MSc Thesis

Energy System Modelling of Discrete Commodity Shipping as a Renewable Energy Export Strategy

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Preface

This report was written by me, a Sustainable Energy Technology student at Delft University of Technology, as part of my Thesis Project.

For my final project in this program, I chose to tackle a complex topic about commodity transport. With a strong focus on renewable energy throughout my studies, the challenge of energy system modelling, particularly in addressing a real-world issue, offered a fascinating area to investigate. Moreover, the project's emphasis on Linear and Mixed-Integer Programming, combined with the use of Python, aligned perfectly with my interests in both mathematics and programming.

Projects such as these are of immense significance as the world confronts the pressing need for clean energy solutions and the looming impacts of climate change. Managing the overproduction of renewable energy is becoming increasingly critical and finding efficient ways to transport surplus energy is essential to achieving a sustainable energy future.

Finally, I would like to thank my supervisors Stefan Pfenninger and Bryn Pickering for their help and support during my Thesis Project.

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Abstract

This report investigates discrete maritime aluminium transport as a strategy for exporting renewable energy from geographically isolated regions, using Iceland as a case study. A detailed Mixed-Integer Linear Programming (MILP) approach within the Calliope energy system modelling framework was used to capture critical operational logistics, including shipment scheduling, time delays, and fuel consumption. Two scenarios were analyzed: discrete maritime aluminium transport and continuous direct electricity transmission via submarine cables. The comparative assessment demonstrated that discrete aluminium transport delivered substantially more energy (10,625 TWh) at significantly lower total costs (USD 33.85 million) compared to direct electricity transmission (689.76 GWh at USD 96.72 million), despite the latter's advantage of continuous delivery and grid integration suitability. Additionally, the sensitivity analyses, involving variations in costs, operational periods, capacities, and fuel consumption, validated the robustness and linear scaling behavior of the models, confirming their reliability under diverse operational scenarios. The findings underscore discrete aluminium shipping as a flexible, scalable, and economically viable alternative to conventional undersea electricity transmission, particularly beneficial for remote islands like Iceland. Future research recommendations include enhancing model generalizability, integrating inventory management, refining fuel consumption estimates, and explicitly assessing environmental impacts.

Contents

1 Introduction

The urgent global challenge of climate change has led to a sweeping movement across countries and industries to drastically reduce greenhouse gas emissions and transition towards sustainable energy systems. In Europe, the European Union (EU) has set ambitious targets to achieve a climate-neutral economy by 2050, with energy system decarbonization at the forefront of these goals. Transitioning to low-carbon energy sources, however, is a complex task, involving significant trade-offs and operational challenges (Pickering et al., 2022). For instance, the intermittency of renewable energy sources, such as wind and solar power, creates variability in energy supply that complicates efforts to meet consistent demand. This variability is especially challenging in industries and applications that require stable, reliable energy supplies, such as the transport of energy-intensive resources across long distances.

As such, energy system optimization is imperative, with a key area in need of this being transport. To effectively address such a transport problem, advanced energy system modelling tools are required. One tool capable of building energy models is the Calliope framework, which also provides spatial and temporal optimization (Pfenninger and Pickering, 2018). However, while it is possible to use continuous power transmissions for modelling within the framework, it needs to be improved to handle more complex cases. One such case is the discrete transportation of energy carriers, within the maritime industry for example.

To effectively setup a test model within Calliope to apply these improvements to, a case study will be built focusing on Iceland. This country is a world leader in renewable energy, producing a majority of its total primary energy supply locally through energy-intensive processes powered primarily by hydropower and geothermal energy, which then gets exported in the form of aluminium. Although this makes Iceland one of the greenest producers of aluminium, transporting the aluminium to its primary markets in Europe requires significant energy. Maritime transport, which consumes fossil fuels and contributes to carbon emissions, is currently the standard method for moving aluminium from Iceland to Europe. As such, optimizing the aluminium transport process between Iceland and the Netherlands to minimize costs is a pressing priority for sustainable supply chain management. The aim of this report is to optimize the transport of renewable energy from Iceland to The Netherlands using discrete maritime aluminium transport, with an energy system modelling approach, and investigate potential trade-offs compared to other methods, such as power transmission.

The remainder of this report is organized as follows:

- Chapter 2 – Literature Review: This chapter explores the theoretical and methodological background relevant to this study. It discusses the limitations of existing transport modelling in energy systems, evaluates the integration of transport in decarbonized energy strategies, and presents recent developments in renewable energy export options, particularly for island systems. The chapter identifies key knowledge gaps and provides the rationale for adopting a Mixed-Integer Linear Programming (MILP) approach within the Calliope framework.
- Chapter 3 – Methodology: This chapter outlines the modelling approach developed to evaluate discrete aluminium transport as a renewable energy export strategy. It details the case study selection, model assumptions, and mathematical formulation, including custom constraints designed to represent discrete shipping events, fuel use, and transport delays. The implementation of the model in the Calliope framework is also described.
- Chapter 4 - Results: This chapter presents a comparison between continuous transmission of renewable electricity via an undersea cable and discrete event-driven aluminium transport. It evaluates aluminium flow patterns, shipping schedules, fuel consumption, and total system costs. Furthermore, sensitivity analyses are conducted to assess model robustness across various operational scenarios.
- Chapter 5 - Discussion: Providing a detailed discussion of the results, this chapter contextualizes the comparative assessment within existing literature, highlighting key policy implications, and critically reflecting on the modelling methods and potential improvements.
- Chapter 6 - Conclusion: The report concludes by summarizing the key findings, emphasizing their strategic significance, and outlining directions for future research.

2 Literature Review

This chapter presents a structured review of the existing literature to establish the theoretical and methodological foundation for modelling discrete, delayed transport of renewable energy in island contexts. First, the chapter provides a justification for improving transport modelling by highlighting significant limitations of conventional energy system optimization models, especially their inability to accurately represent discrete transport events and associated time delays, such as maritime shipment of energy-intensive products. Second, the chapter systematically examines recent methodological advances in energy system modelling and maritime transport optimization. Emphasis is placed on the suitability of Mixed-Integer Linear Programming (MILP) and the Calliope framework for addressing these modelling challenges. Collectively, the literature reviewed here outlines the current knowledge gaps and methodological requirements that justify and guide the development of the modelling approach used in this report.

2.1. Limitations of existing transport modelling in energy systems

Isolated renewable-rich regions like Iceland face unique challenges in exporting surplus energy. With no grid connection to continental markets, Iceland effectively embodies its renewable electricity in energy-intensive products (aluminium) for export (NER, 2024). However, shipping these products introduces discrete transport events and time delays that traditional energy system models struggle to represent. Most optimization frameworks assume continuous, instantaneous flows between regions, an approach suitable for power lines but not for discrete shipments by sea. For example, natural gas transport is typically modelled at a coarse time resolution in energy models (Fodstad et al., 2022), implicitly treating fuel delivery as continuous. This fails to capture the reality of maritime transport, where a ship must be loaded, sail for days, then unload, a process that cannot be approximated by a steady hourly flow. Existing energy system models rarely incorporate the timing of shipments or transit delays, often necessitating assumptions or separate scheduling simulations (Fodstad et al., 2022). This gap means that critical dynamics, such as scheduling a voyage when renewable-derived fuel is abundant, or stockpiling product until a ship returns, are overlooked. In short, conventional models lack in the case of island energy exports, justifying improved transport modelling that can handle discrete shipments and their delays.

Another limitation is the treatment of non-continuous decisions and binary events. Standard linear programming models avoid integer variables for tractability, but this forces oversimplifications like fractional shipping or instantaneous delivery. Delayed delivery can cause supply–demand mismatches if not modelled, and ignoring it can underestimate storage needs or fuel timing issues. Past studies have noted that integrating diverse temporal scales (production vs. transport schedules) in a single model is challenging and often omitted (Fodstad et al., 2022). Even in pipeline gas modelling, researchers have had to introduce MILP formulations to approximate non-linear or time-coupled constraints (Fodstad et al., 2022). Representing a cargo ship's departure and arrival inherently requires binary and time-linking constraints (e.g. a ship either sails on a given day or not, and arrives after a known transit time). Without such discrete modelling, an energy export scenario could be inaccurately represented as a continuous flow of energy, rather than a batched, delayed process. To address these shortcomings, a modelling approach that treats transport as a scheduled discrete event is crucial to accurately simulate the exports of renewable energy from an island via ship.

2.2. Energy system decarbonization and transport integration

Recent energy system studies underline the importance of integrating transport options into decarbonization strategies. For example, Pickering et al. (2022) examine pathways for a carbon-neutral European energy system that eliminates fossil fuel imports, using a high resolution optimization model. Their work explores the diversity of configurations needed to meet demand with renewables under spatial and technical constraints, highlighting trade-offs in network expansion, storage, and resource allocation. Notably, while Europe's case assumes grid interconnections, the study's attention to trade-offs and timing is relevant to an island context. It suggests that when and how energy is transported can significantly affect costs and feasibility. The methodologies in such continental models, often built in flexible frameworks like Calliope, demonstrate how high spatial and temporal resolution can capture complex supply chains. By customizing these frameworks, one can evaluate unconventional transport modes. In fact, the European scenarios indirectly support this approach: they show that eliminating fossil fuels requires not just local renewable deployment but also smart allocation of energy across regions and time. In an Iceland-to-Europe setting, this translates to intelligently scheduling aluminium shipments (as "energy carriers") to align with renewable availability and demand. The literature thus motivates treating maritime transport as an integral part of the energy system, rather than an external logistics issue.

2.3. Renewable energy integration in island systems

Small island energy systems are increasingly integrating renewable energy, driven by goals of sustainability and energy independence. Islands often have abundant wind, solar, or marine resources but face unique challenges due to isolated grids, limited capacity, and high dependence on imported fossil fuels. Achieving high renewable penetration requires careful balancing of the intermittent supply with demand, using strategies such as energy storage, demand management, or grid stabilization measures (Ochoa-Correa et al., 2025). In a systematic review of pathways to 100% renewable island systems, Ochoa-Correa et al. note that advanced storage solutions,including batteries, hydrogen fuel, pumped hydro, and flywheels, are critical for maintaining stability in isolated grids. However, they also found that direct comparative analyses of these long-duration storage options in island contexts remain scarce, indicating a gap in holistic evaluation.

A common issue in island grids is curtailment of renewable generation during periods of oversupply. Without mainland grid connections, excess solar or wind energy may be wasted if not stored or converted. Case studies demonstrate that hydrogen production can absorb surplus power and enhance grid stability; for example, pilot projects on the Faroe Islands and Cape Verde use wind-powered electrolysis to create hydrogen as a long-term energy store, reducing reliance on diesel generators (Ochoa-Correa et al., 2025). Many islands are pursuing 100% renewable energy scenarios by combining multiple resources with storage – yet reaching this goal can produce periods of overproduction relative to local demand. Rather than curtailing valuable clean energy, the concept of energy export has emerged: an island with plentiful renewables could generate more electricity than it needs and transport the excess off-island. This prospect has prompted research into how islands might serve as energy exporters, turning a variability challenge into an economic opportunity (Xu et al., 2023). For instance, Xu et al. modelled a hypothetical "energy-rich" island and found that exporting surplus renewable power is potentially viable, especially if done through cost-effective pathways. Overall, the literature underscores that island renewable integration must address intermittency and oversupply, setting the stage for solutions that either store the extra energy or transport it elsewhere.

In another region-specific analysis, Verrascina (2022) uses Calliope to model the energy transition of Sardinia as it phases out coal and integrates renewables. This study demonstrates the flexibility of the Calliope framework in regional scenarios, exploring pathways for Sardinia's transition while accounting for renewable resource variability. The successful application of Calliope for Sardinia is relevant for this report, which uses the same framework to model aluminium transport and fuel use between Iceland and the Netherlands. This case shows Calliope's effectiveness in integrating localized renewable sources into an island's energy system, aligning with this report's goal of representing Iceland's renewable energy surplus and its impact on fuel requirements for maritime transport. Importantly, when direct grid interconnections are not feasible, recent research emphasizes converting surplus renewable electricity into transportable fuels like hydrogen as a strategic alternative for isolated systems. Non-interconnected areas (islands with no mainland grid link) can leverage such carriers to "export" energy, underscoring the rationale for Iceland's indirect energy export (e.g. via aluminium or hydrogen). These insights reinforce the justification for modelling an island's surplus energy transport, guiding the development of a system that balances local renewable integration with export-oriented use of that energy.

2.4. Maritime transport optimization and fuel efficiency

The field of maritime transport optimization provides tools and insights applicable to energy cargo scheduling. A body of work has focused on reducing shipping costs and emissions through optimal routing, scheduling, and vessel deployment. For example, Wang and Wang (2021) address liner shipping operations by developing a MILP model to schedule heterogeneous vessels on a route, optimizing their departure times and speeds. This kind of operational research, while centered on container ships, demonstrates the value of discrete scheduling for cost minimization, achieving measurable savings (their model cut total costs by 5% in a case study). The principles carry over to energy transports: just as container shipments benefit from optimized timing and vessel choice, aluminium exports can be scheduled to minimize fuel use and waiting time. Moreover, maritime decarbonization studies emphasize fuel efficiency techniques (like slow steaming and routing) to cut emissions. These require modelling the interplay between fuel consumption and schedules, which is a linkage very relevant when the fuel itself is produced from renewables. If ships are to use climate-neutral fuels (e.g. hydrogen or ammonia made in Iceland), the timing of fuel production and refuelling becomes a critical optimization aspect. Researchers have begun to explicitly consider such couplings. For instance, a recent open-source model was developed to assess the costs of shipping hydrogen-based fuels over long distances (Schuler et al., 2023), reflecting growing interest in transporting renewable energy in chemical form. Although that model was primarily a cost calculator, it reinforces the idea that shipping routes, fuel technology, and energy availability must be evaluated together in system planning. These studies collectively underscore that optimizing maritime transport, whether for goods or energy commodities, hinges on careful scheduling and integration with energy supply dynamics.

Groppi et al. (2022) explore various renewable fuel solutions for a small island's maritime transport sector and evaluate these within their EPLANoptMAC model. Focusing on the island of Favignana, their work provides insights into decarbonizing ship-based transport in limited geographic areas with local renewable fuel production. This study used a heuristic optimization approach to optimize the island's transportation energy mix, identifying cost-effective solutions while meeting operational constraints. The challenges of modelling discrete transport events (ship voyages) and fuel consumption align well with Groppi's methodology, emphasizing the need for flexible energy models capable of evaluating both fuel demand and renewable integration in transport-reliant regions. Işıklı et al. (2020) further contribute to this area by developing statistical models to predict ship fuel consumption based on operational factors such as speed and distance. Their work underscores the importance of accurate fuel consumption estimation, which is critical for representing fuel demand in maritime aluminium transport. The methodology presented by Işıklı and colleagues aids this report's modelling of fuel use by providing insights into the operational variables affecting fuel efficiency. By incorporating such empirical models, the optimization could ensure realistic fuel use estimates, supporting a cost-effective and low-carbon transport solution.

Beyond improvements in operational efficiency, recent literature highlights the adoption of carbon-free fuels in shipping as a key decarbonization strategy. One major route for exporting an island's surplus renewable energy is to convert it into transportable energy carriers and ship it via maritime routes. Green hydrogen and green ammonia are the most discussed zero-carbon carriers, as they can be produced from water and air using renewable electricity (power-to-X) and then shipped to markets for use as fuels or feedstocks. Converting electricity into chemical form enables long-distance transport and seasonal storage of renewable energy (Joyo et al., 2025a). This approach leverages existing global shipping infrastructure: ammonia, for example, is already widely traded as an industrial chemical, and liquefied hydrogen shipping technology is emerging. The process, however, incurs energy losses and added cost at each conversion step, from electrolysis, compression or liquefaction, to chemical synthesis (for ammonia), so researchers have focused on identifying the most efficient and economic carrier for a given context.

Multiple comparative studies examine the merits of different hydrogen-based fuels for maritime transport. Hong et al. (2021) performed a broad analysis of hydrogen delivery methods, including compressed H_2 gas, liquefied hydrogen, ammonia (NH_3), and liquid organic hydrogen carriers (LOHC like methylcyclohexane), evaluating each in terms of energy efficiency, greenhouse gas emissions, and cost (Joyo et al., 2025b). A consistent finding is that distance matters in choosing the optimal carrier. For shorter transport distances or smaller scales, direct hydrogen (especially in compressed or liquid form) can be viable; but as distance grows, the efficiency penalties (e.g. boil-off losses for liquid H_2, or the energy cost of compression/refrigeration) become prohibitive. Cava (2024) conducted a multi-criteria analysis of hydrogen supply chains and found that liquid hydrogen is only viable for short-range transport, as its overall efficiency and economics degrade rapidly with longer distances. In contrast, green ammonia often emerges as the most competitive carrier for long-distance shipping of renewable energy. Ammonia carries hydrogen in a chemically bound form, which is easier to ship and store (liquid at moderate pressure or -33°C) compared to cryogenic liquid H_2, and it leverages established handling practices. The trade-off is that ammonia synthesis and later cracking (if converting back to H_2) introduce energy losses, but for intercontinental distances the literature suggests ammonia's benefits outweigh those losses in many cases.

Even within the category of hydrogen-derived fuels, the choice can depend on infrastructure and end-use. Some studies highlight that if the importing end can directly use ammonia (for example in power generation or as ship fuel), it avoids the need to convert back to hydrogen, strengthening ammonia's attractiveness (Thyssenkrupp, 2022) (Spatolisano et al., 2024). Others have explored methanol or synthetic methane as alternative carriers, though these involve carbon inputs and are typically less emphasized in the zero-carbon context. Overall, the consensus is that no single carrier is universally best. A recent techno-economic analysis by Joyo et al. (2025b). assessed offshore wind energy converted to hydrogen vs. ammonia and transported via either pipelines or ships. Production costs remain high for green hydrogen (€6.7–9.8 per kg, or €0.20–0.29/kWh) and green ammonia (€1.9–2.8 per kg, or approximately €0.37–0.55/kWh), reflecting current technology and energy prices. Importantly, that study found transport mode "tipping points": for distances up to a few hundred kilometres, pipelines are more cost-effective than shipping for both H_2 and NH_3, but beyond 500 km shipping becomes necessary and economically favourable. This aligns with other findings that a fixed pipeline (or cable) is preferable for short, high-volume routes, whereas seaborne transport gains advantage at longer distances or when flexibility is needed. A long-range analysis by Spatolisano et al. (2024) comparing HVDC electric transmission to hydrogen pipelines concluded that improving capacity factor and scale is critical to drive down costs, and at very long distances (roughly 4,000 km) delivered hydrogen costs around \$7–10 per kg, which is substantial but potentially achievable under optimal conditions (Miao et al., 2021). Their work underscored that a fully renewable supply chain will require high utilization (few idle periods) to be economic, which is a recurring theme in these studies.

