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Full Charge ahead

Investigating the potential to electrify Europe's ferries

T&E

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Authors: Felix Klann, Leo Tricaud
Modelling: Valentin Simon, Leo Tricaud. Review by Alex Springer.

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Further information

Felix Klann

Maritime Transport Policy Officer

T&E

felix.klann@transportenvironment.org

Mobile: +32 (0) 492 57 22 65

www.transportenvironment.org | BlueSky | LinkedIn

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The findings and views put forward in this publication are the sole responsibility of the authors listed above.

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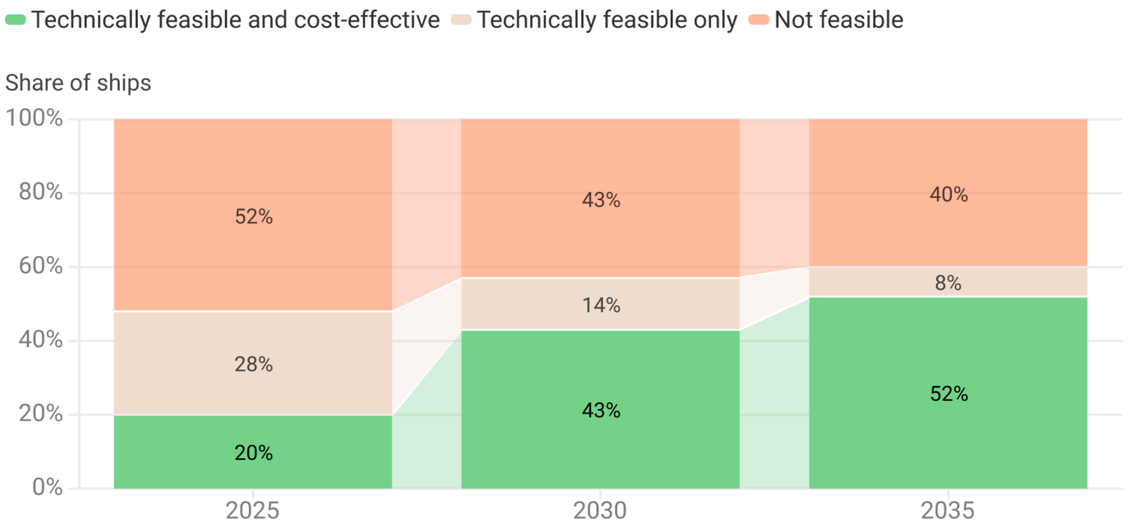
Executive summary

More than half of EU ferries could be electrified and be cost-competitive with fossil-powered ferries by 2035.

Ferries make up a vital part of the EU's transport system, transporting goods and people, and offering lifeline services to remote regions. Yet, the sector's aging fleet of almost 2000 ships spends over 60% of their time within 5 nautical miles of densely populated port areas, contributing significantly to coastal air pollution and causing 15.3 Mt GHG emissions. While many oceangoing ships will have to rely on sustainable fuels, the smaller size of ferries and their predictable routes mean that electrification will offer a competitive alternative:

- **52% of existing ferries could rely on battery-electric propulsion by 2035**
- **For 20%, this switch could be cheaper than fossil fuels already in 2025**
- **Conventional ferries cause between 15 times and, over 100 times more air pollution near major coastal cities like Dublin, Belfast, Piraeus, or Las Palmas than those cities' passenger cars**
- **Requirements for charging infrastructure are the main barrier to adoption, though 57% of ports will require only smaller chargers below 5 MW for a demand of below 5 GWh**

With today's battery technologies, half of Europe's ferries could be electrified



Source: T&E (2025). Start year 2025, 2030 and 2035 with a lifetime of 30 years. Includes fuel costs, ETS costs and battery CAPEX. Biofuel is blended with fossil fuels to meet FuelEU maritime targets. • Scenario with electricity tax

Even more battery-powered ferries could already be competitive. Currently, only electricity is subject to national taxes.

The ferry sector has been largely ignored by many of the EU's industrial strategies and environmental regulation. At the same time, it is often dependent on public support on the national and regional level. By addressing key barriers and strategically targeting regulatory disadvantages, Europe's aging ferry fleet can become a trailblazer and industrial accelerant by becoming the lead maritime sector for the uptake of made-in-EU marine batteries and electric vessels.T&E identified key initiatives that the EU can take to support this transition and secure industrial demand for marine batteries:

- Extend the EU Emission Trading Scheme (ETS) and FuelEU Maritime Regulation (FEUM) to cover all vessels equal or larger than 400 gross tonnage (GT) to cover the largest share of ferry routes, driving at least 8% additional electrification.
- Expand the Alternative Fuels Infrastructure Regulation (AFIR) beyond shore power mandates to ensure sufficient charging infrastructure in major ferry ports.
- Revise EU public procurement and tendering rules to ensure sustainable use of public resources in public procurement procedures, including through zero-emission standards, and favoring made-in-Europe components.
- Integrate marine battery production into the strategic goal to improve battery production capacity, including through the EU Industrial Maritime Strategy.

Even under existing regulations, national and regional governments can already use tools to incentivise or directly require electrification of key routes:

- Utilise the Most Economically Advantageous Tender (MEAT) and Green Public Procurement (GPP) methodologies to include zero-emission qualification criteria in national, and local procurement policy. This is already done by some member states like Denmark, or Spain.
- Reduce national energy taxes on electricity supplied to vessels or reduce port fees for zero-emission ferries through temporal options available in the Energy Taxation Directive.
- Expand Emission Control Areas (ECAs) to outermost regions and end route-specific exemptions.

Section 1

1. State of play of the European ferry fleet

The EU is home to one of the world's largest ferry sectors, with over 904 Ro-Pax vessels and 1012 passenger ships making up 26% and 22% of the world's fleets, respectively. This fleet transports people, vehicles and goods between Europe's ports, often directly into the hearts of tourist locations, industrial hubs and dense urban areas.

Ferries form a critical part of Europe's transport network, linking islands and peripheral regions to the mainland, and transporting around 400 million passengers annually. But passenger and Ro-Pax represent an important share of EU shipping emissions. As all segments of maritime transport need to address their emissions, ferries are no exceptions.

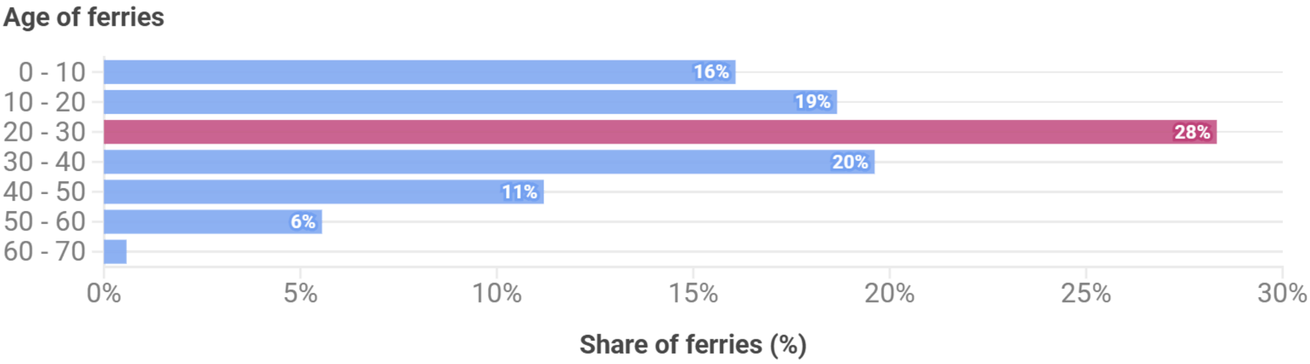
In this report, we first estimate the GHG emissions and air pollution in ports stemming from ferries. We then offer a techno-economic analysis of the potential for electrification to drastically reduce these said emissions, and discuss the policies and incentives that are needed.

1.1 Fleet characteristics

While ferries are a vital link for both mobility and trade within the Union, the fleet is also one of the oldest shipping segments. The average Ro-Pax vessel is 26 years old, and almost one quarter of EU-flagged ferries are over 30 years old. These ships are often kept in service through retrofits rather than being replaced.

Age and design vary significantly by region. In the Mediterranean, ferries tend to be larger, older, and experience seasonal demand peaks. A plurality of the routes we studied are located in the Mediterranean Sea, and ferries in the region transport the most passengers of all the regions studied. In contrast, Baltic and North Sea ferries are generally younger, operate shorter, high-frequency routes, and have been subject to stricter environmental rules for a longer time than Mediterranean ferries, as a result of the sulphur oxide (SO_x) and nitrogen oxides (NO_x) Emission Control Areas.

The average ferry in Europe is 26 years old

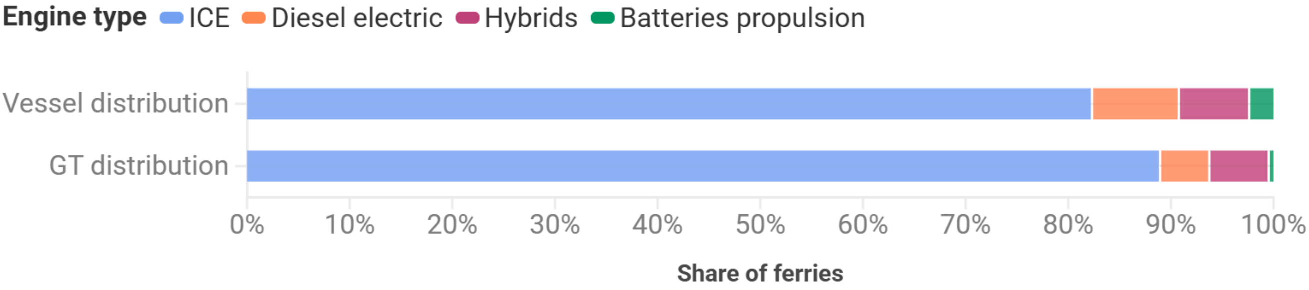


Source: T&E (2025) • Calculation based on the build year of ferries and the year 2025.

In terms of propulsion, ferries operate with ICE and diesel for the vast majority of vessels, with a small share using LNG as well. Diesel-electric vessels still use fossil fuels for propulsion, but use the fuel to power a generator producing electricity that is then used to power the electric motors.

Hybrid vessels represent 7% of the European fleet, with battery-electric ships representing an additional 2%. While a nascent trend, vessels servicing European routes feature a large share of the global electric fleet, backed up by established shipbuilding expertise.

Conventional engines are still dominant for ferries



Source: T&E (2025) based on Clarksons World Fleet Register.

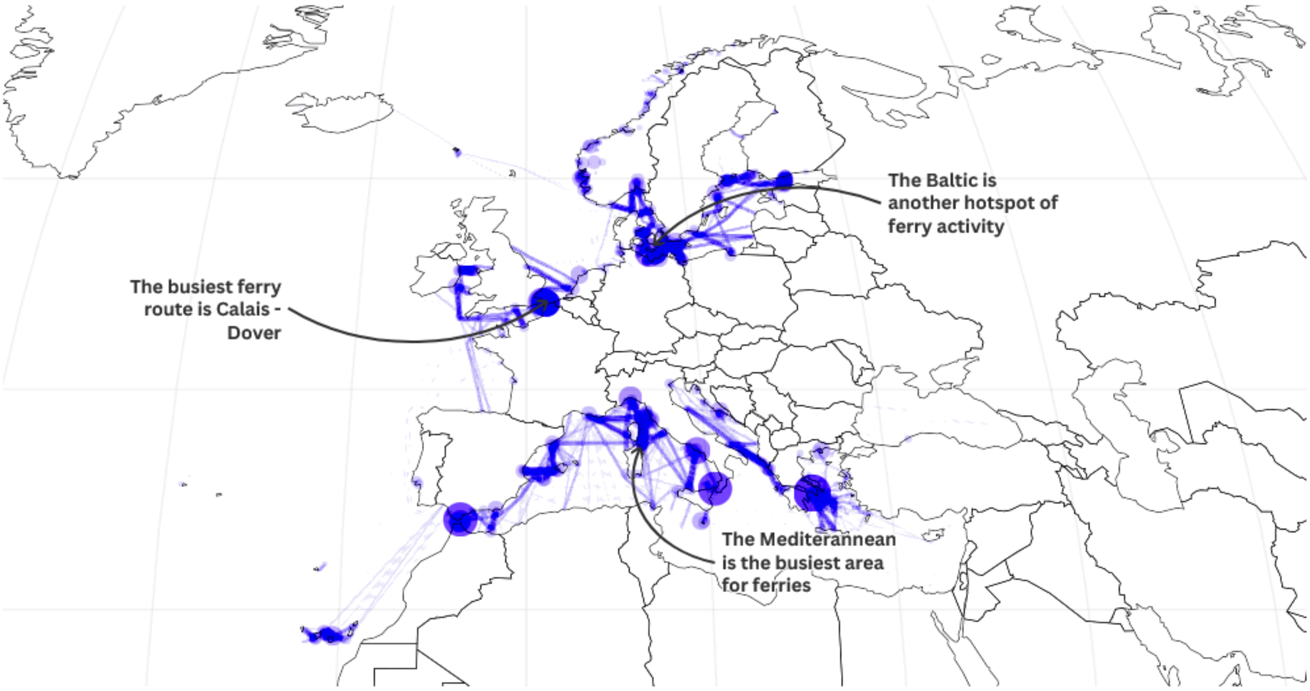
While Ro-Pax ferries are the most represented ships in the sector, it is made up of many diverse ship types. More modern "fast ferries", though few in numbers, cause comparatively high emissions due to their high speeds and high fuel consumption. On the other hand, smaller passenger-only ferries, often serving urban or island connections, are increasingly at the forefront of electrification, particularly in Northern Europe.

1.2 Geographical distribution

Geographically, most ferry services are domestic or intra-EU, and are concentrated in three regions: the Baltic Sea, the North Sea, and the Mediterranean. More than half of all routes operate in the Mediterranean, which also hosts the largest and oldest ferries. The majority of routes connect large Mediterranean islands, such as Corsica, Sardinia and the Balearic islands to their respective home countries. A few routes also connect countries to one another: notably, ferries connect Civitavecchia in Italy to Barcelona in Spain, and Igoumenista in Greece to Ancona in Italy. In the Baltic Sea, ferries sail on North-South routes to connect Scandinavian countries to Germany and Poland on the one hand. On the other, East-West routes connect Germany to the Baltics and Finland. In the North Sea, ferries connect Ireland and the UK to France, Belgium and the Netherlands.

Mediterranean, Channel and Baltic are the ferry hotspots of Europe

CO_2 emissions from ferries



Source: T&E (2025) based on AIS data • Ferries operating in 2023 in the EEA and the UK. Larger points represent more emissions.

1.3 Environmental significance

The environmental footprint of the ferry fleet is significant: In 2023, passenger and Ro-Pax ships accounted for 16.5% of all EU shipping CO_2 emissions reported in the EU MRV system. This figure excludes vessels under 5000 GT, which make up a large part of the fleet but are missing from official statistics. In addition, ferries are a major source of air pollution, emitting sulphur oxide (SO_x), nitrogen oxides (NO_x), particulate matter (PM) and black carbon (BC). Given their frequent operation in urban port areas, these emissions have direct negative health impacts on local populations.

1.4 Regulation

Short- and mid-range passenger and Ro-Pax vessels are subject to overlapping regulatory frameworks. When sailing across borders, specific regulation by the EU as well as the global regulations of the International Maritime Organisation (IMO) apply.

1.4.1 Global/IMO level

Internationally, the MARPOL convention - regulating pollution from fuel use, sewage, garbage and air emissions - requires ships above 400 GT to comply with regulations to promote efficient ships (EEXI & EEDI), while those above 5000 GT must report their fuel use under the IMO Data Collection System (DCS) and comply with the Carbon Intensity Indicator (CII). Additionally, ferries operating in Emission Control Areas such as the Baltic Sea, the Channel, the North Sea and from 2025 the Mediterranean Sea must meet a tighter SO_x limit.

Importantly, IMO regulations apply to ships engaged in international voyages, in parallel to national rules applying at the various ports of call, and to the regulation of the national flag they are registered with. This hierarchy of regulation is established in the UN UNCLOS treaty, and recognised in IMO SOLAS and MARPOL conventions.

While many European ferries operate on purely domestic routes and are therefore outside the scope of several IMO measures, falling instead under EU and national regulation, the EU has transposed (parts of) the global framework into binding law (e.g. Sulphur Directive, Port State Control Directive, or Flag State Control Directive), ensuring consistent enforcement across Member States.

1.4.2 EU level

At the EU level, ferries are subject to the same overarching climate and environmental legislation as other passenger ships. This comprehensive regulatory framework incentivises investments in zero-emission technology and electrification, as compliance would bring both FuelEU compliance benefits and Emissions Trading System (ETS) cost savings.

The Fuel EU Maritime Regulation (FEUM) aims to stimulate the uptake of low- and zero-emission propulsion (including electrification) by requiring ships equal or above 5000 GT to progressively reduce the GHG intensity of the energy used onboard. However, some passenger vessels currently benefit from a set of exemptions until 31 December 2029, for domestic voyages to islands of under 200,000 inhabitants, voyages between outermost regions, transnational public service routes for Member States (MS) without a land border, or for pre-2023 public service island connections (including the Spanish exclaves of Ceuta and Melilla). Beyond carbon-intensity targets, FEUM also mandates large ferries to connect to on-shore power when at berth from 2030.

In parallel, the ETS requires shipping companies to surrender emission allowances based on the ETS scope (i.e. 100% of emissions from intra-EEA voyages, 100% of emissions happening in EEA ports and 50% from voyages between EEA and non-EEA ports) for passenger ships, including ferries above 5000 GT since 2024. As with FEUM, exemptions apply until 31 December 2030 for passenger (excluding cruise ships) and Ro-Pax ferries operating on specific island routes (in the same jurisdiction, without a road/rail link, and under 200,000 inhabitants), operating on transnational public service routes (currently only between Cyprus and Greece), and for voyages to and between outermost region ports of the same MS. Additionally, vessels with ice class IA, IA Super or equivalent are allowed to surrender 5% fewer allowances than their verified emissions.

In addition, the UK is exploring extending international coverage of its own ETS to the maritime sector, which will follow the same parameters as the EU ETS. Companies will have to surrender allowances for emissions from ferries above 5000 GT starting from July 2026. As the text states for now, the UK ETS will only cover emissions at-port and between UK ports, and will exempt only non-commercial government vessels from its coverage.

Recognising the substantial emissions that ships cause in port, the Alternative Fuel Infrastructure Regulation (AFIR) mirrors FEUM and introduces a mandate for maritime ports to provide onshore power supply (OPS) to passenger ships (and container vessels) equal or above 5000 GT by 2030. The mandate applies only for ports that have a sufficient number of annual port calls per ship type (e.g. for ferries, 40) and MS should ensure that enough charging points are available to cover the electrical energy needs of at least 90% of these port calls. Exemptions similar to those detailed for FEUM also apply.

Beyond their GHG emissions, ferries are covered by rules limiting air pollution, embedded in EU legislation (e.g. Sulphur Directive). Additionally, services are subject to EU rules on passenger rights, while access to domestic markets was liberalised in EU “Cabotage” regulation (3577/92/EC). Where essential transport to remote regions requires support, public service obligations and state aid control laws apply.

1.4.3 National level

In addition to this harmonised EU framework, the regulation of ferries also takes place at the national and regional level, and reflects the public service role of many routes. The ferry sector is deeply intertwined with public transport systems and regional connectivity.

The EU's cabotage regulation substantially liberalised the ferry sector, allowing member state-registered vessels to service routes independent of national borders. Where ferries provide crucial public transport functions, but operations are not economically viable, they are often operated with public support or under public ownership. While general state aid restrictions and public procurement directives (2004/17/EC and 2004/18/EC) apply, national or regional cabotage laws also define how public support is provided. This support ranges from publicly funded Public Service Contracts, to Public Service Obligations to direct state ownership of individual ferries. National and regional governments thus have significant leeway in assigning requirements through public tenders and procurement.

As a result, the level of public involvement varies significantly between regions: in the Baltic and North Sea, many ferry routes are commercially viable and operate under market conditions, with specific routes being operated with strong state involvement. Additional requirements are often applied, including environmental standards under existing state aid rules. These requirements have accelerated the uptake of efficient vessels, more competitive pricing, and most recently led to the introduction of some hybrid and fully electric ferries on shorter routes.

