

# MSc Thesis

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

SET 3901: Graduation Project

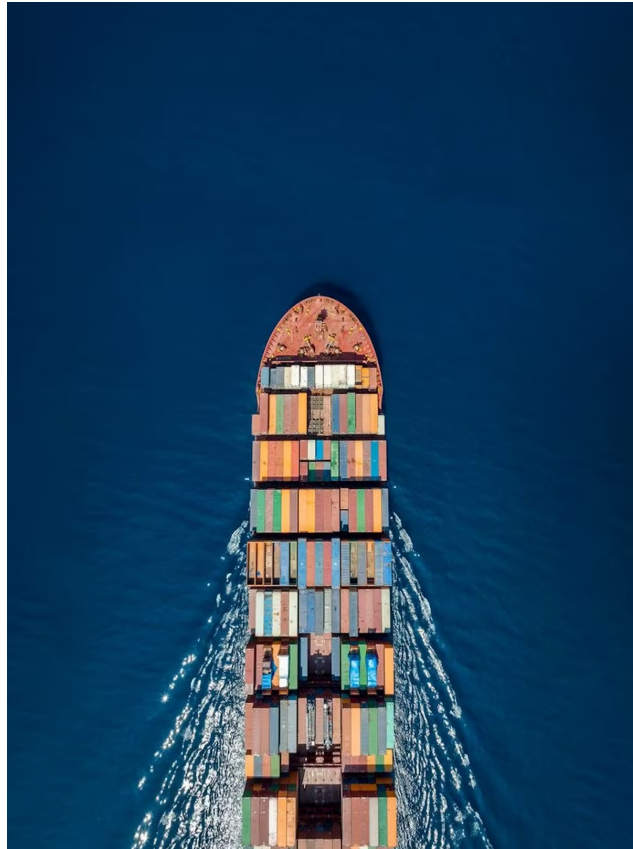
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**TU**Delft

# 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.

*Berat Kaya*  
*Delft, June 1, 2025*

# Abstract

As island systems transition to high shares of renewable energy, strategies for exporting surplus electricity become essential for economic and environmental optimization. This report investigates the feasibility of using discrete maritime transport of aluminium, a highly energy-intensive commodity, as an indirect energy export pathway. Focusing on Iceland, which produces aluminium using abundant local renewable energy, and its trade with the Netherlands, the study develops a Mixed-Integer Linear Programming (MILP) model implemented in the Calliope framework. The model explicitly incorporates discrete shipment events, transport delays, and fuel consumption, capturing the logistical complexities of maritime export. Results show that strategic ship scheduling can align with periods of high renewable availability to minimize fuel use and system costs. A comparative analysis with a simplified continuous-flow scenario highlights the limitations of traditional modelling approaches and underscores the value of discrete-event energy system modelling. This work contributes a novel transport modelling approach and supports the broader goal of integrating flexible, low-carbon transport solutions into renewable-rich island energy systems.

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# 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 (Verrascina, 2022). 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 emissions and fuel 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 the outcomes of both a simplified continuous transport scenario and the main discrete event-driven model. It evaluates aluminium flow patterns, shipping schedules, fuel consumption, and total system costs.
- Chapter 5 – Discussion: The results are critically analysed in this chapter, with a focus on interpreting the implications for energy system design and sustainability. Trade-offs between operational complexity, cost, and environmental impact are discussed. The chapter also considers alternative export strategies and outlines key lessons for future energy system modelling efforts.
- Chapter 6 – Conclusion: The report concludes with a summary of key findings and methodological contributions. Future work is also proposed.

# 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 pipelines or 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 linear programming 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  $-33^\circ\text{C}$ ) 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. It reported that production costs for green hydrogen remain high (€6.7–9.8 per kg, or €0.20–0.29/kWh) and for green ammonia €1.9–2.8 per kg ( $\approx$ €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 4000 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 off-shore 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 1000 km, significantly better than HVAC cables (6–7% per 1000 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 3200 km and reach ocean depths near 1900 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 4000 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).

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.



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. Synthesis of finding and knowledge gaps

The literature converges on several key insights relevant to transporting surplus renewable energy from islands. First, context is everything: the optimal export solution depends strongly on the island's situation, its distance to other grids, the scale of surplus generation, and the available technologies. If an island is relatively close to large electricity demand centres, investing in a submarine HVDC cable is often the preferred strategy, benefiting from high efficiency and avoiding intermediate conversions (Xu et al., 2023). If the island is remote, shipping energy carriers like hydrogen or ammonia becomes favourable, with ammonia usually outperforming direct hydrogen for long hauls due to easier handling and lower transport loss (Cava, 2024). Second, utilization rate (capacity factor) is a critical economic driver across all options. High renewable variability can hurt the economics of both cables and tankers if they are underutilized; thus, strategies to increase steady output (like over-sizing renewables and using storage or scheduling shipments cleverly) are essential (Miao et al., 2021). Third, the technologies are complementary rather than mutually exclusive. For example, an island might use a cable to export some power and also convert excess into hydrogen for local industrial use or seasonal storage. Studies increasingly consider hybrid approaches and stress the need for integrated planning that can evaluate electricity and fuel export in one framework (Xu et al., 2023).