In summary, the maritime transport of renewable energy carriers is deemed technically feasible but comes with significant energy conversion losses and capital costs. Common findings across the literature are that green ammonia is a promising vector for exporting large renewable surpluses over long distances due to its relative ease of transport, and that green hydrogen (especially liquefied) can serve shorter routes or niche applications (Cava, 2024). Research also highlights practical challenges, e.g. hydrogen embrittlement in pipelines and tanks, ammonia toxicity, and the need for an international safety framework, but these are gradually being addressed as pilot projects move forward. The first international liquid hydrogen shipment was demonstrated in 2022 (Australia to Japan), and several projects are underway to ship green ammonia to energy-importing countries in Asia and Europe. These developments, supported by the literature's techno-economic analyses, reinforce the idea that maritime export of renewable energy is viable, provided the right carrier is chosen for the distance and scale in question. However, the costs remain high with current technology, indicating a need for optimization and innovation to close the gap between renewable-rich islands and global energy demand centres (Joyo et al., 2025a) (Spatolisano et al., 2024).

2.5. Submarine power cables for energy export

An alternative to shipping energy as molecules is to export electricity directly via submarine power cables. Undersea electrical interconnections have long been used to link islands to mainland grids or to connect offshore renewables to onshore networks. Modern high-voltage direct current (HVDC) cables are the preferred technology for bulk power transmission over long distances, due to their lower losses and greater stability compared to HVAC (high-voltage alternating current) for submarine routes. Typical loss rates for HVDC are on the order of only 3.5% per 1,000 km, significantly better than HVAC cables (6–7% per 1,000 km) (Spatolisano et al., 2024). This high efficiency makes HVDC export attractive for relatively long distances, and numerous projects in Europe and elsewhere have implemented subsea HVDC links in the range of a few hundred kilometres (for example, linking offshore wind farms or connecting islands like Malta, Sicily, Crete, and others to mainland grids). When an island's renewable generation exceeds its demand, exporting electricity via cable allows real-time transfer of that surplus to external grids, effectively treating the island as a power plant feeding a larger network (Xu et al., 2023).

The feasibility of submarine cables depends on geography and economics. Installation of undersea cables involves high upfront costs, including not only the cable manufacturing but also laying the cable and converter stations at each end. These costs scale roughly with distance and capacity; thus there is a distance horizon beyond which cables become prohibitively expensive or technically challenging. The literature documents dramatic examples: the proposed Australia–Singapore HVDC mega-project would span about 3,200 km and reach ocean depths near 1,900 m, which introduces immense technical hurdles. Gordonnat and Hunt (2020) provide a holistic analysis of this case, identifying key challenges such as the logistics of manufacturing and transporting extremely long cables, deep-sea installation in rough terrains, and coordinating multiple suppliers and cable-laying vessels. They conclude that such an intercontinental link, while possibly offering huge benefits (exporting Australia's vast solar resources to Southeast Asia), is "very ambitious" and would require unprecedented levels of project integration and risk management. This underscores that ultra-long subsea inter-connectors are at the edge of current capabilities. More common are shorter links (tens to low hundreds of kilometres) which are already proven. For those, the main considerations are cost-effectiveness and utilization: an expensive cable must carry a high and steady load (high capacity factor) to justify its investment (Spatolisano et al., 2024).

Comparative studies between cables and chemical carriers help delineate their respective niches. Xu et al. (2023) examined an island exporting energy either as electricity (via HVDC cable) or as hydrogen fuel, optimizing the island's energy system for each case. Their model, which integrated multiple renewables (solar, wind, wave, biomass) and even accounted for heating and hydrogen uses on the island, found that exporting electricity was more cost-effective than exporting hydrogen for the scenario analysed. Specifically, the optimal solution was to install an HVDC link to deliver 51 GWh of surplus electricity annually to a mainland, at an estimated annualized cost of ¥292 million (€42 million) (Xu et al., 2023). This was cheaper than the equivalent export of energy via hydrogen, even when considering the necessary infrastructure and conversion losses for the hydrogen route. The implication is that, when geography permits (the mainland is not too distant), a direct cable connection can be the most economical and straightforward method to export renewable energy. Electricity export avoids double conversion (electricity to fuel and back to electricity) and can take advantage of the high efficiency of modern HVDC transmission (Spatolisano et al., 2024).

On the other hand, when distances grow or physical interconnection is infeasible (e.g. small island nations in mid-ocean with no nearby grids), the cable option falls away and maritime shipping of carriers becomes the default. Even for moderate distances, one must consider redundancy and risk: undersea cables are single points of failure and can be disrupted (by anchoring accidents, earthquakes, etc.), whereas shipping provides more flexible and diversifiable routes. Some researchers have pointed out that gas pipelines can be seen as an analog to cables, for instance, an undersea hydrogen pipeline could directly send chemical energy to shore. A study from Nanyang Technological University noted that for offshore transmission, hydrogen pipelines tend to be cheaper than undersea HVDC cables at equal capacity (partly because undersea cables need costly insulation and protection), though on land the economics can be closer to parity around the 4,000 km range (Spatolisano et al., 2024). The break-even distance between exporting as electricity or as molecules is a moving target that depends on technology costs, but multiple analyses concur that there is a crossover point: relatively short distances favour cables, and very long distances force a shift to energy carriers (Joyo et al., 2025a).

Among proposed interconnection projects, the Iceland-UK HVDC cable (IceLink) has gained significant attention due to its ambitious goal of linking Iceland's renewable energy resources directly to the UK electricity market. Estimated project costs for IceLink have ranged significantly depending on design specifics, but recent estimates suggest costs in the region of 3 to 4 billion Euros for approximately 1,000 km of HVDC cable capable of transmitting up to 1,000 MW of power. The central cost scenario includes a 1,200 km long cable (Askja, 2016). While HVDC technology offers high transmission efficiency, typically around 3.5% losses per 1,000 km, the substantial upfront infrastructure investments and challenges associated with deep-sea cable laying and maintenance must also be considered. A minimum strike price of approximately 130 USD/MWh is expected.

In conclusion, submarine power cables are a highly efficient means of exporting renewable power from islands, with existing technology capable of hundreds of kilometres of transmission. They shine in scenarios of continuous high power transfer and when an island is geographically close enough to a larger grid. The method is proven and has the advantage of instant power delivery and grid support (helping stabilize both the island and mainland system). The downsides are heavy capital cost and limited applicability over extreme distances or geographies. The literature thus positions cables as a crucial part of the toolkit for renewable islands, but one that must be evaluated against alternative pathways (like fuels) especially as the island-to-market distance grows beyond regional scales (Spatolisano et al., 2024).

2.6. Optimization models for energy transport scheduling and logistics

To determine the best strategies for exporting renewable energy, researchers have developed a variety of optimization models and decision-support tools. These models aim to capture the complex techno-economic trade-offs in scheduling production, storage, and transport of energy from islands. The methodologies range from high-level scenario analysis to detailed operational scheduling, often borrowing techniques from energy systems optimization, supply chain logistics, and power systems planning.

A prominent approach in the literature is to formulate a capacity expansion and dispatch optimization, where the mix of generation, storage, and export infrastructure is chosen to minimize total costs or maximize net benefits. For example, Xu et al. (2023) built a comprehensive island energy system model using the P-graph framework, integrating electrical, thermal, and hydrogen subsystems. The model optimized the island's investments and operations to minimize a multi-component objective function that included capital costs, operating costs, and even a carbon footprint cost (environmental externality). By considering both economic and environmental criteria, such models can identify "optimal dispatch structures", in Xu's case, indicating that a certain level of export via cable was preferred over hydrogen under given assumptions. Other studies extend the objective to multi-criteria decision analysis. Cava (2024), for instance, evaluated hydrogen export routes with a weighted assessment of energy efficiency, economic cost, geopolitical risk, and environmental impact. Their multi-criteria analysis allowed them to rank options (e.g. importing country A via ammonia vs. country B via H_2) in a more holistic way, reflecting real-world decision factors beyond pure economics.

When it comes to operational scheduling, determining how an island's energy export system should run day-to-day or hour-to-hour, the literature reveals significant challenges and emerging solutions. A key complexity is the temporal mismatch: renewable generation is variable, while export logistics (such as ship departures or cable transmission schedules) may need to be planned or buffered with storage. Simple deterministic models often assume idealized steady-state operation (e.g. constant hydrogen production to fill a tanker); however, real systems require flexibility and contingency planning. Researchers have begun to apply advanced optimization techniques to handle this. Liu (2024) introduced a two-stage distributively robust optimization (DRO) model for a port energy hub that produces hydrogen and converts it to ammonia for export. The two-stage setup optimizes day-ahead production and storage scheduling, then adjusts in real-time (intra-day) as uncertainties in renewable supply are realized. By using DRO, the method guards against worst-case deviations in wind/solar output without being overly conservative. The results showed that an hourly scheduling interval was feasible for smoothly operating the ammonia synthesis process, and that the DRO-based schedule achieved a good balance between economic performance and robustness against fluctuations (Liu, 2024). This kind of approach is highly relevant to island export scenarios, where uncertainty in renewable generation is a primary concern and shipping schedules or grid commitments must be met reliably.

Another thread of research deals explicitly with the logistics of maritime transport. For instance, conceptual studies on “hydrogen vessel” systems propose using ships as movable storage to pick up hydrogen from an island and deliver it to a mainland on a regular schedule (Sui et al., 2024). Optimization models for such systems need to decide on fleet size, tanker capacity, and sailing schedules alongside the production rate of hydrogen and the use of intermediate storage tanks. These are effectively supply chain optimization problems with energy-specific constraints. While literature directly focusing on island export logistics is still limited, analogous problems are tackled in hydrogen supply chain papers. Common findings are that synchronization between production and transport is crucial: a mismatch can lead to either curtailed production (if storage is full and no ship is available) or idle ships (if not enough hydrogen is ready), both of which increase cost. Ensuring a steady output (high capacity factor for electrolyzers or cable throughput) was frequently noted as key to lowering unit costs of delivered energy (Miao et al., 2021). To address this, some models incorporate demand-side management or flexible operation. For example, over-producing hydrogen when renewable output is high and storing it, then drawing down storage when output calms, to keep exports steady.

2.7. Mixed-integer optimization in energy system models

Methodologically, most optimization models in this domain are formulated as mixed-integer linear programs (MILP) or non-linear programs capturing both investment decisions (what infrastructure to build) and operational decisions (how to dispatch energy flows). The turn to Mixed-Integer Linear Programming (MILP) is a natural evolution as we introduce binary variables for shipments and other on/off decisions. MILP is widely used in energy systems research whenever discrete choices are involved, from unit commitment in power systems to infrastructure placement and supply chain design. For instance, Silva et al. (2024) formulate a MILP model for optimal design of a future hydrogen supply network, including production and transportation infrastructure. Similarly, multi-period MILP models have been applied to green hydrogen supply chains to decide facility locations, transportation modes, and storage, all while minimizing cost or emissions. These examples demonstrate that MILP optimization can effectively handle the combination of investment decisions and operational scheduling in an energy context. The trade-off is computational complexity, but modern solvers and careful model formulation often make it tractable for moderate scales. In the case of transporting Iceland’s energy via ships, the decision to send a shipment in a given time period is binary, as is the decision to use (or not use) a particular fuel tank at a given time. Using MILP allows the model to rigorously choose optimal shipping schedules (an inherently integer problem) alongside the continuous decisions of energy production and consumption. This integrated approach is supported by recent studies: Wang et al. (2022) integrated vehicle routing with power system reconfiguration in a MILP, and others have noted that combining operational scheduling with planning models is achievable through integer programming at the cost of greater solution times (Fodstad et al., 2022). Given the moderate scale of a two-node Iceland–Netherlands system, a MILP approach is feasible and warranted for the accuracy gains. By capturing the on/off nature of shipments and the timing of fuel use, the model could explore strategies like skipping shipments during low renewable periods or sending extra shipments when excess power would otherwise be curtailed. No purely linear model could capture these dynamics, hence the need for MILP in the transport optimization.

To incorporate discrete transport events in energy models, some researchers have proposed novel scheduling frameworks. A particularly relevant concept is the “separable” scheduling of mobile energy resources introduced by Wang et al. (2022). In their study on distribution grid resilience, Wang and colleagues propose a Separable Mobile Energy Storage System (SMESS) approach. “Separable” denotes that the mobile carrier (e.g. a truck or ship) and the energy payload (battery modules, or by analogy, shipments of aluminium) are treated as independent components. This allows a single carrier to transport multiple batches in sequence and deploy them optimally, rather than assuming a fixed continuous flow. Crucially, they formulate the joint routing and scheduling of the carrier and modules as a MILP problem. The SMESS framework explicitly models each trip as a discrete event and includes time delays for moving resources, closely mirroring the challenges of batch transport in our island scenario. By separating the vehicle’s movement from the resource itself, the model can decide, for example, to delay a trip until enough fuel is available or to reroute a tanker to where it’s most needed. This idea directly informs the present report: we can treat the aluminium shipments (energy carriers) and the fuel supply for ships as interdependent but distinct elements, scheduled through binary decision variables. In practice, that means the model can decide to send a ship only when certain conditions are met (adequate aluminium stock, lower fuel price due to high renewable output, etc.), rather than enforcing a regular continuous delivery. Their MILP scheduling responded to emergencies by rapidly redeploying mobile units, thus highlighting system resilience and flexibility. In a non-emergency context like Iceland’s exports, the same emphasis on flexibility translates to economic and environmental gains: the model can defer shipments during dips in renewable generation and accelerate them when surplus power makes synthetic fuel cheap.

This ensures that transport is synergistic with the energy system's state, a strategy supported by the separable scheduling literature. The takeaway is that discrete-event MILP models have been successfully used to coordinate mobile energy carriers with supply conditions, validating the use of this approach. By adopting similar MILP scheduling, the aim is to handle the complexity of tracking ship location, departure/arrival timing, and fuel consumption within a unified optimization framework.

Zhang et al. (2014) present a multi-objective optimization framework that balances economic and environmental objectives within supply chain management. Their focus on minimizing both cost and carbon emissions offers a useful basis for multi-criteria models, which seeks to balance sustainability goals with operational fuel costs in a discrete energy transport system. The methods for evaluating trade-offs in Zhang et al.'s work provide guidance for structuring the model's objectives and constraints. In particular, their approach of simultaneous cost-carbon minimization supports the aim to integrate sustainable practices into an energy-intensive supply chain (the shipping of aluminium), ensuring that financial costs and emissions are jointly optimized.

Among the modelling tools referenced in the literature, the Calliope framework emerges as a particularly suitable platform for implementing MILP-based energy system models. Designed for high temporal and spatial resolution, Calliope supports both linear and mixed-integer formulations and allows the definition of custom constraints, capabilities which are crucial for capturing complex dynamics such as renewable variability, discrete transport schedules, and time delays (Pfenninger and Pickering, 2025). Its open-source structure has been successfully used in a variety of regional and national energy system studies (Pfenninger and Pickering, 2018), and offers a transparent and extensible environment for scenario development. In the context of this report, Calliope's flexibility enables the integration of custom MILP constraints derived from the separable scheduling literature, allowing discrete maritime aluminium transport to be embedded directly within a broader energy system optimization. This positions Calliope not only as a computational tool, but also as a modelling paradigm that aligns with the methodological needs highlighted in recent research on island energy exports.

Across these studies, the common objective is to minimize the levelised cost of delivered energy or maximize the net revenue from exports, while satisfying technical constraints. Many find that with current costs, exporting renewable energy (whether via cable or carrier) is marginally economic at best, but there is optimism that with technology learning curves and optimal operation, it can be made competitive with conventional energy trade (Joyo et al., 2025a). The use of optimization models is crucial for pinpointing what combination of factors (e.g. larger electrolyzers vs. more storage vs. more frequent shipments) can yield the best outcome. They also help identify sensitivities,for instance, how results change if hydrogen prices drop or if shipping fuel costs rise, which is important for robust planning. In summary, optimization-based studies provide valuable guidance on the design and operation of island energy export systems, though they must continually evolve to incorporate uncertainties, non-linear process dynamics, and multi-criteria objectives that reflect the real-world decision environment.

2.8. Literature Synthesis and Methodology Alignment

This section synthesizes the reviewed literature and clarifies which modelling elements have been incorporated into the present work. While Chapter 2 discussed a wide range of studies and approaches relevant to renewable energy export and discrete maritime transport, it is important to highlight which specific insights have directly informed the model implementation.

A central methodological choice in this report is the adoption of the separable scheduling framework proposed by **Wang et al. (2022)**. Their Mixed-Integer Linear Programming (MILP) model allows explicit scheduling of mobile energy carriers and resource payloads, capturing the discrete nature of departure and arrival events alongside operational constraints. This methodology aligns directly with the requirements of modelling aluminium transport between Iceland and the Netherlands, where shipment frequency, delay, and ship availability must be treated as binary or time-coupled variables.

As such, their formulation was adapted to implement the state-dependent ship scheduling and transport constraints in the **Calliope** framework, which had its capabilities demonstrated by **Pfenniner and Pickering (2018)**. The framework cleanly separates the data from the mathematical formulation, making it straightforward to add our new transport constraints. Moreover, using an existing framework like Calliope ensures that the model aligns with best practices in energy systems modelling, and results can be compared or extended in the future. In summary, Calliope's multi-node, multi-period optimization approach, augmented with MILP features, provides an ideal platform for this subject. The reviewed literature supports this choice, thus insights from high-resolution energy modelling, maritime optimization, and MILP scheduling of energy transports are combined into a coherent modelling strategy. This literature foundation gives confidence that a MILP-driven Calliope model can capture the complex interaction between Iceland's renewable energy overproduction, the timing of fuel and aluminium production, and the logistics of maritime transport, thus filling the gap identified in current energy system models.