By contrast, in the Mediterranean and Atlantic, many ferry connections are still operated with direct state subsidies, under concession contracts, or regulated tariffs, with less stringent or no environmental requirements. Compared to commercially operated and competitive routes, older vessels remain in service, as is the case for island services in Greece, Italy, Spain, France, and Portugal.

This patchwork of national approaches means that ferries face uneven regulatory pressure across Europe. This has implications for both investment decisions and the speed of fleet renewal. A salient example is Norway's regulation on cabotage that, combined with sustainable provisions in public support and additional environmental obligations, has led to a significantly more modern ferry fleet with a large share of vessels that utilise electrification or alternative fuels. EU law permits similar environmental requirements under the MEAT principles (most economically advantageous tender) of public procurement rules, though environmental requirements are optional.

An example of successful national regulation beyond EU standards is the transposition into national law of the OSPAR convention. Under it, eleven EU member states, Norway, the UK, Switzerland, and Luxembourg as well as the EU agreed to ban discharge of waste water from Exhaust Gas Cleaning Systems (EGCSs), or "scrubbers" near coasts and ports of the north-east Atlantic.

Section 2

2. Ferry traffic and emissions

2.1 Methodology overview

We used a bottom-up model to calculate 2023 traffic and tank-to-wake (TtW) energy and emissions for each ferry above 400 gross tons (GT) operating in Europe, based on AIS data and individual ship technical specifications. We included all trips within, to or from the EEA and the UK. We included the voyages of hybrid ferries but we discounted their potential emissions, as they cannot be predicted reliably without battery usage statistics. The analysis covers GHGs and air pollutants, including CO_2, CH_4, N_2O, black carbon (BC), SO_x, NO_X and $PM_{2.5}$. We compared ferry air pollution within 5 nm of each port to that from cars registered in the respective cities. Emission factors follow the IMO Fourth Greenhouse Gas Study, and fuel use assumptions reflect real-world compliance with sulphur standards. The full methodology can be found in Annex 1.

2.2 Total traffic and GHG emissions

We find that 1043 European ferries emitted 15.3 Mt CO_2e in 2023, with 88% from CO_2 and 9% from black carbon, an extremely potent global warming agent made up of particles from incomplete combustion.

We identify 2.6 million voyages over the year, 80% of which were made by ferries between 400 and 5000 GT. Despite this, ferries over 5000 GT account for 88% of total emissions. As a result, 12% of ferry emissions are exempt from the EU ETS due to their small vessels' size, which currently applies only to ships above 5000 GT.

GT category	Ships	Voyages	CO_2 (t)	CH_4 (t)	N_2O (t)	BC (t)	100-year CO_2e (t)
400-5000 GT	632	2,041,542	1,696,914	328	84	134	1,849,988
>5000 GT	411	512,574	11,756,789	9,835	625	1,355	13,439,770
Total	1043	2,554,116	13,453,702	10,163	709	1,488	15,289,758

Table 1: Ferry GHG and air pollution emissions.

2.3 Route-level traffic and GHG emissions

Top routes in terms of CO_2 emissions include long-distance, low frequency crossings, short high-frequency crossings and everything in between, highlighting the diversity of the ferry sector. The most polluting routes are the Baltic crossing between Helsinki and Travemünde, despite only 700 voyages, and the short Calais-Dover crossing, with over 24,000 crossings per year. Three of the top five most CO_2-emitting routes are under 100 nautical miles (nm), and 6 out of top 10 routes exceed this threshold.

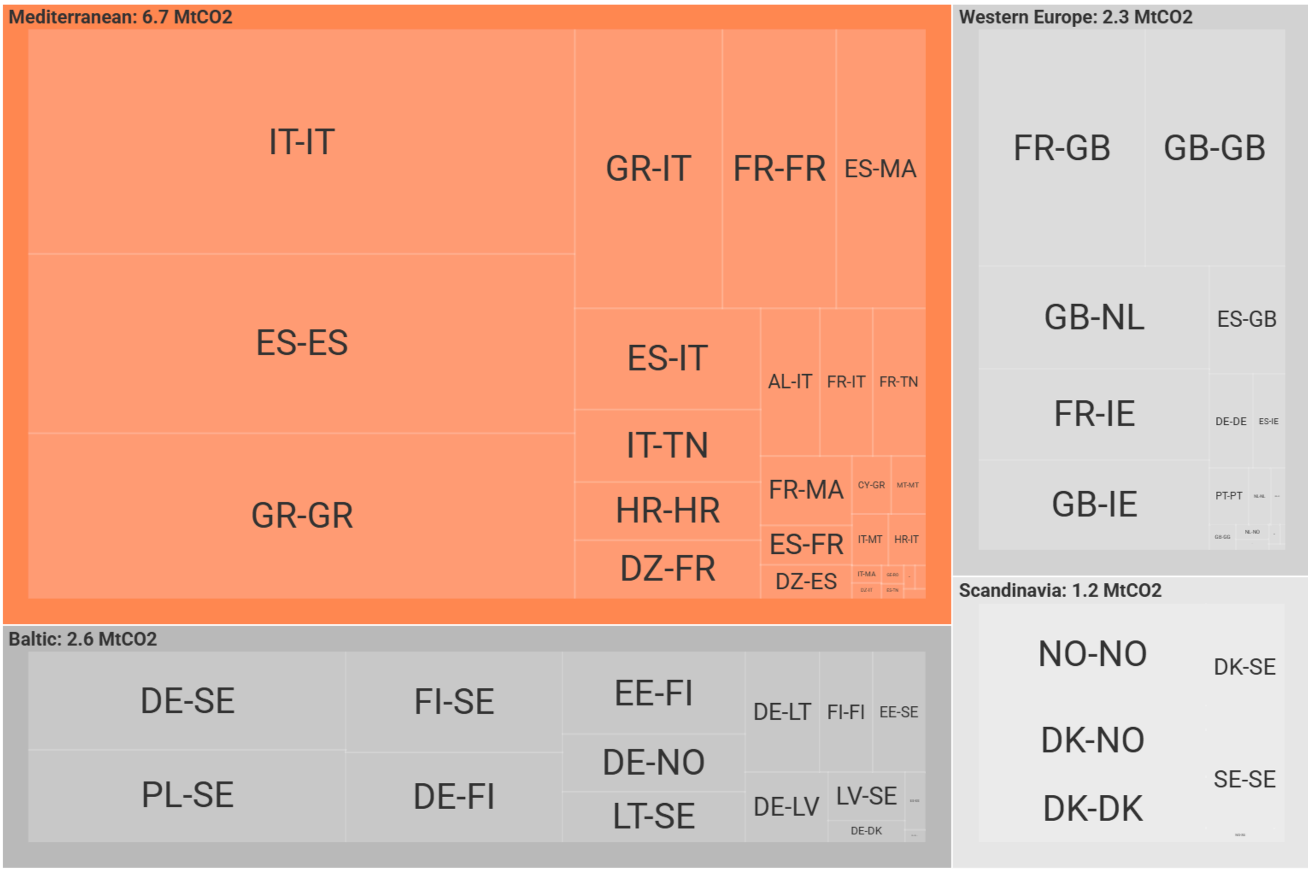
Rank	Route (ports)	Countries	Ships	No of voyages	Annual CO_2 (t)	Average voyage distance (nm)	Average voyage duration (h)
1	Helsinki - Travemünde	FIN - DEU	6	707	300,065	658	30
2	Calais - Dover	FRA - GBR	11	24,389	292,133	25	2
3	Helsinki - Tallinn	FIN - EST	9	10,109	221,457	47	3
4	Dublin - Holyhead	IRL - GBR	10	5963	192,651	61	3
5	Palma Mallorca - Valencia	ESP - ESP	17	2485	187,595	147	8
6	Barcelona - Civitavecchia	ESP - ITA	5	529	181,694	460	22
7	Napoli - Palermo	ITA - ITA	18	1876	168,247	178	11
8	Golfo Aranci - Livorno	ITA - ITA	18	1663	158,751	162	10
9	Rostock - Trelleborg	DEU - SWE	12	3859	150,458	95	6
10	Malmoe - Travemünde	SWE - DEU	5	1923	150,139	151	9

Table 2: Ferry routes, ranked by CO_2 emissions.

2.4 Country-level traffic and GHG emissions

The Mediterranean Sea has the highest CO_2 emissions from ferries, with domestic routes in Italy, Spain and Greece being the highest emitting in absolute terms. Emissions in Scandinavian countries are more evenly distributed, with domestic Norwegian routes being the largest emitters. In the Baltic Sea, connections between Sweden and Poland, Germany and Finland are among the highest emitting ones. Overall, emissions in Northern Europe appear to be more heavily weighted towards international connections, whereas emissions in the Mediterranean are more concentrated on domestic routes.

The Mediterranean Sea is the principal hotspot for ferry emissions



Source: T&E (2025) based on AIS data • Routes are bidirectional. Size of block represents the aggregated CO2 emissions emitted on the route. Only routes with more than 10 voyages counted.

The table below presents the top 10 European countries by voyage-based CO_2 emissions (full ranking in Annex 2), with emissions split equally between departure and arrival countries. Italy leads in terms of emissions with 2.4 Mt CO_2, followed by Spain and Greece; together these three account for 5.7 Mt CO_2. Italy's emissions stem primarily from domestic traffic and port stays (75%). France and the UK's emissions are predominantly from international crossings (53% and 49% respectively). Conversely, Greece exhibits a high domestic concentration, with 82% of ferry CO_2 attributed to national services. Norway, despite accounting for nearly 1.2 million voyages, has relatively low emissions due to shorter routes and smaller vessels; notably, international voyages comprise under 1% of trips yet generate one-third of its emissions due to the large size of international ferries.

Rank	Country	Ships	Voyages	Share of domestic voyages (%)	Voyage and port CO_2 (t)	Share of domestic and port CO_2 (t)
1	Italy	210	231,695	97.5%	2,372,319	75%
2	Spain	126	80,667	80.1%	1,769,088	78%
3	Greece	177	188,840	98.6%	1,541,326	82%
4	United Kingdom	108	175,484	85.8%	1,204,772	51%
5	France	112	41,457	48.7%	1,148,122	47%
6	Sweden	98	106,033	60.6%	1,008,529	25%
7	Germany	83	71,065	56.7%	660,750	16%
8	Norway	222	1,176,275	99.6%	656,784	67%
9	Finland	47	76,200	87.0%	536,626	25%
10	Denmark	77	182,069	72.1%	482,524	58%

Table 3: Overview of ferry activity by country, ranked by CO_2 *emissions.*

2.5 Port-level traffic and GHG emissions

Splitting CO_2 emissions between both ports of a voyage, we present a similar ranking for the top 10 ports in terms of CO_2 emissions, with the full top 50 ranking available in Annex 2. Mediterranean ports dominate with 7 of the top 10 positions. Barcelona has the highest level of CO_2 emissions, though the top 5 ports, from 5 different countries, are closely matched. Consistent with national patterns, Barcelona is served by fewer, longer trips while Piraeus operates more frequent, shorter crossings, with the average distance for voyages arriving in Barcelona being almost three times as long as the voyages arriving to Piraeus. Genova and Marseille also rank in the top spots despite comparatively few voyages.

Rank	Port	Country	Ships	Voyages	Voyage and port CO_2 (t)	Avg. Distance (nm)
1	Barcelona	Spain	42	3244	327,924	208
2	Piraeus	Greece	86	9597	318,748	73
3	Helsinki	Finland	17	5957	316,696	101
4	Travemuende	Germany	21	2620	311,542	237
5	Genova	Italy	47	1631	292,435	311
6	Marseille	France	34	1501	252,942	304
7	Livorno	Italy	48	2694	249,920	146
8	Palermo	Italy	34	2056	230,149	219
9	Civitavecchia	Italy	26	1302	213,700	260
10	Trelleborg	Sweden	18	4978	203,590	108

Table 4: Major ferry port, ranked by associated CO_2 emissions.

2.6 Total air pollution near European ports

We find that ferries collectively spent close to 5 million hours sailing or moored less than 5 nautical miles from European ports in 2023, emitting 6848 tonnes of SO_x, 64,486 tonnes of NO_x and 2367 tonnes of $PM_{2.5}$. This represents 60% of the vessels' year, highlighting the concentration of air pollution from ferries near populated coastal areas.

Total time close to ports (h)	Total fuel consumption (t)	Total SO_x (t)	Total NO_x (t)	Total $PM_{2.5}$ (t)
4,929,493	1,455,429	6848	64,487	2368

Table 5: Urban air pollution caused by ferries.

2.7 Port-level air pollution

Due to the growing expansion of Sulphur Emission Control Areas (SECAs), air pollution in ports is expected to trend downwards in future years. On 1 May 2025, the Mediterranean Emission Control Area (ECA) was implemented, mandating a maximum sulphur content of 0.1% in fuels used by ships sailing in the Mediterranean Sea. The North Atlantic ECA, which covers part of the exclusive economic zones (EEZ) of Spain, Portugal, France, the UK, Ireland and Iceland, will introduce similar requirements, in addition to a limit on Nitrogen Oxide emissions. Originally planned to enter into force in 2027, its adoption at the IMO was delayed by approximately six months. We modelled air pollution in European ports based on three scenarios across three points in time: Without either ECA (2023), with the Mediterranean ECA only (2025), and including both the Mediterranean and the North Atlantic ECA (2027).

In 2023, Algeciras and Piraeus were the most polluted ports, while four Italian ports were among the top ten. By 2025, all Italian ports drop from the top ten, replaced by four ports in the UK and Ireland not covered by any SECA, with Dublin being the most polluted port. As the North-East Atlantic ECA enters into force in 2027, we anticipate that ports in the Canary Islands will become the most polluted in Europe, due to not being covered by any ECAs, indicating that the most polluted ports are systematically outside SECAs. Unsurprisingly, other top polluted ports are those featuring the most activity.

Rank	Port	Country	Ferries	SO_x from ferries (kg)	SO_x from cars (kg)	Ratio of ferries to cars SO_x	CO_2 emissions (t)
1	Dublin	IRL	12	92,081	5813	15.8	38,081

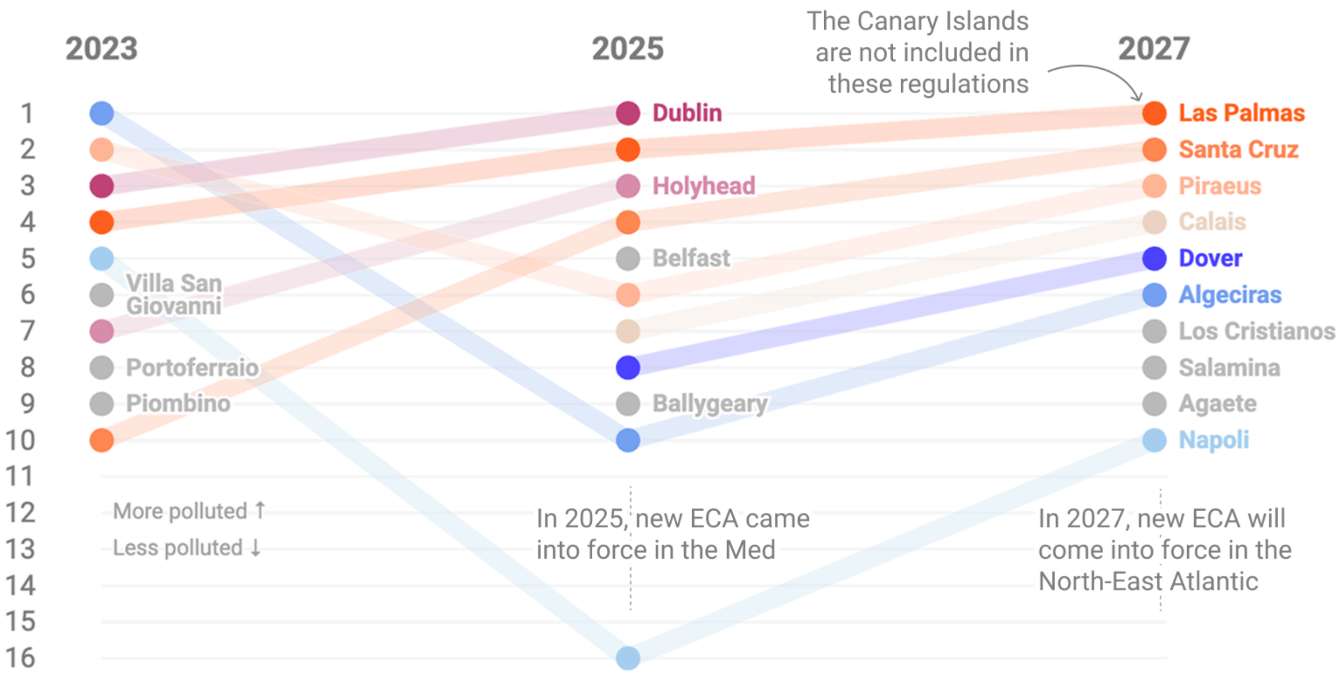
2	Las Palmas	ESP	19	83,125	2471	33.6	40,824
3	Holyhead	GBR	11	80,265	96	837	28,700
4	Santa Cruz	ESP	18	71,993	1613	44.6	30,198
5	Belfast	GBR	15	62,840	1750	39.8	23,579
6	Piraeus	GRC	86	52,178	1787	29.2	95,414
7	Calais	FRA	13	51,028	405	125.9	83,745
8	Dover	GBR	12	49,258	780	63.1	87,769
9	Ballygeary	IRL	13	47,230	13	3659.3	23,955
10	Algeciras	ESP	39	44,840	798	60.5	81,276

Table 6: Comparison of SO_x pollution from ferries close to ports, 2025.

In 2025, Dublin, Las Palmas and Holyhead are projected to be the most polluted ports, with between 92 and 80 tonnes of SO_x emitted. In port cities where car registration data is available, ferry SO_x emissions exceed those from local car fleets by over a factor of 10 for large cities like Dublin and Piraeus. This stark imbalance highlights the disproportionate air pollution impact of ferries, especially in high-traffic port cities and limited emission controls. Even enhanced maximum sulphur limits of 0.1% are 100 times less stringent for ships than they are for cars.

New air Emission Control Area (ECA) are expected to have an important impact on ferry air pollution

Air pollution ranking



Source: T&E (2025) • Data are from 2023 and modeled based on the SECAs once into force.

Section 3

3. Techno-economic assessment of decarbonisation technologies

Similarly to other shipping segments, ferries need to reduce their GHG emissions. This can happen by integrating energy efficiency measures (e.g. wind-assist propulsion), connecting to shore side electricity (OPS) and alternative energy sources. However, the ferry sector occupies a unique position: unlike long-haul merchant shipping, ferries have very different characteristics, such as their shorter routes, predictable schedules and smaller vessel sizes, that invite a separate evaluation of zero-emission technologies. The main objective of this analysis is to investigate the technical and economic feasibility of different alternative zero-emission fuels and battery technology in European ferry operations.

3.1 Methodology overview

We assessed the potential of the following propulsion technologies and fuels to decarbonise the European ferry fleet:

- Battery-electric
- Hybrid-electric
- E-hydrogen (LH_2)
- E-methanol
- E-ammonia
- HVO biofuel

We selected ships eligible for each technology considering operational patterns, number of ports served and voyage frequency, with stricter criteria for battery-electric ferries to ensure charging feasibility. For each option, we assessed the technical feasibility of every ship in the fleet and compared its total cost of ownership (TCO) of a conventional ferry running on a FuelEU-compliant fuel mix. We evaluate ferries' technical feasibility first: for ferries that can operate on their most critical route with batteries, we then compare the CAPEX and lifetime operational costs of a battery-electric vessel to a diesel-powered one.

We modelled newbuild ferries built in 2025, 2030 and 2035, assuming a 30-year vessel lifetime. We defined a "most critical" representative route for each vessel based on voyage share and distance, and used it to size batteries or fuel storage. We conservatively assumed the same operational characteristics and no additional space required for alternative-propulsion systems. We derived battery characteristics from industry sources and adjusted to forecast conservative future technology developments. For alternative fuels, we accounted for lower energy densities and higher CAPEX for engines or fuel cells. Given the long time horizon considered and current trends and expectations, we assumed fossil fuel prices would return to pre-COVID levels, while electricity prices would stay at their current level. We also analysed the impact of electricity taxes on the overall results as these significantly affect TCO and several European countries have already reduced taxes on shore power. We used prices from DNV for e-fuels and Stratas Advisors for biofuels. Finally, we assumed that ships of more than 400 GT would be included in the ETS and FuelEU maritime from 2030 onwards.

The full methodology is detailed in Annex 1.

