$5 M + \$1.2 M = **\$6.2 M** NPV per train (again, very rough). - **Hybrid:** CAPEX \$6 M. Fuel 17.5k L/yr * \$1.2 = \$21k/yr; 30yr NPV ~\$420k. Maintenance \$33k/yr NPV ~\$660k. Total ≈ \$6 M + \$1.08 M = **\$7.08 M**. (So hybrid slightly higher than diesel in this baseline – fuel savings didn't fully offset higher CAPEX in NPV terms here.) - **Hydrogen:** CAPEX \$10 M. Fuel 20k kg/yr * \$6 = \$120k/yr; 30yr NPV ~\$2.4 M. Maintenance \$30k/yr NPV ~\$600k. Total ≈ \$10 M + \$3.0 M = **\$13.0 M**.

In this baseline, diesel appears cheapest, hybrid ~15% higher, hydrogen about double the cost in NPV. However, this is just one scenario. Let's stress test different scenarios:

- **High Fuel Price / Carbon Tax Scenario:** Suppose diesel averages \$2.00/L in the future (due to taxes or oil prices), and hydrogen \$4/kg (cheaper with scale). Now diesel's fuel NPV doubles to ~$1.2 M, hydrogen's fuel NPV drops to ~$1.6 M. Diesel TCO becomes ~$6.8 M, hybrid ~$6.7 M (because hybrid saves a lot on expensive diesel), and hydrogen ~$12.2 M. Here the hybrid actually slightly undercuts diesel in NPV – fuel cost swings can flip the ranking. Hydrogen is still ~80% above diesel, but better than before.
- **Technology Improvement Scenario:** By 2035, say fuel cell trains cost only 1.5× diesel (so \$7.5 M vs \$5 M)[17], and hydrogen price \$3/kg. Recalculate hydrogen: CAPEX \$7.5 M, fuel 20k_\$3 = \$60k/yr (NPV ~\$1.2 M). Then hydrogen TCO ≈ \$7.5 M + \$1.8 M = \$9.3 M_*. Now hydrogen is only ~50% more than diesel's \$6.2 M. If also diesel fuel is taxed up (making diesel OPEX higher), the gap narrows further. With strong climate policies and tech advancement, one could envision hydrogen TCO approaching parity with diesel by the 2040s[88].
- **Low Utilization / Fewer Service Days:** If trains run less (e.g., only 1 round-trip 5 days a week, or shorter trips), fuel use drops and so the importance of OPEX diminishes relative to CAPEX. In such a case, the high-capex hydrogen option becomes relatively worse (because you're not utilizing the expensive asset fully). Conversely, if utilization were *higher* (multiple trips per day), then the fuel-heavy diesel looks worse due to compounding fuel costs, and the high efficiency of hydrogen becomes more valuable in the long run.
- **Including Externality Costs:** If we internalize carbon at \$100/t and add health costs as earlier, diesel would carry extra ~$50k/year in external costs not paid by the operator. Over 30 years NPV ~$0.9 M. Hydrogen's external cost near zero. That would further tilt lifecycle cost advantage toward hydrogen by almost \$1 M. In a societal TCO sense (not just operator), hydrogen and hybrid are more competitive. This could justify subsidies or carbon credits to the project.

In general, these scenarios show that **the ranking of TCO can change under different assumptions**. Diesel starts cheapest in pure private cost terms today, but is very sensitive to fuel price increases and carbon costs. Hybrid usually offers a slight economic benefit if fuel prices rise or if initial cost premiums are kept low – even in our baseline, the difference was small, and with higher diesel prices the hybrid can pay back its extra cost quickly[38]. Hydrogen, under current cost structure, has a higher total cost of ownership, but **the gap is projected to close**. A study by Argonne National Lab (2019) similarly found that without incentives hydrogen locomotives had higher TCO than diesel, but with anticipated fuel cost declines and higher diesel prices, hydrogen could break even or save money over the life cycle[89]. Importantly, a public agency might evaluate costs differently than a private operator: public benefits of zero emissions (health, climate) might justify paying a premium or obtaining government funding to cover that premium.