The literature on energy export via undersea power cables provides a critical comparison to the aluminium shipping pathway. **Xu et al. (2023)** model scenarios involving either hydrogen export or cable-based electricity transfer and conclude that HVDC cables are preferable at short-to-medium distances. **Gordonnat and Hunt (2020)** and **Spatolisano et al. (2024)** evaluate mega-projects such as Australia–Singapore and detail the technical and financial barriers to ultra-long cable links. Of particular relevance is the **IceLink project** between Iceland and the UK (Askja, 2016), estimated to cost €3–4 billion. These works highlight that while HVDC export is efficient for regional connections, it faces limitations in deep-sea or intercontinental contexts. This reinforces the value of modelling discrete shipping as an alternative export mode for Iceland.

While the empirical fuel modelling work of **Işıklı et al. (2020)** provides valuable insights into operational fuel consumption based on ship speed and distance, such granular regressions are not implemented in this version of the model. Instead, a simplified but operationally meaningful fuel consumption rate is applied. Nonetheless, the inclusion of their methodology points to a promising direction for future work, particularly in enhancing model realism through data-driven operational energy use. Similarly, studies such as **Ochoa-Correa et al. (2025)** and **Fodstad et al. (2022)** offer practical insights into island-scale renewable strategies and discrete pipeline scheduling respectively. Their methods were not implemented directly, but they conceptually reinforced the need for flexible, modular MILP frameworks that can accommodate interdependent scheduling, storage, and transport decisions, providing useful framing, assumptions and background.

Table 2.1 summarizes the literature reviewed in this chapter, identifying the modelling techniques used, their key contributions, and whether they were implemented in the current work or suggested for future development.

Table 2.1: Summary of relevant literature and implementation status

Study	Modelling Approach	Key Contribution	Used	Future Work
Wang et al. (2022)	MILP with separable scheduling	Discrete shipping model with time delays	Yes	–
Pfenninger and Pickering (2018)	Calliope open-source energy system modelling	High-resolution temporal/spatial modelling with custom constraints; framework used for this report	Yes	–
Askja (2016)	Project report	IceLink HVDC feasibility and cost analysis	Yes	–
Fodstad et al. (2022)	MILP for gas pipelines	Discrete fuel delivery and time-coupled flow constraints	Conceptually	–
Silva et al. (2024)	MILP for H_2 networks	Design and dispatch of energy infrastructure	Conceptually	–
Zhang et al. (2014)	Multi-objective MILP	Cost-emissions trade-offs in supply chains	Conceptually	–
Ochoa-Correa et al. (2025)	Systematic review	Island renewable strategies and storage options	Conceptually	–
Verrascina (2022)	Calliope model	Renewable transition for Sardinia	Conceptually	–
Xu et al. (2023)	P-graph, scenario model	Electricity vs. hydrogen export optimisation	Conceptually	–
Spatolisano et al. (2024)	Techno-economic comparison	HVDC vs. hydrogen pipelines for long distances	Conceptually	–
Işıklı et al. (2020)	Empirical regression model	Fuel use estimation based on operational parameters	No	Yes
Groppi et al. (2022)	Heuristic optimisation	Island-scale renewable shipping solutions	No	Yes
Gordonnat and Hunt (2020)	Case study analysis	Deep-sea HVDC cable risks (e.g. Australia–Singapore)	No	Yes
Cava (2024)	Multi-criteria evaluation	Optimal energy carrier selection for export	No	Yes
Joyo et al. (2025a,b)	Techno-economic analysis	Costs and tipping points for fuel shipping routes	No	Yes
Liu (2024)	Two-stage robust optimisation	Scheduling hydrogen under renewable uncertainty	No	Yes
Sui et al. (2024)	MILP for hydrogen vessels	Synchronisation of storage and ship scheduling	No	Yes
Hong et al. (2021)	Comparative efficiency study	Performance of hydrogen/ammonia/LOHC pathways	No	Yes

This synthesis bridges the literature review and methodology by clarifying that the report's model is not a generic implementation of MILP in Calliope, but is explicitly adapted from established, peer-reviewed frameworks for scheduling energy exports with operational realism. Elements such as time delay constraints, discrete departure logic, and resource-state tracking draw directly from this foundation.

Techniques not implemented (e.g., empirical fuel models or robust optimisation under uncertainty) represent extensions that could enhance model fidelity in future versions. Incorporating these could allow for better representation of stochastic energy availability, more detailed vessel operations, and scenario planning under uncertainty, which are areas that remain open in current literature.

Despite the progress in this field, there still remain some notable gaps and challenges in the literature:

- Limited focus on islands as exporters: Most renewable energy research on islands has aimed at self-sufficiency and replacing local fossil generation. The notion of regularly exporting large energy surpluses is relatively new. Real-world examples are scarce, so studies must simulate hypothetical scenarios. This gap underlines the importance of models and case studies to explore how an "energy exporting island" can function.
- Integrated modelling of diverse export modes: Few works compare electricity export and hydrogen/ammonia export within the same optimization framework. Xu et al. (2023) is one such example, but it was a specific case with its own assumptions. A more generalized model that can endogenously choose between cable vs. shipping investments (or a combination) under various conditions would provide deeper insight.
- Operational logistics and scheduling: The challenges of scheduling, e.g. timing hydrogen production to ship departure, managing storage tank levels, maintenance downtime for cables or electrolyzers, are often abstracted away in models. There is a gap in detailed logistics modelling for island energy export. Incorporating elements like ship routing, queuing, and repair schedules into energy models is complex, but necessary for realistic planning.
- Uncertainty and resilience: Many studies use deterministic assumptions (fixed demand, fixed renewable profiles, single values for costs). Real systems will face uncertainty in renewable output (weather variability), market prices for hydrogen or electricity, and potential disruptions (a cable fault or a delayed ship). The literature has begun to address this with robust and stochastic optimization techniques (Liu, 2024), but applications in the specific context of island energy export are still limited.
- Environmental and regulatory considerations: While most academic papers focus on techno-economics, practical deployment will hinge on environmental impacts (e.g. ammonia spills risk, undersea cable impacts on marine life) and regulatory frameworks (e.g. cross-border energy trading agreements, safety codes for hydrogen fuelling). These aspects are often mentioned qualitatively but not deeply analysed in optimization studies. This represents a gap between modelling and real-world implementation.

In pulling these threads together, it is evident that modelling an island's energy export system involves bridging the power systems domain and the maritime transportation domain, each with its own complexity. Challenges include handling multi-scale dynamics (fast electrical fluctuations vs. slow shipping cycles), the combination of integer decisions (number of ships, yes/no build cable) with continuous operation decisions, and ensuring the model remains computationally tractable. The literature provides pieces of this puzzle (e.g. power flow models, supply chain models, etc.), but a comprehensive model must intelligently simplify certain aspects to solve the whole. Recognizing these challenges in prior work strengthens the rationale for the report's methodological choices.

In conclusion, the systematic survey of current research confirms that exporting locally generated renewable energy from an island is technically feasible and can be economically reasonable under favourable conditions, but choosing and operating the right export pathway is a complex decision. Common findings, such as the superiority of cables at short range and ammonia at long range, or the importance of high utilization, provide guiding principles. At the same time, gaps in existing studies, especially regarding integrated, detailed modelling, leave room for contributions. This report's approach is therefore justified as an effort to fill those gaps by developing and applying an optimization framework that captures the salient trade-offs and constraints identified in the literature. By doing so, the work will help advance understanding of how island systems can optimally contribute to the broader clean energy transition, turning their renewable abundance into an exportable resource for global benefit.

3 Methodology

This report uses a case study focused on Iceland and the Netherlands to explore the optimisation of aluminium transport within a climate-neutral energy framework. These two countries were selected based on Iceland's unique energy profile and the established trade relationship between Iceland as a major aluminium exporter and the Netherlands as a primary importer. The aim is to develop an optimization model that minimizes costs associated with transporting aluminium between Iceland and the Netherlands. By modelling a two-node system where aluminium is produced in Iceland using renewable energy and transported by ship to meet demand in the Netherlands, this report explores the trade-offs with possible alternatives such as electricity transmission via undersea cables. The model is constructed using the Calliope framework.

3.1. Case study rationale

Iceland is uniquely positioned as an ideal location for examining renewable energy-driven production due to its abundant natural resources and overproduction of renewable energy. Unlike many countries in Europe, Iceland derives the majority of its total primary energy supply locally from renewable sources, particularly geothermal and hydropower. Iceland produces approximately ten times as much electricity per resident as the European Union average, making it one of the most energy-rich nations per capita (Askja, 2025). However, this overproduction poses the challenge of effectively utilising the surplus energy, as direct export of electricity from Iceland to Europe is technically and economically challenging due to its geographic isolation and the high costs associated with long-distance electricity transmission infrastructure.

One solution Iceland has adopted is to export this surplus renewable energy indirectly by refining aluminium (Askja, 2025). Aluminium refining is an energy-intensive process, and by using its excess electricity for this purpose, Iceland has created a sustainable method of "exporting" energy in the form of aluminium. This aluminium is then shipped internationally, with the Netherlands as one of the primary importers. This report's case study thus provides an opportunity to investigate the efficiency and sustainability of aluminium as an energy export medium and evaluate its trade-offs against other possible methods, such as direct electricity transmission.

The Netherlands was chosen as the import destination for Iceland's aluminium due to its role as one of Iceland's key aluminium trading partners. As a major industrial and logistics hub within Europe, the Netherlands is strategically positioned to import and distribute aluminium throughout the continent. This established trade relationship between Iceland and the Netherlands provides a practical basis for modelling aluminium transport and allows for a realistic assessment of the trade-offs involved in using aluminium as a carrier of Iceland's renewable energy exports.

By focusing on Iceland and the Netherlands, this case study can provide valuable insights into the economic trade-offs of using aluminium as a renewable energy export method. Following the modelling, the study will assess the efficiency of this approach compared to alternatives such as submarine power cables for direct electricity transmission. The high capital and technical requirements of submarine cables, as well as transmission losses over long distances, make direct power transmission challenging.

3.2. Model structure, assumptions and limitations

The model is structured around a two-node system. Node 1 represents Iceland (64.1355°N, 21.8954°W), where electricity is converted to aluminium using renewable energy sources (e.g. hydropower and geothermal energy) and refuelling occurs. Node 2 represents the Netherlands (52.3676°N, 4.9041°E), where there is a continuous demand for aluminium and a continuous necessity for fuel to reach it (also modelled as a demand). This node serves as the destination for aluminium shipments from Iceland. The primary focus is modelling the discrete commodity transport of aluminium from Iceland to the Netherlands, emphasizing transport delays, discrete shipment scheduling, and operational fuel consumption.

The transport of aluminium between these nodes is modelled as a discrete event with hourly time steps from 2005-01-01 until 2005-01-31. Each voyage also consumes fuel on an hourly basis. Additionally, the model incorporates a time delay of 72 hours to reflect the transit period between Iceland and The Netherlands. The route is taken as a straight line, as seen in Figure 3.1, for simplicity.

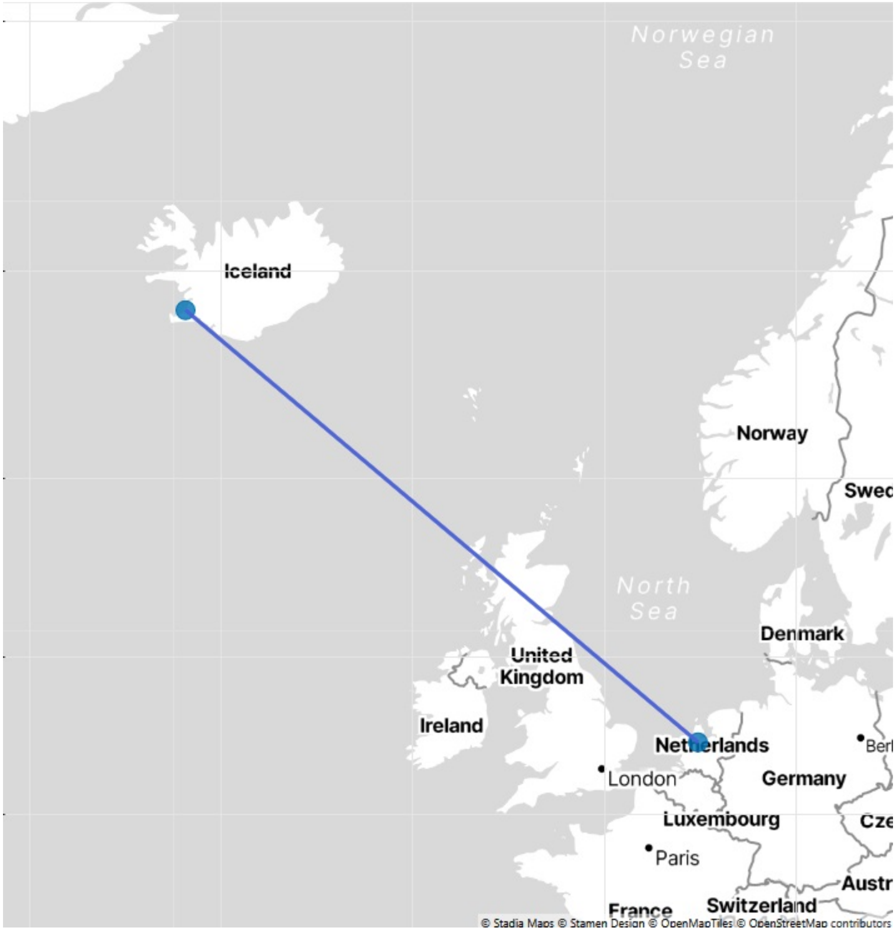

Figure 3.1: The route for the ships travelling between Iceland and The Netherlands.

Aluminium and fuel supply in Iceland are assumed to be unlimited for the duration of the model, given the availability of renewable resources. They are assigned costs of 0.0025 and 0.0005 USD per Mt, respectively, based roughly on current aluminium and cargo ship fuel prices (S&B, 2025) (TE, 2025). Aluminium is produced by smelters, which are powered by renewable electricity. Modern smelters can reach efficiencies as high as 96% (Haarberg, 2016), which is the conversion efficiency used in the model. Around 17 MWh of electricity is required to produce 1 tonne of aluminium (Gautam et al., 2018).

Demand in the Netherlands is continuous, at a constant hourly rate. Operational complexities such as detailed port handling times or loading/unloading delays and environmental impacts, including emissions, are not modelled explicitly. Overall, this setup provides a focused and realistic depiction of logistical constraints inherent in discrete maritime commodity transport, highlighting key operational challenges and system behaviours.

3.3. Model mathematics

The mathematical model is based on Mixed-Integer Linear Programming (MILP), adapted from the separable scheduling approach outlined by Wang et al. (2022). The MILP framework enables discrete event scheduling and optimizes the timing and fuel usage of aluminium shipments, incorporating dynamic fuel costs and energy availability. Next, the sets, parameters, variables and constraints making up the model will be shown.

Sets

- T: Set of time spans (e.g., $T = \{1, 2, \ldots, D\}$), where D is the length of the scheduling horizon.
- $N = \{1, 2\}$: Set of nodes (e.g., port in Iceland and port in the Netherlands).
- S: Set of ships.
- F: Set of fuel depots.

Parameters

- c_s: Carrying capacity of ship s.
- η_s: Fuel consumption rate of ship s.
- σ_s: Fuel capacity of ship s.
- α_i: Initial aluminium stock at node i.
- β_i: Aluminium demand at node i.

Variables

- $x_{s,i,t}$: Binary variable indicating if ship s is at node i during time span t.
- $y_{s,i,t}$: Binary variable indicating if ship s is travelling to node i during time span t.
- $a_{s,i,t}$: Amount of aluminium transported by ship s to node i during time span t.
- $f_{s,i,t}$: Amount of fuel consumed by ship s at node i during time span t.
- $\phi_{i,t}$: Amount of aluminium stock at node i during time span t.
- $\theta_{f,t}$: Amount of fuel at depot f during time span t.

Constraints

The constraints that define the behaviour and limitations of the system for optimising aluminium transport in Calliope were based on the following formulations. It is important to note that all of these formulations were explicitly modelled in Calliope, as Calliope's pre-defined math already handles their implementation.

1. State transition of ships

The state transition constraints ensure that a ship can only be in one state at any given time: either stationary at a node or travelling between nodes.

$$x_{s,i,t+1} \geq x_{s,i,t} + y_{s,i,t} - 1, \quad \forall s \in S, \forall i \in N, \forall t \in T \tag{3.1}$$

$$x_{s,i,t+1} \leq x_{s,i,t} + y_{s,i,t}, \quad \forall s \in S, \forall i \in N, \forall t \in T \tag{3.2}$$

- **Variables:**
  - $x_{s,i,t}$: A binary variable indicating if ship s is at node i during time span t (1 if at the node, 0 otherwise).
  - $y_{s,i,t}$: A binary variable indicating if ship s is travelling from node i during time span t (1 if travelling, 0 otherwise).
- **First Constraint** $x_{s,i,t+1} \geq x_{s,i,t} + y_{s,i,t} - 1$:
  - Ensures that if a ship was at node i in the previous time step ($x_{s,i,t} = 1$) and started travelling ($y_{s,i,t} = 1$), it will not remain at the node in the next time step ($x_{s,i,t+1} = 0$).
- **Second Constraint** $x_{s,i,t+1} \leq x_{s,i,t} + y_{s,i,t}$:
  - Prevents the ship from being at the node and in transit simultaneously.
  - Ensures logical movement by enforcing that if the ship is travelling, it will not be counted as "at the node" in the subsequent time step.

2. Ship capacity constraint

This constraint limits the amount of aluminium a ship can carry to its maximum capacity.

$$a_{s,i,t} \leq c_s \cdot (1 - y_{s,i,t}), \quad \forall s \in S, \forall i \in N, \forall t \in T \tag{3.3}$$

- **Variables:**
  - $a_{s,i,t}$: Amount of aluminium transported by ship s to node i during time span t.
  - $y_{s,i,t}$: Binary variable indicating if the ship is moving during time step t.
  - c_s: Carrying capacity of ship s.
- The term $(1 - y_{s,i,t})$ again enables aluminium transport only when stationary.
  - When $y_{s,i,t} = 0$, $a_{s,i,t} \leq c_s$ allows loading up to the ship's capacity.
  - When $y_{s,i,t} = 1$, $a_{s,i,t} = 0$, preventing loading while in transit.