The evidence base includes a mix of methodological approaches. Techno-economic case studies (including many in journals like *Energy* and *IJHE*) typically make specific assumptions about costs and then compare options on levelized cost of energy (LCOE) delivered (Joyo et al., 2025a). These are useful for understanding current viability but can become quickly outdated as costs change. Optimization models add value by finding the best configuration under given inputs, sometimes revealing non-intuitive solutions (e.g. preferring a combination of smaller ships and larger storage to minimize cost, or finding that adding a secondary export product like oxygen from electrolysis could improve economics). However, optimization results are sensitive to input data and model scope, and not all models capture the full complexity (e.g. real shipping schedules or social acceptance factors). Multi-criteria and simulation studies broaden the perspective but may sacrifice optimality or rigour in trade-off quantification. The systematic review by Ochoa-Correa et al. (2025) highlights that many island energy studies focus on technical solutions but do not comprehensively compare all options side-by-side.

Despite the progress in this field, there remain 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.

## 2.9. Selection of a MILP-enabled calliope framework

To implement the above ideas, the Calliope energy system modelling framework with MILP capabilities is used. Calliope has flexibility in representing custom technologies and constraints, as well as support for multi-scale analysis. It is an open-source framework designed for arbitrarily high spatial and temporal resolution in energy modelling, which is essential for capturing the hourly renewable variability and multi-day shipping cycles in this case. Importantly, Calliope's solver interface can handle both linear and mixed-integer formulations. In fact, Calliope explicitly allows users to define binary decision variables for capacities or operations, and it can leverage commercial MILP solvers to tackle the resulting problem (Pfenninger and Pickering, 2018). This capability has been demonstrated in prior studies, for example, Calliope has been utilized for national-scale models and even extended with piecewise linearization for complex technology behaviours (Pfenninger and Pickering, 2025). 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 over-production, the timing of fuel and aluminium production, and the logistics of maritime transport, thus filling the gap identified in current energy system models.

# 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 involved in transport scheduling and fuel consumption. 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.

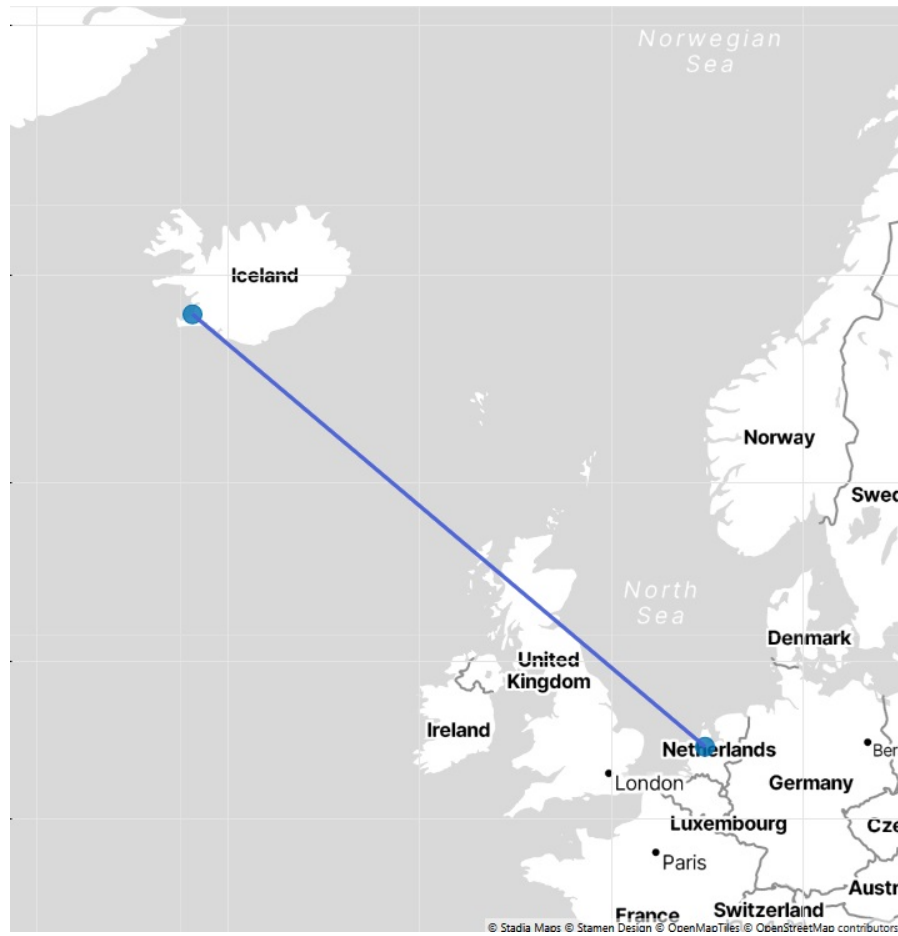
The Netherlands was chosen as the import destination for Iceland's aluminium due to its role as one of Iceland's key aluminium trading partners. As a major industrial and logistics hub within Europe, the Netherlands is strategically positioned to import and distribute aluminium throughout the continent. 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 aluminium is produced using renewable energy sources (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 is assumed to be unlimited for the model duration, given renewable resource availability. They were given a cost of 0.0025 and 0.0005 USD per MTon respectively, which are roughly based on current aluminium and cargo ship fuel prices (S&B, 2025) (TE, 2025). Demand in the Netherlands is continuous at a constant hourly rate. Operational complexity such as detailed port handling times or loading/unloading delays and environmental impacts, including emissions, were 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.