For the Island corridor, a lifecycle analysis should also consider **ridership and revenue** in each scenario: cleaner trains might attract more ridership or enable carbon credits, etc. However, that's beyond our scope here, which focuses on costs and emissions.

To put a concrete number, if we were to choose a scenario around 2035 with moderate fuel prices and some tech improvement: diesel TCO per train might be on the order of \$6–7 million (NPV), hybrid \$6.5–8 million, and hydrogen \$9–10 million. Scaling up to a fleet of 6–8 trains, we'd multiply those figures (and add infrastructure in hydrogen's case). So initially, hydrogen could be say \$30–\$40 million more expensive in NPV terms than diesel for the whole system. But if we then monetize emissions differences (hydrogen saving perhaps 5,000+ tonnes CO_2 over 30 years per train, and tons of NO_x/PM), the societal savings could be in the same tens-of-millions ballpark, offsetting that difference[85][90]. This is the classic environment vs economy trade-off, although fast-changing economics of technology are steadily eroding the conflict.

It's also worth noting **residual value**: After 30 years, diesel equipment might be near end of life (or obsolete if fossil fuels are being phased out), whereas newer tech might hold value or be repurposed. If by 2055 diesel usage is heavily restricted or fuel is very costly due to climate regulations, a diesel fleet might incur additional costs (retrofits or early retirement) not captured in a simple NPV.

Conclusion of TCO: Diesel has a lower initial cost and potentially lower TCO in the short term, but is exposed to future fuel price and policy risk. Hybrids slightly increase upfront cost but reduce operating costs, often yielding a favorable lifecycle economics especially if fuel costs rise – they can be seen as an insurance against fuel volatility. Hydrogen currently shows a higher lifecycle cost, but the trajectory is toward improvement; a strategic approach could minimize that premium by timing the adoption when conditions are optimal (see next section). If one evaluates from a public interest perspective (with carbon pricing and health costs), hydrogen and hybrids likely already have a net positive lifecycle benefit compared to diesel. This suggests that **with modest subsidies or policy incentives**, hydrogen trains could become life-cycle cost competitive with diesel in the 2030 timeframe[30][31], and hybrids may be cost-competitive immediately in high-fuel-cost contexts.

Deployment Scenarios and Phased Adoption

Transitioning a 225 km rail corridor to sustainable propulsion is not an overnight switch – it requires careful planning of investments over time. Here we present potential **deployment scenarios** for Vancouver Island rail, including a phased approach that starts with diesel or hybrids and progresses to hydrogen. We also consider how infrastructure roll-out can be staged and aligned with broader policy goals like CleanBC's climate targets.

Scenario 1: "Diesel Now, Diesel Later" (Business-as-Usual)

Description: Reintroduce service using only diesel trains (possibly modern low-emission models or refurbished units) and continue using diesel for the foreseeable future. No immediate plans to adopt new technology.

Pros: Lowest initial cost and simplest implementation. Proven technology, minimal training required. Quickest path to getting trains running – could potentially use existing refurbished rolling stock (e.g. former VIA Rail RDCs) to save money. Least dependency on uncertain tech or fuel sources.

Cons: Does not align with climate goals – locks in high GHG and pollutant emissions for decades. Likely to face increasing operating costs from carbon pricing and fuel volatility. Could become obsolete or face regulatory pressure as Canada moves toward net-zero 2050. Missed opportunity for leadership in clean transportation. Social license might be weaker (public and First Nations might prefer clean solutions).

Assessment: This scenario is essentially *not sustainable* beyond the short-term. While it could jump-start rail service by late 2020s, it would almost certainly require a later retrofit or replacement with cleaner tech to meet 2040s emissions mandates. Thus, it risks stranded assets or expensive mid-life upgrades. Most stakeholders envision something more advanced than pure diesel, so this is mainly a reference case.