3.2 Assessment of battery-electric ferries

3.2.1 Ship selection

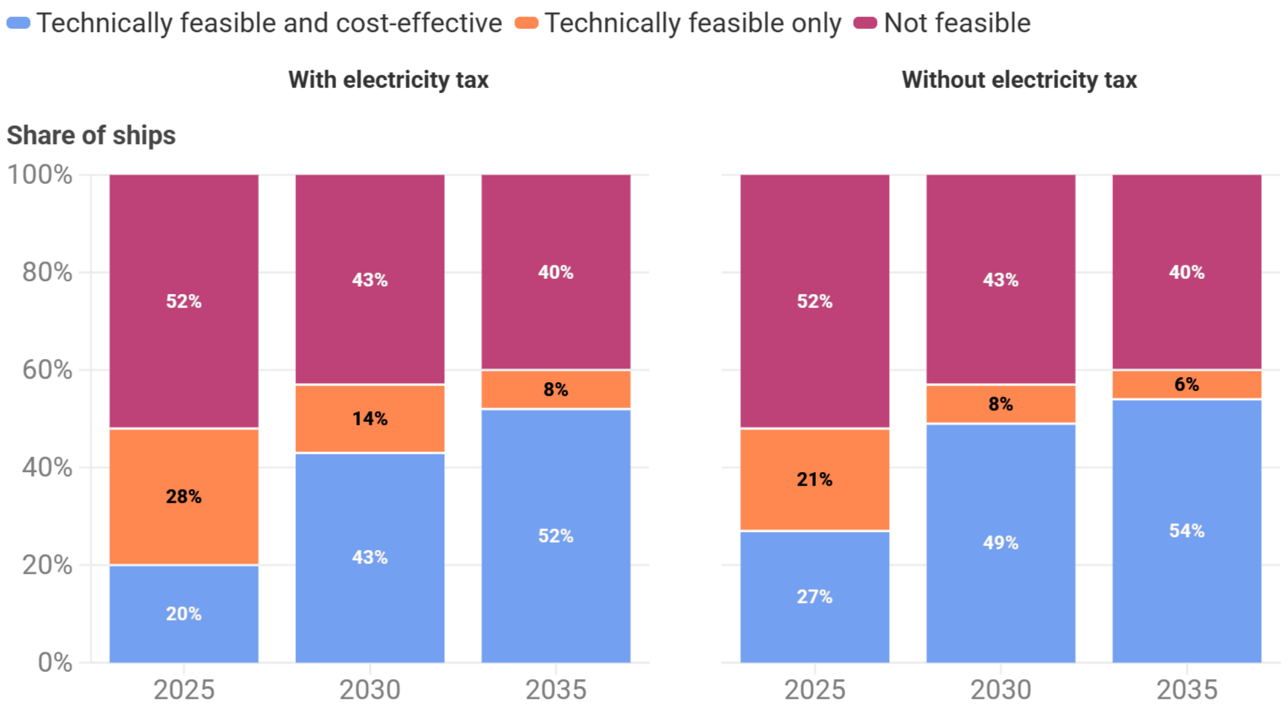
Out of the 1043 ferries in the current fleet, 904 run on conventional fuels and have sufficient data to include them in the TCO analysis. These formed the basis of our analysis. To control for heterogeneous schedules and potential differences in infrastructure availability, we limited eligibility to ferries visiting a small number of ports. We defined this as ships visiting less than ten ports across 95% of their distance sailed. This conservatively classifies 70 ferries as not electrifiable, despite them showing potential if all their ports were to install the necessary charging infrastructure. In the rest of this section these ferries are classified as "not feasible or cost-effective" although their TCO wasn't calculated. This creates a sample of 834 ferries that can potentially be electrified.

3.2.2 Fleet technical feasibility and cost-effectiveness

We find that already today, 20% of European ferries would be cheaper as battery-electric newbuilds than as conventional ones, with an additional 28% of ferries technically feasible but not cost-effective. Removing taxes on shore-side electricity increases the estimated share of cost-competitive electrification to 27% of the fleet. Given the conservative assumptions made regarding battery characteristics (i.e. C rates, energy densities and prices) and operational constraints (i.e. no increase in port stop durations), the true technological electrification potential of electric ferries is likely even higher, if the necessary charging infrastructure can be installed at ports. Alternative options such as redesigning vessels, operating different schedules or technologies like battery swapping could further drive up electrification potential.

In 2035, economic feasibility is expected to rise to 52% for newbuilds thanks to improvements in battery technology and higher predicted ETS prices, among other factors, with an additional 8% technically feasible only. Without electricity taxes, the share of economically-feasible ferries would increase by 2 percentage points to 54%. These numbers show the high potential for batteries to decarbonise the ferry fleet while saving costs, with the effect most pronounced in 2025, where cost-competitiveness is a major barrier. In contrast, in 2030 and 2035 electrification is usually competitive wherever it is technically feasible. The share of ferries that are only technically feasible shrinks in 2030 and 2035, as the business case for battery-electric ferries strongly improves.

With today's battery technologies, half of Europe's ferries could be electrified.



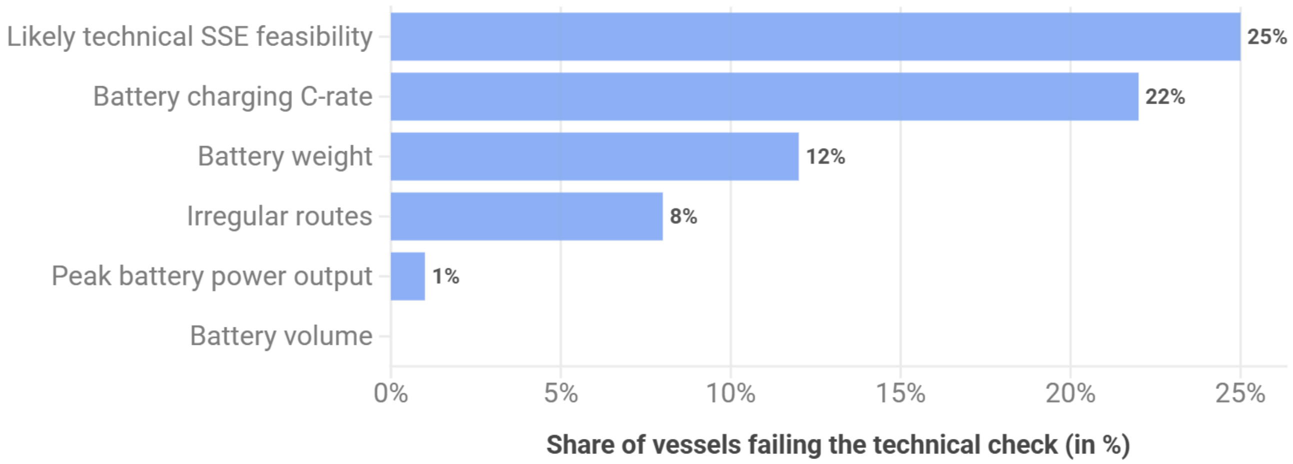
T&E (2025). Start year 2025, 2030 and 2035 with a lifetime of 30 years. Includes fuel costs, ETS costs and battery CAPEX. Biofuel is blended with fossil fuels to meet FuelEU maritime targets.

3.2.3 Technical feasibility analysis

In 2025, an estimated 48% of newbuild ferries could technically operate as fully battery-electric. Looking closer at the remaining barriers to technical electrification feasibility, charging requirements clearly appear as the most critical barrier: either insufficient energy is delivered due to the charging connections being undersized, or the battery is unable to charge fast enough. Battery charging speed (known as C-rate) is the excluding factor for 22% of the fleet, with many ferries having turnaround times that are too short to recharge. For these vessels, although OPS connections can deliver sufficient energy while they are at berth, the technical specifications of their batteries preclude them from being recharged at sufficient speeds. On the other hand, and with some overlap, undersized shore-side chargers exclude 25% of the fleet. In this case, the charger lacks sufficient power to charge the battery. For most ferries, battery-related constraints will be easier to solve than shore charging constraints, thanks to the rapid expected improvements in battery technology. By 2035, only 10% of newbuilds would be disqualified by battery charging power requirements if we assume a doubling of the C-rating. On the other hand, increasing the available power of shore-charging ports will require investments to deploy the required infrastructures.

Battery volume and weight are less critical and mostly concern ships which can't fulfill charging requirements regardless. 12% of vessels are not technically feasible due to the excess weight of batteries. Assuming that the battery system could take up an additional 10% of each ship's available space by separating it into multiple modules, volume is a limiting factor for no vessels. Finally, batteries' continuous peak power output doesn't appear to be a concern: selecting a Depth of Discharge (DoD) between 40% and 80% gives sufficient capacity to meet required maximum power output for 99% of vessels. Thus, battery energy capacity and power appear to be sufficient to meet voyage requirements.

Insufficient SSE feasibility and battery C-rates are the main bottlenecks to ferry electrification



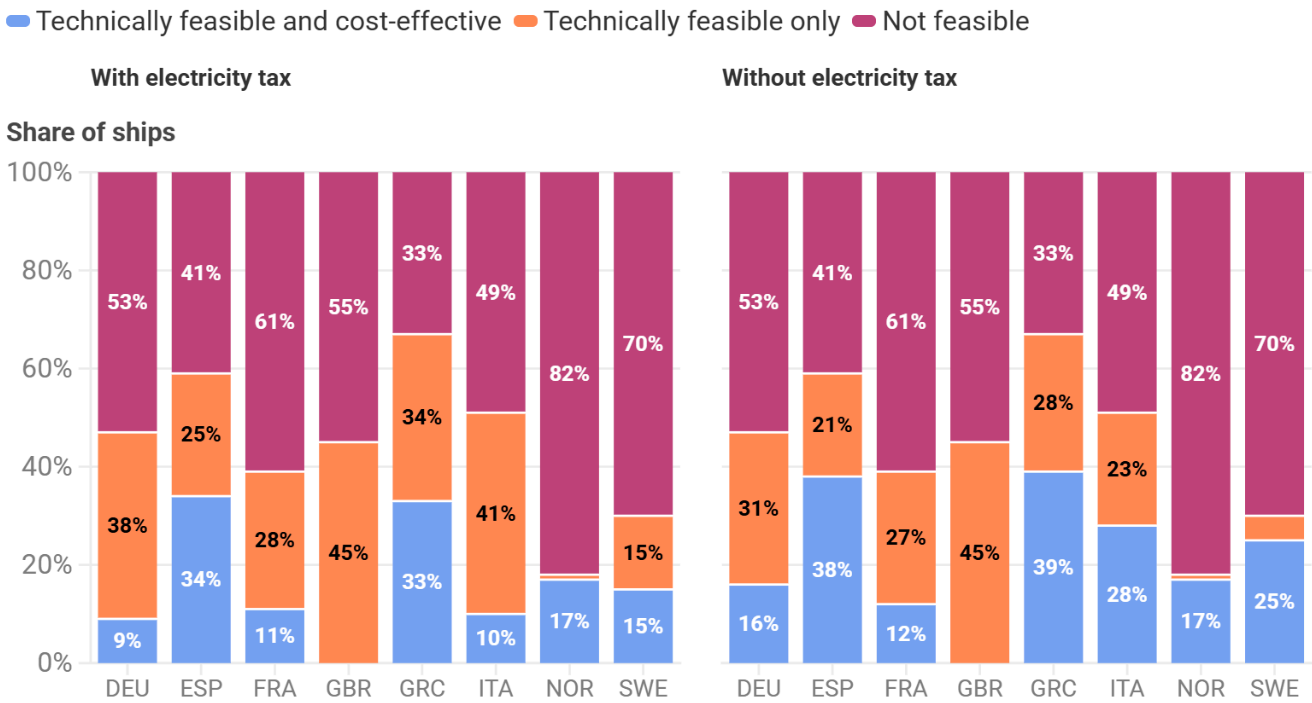
Source: T&E (2025) • Build year 2025. Categories are not exclusive and may overlap.

3.2.4 Technical feasibility and cost-effectiveness by country

While an estimated total of 20% of sampled ferries could be cost-effectively replaced by electric newbuilds in 2025 - rising to 52% in 2035 - results vary widely between countries, mainly due to differences in voyage patterns and electricity prices. Among the main ferry countries, Spain and Greece have the highest estimated shares of cost-effective electric ferries in 2025, with 34% and 33% respectively.

Conversely, none of the analysed vessels in the UK appear to be cost-effective with batteries, while other key maritime countries such as Italy (10%) and France (11%) fall in between. This is due to higher electricity prices in the UK, penalising battery-electric propulsion. Furthermore, vessels in the UK are not subject to FuelEU-type carbon-intensity targets and the UK ETS alone (which is assumed to take effect in 2026) will not sufficiently close the TCO gap between battery-electric and diesel-based operations. Removing electricity taxes naturally improves electric ferries' competitiveness, with notable improvements in Germany (+7%), Sweden (+10%) and Italy (+18%).

Battery feasibility is highly dependent on country electricity prices

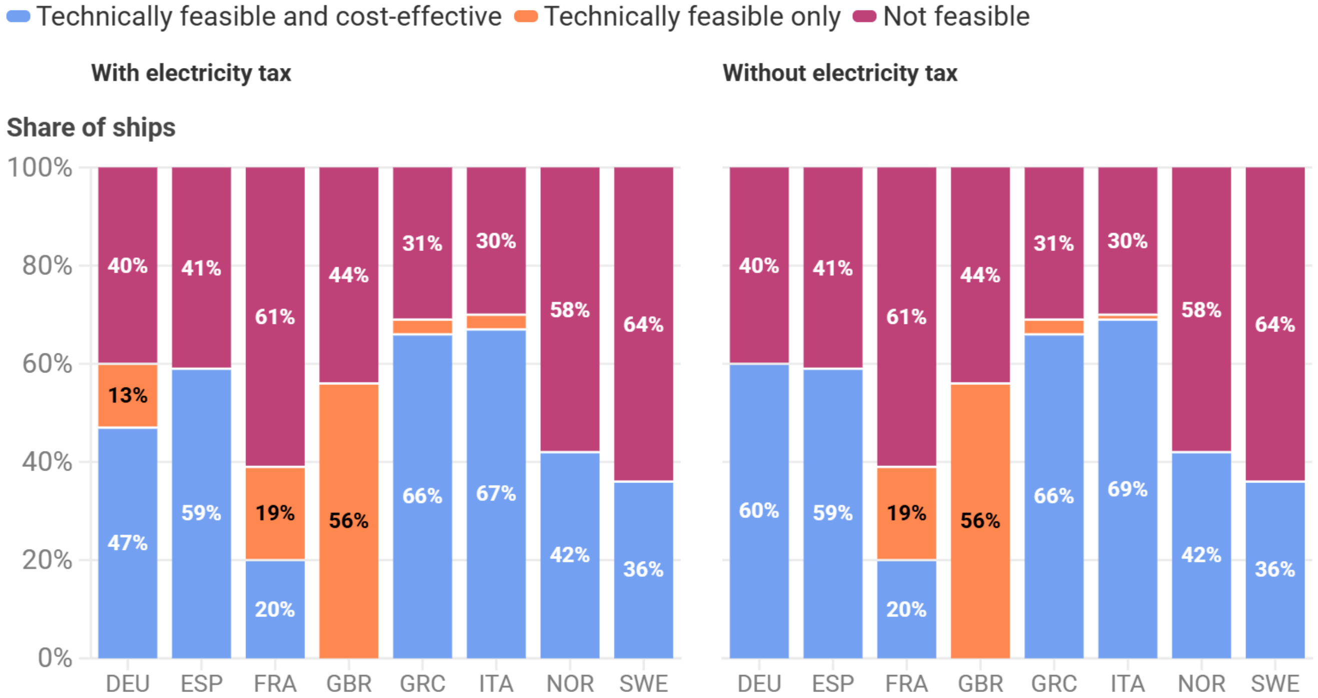


Source: T&E (2025) • 2025 build year with a lifetime of 30 years. Ferries sailing on international routes are counted for both countries. Only countries with high number of ferries shown.

For 2025, Norway's estimated potential for cost-effective electric ferries (at 17%) sharply contrasts with Norway already having the highest share of electric and hybrid ferries in Europe. Those vessels are removed from the sample and are not included in the results presented above. In consequence our results exhibit a bias as we only examine the remaining vessels that are not already electrified, and are therefore less likely to be electrifiable. In our model, we estimate low technical feasibility due to short stops of Norwegian ferries and related high required C-rates. 102 of the 131 ferries with a representative route in Norway have stops of 20 minutes or less and 81 of those are marked as not technically feasible because of difficulties to charge the battery fast enough. By 2035, for which C-rates are assumed to be twice those of 2025, an estimated 42% of ferries are estimated to be cost-competitive, marking the significant impact of overcoming this barrier.

For 2035, the main ferry countries with the highest share of cost-effective newbuilds are Italy (67%), Greece (66%) and Spain (59%). France and the UK remain at the bottom in terms of estimated economic feasibility: only 20% of ferries in France, and still 0% in the UK. For France, the main barrier to technical feasibility is insufficient power in ports. Moreover, ferries operating between France and the UK must also contend with high electricity costs.

By 2035, battery feasibility will be over 50% in most countries



Source: T&E (2025) • 2035 build year with a lifetime of 30 years. Ferries sailing on international routes are counted for both countries. Only countries with high number of ferries shown.

3.2.5 Cost and CO_2 savings

We estimate substantial cost savings from electric ships, even with electricity taxes. Cost-effective 2025 newbuilds could save 14% in energy and ETS costs over their lifetime, for a total of €684 million over the whole electrifiable fleet. 2035 newbuilds could save 32% in energy and ETS costs, for a total of €6.4 billion over the whole electrifiable fleet. Lifetime CO_2 savings from electrification could be 8% of total fleet CO_2 in 2025, increasing to 24% in 2035. Cost-savings do not scale parallel to the share of cost-effective electric ships because smaller ships tend to be more easily electrifiable.

For cost-effective electric ferries, TCO breakeven is reached quickly, especially for ships built after 2030. This shows the importance of energy costs in the business case and how profitable electric ferries could be if ferry operators can access cheap(er) electricity. Even the estimated

2025 newbuilds reach breakeven within two thirds of the typical ferry lifetime. In contrast, fossil-powered newbuilds face higher fuel prices over the ships' lifetime.

Ferry build year	Share of cost-effective ships	Lifetime cost savings (€M)	Lifetime cost savings (%)	Lifetime CO_2 savings (Mt CO_2)	Lifetime CO_2 savings (%)	Mean TCO breakeven year
2025	20%	684	14%	33	8%	19
2030	43%	3571	25%	80	20%	9
2035	52%	6395	32%	96	24%	6

Table 7: Potential cost and CO_2 emissions savings from cost-effective ferry electrification.

3.2.6 Sensitivity analysis for cost-competitive battery-electric ferries

Battery adoption depends mainly on electricity and fuel prices. Our sensitivity analysis in 2025 shows that a 25% increase in electricity prices reduces battery feasibility by about 10 percentage points (pp), while a 25% decrease in electricity prices increases battery feasibility by 11 pp. Policy exemptions would impact adoption significantly: excluding small ferries (under 5000 GT) from FuelEU targets reduces battery uptake by 8 pp, while a similar ETS exemption reduces it by 8 pp. Removing electricity taxes increases adoption by 7 pp. The discount rate has moderate effects with a 3 pp reduction leading to a 8 pp increase, and a similar increase leading to a 7 pp reduction in feasibility. A decrease in the cost of the FuelEU-compliant fuel mix by 25% leads to a reduction by 13 pp of battery feasibility, while an increase by 25% leads to an increase by 12 pp of the feasibility rate. Battery prices and charging rates (C-rating) have smaller impacts of 2-3 pp.

By 2035, the relevance of electricity prices and consumption decreases. In 2035, a 25% increase in electricity prices reduces battery feasibility by only 7 pp, while a 25% decrease improves it by 2 pp. Likewise, a 25% reduction in the FuelEU-compliant fuel mix cost leads to a fall of 12 pp in feasibility. Finally, FUEM remains a key parameter. Not including small ferries (over 400GT) in the fuel standard would lead to a reduction in feasibility from 52% to 36%.

3.2.7 Port electric power requirements

We analysed the additional electric power and energy needs faced by ports to support charging infrastructure planning. For the 474 cost-effective electric newbuilds in 2035, total yearly energy demand is 5.4 TWh. Around 68% of this, i.e. 3.7 TWh is consumed on the representative routes we assessed. 57% of ports will only need to provide chargers below 5 MW and less than 5 GWh of electricity per year. The additional power needs would not be trivial, but is much lower than T&E's estimated power demand due to the AFIR regulation, which will amount to more than 5.3 TWh in major ports alone.

