NATIONAL TECHNICAL UNIVERSITY OF ATHENS

SCHOOL OF NAVAL ARCHITECTURE AND MARINE ENGINEERING
LABORATORY FOR MARITIME TRANSPORT

Nuclear Power and Greek Shipping

Strategic Opportunities, Commercial Benefits and Regulatory Challenges



Athens, November 2026

Nuclear Power and Greek Shipping

Strategic Opportunities, Commercial Benefits and Regulatory Challenges

A study performed
by

Dimitrios V. Lyridis
Professor, School of Naval Architecture and Marine Engineering
Director, Laboratory for Maritime Transport

Dimitrios M. Korres
Chemical Engineer, Ph.D., Senior Research Associate

George Dimopoulos
Associate Professor, School of Naval Architecture and Marine Engineering

Contents

Contents i

List of Figures iii

List of Tables iv

Abbreviations v

Extended Summary 1

1. Introduction – Why should Greece care early 4

2. Greek Shipping and the Decarbonization Challenge 7

2.1. The Greek-owned fleet 7

2.2. Economic weight 7

2.3. Fleet composition and market exposure 8

2.4. Fuel consumption by vessel category 9

2.5. Exposure to carbon pricing 11

3. Nuclear Power as a Maritime Energy Option 12

3.1. How a nuclear ship works 12

3.2. Experience so far 14

3.3. Reactor technologies 14

3.4. Small modular reactors and power levels 17

3.5. Floating nuclear power plants 17

3.6. Current projects and actors 17

4. Benefits and Challenges for Greek Shipping 19

4.1. Economic Benefits 19

4.1.1. Fuel Cost Calculations 19

4.1.2. Emissions Cost Calculations 23

4.1.3. CAPEX 29

4.1.4. Decommissioning 31

4.1.5. Lifecycle perspective 31

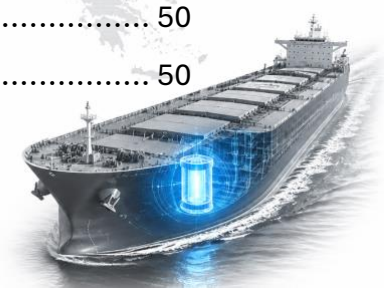
4.1.6. Indicative scaling to other ship types 35

4.2. Operational Benefits 36

4.2.1. Higher speed and more voyages 37



4.2.2. Refuling intervals 38
4.2.3. Avoided bunkering and fuel-supply risk 38
4.2.4. Cargo capacity 38
4.2.5. Power for ports 38
4.3. Strategic Benefits 39
4.3.1. Shaping the international rules 39
4.3.2. Know-how, universities and research 39
4.3.3. Shipyards 39
4.3.4. Port-energy business models 40
4.3.5. Energy security 40
4.3.6. Positioning 40
4.4. Challenges 40
4.4.1. Licensing framework 41
4.4.2. Port access and emergency planning 43
4.4.3. Spent fuel and radioactive waste 44
4.4.4. Safeguards and non-proliferation 44
4.4.5. Security and piracy 45
4.4.6. Insurance 45
4.4.7. Liability 45
4.4.8. Public acceptance 45
4.4.9. Crew and training 46
4.4.10. Fuel supply chain 46
4.4.11. Financing and business model 46
5. Benefits for Greek Ports and Maritime Infrastructure 47
5.1. Shore power and floating nuclear power plants 47
5.2. Nuclear energy for marine fuel production 47
5.3. Hosting nuclear ships 48
5.3.1. Environmental radiation monitoring and emergency preparedness 48
5.4. Short-sea and coastal shipping 49
6. Conclusions – Roadmap 50
6.1. Roadmap 50
6.1.1. Phase 1: Knowledge and monitoring, 2026–2027 50



6.1.2. Phase 2: Regulatory preparation, 2027–2030 51
6.1.3. Phase 3: Port and shipyard feasibility studies, 2028–2032 51
6.1.4. Phase 4: Participation in international pilots, 2030–2035 51
6.1.5. Phase 5: Commercial adoption, post-2035 52

List of Figures

Figure 1: Key regulatory milestones for maritime nuclear power and shipping decarbonisation 5
Figure 2: Greek-owned share of the world fleet by segment, as a percentage of world deadweight tonnage (ships above 1,000 gt; January 2026 data). Source: UGS Annual Report 2025–2026, Table 1 (UGS calculations based on S&P Global Market Intelligence data). 7
Figure 3: Energy density in the case study: annual quantities that deliver the same useful ship energy (50% engine efficiency for chemical fuels, 40% conversion efficiency for the nuclear plant). 12
Figure 4: Illustrative nuclear-electric system using a steam Rankine cycle. 13
Figure 5: Reactor families considered for maritime use, shown schematically. 16
Figure 6: Sensitivity of the 25-year EU ETS cost (100% EU scope, undiscounted) to a constant EUA price. 25
Figure 7: FuelEU Maritime GHG-intensity limits compared with the well-to-wake intensities calculated in this report (GWPs 25/298). 27
Figure 8: Capesize case: composition of indicative undiscounted 25-year costs (midpoints; range bars show scenario bounds, not statistical confidence intervals). .. 33
Figure 9: Break-even nuclear newbuilding CAPEX versus HFO as a function of the discount rate, compared with the assumed USD 300–500 million range. Source: calculations in this chapter. 35
Figure 10: Illustrative (conceptual) arrangement of a nuclear propulsion plant in a Capesize bulk carrier. 37
Figure 11: Main barriers to the use of nuclear power in Greek shipping. 41
Figure 12: Regulatory responsibilities and approval framework for a nuclear-powered merchant ship. 42
Figure 13: "Pink Corridor" (illustrative) between the ports of Felixstowe (UK) and Charleston (USA).[80] 44