3. Fuel consumption and restock Constraint (Refuel/Restock only when not travelling)

This constraint limits fuel consumption or restocking to times when the ship is stationary at a node.

$$f_{s,i,t} \leq \sigma_s \cdot (1 - y_{s,i,t}), \quad \forall s \in S, \forall i \in N, \forall t \in T \tag{3.4}$$

- **Variables:**
  - $f_{s,i,t}$: The amount of fuel consumed or restocked by ship s at node i during time span t.
  - $y_{s,i,t}$: Binary variable indicating if ship s is travelling from node i during time span t.
  - σ_s: Fuel capacity of ship s.
- The term $(1 - y_{s,i,t})$ acts as an "enabler" for refueling:
  - When $y_{s,i,t} = 0$ (stationary), $f_{s,i,t} \leq \sigma_s$ allows refueling up to capacity.
  - When $y_{s,i,t} = 1$ (travelling), $f_{s,i,t} = 0$, preventing refueling while in transit.

4. Aluminium stock balance

This constraint maintains the aluminium stock balance at each node over time, accounting for aluminium transported and local demand.

$$\phi_{i,t+1} = \phi_{i,t} + \sum_{s \in S} a_{s,i,t} - \beta_i, \quad \forall i \in N, \forall t \in T \tag{3.5}$$

- **Variables:**
  - $\phi_{i,t}$: The amount of aluminium stock at node i during time step t.
  - $a_{s,i,t}$: Amount of aluminium transported by ship s to node i during time span t.
  - β_i: Aluminium demand at node i.
- Updates stock at node i for the next time step based on:
  - Previous stock, incoming aluminium from ships, and demand.

5. Fuel depot balance

This constraint tracks the fuel available at each depot over time.

$$\theta_{f,t+1} = \theta_{f,t} - \sum_{s \in S} f_{s,i,t}, \quad \forall f \in F, \forall t \in T \tag{3.6}$$

- **Variables:**
  - $\theta_{f,t}$: The amount of fuel at depot f during time span t.
  - $f_{s,i,t}$: Amount of fuel consumed by ship s at node i during time span t.
- Updates fuel stock at depot f for the next time step by deducting fuel consumed by all ships.

3.4. Model Implementation in Calliope

The model is implemented in the Calliope framework, which supports the configuration of custom constraints and dynamic energy systems. Calliope enables the integration of the aforementioned constraints, ensuring that the fuel costs and aluminium transport schedules are optimised. The model structure, along with the transport constraints, is specified across multiple `.yaml` files, each of which defines different aspects of the system. These files establish the nodes, technologies, and custom constraints required for the aluminium transport model and are as follows:

- `model.yaml`: This file contains the overall configuration for the model, specifying the model structure and key settings, including the optimisation objective, time horizon, solver (gurobi) and overarching parameters that guide the simulation of aluminium transport between Iceland and the Netherlands.
- `scenarios.yml`: This file specifies the start and end date of the model, as well as the time step resolution.
- `locations.yaml`: This file defines the nodes in the model. Specifically, Iceland as the aluminium production and fuel supply location and the Netherlands as the aluminium demand destination.
- `techs.yaml`: This file outlines the technologies used in the model, including aluminium/fuel supply, demand and transport/consumptions technologies. Each technology is specified with its operational constraints and capacity limits.
- `custom_constraints_delay.yml`: This file defines the time delay constraints in the model, ensuring that aluminium sent from Iceland at time t only arrives in the Netherlands after a fixed delay of 72 hours. This constraint captures the transit time and enforces realistic timing for aluminium shipments.

$$\text{flow\_out}_{\text{NL,aluminium},t} = \begin{cases} \text{flow\_in}_{\text{IS,aluminium},t-72}, & \text{if } t \geq 72 \\ 0, & \text{otherwise} \end{cases}$$

- `custom_constraints_state.yml`: This file implements the state transition constraints for the transport ship. It ensures that the ship's location and state (either stationary at a node or travelling) are updated sequentially, allowing for realistic movement between nodes and prohibiting simultaneous presence at multiple locations. It is built with the following components.

  1. Binary variables

  This binary variable indicates whether a ship departs from Iceland at timestep t.

  $$\text{ship\_depart}_t \in \{0, 1\}$$

  This variable tracks if a ship is available at Iceland at timestep t.

  $$\text{ship\_available}_t \in \{0, 1\}$$

2. Constraints

Shipping capacity link, this ensures aluminium only flows when a ship departs:

$$\text{flow\_in}_{\text{aluminium},t} \leq \text{ship\_depart}_t \cdot \text{flow\_cap\_max}$$

Ship limit which restricts ship departures to once every 144 hours:

$$\sum_{i=0}^{143} \text{ship\_depart}_{t+i} \leq 1 \quad \forall t$$

Ship availability limit, meaning it can only depart if it's available:

$$\text{ship\_depart}_t \leq \text{prev\_available}_t$$

Where:

$$\text{prev\_available}_t = \begin{cases} 1, & t = 0 \\ 0, & t \geq 72 \\ \text{ship\_available}_{t-1}, & \text{otherwise} \end{cases}$$

The following constraint models the ship round-trip cycle logic:

$$\text{ship\_available}_t = \text{prev\_available}_t + \text{ship\_returned}_t - \text{ship\_depart}_t$$

With:

$$\text{prev\_available}_t = \begin{cases} 1, & t = 0 \\ \text{ship\_available}_{t-1}, & t > 0 \end{cases}$$

$$\text{ship\_returned}_t = \begin{cases} \text{ship\_depart}_{t-144}, & \text{if } t \geq 144 \\ 0, & \text{otherwise} \end{cases}$$

The model is built and executed in Calliope, with the results exported for further analysis. Data processing and visualisation are partially performed in Jupyter Notebook, where the model outputs are analysed to interpret transport schedules and overall system efficiency. The Jupyter Notebook allows for the application of data processing techniques to extract insights, generate visual representations (such as graphs and charts), and explore the impact of different scenarios on fuel costs and aluminium transport timing. Additional visualisation is performed with the Calligraph tool.

3.5. Simple scenario

To test the model formulation, a few scenarios were constructed. First, a simple scenario was developed with direct, instantaneous transmission of aluminium, without any additional custom math, to demonstrate the starting conditions for the more complex formulations used later on. In this simplified scenario, aluminium transport was modelled as a continuous flow at 3,000 tons per hour, with no transport delays or discrete ship departures. Figure 3.2 and Figure 3.3 show steady and continuous aluminium inflow and outflow, respectively, indicating a constant and uninterrupted flow of aluminium from Iceland to the Netherlands, while perfectly meeting demand.

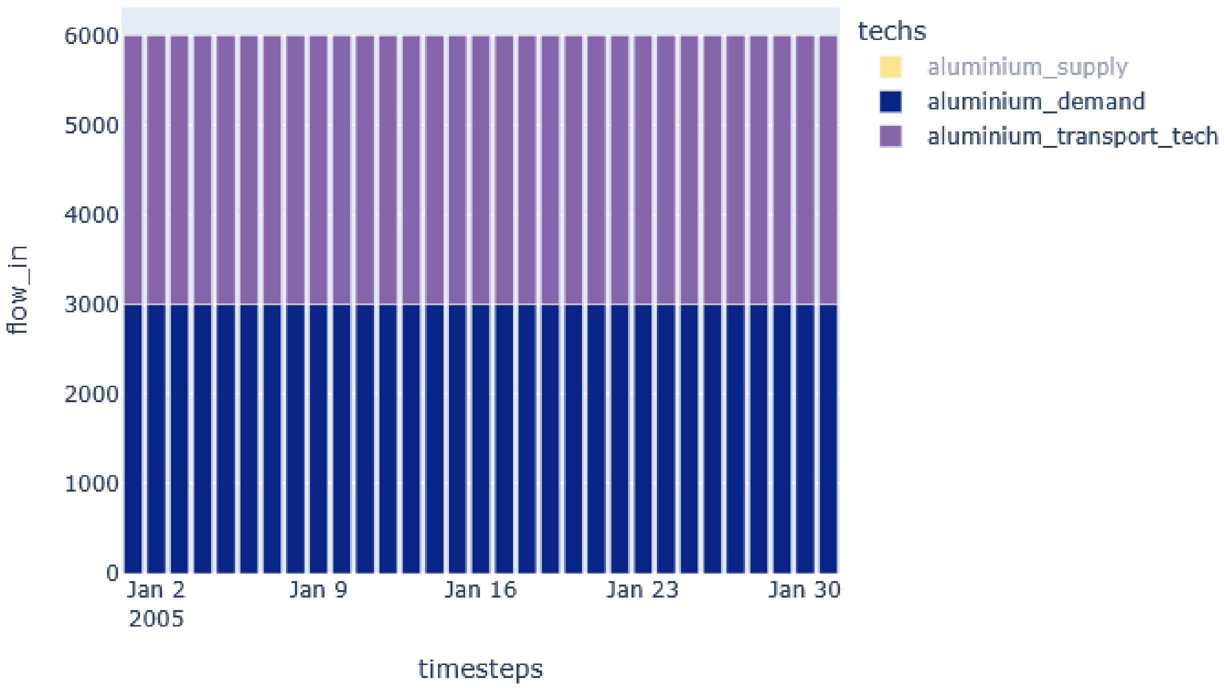

Figure 3.2: Simple model aluminium flow in.

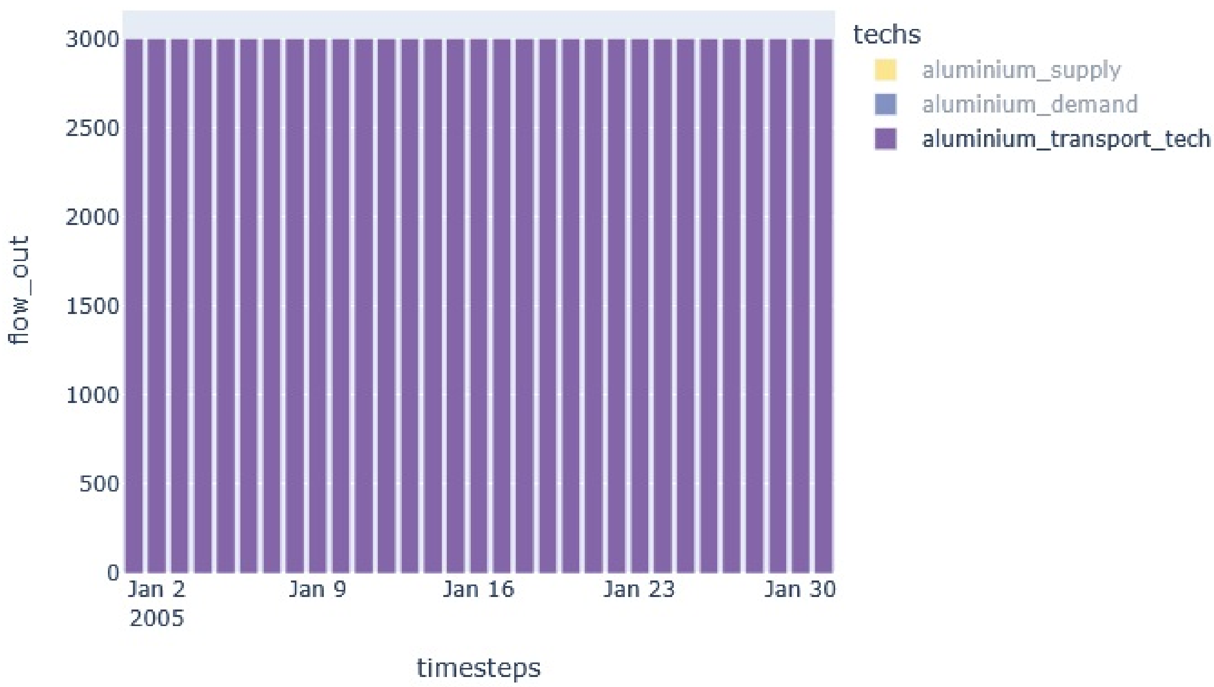

Figure 3.3: Simple model aluminium flow out.

The system-wide levelised cost and total cost are displayed in Table 3.1. As the demand is met on an hourly basis, the levelised cost of aluminium is also applied hourly, leading to a relatively large total cost of roughly 5.5 billion USD. The levelised cost is taken the same as for the advanced scenario at 0.0025 USD per Mt, for simplicity.

Table 3.1: System-wide cost results for the simple model.

Resource	Levelised Cost (USD/Mt)	Total Cost (million USD)
Aluminium	0.0025	5,500

3.6. Advanced scenario

The advanced scenario integrates realistic operational constraints, including discrete shipping schedules, delayed arrivals, and explicit fuel usage. First, a look at the ship scheduling and availability parameters.

Figure 3.4 illustrates the binary ship departure variable (ship_depart), highlighting discrete ship departures at regular intervals roughly every six days (144 hours), complying with the custom constraints implemented.

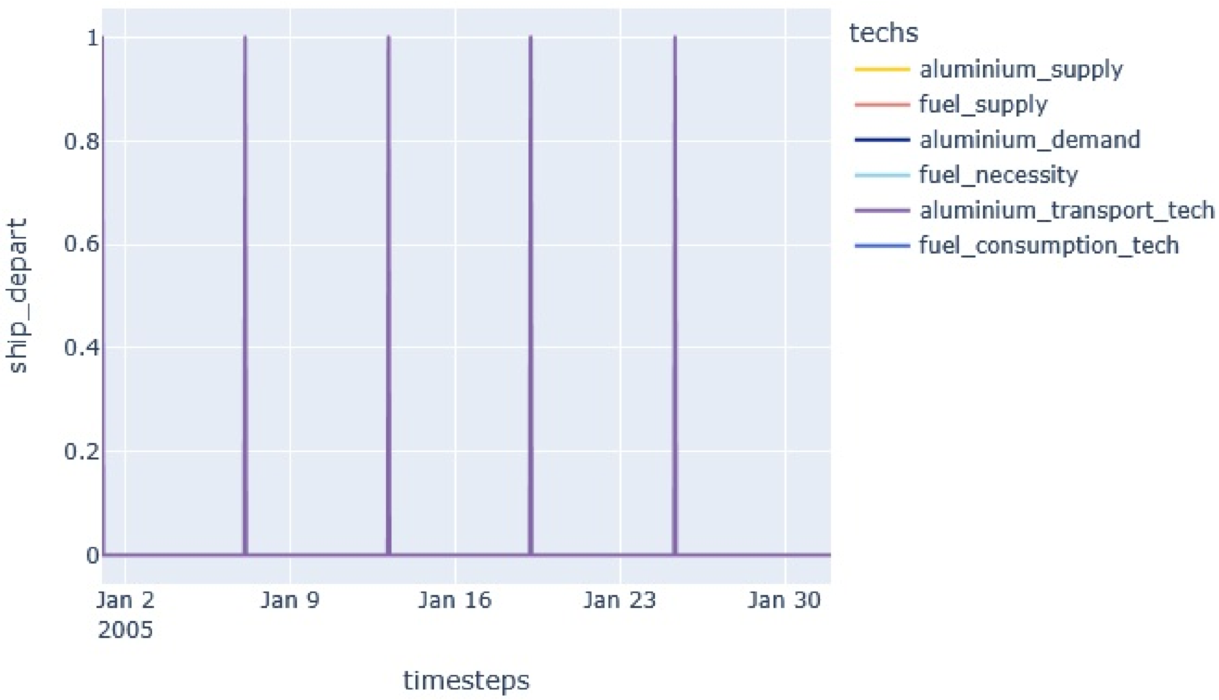

Figure 3.4: Advanced model ship depart binary variable.

Figure 3.5 shows the ship availability (ship_available) at the Iceland node, clearly reflecting the cyclic nature of ship operations: the ship becomes unavailable upon departure and returns to availability after completing a 144-hour round trip.

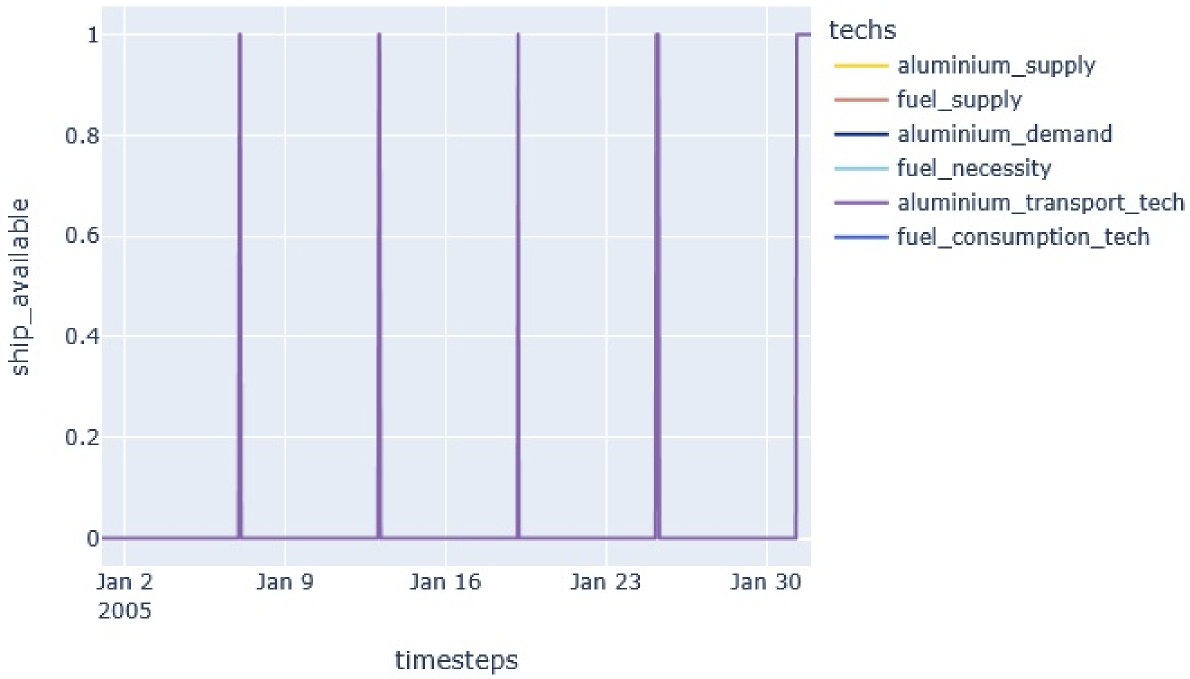

Figure 3.5: Advanced model ship available binary variable.