## Sets

- $T$ : Set of time spans (e.g.,  $T = \{1, 2, \dots, D\}$ ), 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  $s$ .
- $\eta_s$ : Fuel consumption rate of ship  $s$ .
- $\sigma_s$ : Fuel capacity of ship  $s$ .
- $\alpha_i$ : Initial aluminium stock at node  $i$ .
- $\beta_i$ : 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.

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

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

#### • 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.

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

- **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.

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

- **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  $t$ .
- $\sigma_s$ : 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.

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

- **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  $t$ .
- $\beta_i$ : 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.

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

- **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.yaml`: 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.yaml`: 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.yaml`: 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.

By structuring the model through these configuration files and leveraging Jupyter Notebook and Calligraph for post-processing, the methodology provides a comprehensive, flexible framework for evaluating the aluminium transport model.

# 4 Results

The results presented in this chapter demonstrate the outcomes of optimizing discrete maritime transportation of aluminium between Iceland and the Netherlands, using the Calliope energy system model. Two scenarios were analysed: a simplified scenario (continuous direct transmission without discrete scheduling or fuel constraints) and the main discrete transport scenario incorporating explicit scheduling, delays, and fuel consumption.

## 4.1. Simple scenario

The conditions for this scenario were suitable for modelling in Calliope without any additional custom math and serve mainly as a demonstration of the starting conditions for the main scenario. In this simplified scenario, aluminium transport was modelled as a continuous flow at 3000 tons per hour with no transport delays or discrete ship departures. Figure 4.1 and Figure 4.2 show steady and continuous aluminium inflow and outflow respectively, indicating a constant and uninterrupted aluminium flow from Iceland to the Netherlands, while meeting the demand perfectly.

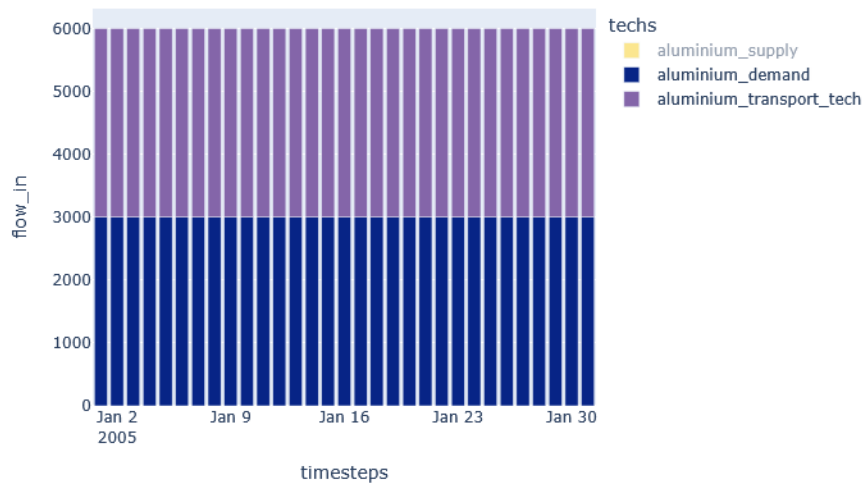


Figure 4.1: Simple model aluminium flow in.