List of Tables

Table 1: Composition of the Greek-Controlled Fleet by Vessel Type and Typical Market Exposure[1] 8
Table 2: Indicative relevance of nuclear propulsion by ship type. 9
Table 3: Average activity and fuel consumption per ship in 2018, by ship type and size (Fourth IMO GHG Study 2020, Table 35). 10
Table 4: Reactor technologies considered for maritime use, in plain terms (temperatures and pressures indicative). 15
Table 5: Comparison of various conventional fuel options 19
Table 6: Conventional Fuel cost comparison over 25 years..... 20
Table 7: Rough advanced reactor fuel estimate 22
Table 8: 25 year nuclear fuel cost estimation 23
Table 9: EU ETS vs. FuelEU mechanisms..... 24
Table 10: Reference list of emission factors 24
Table 11: Emissions cost for the EU ETS over 25 years..... 26
Table 12: Decreasing FuelEU emissions limits 27
Table 13: FuelEU penalty table by period — 100% EU scope (unmultiplied penalty benchmark; last column: repeated-deficit scenario with the Article 23(2) multiplier) .. 28
Table 14: Combined ETS and FuelEU costs (unmultiplied penalty benchmark and repeated-deficit scenario)..... 29
Table 15: CAPEX Estimations for a new Capesize / Newcastlemax-size bulk carrier ordered now..... 29
Table 16: Indicative decommissioning costs for the various fuel options 31
Table 17: Capesize case: indicative undiscounted 25-year cost components (USD million). 32
Table 18: Capesize case: present value of the Table 17 cost components at an 8% real discount rate (USD million). 34
Table 19: Capesize case: break-even nuclear newbuilding CAPEX versus HFO in present-value terms (USD million; midpoint values for the other cost components).... 34
Table 20: Indicative scaling of the case study to other ship types (25-year values; regulatory costs at 100% EU scope). 36



Abbreviations

ABS	American Bureau of Shipping
ATLAS	Atomic Technology Licensed for Applications at Sea (IAEA initiative)
CAPEX	Capital expenditure
DWT	Deadweight tonnage
EEAE	Greek Atomic Energy Commission
EMSA	European Maritime Safety Agency
EPZ	Emergency planning zone
ETS	Emissions Trading System (EU)
EUA	EU Allowance (one ton of CO_2eq under the EU ETS)
FHR	Fluoride salt-cooled high-temperature reactor
FNPP	Floating nuclear power plant
GHG	Greenhouse gas
GT	Gross tonnage
HALEU	High-assay low-enriched uranium (5–20% U-235)
HFO	Heavy fuel oil
HTGR	High-temperature gas-cooled reactor
IAEA	International Atomic Energy Agency
IMO	International Maritime Organization
ISWG-GHG	IMO Intersessional Working Group on Reduction of GHG Emissions from Ships
LCV	Lower calorific value
LEU	Low-enriched uranium (typically 3–5% U-235)
LFR	Lead-cooled fast reactor
LNG	Liquefied natural gas
MEPC	IMO Marine Environment Protection Committee
MSC	IMO Maritime Safety Committee
MSR	Molten salt reactor
MWth	Megawatt thermal
MWe	Megawatt electric
NEMO	Nuclear Energy Maritime Organization
NPT	Treaty on the Non-Proliferation of Nuclear Weapons
NZF	IMO Net-Zero Framework
OPS	Onshore power supply
PV	Present Value
PWR	Pressurised water reactor
RFNBO	Renewable fuel of non-biological origin
sCO_2	Supercritical carbon dioxide (Brayton power cycle)
SDC	IMO Sub-Committee on Ship Design and Construction
SFR	Sodium-cooled fast reactor
SMR	Small modular reactor
SOLAS	International Convention for the Safety of Life at Sea
tHM	Tons of heavy metal (uranium in the fuel)
TRISO	Tri-structural isotropic coated-particle fuel
TtW	Tank-to-wake
WtT	Well-to-tank
WtW	Well-to-wake
ULCV	Ultra-large container vessel
VHTR	Very-high-temperature reactor
VLCC	Very large crude carrier
VLOC	Very large ore carrier
VLSFO	Very low sulphur fuel oil



Extended Summary

Greek shipowners control a fleet of nearly 5,800 vessels, more than 19% of global tonnage, and over 98% of that capacity serves trades to and from third countries.[1,2] Greek shipping is therefore more exposed than almost any other national fleet to how the global fuel transition is regulated and priced.

That pressure is already real in Europe. The EU ETS has covered shipping since 2024, and allowances must be surrendered for 100% of in-scope emissions from 2026 onwards (surrendered in the following year).[3] FuelEU Maritime has applied since 2025, with a well-to-wake GHG-intensity limit that tightens from −2% to −80% by 2050. At global level, the IMO Net-Zero Framework was approved in April 2025, but its adoption was adjourned in October 2025. It remains under negotiation ahead of MEPC 85 (30 November – 3 December 2026).[4,5]

Nuclear propulsion offers zero operational GHG emissions, very high energy density and long intervals between refuling. Outside Russia, however, no civilian maritime nuclear facility has been commissioned for more than 40 years. The applicable IMO Code dates from 1981 and was written around pressurised water reactors; its revision is planned for completion in 2030.[6,7]

For the Capesize case study in Chapter 4 (18,000 t of HFO per year, 25 years), 25-year fuel costs range from about USD 225 million (HFO) to about USD 880–915 million (green ammonia, e-methanol). For an advanced reactor they are about USD 26–158 million. At 100% EU scope, EU ETS and FuelEU costs for HFO reach about €391 million if FuelEU penalties are not escalated, or about €904 million if the penalty multiplier for consecutive deficits applies, versus zero for nuclear. Against this, the nuclear option would cost an estimated USD 300–500 million to build (USD 75–80 million for a conventional Capesize) and USD 40–80 million to decommission. On an undiscounted basis the nuclear option lands at USD 366–738 million over 25 years, compared with USD 723–733 million for HFO (about USD 1.28 billion with the penalty multiplier) and about USD 1.0 billion for the e-fuel options. Discounting changes the picture: at 8% a year, the HFO case falls to about

[1] Union of Greek Shipowners, “Annual Report 2025–2026: Greek Shipping continues to be a World-Leading Force”, press release, May 2026 (accessed 13/10/2026) link.
[2] G. Howard, “Greek fleet continues growth in 2025” (reporting the UGS Annual Report 2025–2026), Seatrade Maritime News, 27/5/2026 (accessed 13/10/2026) link.
[3] European Commission, “FAQ – Maritime transport in EU Emissions Trading System (ETS)”, phase-in of the surrender obligation (accessed 19/10/2026) link.
[4] J. Gabbatiss, M. Lempriere, “Q&A: How countries got the global ‘net-zero’ shipping deal ‘back on track’”, Carbon Brief, 5/5/2026 (accessed 13/10/2026) link.
[5] “ISWG-GHG 22: Working Group Ends With Net-Zero Framework Text Expected at MEPC 85”, Ship & Bunker, September 2026 (accessed 13/10/2026) link.
[6] O.C. Reistad, E. Ovrum, E. Stensrud, A.S.S. Ness, Maritime Nuclear Propulsion – Technologies, commercial viability, and regulatory challenges for nuclear-powered vessels, DNV White Paper, 2025 link.
[7] IMO, “Sub-Committee on Ship Design and Construction (SDC 12), 19–23 January 2026”, meeting summary (accessed 13/10/2026) link.