Scenario 2: "Hybrid Transition" (Diesel to Hybrid to… maybe Hydrogen)

Description: Phase 1 (2025–2030): Launch service with diesel trains, but design the fleet to be upgradable or plan to procure hybrid battery-diesel units as soon as practical. Possibly start with a mix: e.g. some refurbished diesels initially, and pilot one *battery-diesel hybrid* by 2028 to test performance. **Phase 2 (2030–2040):** Gradually replace or retrofit diesel units with hybrids. For instance, by 2035 aim for the entire fleet to be hybrid diesel-electric, cutting fuel use and emissions ~30–50%. **Phase 3 (Post-2040):** Evaluate hydrogen or full electrification once technology is very mature and funding available; hybrids could continue alongside or be converted if feasible (some hybrid locomotives could potentially be converted to full battery-electric or have fuel cell modules added – this is speculative but conceivable).

Pros: Spreads out capital costs and technology risk. Allows early service with diesel to generate ridership and revenue, then improves environmental performance when hybrids become more readily available (hybrid train tech is evolving too). Reduces emissions steadily, hitting perhaps ~50% GHG reduction by 2040 (from hybrid efficiency plus cleaner diesel fuel). Hybrids require no new fuel infrastructure, so Phase 1 and 2 avoid major infrastructure spend – they keep using diesel supply. This scenario is relatively *low-risk and flexible*; if hydrogen never pans out, the system still has improved efficiency; if hydrogen does become viable, the system can pivot then.

Cons: Still uses diesel fuel for ~10–15 years or more, so not zero-emission. Only partial alignment with climate targets – by 2030 CleanBC aims for significant GHG cuts, and hybrids alone might not meet the province's ambition of deep reductions. Possibly seen as *incremental* –

might not attract the same level of excitement or funding as a bold zero-emission project. Also, managing a mixed fleet (diesel vs hybrid) could complicate maintenance and operations during transition.

Assessment: This phased approach is pragmatic. It recognizes hydrogen may not be economically optimal immediately, and hedges by using hybrids in the interim. It aligns with **CleanBC 2030 targets** to some degree by achieving some reduction (CleanBC aims for 40% GHG reduction by 2030 – hybrids could contribute toward that, though full decarbonization requires the next phase)[90]. It could leverage provincial support for any initiative that reduces emissions, e.g. grants for hybrid retrofits might be obtainable. By 2040, if hydrogen is proven and cheaper, a further transition can occur. Essentially, this scenario is "start now with what's available, improve gradually, don't wait for perfect tech." Many railways adopt this logic (piloting hybrids while keeping an eye on hydrogen developments).

Scenario 3: "Hydrogen Leapfrog" (Direct to Hydrogen)

Description: Bypass diesel improvements and go straight to hydrogen fuel cell trains as soon as possible. For example, **Phase 1 (2025–2028):** conduct a pilot with one or two hydrogen trainsets on a portion of the line (e.g. Victoria–Nanaimo), perhaps in partnership with technology providers (as Island Rail Corp has proposed for a pilot to Malahat SkyWalk)[4]. Build a small-scale hydrogen fueling facility for this pilot (or use mobile refuelers). **Phase 2 (2030):** If pilot succeeds, scale up to full corridor hydrogen service by early 2030s. Procure a fleet of H_2 trains (6–12 units) and construct full-capacity hydrogen production (likely an electrolyzer using BC Hydro power) and fueling infrastructure. Diesel rolling stock, if any was used temporarily, is retired or reassigned elsewhere. Essentially achieve near 100% zero-emission operation by 2030 or shortly after. **Phase 3 (2030–2040):** Expand service frequency as needed with additional hydrogen trains (up to 20 if demand grows), and continuously improve efficiency as fuel cell tech advances. Possibly integrate with other hydrogen initiatives on the Island (e.g. hydrogen buses or trucks) to share infrastructure and drive costs down.

Pros: Maximal environmental benefit in the shortest timeframe – essentially aligns with or exceeds CleanBC targets (virtually eliminating rail GHG by 2030)[90]. Positions Vancouver Island as a leader in green transportation, potentially attracting federal funding (Canada has funds for hydrogen projects) and positive public reception. Hydrogen trains produce zero pollution along the line, preserving the Island's clean air and appealing to tourists (a marketing point: riding a zero-emission train through pristine landscapes). Long-term, this avoids the need to replace diesel assets – you invest once in the future-proof solution. It also could create synergies with BC's growing hydrogen sector (for example, generating hydrogen could help utilize surplus hydroelectricity or serve as energy storage, etc.). Maintenance and operations would eventually be simpler (all one technology, no dual systems).