A small number of ports dominate total demand: by 2035, the ten highest-consumption ports could account for a quarter of all energy demand from ferries, if all technically feasible vessels were electrified. Dover (379 GWh) and Calais (284 GWh) alone represent 14% of the total, despite serving only a total of 12 ferries combined. Those are relatively large ferries crossing the Channel several times a day – a unique configuration, since ferries performing several voyages a day elsewhere tend to be small vessels. Several other high-throughput ports: Algeciras, Swinoujscie, Napoli, Palermo, and Piraeus, also exceed 130 GWh per year in electricity demand.

The table below presents the estimated peak charger capacity needed for each port and their energy consumption for 2035.

Majority of ports need to supply less than 5MW charging power

Energy/Power bin	0-2 GWh	2-5 GWh	5-10 GWh	10-50 GWh	50-100 GWh	100-400 GWh
0-2 MW	142	15	3	0	0	0
2-5 MW	67	30	17	6	0	0
5-10 MW	18	20	13	17	0	0
10-20 MW	13	5	13	21	0	6
20-30 MW	0	0	2	19	11	6

Source: T&E (2025) • Based on a 2035 start year. Power bins are based on required power to charge the battery. Energy bins are based on quantity of energy consumed by vessels on their main routes.

Due to tight turnaround times, estimated peak charger capacity needs do not always follow annual energy demand. For example, island ports such as Santa Cruz de la Palma (16 MW) or Heraklion (14 MW) require high-power connections despite relatively low yearly usage. This underscores the importance of efficient berth scheduling to avoid potentially costly grid reinforcements.

As expected from earlier traffic results, demand is highly concentrated in cross-Channel and Baltic routes and in Mediterranean ferry hubs. Targeted regional infrastructure planning should thus deliver most benefits while avoiding over-investment around low-use ports.

3.2.8 Improvement in battery parameters

For the base scenario and a start date of 2030, our optimisation model shows that up to 43% of vessels could be technically and economically feasible in 2030, with an additional 14%

technically feasible only. In the table below, we present the base scenario, and the results for maximising feasibility obtained when increasing one variable from the values of 339 Wh/L (volumetric energy density), 225 Wh/kg (energy density weight) and a C-rating of 1.5 (charge rate). Results indicate that the main bottleneck in making more ferries technically electrifiable is the battery C-rating: many ferries only stop for short durations during the day, limiting their ability to recharge the battery. Assuming no operational changes, an increased C-rating would allow those ferries to charge faster, thereby increasing feasibility. By increasing the batteries' C-rating to a value of 5, 68% of ferries could be technically-feasible, out of which 53% of ferries could be economically-feasible in 2030, an increase of respectively 11 pp and 10 pp compared to the base scenario. In comparison, by 2030, volumetric and gravimetric density cease to be technical bottlenecks in our modelling.

Variable increased	Volumetric density (Wh/L)	Gravimetric density (Wh/kg)	Continuous charging C-rating	Share of technically feasible ferries	Share of economically feasible ferries
Base scenario	339	225	1.5	57%	43%
Volumetric density	**339**	225	1.5	57%	43%
Gravimetric density	339	**225**	1.5	57%	43%
Charging C-rating	339	225	**5**	68%	53%
All variables	**339**	**225**	**5**	68%	53%

Table 8: Sensitivity analysis of battery parameters.

3.3 Assessment of hybrid-electric ferries

3.3.1 Ship selection

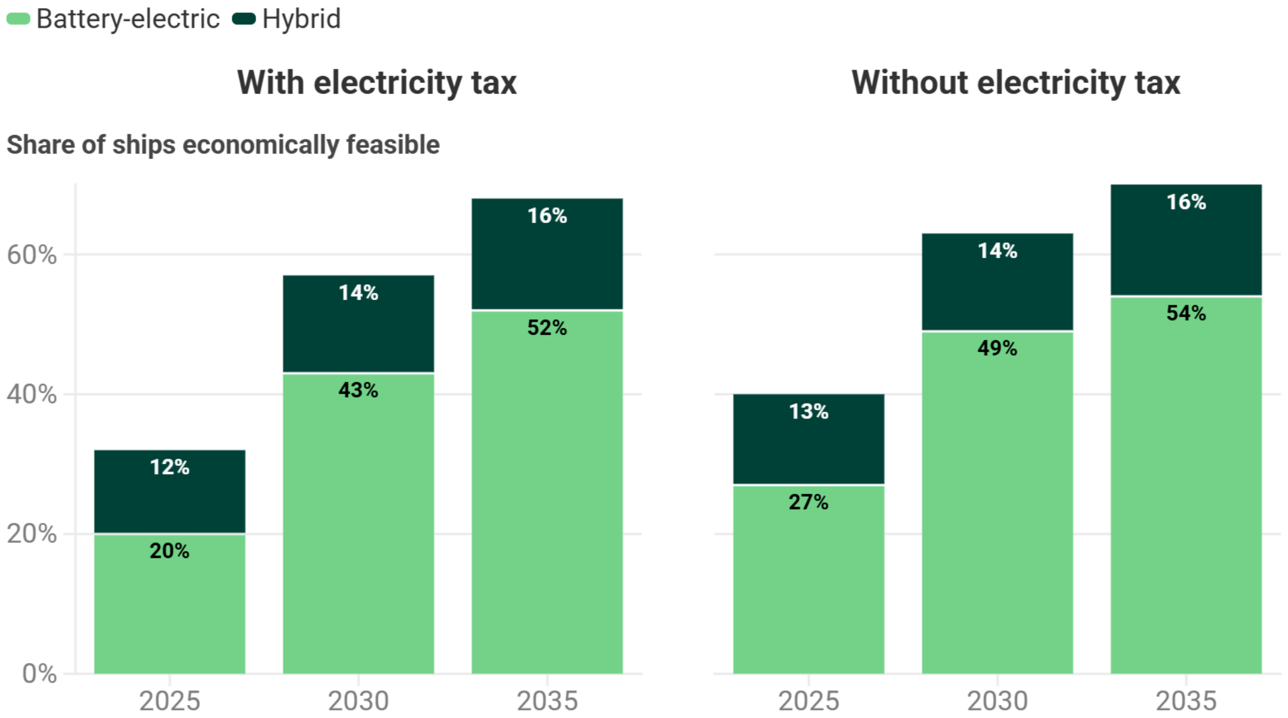
The sample of ferries we studied is the same as the one used in Section 3.2. Out of 904 ferries on conventional fuels and with sufficient data, we removed 70 with irregular schedules, creating a sample of 834 ferries that could potentially be electrified.

We prioritised maximum potential electrification for vessels: if a vessel can technically operate as a battery-electric vessel, we assumed it would operate as such. We only modeled as hybrids the vessels that are not yet technically suitable for battery-electric operations based on existing technologies. For these, we calculated technological and economic feasibility based on the assumption that between 50% and 95% of the vessel's required energy to perform a representative voyage should be delivered by the battery. We select this assumption since our goal is to minimise GHG emissions from ferries. In our hybrid model, onboard diesel generators produce electricity to power the electric motors and to supplement the electricity stored in batteries, which are charged at berth.

3.3.2 Fleet technical feasibility and cost-effectiveness

In section 3.2.2, our assessment concluded that 20% of European ferries could already operate more cheaply as battery-electric newbuilds than based on conventional propulsion technology in 2025. We find that an additional 12% of ferries would be technically feasible and economically competitive as hybrid electric vessels, increasing to a total of 32% the share of the European ferry fleet that could be replaced by full or partial battery electric propulsion systems already in 2025. By 2035, up to 52% of ferries would be viable as battery-electric newbuilds, and an additional 16% would be viable as hybrid vessels, for a total of 68% of the overall fleet. Removing shore-side electricity taxes has only limited impact on hybrid feasibility rates, since while it allows more non-feasible vessels to be hybrids, it also allows more hybrids to be fully battery-electric ferries.

Hybrids increase electrification potential by up to 16 percentage points



T&E (2025). Start years 2025, 2030 and 2035 with a lifetime of 30 years. Categories may not add up due to rounding.

3.3.3 Technical feasibility and cost-effectiveness by country

Cost-effectiveness results vary widely across countries, mainly due to differences in voyage patterns and electricity prices. In 2025, hybrids can add between 3 and 20 pp in cost-effective feasibility to a country's ferry fleet. Greece, which has already high battery-electric feasibility, only sees small gains of 4 pp. Italy, Germany and Spain have intermediate gains, respectively 16 pp, 10 pp, and 12 pp. Norway and Sweden can increase feasibility by 20 and 19 pp respectively. It appears that since non-feasibility for ferries in those countries derives from the C-rating of batteries being too low, hybrids can increase feasibility by limiting charging requirements at port. Finally, France and the UK have both 3 ferries that could be hybrid. These two countries have a respective 9% and 23% of ferries that would be technically feasible as hybrids but their cost-effectiveness is limited by high electricity prices.

3.3.4 Cost and CO_2 savings

We find cost savings from hybrid ships to be similar to those for battery electric vessels. Hybrid vessels must still surrender ETS allowances and procure alternative low carbon/renewable fuels in relation with the operation of the onboard genset, but have lower electricity purchasing needs from shore and lower battery-related CAPEX costs compared to pure battery-electric vessels. Cost-effective 2025 hybrid newbuilds are estimated to save 14% in fuel and ETS costs over their lifetime, equivalent to battery-electric vessels. By 2035, pure battery-electric ships could save 32% in fuel and ETS costs, with hybrids achieving average cost reductions of 36%. Although hybrid-electric vessels have lower CAPEX costs, they would still have to surrender ETS allowances for the emissions from fuel consumption.

For cost-effective ferries, the TCO breakeven year is 16 years for hybrids and 19 years for battery-electric ships built in 2025. This goes down to approximately 6 years for battery-electric newbuilds and 4 years for hybrid newbuilds entering the fleet from 2035 onwards. Hybrid and battery-electric vessels differ in terms of lifetime CO_2. Savings increase from 8% of total fleet CO_2 in 2025 to 24%, in 2035 for battery electric vessels. For hybrid vessels, lifetime CO_2 savings go from 10% to a maximum of 18% of total fleet emissions by 2035. Economic feasibility for hybrid vessels is inferior to battery-electric vessels, but because hybrid vessels tend to be larger, lifetime CO_2 savings remain significant. Combined with full electrification potential, this would amount to a 42% reduction of CO_2 emissions from the European ferry fleet.

3.3.5 Sensitivity analysis

Looking at the sensitivity analysis for hybrid technology, the results follow the same pattern as for battery-electric vessels. A FEUM exemption for small vessels would reduce viability by approximately 2 pp. Conversely, the domestic electricity taxes exemption provides a modest positive benefit of less than 2 pp when implemented.

Among the quantitative parameters, ship energy demand shows the largest sensitivity with a 25% increase in energy demand leading to a 4 pp decrease in feasibility and a 25% decrease in energy demand leading to a 1 pp increase. Electricity prices also demonstrate notable effects, with a 25% price decrease causing a 2 pp increase in feasibility while a similar increase in electricity prices produces a 4 pp decrease, highlighting cost vulnerability. The discount rate proves influential as well, with a 3% variation causing approximately ±3 pp swings. Overall, regulatory exemptions and operational parameters like energy demand and electricity pricing emerge as the most critical factors affecting hybrid technology viability.

3.3.6 Port electric power requirements

For hybrids, we calculated an additional total yearly electricity demand of 3 TWh, with 2.1 TWh being consumed on the representative routes we assessed for 2035. The ports and routes distribution presented below exhibits similar patterns as for battery-electric vessels presented in section 3.2.7, both in terms of energy demand and geographical concentration: 34% of vessels will require less than 5 GWh of energy during the year and 5 MW of charging power. However, hybrid-electric vessels tend to be larger compared to battery-electric ferries: this translates into a marked increase in the required power, with 55 ports requiring 20+ MW. Notably, while this impact is additional to the required charging infrastructure to most fully-electric ferries, the real-life power requirements depend on both the power requirement of the vessel and the share of hybridisation. Nonetheless, additional peak power demand from larger hybrid vessels should be separately considered when planning electricity grid expansions.

Hybrid-electric ferries require larger chargers, more power

Energy / Power bin	0-2 GWh	2-5 GWh	5-10 GWh	10-50 GWh	50-100 GWh	100-400 GWh
0-2 MW	25	0	0	0	0	0
2-5 MW	32	4	0	0	0	0
5-10 MW	6	4	0	2	0	0
10-20 MW	21	8	9	14	1	0
20-30MW	1	4	2	37	9	2

Source: T&E (2025) • Based on a 2035 start year. Power bins are based on required power to charge the battery. Energy bins are based on quantity of energy consumed by vessels on their main routes.

3.4 Assessment of e-fuels and biofuels

We performed a TCO analysis for several e-fuels and biofuels, and compared the results to those obtained by modelling battery-electric and hybrid ferries. We modelled operating ferries with e-methanol, e-ammonia, liquid e-hydrogen (e-LH2) and hydrotreated vegetable oil (HVO). We compared the results to the base case of a FuelEU-compliant mix of MDO, FAME and HVO, or LNG and biomethane, depending on the fuel currently used by each vessel.

We assumed that for e-methanol, e-ammonia and HVO, those fuels would be used in internal combustion engines (ICEs). For e-LH2, we modelled energy conversion using solid-oxide fuel cell technology, a promising option in transport for energy stored in hydrogen, though H2 dual-fuel ICEs are increasingly more available and powerful.

3.4.1 Technical feasibility

Similar to the assessment of battery-electric feasibility in sections 3.2 and 3.3, we evaluated technical feasibility of alternative fuels based on whether ferries could perform a representative voyage using the given technology. We used two criteria: whether a vessel has sufficient fuel storage capacity and whether it has sufficient energy to perform a representative voyage.

To assess fuel storage capacity, we assumed that for e-methanol, e-ammonia and HVO, the existing fuel tank volume could be used. For e-LH2, fuel cells require less space than an ICE, but additional equipment is required to store the fuel. We used an empirical formula based on engine power (see Annex 3.6.2) to calculate available space.

For a 2025 build year, we found that 679 ferries out of 904 are technically feasible when using e-LH2, with the remainder ineligible because we cannot calculate the available volume for hydrogen storage tanks (see Annex 3.2.2). For the remaining fuels, 890 out of 904 vessels are technically feasible. 14 vessels were removed due to their small fuel tanks below 10 cubic meters, the minimum threshold we set for the modelling. Still, all ferries have enough space to transport the fuel required for their most critical voyages, as ferries tend to operate on short routes relative to their size, limiting their energy needs compared to other vessel types.

3.4.2 Economic feasibility

For a 2025 build year, e-fuels and bio-fuels, economic feasibility depends on whether the increased CAPEX and fuel costs can be compensated by reduced ETS costs. In the base case, no alternative fuel is economically competitive with the default pathway where a vessel blends fossil fuel (LNG or MDO) with an increasing share of biodiesel or biomethane. ETS prices are too low to compensate for the increase in fuel costs and CAPEX. When modelling a ferry using only biofuels against the base case, fuel costs are higher compared to blending MDO and HVO, making it economically not competitive.

For a 2035 build year, 76% of ferries are feasible and competitive with e-ammonia, and 28% with e-LH2. Those results are driven by higher ETS costs in the future, the need to blend in higher quantities of biofuels to comply with FuelEU carbon intensity targets, and a forecasted decrease in the cost of e-fuels. Furthermore for e-LH2, it benefits from the higher efficiency of fuel cells compared to ICE, allowing it to use less fuel to deliver the same output energy. However, these results exclude potential costs for safety equipment necessary to operate with these fuels.

3.4.3 Sensitivity analysis

We use the same sensitivity checks as applied to battery-electric feasibility in sections 3.2 and 3.3, with the exceptions of the ones specific to battery-capacity and charging power. In addition, we add a sensitivity check where we increase the number of voyages before a vessel can bunker.

For a 2035 build year, the analysis reveals stark differences in viability among alternative fuels when compared against the standard scenario. E-ammonia is the most feasible option, with 76% of ferries cost-competitive under base case assumptions. E-hydrogen increases feasibility to 28% in the base case, owing to the higher fuel costs and fuel cell CAPEX. E-methanol and HVO show no cost-effectiveness under base conditions and all sensitivity scenarios.

Results are highly sensitive to changes in the base-case fuel prices: a reduction of 25% in fuel costs for a vessel operating with a fossil fuel mix will reduce economic feasibility to 0% for ammonia, and to 7% for e-LH2. An increase of 25% in price can raise e-LH2 feasibility to 50% of the fleet, and 84% for green ammonia. This highlights the underlying results' uncertainty: although e-fuels can play a strong role in helping decarbonise ferries, their economic feasibility under current regulations is contingent on reducing the cost difference between them, fossil fuels, and biofuels.

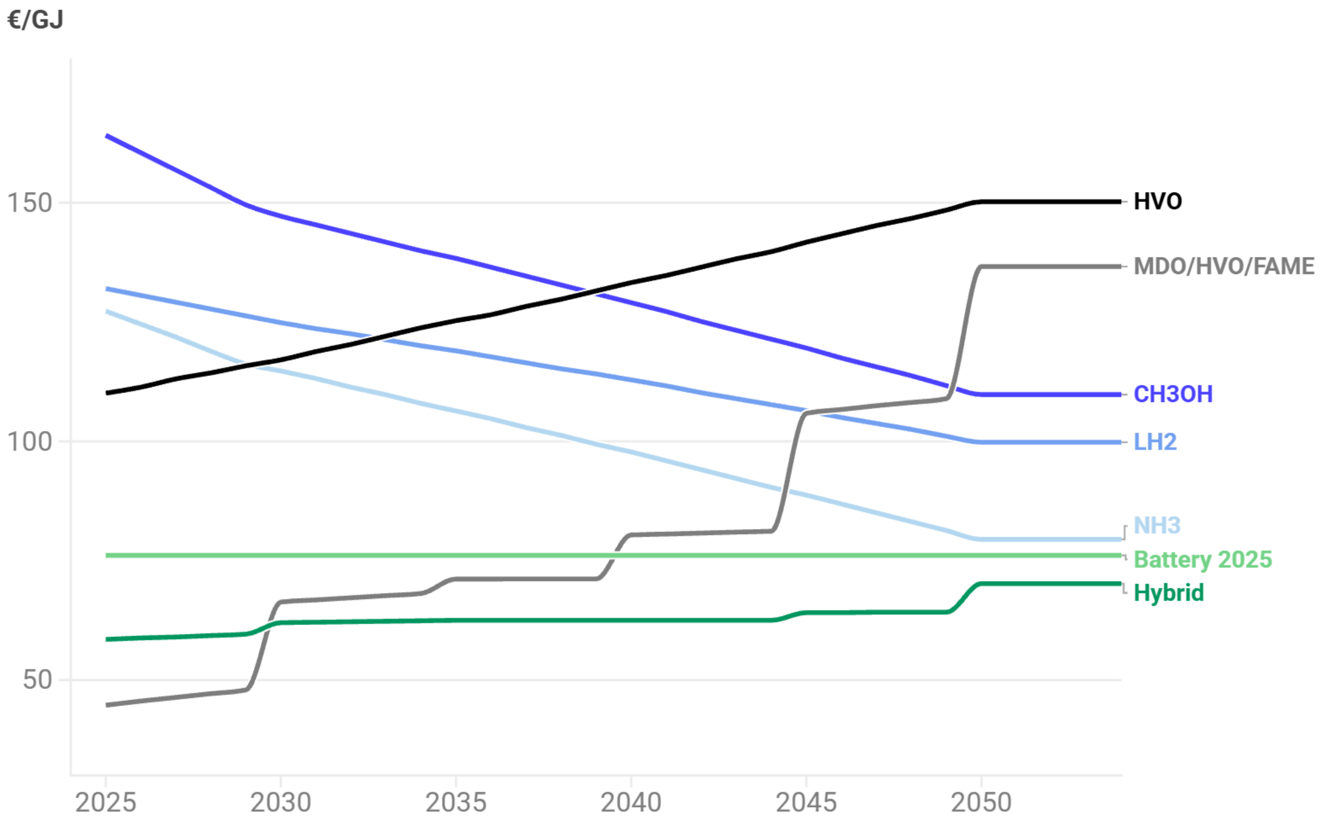
3.4.4 Comparison between technologies

We compare annualized costs per gigajoule of energy used between technologies. For each feasible ferry, we sum the OPEX for each year with the average CAPEX, annualized and spread equally over all the years of the ferry's lifetime. We then compute the average per technology for all vessels that are technically-feasible for said technology. Since we use a constant price for electricity, and because CAPEX is spread evenly across all years, cost per gigajoule for battery-electric vessels is constant. For the baseline MDO/HVO/FAME mix, the cost increases with the rise in forecasted HVO and FAME and ETS prices, and the changing targets of FEUM. Further, due to technological maturity on the one hand, and supply constraints on the other side, E-fuel prices are expected to decrease in the future, while the price of waste-based HVO is expected to increase due to higher demand and low potential for increased production.