USD 299–304 million (419–425 million with the multiplier), while the nuclear case falls only to USD 317–579 million, because a larger share of its cost is incurred up front. The comparison is a screening of selected cost components, not a business case, and it does not show an unconditional cost advantage for nuclear. Because no merchant reactor yet has a market price, the outcome is decided mainly by reactor CAPEX, the discount rate and the ship's exposure to EU rules. DNV's fleet scenarios find nuclear competitive at reactor costs below roughly USD 18,000/kWe if shipping reaches net zero by 2050, and below about USD 8,000/kWe without full decarbonisation; these are scenario thresholds, not break-even prices for every ship.[6]

Nuclear fits best on large, high-power, highly utilised vessels on predictable routes, such as very large bulk carriers, large tankers and large container ships. It fits poorly on short-sea vessels, small ferries and ships trading irregularly on the spot market.[8] That last point matters for the Greek tramp fleet. Domestic ferry routes are better served by electrification.[9]

The decisive barriers are institutional rather than physical. They include licensing, port access, nuclear liability (the 1962 convention never entered into force), insurance (P&I club rules exclude nuclear risks arising from a nuclear ship's fuel), fuel supply (HALEU), crew competence, financing and public acceptance, which is comparatively low in Greece for nuclear energy in general (about 30% support for nuclear energy in a 2025 survey), although views of nuclear propulsion for large commercial ships are more evenly divided.[10,11,12,13]

Greece's opportunity lies in early preparation more than immediate deployment. That means shaping the IMO rules now being drafted, building regulatory capacity (EEAE), adopting rules for the port entry of commercial nuclear ships (current Greek arrangements cover only military vessels), training people, and studying port-energy applications.[14] The government's decision of July 2026 to set up an inter-ministerial

---

[8] G. Dimopoulos, A. Vlachou, "Perspectives on Marine Nuclear Energy Systems: Thermodynamics, Economics, and System Integration", 9th International Symposium on Ship Operations, Management & Economics (SOME), SNAME, Athens, 15–16 September 2026.

[9] G. Remoundos, M. Lekakou, G. Stergiopoulos, D. Gavalas, I. Katsounis, S. Peppa, D. Pagonis, K. Vaagsaether, "Technological Readiness and Implementation Pathways for Electrifying Greek Coastal Ferry Operations: Insights from Norway's Zero-Emission Ferry Transition", Energies, 18(17) (2025), 4582 doi.

[10] R. Peroni, "Nuclear propulsion for commercial shipping: can the law keep up?", Reed Smith, 13/5/2025 (accessed 13/10/2026) link.

[11] The Swedish Club, Rules & Exceptions, Part Two – Comments, Rule 11, Section 7 "Nuclear risks", comment 11.7.3 (accessed 13/10/2026) link.

[12] "Floating nuclear power plants 'realistic' for Greece", World Nuclear News, 28/5/2026 (accessed 13/10/2026) link.

[13] G. Laskaris et al., Floating Nuclear Power Plants for Greece: Conclusions and Policy Recommendations from a PESTLE Study, Deon Policy Institute, May 2026, pp. 34–35 link.

[14] G. Laskaris, I. Kourasis, S. Hirdaris, A. Platias, Nuclear Energy in Shipping: A New Technological Revolution in Maritime Transport and Greece's Role, Deon Policy Institute, June 2025, p. 27 link



committee on nuclear energy gives an institutional starting point.[15] Chapter 6 sets out a phased roadmap.

[15] "Greece Launches Nuclear Energy Debate as Power Needs Grow", GreekReporter, 3/8/2026 (accessed 13/10/2026) link.



1. Introduction – Why should Greece care early

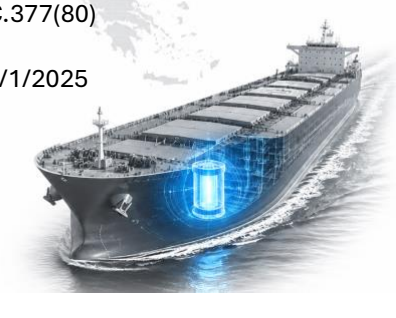
International shipping emits about one billion tons of CO_2-equivalent per year.[16] In 2023 the IMO set a net-zero target for international shipping "by or around, i.e. close to, 2050". Its indicative checkpoints are reductions of at least 20% (striving for 30%) by 2030 and at least 70% (striving for 80%) by 2040, both against 2008. By 2030, zero or near-zero GHG fuels and energy sources should provide at least 5%, striving for 10%, of the energy used.[17]

Within the EU, these goals are already enforceable. The EU ETS and FuelEU Maritime (Section 4.1.2) put a direct price on emissions and on the GHG intensity of fuel used on voyages to and from EU ports. The global measure that would extend carbon pricing to all large ships, the IMO Net-Zero Framework, has had a difficult path. It was approved at MEPC 83 in April 2025, but adoption was adjourned for a year in October 2025. MEPC 84 (April 2026) agreed to carry the original framework forward as the basis for further work.[4] The September 2026 intersessional meeting (ISWG-GHG 22) ended without agreement on changes. A further intersessional meeting (23–27 November 2026) and MEPC 85 (30 November – 3 December 2026) are scheduled, followed by a resumed extraordinary session on 4 December 2026, subject to MEPC 85.[5]

Whatever happens in these meetings, the fuel problem remains. Carbon-neutral fuels for conventional ships are estimated to cost USD 1,000–2,300 per ton of VLSFO-equivalent, compared with about USD 500 per ton for conventional fuel.[6] They also need very large quantities of renewable electricity. The volume of green fuels needed to replace fossil fuels in the world fleet has been estimated at more than 500 million tons per year, roughly 80% of today's total renewable electricity production.[14]

This is why nuclear power has returned to the shipping agenda. It produces no direct GHG emissions, has very high energy density, and allows long operating periods with minimal refuling. These qualities matter most on long-haul routes.[8] Interest is also visible in industry. Norway's NuProShip project screened 99 reactor developers and selected three designs for further study.[18] Classification societies such as ABS have issued rules for nuclear power systems. The Nuclear Energy Maritime Organization (NEMO) was founded in April 2024, and the IAEA is preparing its ATLAS initiative.[14] In June 2025 the IMO agreed

[16] H. Schøyen, K. Steger-Jensen, "Nuclear propulsion in ocean merchant shipping: The role of historical experiments to gain insight into possible future applications", Journal of Cleaner Production, 169 (2017), 152–160 link.
[17] IMO, 2023 IMO Strategy on Reduction of GHG Emissions from Ships, Resolution MEPC.377(80) (accessed 13/10/2026) link.
[18] "Three SMRs selected for evaluation in ship propulsion study", World Nuclear News, 7/1/2025 (accessed 13/10/2026) link.