Cons: High upfront cost and risk. This requires heavy capital investment early on – not just in trains but also hydrogen infrastructure, as discussed (tens of millions). If ridership or revenue is uncertain, committing huge funds upfront could be risky. There's technology risk: while hydrogen trains have proven themselves in Europe (e.g. Germany's iLints have run for several years successfully[73]), it's still new in North America (a trial in Quebec in 2023, and plans for Alberta and California, but no long-term deployments yet). Any hiccups (fuel supply issues, reliability problems) could disrupt service or incur unforeseen costs. Additionally, during the build-up (2025–2030), the corridor would likely remain unused or underused until the hydrogen system is ready, meaning further delay in providing mobility benefits to the population. Operationally, going hydrogen means setting up an entirely new supply chain on the Island (fuel delivery or production, safety regimes, etc.) with no prior local expertise – a steep learning curve initially.

Assessment: The leapfrog scenario is bold and aligns with ideal decarbonization pathways (no new diesel assets – straight to zero-emission). It likely requires strong government backing. The 2025 pilot in Charlevoix, Quebec (Alstom's hydrogen train in summer 2023) provides a template – that project had significant funding and was a short-term demo. For a full service, Vancouver Island would need to secure capital for both track rehab and hydrogen tech simultaneously. A possible middle-ground is a **incremental hydrogen scenario**: perhaps start with a pilot segment (Victoria to Duncan or Nanaimo) with one hydrogen train to gain experience, while running diesel or hybrid on the remainder initially, then scale up. This hybrid scenario in terms of tech mix could mitigate some risk – proving hydrogen on a smaller scale before full conversion.

Phased Infrastructure Staging

No matter the scenario, **infrastructure upgrades can be staged geographically and by component**: - **Track & Structures:** Likely done in phases (the corridor could be opened in sections as they are upgraded). For instance, focus on the **Victoria–Nanaimo segment first**, as it has the largest population and tourism draws. Indeed, Island Rail Corp's vision targets the southern half first[4]. Opening that segment with initial trains (diesel or hydrogen) generates momentum and revenue, then extend to Courtenay in phase 2, and Port Alberni branch in phase 3 if warranted. - **Hydrogen Infrastructure:** If going the hydrogen route eventually, one could build a modest-capacity electrolyzer and fueling station at a central location (maybe Nanaimo or Duncan, roughly mid-Island) for an initial few trains. This could supply a pilot service Victoria–Nanaimo. Later, if the whole line is to be hydrogen, either expand that station or add a second at another strategic location (perhaps Courtenay for the northern terminus). Staging the H_2 infrastructure prevents over-investing before the service ramps up. Mobile hydrogen refueling units (essentially trucks or rail cars that carry hydrogen) could even be used in early trials to avoid building permanent facilities until proven. - **Electric Grid Upgrades:** If hybrids or hydrogen require electricity (for charging or H_2 production), coordination with BC Hydro is needed. A phased approach might start with using existing grid capacity for a small electrolyzer, then upgrading substations for a larger electrolyzer later on. CleanBC's electrification programs might help fund such upgrades (there's a CleanBC Facilities Electrification Fund, for example, supporting industries to connect to clean power[91][92]). - **Maintenance Facilities:** Initially, a simple maintenance base for diesel rolling stock could be used (perhaps the old Victoria yard or Nanaimo yard). If hydrogen trains are introduced, the facility may need retrofits (ventilation, hydrogen sensors). One might prepare for that in advance by building a new facility or upgrading one in stages – e.g., first build a basic shed for diesel/hybrid, later install hydrogen-safety features when H_2 trains arrive. - **Staff Training:** Staging also applies to workforce development. Diesel mechanics can be hired/trained first (lots of those around). Over time, retrain some in high-voltage and hydrogen handling. By the time the first hydrogen train is delivered, have a core team trained (perhaps in collaboration with Alstom or whoever supplies the train, since they often provide training).