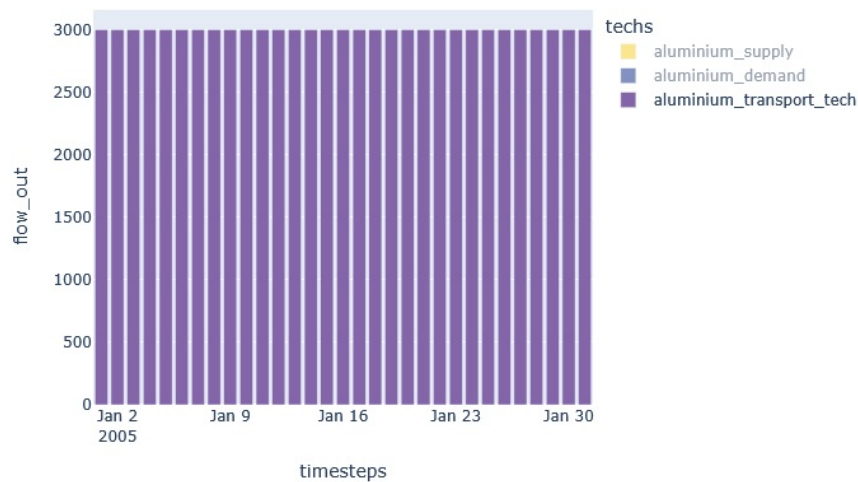
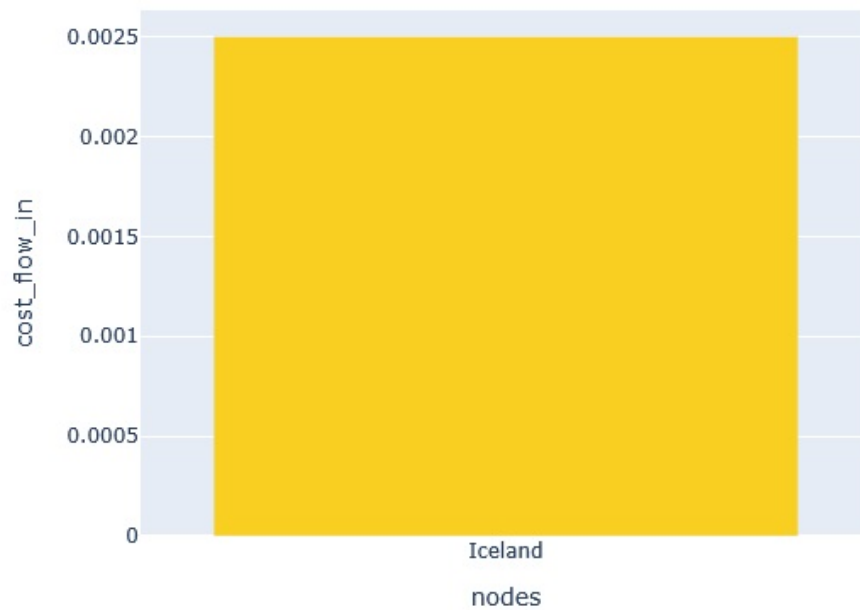
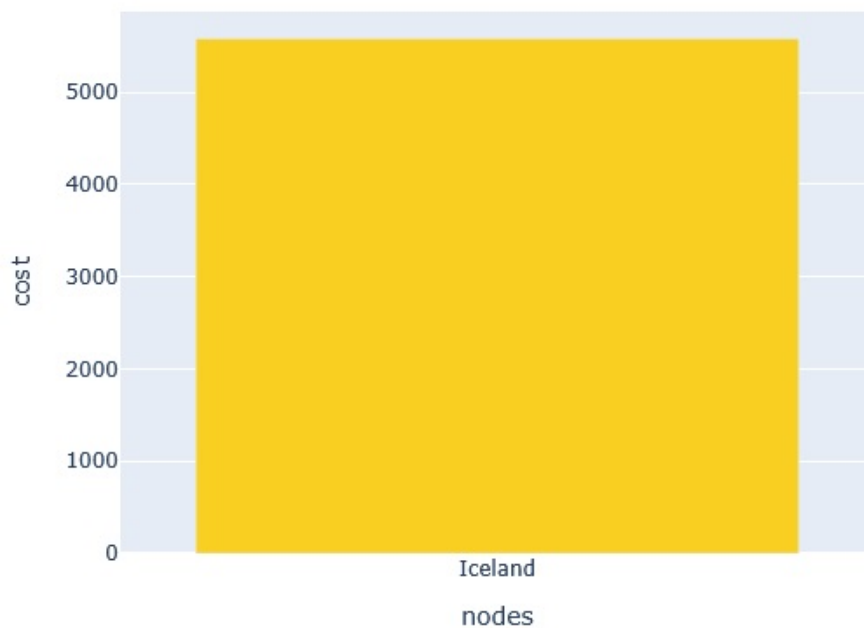


Figure 4.2: Simple model aluminium flow out.

The system-wide levelised cost (equal to the flow in cost in this case) and total cost are depicted in Figure 4.3 and Figure 4.4 respectively. As the demand is met on an hourly basis, the cost for flow in of aluminium is also applied hourly, leading to a relatively large total cost of roughly 5.5 billion USD. The flow in cost is taken the same as for the main scenario at 0.0025 USD per MTon, for simplicity.



**Figure 4.3:** Simple model system-wide levelised cost.



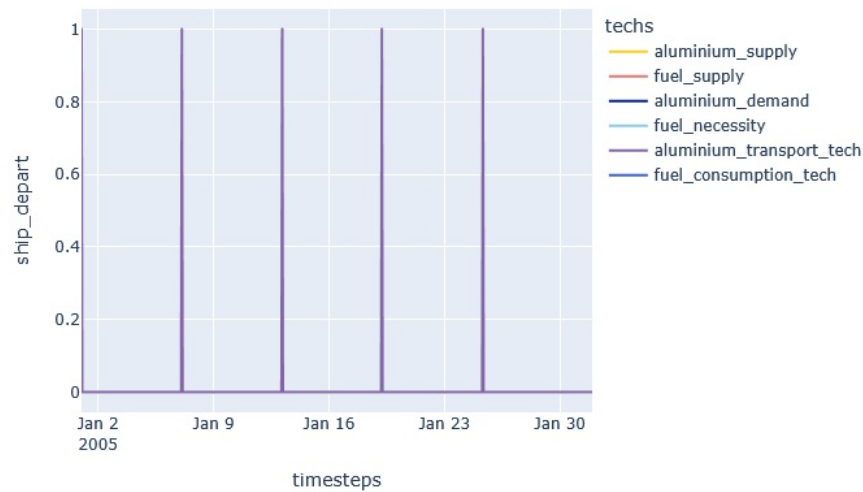
**Figure 4.4:** Simple model total cost.