to revise its 1981 Nuclear Code. The revised Code is planned for finalisation and adoption in 2030.[19,7]

Greece has particular reasons to engage early. Its shipowners control the largest fleet in the world. They also face transition costs whose allocation between owners and charterers depends on charter terms.[20] And the rules that will decide whether nuclear ships can trade, enter ports and be insured are being drafted now. Greece has a record of defending its maritime interests independently within the IMO.[21] In March 2026 the Prime Minister stated that "at this point, we have no credible solutions to decarbonize shipping". He argued that nuclear should be part of that discussion and announced a high-level ministerial committee.[22] The cabinet approved an inter-ministerial committee on 30 July 2026, with a mandate to assess the technical, economic, environmental, institutional and social aspects of nuclear energy. No decision has been taken to build a nuclear plant.[15]

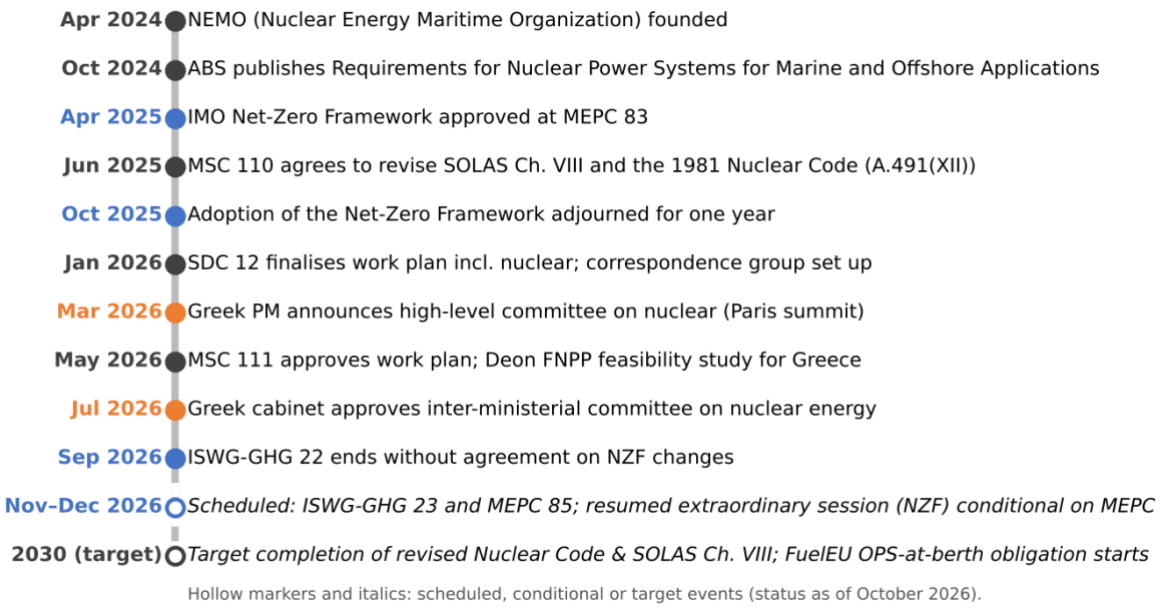


Figure 1: Key regulatory milestones for maritime nuclear power and shipping decarbonisation

Hollow markers and italics denote scheduled, conditional or target events: MEPC 85 is scheduled, the resumed extraordinary session is conditional on MEPC 85, and 2030 is the target for completing the revised Nuclear Code, not an assured adoption or entry-into-force date (sources as cited in Chapters 1 and 4).

[19] WNTI, ITF and RINA, "Work plan for revision of SOLAS chapter VIII and the Code of Safety for Nuclear Merchant Ships", IMO document SDC 12/9, 17/10/2025 link.
[20] Thommessen, "FuelEU Maritime comes into force 1 January 2025 – are your contracts ready?" (accessed 13/10/2026) link.
[21] D. Grekos, "External Maritime Policy of the EU: A Unilateral Initiative of Greece in the IMO", TransNav, the International Journal on Marine Navigation and Safety of Sea Transportation, 18(1) (2024), 151–158 link.
[22] "Prime Minister Kyriakos Mitsotakis' address at the 2nd Nuclear Energy Summit in Paris", Greek News Agenda, 13/3/2026 (accessed 13/10/2026) link.

The present report aims to respond to three questions. Chapters 1 and 2 examine the reasons behind the return of nuclear power to the shipping agenda now, while chapter 3 describes technologies and applications that are plausible. Their potential economic, operational, and strategic impact on Greek Shipping, as well as challenges remaining, are studied in Chapters 4 and 5. Finally, Chapter 6 proposes a phased roadmap. The report presents nuclear as a serious strategic option for specific segments, not as a settled or universal solution.



2. Greek Shipping and the Decarbonization Challenge

2.1. The Greek-owned fleet

The Union of Greek Shipowners (UGS) reports that the Greek-owned fleet grew in 2025 to 5,798 ships and 458 million dwt, or 19.1% of the global fleet. It also accounts for 61% of the EU-controlled merchant fleet. By segment, Greek owners control 2,766 bulk carriers (22% of the world dry bulk fleet), 1,064 tankers (26%) and 172 LNG carriers (23%) (shares of world deadweight tonnage, ships above 1,000 gt, based on S&P Global Market Intelligence data for January 2026)[1]. Their orderbook stands at 725 vessels, worth about USD 60 billion. More than 98% of the fleet's capacity carries cargo to and from third countries, and in 2025 it made more than 175,000 port calls in 171 countries.[1,2] On UNCTAD's ownership statistics (January 2025), Greece ranks first in the world with 16.4% of global dwt. The difference from the UGS figure reflects different data sources and definitions.[23]