Alignment with CleanBC and Federal Goals

CleanBC, the province's climate action plan, calls for a 40% reduction in GHGs by 2030 (relative to 2007) and a path to net-zero by 2050[93][90]. Transportation is a major focus, including shifting to zero-emission vehicles and fuels. A resurrected Island rail line has the potential to reduce emissions by attracting riders who might otherwise drive, but if it's diesel-powered, those gains could be undermined by the train's own emissions. **Thus, propelling the trains with clean energy is key to maximizing the climate benefit of the project.** A diesel train might emit as much CO_2 per passenger-km as a few dozen cars if not well-patronized, whereas a hydrogen or electric train would be essentially emissions-free per passenger. In terms of regional policy: - BC's Low Carbon Fuel Standard (LCFS) requires increasing reductions in fuel carbon intensity. This will push the cost of diesel up and encourage alternatives like renewable diesel, hydrogen, etc. By 2030, fuels must be significantly cleaner or pay credits – a railway using diesel might need to buy credits, whereas using hydrogen might generate credits. Vancouver Island railway could perhaps generate carbon credits (under BC's system or federal Clean Fuel Regulations) if using green hydrogen – an extra revenue or cost-offset opportunity. - CleanBC's **Hydrogen Strategy** (released 2021) identifies transportation, including rail, as a target sector for deploying clean hydrogen. The province is funding pilot projects (like hydrogen buses, trucks, and a mention of rail possibilities)[94]. Aligning the Island rail project with these initiatives could unlock funding. For example, the Canada Infrastructure Bank and provincial grants have shown interest in hydrogen transport (the CIB in 2022 invested \$277 M in an Alberta freight railway hydrogen project). - Federally, Canada's **2030 Emissions Reduction Plan** and 2050 net-zero accountability mean that any new infrastructure should be as low-carbon as possible to avoid future retrofit costs. VIA Rail and others are exploring hydrogen and battery trains – a successful project on Vancouver Island would be a valuable demonstration aligning with national goals to decarbonize medium-distance transport. - **First Nations and local governments** on the Island have expressed interest in sustainable development. A rail service that is quiet and non-polluting may receive stronger community support, especially if it serves First Nations communities along the line without degrading local air quality. This fits into broader reconciliation and environmental justice narratives: indigenous communities often bear disproportionate burdens of pollution; hydrogen trains would ensure the restored rail line doesn't introduce new burdens.

In practical terms, a phased adoption strategy might look like this timeline:

- **2025–26:** Secure funding, finalize business case. Possibly acquire a few used diesel railcars to begin limited service on a rehabilitated segment by 2026 (as a quick start).
- **2027–28:** Implement a **Hydrogen Pilot Project**. For example, bring one hydrogen train (perhaps via a partnership with Alstom or another supplier) to run a trial service on part of the route[95]. Use this period to train staff and test infrastructure in BC conditions. Apply for CleanBC and federal pilot funds.
- **2030:** Based on pilot results, start scaling up hydrogen. Order a fleet of, say, 5–8 hydrogen trains to cover core services from Victoria to Courtenay. Construct a permanent hydrogen fueling station (sized for initial fleet, but with space to expand). Meanwhile, any remaining diesel units can be outfitted with battery kits to make them hybrids, reducing emissions in the interim.