Second, a look at aluminium transport in such an advanced scenario. Figure 3.6 and Figure 3.7 depict the aluminium inflow and outflow, respectively. Aluminium departures from Iceland occur at discrete intervals, aligned with the ship's departure schedule, resulting in pronounced peaks of 3,000 tons rather than continuous flow. The delayed arrival constraint manifests clearly, with inflows at the Netherlands node appearing exactly 72 hours after departures from Iceland.

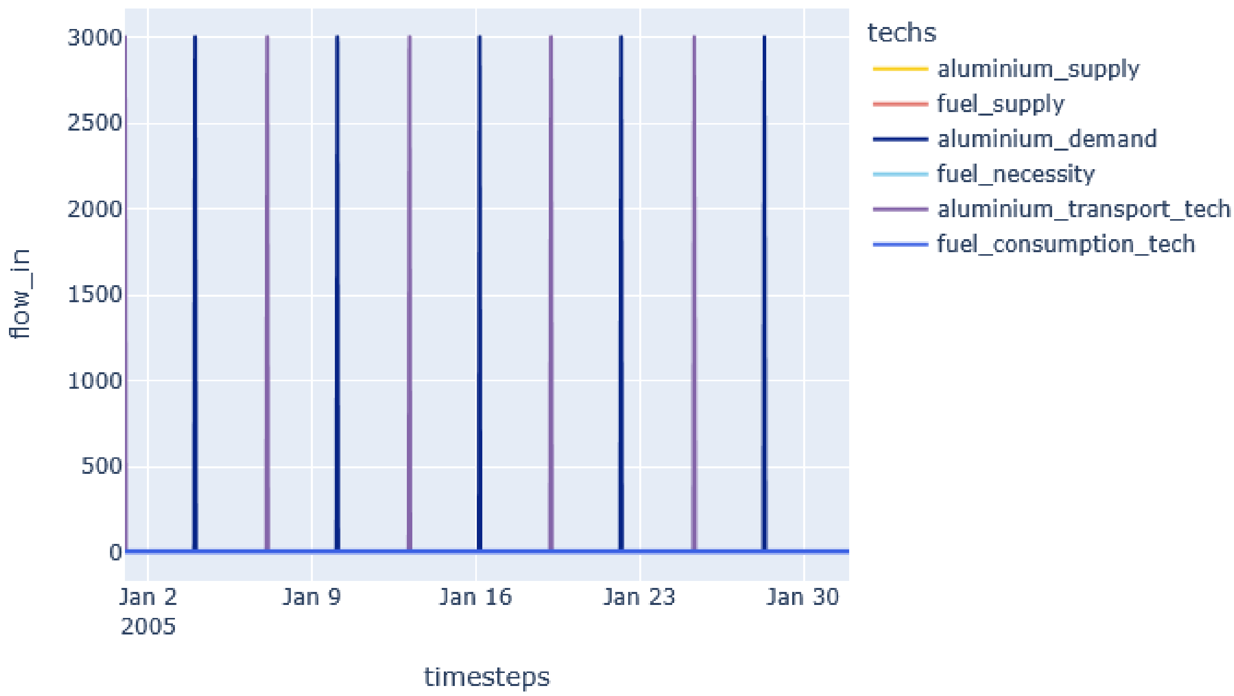

Figure 3.6: Advanced model aluminium flow in.

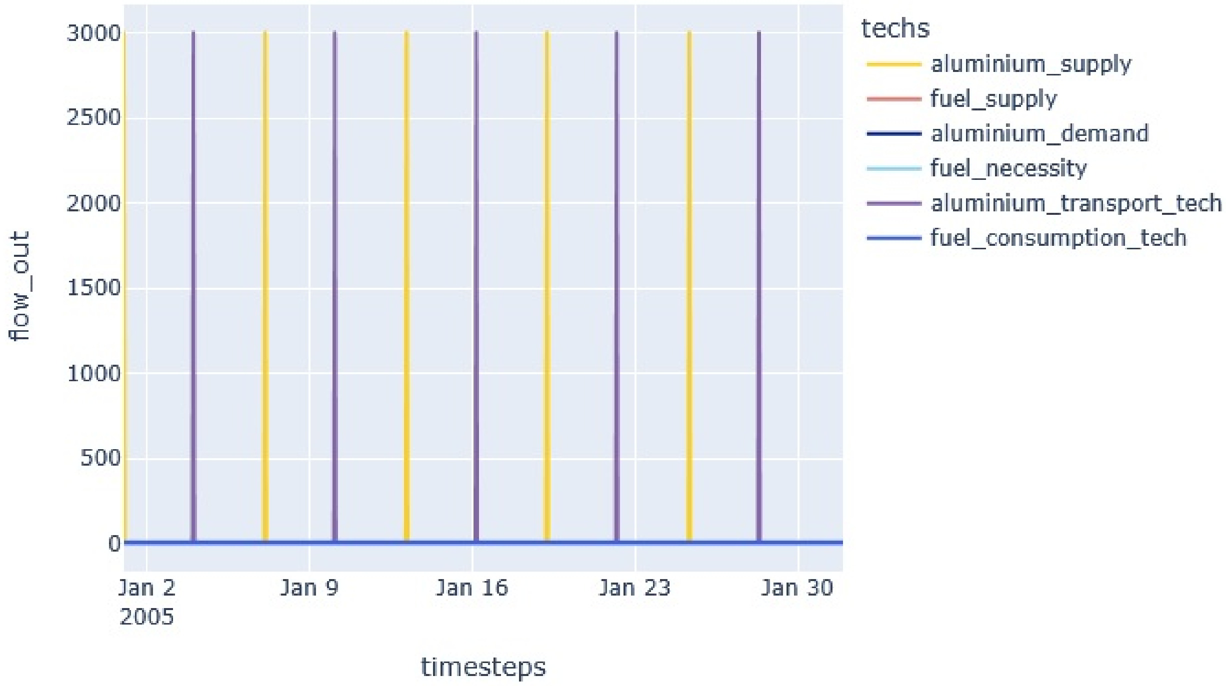

Figure 3.7: Advanced model aluminium flow out.

Table 3.2 presents the system-wide levelised cost and total cost for this scenario. As the demand is only met at 5 different times, the total cost is naturally much lower compared to the simple scenario. The fuel and aluminium cost total is roughly 40 million USD, with a levelised cost of 0.0005 and 0.0025 USD per Mt respectively.

Table 3.2: Levelised and total cost breakdown by resource for the advanced model.

Resource	Levelised Cost (USD/Mt)	Total Cost (million USD)
Aluminium	0.0025	35
Fuel	0.0005	5
Total	**0.0030**	**40**

Finally, fuel is also consumed in the advanced scenario. Figure 3.8 details the fuel supply, and Figure 3.9 illustrates the hourly fuel consumption of 7 tonnes per hour associated with aluminium transport. This steady fuel usage corresponds directly to the operational activity of the ship during transport. Fuel is burned at every time interval, as the ship is assumed to be in a constant state of travel. It is further assumed that there is sufficient fuel on board for a round trip, after which refuelling occurs in Iceland. However, this refuelling process is not explicitly modelled.

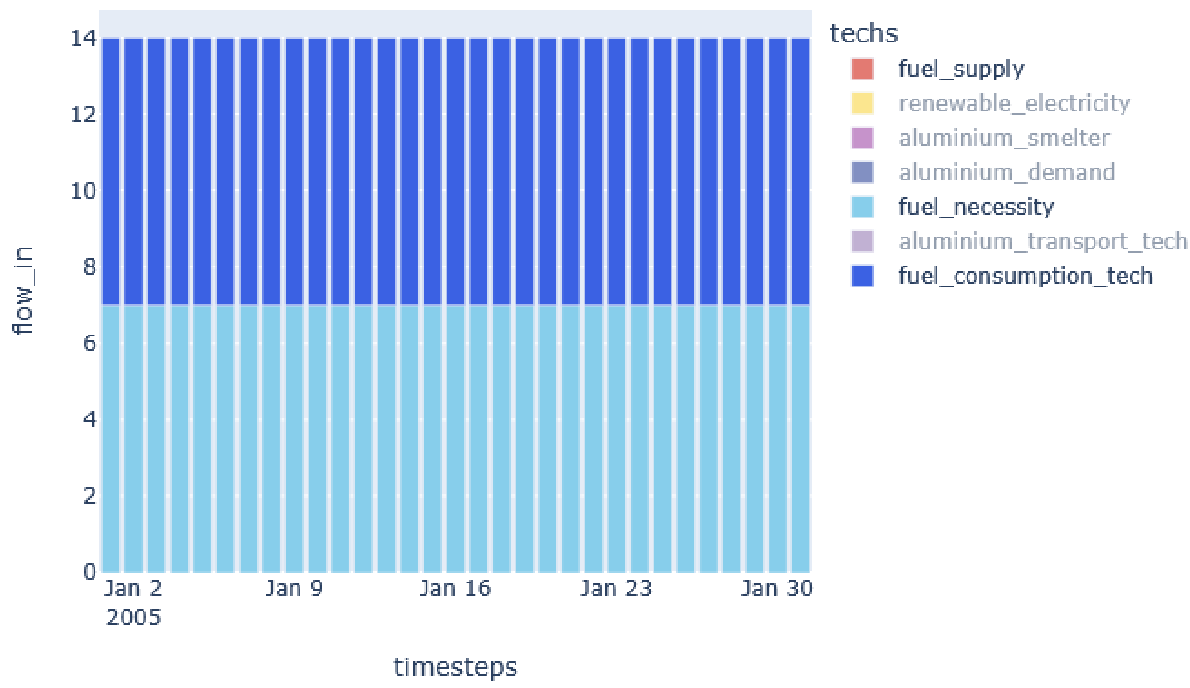

Figure 3.8: Advanced model fuel flow in.

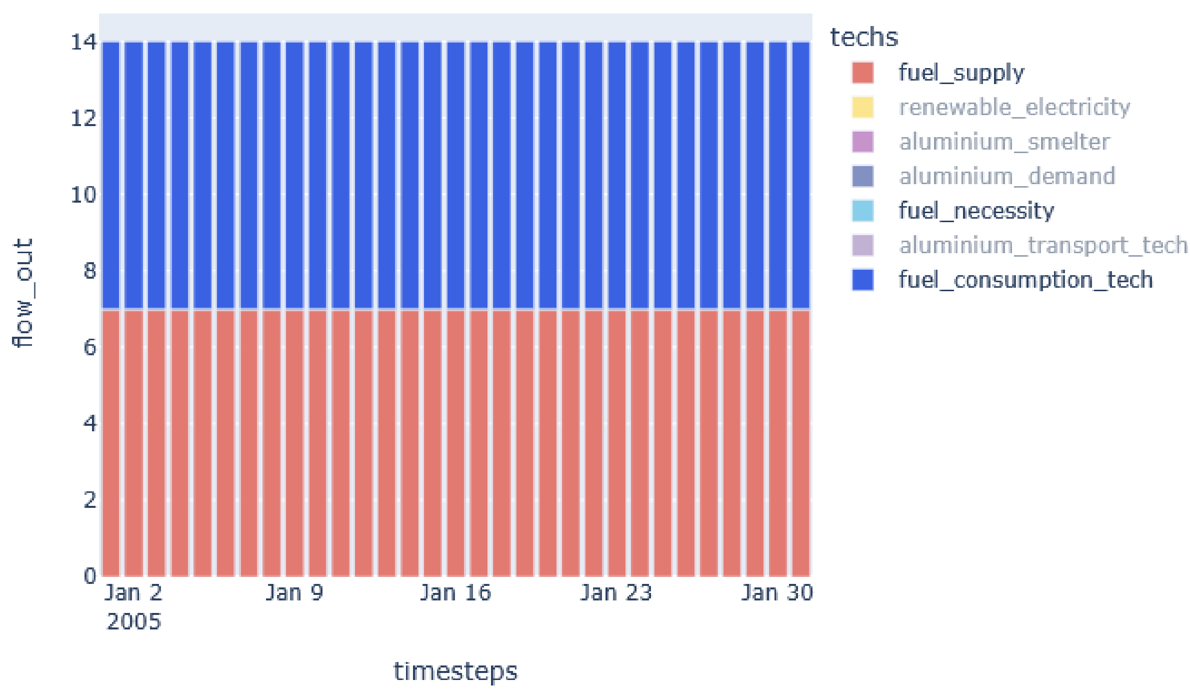

Figure 3.9: Advanced model fuel flow out.

In conclusion, the simplified continuous scenario serves as a baseline to test the implementation and stability of the modelling framework. Its primary role is to validate flow structures and economic behaviour in the absence of complex constraints. In contrast, the advanced discrete shipping scenario successfully integrated custom constraint logic to enforce ship scheduling, transport delays, and fuel consumption. This demonstrates the model's capability to capture complex logistical dynamics within an energy system framework. The outputs confirm that the model behaves as intended, with realistic timing of aluminium deliveries, fuel usage patterns, and periodic cost structures that reflect discrete shipping operations.

4 Results

The results presented in this chapter demonstrate the outcomes of optimizing the direct transmission of renewable electricity and the discrete maritime transportation of aluminium between Iceland and the Netherlands, using the Calliope energy system model. The chapter is structured around a comparison of these two transport methods. Electricity is transmitted via an undersea cable, while shipping involves converting renewable electricity into aluminium bars through smelting, which are then transported by sea. The chapter concludes with a sensitivity analysis, evaluating the robustness of the results under varying assumptions.

4.1. Undersea electricity transmission

First, the transmission of renewable electricity via an undersea cable was optimised. This optimisation is based on a simplified continuous-flow scenario, in which aluminium transport between Iceland and the Netherlands was modelled as a steady, uninterrupted flow of 3,000 tonnes per hour, without incorporating logistical complexities such as shipment delays, discrete events, or fuel consumption.

For this optimisation, realistic values for electricity transmission were used, based on the IceLink subsea power cable. This 1,200 km cable has a capacity of 1 GW, a loss rate of 3.5% per 1,000 km (resulting in a total loss rate of 4.2%), and a variable cost of 130,000 USD per GWh.

The results are displayed in Figure 4.1 for power inflow and in Figure 4.2 for power outflow. After accounting for transmission losses, 0.958 GW of daily power was delivered, continuously meeting the demand over the month of January. The total amount of power delivered is roughly 689,76 GWh.

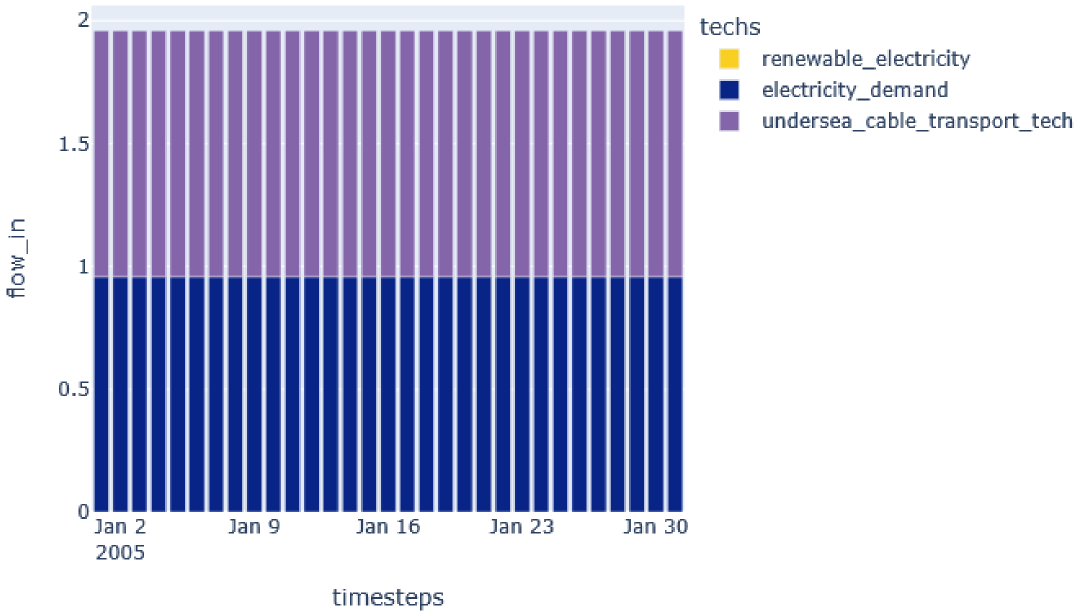

Figure 4.1: Undersea cable flow in.

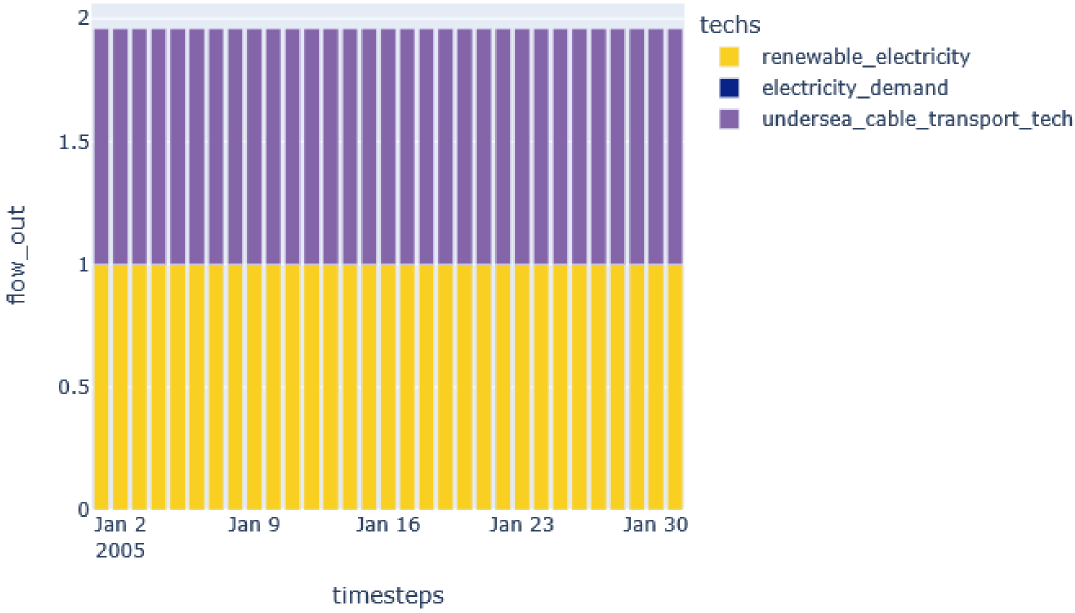

Figure 4.2: Undersea cable flow out.