Hybrid and battery-electric vessels are the cheapest options among the technologies we examine, with a cost by 2050 of €69/GJ and €73/GJ respectively by 2050. By 2040, battery costs are forecasted to be inferior to the baseline scenario's cost. By 2045, e-ammonia costs are expected to be lower than the baseline's. E-ammonia is the cheapest e-fuel, with a cost of €79/GJ by 2050.

E-fuels eventually overtake a MDO - HVO fuel mix by 2050

Annualized costs for selected energy scenarios



Source: T&E (2025) • Cost curves include annual OPEX and annualized CAPEX. Start date of 2025.

Section 4

4. Discussion and recommendations

Ferries provide essential services to Europe's citizens. Yet, our analysis shows that they are also responsible for a significant share of air pollution in densely populated ports areas.

Beyond air pollution, electrification offers a unique opportunity to significantly reduce GHG emissions: Today, 20% of EU ferries could be cheaper as battery-electrics, rising up to 52% in 2035. Hybrid ferries further raise the potential to at least 32% in 2025, or 68% in 2035.

Key reforms of EU policy to enable this transition and support domestic industry:

1 Expand the ETS and FuelEU Maritime to cover vessels >400GT, ensuring coverage of the most electrifiable ferry segments.

80% of annual voyages are undertaken by ships between 400 and 5000 GT, which show high potential and require smaller port-side infrastructure to accommodate electrification. The inclusion of smaller ferries in the upcoming legislative revisions would level the playing field, drive almost 10% additional electrification, increase revenues for re-investment, and create certainty for projects already under development.

2 Expand the Alternative Fuels Infrastructure Regulation (AFIR) beyond shore power mandates to include vessel charging infrastructure.

Many ports are planning and investing in their grids and infrastructure to accommodate the implementation of OPS mandates under AFIR. The explicit reference of maritime charging infrastructure can drive co-investment opportunities, anticipate future demand from electric vessels, and avoid redundancies for grid expansion plans in the key TEN-T ports, in particular for vessels below 5000 GT.

3 Revise EU procurement rules to ensure sustainable use of public resources including through zero-emission standards.

While not yet covered under EU climate rules, smaller ferries more often operate under public contracts, support, or service obligations - a key opportunity to leverage demand for this segment and generate co-benefits for local populations. The reform of public procurement in the EU should integrate binding local content requirements, as well as resilience criteria to promote sustainable products and practices. Stimulating demand through public procurement creates the necessary market conditions for decarbonised products, enables economies of scale to reduce costs and increase accessibility, following the direction taken in the Net Zero Industry Act.

4 Integrate marine battery production into strategic battery production capacity goals, including through the EU Industrial Maritime Strategy.

The European shipbuilding and maritime equipment industries hold a competitive advantage in developing complex and bespoke vessels and technologies. Electrifying European ports, coastal and short-sea shipping would reduce Europe's reliance on imported fossil fuels, enhance the EU's energy resilience, and maintain high-value manufacturing jobs. Electric shortsea transport can additionally function as dual-use assets, which can serve both civilian and military purposes.

Under existing regulations, national and regional governments can already use key policies:

5 Utilise the Most Economically Advantageous Tender (MEAT) and Green Public Procurement (GPP) methodologies.

Existing state aid rules offer a range of optional sustainability criteria. Zero-emission criteria can be introduced under the 'most economically advantageous tender' (MEAT) procedure. When not directly involved in the project, authorities can establish coordination forums to connect relevant stakeholders to facilitate integrated planning between ferry owners, grid operators, and port authorities.

6 Reduce national taxes and duties on electricity supplied to vessels, as already provided in the Energy Taxation Directive.

Beyond shore side power supply, the price of electricity and associated taxation are key issues for electrification. Reducing national taxes on shoreside electricity can immediately support the deployment of electric ferries contributing to a level playing field for either energy source, where electrification can benefit from its inherent efficient energy use.

7 Expand Emission Control Areas (ECAs) to outermost regions and end route-specific exemptions.

Europe's most polluted ports are consistently those located outside of Emissions Control Areas in the EU's exempt outermost regions. These exemptions are denying remote communities the benefits of readily available cleaner vessels - low-pollution fuels, battery-, and hybrid-electric.

Annex 1 - Methodology

1. Ship selection

To establish the list of ferries to analyse, we selected vessels for the year 2023, if they meet all the following conditions:

- They are classified as 'Ro-Pax' in the EU MRV in 2023, or classified as 'Ferry' in Clarksons' World Fleet Register (WFR), or classified as Passenger/General Cargo', 'Passenger/Ro-Ro Cargo' or 'Passenger' as per StatCode 5 Level 4 classification in IHS Markit (now S&P Global) Core Ship Database
- They are not labelled as 'Cruise ship' in Clarksons' World Fleet Register, as that would point to incorrect classification in the other databases
- Their gross tonnage is greater than or equal to 400 GT
- They have a passenger capacity superior or equal to 12 passengers (as per Ro-Ro vs. Ro-Pax definition)
- They have more than 50 raw AIS observations within a bounding box defined by points A (longitude = 35, latitude = 72) and B (longitude = -32, latitude = 26)
- They have more than 10 voyages to/from the EEA or the UK

Moreover, we excluded 30 ships after manually confirming they are not ferries (e.g. mislabelled training ships), and we removed vessels that do not have sufficient quality data e.g. if they sailed less than 500 nautical miles or made less than 20 voyages in 2023 .

This yielded 1043 vessels, hereafter named European ferries, that compose our sample.

2. Ferry traffic, greenhouse gas emissions and air pollution

This section describes the methodology we followed to analyse European ferries' 2023 traffic and TtW emissions. We used a bottom-up model to derive individual ship's emissions and voyages, we applied several post-processing steps and when aggregated ferries' traffic, GHG emissions and air pollution, and compared the latter to that of European cars.

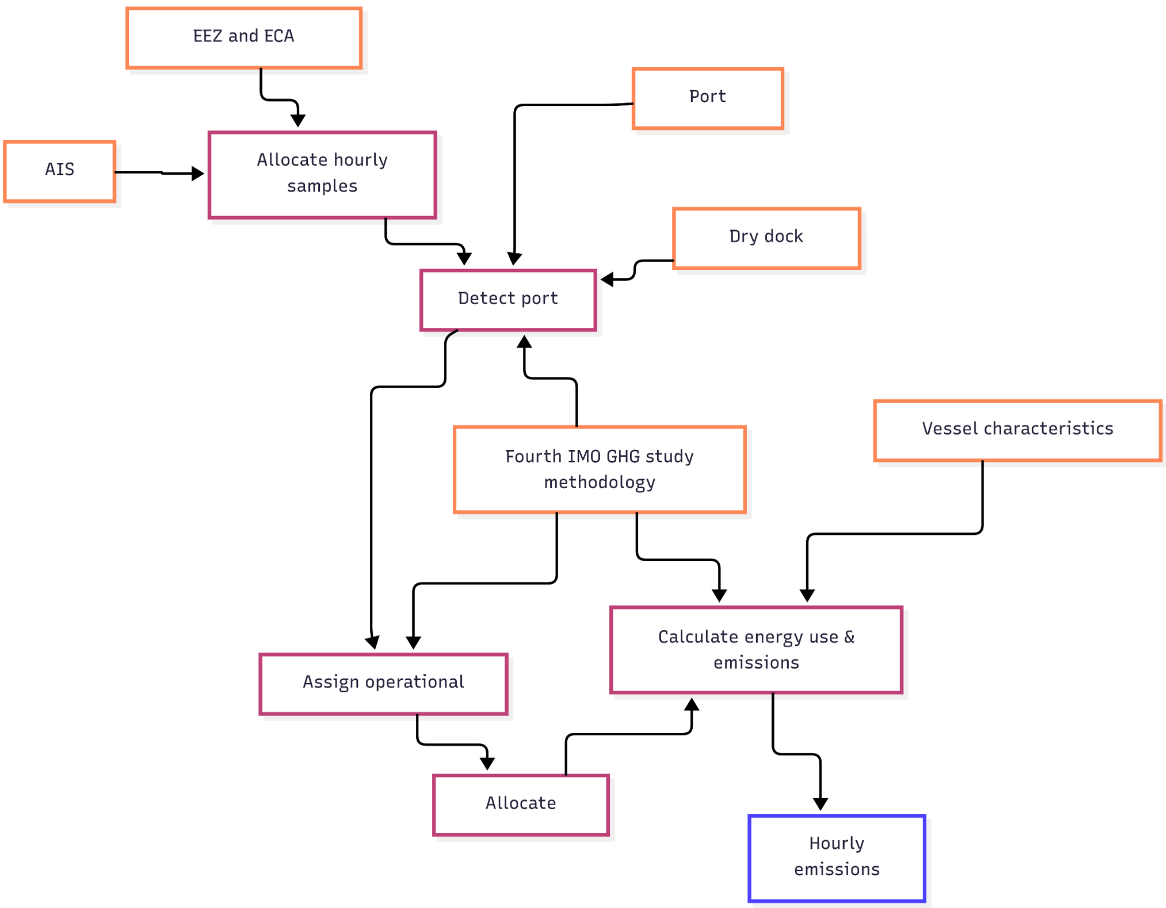
2.1. Calculation of individual ship emissions

Our bottom-up emission calculation model is based on the methodology outlined in the Fourth IMO Greenhouse Gas (IMO4GHG) study. It calculates GHG and air pollutant emissions at a ship level using automatic identification system (AIS) data and ship technical specifications. We improved the model to better identify small ferry stops and voyages.

We used ship technical specifications from Clarksons' World Fleet Register (WFR) and IHS Markit (now S&P Global) Core Ship Database (CSD) and pre-processed them to fill data gaps, combining instruction from the IMO4GHG study and our infilling methods. We also imported 2023 AIS data from Spire. AIS messages are sent by ships at regular intervals during their operation and contain information such as timestamp, position, speed and draught of the vessel. We removed erroneous entries from the AIS data, resampled it at 5-minute intervals and infilled the gaps in the time series for position speed, draught and voyage status (i.e. moored, anchored, cruising or other navigational statuses).

As can be seen in the figure below, our model is implemented in 5 steps:

1. Allocation of hourly samples into Exclusive Economic Zones (EEZs) and ECAs in Europe
2. Detection of port stops
3. Assignment of operational phases
4. Allocation of voyages
5. Calculation of vessel energy consumption and emissions.



EEZ and ECA shapefiles come from publicly available sources. Our port shapefile is a collection of publicly available databases such as the World Port Index, Eurostat and OpenStreetMap. Additionally, we identified dry docks by analysing ship behaviour in AIS data and confirming locations manually. We included the SECAs covering the North Sea, the Baltic Sea, and the new Mediterranean Sea SECA that came into force in May 2025.

We calculated emissions of CO_2, CH_4, N_2O, black carbon (BC), SO_X, NO_X and $PM_{2.5}$ using emission factors from the Fourth IMO GHG study. We could not model the connection to on-shore power at berth (OPS) at ports due to lack of data but given the limited extent of this practice among ferries, this does meaningfully impact on the results. We assumed no emission during dry dock stops.

In estimating emissions, we assumed that the ferries equipped with dual-fuel LNG engines were running exclusively on LNG since we lack data to determine the exact fuel mix used onboard. Other vessels were assumed to run on HFO, VLSFO or MGO, depending on the relevant fuel sulphur standards in place in a given geographical area. Specifically:

- Ships in SECAs are required to use fuel with at most 0.1% sulphur content or rely on exhaust gas cleaning systems, i.e. scrubbers, to respect SO_X standards.
- Ships at berth or at anchor within the boundaries of European ports must follow this same rule for port stays above two hours.
- Ships sailing outside SECAs are required to use residual fuels complying to a maximum 0.5% sulphur content mandated under both EU Sulphur Directive and global MARPOL Annex VI.

We used Clarksons' WFR to identify ships equipped with scrubbers and assumed they were using 2.6% sulphur (2.6% S) HFO, with scrubber treatment of exhaust gases when needing to comply with 0.1% sulphur standards. To calculate the resulting emission changes, we used the relative emission change after scrubber using HFO (2.6% S) compared with MGO (0.1% S), from the ICCT's 2020 scrubbers study, shown in the table below. In the absence of data we assumed CH_4 and N_2O emissions didn't change. In ports where the use of open-loop scrubbers is forbidden, we assumed 0.1% MGO is used instead.

CO_2	BC (SSD)	BC (MSD)	SO_x	NO_x	$PM_{2.5}$
+4%	+353%	+81%	-52%	0%	+61%

Table 9: Applied adjustment factor to GHG emissions and air pollution due to the use of exhaust gas cleaning systems (scrubbers).

2.2 Post-processing of ship emissions

We performed several post-processing steps on our data:

- For battery-electric and hybrid ferries i.e. vessels where the engine type is listed as “Batteries propulsion” or “Batteries & Diesel”, we set emissions to zero. For battery-electric vessels, tank-to-wake emissions are null. For hybrid vessels, we cannot calculate the share of effective battery power so any estimate would be inaccurate.
- Due to AIS data quality and ferry short turnaround times, some vessels in our sample have “circular voyages”. A circular voyage is a round trip between two ports, where the middle port call is not detected, e.g. two voyages, from port A to port B and from port B to port A are recorded as one voyage from port A to port A. We reconstruct round trips from circular voyages when possible.
    - If a circular voyage shares a port with one of the vessel’s frequent routes, and the distance sailed is within 85 to 115% of the mean distance sailed during a round trip on this route, then we replace the circular voyage by a round trip.
    - In cases where there are several matches, we prioritise the one with the closest distance. We assume the port stop duration and port emissions are equivalent to the median of all port stops by this vessel in this port.
    - In cases where this value is higher than one third of the total duration and emissions of the examined voyage, we use one third of the total duration and emissions instead. Duration and emission values for the in- and out-bound voyages are calculated as half of the remainder emissions each.
    - In our sample, 6.44% of all voyages are circular: of those, we reconstructed 12.14% of that group that fit the criteria outlined above. In consequence, 5.66% of all voyages cannot be reconstructed and remain circular.
- We excluded the remaining circular voyages when counting the number of voyages to avoid aggregating false voyages.
- For circular voyages over 30 nautical miles, we reduced CO_2 emissions by 50%. We assumed that our model missed a port stop in those cases, and therefore it would skew results to attribute 100% of CO_2 emissions to the one detected port stop.
- For circular voyages under 30 nautical miles, we assumed that the voyages are displacements within port, and we kept 100% of the CO_2 emissions.
- We zeroed emissions for all voyages over 1000 nautical miles, and excluded them when counting the number of voyages.

2.3 Aggregation of traffic and voyage emissions

We aggregated ship voyage counts and emissions per:

1. Route: port emissions are assigned to the preceding voyage, voyage counts and emissions are attributed to the corresponding bidirectional route
2. Ports: port emissions are assigned to their respective port, voyage emissions are split in half between departure and arrival port, while voyage counts are attributed to the arrival port.
3. Country: port emissions are assigned to their respective country, voyage emissions are split in half between departure and arrival country, while voyage counts are attributed to the arrival country.

In total, 2,555,007 voyages were attributed to routes with at least one port in the EEA or the UK.

2.4. Aggregation and comparison of air pollution

We defined emissions "close to ports" as all emissions emitted by ships within 5 nautical miles (nm) of the main coordinates of European ports listed in our ports database. This yielded the total fleet emissions presented in the report. We then used voyage data to attribute air pollution to specific ports: emissions within 5 nm of a port's coordinates were counted only if the port was the departure or arrival of the voyage. If emissions fell within 5 nm of two ports, they were assigned to the nearest one. We excluded stops lasting over seven days to filter out erroneous AIS signals , dry dock stops, or atypical ship behaviour, which may indicate engines were not operating normally.

We computed emissions within port-adjacent zones under three distinct regulatory scenarios: first, incorporating solely the Sulphur Emission Control Areas (SECAs) operational in 2023; second, augmenting this baseline with the proposed Mediterranean SECA; and third, incorporating both the Mediterranean and North-East Atlantic SECAs. While the computational methodology remained consistent across all iterations, each successive scenario expanded the geographical extent within which vessels were mandated to utilize low-sulphur fuels.

We compared maritime vessel emissions with automobile emissions in port cities and in the Exclusive Economic Zones (EEZs) of countries through which vessels transited. Municipal automobile numbers, presented in the table below, were obtained from publicly available datasets. Data correspond to 2023 where available, with exceptions for French and Irish ports (2022) and Croatian ports (2019). Where direct municipal data were unavailable, we estimated automobile numbers by applying the per capita vehicle ownership rate of the smallest statistical unit encompassing the port for which data existed (NUTS 2 or NUTS 3 regions) to the respective port population. This estimation approach was applied to all Maltese and Greek ports, as well as British ports excluding Dover and Belfast. Since urban centers typically exhibit lower per capita vehicle ownership than broader regional areas, our port-level automobile estimates likely represent upper bounds, rendering ship-to-automobile emission comparisons more conservative. Port demographic data were retrieved from public sources, using the closest available year prior to 2023.

Car numbers per country, car emission factors and distribution of cars per Euro category came from the European Union Transport Roadmap Model (EUTRM). On average, European cars emitted 0.012 kg SO_x, 4.278 kg NO_x and 0.537 kg $PM_{2.5}$ in 2022 per vehicle. We assumed car fleets consisted entirely of diesel vehicles, which have higher NO_x emissions than petrol cars. This makes our ship-to-car comparisons conservative—underestimating ferries pollution relative to cars—since including petrol cars would lower average car emissions.

Port city	Country	Number of registered passenger cars	Year	Source
Algeciras	ESP	65,469	2023	Spanish Traffic Directorate (DGT) - Vehicle Statistics Database
Los Cristianos	ESP	55,038	2023	
Agaete	ESP	2826	2023	
Barcelona	ESP	571,061	2023	
Ibiza	ESP	37,130	2023	
Palma Mallorca	ESP	261,533	2023	
Santa Cruz De Tenerife	ESP	132,345	2023	
Valencia	ESP	382,704	2023	
Las Palmas De Gran Canaria	ESP	202,766	2023	
Tallinn	EST	285,934	2023	Eurostat - Road vehicles by type and region (tran_r_vehst)
Calais	FRA	33,259	2022	French Ministry of Ecological Transition - Data on the French vehicle fleet as of January 1, 2023
Bastia	FRA	22,282	2022	
Toulon	FRA	87,535	2022	
Marseille	FRA	384,847	2022	
Holyhead	GBR	7869	2023	UK Government - Vehicle licensing statistics 2023
Belfast	GBR	143,572	2023	
Larne	GBR	11674	2023	
Cairnryan	GBR	N/A. *Ferry terminal is located in a small remote village without reliable population data*	2023	
Dover	GBR	64,000	2023	

Piraeus	GRC	146,628	2023	Eurostat - Road vehicles by type and region (tran_r_vehst)
Salamina	GRC	26,365	2023	
Port Of Paros	GRC	5663	2023	
Mykonos	GRC	4175	2023	
Naxos	GRC	5736	2023	
Igoumenitsa	GRC	10,562	2023	
Port Of Tinos	GRC	3484	2023	
Perama	GRC	22,348	2023	
Syros	GRC	8238	2023	
Irakleion	GRC	87,141	2023	
Thassos	GRC	5320	2023	
Split	HRV	89,473	2019	Ministarstvo Unutarnjih Poslova
Dublin	IRL	476,937	2022	Central Statistics Office of Ireland - CSO Interactive Data Visualisation Hub
Ballygeary	IRL	1059	2022	
Villa San Giovanni	ITA	8377	2023	ACI (Italian Automobile Club) - Studies and research: data and statistics - Open Data
Portoferraio	ITA	8929	2023	
Piombino	ITA	21,002	2023	
Tremestieri	ITA	15,833	2023	
Porto D'Ischia	ITA	12,058	2023	
Pozzuoli	ITA	55,131	2023	
Ancona	ITA	63,001	2023	
Civitavecchia	ITA	34,618	2023	
Napoli	ITA	553,185	2023	
Genova	ITA	266,651	2023	
Livorno	ITA	89,293	2023	
Messina	ITA	146,252	2023	
Palermo	ITA	396,273	2023	
Bari	ITA	184,762	2023	
Cirkewwa	MLT	8113	2023	National Statistics Office Malta - Regional Statistics Malta 2024 Edition
Mgarr	MLT	2622	2023	

Table 10: Registered passenger cars of largest ports.