- **2030–2035: Hybrid/Hydrogen Mix Operation.** During this phase, some trains are hydrogen, some are hybrid diesel – ensuring reliability while new tech is still ramping. Gradually phase out pure diesels. Possibly run hydrogen on the busiest runs and hybrids on less frequent runs or as backup.
- **By 2035:** Achieve >80% of passenger-km on the corridor powered by zero-emission trains. This aligns with CleanBC's 2030/2035 ambitions (e.g. by 2035, aim for near-zero emissions in public transport sector).
- **2035–2040:** Expand service frequency if demand grows (maybe going from 6 to 12 trainsets to allow bi-hourly service or additional tourist trains). All new trains acquired are hydrogen or battery electric. Continue to retire diesel assets. Also by this time hydrogen technology costs are lower, making each new purchase easier to justify economically.
- **2040:** The rail service is essentially fully zero-emission (combination of hydrogen and perhaps some battery-electric for shorter shuttle routes if applicable). This meets the spirit of Canada's aim to have most transportation decarbonized by 2040–2050. Infrastructure like the Port Alberni branch could be re-opened at this stage with hydrogen trains (since running diesel solely for that branch might be politically/environmentally less acceptable by then).
- **2040–2050:** Optimize and innovate – maybe integrate on-board energy storage improvements, or if one day BC decided to electrify with overhead wires on certain sections, the hydrogen trains could be dual-mode, etc. But presumably, hydrogen tech by 2050 would be very advanced (fuel cell trains could be old hat by then, replaced by next-gen or possibly superseded by something like battery if energy density improves dramatically – though hydrogen is likely still better for long range).

This phased timeline ensures that **by 2050, the rail line is firmly part of the net-zero solution**. The initial years focus on making the project financially and operationally viable (since an unused rail line emits nothing but also serves no one – a balance must be struck). The latter years focus on eliminating the residual emissions in time for mid-century goals.

To conclude this section, the recommended pathway is a **phased adoption** where **diesel or hybrid service kicks off the rail revival as soon as possible, but with a clear plan and commitment to transition to hydrogen by the 2030s**. This mitigates risk and spreads cost, while ultimately delivering a fully sustainable transportation corridor. Importantly, the plan should remain adaptive: if hydrogen tech accelerates faster (e.g. costs plummet by 2028), the transition can be sped up; if hydrogen stalls, the project can fall back on hybrids longer and perhaps incorporate more renewable diesel to cut carbon. Flexibility and regular check-ins (e.g. a review in 2028, 2032, etc.) will ensure the Island Corridor can take advantage of the best available solutions as technology and economics evolve.

Conclusion

Reviving the Vancouver Island rail corridor is not only a transportation endeavor but also an opportunity to set a benchmark for sustainable regional transit. This comparative analysis shows that **each propulsion option offers distinct trade-offs**:

- **Diesel** traction is the *status quo* baseline – technologically straightforward and cost-effective upfront, but **burdened by high emissions** and likely to become increasingly untenable in a carbon-constrained future. Relying solely on diesel would mean lower capital requirements now, yet it would incur large fuel costs and externality costs over time, and potentially face regulatory or societal pressure as BC and Canada push toward decarbonization. In essence, diesel may save money in the short run but defer costs to the environment and future generations (or future project managers who must later retrofit or replace the system)[96][97].

- **Hydrogen fuel cell** trains represent the *innovative zero-emission solution*, offering **clean operations with performance on par with diesel**. They align with long-term climate goals by virtually eliminating operational GHGs (especially if green hydrogen is used) and improving local air quality by cutting NO_x/PM to zero[54][56]. The analysis showed hydrogen can reduce life-cycle emissions by 75–100% compared to diesel, making it the only option that truly "future-proofs" the rail line environmentally[71][72]. The challenge is the **higher initial CAPEX**: both vehicles and infrastructure are costly today[98][99]. However, trendlines are favorable – costs are projected to decline as the technology scales and benefits of hydrogen (like cheap renewable fuel and avoidance of carbon taxes) accrue over the years[29][32]. Hydrogen trains are already moving from pilot to reality in several jurisdictions worldwide, and Vancouver Island could similarly leverage partnerships and grants to implement them. Over a 30-year horizon, the hydrogen pathway is likely the only one that can achieve net-zero emissions, thus if climate impact is a paramount concern, this is the *destination* technology for the corridor.