This method yielded a total system-wide cost of approximately 96.72 million USD, with a levelised cost of electricity of 0.13 USD per kWh, summarised in Table 4.1.

Table 4.1: System-wide cost results for the undersea cable.

Resource	Power (GW)	Total Energy (GWh)	Levelised Cost (USD/GWh)	Total Cost (million USD)
Electricity	0.958	689.76	0.13	96.72

4.2. Aluminium conversion and transport

Second, the discrete shipping of aluminium was optimised. This is based on the advanced discrete shipping scenario, key operational constraints such as discrete shipping schedules, transport delays, and explicit fuel consumption were integrated. Aluminium shipments departed from Iceland at intervals of roughly 144 hours (approximately six days), corresponding directly with ship availability and cycle times. Each shipment carried discrete batches of 3000 tonnes of aluminium. The model explicitly incorporated a transit delay of 72 hours between Iceland and the Netherlands, resulting in a noticeable temporal lag between departures from Iceland and arrivals in the Netherlands. This realistic representation captured the critical logistical dynamics absent from traditional continuous-flow models.

For this optimisation aluminium smelters with an current efficiency of 96% were used. As seen in Figure 4.3 for the aluminium flow in and Figure 4.4 for the flow out, renewable electricity powers the smelters, resulting in ships carrying and delivering 125 Mt of aluminium per shipment, still departing with a new shipment every 144 hours. With a total of 5 shipments a total of 625 Mt of aluminium was delivered, which comes down to 10,625 TWh of energy. Fuel consumption in this scenario remained steady at approximately 7 tonnes per hour during transport as illustrated in Figure 3.8 and Figure 3.9, reflecting constant operational activity while the ship was in transit. Although refuelling specifics were not explicitly modelled, sufficient fuel availability for round-trip voyages was assumed.

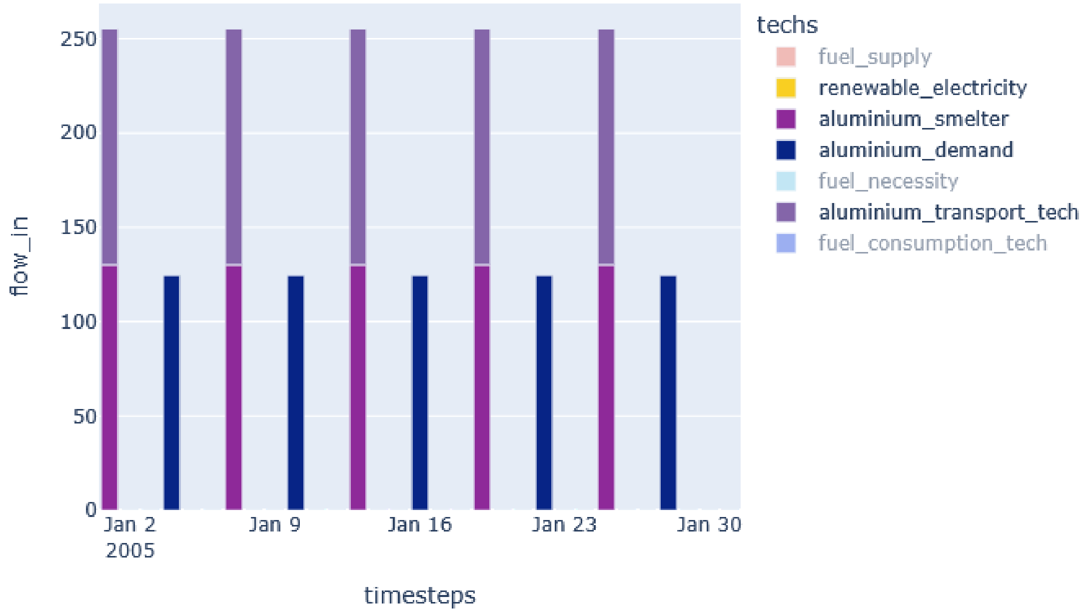

Figure 4.3: Aluminium transport flow in.

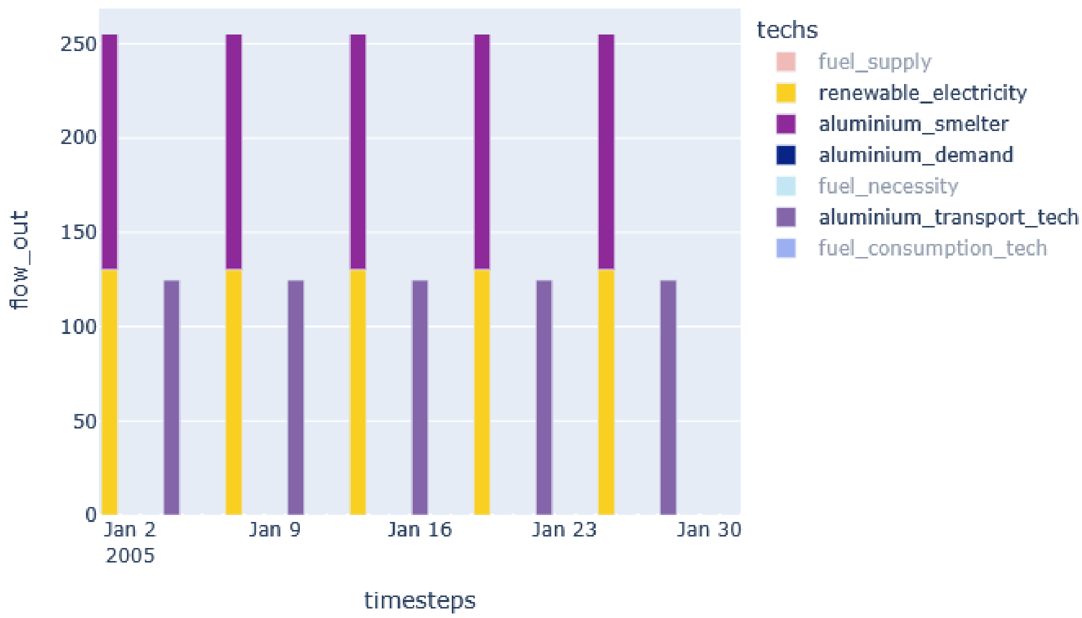

Figure 4.4: Aluminium transport flow out.

The aluminium transport method resulted in a substantially lower total cost compared to the undersea cable, with a total system-wide cost of roughly 41.66 million USD. The breakdown (summarised in Table 4.2) was approximately 39.06 million USD attributed to aluminium transport, and 2.6 million USD to fuel, based on their respective levelised costs of 0.0025 and 0.0005 USD per Mt.

Table 4.2: Levelised and total cost breakdown by resource for aluminium transport.

Resource	Cargo (Mt)	Total Energy (TWh)	Levelised Cost (USD/Mt)	Total Cost (million USD)
Aluminium	125	10,625	0.0025	39.06
Fuel	-	-	0.0005	2.6
Total	-	-	**0.0030**	**41.66**

4.3. Comparative assessment

The comparison between discrete maritime transport and direct electricity transmission highlights critical distinctions. While submarine cables offer continuous, instantaneous energy transfer with relatively low transmission losses, they involve substantial initial investments, complex infrastructure maintenance, and vulnerability to disruptions. Conversely, discrete maritime transport, exemplified through aluminium shipping, offers flexibility, lower infrastructure risks, and reduced capital intensity but at the cost of higher operational complexity and potential carbon emissions from maritime fuel usage.

For Iceland, a comparative evaluation of a submarine power cable such as *IceLink* versus discrete maritime aluminium transport reveals key trade-offs. First, *IceLink*'s capital-intensive nature (approximately €3.5 billion) contrasts with the lower initial investment and flexible scalability of maritime shipping (around $40 million per operational cycle). Second, the total cost of aluminium transport ($41.66 million) is lower than that of electricity transmission ($96.72 million) over the modelling period. Moreover, the total amount of energy delivered via aluminium transport (10,625 TWh) is significantly greater than that of electricity transmission (689.76 GWh). However, *IceLink* provides a continuous, high-volume transmission service, ensuring steady energy availability suitable for real-time grid integration.

Additional trade-offs include:

- **Cost:** While *IceLink* requires substantial upfront investment, maritime shipping allows for lower entry costs and modular expansion.
- **Environmental Impact:** Direct HVDC cable transmission has significantly lower operational emissions compared to maritime shipping, which relies on fossil fuels and consumes approximately 7 tons of fuel per hour.
- **Reliability and Risk:** HVDC cables entail risks related to deep-sea installation and potential maintenance challenges, whereas maritime shipping offers greater logistical flexibility and adaptability in the face of disruptions.
- **Scalability:** *IceLink*'s fixed transmission capacity (~1,000 MW) limits its scalability, whereas maritime shipping can be incrementally adjusted to meet changing export demands.

Taken together, the results of this comparative case study suggest that discrete aluminium shipping represents a financially and logistically viable export pathway for Iceland's renewable energy, particularly when evaluated over short- to medium-term horizons with limited infrastructure investment. While direct electricity transmission via submarine cables like IceLink offers superior environmental performance and continuous delivery suited for grid integration, its high capital cost, fixed capacity, and infrastructure rigidity pose significant trade-offs. In contrast, aluminium shipping delivers larger energy quantities over the modelled period at lower total system cost and with operational flexibility, albeit with higher emissions and complexity in scheduling. Ultimately, neither method emerges as categorically superior; rather, the findings support the strategic value of maintaining both approaches as complementary tools in Iceland's broader renewable energy export portfolio, depending on long-term goals, market demand, and evolving technological capabilities.

4.4. Sensitivity Analyses

To assess the robustness of the model results and identify key drivers of system cost and energy delivery, a series of sensitivity analyses were performed on both the continuous undersea transmission and discrete aluminium transport. Each analysis explores how varying a single parameter such as cost, timespan, capacity, or fuel consumption affects total system cost and energy transport characteristics. Unless otherwise noted, energy flows remain structurally consistent with the baseline scenarios.

First, aluminium and electricity cost inputs were doubled and halved to explore sensitivity to economic parameters.

- When costs were doubled, the transmission total system cost increased to 193.44 million USD, while the aluminium cost rose to 78.13 million USD, maintaining the same flow profile as in Figure 4.4. With the fuel cost staying the same the total aluminium transport cost rose to 80.73 million USD.
- When costs were halved, the electricity transmission cost dropped to 48.36 million USD and the aluminium cost to 19.53 million USD, again with unchanged flow characteristics and fuel costs. As such, the total aluminium transport cost rose to 22.13 million USD.

These results show an expected and nearly linear relationship between cost inputs and total system cost, highlighting the influence of unit costs on the model outcomes.

Second, the temporal scope of the model was extended and reduced to examine the effect of simulation duration on cost and delivery patterns.

- A three-month model run led to proportional increases in total cost: 280.80 million USD for the electricity transmission, 117.19 million USD for the aluminium transport and 7.56 million USD for the fuel (totalling 124.75 million USD), with a similar but extended flow pattern as seen in Figure 4.5 and Figure 4.6.
- A two-week run resulted in reduced costs of 43.68 million USD (electricity), 15.63 million USD (aluminium), 1.18 million USD (fuel) and 16.81 million USD (total aluminium transport), illustrated in Figure 4.7 and Figure 4.8.

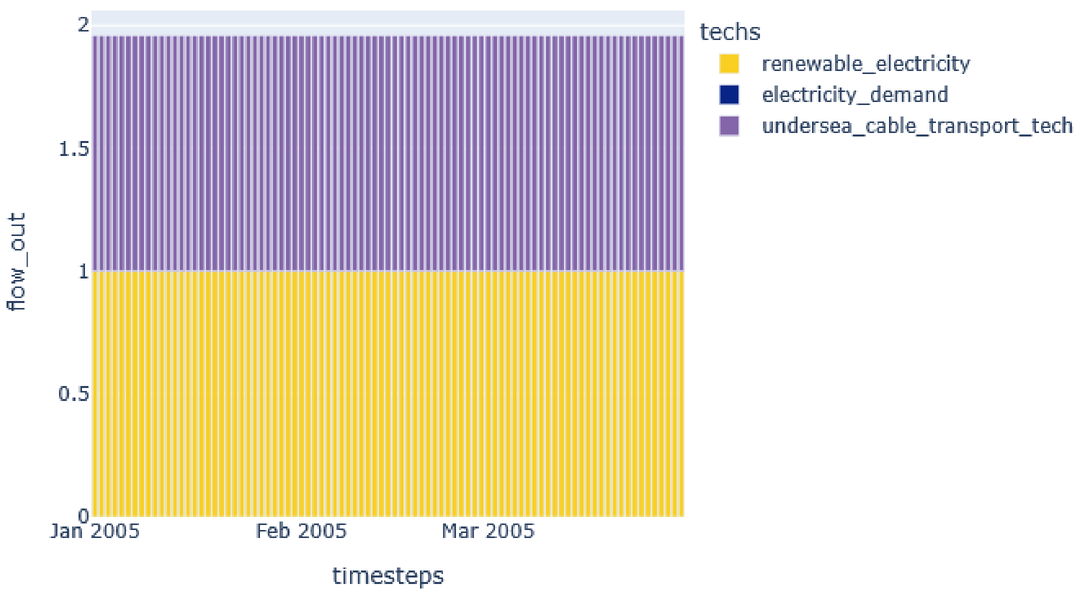

Figure 4.5: Three-month electricity model.

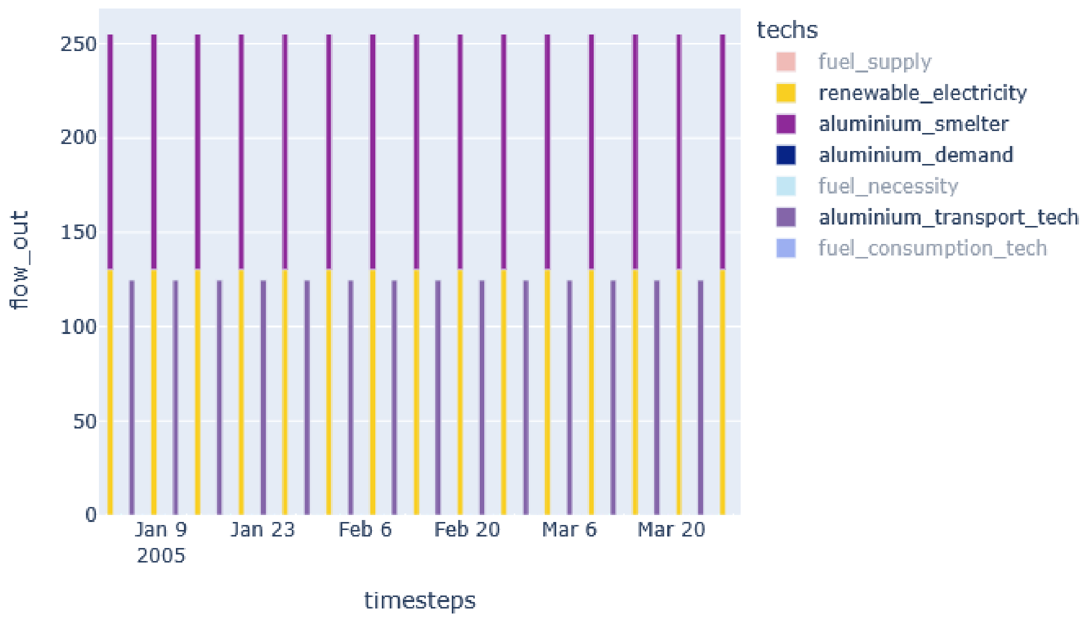

Figure 4.6: Three-month aluminium model.

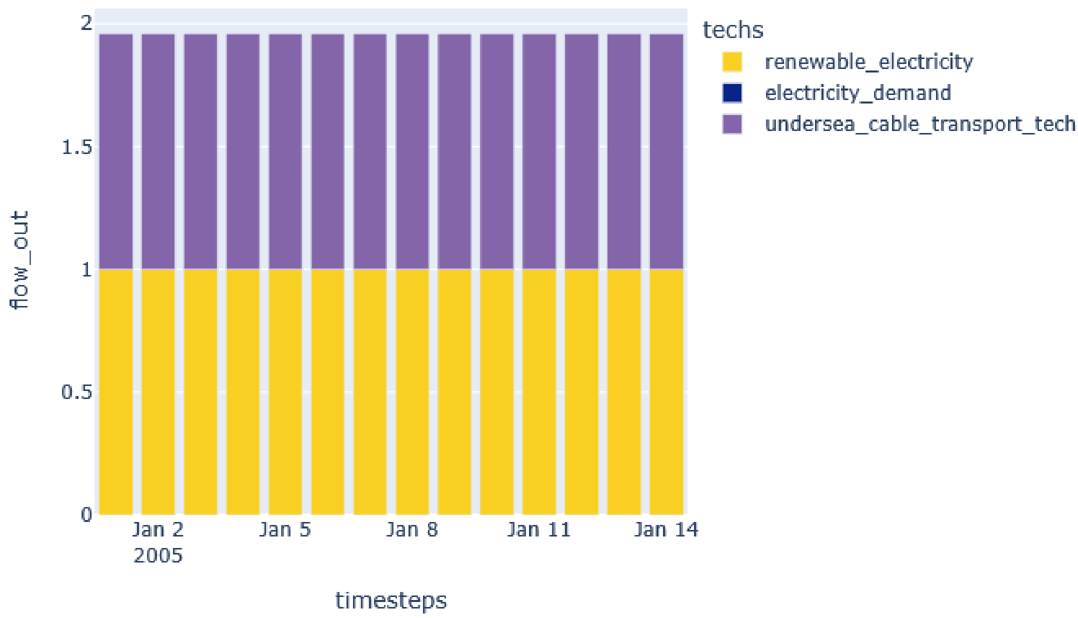

Figure 4.7: Two-week electricity model.