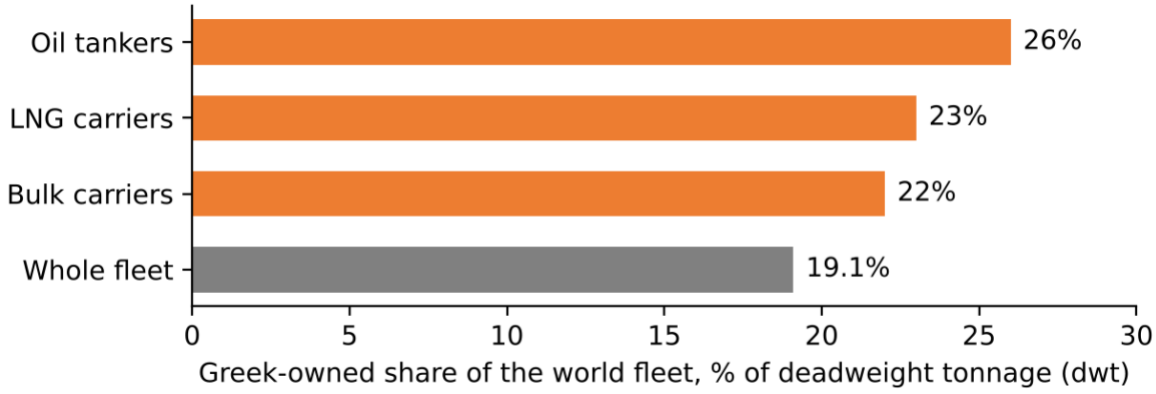


Figure 2: Greek-owned share of the world fleet by segment, as a percentage of world deadweight tonnage (ships above 1,000 gt; January 2026 data). Source: UGS Annual Report 2025–2026, Table 1 (UGS calculations based on S&P Global Market Intelligence data).

2.2. Economic weight

According to the UGS, shipping directly and indirectly accounts for 7–8% of Greek GDP and supports about 200,000 jobs.[1] A McKinsey analysis cited by the Deon Policy Institute gives at least 7% of GDP and about 150,000 jobs directly linked to the sector.[14] The difference reflects how indirect employment is counted. On either measure, the cost of the fuel transition is a macroeconomic issue for Greece, not just a sectoral one.

[23] UNCTAD, Review of Maritime Transport 2025 (fleet data as of January 2025), as reported in "Greece remains world's maritime powerhouse in 2025", OT.gr, 26/9/2025 (accessed 13/10/2026) link.



2.3. Fleet composition and market exposure

Table 1 summarises the composition of the Greek-controlled fleet and the dominant market structure of each segment. Most of the Greek fleet trades in tramp markets (spot and time charter). Who bears fuel and compliance costs therefore depends on the charterparty. Under the BIMCO FuelEU clause, for example, the financial burden of non-compliance under time charters falls on charterers, who choose fuels and routes. [20]

Table 1: Composition of the Greek-Controlled Fleet by Vessel Type and Typical Market Exposure[1]

*(The table **DOES NOT IMPLY** uniform chartering arrangements within each segment but highlights the dominant market structures that shape operational flexibility, fuel procurement, and cost-recovery mechanisms)*

Vessel segment	Global Share of Greek-controlled fleet (DWT,%)	Typical market structure	Relevance for decarbonization analysis
Bulk carriers	22%	Tramp (spot / time charter)	High exposure to freight cyclicality; limited and market-dependent cost pass-through
Oil tankers	26%	Tramp (spot / time charter)	Fuel and compliance cost allocation depends on charterparty form
Chemical and product tankers	16%	Tramp / semi-industrial	Greater technical constraints; cost recovery varies by contract
Gas carriers (LNG)	23%	Tramp / project-based	Route and terminal specificity; fuel choice constrained by nature
Gas carriers (LPG)	11%	Tramp	Exposure to fuel availability and charterer fuel clauses
Container ships	8%	Liner (scheduled services)	Higher ability to internalise compliance via surcharges and service contracts
Vehicles Carriers	8%	Liner / semi-liner	Partial cost pass-through; dependent on long-term contracts

Table 2 gives a first, qualitative view of how relevant nuclear propulsion is to each ship type. A recent NTUA assessment[8] points in the same direction for large, high-power ships. It rates large bulk carriers, large container ships and offshore/floating units as having "very high" nuclear suitability, and large tankers, ice-class vessels and large cruise ships as "high". Short-sea vessels, small ferries, low-utilisation ships and ships on irregular (spot) routes are rated "low". Its rating for large bulk carriers is higher than the "medium" in Table 2, mainly because of their large hull volume and high utilisation, and the authors single out very large ore carriers (VLOCs) on stable trades. The "medium" rating in Table 2 is the present authors' assessment and reflects the Greek tramp-market context, in which many large bulk carriers trade on the spot market. For a Greek tramp fleet, the implication is that the trading pattern and the length of employment matter as much as ship size. Large ships on long-term industrial contracts are the natural early candidates.



Table 2: Indicative relevance of nuclear propulsion by ship type.

Ship type	Nuclear relevance	Why
Ultra-large container vessels	High	High power demand, regular long routes, value of speed
VLCCs / ULCCs	High to medium	High fuel consumption, long voyages
Large bulk carriers	Medium	Large fleet segment, but lower speed requirements
LNG carriers	Medium	Energy-intensive, but already tied to gas cargo systems
Ferries / short-sea shipping	Low in near term	Port proximity, public acceptance, smaller power demand
Cruise ships	Technically interesting but politically sensitive	High hotel load, but passenger acceptance is a major issue

2.4. Fuel consumption by vessel category

The case for a reactor rests on the energy it replaces, so it matters where fuel is burned. The Fourth IMO GHG Study gives detailed 2018 results for each ship type and size, including the average fuel consumption per ship. Table 3 extracts the size categories most relevant to this report.[24]

These are modelled fleet averages based on observed ship activity data. They therefore reflect each segment's observed mix of speeds, waiting time and port time. Large bulk carriers and tankers spent about 195–260 days at sea in 2018, at average speeds of 11–12 knots, while the largest container ships sailed at about 16.5 knots. The data are from 2018. More recent fuel data reported to IMO give a similar order of magnitude for the largest container ships: about 22,000 tonnes per ship in 2023 for container ships of 200,000 dwt and above (about 3.06 million tonnes for 139 ships; the DCS size category is defined by deadweight and is not identical to the TEU classes in Table 3).[25]

[24] IMO, Fourth IMO GHG Study 2020 – Full report and annexes, London, 2021, Section 2.5, Table 35 "Detailed results for 2018 describing the fleet (international, domestic and fishing) analysed using the bottom-up method" link.

[25] IMO, "Report of fuel oil consumption data submitted to the IMO Ship Fuel Oil Consumption Database in GISIS (Reporting year 2023)", MEPC 82/6/38, 26/7/2024, Annex, Tables 2 and 3 (averages per ship calculated by the author from the reported totals) link.



Table 3: Average activity and fuel consumption per ship in 2018, by ship type and size (Fourth IMO GHG Study 2020, Table 35).