## 4.2. Main scenario

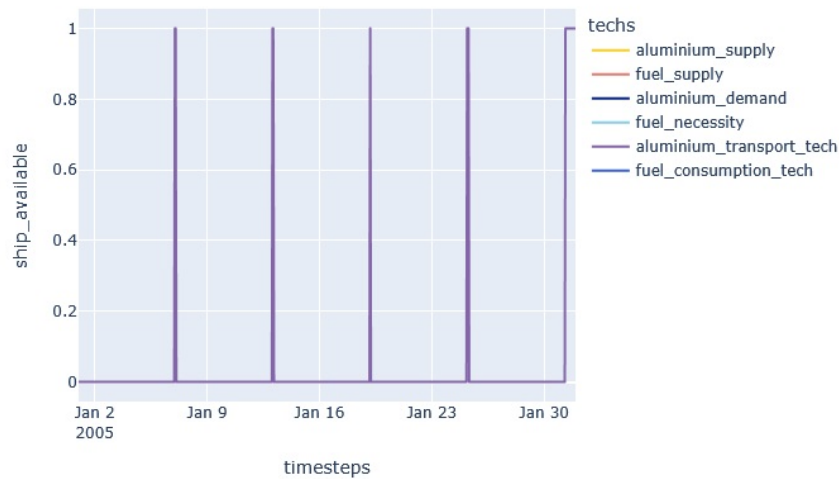
The main scenario integrates realistic operational constraints, including discrete shipping schedules, delayed arrivals, and explicit fuel usage.

### 4.2.1. Ship scheduling and availability

Figure 4.5 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 4.6 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.



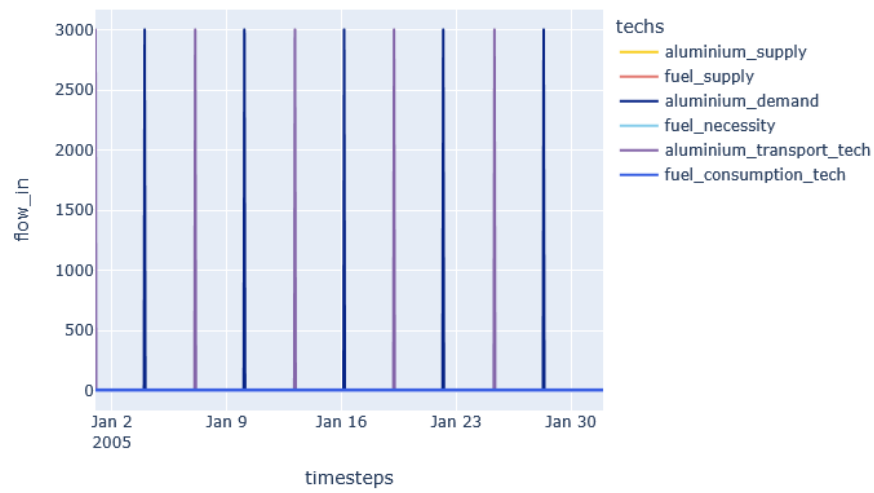
**Figure 4.5:** Main model ship depart binary variable.



**Figure 4.6:** Main model ship available binary variable.

### 4.2.2. Aluminium flow dynamics

Figure 4.7 and Figure 4.8 depict the aluminium inflow and outflow for the main scenario, respectively. Aluminium departures from Iceland occur at discrete intervals, aligned with the ship's departure schedule, resulting in pronounced peaks of 3000 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 4.7:** Main model aluminium flow in.