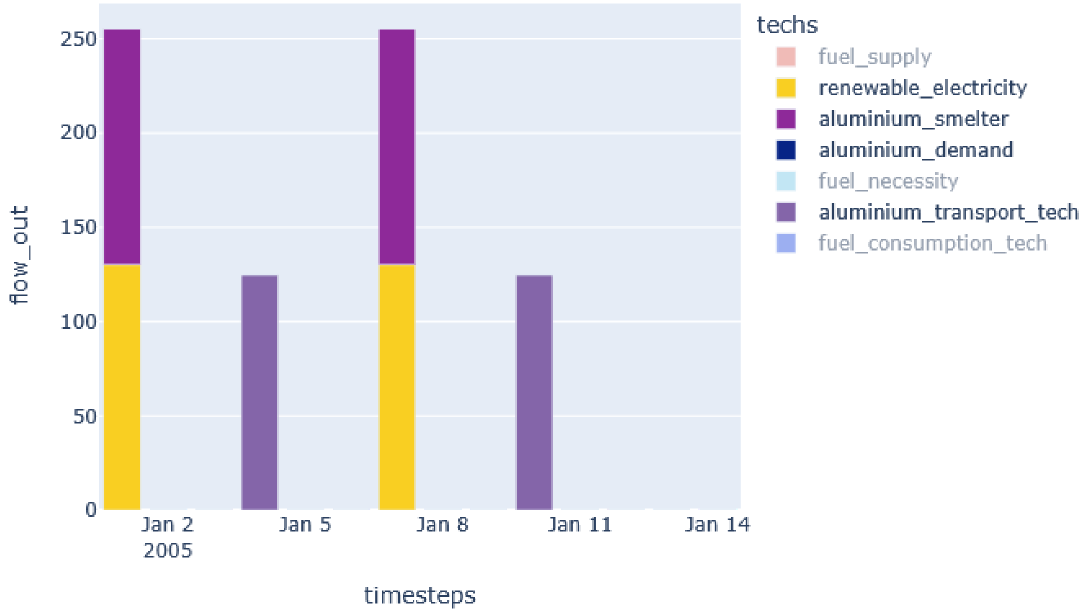

Figure 4.8: Two-week aluminium model.

These findings confirm that both models exhibit predictable scaling behavior over different time horizons, maintaining internal consistency when the simulation period is extended or shortened. Minor discrepancies in linearity can largely be attributed to the differing lengths of the time windows. For instance, the two-week scenario spans 14 days, while the baseline scenario covers 31 days, resulting in proportional differences that are not exact multiples. The shorter length of February also contributes slightly to the non-linearity observed in the three-month model.

Third, altering the transport capacity similarly changed flow dynamics and system cost.

- With a doubled cable capacity, the electricity transmission's cost increased to 193.44 million USD, with the hourly flow out nearly doubling (1.916 GW) compared to the base case (Figure 4.9). The aluminium cost was increased to 78.13 million USD, while fuel cost again remained unchanged at 2.60 million USD, totalling 80.73 million USD (Figure 4.10).
- With half capacity, the electricity transmission's cost dropped to 48.36 million USD, with flow out reduced to 0.479 GW (Figure 4.11). The aluminium decreased (19.53 million USD, 2.60 USD million USD fuel cost and 22.13 total; Figure 4.12).

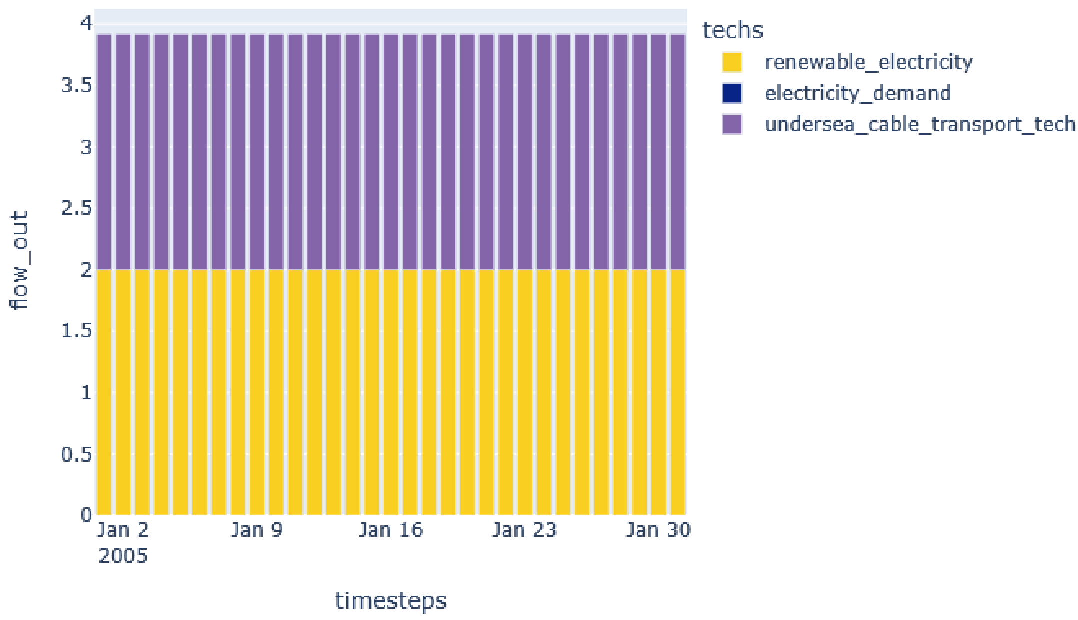

Figure 4.9: Double capacity electricity model.

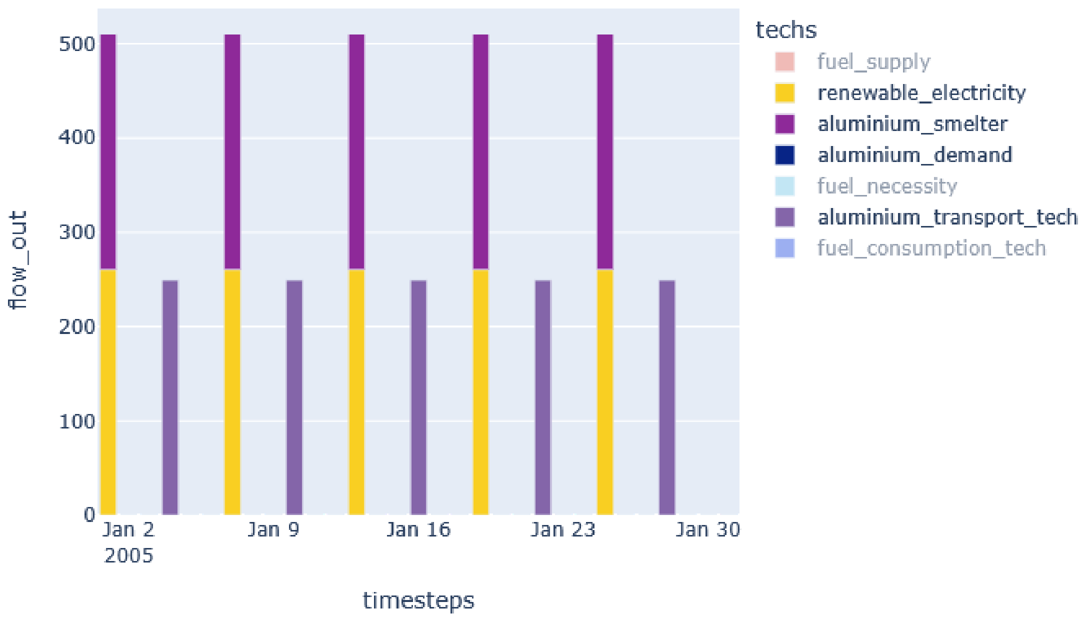

Figure 4.10: Double capacity aluminium model.

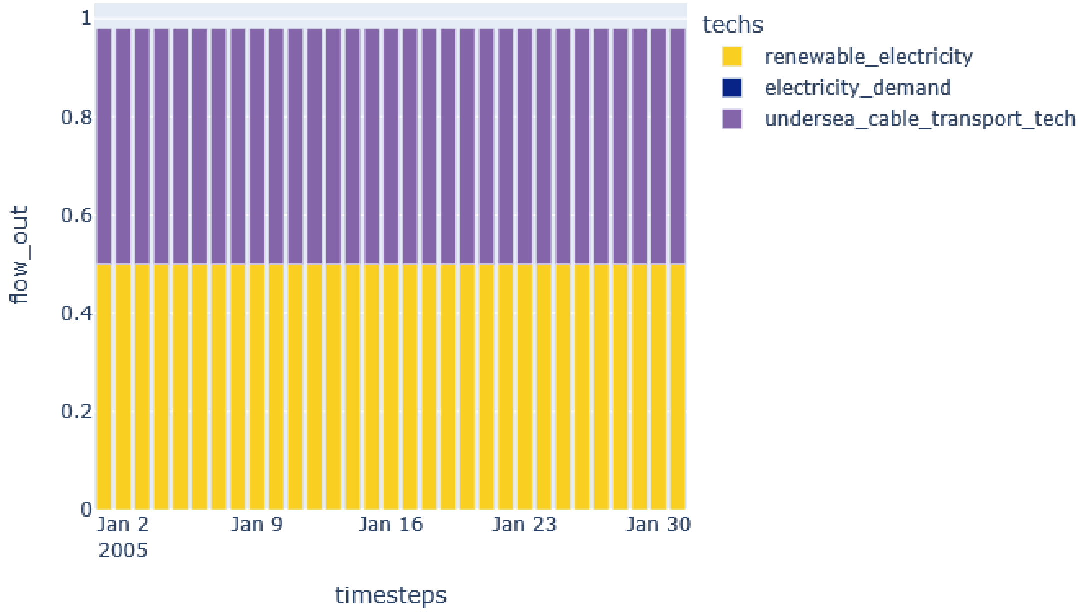

Figure 4.11: Half capacity electricity model.

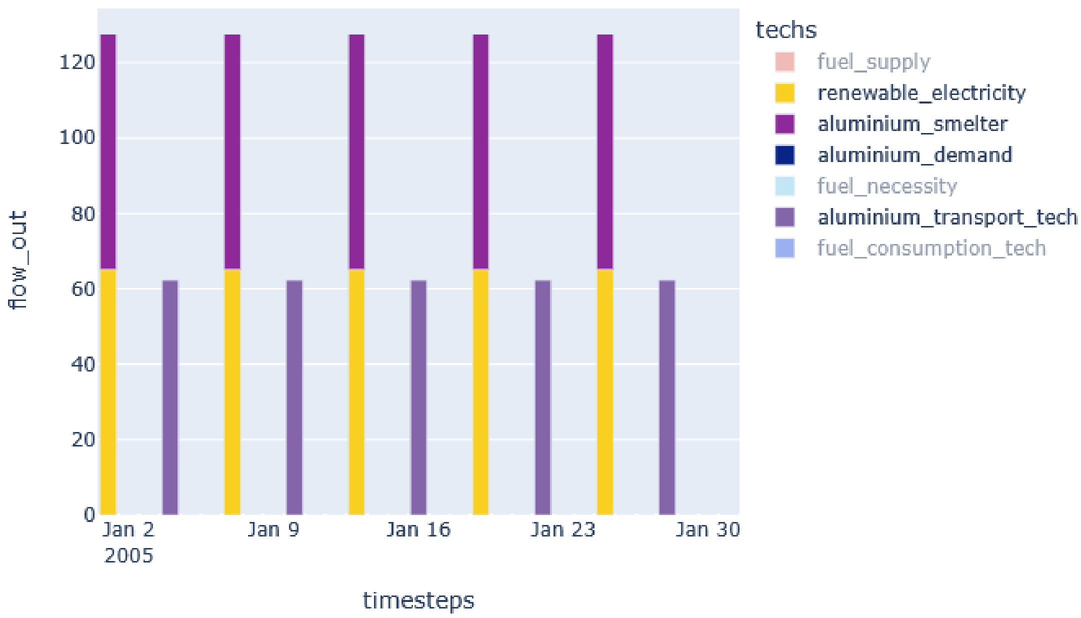

Figure 4.12: Half capacity aluminium model.

This demonstrates that changes in capacity result in corresponding cost differences, once again indicating a linear relationship for the transported resource.

Finally, in the aluminium transport model, the ship's fuel consumption rate was doubled and halved to assess its effect on system cost.

- At higher fuel consumption, the aluminium cost remained the same at 39.06 million USD and the fuel cost increased to 5.21 million USD, leading to a total of 44.27 million USD (Figure 4.13).
- At lower fuel consumption, the aluminium cost again stayed the same, but the fuel cost dropped to 1.30 million USD, giving a total of 40.36 million USD (Figure 4.14).

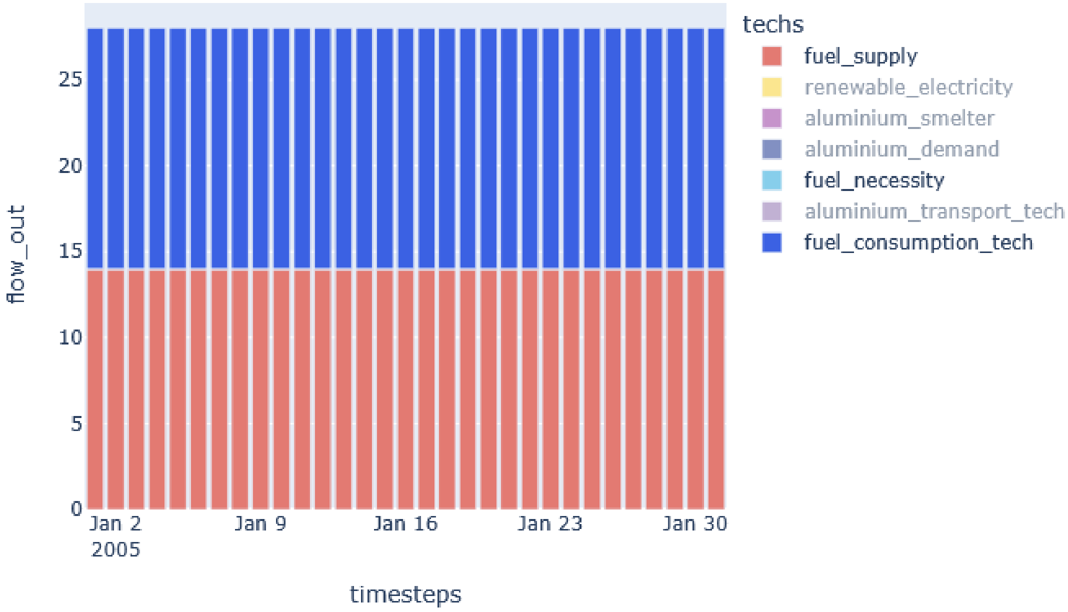

Figure 4.13: Double fuel consumption aluminium model.

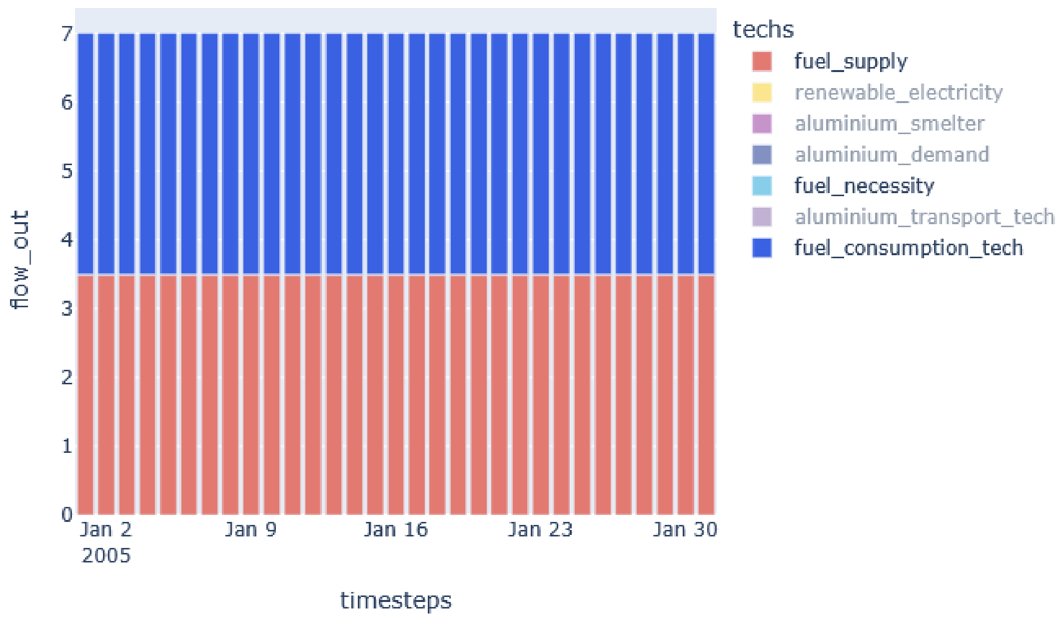

Figure 4.14: Half fuel consumption aluminium model.

Although aluminium cost remained at 39.06 million USD in both cases the fuel costs reacted linearly to the changes in consumption.

Table 4.3 summarises the results of the sensitivity analyses.

Table 4.3: Summary of Sensitivity Analysis Results

Sensitivity Case	**Model**	**Total Cost (M USD)**	**Change**
Base	Electricity Aluminium	96.72 41.66	- -
Double cost	Electricity Aluminium	193.44 80.73	Linear increase Linear increase
Half cost	Electricity Aluminium	48.36 22.13	Linear decrease Linear decrease
3-month period	Electricity Aluminium	280.80 124.75	Linear increase Linear increase
2-week period	Electricity Aluminium	43.68 16.81	Linear decrease Linear decrease
Double capacity	Electricity Aluminium	193.44 80.73	Linear increase Linear increase
Half capacity	Electricity Aluminium	48.36 22.13	Linear decrease Linear decrease
Double fuel consumption	-	44.27	Linear increase
Half fuel consumption	-	40.36	Linear decrease

In conclusion, sensitivity analyses performed within both transport methods underscored the robustness of the model's outcomes under varying assumptions regarding costs, transit periods, capacity and fuel consumption.

Overall, the sensitivity analyses confirm the robustness of both the continuous transmission and discrete, event-driven maritime transport models, as they exhibit consistent linear relationships when key parameters are varied, demonstrating reliable performance for modelling renewable energy exports from geographically isolated regions like Iceland.

5 Discussion

The results presented in this report provide valuable insights into discrete commodity transport as a renewable energy export strategy, specifically through the case of maritime aluminium shipping between Iceland and the Netherlands. The developed Calliope-based MILP model successfully captured the discrete nature of maritime logistics, transport delays, and associated operational complexities, addressing a key gap in conventional energy system modelling. In addition to validating the operational logic of the discrete shipping model, a comparative analysis was conducted against a continuous electricity transmission scenario. This comparison highlighted fundamental trade-offs in cost structure, scalability, and infrastructure requirements between shipping energy in embodied form and transmitting it directly via undersea cables.