3. Techno-economic assessment of decarbonisation technologies

In this section we present the main inputs, assumptions and methods used to assess how different propulsion technologies and fuels can decarbonise the European ferry fleet. We outline the general approach, as well as the selection of ships, and representative routes considered in each assessment. We then detail the methodology for each evaluation.

3.1 General approach

We assessed the decarbonisation potential of the following propulsion technologies and fuels:

- Battery-electric
- Hybrid-electric
- E-liquid hydrogen (LH_2)
- E-methanol (CH3OH)
- E-ammonia (NH3)
- HVO biodiesel

For each option, we assessed the technical feasibility of every ship in the fleet and compared its total cost of ownership (TCO) with that of a conventional ferry running on a FuelEU-compliant fuel mix. Our analysis was based on the operational characteristics and dimensions of the existing ferries, assuming conservatively that alternative-propulsion ships would share these characteristics. In practice, some design and operational adjustments are possible with little impact on TCO.

3.2 Ship selection

Due to their technical and operational characteristics, not all European ferries, as defined in section 1, are eligible for techno-economic assessment of all decarbonisation solutions. In this section we explain the selection of ships retained for each analysis.

3.2.1 Ships selection for the e-fuels and biofuels propulsion assessment

For the alternative fuel section, vessels are excluded if:

- They are already labelled as hybrid or battery-electric
- They have less than 100 voyages during the year. Such ships do not represent a meaningful share of the traffic.

3.2.2 Ships selection for the battery- and hybrid-electric propulsion assessment

Battery-electric ferries have specific charging requirements in terms of time and infrastructure. To control for this, we only studied vessels that sail between a small number of ports. We assumed that the ships that sail between many ports would require too heavy investments to make sure all ports have the required charging infrastructure.

We take the sample defined in section 3.2.1 and remove vessels if:

- The number of unique ports required to reach 95% of total distance sailed by the vessel is strictly above 10. We assumed charging infrastructure is less likely to be fully available for vessels visiting more ports. We used a 5% margin to account for inaccuracies in AIS data, and assumed that vessels could make minor adjustments to their voyages in case they were to be electrified.

The samples we use for the analysis are detailed in the table below.

Size	Original sample	Used for 3.2.1 alternative fuels	Used for 3.2.2 battery electric
Below 5000 GT	632	526	487
Above 5000 GT	411	378	347
Total	1043	904	834

Table 11: Sample of ferry vessels by size bucket and feasibility analysis.

3.3. Representative voyage characteristics

For the purpose of the TCO analysis, we extracted the following data points for each vessel from T&E SEA model's output:

- The number of voyages per year
- The total energy demand (in kWh), fuel consumption (in tonnes) and time spent at berth (in hours).

Those metrics are summed over the whole year.

For each vessel, we define a representative route, used to model decarbonisation costs. The route is non-directional, and selected based on the following criteria:

- The route represents at least 10% of all voyages
- The route represents at least 10% of all distance
- The route represents at least 10 voyages

If several routes fit those criteria, we select the route with the highest mean distance as the representative route. For the representative voyages, we add the following parameters:

- The energy demand (in kWh), selected as the 75th percentile
- The fuel consumption (in tonnes), selected as the 75th percentile
- The time at berth (in hours), selected as the 50th percentile
- The energy demand at berth (in kWh), selected as the 50th percentile
- The peak power consumption (in MW), selected as the 99th percentile
- The average AIS draught (in m), taken as the average

The table below presents several summary statistics for key variables. Number of voyages is the number of vessels done on the main route by a ferry. It exhibits a right skew, with smaller vessels (below 5000 GT) doing many short voyages, while larger ferries tend to sail longer routes and therefore do less voyages. The ferry with the most voyages that could be eligible for electrification is the MF Mary, operating in Denmark. This ferry made on average 58 trips a day on the Hvalpsund-Sundsøre route in 2023.

CO_2 emissions are TtW emissions aggregated during the year for each vessel. For vessels already running on batteries are attributed 0 tonnes of TtW CO_2 emissions. It also exhibits a right skew: our sample has more small ferries, but those emit much less than larger ferries. Notably, the most polluting ferry is MS Cruise Roma, the world's longest cruise-ferry operating between Barcelona and Civitavecchia. The vessel has 5.5 MWh installed battery capacity to be used to power diesel generators within ports. Since the battery is not used for propulsion, and the energy demand within ports is low (3% of overall energy demand), we do not qualify the vessel as a hybrid for the modelling. The longest route is Marseilles - Tanger Med, for a one-way distance of 755 nautical miles and a duration of 42 h.

Variable	Number of voyages	TtW CO_2 emissions (in t)	Distance per voyage (in nm)	Time spent at port (in h)
Min	10	0	0.15	0.08
Mean	2451	13,419	17.71	2.51
Median	1163	4410	77.87	0.83
Max	18,995	126,391	755	127.92

Table 12: Summary statistics for the ferry vessel sample. For each vessel, distance per voyage represents the vessel's main route. Time spent at port aggregates median port stop durations.

3.3. FuelEU-compliant fuel mix

For the TCO analysis, we compare several technologies to a base case of a vessel running on a FuelEU compliant fuel mix of fossil fuels and biofuels. FuelEU maritime requires vessels above

5000 GT to meet GHG intensity targets. In cases where a vessel sails both inside the EEA and outside, the GHG intensity targets must be met for 100% of the energy used between EEA ports, and 50% for inbound and outbound voyages. Here, we defined a FuelEU compliant fuel mix as a fuel mix with a Well-to-Wake carbon intensity equal to the FuelEU target for the given year.

We defined two fuel mixes:

- A mix of MDO, FAME and HVO for vessels running on MDO. Vessels blend in up to 30% of total energy used as FAME, and then add HVO as required to meet the targets. In cases where the vessel is unable to meet the FuelEU targets with 30% FAME (past-2050), then sufficient FAME is replaced by HVO so as to meet the targets.
- A mix of LNG and biomethane for vessels running on LNG

For every year, for vessels operating exclusively in the EEA, we calculated the proportion of biofuels required so that the fuel mix WtW intensity is equal to the FuelEU defined target. We then defined the fuel mix price as the weighted average of the two or three fuels, with the weights being the respective proportions of each fuel in the mix.

For vessels operating on inbound / outbound routes (e.g. Calais - Dover), the European commission states that all *"renewable and low-carbon fuels"* used in international voyages can be used to meet the vessel's intensity targets in regard to its international voyages. We modelled those vessels as using just enough biofuels to meet the FuelEU intensity targets for the FEUM-covered energy, and MDO or LNG for the remainder. For vessels fully outside the EEA (e.g. domestic UK ferries), we modeled them using only fossil fuels, as they do not face comparable regulations.

We modeled compliance with FuelEU targets only, given the uncertainty over the IMO's Net-zero Framework.

Fuel	Fuel prices (€/t)	Fuel prices (€/GJ)	Source
MDO	665	15.57	Average 2019 European price from Stratas Advisor historical bunker fuel prices. Constant over time.
LNG	536	10.91	Average 2019 European price from Stratas Advisor historical bunker fuel prices. Constant over time.

Table 13: Fossil fuel prices assumptions. In 2025 €

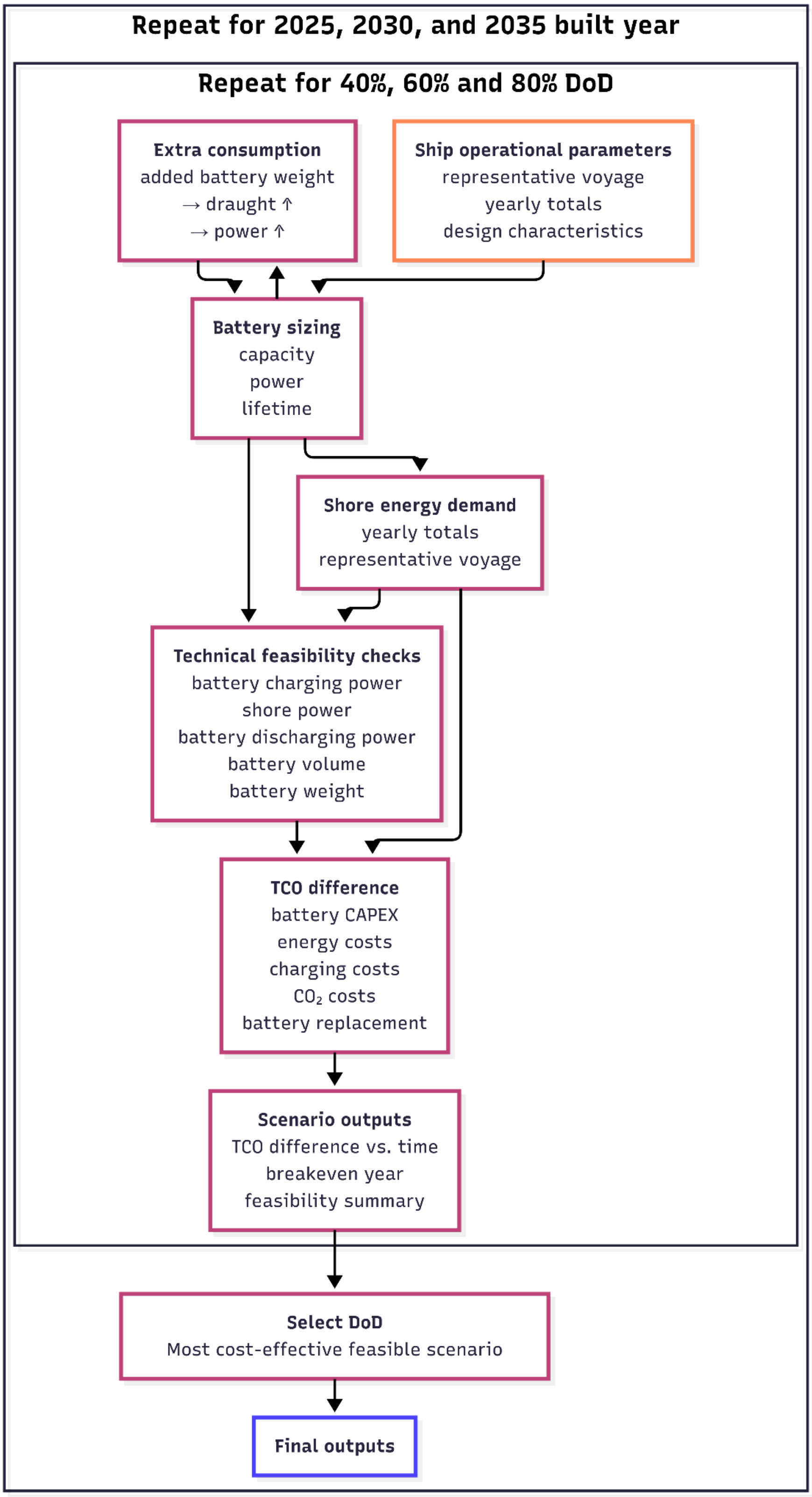
3.4 Battery-electric ferries assessment

3.4.1 General approach

The procedure we followed to evaluate electric ferries' potential to decarbonise the European ferry fleet is outlined in the figure below.

For each eligible conventional ferry of the current European fleet, we modeled a battery-electric ferry to be built in 2025, 2030 or 2035. We assessed three battery depths of discharge (DoD): 40%, 60% and 80% DoD. This ensures the battery capacity of each ship is tailored to its use case. As explained in section 3.2., we extracted operational parameters for each ship.

We sized batteries based on voyage energy needs and DoD, accounting for extra consumption due to battery weight. We also computed yearly energy needs. These parameters allowed us to calculate the TCO difference between the electric and conventional ferries. We verified technical feasibility by checking battery charging power, shore charging power, battery discharging power, volume and weight constraints. Finally, we selected the most cost-effective feasible solution among studied DoDs.



Repeat for 2025, 2030, and 2035 built year
Repeat for 40%, 60% and 80% DoD
Extra consumption
added battery weight
→ draught ↑
→ power ↑
Ship operational parameters
representative voyage
yearly totals
design characteristics
Battery sizing
capacity
power
lifetime
Shore energy demand
yearly totals
representative voyage
Technical feasibility checks
battery charging power
shore power
battery discharging power
battery volume
battery weight
TCO difference
battery CAPEX
energy costs
charging costs
CO₂ costs
battery replacement
Scenario outputs
TCO difference vs. time
breakeven year
feasibility summary
Select DoD
Most cost-effective feasible scenario
Final outputs

3.4.2 Battery pack characteristics

The following table summarizes the battery pack characteristics we used in the analysis. Prices, energy densities, C-rates, and lifetimes are from industry sources and adjusted conservatively to reflect current and future marine battery technology.

Year	Price (€/kWh)	Volumetric density (Wh/L)	Gravimetric density (Wh/kg)	Continuous charge C-rate	Peak discharge C-rate
2025	300	242	161	1	3
2030	102	339	225	1.5	3
2035	70	600	333	2	3
2040	66	Not applicable			
2045	66				
2050	66				
2055	66				
2060	66				
2065	66				

Table 14: Assumed battery pack characteristics by build year. Price in 2025 €

Battery prices

The current (2025) marine battery pack price of €300/kWh is informed by discussions with battery suppliers. This is roughly three times the current average lithium-ion battery pack cost, per BNEF. The price gap is mainly due to limited production capacity and high certification costs. However, in the long term, there is no structural reason for marine batteries to remain significantly more expensive than automotive or grid batteries. The increase in cost due to different packaging, safety and sizing requirements should remain marginal. To forecast future marine battery prices, we therefore used BNEF's price outlook with a 5-year delay, applying a floor of 120% of BNEF's 2035 price to account for marine-specific requirements.

Energy densities

We assumed NMC (Nickel Manganese Cobalt) batteries for 2025 and 2030, as they are widely used in transport and proven in vessels like the e-ferry Ellen. For 2035, we assumed solid-state batteries, which offer better energy density, longer lifespans, higher C-ratings, and lower thermal runaway risk compared to NMC. Although solid-state technology remains costly and unlikely for near-term maritime adoption, we estimate deployment by 2035.

For 2025, we used energy densities from Kaptein NMC Compass Core marine batteries, the lower cost variant of the Kaptein NMC Compass series commercialised by TESVOLT OCEAN. Values are taken at string level, accounting for space loss from the power distribution unit. We've assumed these densities are realised at the ship level. Actual installations require additional space for battery room arrangements and add-ons, but this is partially offset by reduced engine room size in electric vessels.

The 2030 gravimetric density corresponds to today's high-end NMC cell densities, i.e. ~300 Wh/kg. We used a packing fraction of 0.75, same as today's marine battery packs. Volumetric density is derived using the same ratio to gravimetric density as in 2025. This approach is conservative given reported values as high as 600-800 Wh/L.

For 2035, we assumed all-solid-state battery densities currently in pilot production, with volumetric densities around 600 Wh/L and a ratio of Wh/kg to Wh/L of 1.8. We used the same packing fraction of 0.75.

C-rates

Battery cycle lifetime degrades with higher C-rates, so we used 1C charging rates in 2025. Peak discharge C-rate is higher because it is not meant to be sustained for prolonged periods. Our reference module supports up to 4C/4C with liquid cooling. A wide array of batteries already exists with tradeoffs between C-rates, energy densities and lifetime; the actual selection will depend on the particular operational characteristics of each ferry. This and expected improvements in battery technology justify higher C-rates in 1.5C and 2C in 2030 and 2035, respectively.

Lifetime

Life expectancy	Cycle lifetime (40% DoD)	Cycle lifetime (60% DoD)	Cycle lifetime (80% DoD)
15 years	12,000	9000	6000

Table 15: Assumed lifetime of marine batteries in cycles by Depths of Discharge (DoD).

The reference module used for 2025 lasts 6000 cycles at 80% DoD and 1C/1C, and higher values exist today. Characterisation data for other DoDs is scarce. We chose conservative values informed by the "*2022 Grid Energy Storage Technology Cost and Performance Assessment*" report from the US department of energy, which shows there's great potential for NMC battery cycle lifetime to increase at lower DoDs. We held lifetime constant across future years given the wide spectrum of reported cycle lifetimes for future cell technologies. In addition to cycle lifetime, we capped battery calendar life at 15 years in accordance with the literature.

3.4.3 Battery sizing and energy calculations

We sized battery capacity based on representative voyage energy requirements and studied DoD. We used the following energy efficiency assumptions from the e-ferry Ellen report:

- Shore-to-hotel energy efficiency: 0.92
- Shore-to-battery energy efficiency: 0.92
- Battery-to-consumer energy efficiency: 0.92

We estimated increased energy demand due to battery weight using the Admiralty formula for power increase and a water plane displacement formula for draught increase. We used a ship water plane coefficient of 0.8 and a sea water density of 1.026 t/m^3. We calculated the weight difference as battery weight minus voyage fuel weight plus a 20% margin.

3.4.4 TCO comparison

We computed TCO differences between battery and conventional ferries in 2025 €, net present value terms, accounting for:

- Battery CAPEX
- Electricity costs
- Charging infrastructure costs
- FuelEU compliant fuel mix costs
- ETS costs

We assumed the variation of the following cost components to be equal or negligible for electric and conventional ferries:

- Ship construction, excluding battery: engines represent a small portion of total costs and electric motors are expected to be cheaper than conventional engines, allowing us to consider battery capital costs as additional to ship newbuild capital costs.
- Engines and components replacement (e.g. battery management system): given the lower cost of electric propulsion systems, the additional costs are deemed negligible.
- Labour and maintenance: due the simpler operation and maintenance of electric motors, moderate savings are expected but are excluded for simplification.
- Insurance, marketing, overhead, etc: we identified no reason to assume major differences in these cost categories
- Back-up diesel generator: although some ferries are likely to install back-up diesel generators with battery-electric systems, their impact on the overall economics was

assumed to be negligible. Additionally, several ferries such as MF Ampere and e-ferry Ellen have demonstrated years-long operation without the need of a back-up generator.

The main parameters used for the TCO calculation are given in the table below. Where necessary, prices were converted to 2025 €.

Parameter	Value	Source/Note
Ferry lifetime (years)	30	E-ferry Ellen report
Discount rate	7%	Based onto MMMZCS study on battery-powered vessels and EMSA study on ammonia
Electricity prices (€)	Various	Average of 2024 grid electricity prices for non-household consumers by country and consumption band, assuming ferries as only consumers. Prices without VAT. UK prices and non-EU prices from other sources. Constant over time.
Levelised cost of charging infrastructure (€/MWh)	50	Chosen as a reasonable estimate based on direct and back-calculated study results. Constant over time. Available study results and public information provide values of €26, €30, €60 and €67/MWh.
FuelEU-compliant fuel mix price (€/t)	Various	See section 3.3.
ETS price (€)	Various	BNEF EU ETS Carbon Pricing Model 1.2. Evolves over time.

Table 16: Key parameters and sources for calculating battery-electric TCO. Price in 2025 €

Following current trends and expectations, and given the long time horizon considered, we assumed electricity prices stay at the current price levels in the future. We used average national grid prices by consumption band from Eurostat between 2024 S1 to 2025 S1 2015-2019 for EEA countries. For the UK, prices are averaged for the year 2024 only, using the same bands as Eurostat. For Morocco, we use one single consumption price, averaged for the year 2024 only.

We kept them constant over time to avoid unreliable predictions. Two price scenarios were studied:

- Excluding all electricity taxes and network charges
- Excluding VAT and recoverable taxes only

We assumed that VAT and recoverable taxes are indeed recovered by ferry operators.

Electricity prices are based on the individual consumption of each ferry but, in reality, port agreements and aggregated demand may secure lower rates and hedge against electricity spot markets. On the other hand we did not assume any premium charged by ports on grid electricity prices.

We assumed battery replacement upon reaching maximum cycle or calendar lifetime, whichever comes first. Replacement costs correspond to battery prices in that year, using linear interpolation. We assumed no residual value for retired batteries as their second life is still highly uncertain.

We assumed the ETS to cover ships of more than 5000 GT from 2025 and ships of more than 400 GT from 2030. Likewise, FuelEU maritime intensity targets cover ships of more than 5000 GT from 2025 and ships of more than 400 GT from 2030.

3.4.5 Technical feasibility checks

We tested the technical feasibility of each electric ferries against five criteria:

- Battery charging power
- Shore supply power
- Battery peak discharging power
- Battery volume
- Battery weight

We considered a ship feasible if all five criteria were met. In practice, there is margin in ship design, technological, and operational choices to accommodate more electric ships than our analysis yielded.