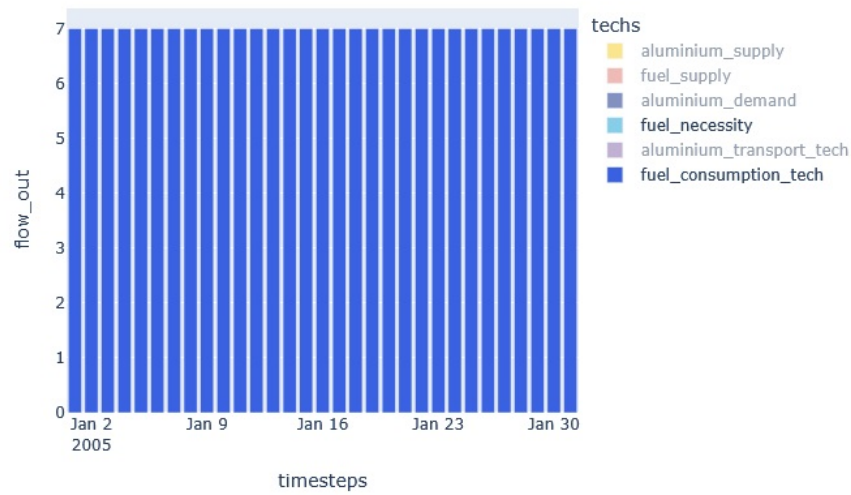


**Figure 4.8:** Main model aluminium flow out.



### 4.2.3. Fuel consumption

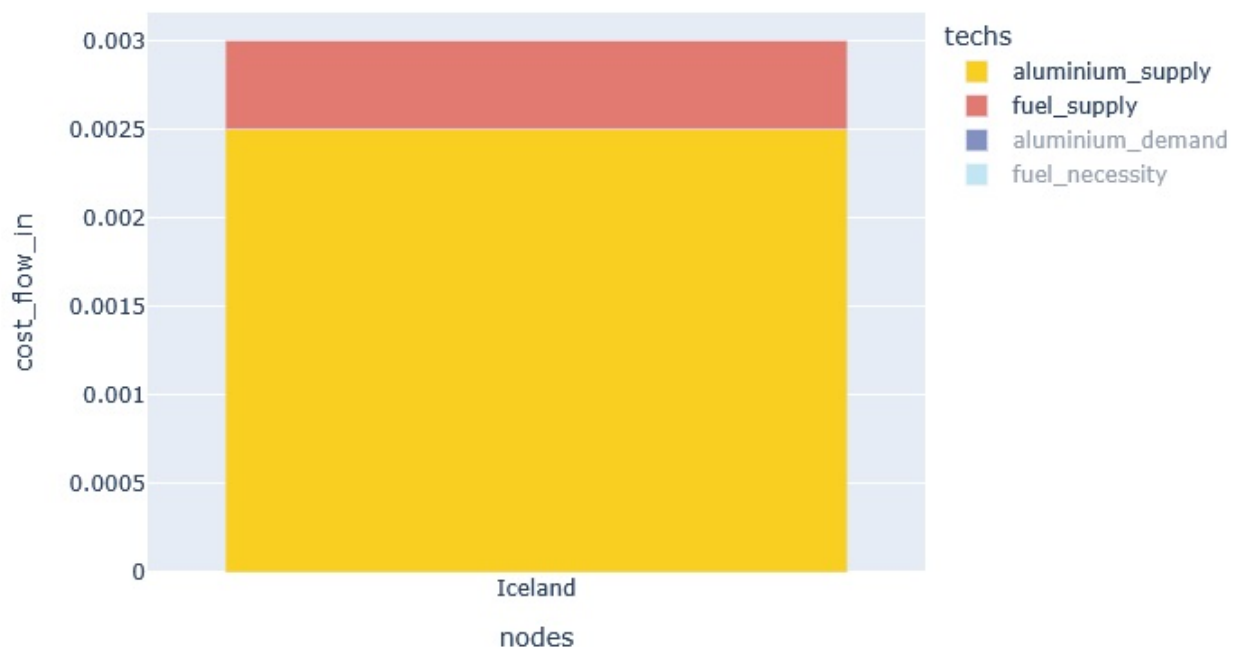
Figure 4.9 details the hourly fuel consumption of 7 tons per hour associated with aluminium transport. This steady fuel usage aligns directly with the operational activity of the ship during transport. Fuel is burned at every time interval as the ship is essentially in a constant state of travel and it is assumed there is enough fuel for a round trip, after which refuelling happens at Iceland. This is not explicitly modelled.



**Figure 4.9:** Main model fuel consumption.

### 4.2.4. Economic analysis

The system-wide levelised cost, is shown in Figure 4.10, while the total system cost for the main scenario is shown in Figure 4.10. 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 are roughly 40 million USD, with a flow in cost of 0.0005 and 0.0025 USD per Mton respectively.



**Figure 4.10:** Main model system-wide levelised cost.



Figure 4.11: Main model total cost.

### 4.3. Comparative assessment

The simplified continuous scenario served as a baseline to test the implementation and stability of the modelling framework. Its primary role was to validate flow structures and economic behaviour in the absence of complex constraints. In contrast, the main 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.

At this stage, a direct economic comparison between the simplified and discrete scenarios is not meaningful. The simplified scenario is highly idealized and does not incorporate the infrastructure costs or losses associated with (undersea) electricity transmission, nor does it account for operational complexities. This comparison will be provided in the next section.

# 5 Discussion

The modelling results presented in this study highlight critical insights into the feasibility and operational dynamics of using discrete commodity shipping as a strategy for exporting renewable energy, specifically in the context of Iceland's aluminium exports to the Netherlands. This chapter critically discusses these findings, evaluating their implications for sustainable maritime transport and renewable energy integration within broader energy systems.

## 5.1. Interpretation of results

The main scenario successfully incorporated discrete shipping schedules, realistic transit delays, and explicit fuel consumption patterns into the energy system model. The periodic and discrete nature of shipments accurately represents real-world maritime transport, contrasting with the simplified scenario's continuous, uninterrupted flow. These discrete intervals align realistically with operational constraints, validating the model's practical applicability.

Notably, the discrete scheduling scenario clearly demonstrated that the temporal alignment of shipments with renewable energy availability significantly affects fuel efficiency and operational costs. The periodic peaks in aluminium shipments, coupled with corresponding fuel consumption, underline the importance of strategically timing shipments to minimize fuel use and optimize cost-efficiency.

## 5.2. Sustainability and economic trade-offs

The results underscore a vital trade-off between operational simplicity and system efficiency. Continuous energy flow models, while operationally straightforward, fail to capture the nuanced realities of shipping logistics. The discrete model's insights highlight the practical benefits of explicitly scheduling shipments, particularly regarding fuel savings and cost minimization.

Furthermore, the fuel consumption patterns revealed in the model emphasize the potential sustainability gains from aligning maritime operations closely with renewable energy availability. However, this alignment introduces complexity into logistics management, necessitating advanced scheduling and forecasting tools to optimize ship utilization and minimize idle times or energy waste.

## 5.3. Possible alternatives

It is acknowledged that there are potential alternative renewable energy export methods, particularly submarine power cables. 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.

Thus, the viability of discrete maritime shipping as an export strategy heavily depends on specific regional contexts, economic frameworks, and sustainability goals. For Iceland, leveraging its surplus renewable energy in aluminium exports provides a practical balance between infrastructure investment and operational flexibility, especially given its geographical constraints.

## 5.4. Recommendations and future research directions

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.

Moreover, 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.