5.1. Contextualisation and implications

The developed model expands on existing methodologies by explicitly incorporating discrete-event scheduling and shipment delays within energy system modelling frameworks, addressing shortcomings noted in prior research (Fodstad et al., 2022; Wang et al., 2022). Conventional energy system models typically assume continuous energy flows, which inadequately represent logistical realities. This report's approach provides an advanced level of realism, crucial for accurate strategic planning and decision-making in energy export scenarios.

Moreover, this study contributes to discussions raised by Spatolisano et al. (2024) and Xu et al. (2023), highlighting that direct HVDC electricity transmission is economically favourable only under certain geographic and operational conditions. The results in this report reinforce this notion, showing discrete aluminium shipping can economically compete under specific scenarios, especially considering Iceland's remote geographical context and associated infrastructure challenges of submarine cable projects like IceLink.

From a policy and planning perspective, the findings suggest that discrete aluminium shipping is a strategically flexible option for energy export from renewable-rich islands. Policymakers should consider aluminium as a viable energy carrier, particularly where investment in fixed infrastructure like undersea cables is prohibitively expensive or logistically challenging. This strategy also supports economic diversification and resilience by providing scalable, modular infrastructure adaptable to changing demand conditions.

However, maritime shipping introduces environmental trade-offs, notably higher emissions from fuel use. Thus, policies should focus on integrating renewable or carbon-neutral maritime fuels and improving vessel efficiency, aligning with broader decarbonization targets. Additionally, regulatory frameworks should incentivize optimized scheduling to align shipments with renewable availability, minimizing environmental impacts.

5.2. Recommendations and future research directions

Future work should focus on several critical areas:

- Expanding Model Generalizability: Develop formulations capable of handling multiple ships and locations simultaneously, letting the model endogenously determine optimal shipping routes, schedules, and fleet sizes. This would significantly increase the applicability of the model to other geographical contexts and commodities.
- Incorporating Inventory and Storage Management: Explicitly model storage capacities and buffer stocks at nodes, enabling more accurate logistical planning and reducing risks associated with demand-supply mismatches.
- Robustness and Uncertainty Modelling: Introduce stochastic or robust optimization methods to address uncertainties in renewable energy generation, fuel prices, and demand fluctuations. Approaches like two-stage distributively robust optimization (Liu, 2024) could enhance the model's resilience and decision-making reliability.

- Environmental and Emissions Considerations: Integrate explicit emissions calculations into the optimization objective, allowing policymakers to balance economic and environmental goals more transparently.
- Data-Driven Operational Refinement: Utilize empirical regression models (Işıklı et al., 2020) to refine fuel consumption estimations based on operational parameters like ship speed, sea state, and cargo load.

The methodological contribution of this report lies in the explicit inclusion of discrete shipment constraints and delay logic within the Calliope MILP framework. While effective for the Iceland–Netherlands case, the current formulation is highly specific, with fixed node locations and shipment schedules. Extending this research to multi-node and multi-carrier scenarios could provide valuable insights into more complex global supply chains, enhancing the model's generalizability and applicability to diverse renewable energy export contexts. To implement such generalizations, future models should incorporate the following improvements:

- Parameterize origin–destination pairs: Replace hardcoded locations like `Iceland` and `Netherlands` with sets of nodes (e.g., `origins`, `destinations`) to allow dynamic routing and a more general model structure.
- Dynamic routing and delay logic: Instead of using a fixed delay (e.g., 72 hours), define a lookup table or matrix with transport delays for each origin–destination pair. Use this to apply route-specific delays in a more flexible and realistic manner.
- Support for multiple ships: Introduce a new set representing individual ships and define decision variables such as `ship_depart[ship, t]` and `ship_available[ship, t]`. This enables modelling of multiple vessels operating in parallel and allows optimization of fleet utilization.
- Automated shipment decisions: Allow the model to choose optimal shipment routes, timing, and the number of ships dynamically, based on supply, demand, and cost optimization across all node pairs. This removes the need for manually predefined routes or schedules.
- Adaptability to other carriers: Generalize the model structure so it can simulate other discrete energy carriers, such as hydrogen, ammonia, or synthetic fuels. Carrier-specific parameters (e.g., energy density, storage losses, transport efficiency) could be configured to evaluate different export strategies within the same modelling framework.

Moreover, based on these findings, it is recommended that future research further explores integrated energy-export systems combining discrete maritime shipping and direct electricity transmission. Hybrid approaches could exploit the benefits of both methodologies, improving overall sustainability and resilience.

Additionally, further enhancements of the model could integrate environmental impacts explicitly, such as carbon emissions accounting, to more comprehensively evaluate sustainability performance. Incorporating uncertainty in renewable energy generation and fuel prices through stochastic optimization could also provide deeper insights into operational robustness and risk management.

Finally, certain constraints formulated in the mathematical model, specifically the fuel consumption and restock constraint, aluminium stock balance, and fuel depot balance, were defined but not actively enforced. These constraints represent valuable extensions for future research. Enforcing them in subsequent models could provide a more accurate depiction of dynamic storage levels, logistical dependencies, and system resilience. For instance, explicitly modelling the aluminium stock balance would allow for the exploration of buffer strategies to accommodate variable shipping schedules, while fuel depot balance constraints could simulate the operational impacts of limited fuel availability or refuelling delays. Incorporating these aspects would enhance the model's fidelity and allow for more comprehensive scenario analysis.

Overall, this report demonstrates that discrete maritime transport of aluminium is a promising renewable energy export strategy for islands like Iceland. However, realizing its full potential requires addressing the outlined methodological and practical challenges. Future models incorporating these enhancements could significantly influence strategic planning and policy development, supporting sustainable and economically viable renewable energy export pathways.

6 Conclusion

This report has investigated discrete maritime aluminium transport as a strategy for exporting renewable energy from geographically isolated regions, with Iceland as a specific case study. By employing a detailed Mixed-Integer Linear Programming (MILP) approach within the Calliope framework, this study successfully demonstrated the feasibility and practicality of modelling discrete logistical constraints, such as shipment scheduling, delays, and fuel usage, in energy system optimization models.

Two primary scenarios were compared: discrete maritime aluminium transport and continuous direct electricity transmission via submarine cables. A key comparative assessment indicated that discrete aluminium shipping delivered significantly more energy (10,625 TWh) at a lower total cost (USD 33.85 million) compared to direct electricity transmission (689.76 GWh for USD 96.72 million). These numerical insights clearly illustrate that while submarine cable projects such as IceLink offer continuous and immediate energy transfer ideal for grid integration, they involve considerable upfront capital (approximately €3.5 billion) and infrastructure vulnerabilities. In contrast, maritime aluminium transport provided flexibility, lower initial investment (USD 40 million per operational cycle), and strategic scalability, albeit with higher operational complexity and environmental impacts from fuel use.

Sensitivity analyses further validated the robustness of both modelling approaches, demonstrating consistent and predictable scaling behavior across a range of scenarios. Minor deviations identified in these analyses were primarily due to calendar-based variations (e.g., differing month lengths), rather than intrinsic model inconsistencies.

Nonetheless, the current model formulation presents some limitations, primarily due to its specificity to the Iceland-Netherlands case. Future research should focus on expanding the generalizability of the model by allowing dynamic determination of optimal shipment routes, multiple ships, and diverse node configurations. Additional improvements could include explicit integration of inventory management strategies, enhanced fuel consumption modelling based on empirical operational data, and explicit environmental impact assessments.

From a strategic standpoint, the discrete aluminium transport model demonstrates significant potential as a viable renewable energy export strategy. However, policymakers must carefully consider trade-offs involving economic viability, environmental impact, and infrastructure resilience. Ultimately, the optimal choice between discrete aluminium transport and direct electricity transmission depends on specific contextual factors, including distance to markets, infrastructure costs, renewable energy intermittency, and environmental objectives.

In conclusion, this report highlights that discrete maritime aluminium shipping represents a promising alternative to traditional submarine cable-based energy transmission. By successfully incorporating complex logistical dynamics into energy system modelling, the study advances the field and provides valuable decision-support tools for planning sustainable energy export pathways.

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A Appendix: YAML configuration files undersea electricity transmission

A.1. model.yaml

Listing A.1: model.yaml configuration file

```yaml
import:
  - "model_config/techs.yaml"
  - "model_config/locations.yaml"
  - "scenarios.yaml"

config:
  init:
    name: main model
    calliope_version: 0.7.0
    time_subset: ["2005-01-01", "2005-01-31"]
    broadcast_param_data: true

  build:
    ensure_feasibility: false
    mode: plan

  solve:
    solver: gurobi
    zero_threshold: 1e-10

parameters:
  objective_cost_weights:
    data: 1
    index: [monetary]
    dims: costs
  bigM: 1e6

data_tables:
  time_varying_parameters:
    data: data_tables/supply_and_demand.csv
    rows: timesteps
    columns: [comment, nodes, techs, parameters]
    drop: comment
  cost_parameters:
    data: data_tables/costs.csv
    rows: techs
    columns: [parameters, comment]
    drop: comment
    add_dims:
      costs: monetary
```

A.2. scenarios.yaml

Listing A.2: custom_constraints_delay.yml configuration file

```yaml
scenarios:
  default:
    timeseries:
      time:
        coordinates:
          - time
        data:
          time:
            interval: 1H  # Time steps are hourly
            start: 2005-01-01  # Start date
            end: 2005-01-31  # End date
```

A.3. locations.yaml

Listing A.3: nodes.yaml configuration file

```yaml
##
# nodes
##

nodes:
  Iceland:
    latitude: 64.1355
    longitude: -21.8954
    techs:
      renewable_electricity:
        carrier: electricity

  Netherlands:
    latitude: 52.3676
    longitude: 4.9041
    techs:
      electricity_demand:
        carrier: electricity
        cost_flow_in:
          data: -1
          dims: costs
          index: monetary
```

A.4. techs.yaml

Listing A.4: nodes.yaml configuration file

```
##
# TECHNOLOGY DEFINITIONS
##

techs:
  ##
  # Supply
  ##

  renewable_electricity:
    name: "Renewable Electricity"
    color: "#F9CF22"
    base_tech: supply
    carrier_out: electricity
    flow_cap_max: .inf

  ##
  # Demand
  ##

  electricity_demand:
    name: "Electricity Demand"
    color: "#072486"
    base_tech: demand
    carrier_in: electricity

  ##
  # Transmission
  ##

  undersea_cable_transport_tech:
    link_from: Iceland
    link_to: Netherlands
    one_way: true
    name: "Electricity Transport"
    color: "#8465A9"
    base_tech: transmission
    carrier_in: electricity
    carrier_out: electricity
    flow_cap_max: 1 # Maximum flow capacity for renewable transmission in GWh
    flow_out_eff: 0.958
```

B Appendix: YAML configuration files aluminium transport

B.1. model.yaml

Listing B.1: model.yaml configuration file

```yaml
import:
  - "model_config/techs.yaml"
  - "model_config/locations.yaml"
  - "scenarios.yaml"

config:
  init:
    name: main model
    calliope_version: 0.7.0
    time_subset: ["2005-01-01", "2005-01-31"]
    broadcast_param_data: true

  build:
    ensure_feasibility: false
    mode: plan
    add_math: [custom_constraints_state.yml, custom_constraints_delay.yml]

  solve:
    solver: gurobi
    zero_threshold: 1e-10

parameters:
  objective_cost_weights:
    data: 1
    index: [monetary]
    dims: costs
  bigM: 1e6

data_tables:
  time_varying_parameters:
    data: data_tables/supply_and_demand.csv
    rows: timesteps
    columns: [comment, nodes, techs, parameters]
    drop: comment
  cost_parameters:
    data: data_tables/costs.csv
    rows: techs
    columns: [parameters, comment]
    drop: comment
    add_dims:
      costs: monetary
```

B.2. scenarios.yaml

Listing B.2: custom_constraints_delay.yml configuration file

```
scenarios:
  default:
    timeseries:
      time:
        coordinates:
          - time
        data:
          time:
            interval: 1H  # Time steps are hourly
            start: 2005-01-01  # Start date
            end: 2005-01-31  # End date
```

B.3. locations.yaml

Listing B.3: nodes.yaml configuration file

```yaml
##
# nodes
##

nodes:
  Iceland:
    latitude: 64.1355
    longitude: -21.8954
    techs:
      fuel_supply:
        carrier: fuel
      renewable_electricity:
        carrier: electricity
      aluminium_smelter:

  Netherlands:
    latitude: 52.3676
    longitude: 4.9041
    techs:
      aluminium_demand:
        carrier: aluminium
        cost_flow_in:
          data: -1
          dims: costs
          index: monetary
      fuel_necessity:
        carrier: fuel
        cost_flow_in:
          data: -1
          dims: costs
          index: monetary
```

B.4. techs.yaml

Listing B.4: nodes.yaml configuration file

```
##
# TECHNOLOGY DEFINITIONS
##

techs:
  ##
  # Supply
  ##

  fuel_supply:
    name: "Fuel Supply"
    color: "#E37A72"
    base_tech: supply
    carrier_out: fuel
    flow_cap_max: .inf

  renewable_electricity:
    name: "Renewable Electricity"
    color: "#F9CF22"
    base_tech: supply
    carrier_out: electricity
    flow_cap_max: .inf

  ##
  # Demand
  ##

  aluminium_demand:
    name: "Aluminium Demand"
    color: "#072486"
    base_tech: demand
    carrier_in: aluminium

  fuel_necessity:
    name: "Fuel Necessity"
    color: "#87CEEB"
    base_tech: demand
    carrier_in: fuel

  ##
  # Conversion
  ##

  aluminium_smelter:
    name: "Aluminium smelter"
    color: "#8E2999"
    base_tech: conversion
    carrier_in: electricity
    carrier_out: aluminium
    flow_out_eff: 0.96

  ##
  # Transmission
  ##

  aluminium_transport_tech:
    link_from: Iceland
    link_to: Netherlands
    one_way: true
    name: "Aluminium Transport"
    color: "#8465A9"
    base_tech: transmission
```

```yaml
    carrier_in: aluminium
    carrier_out: aluminium
    flow_cap_max: 3000 # Maximum storage capacity for aluminium transport in Mton
    flow_out_eff: 1

  fuel_consumption_tech:
    link_from: Iceland
    link_to: Netherlands
    one_way: true
    name: "Fuel Consumption"
    color: "#3B61E3"
    base_tech: transmission
    carrier_in: fuel
    carrier_out: fuel
    flow_cap_max: 7 # Hourly fuel consumption during aluminium transport in Mton
    flow_out_eff: 1
```

B.5. custom_constraints_delay.yml

Listing B.5: custom_constraints_delay.yml configuration file

```yaml
constraints:
  balance_transmission:
    where: base_tech=transmission AND NOT techs=aluminium_transport_tech

  aluminium_transport_delay:
    description: >
      Enforce a 72-hour delay for aluminium transport from Iceland to Netherlands.
      The amount arriving at NL at time t equals the amount sent from Iceland at time t
          - 72.
    foreach: [techs, timesteps]
    where: techs=aluminium_transport_tech
    equations:
      - expression: >
          flow_out[nodes=Netherlands, carriers=aluminium]
          == default_if_empty(
               roll(flow_in[nodes=Iceland, carriers=aluminium], timesteps=72),
               default=0
             )
```

B.6. custom_constraints_state.yml

Listing B.6: custom_constraints_state.yml configuration file

```yaml
variables:
  ship_depart:
    description: "1 if a ship departs with an aluminium shipment from Iceland in this
        timestep, else 0"
    foreach: [techs, timesteps]
    where: techs=aluminium_transport_tech AND nodes=Iceland
    domain: integer # bound to 0-1 to make it binary
    bounds:
      min: 0
      max: 1

  ship_available:
    description: "Number of ships available at origin (Iceland) at a given timestep"
    foreach: [techs, timesteps]
    where: techs=aluminium_transport_tech AND nodes=Iceland
    domain: integer # non-negative integer
    bounds:
      min: 0
      max: 1 # number of ships, 1 in this case

constraints:
  shipping_capacity_link:
    description: "Allow aluminium flow out of Iceland only when a ship departs (enforce
        discrete ship usage)"
    foreach: [nodes, techs, timesteps]
    where: techs=aluminium_transport_tech AND nodes=Iceland
    equations:
      - expression: flow_in[carriers=aluminium] <= ship_depart * flow_cap_max

  ship_limit:
    description: "There's only one ship so you can only have one departure every 144
        hours"
    foreach: [nodes, techs, timesteps]
    where: techs=aluminium_transport_tech AND nodes=Iceland
    equations:
      - expression: sum_next_n(ship_depart, timesteps, 144) <= 1

  ship_availability_limit:
    description: "You can only depart if there is availability"
    foreach: [nodes, techs, timesteps]
    where: techs=aluminium_transport_tech AND nodes=Iceland
    equations:
      - expression: ship_depart <= $prev_available
    sub_expressions:
      prev_available:
        # For t=0, set initial number of ships; for t>0, use previous timestep's
            availability
        - where: timesteps = get_val_at_index(timesteps=0) # first timestep
          expression: "1" # number of ships
        - where: timesteps >= get_val_at_index(timesteps=-72) # no ship departs the last
             72 hours
          expression: "0"
        - where: NOT timesteps = get_val_at_index(timesteps=0) AND NOT timesteps >=
            get_val_at_index(timesteps=-72)
          expression: roll(ship_available, timesteps=1) # ship_available at t-1

  ship_roundtrip_cycle:
    description: >
      Ensures the ship returns to origin before another departure can occur.
      ship_available(t) = ship_available(t-1) + (returning ship at t) - (departing ship
          at t).
    foreach: [techs, timesteps]
```

```
    where: techs=aluminium_transport_tech AND nodes=Iceland
    equations:
      - expression: ship_available == $prev_available + $ship_returned - ship_depart
    sub_expressions:
      prev_available:
        # For t=0, set initial number of ships; for t>0, use previous timestep's
           availability
        - where: timesteps = get_val_at_index(timesteps=0) # first timestep
          expression: "1" # number of ships
        - where: NOT timesteps = get_val_at_index(timesteps=0)
          expression: roll(ship_available, timesteps=1) # ship_available at t-1
      ship_returned:
        # ship_returned at time t equals ship_depart at time t - 72 (a ship that left 72
            hours ago returns now)
        - expression: default_if_empty(roll(ship_depart, timesteps=144), default=0)
        # use 2*72 = 144 for the return (round-trip). The roll shifts departures forward
            by 144h.
```