Battery charging power

We checked whether maximum battery charging power exceeded requirements. We derived maximum battery charging power from battery capacity and charging C-rate. We determined battery charging power requirement based on the schedule of the representative route, assuming no change compared to the conventional ferry. We classified ferries schedules in two groups:

1. Mixed stop schedule: several short stops separated by one longer stop, typically overnight, as illustrated in the following figure from e-ferry Ellen slide deck. Long stops allow for slow charging until full capacity, while short stops provide faster top-ups. We

assumed charging rates of 0.5C and 1C respectively, and minimum state-of-charge of 20% for reserve capacity and to preserve battery lifetime. We considered this schedule applicable to ferries whose mean number of short stops between long stops is between 3 and 20. This reduces maximum charging power requirement compared to full recharge at every stop.

2. Identical stop schedule: for other ships, we assumed full recharge at every stop.

This approach is conservative, as operators will likely modify schedules to fit the requirements of operating using battery powered vessels. This would however have some impact on ferries' business case and is difficult to project without detailed operational data.

Shore supply power

We verified that requirements from battery charging and hotel load demand were lower than maximum shore supply power. We assumed a maximum charger power of 30 MW for TEN-T ports and 15 MW for others. This is a simplified assumption; real values depend on grid connection, specific demand, and local capacity. A precise mapping of ports maximum power supply is out of the scope of this study.

Battery peak discharging power

We checked that battery peak discharging power, calculated as battery capacity times peak discharging C-rate, was above peak power requirements, extracted from our in-house model and adjusted for power increase due to battery weight and efficiency losses.

Battery volume

We verified that battery volume was smaller than that of conventional ferry fuel capacity. Fuel capacity for each ship came from Clarksons WFR or IHS CSD, either directly or from a nearest neighbour regression when values were missing.

The comparison omits:

- The fuel tank and battery overhead space
- The engine room reduction expected for battery vessels compared to conventional vessels
- the more flexible configuration of battery-electric systems within the ship since they do not need to be arranged around a central drive shaft

The net effect of these simplifications was deemed negligible compared to battery volume.

Battery weight

We only accepted draught increases due to battery weight below 10% of the average representative voyage draught, in order to preserve the stability of the ship. In the absence of scantling draught data for each vessel, this provided a reasonable estimate of weight increase limit. In reality, batteries may be able to replace ballast used in conventional ships, offering extra margin.

3.4.6 Battery parameter optimisation

We modeled the requisite improvements in specific battery parameters to maximize the technical and economic feasibility of battery-electric propulsion. The objective of this analysis was to explore the technological advancements necessary to maximize feasibility, rather than to evaluate a realistic deployment scenario. Our analysis focused on three key variables:

- Battery energy density, measured in Wh/kg
- Battery volumetric density, measured in Wh/L
- Battery C-rating

We anticipated that increases in these parameters would expand the proportion of technically feasible vessels by constraining the volume and mass of onboard battery systems. Furthermore, elevated C-ratings enable more vessels to recharge during brief port calls and potentially permit the use of smaller battery configurations, thereby reducing capital expenditure (CAPEX).

We employed a grid search methodology to identify optimal parameter values that maximize the proportion of eligible vessels. Minimum values for each parameter were set equal to current 2025 specifications, while maximum bounds were established at ten times these baseline values. We generated evenly distributed intermediate values within these ranges as model inputs, systematically evaluated all parameter combinations, and identified those yielding maximal feasibility outcomes.

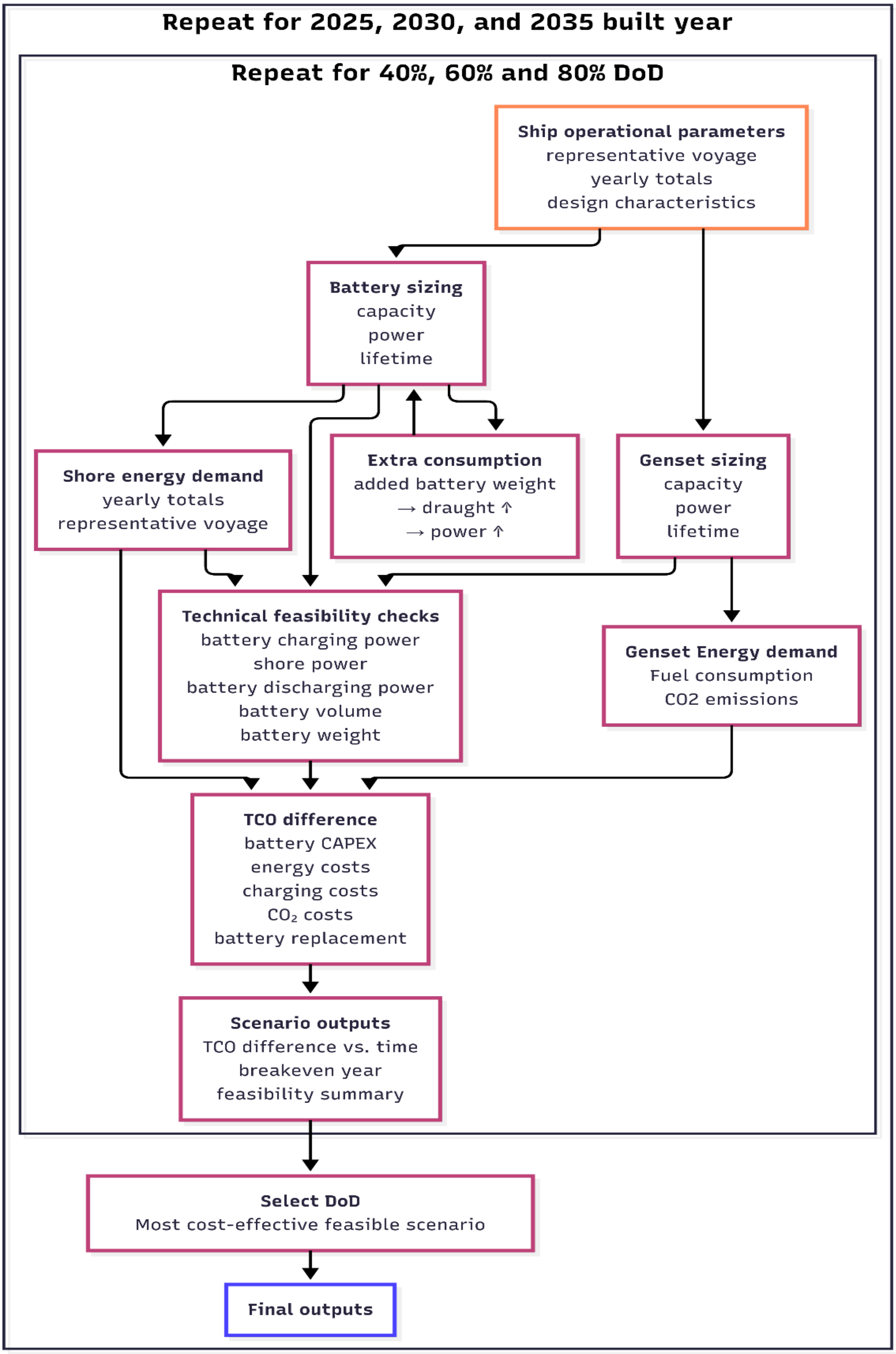
3.5 Hybrid-electric ferries assessment

3.5.1 General approach

We modelled hybrid ferries under a "range extender" model (also known as a series hybrid), in which hybrid ferries operate with a battery and a generator (genset) to produce electricity. We follow the model presented by Guarnieri et al for hybrid vessels, but we made some simplifications to accommodate the wide range of ferries we examine. Under this model, when in operation, ferries draw first from their battery. Once the battery reaches its depth of discharge, the generator is activated at a constant load to power the vessel. Energy in excess of what the vessel requires is used to recharge the battery. Once the vessel returns to berth, the battery is recharged by connecting to the grid. In addition, at berth, all power required by the vessel is provided by OPS connections. In the same manner as in 3.4.5, vessels that exhibit a pattern of short stops followed by a longer rest time can be recharged more slowly and fully during long stops, and more quickly but partially during short stops. For vessels that exhibit no such pattern, we assumed that they were fully recharged at each stop.

Hybrid models have one important advantage over fully electric vessels: because they can be recharged while operating, a hybrid ferry does not face the same charging constraints in terms of energy required to recharge the battery. Moreover, they can provide sizable reductions in emissions and energy costs compared to conventional diesel vessels for the transport of passengers, as shown by Miretti et al and Bennabi et al.

The procedure we followed to evaluate hybrid ferries' potential to decarbonize the European ferry fleet is outlined in the figure below. We tested eligibility based on the same parameters outlined in 3.4.1.


Repeat for 2025, 2030, and 2035 built year
Repeat for 40%, 60% and 80% DoD
Ship operational parameters
representative voyage
yearly totals
design characteristics
Battery sizing
capacity
power
lifetime
Shore energy demand
yearly totals
representative voyage
Extra consumption
added battery weight
→ draught ↑
→ power ↑
Genset sizing
capacity
power
lifetime
Technical feasibility checks
battery charging power
shore power
battery discharging power
battery volume
battery weight
Genset Energy demand
Fuel consumption
CO2 emissions
TCO difference
battery CAPEX
energy costs
charging costs
CO₂ costs
battery replacement
Scenario outputs
TCO difference vs. time
breakeven year
feasibility summary
Select DoD
Most cost-effective feasible scenario
Final outputs

3.5.2 Battery and engine sizing and energy calculations

For the battery part of the hybrid vessel, we assumed the same characteristics as in 3.4.2 Furthermore, we used the same parameters as in part 3.4.3 to model the operation of the battery.

To size the battery, we maximized the energy drawn from the battery during operations while fulfilling all technical feasibility checks. We constrained the energy provided by the battery to be strictly superior to 50% of the energy required during a representative voyage for each ferry, since our goal is for the genset to act as a range extender. For each vessel, we then tested a series of proportions P, representing the proportion of the energy required during a representative voyage drawn from the battery. We tested values of P in increments of 5% for each vessel, and selected the highest value P that allowed the vessel to pass all technical feasibility checks.

A value of P = 1 indicates the vessel is fully powered by the battery, while a value between 50% and 95% indicates that the vessel can operate as a hybrid. If a vessel cannot pass all technical feasibility checks for all tested values of P, we marked the vessel as not suitable to be electrified as a hybrid. The genset must provide the remainder of the energy that is not provided by the battery (equivalent to 1 - P of the energy required during a representative voyage). We assumed that the ship parameters linked to the genset operations were reduced linearly based on the energy proportion provided by the genset. Notably, the engine operating time and fuel tank volume are rescaled by 1 – P.

To set the genset power rating, we calculated two variables:

- The peak power requirement from the vessel on its representative route.
- The power required to produce the energy coming from the genset during operation time. Assuming the engine operates at constant load, we calculated it as

$$P_{req,genset} = E_{genset} / t_{operation}$$

with P the required power rating in MW, E the energy output in MWh and t the time in h during which the genset is operation.

We selected the genset power rating as the largest value between and for each vessel. We then add a 25% safety margin to the power rating to guarantee the vessel can be powered in cases of unforeseen circumstances.

We used additional parameters to model the relation between the generator and the battery based on IMO4GHG and section 3.4.3:

- Genset efficiency: 0.432
- Genset-to-battery efficiency: 0.92
- Genset-to-propeller efficiency: 0.92

3.5.3 TCO comparison

For the battery part, we use the same method, fuel costs, CAPEX and modelling parameters as in 3.4.4 for the TCO comparison. The base case of a conventional diesel ferry complying with FuelEU targets is kept the same as well.

Because of the generator part, hybrid vessels have fuel costs and emission costs. We calculated the total fuel costs based on the energy provided by the generator. In addition, we calculated ETS costs, based on the emissions from the generator. Finally, we defined a FuelEU–compliant fuel mix for each vessel including electricity. In the instances where an energy mix of electricity and diesel is not sufficient to meet FuelEU targets, we assumed that vessels would blend biodiesel in amounts required to meet the targets.

The cost structure for the hybrid vessel is:

$$Cost = E_{elec} * P_{elec} + Q_{fuel} * P_{fuel}$$

Where E_{elec} is the energy delivered from the grid to the battery and to the vessel at berth, and Q_{fuel} is the total amount of the fuel mix in tonnes consumed to operate the generator.

For CAPEX, we assumed that there was no meaningful difference in costs between the generator and diesel ICE CAPEX costs.

3.5.5 Technical feasibility checks

We performed the same technical feasibility checks as in 3.4.5 for the battery, with the difference that the battery is partially charged during operation by the generator, which reduces the charging requirements once at berth.

By construction, the genset is sized to deliver sufficient energy once the battery is discharged.

Additional or modified checks are:

- Fuel availability
- Hybrid system volume
- Energy balance

Fuel availability

We verified that vessels maintained sufficient fuel capacity to supply the energy requirements of the generator set (genset) throughout a representative voyage. Fuel capacity, as defined in Section 3.4.5, was adjusted by a factor of 1 - P, where P represents the proportion of energy supplied by the battery system. We then calculated the maximum power output achievable by the genset if all available fuel were consumed, and confirmed that this capacity met or exceeded the genset energy requirements for the representative voyage.

Hybrid system volume

We verified that the combined volume of the battery and fuel tank did not exceed the volume occupied by the fuel tank in the baseline configuration.

Energy balance

We verified that the annual energy balance was maintained, ensuring that the sum of shore power supplied for battery charging and hotel loads during berth operations, combined with genset-generated energy, was sufficient to meet the vessel's total annual energy demand.

3.6 E-fuels and biofuels assessment

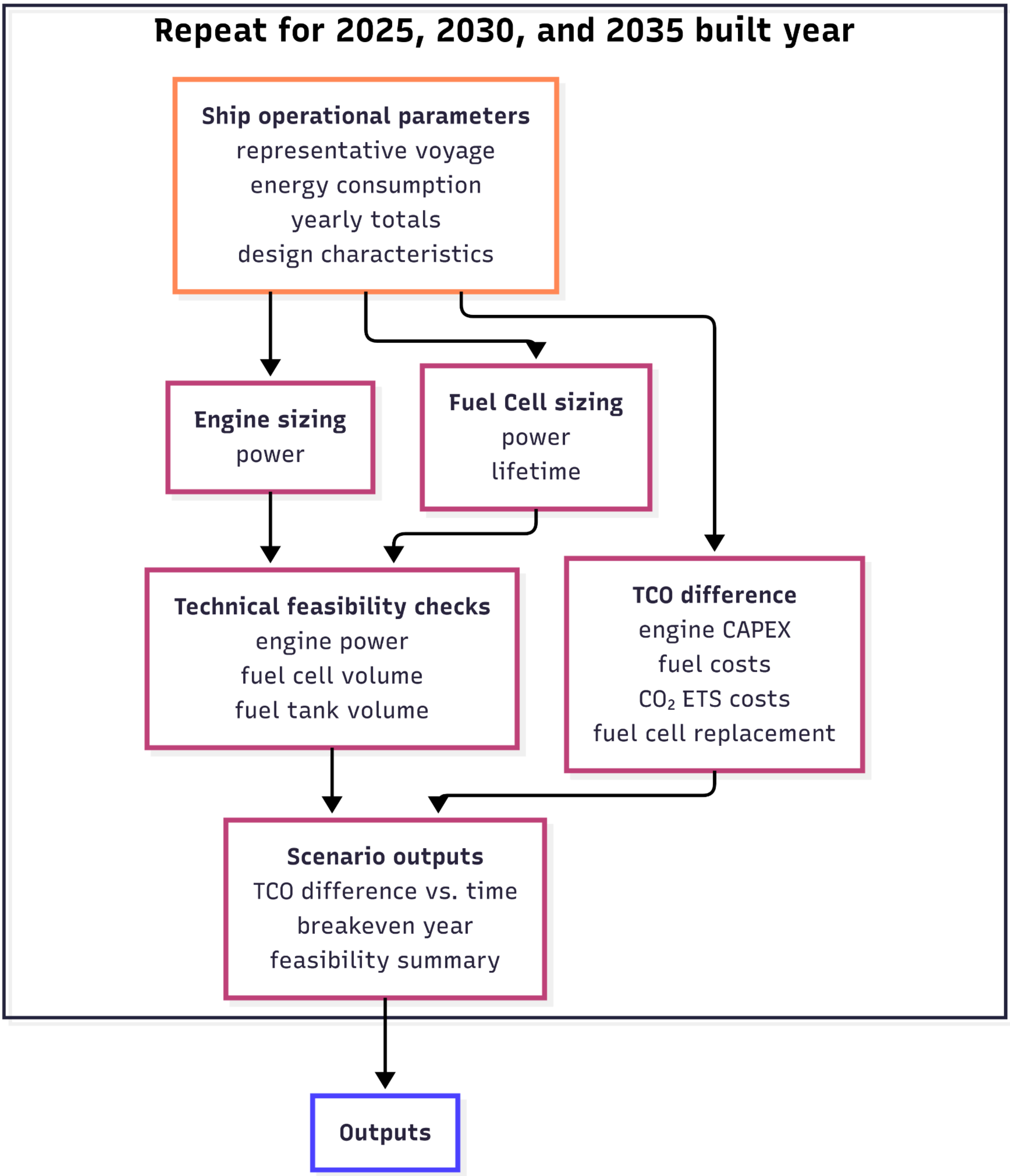
3.6.1 General approach

We evaluated the feasibility for other technologies and fuels and compared the results with battery-electric and hybrid-electric vessels. Depending on the fuel, we assumed the fuels would be used in an internal combustion engine or in a fuel cell. The fuels we selected represent a range of bio- and e-fuels that have received interest to be used as fuels for the maritime sector. The options examined are shown in the table below.

Fuel	Engine Type
e-LH_2	SOFC (Solid Oxide Fuel Cell)
e-ammonia	ICE
e-methanol	ICE
HVO	ICE

Table 17: Alternative fuel engine technologies

The goal of this section is to explore credible alternative options to decarbonise ferries beyond batteries, and assess how they would compare. We assess the fuels following the same method as for battery-electric and hybrid vessels, examining technical feasibility on a representative voyage and economic feasibility over a vessel's lifetime.


Repeat for 2025, 2030, and 2035 built year
Ship operational parameters
representative voyage
energy consumption
yearly totals
design characteristics
Engine sizing
power
Fuel Cell sizing
power
lifetime
Technical feasibility checks
engine power
fuel cell volume
fuel tank volume
TCO difference
engine CAPEX
fuel costs
CO_2 ETS costs
fuel cell replacement
Scenario outputs
TCO difference vs. time
breakeven year
feasibility summary
Outputs

3.6.1 Economic feasibility

We compute TCO differences between alternative fuels and conventional ferries. Economic feasibility is evaluated over the whole 30-year lifetime of ferries.

We examined the following variables:

- Additional CAPEX required for fuel cells and dual fuel ammonia ICE engine versus conventional diesel engines.
  - For methanol, we assumed that dual-fuel methanol ICE engine costs would converge with conventional engines: DNV finds minimal difference in CAPEX between a diesel and methanol vessel. Likewise, EMSA finds that CAPEX differences are very small compared to OPEX differences for methanol.
  - For ammonia, dual-fuel ammonia ICE engine CAPEX are assumed to be constant in time due to the lack of data on future costs.
  - For HVO, we assumed no difference in CAPEX
- Additional CAPEX required for the fuel tank:
  - Hydrogen and ammonia require dedicated onboard tanks and piping systems, and therefore have additional CAPEX to build and install the fuel tank.
  - The cost of storage is assumed to be proportional to the engine's power, following EMSA's approach.
- The difference in fuel costs between alternative fuels and fossil fuels.
- The difference in ETS costs between alternative fuels and fossil fuels.
- The difference in FuelEU Maritime penalties between alternative fuels and fossil fuels.
- We consider that e-fuels are zero-rated for TtW and WtW emissions. HVO is assumed to originate from waste cooking oil, and is zero-rated for TtW emissions covered by the ETS.

In addition to the parameters used for battery-electric ferries, the following parameters are used for the TCO calculation. For e-fuels, we use fuel costs due to the lack of reliable fuel price data. However, costs are likely to go down in the future. Prices for MDO, LNG, FAME , ETS, the discount rate and ferry lifetime are the same as in part 3.4. Likewise, we assume negligible variation in labour and maintenance costs. As in part 3.4, we compare e-fuels and biofuels to a mix of fossil fuels and biofuels, either MDO, HVO and FAME or LNG and biomethane depending on the vessels.