Ship type and size	Ships	Average dwt	Days at sea	Average speed at sea (kn)	Average fuel consumption (kt/year)
Bulk carrier 100,000–199,999 dwt (Capesize)	1,242	169,868	252	11.2	10.1
Bulk carrier ≥200,000 dwt (VLOC)	516	251,667	258	11.8	13.6
Oil tanker 60,000–79,999 dwt (Panamax)	429	72,826	194	11.6	9.0
Oil tanker 80,000–119,999 dwt (Aframax)	1,029	109,262	195	11.2	9.7
Oil tanker 120,000–199,999 dwt (Suezmax)	597	155,878	220	11.4	13.3
Oil tanker ≥200,000 dwt (VLCC/ULCC)	755	307,866	252	11.9	19.3
Container ship 14,500–19,999 TEU (ULCV)	101	179,871	250	16.5	31.0
Container ship ≥20,000 TEU (ULCV)	44	195,615	210	16.3	25.5
Liquefied gas tanker 100,000–199,999 m^3	436	83,661	271	14.9	27.6
Vehicle carrier ≥50,000 GT	487	20,947	281	15.5	11.5

Source: IMO, Fourth IMO GHG Study 2020, Table 35. Fuel consumption is the sum of main engine, auxiliary engine and boiler consumption; labels in brackets are approximate commercial vessel names (for example, not every bulk carrier above 200,000 dwt is an ore carrier)[26,27]. Fuel consumption is given in kt/year (thousand tonnes per year) and is the sum of the source's rounded main-engine, auxiliary-engine and boiler values.

The figure used in the case study of Chapter 4 (18,000 tons of HFO per year for a Capesize bulk carrier) was retained, for consistency, from the recent report on the "Implications of the IMO Net-Zero Framework for Greek shipping and economy".[28] It is a working assumption for an intensively operated Capesize, not a verified operating profile of a specific vessel. It is higher than the 2018 averages for Capesize bulk carriers, and therefore represents a more intensive operating profile, with more days at sea and/or higher speed, than the fleet average. The energy, fuel, emissions, fuel-cost and regulatory-cost results in Chapter 4 scale linearly with annual fuel consumption (newbuilding and decommissioning costs do not), so they can easily be adjusted: at the 2018 Capesize average, they would be about 44% lower.

[26] Baltic Exchange, "Main Vessel Types" (accessed 18/10/2026) link

[27] A. Hajda, "How does MarineTraffic categorise Commercial Market and Commercial Size Class?", MarineTraffic (accessed 18/10/2026) link

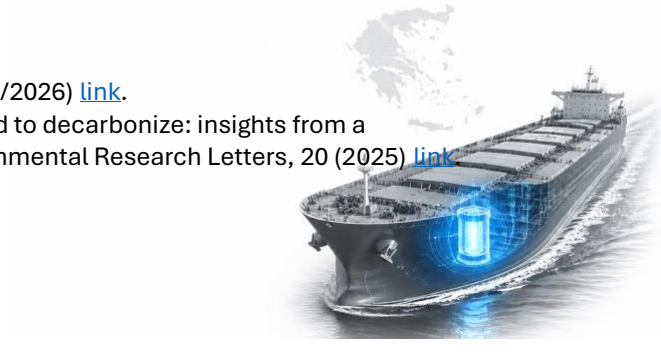
[28] D. Lyridis, G. Dimopoulos, D.M. Korres, "Implications of IMO Net-Zero Framework on Greek Shipping and Economy", National Technical University of Athens, February 2026, Section 5.3



2.5. Exposure to carbon pricing

Under the EU ETS, 100% of emissions on intra-EU voyages and at berth are covered, but only 50% of emissions on voyages between EU and non-EU ports. Since 2026 the scheme has also covered methane and nitrous oxide.[3] FuelEU Maritime applies to ships above 5,000 GT carrying passengers or cargo for commercial purposes and calling at EU ports.[29] Because Greek ships trade mostly between third countries, a large share of their activity currently falls outside these EU instruments. Every call at an EU port, however, brings a voyage into scope. If the IMO Net-Zero Framework is adopted, it would apply to ships above 5,000 GT worldwide, which account for about 85% of the sector's CO_2 emissions.[14] Modelling of the Greek fleet suggests that even ambitious combinations of mature on-board technologies and cleaner fuels would fall short of fully decarbonising the sector by 2050.[30] This gap is why harder-to-abate options, nuclear among them, deserve assessment for the deep-sea segments.

[29] ABS, FuelEU Maritime – Questions & Answers (accessed 13/10/2026) link.
[30] P. Koundouri, A. Alamanos, C. Deranian, O. Nisiforou, "Too hard to decarbonize: insights from a decision support tool for the Greek maritime operations", Environmental Research Letters, 20 (2025) link.



3. Nuclear Power as a Maritime Energy Option

This chapter explains in plain terms how a nuclear-powered ship works, what has been learned from the ships built so far, and which reactor technologies are now being considered for commercial use at sea.

3.1. How a nuclear ship works

A nuclear reactor is a source of heat. Inside the fuel, uranium-235 atoms split (fission) when struck by neutrons, releasing energy and more neutrons that sustain a controlled chain reaction. The heat is carried away by a coolant and used to drive a turbine. In a conventional steam ship, the boiler burns oil or LNG; in a nuclear ship, the reactor and a steam generator take the boiler's place.[6] Complete fission of 1 kg of U-235 yields around 24 million kWh, two to three million times the energy of the same mass of oil or coal.[31]