Additionally, 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.

Finally, extending this research to multi-node and multi-carrier scenarios could yield valuable insights into more complex global supply chains, enhancing generalizability and applicability to diverse renewable energy export contexts.

# 6 Conclusion

This report explored the viability and optimization of discrete commodity shipping as a strategy for exporting surplus renewable energy from island systems, with a particular focus on Iceland's aluminium exports to the Netherlands. By integrating discrete-event maritime transport modelling into the Calliope energy system framework, the aim was to fill a critical methodological gap in current energy system optimization literature. Namely, the limited capacity of traditional models to represent discrete shipments and transport delays.

The results demonstrate that discrete maritime transport can be effectively modelled using a MILP-enabled version of Calliope, incorporating key operational constraints such as ship scheduling, travel delays, and fuel consumption. The main scenario developed in this work realistically captured the periodic nature of shipping operations and highlighted the interplay between shipment timing and system-wide energy and cost efficiency. Compared to the idealized continuous flow scenario, the discrete model introduced operational realism, enabling a more nuanced assessment of logistics, energy usage, and cost dynamics.

Several key insights emerged from the model outcomes:

- Temporal scheduling is crucial: Optimally timing shipments significantly affects both fuel consumption and overall cost. The model's ability to align aluminium departures with available renewable energy can support more sustainable and economical maritime logistics.
- Trade-offs compared to alternatives: While discrete shipping introduces scheduling complexity and fuel costs, it offers flexible export capability with lower capital requirements compared to infrastructure-intensive alternatives like submarine HVDC cables. These trade-offs must be assessed in light of each region's geography, renewable surplus, and export objectives.
- Modelling enhancements are valuable: The integration of custom constraints into Calliope expanded its functionality, showcasing how flexible energy system models can be adapted to capture real-world transport behaviours. This approach provides a foundation for future research involving multi-node systems, multiple ships, or variable renewable inputs.

Despite these contributions, several limitations were acknowledged. The model did not include environmental impacts such as maritime emissions, dynamic renewable availability, or storage infrastructure. Additionally, the economic comparison with submarine cables was preliminary and requires further elaboration using consistent cost assumptions and infrastructure models.

## 6.1. Future Work

The findings from this report point to several directions for further investigation:

- Expanding the model to incorporate multiple ships, fuel types (e.g., green ammonia), or hybrid export strategies (e.g., combining cable and shipping).
- Including stochastic renewable generation profiles to assess resilience and uncertainty.
- Developing a techno-economic comparison between commodity shipping, green hydrogen export, and HVDC cable transmission under identical conditions.
- Integrating lifecycle emissions and environmental impact metrics into the model to support more holistic sustainability evaluations.

In conclusion, this report has demonstrated that discrete commodity shipping is not only a viable but potentially advantageous method of renewable energy export in specific island contexts. With proper modelling tools and optimization strategies, it can serve as an effective complement to conventional electricity transmission, supporting the global transition toward clean, flexible, and geographically inclusive energy systems.

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# A Appendix: YAML configuration files

## A.1 model.yaml

Listing A.1: model.yaml configuration file

```
1 import:
2   - "model_config/techs.yaml"
3   - "model_config/locations.yaml"
4   - "scenarios.yaml"
5
6 config:
7   init:
8     name: main model
9     calliope_version: 0.7.0
10    time_subset: ["2005-01-01", "2005-01-31"]
11    broadcast_param_data: true
12
13  build:
14    ensure_feasibility: false
15    mode: plan
16    add_math: [custom_constraints_state.yml, custom_constraints_delay.yml]
17
18  solve:
19    solver: gurobi
20    zero_threshold: 1e-10
21
22 parameters:
23   objective_cost_weights:
24     data: 1
25     index: [monetary]
26     dims: costs
27   bigM: 1e6
28
29 data_tables:
30   time_varying_parameters:
31     data: data_tables/supply_and_demand.csv
32     rows: timesteps
33     columns: [comment, nodes, techs, parameters]
34     drop: comment
35   cost_parameters:
36     data: data_tables/costs.csv
37     rows: techs
38     columns: [parameters, comment]
39     drop: comment
40   add_dims:
41     costs: monetary
```

## A.2. scenarios.yaml

**Listing A.2:** custom\_constraints\_delay.yml configuration file

```
1 scenarios:
2   default:
3     timeseries:
4       time:
5         coordinates:
6           - time
7       data:
8         time:
9           interval: 1H # Time steps are hourly
10          start: 2005-01-01 # Start date
11          end: 2005-01-31 # End date
```

## A.3. locations.yaml

**Listing A.3:** nodes.yaml configuration file

```
1 ##
2 # nodes
3 ##
4
5 nodes:
6   Iceland:
7     latitude: 64.1355
8     longitude: -21.8954
9     techs:
10       fuel_supply:
11         carrier: fuel
12       aluminium_supply:
13         carrier: aluminium
14
15   Netherlands:
16     latitude: 52.3676
17     longitude: 4.9041
18     techs:
19       aluminium_demand:
20         carrier: aluminium
21       cost_flow_in:
22         data: -1
23         dims: costs
24         index: monetary
25       fuel_necessity:
26         carrier: fuel
27       cost_flow_in:
28         data: -1
29         dims: costs
30         index: monetary
```