We assumed dual-fuel ICE engines, like diesel ICE engines, will not require to be replaced during the lifetime of the vessel. Indeed, Wang & Wright find that ICEs have an expected lifetime of 30 years, similar to a ferry lifetime. For fuel cells, various numbers are used in the literature: Percic et al find that for ferries, they must be replaced after 20,000 h of use. Kopasz et al forecast that fuel cells could have a lifetime of 25,000 h, with a target of 30,000 h for ferries. Finally, van Veldhuizen et al find lifetime for fuel cells between 30,000 and 90,000 h based on industry information, but not examining specifically fuel cells for the maritime sector. Since at-sea conditions are likely to worsen fuel cell lifetime compared to stationary uses, we assumed a value of 20,000 h.

Mylonopoulos et al use a replacement cost of 50% of CAPEX of a new fuel cell. Other studies on non-shipping applications have estimated that replacement costs represent only 30-40% of the initial CAPEX, with some going suggesting replacement costs as low as 25% of initial CAPEX. We adopted a conservative approach and ultimately used a replacement cost of 50%. No residual value is assumed for the fuel cells.

For fuel cells, we assume an efficiency of 54%, in line with Schreuder et al. Similarly, Elkafas et al assess efficiencies between 35 and 60% for fuel cells produced by the industry, with the majority of fuel cells in the 50-60% range. Wang & Wright find a similar range of 50-60% for SOFC efficiency, supporting that fuel cells commonly require less energy compared to ICE.

Mylonopoulos et al find that we can expect fuel cells to lose up to 15% of their power during their lifetime due to aging, a number corroborated by van Veldhuizen et al who find a degradation within the range of 10-15%. The United State's Department of Energy reports degradation rates on fuel cells from 32% for 20,000 h of use, with a mean degradation value of 16%.We assumed fuel cells must be sized with a 18% safety margin, to still be able to deliver the required power even at the end of their lifetime with a 15% degradation in power. We assume that methanol or ammonia require 5% of MDO as a pilot fuel.

CAPEX - Propulsion system - €/kW		
Year	***Fuel Cell (*van Veldhuizen et al.*)***	***Duel-use ammonia ICE (*EMSA*)***
2025	4780	330
2030	2000	
2035	1250	

Table 18: Investment cost of propulsion systems. Interpolated for 2025. High interval values chosen for 2025 and 2030. For 2035, average of the 2030 interval used.

CAPEX - Storage costs - €/kg		
Fuel	***LH2 (*EMSA)**	***NH3 (*EMSA*)***
Costs	50.31	0.93

Table 19: Investment cost of fuel storage systems.

3.6.2 Technical feasibility

We evaluated the space required to store the various alternative fuels. The space required is calculated for every voyage based on the energy demand and the energy density (in GJ / m^3) of the fuel.

We calculated the available space on the vessel:

- For e-ammonia and e-methanol, we assume the available space is similar to a diesel-powered ship, as the technology requires the same space.
- For liquid hydrogen, fuel cells are more compact than ICE. More space can be used to store fuel in this case. We followed Comer's formula to calculate the volume space available for a LH2-powered vessel, based on the characteristics of a diesel-powered vessel:

$$V_{LH2,\,capacity} = 5 \times V_{ICE} - 2 \times V_{FC} + V_{tank}$$

Where V_{ICE} is the volume taken by the existing ICE, V_{FC} is the volume taken by the fuel cells and V_{tank} is the volume of the existing tank, all expressed in m^3.

Based on formulas outlined by Minnehan & Pratt, ICE and fuel cell volumes are calculated using the engine's power as: .

$$V_{ICE} = \frac{P_{me} - 1906}{54.066} \text{ and } V_{FC} = \frac{P_{me} - 73.331}{55.944}$$

with P_{me} the power of the main engine expressed in kW.

These empirical formulas can yield impossibly small or even negative numbers for hydrogen fuel system volume for vessels with a small engine power. The smallest vessel used to define the empirical formulas above had a total volume of 16 m^3, therefore we use this value as the bottom threshold under which we consider a vessel is not technically able to be powered with LH2. For other fuels, we set a threshold value of 10 m^3.

3.7. Fuel prices

FAME is used exclusively to calculate the base case scenario fuel mix cost. HVO is used both to calculate the base case scenario fuel mix cost, and as a standalone fuel in part 3.6. All the other fuels are used in part 3.6 only.

Fuel prices - €/GJ						
Year	*HVO (Stratas Advisors)*	*FAME (Stratas Advisors)*	*bio-LNG (DNV)*	*e-Methanol (DNV)*	*e-Ammonia (DNV)*	*e-LH2 (DNV)*
2025	40.9	29.8	22.9	64.0	48.6	50.7
2030	43.4	29.8	24.5	56.6	43.0	47.0
2035	46.5	29.8	26.3	53.0	39.6	43.9
2040	49.5	29.8	27.9	49.3	36.2	40.8
2045	52.6	29.8	29.9	45.5	32.6	37.5
2050	55.7	29.8	31.7	41.6	28.9	34.0

Table 20: Fuel prices

Annex 2 - Detailed results

1. Rankings by absolute CO_2 emissions

Rank	Route (ports)	Countries	Ships	Voyages	CO_2 (t)	Average distance sailed (nm)	Average duration (h)
1	Helsinki - Travemuende	FIN - DEU	6	707	300,065	658	30
2	Calais - Dover	FRA - GBR	11	24389	292,133	25	2
3	Helsinki - Tallinn	FIN - EST	9	10109	221,457	47	3
4	Dublin - Holyhead	IRL - GBR	10	5963	192,651	61	3
5	Palma Mallorca - Valencia	ESP - ESP	17	2485	187,595	147	8
6	Barcelona - Civitavecchia	ESP - ITA	5	529	181,694	460	22
7	Napoli - Palermo	ITA - ITA	18	1876	168,247	178	11
8	Golfo Arnaci - Livorno	ITA - ITA	18	1663	158,751	162	10
9	Rostock - Trelleborg	DEU - SWE	12	3859	150,458	95	6
10	Malmoe - Travemünde	SWE - DEU	5	1923	150,139	151	9
11	Kiel - Oslo	DEU - NOR	2	695	147,068	390	20
12	Irakleion - Piraeus	GRC - GRC	14	1489	144,976	189	11
13	Swinoujscie - Ystad	POL - SWE	7	3567	144,584	100	7
14	Ancona - Patra	ITA - GRC	4	499	144,097	527	23
15	Genova - Palermo	ITA - ITA	12	632	138,711	448	23
16	Kiel - Klaipeda	DEU - LTU	4	700	137,972	424	20
17	Barcelona - Palma Mallorca	ESP - ESP	15	2170	128,801	141	8
18	Algeciras - Tanger Med	ESP - MAR	29	19694	123,701	24	2
19	Gdynia - Karlskrona	POL - SWE	4	1656	121,047	182	11
20	Genova - Tunis	ITA - TUN	10	424	120,753	479	25
21	Las Palmas - Santa Cruz	ESP - ESP	12	4199	113,328	53	2
22	Ballygeary - Dunkerque	IRL - FRA	4	457	113,200	501	25
23	Swinoujscie - Trelleborg	POL - SWE	14	2775	112,788	107	7
24	Elleholm - Klaipeda	SWE - LTU	12	1074	111,520	229	14
25	Livorno - Olbia	ITA - ITA	13	954	110,161	172	9
26	Ancona - Igoumenitsa	ITA - GRC	5	543	109,080	416	20
27	Belfast - Cairnryan	GBR - GBR	5	4034	108,091	42	2
28	Belfast - Birkenhead	GBR - GBR	2	1410	105,517	151	8
29	Dover - Dunkerque	GBR - FRA	5	6959	99,201	37	2
30	Arhus - Sjaellands Odde	DNK - DNK	4	7764	99,196	39	1
31	Hull - Rotterdam	GBR - NLD	2	708	97,235	220	12

32	Marseille - Tunis	FRA - TUN	5	273	94,628	486	25
33	Hirtshals - Larvik	DNK - NOR	2	1218	92,865	88	4
34	Amsterdam - Tyne	NLD - GBR	2	661	92,471	286	17
35	Harwich - Rotterdam	GBR - NLD	4	1491	91,332	119	8
36	Travemuende - Vec-Liepaja	DEU - LVA	4	547	89,342	420	22
37	Piraeus - Port Of Paros	GRC - GRC	14	1954	84,557	102	4
38	Hirtshals - Kristiansand	DNK - NOR	5	2372	84,096	79	3
39	Genova - Porto Torres	ITA - ITA	12	702	83,450	224	16
40	Ouistreham - Portsmouth	FRA - GBR	3	1974	82,657	109	6
41	Barcelona - Tanger Med	ESP - MAR	10	337	82,224	576	31
42	Alger - Marseille	DZA - FRA	7	272	81,936	414	26
43	Travemuende - Trelleborg	DEU - SWE	9	1701	81,390	140	9
44	Barcelona - Ibiza	ESP - ESP	15	1283	81,280	162	9
45	Helsinki - Stockholm	FIN - SWE	4	670	81,080	288	17
46	Cherbourg - Dublin	FRA - IRL	3	395	80,398	392	19
47	Ballygeary - Cherbourg	IRL - FRA	5	503	80,253	331	18
48	Bastia - Marseille	FRA - FRA	7	722	80,136	229	16
49	Bari - Patra	ITA - GRC	3	483	78,841	319	16
50	Livorno - Palermo	ITA - ITA	2	306	76,278	384	20

21: Ranking of routes by CO_2 emissions, based on total CO_2 emitted by all ships travelling.

Rank	Country	Ships	Voyages	Share of domestic voyages (%)	Voyage and port CO_2 (t)	Share of domestic and port CO_2 (t)
1	Italy	210	231,695	97.5%	2,372,319	75%
2	Spain	126	80,667	80.1%	1,769,088	78%
3	Greece	177	188,840	98.6%	1,541,326	82%
4	United Kingdom	108	175,484	85.8%	1,204,772	51%
5	France	112	41,457	48.7%	1,148,122	47%
6	Sweden	98	106,033	60.6%	1,008,529	25%
7	Germany	83	71,065	56.7%	660,750	16%
8	Norway	222	1,176,275	99.6%	656,784	67%
9	Finland	47	76,200	87.0%	536,626	25%
10	Denmark	77	182,069	72.1%	482,524	58%
11	Ireland	25	5,905	6.9%	336,782	12%
12	Poland	42	5,688	24.0%	239,848	21%
13	Netherlands	27	16,465	82.7%	205,334	24%
14	Estonia	23	17,447	66.6%	196,958	29%
15	Croatia	56	79,681	99.7%	184,672	95%

16	Lithuania	18	1,016	0.0%	143,392	10%
17	Latvia	8	734	0.1%	75,409	12%
18	Malta	14	38,036	98.5%	44,236	78%
19	Portugal	15	36,385	100.0%	37,232	99%
20	Cyprus	8	179	1.7%	18,563	24%

Table 22: Ranking of countries by CO_2 *emissions.*

Rank	Port	Country	Ships	Voyages	Voyage and port CO_2 (t)
1	Barcelona	Spain	42	3244	327,924
2	Piraeus	Greece	86	9597	318,748
3	Helsinki	Finland	17	5957	316,696
4	Travemuende	Germany	21	2620	311,542
5	Genova	Italy	47	1631	292,435
6	Marseille	France	34	1501	252,942
7	Livorno	Italy	48	2694	249,920
8	Palermo	Italy	34	2056	230,149
9	Civitavecchia	Italy	26	1302	213,700
10	Trelleborg	Sweden	18	4978	203,590
11	Dover	United Kingdom	13	15681	187,039
12	Ancona	Italy	12	970	186,102
13	Palma Mallorca	Spain	23	2937	177,785
14	Kiel	Germany	9	1062	173,279
15	Ballygeary	Ireland	13	1820	162,674
16	Patra	Greece	14	913	161,065
17	Dublin	Ireland	12	3624	160,598
18	Calais	France	14	12226	154,989
19	Napoli	Italy	57	14408	146,617
20	Klaipeda	Lithuania	18	1016	143,392
21	Tallinn	Estonia	13	5242	138,350
22	Igoumenitsa	Greece	30	3844	136,952
23	Las Palmas De Gran Canaria	Spain	19	4343	133,471
24	Rotterdam	Netherlands	15	1467	132,353
25	Swinoujscie	Poland	21	3183	131,827
26	Valencia	Spain	21	2028	130,092
27	Portsmouth	United Kingdom	16	15917	126,846
28	Stockholm	Sweden	10	1822	123,772
29	Algeciras	Spain	39	16745	115,277
30	Santa Cruz De Tenerife	Spain	18	4755	114,839
31	Nynashamn	Sweden	10	1727	114,667
32	Dunkerque	France	17	3721	113,258

33	Belfast	United Kingdom	15	2737	110,929
34	Olbia	Italy	26	1042	110,459
35	Bastia	France	28	1673	109,446
36	Ibiza	Spain	32	8269	107,251
37	Oslo	Norway	12	22430	106,439
38	Golfo Arnaci	Italy	32	1112	105,331
39	Bari	Italy	14	1127	102,717
40	Hirtshals	Denmark	6	2017	98,570
41	Ystad	Sweden	15	3677	97,567
42	Holyhead	United Kingdom	11	2988	96,194
43	Cherbourg-Octeville	France	14	691	87,405
44	Toulon	France	15	890	84,492
45	Irakleion	Greece	19	1198	83,788
46	Malmoe	Sweden	5	966	79,166
47	Rostock	Germany	16	5348	78,932
48	Bjorko	Sweden	10	1567	75,308
49	Frederikshavn	Denmark	18	3450	74,036
50	Goteborg	Sweden	9	1837	68,620

Table 23: Ranking of ports by CO_2 *emissions.*

2. Techno-economic feasibility of highest-emitting routes

All vessels economically feasible are also tech feasible.

		2025 Build				2035 Build			
		Battery Ship		Hybrid Ship		Battery Ship		Hybrid Ship	
ROUTE	No. ships	Tech. feasible	Tech. & Econ. Feasible	Tech. feasible	Tech. & Econ. Feasible	Tech. feasible	Tech. & Econ. Feasible	Tech. feasible	Tech. & Econ. Feasible
Helsinki - Travemünde	3	0%	0%	0%	0%	0%	0%	0%	0%
Calais - Dover	9	100%	0%	0%	0%	100%	0%	0%	0%
Helsinki - Tallinn	6	17%	0%	83%	83%	17%	17%	83%	83%
Dublin - Holyhead	4	50%	0%	50%	0%	50%	0%	50%	0%
Palma Mallorca - Valencia	3	33%	0%	67%	67%	33%	33%	67%	67%
Barcelona - Civitavecchia	2	0%	0%	0%	0%	0%	0%	0%	0%
Golfo Aranci - Livorno	1	0%	0%	0%	0%	0%	0%	0%	0%

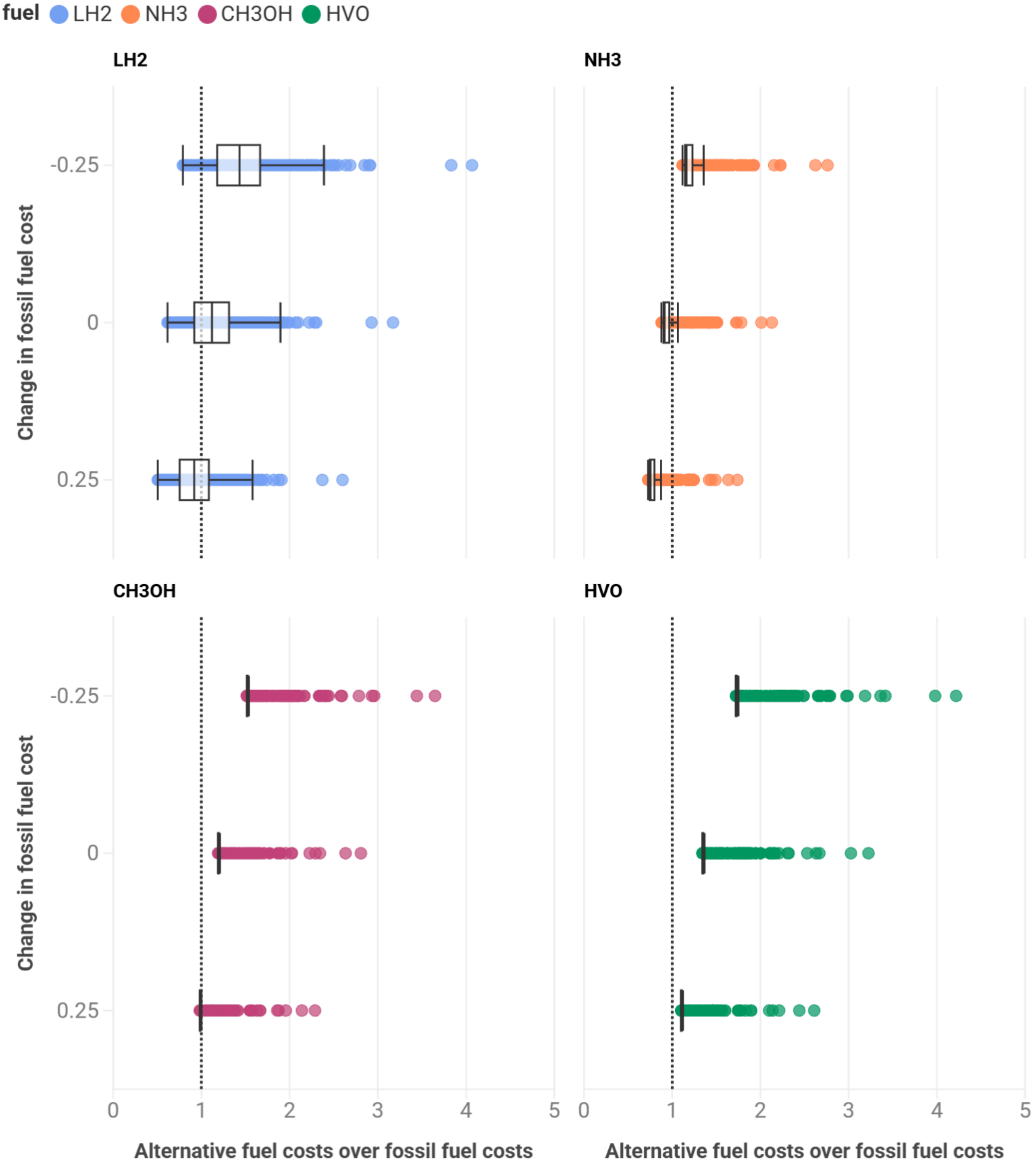
Napoli - Palermo	5	100%	0%	0%	0%	100%	100%	0%	0%
Rostock - Trelleborg	2	0%	0%	100%	100%	0%	0%	100%	100%
Malmö - Travemünde	4	20%	0%	80%	20%	20%	20%	80%	80%
Kiel - Oslo	2	0%	0%	0%	0%	0%	0%	0%	0%
Heraklion - Piraeus	4	100%	0%	0%	0%	100%	100%	0%	0%
Swinoujscie - Ystad	6	100%	50%	0%	0%	100%	100%	0%	0%
Ancona - Patras	2	0%	0%	0%	0%	0%	0%	0%	0%
Kiel - Klaipeda	2	0%	0%	0%	0%	0%	0%	0%	0%
Genova - Palermo	2	0%	0%	0%	0%	0%	0%	0%	0%
Barcelona - Palma Mallorca	5	40%	20%	20%	20%	40%	40%	20%	20%
Algeciras - Tanger Med	14	86%	64%	0%	0%	86%	86%	0%	0%
Gdynia - Karlskrona	3	0%	0%	0%	0%	0%	0%	0%	0%
Genova - Tunis	2	0%	0%	0%	0%	0%	0%	0%	0%

Table 24: Feasibility of battery-electric and hybrid ferries on most-critical routes.

3. Sensitivity results

Testing price fluctuations in a conventional fuel mix of VLFO and HVO reveals that the hydrogen-derived e-fuels become competitive under very favorable conditions. Starting in 2035, ammonia and e-hydrogen have several vessels economically competitive against a FuelEU-compliant fuel mix. For Ammonia, the results show less variation and a slight cost-advantage under the base case. Due to the e-fuel results having low variability between vessels, variations in the input factors lead to limited swings in feasibility. An increase of 25 % in the cost of a conventional fuel mix leads to only a few percentage points higher feasibility for ammonia and e-hydrogen.

Alternative fuel results are relatively insensitive to changes in fossil fuel costs



Source: T&E (2025) • Start year of 2035. Variation in feasibility for alternative fuels based on changes in the fossil fuel mix costs.

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