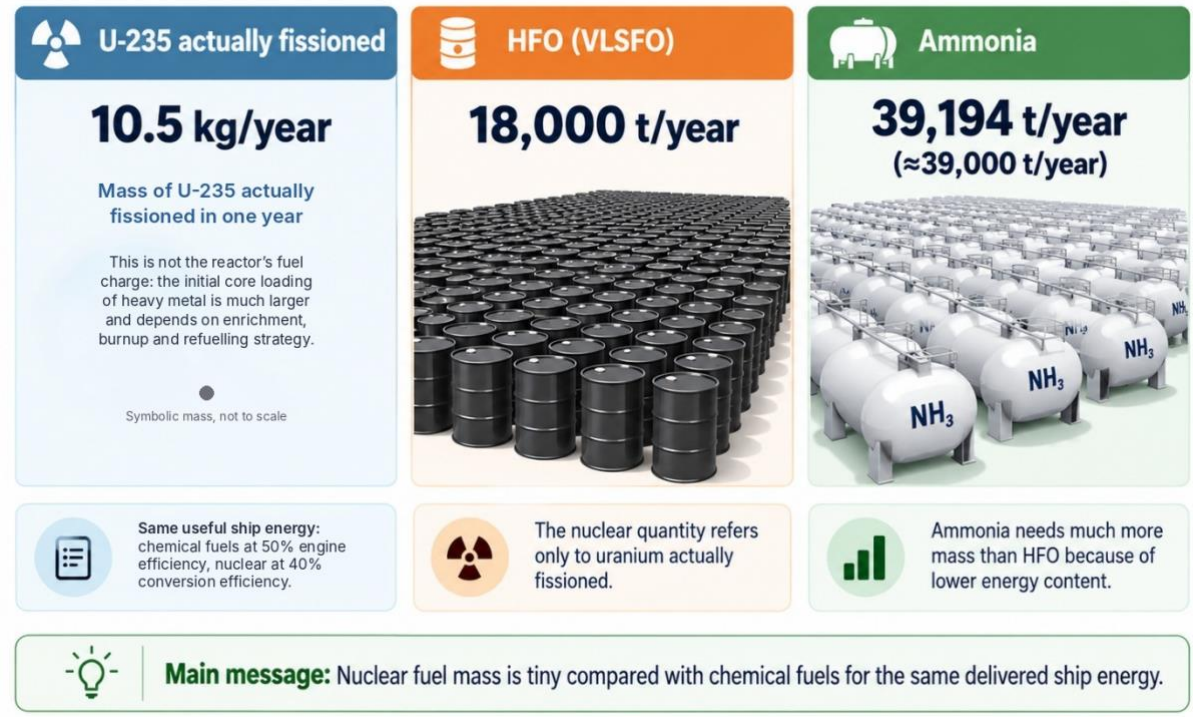


Figure 3: Energy density in the case study: annual quantities that deliver the same useful ship energy (50% engine efficiency for chemical fuels, 40% conversion efficiency for the nuclear plant).

Illustrative comparison of the annual quantities required in the case study: approximately 10.5 kg of U-235 actually fissioned, compared with 18,000 t/year of HFO and about 39,000 t/year of ammonia. The mass fissioned is not the reactor's fuel inventory; the initial core loading of heavy metal is much larger. The chemical-fuel quantities are annual throughput, not the tank capacity needed at any one time.

The extraordinary energy density of nuclear fuel is one of the main reasons why nuclear propulsion remains strategically interesting for large ships. A very small fuel mass can translate into long refueling intervals and reduced dependence on bunker availability,

[31] European Nuclear Society, "Fuel comparison" (accessed 13/10/2026) link.



while also highlighting that the central challenges of nuclear propulsion lie elsewhere: reactor cost, shielding, safety, licensing, fuel-cycle infrastructure and public acceptance. In other words, the fuel itself is not the limiting factor; the surrounding institutional and engineering system is.

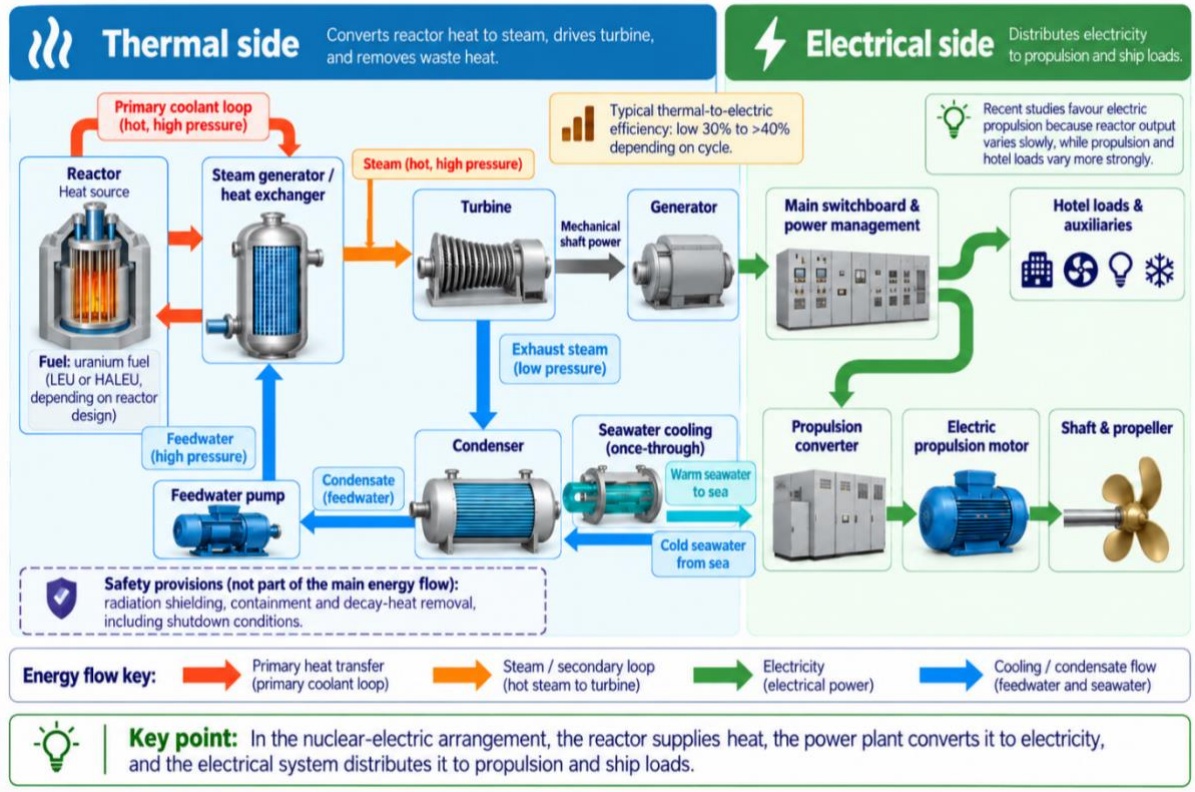


Figure 4: Illustrative nuclear-electric system using a steam Rankine cycle.

The general architecture follows Dimopoulos & Vlachou (2026); the cycle drawn is an author simplification, and the primary-loop labelling corresponds to a PWR-type example rather than to all candidate reactors.

The turbine can drive the propeller through a gearbox (nuclear-mechanical) or a generator (nuclear-electric). Recent studies prefer electric propulsion, because it decouples the reactor's slowly varying output from the highly variable propulsion and hotel loads and makes redundancy easier.[8] Thermal-to-electric efficiencies are typically in the low thirties per cent and can exceed 40%.[6] Supercritical CO_2 (sCO_2) Brayton cycles can reach about 45% at reactor outlet temperatures around 600 °C, with much smaller machinery than steam plants.[8] However, sCO_2 systems are at a lower technology readiness level than steam Rankine plants, particularly at sea, where turbomachinery design, transient operation and control, and long-term reliability remain to be addressed.[8] Figure 4 shows the main elements for a steam Rankine example.