## A.4. techs.yaml

Listing A.4: nodes.yaml configuration file

```

1 ##
2 # TECHNOLOGY DEFINITIONS
3 ##
4
5 techs:
6   ##
7   # Supply
8   ##
9
10  fuel_supply:
11    name: "Fuel Supply"
12    color: "#E37A72"
13    base_tech: supply
14    carrier_out: fuel
15    flow_cap_max: .inf
16
17  aluminium_supply:
18    name: "Aluminium Supply"
19    color: "#F9CF22"
20    base_tech: supply
21    carrier_out: aluminium
22    flow_cap_max: .inf
23
24  ##
25  # Demand
26  ##
27
28  aluminium_demand:
29    name: "Aluminium Demand"
30    color: "#072486"
31    base_tech: demand
32    carrier_in: aluminium
33
34  fuel_necessity:
35    name: "Fuel Necessity"
36    color: "#87CEEB"
37    base_tech: demand
38    carrier_in: fuel
39
40  ##
41  # Transmission
42  ##
43
44  aluminium_transport_tech:
45    link_from: Iceland
46    link_to: Netherlands
47    one_way: true
48    name: "Aluminium Transport"
49    color: "#8465A9"
50    base_tech: transmission
51    carrier_in: aluminium
52    carrier_out: aluminium
53    flow_cap_max: 3000 # Maximum storage capacity for aluminium transport
54    flow_out_eff: 1
55
56  fuel_consumption_tech:
57    link_from: Iceland
58    link_to: Netherlands
59    one_way: true
60    name: "Fuel Consumption"
61    color: "#3B61E3"
62    base_tech: transmission

```

```
63   carrier_in: fuel
64   carrier_out: fuel
65   flow_cap_max: 7 # Hourly fuel consumption during aluminium transport
66   flow_out_eff: 1
```

## A.5. custom\_constraints\_delay.yml

Listing A.5: custom\_constraints\_delay.yml configuration file

```
1 constraints:
2   balance_transmission:
3     # Update base constraint to ignore `aluminium_transport_tech`. We'll deal with it in
4     # the next section.
5     where: base_tech=transmission AND NOT techs=aluminium_transport_tech
6
7   aluminium_transport_delay:
8     description: >
9       Enforce a 72-hour delay for aluminium transport from Iceland to Netherlands.
10      The amount arriving at NL at time t equals the amount sent from Iceland at time t
11      - 72.
12     foreach: [techs, timesteps]
13     where: techs=aluminium_transport_tech
14     equations:
15       - expression: >
16         flow_out[nodes=Netherlands, carriers=aluminium]
17         == default_if_empty(
18           roll(flow_in[nodes=Iceland, carriers=aluminium], timesteps=72),
19           default=0
20         )
```

## A.6. custom\_constraints\_state.yml

Listing A.6: custom\_constraints\_state.yml configuration file

```

1 variables:
2   ship_depart:
3     description: "1 if a ship departs with an aluminium shipment from Iceland in this
4       timestep, else 0"
5     foreach: [techs, timesteps]
6     where: techs=aluminium_transport_tech AND nodes=Iceland
7     domain: integer # bound to 0-1 to make it binary
8     bounds:
9       min: 0
10      max: 1
11
12   ship_available:
13     description: "Number of ships available at origin (Iceland) at a given timestep"
14     foreach: [techs, timesteps]
15     where: techs=aluminium_transport_tech AND nodes=Iceland
16     domain: integer # non-negative integer
17     bounds:
18       min: 0
19       max: 1 # number of ships, 1 in this case
20
21 constraints:
22   shipping_capacity_link:
23     description: "Allow aluminium flow out of Iceland only when a ship departs (enforce
24       discrete ship usage)"
25     foreach: [nodes, techs, timesteps]
26     where: techs=aluminium_transport_tech AND nodes=Iceland
27     equations:
28       - expression: flow_in[carriers=aluminium] <= ship_depart * flow_cap_max
29
30   ship_limit:
31     description: "There's only one ship so you can only have one departure every 144
32       hours"
33     foreach: [nodes, techs, timesteps]
34     where: techs=aluminium_transport_tech AND nodes=Iceland
35     equations:
36       - expression: sum_next_n(ship_depart, timesteps, 144) <= 1
37
38   ship_availability_limit:
39     description: "You can only depart if there is availability"
40     foreach: [nodes, techs, timesteps]
41     where: techs=aluminium_transport_tech AND nodes=Iceland
42     equations:
43       - expression: ship_depart <= $prev_available
44     sub_expressions:
45       prev_available:
46         # For t=0, set initial number of ships; for t>0, use previous timestep's
47         # availability
48         - where: timesteps = get_val_at_index(timesteps=0) # first timestep
49         expression: "1" # number of ships
50         - where: timesteps >= get_val_at_index(timesteps=-72) # no ship departs the last
51           72 hours
52         expression: "0"
53         - where: NOT timesteps = get_val_at_index(timesteps=0) AND NOT timesteps >=
54           get_val_at_index(timesteps=-72)
55         expression: roll(ship_available, timesteps=1) # ship_available at t-1
56
57   ship_roundtrip_cycle:
58     description: >
59       Ensures the ship returns to origin before another departure can occur.
60       ship_available(t) = ship_available(t-1) + (returning ship at t) - (departing ship
61         at t).
62     foreach: [techs, timesteps]

```



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