- **Diesel-hybrid** (battery-assisted diesel) emerges as a *pragmatic intermediary*, delivering **tangible fuel and emissions reductions (20–50%) at relatively low incremental cost and complexity**[60][61]. Hybrids can be seen as a "no regrets" improvement – they save fuel (hence money and carbon) from day one, use existing fuel infrastructure, and can smooth the transition by familiarizing crews with battery systems. While hybrids alone cannot meet long-term climate goals (they still emit roughly half the CO_2 of diesel, which is too much by 2050 standards)[100][101], they are an excellent *bridging solution* for the 2020s and 2030s. The hybrid approach could secure early emission gains and operational savings while buying time for hydrogen tech to mature and for funding to materialize. Essentially, hybrids enable the Island railway to start the decarbonization journey immediately rather than waiting.

The **Lifecycle Cost analysis** indicated that when considering 30-year horizons, fuel costs dominate total expenses, meaning efficiency improvements (hybrid) or fuel switching (hydrogen) can yield substantial savings in the long term[102][103]. Under conservative assumptions, diesel had the lowest TCO, but under many plausible future scenarios (higher carbon prices, tech cost reductions) the gap narrows or reverses in favor of cleaner options. Additionally, when accounting for monetized externalities – the social cost of carbon and health impacts – the calculus shifts toward hybrids and hydrogen being more beneficial overall. In a societal cost-benefit sense, investing in the cleaner technology yields dividends in avoided climate damage and improved public health[82][83]. This aligns with findings from the broader literature and the Island's own BEMU (battery-electric) study, which found a **Benefit-Cost Ratio > 1 when including emissions and social benefits**[84][85].

Recommendation: A phased strategy that marries the immediate practicality of diesel/hybrid with a committed transition to hydrogen is recommended. In practical terms: - **Phase 1 (Next 5 years):** Rehabilitate priority segments of the corridor and launch service with available rolling stock (diesel or hybrid). Use this phase to build ridership and operational experience, while minimizing new emissions through interim measures (e.g. use biodiesel blends to slightly cut carbon intensity, implement anti-idling practices). - **Phase 2 (Mid 2020s–early 2030s):** Introduce pilot hydrogen trains in partnership with industry and government programs. Begin developing hydrogen fueling capacity on a small scale. Also, procure next-generation hybrid or dual-mode equipment as needed to expand service. - **Phase 3 (2030s):** Scale up hydrogen to full corridor service, incrementally replacing diesel/hybrids. By 2035, aim for the majority of trains to be hydrogen fuel cell powered, using locally produced green hydrogen (leveraging BC's clean electricity). Infrastructure like electrolyzers and refueling stations would be fully built out by this stage, potentially with capacity to spare (which could even supply other hydrogen vehicles on the Island, creating a regional hydrogen ecosystem). - **Phase 4 (2040):** Diesel usage ends (except perhaps for maintenance vehicles or backup units, if any). The system operates as a **zero-emission rail line**, contributing to provincial and national GHG targets. Any further expansions (like higher frequency or new routes) would use zero-emission equipment from the outset.

This roadmap aligns well with **CleanBC's timeline** – significant GHG reductions by 2030 (via hybrids and initial H_2) and virtually complete decarbonization by 2040[90]. It also provides a structured approach to investment: spreading costs over phases and learning by doing in the pilot phase reduces risk. The phased plan should be integrated with funding applications: e.g. seek federal green infrastructure grants for Phase 2 (hydrogen pilot) and for Phase 3 (full rollout) by demonstrating Phase 1 success and the emissions benefits.

In conclusion, Vancouver Island's rail corridor can become a **showcase of sustainable transportation**. By carefully evaluating and combining propulsion options, the Island can enjoy the economic and social benefits of restored rail service – improved mobility, tourism development, job creation – *while minimizing environmental footprint*. Choosing diesel may be cheapest today, but it would **sacrifice the long-term vision** and ultimately cost more in external harms and retrofits. Embracing hybrid and hydrogen technologies positions the project on the cutting edge, tapping into innovation and potentially attracting external support (as governments love funding "shovel-worthy" green projects). Technical analysis supports that a transition to zero-emission rail is feasible and can be achieved in alignment with maintenance cycles and budget planning. The result will be a 21st-century rail service that Islanders can be proud of: quiet, efficient, and clean – whisking passengers across the beautiful landscapes of Vancouver Island **with only water vapor for exhaust**, and forging a path for other regions to follow in rail decarbonization[96][97].

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