Natural uranium contains only 0.7% U-235, so fuel is enriched. Commercial land-based plants use low-enriched uranium (LEU, about 3–5%). The merchant concepts assessed in this report assume enrichment below 20%, an important non-proliferation and safeguards objective. This is a design assumption rather than a universal rule: some



civilian maritime reactors have used highly enriched uranium (Russia's Sevmorput reportedly used 90% enriched fuel, and Arktika-class icebreaker reactors 45–75%).[6] Many new marine designs start from HALEU, enriched up to just under 20%, because higher enrichment allows more compact cores. Naval reactors (e.g. in the US) use fuel enriched above 90%, which is not available to merchant ships. Fuel is loaded and changed only at specially equipped and licensed yards.[6]

3.2. Experience so far

Over 160 ships, almost all naval, have been powered by more than 200 small reactors.[32] Four civilian merchant ships were built. The US NS Savannah, the first nuclear cargo-passenger ship, entered service in 1962 with a 74 MWth reactor. It was a technical success but not economically viable.[32] Its specialised crew numbered more than three times that of a conventional ship, and operating costs far exceeded those of fossil-fueled ships.[6] Germany's Otto Hahn sailed about 650,000 nautical miles on 126 voyages before being converted to diesel in 1982. Japan's Mutsu suffered technical and political problems.[32] All three used pressurised water reactors and showed that merchant nuclear propulsion is technically feasible. They also showed that port and canal access can be difficult and that up-front, refueling and decommissioning costs are large and uncertain.[16] Only Russia has run a maritime nuclear fuel cycle at industrial scale. This includes its icebreaker fleet based in Murmansk and the floating power plant Akademik Lomonosov, which has supplied electricity and heat to Pevek since 2019. [6,14] Russia also operated the nuclear cargo ship Sevmorput from 1988.[14]

3.3. Reactor technologies

Reactor types differ in their fuel, their coolant and whether a moderator is used to slow the neutrons. The Generation IV International Forum identifies six advanced systems: the very-high-temperature, sodium-cooled fast, supercritical-water, gas-cooled fast, lead-cooled fast and molten salt reactors.[33] Table 4 summarises the options relevant to ships.

For merchant ships, reactor choice is a problem with many constraints, not a contest of thermodynamic performance. A systematic screening by Emblemsvåg et al. (2025), as summarised by Dimopoulos and Vlachou, started from more than 80 small modular reactor (SMR) concepts and excluded designs with high primary pressure (above ~60 bar), reliance on active safety systems, enrichment above civilian thresholds, refueling intervals inconsistent with dry-docking, reactive coolants such as sodium, or insufficient technological maturity. It narrowed the field to three families: HTGRs, fluoride salt-cooled

[32] World Nuclear Association, "Nuclear-Powered Ships", updated 18/5/2026 (accessed 13/10/2026) link.
[33] Generation IV International Forum, "Generation IV Criteria and Technologies" (accessed 13/10/2026) link.



reactors with solid fuel (FHR) and lead-cooled fast reactors.[8] These are the results of that screening exercise, not an industry-wide prohibition of other reactor types. NuProShip reached a consistent result. It selected a fluoride salt-cooled reactor with TRISO fuel (Kairos Power), a helium-cooled gas reactor with TRISO fuel (Ultra Safe Nuclear Corporation) and a lead-cooled reactor (Blykalla) for detailed assessment.[18] DNV similarly points to low-pressure Generation IV designs or heat-pipe reactors, and to refuling intervals of at least five years to match dry-docking.[6] Liquid-fuel molten salt reactors are currently excluded from such screening because of unresolved fuel handling, safeguards and regulatory acceptance issues, even though some developers continue to pursue them.[8,14]

Table 4: Reactor technologies considered for maritime use, in plain terms (temperatures and pressures indicative).

Reactor family	How it works (in plain words)	Coolant, conditions, fuel	Maritime assessment in recent studies
Pressurised water reactor (PWR)	Water under high pressure cools the core and slows (moderates) the neutrons; heat raises steam in a second circuit.	Water, ~280–340 °C, 150–160 bar; LEU 3–5%	The dominant reactor type in operational marine service (Savannah, Otto Hahn, Mutsu, Russian icebreakers, most naval vessels); other types have been used only exceptionally (Soviet Alfa-class lead-bismuth submarines, USS Seawolf's sodium-cooled reactor).[6,32] Excluded in the cited screening for merchant use because of high pressure, refuling interval and crew needs.
High-temperature gas-cooled reactor (HTGR / VHTR)	Helium gas carries heat from a graphite core containing robust TRISO particle fuel.	Helium, outlet 700–950 °C, 40–80 bar; TRISO (HALEU)	Candidate in the cited screening: passive safety, high temperature, good licensing basis; drawbacks are pressure vessels and volume.
Fluoride salt-cooled high-temperature reactor (FHR, solid-fuel MSR)	Solid TRISO fuel cooled by molten fluoride salt at near-atmospheric pressure.	Salt, outlet 650–800 °C, 1–10 bar; TRISO	Candidate in the cited screening: low pressure, compactness; issues are corrosion, fuel handling and safeguards.
Molten salt reactor, liquid fuel (MSR)	The fuel is dissolved in the molten salt, which is both fuel and coolant.	Salt, outlet 650–800 °C, 1–5 bar; HALEU	Currently excluded in screening because of fuel handling, safeguards/accountancy and licensing, although several developers (e.g. Core Power with TerraPower, a CSSC container ship design) pursue it.
Lead-cooled fast reactor (LFR)	Liquid lead (or lead-bismuth) cools a compact core without a moderator (fast neutrons).	Lead, outlet 400–650 °C, 1–5 bar; solid fuel	Candidate in the cited screening: low pressure, long core life, lead does not react exothermically with water or oxygen; issues are coolant mass and corrosion.
Sodium-cooled fast reactor (SFR)	Liquid sodium cools a fast-neutron core.	Sodium, outlet 480–550 °C, 1–5 bar	Considered unsuitable at sea because sodium reacts violently with water.
Gas-cooled fast reactor (GFR)	Helium-cooled fast-neutron reactor (Generation IV concept).	Helium, outlet ~850 °C	Listed among proposed technologies; no marine-specific assessment found in the sources used here.
Heat-pipe reactor (micro-reactor)	Sealed heat pipes passively carry heat out of a solid core: few or no moving parts.	Up to ~5 MWth; HALEU (UN, TRISO or U-Zr)	Considered for floating power plants and small applications (e.g. Westinghouse eVinci with Core Power); no operating megawatt-scale design yet.

Sources for Table 4: Dimopoulos & Vlachou (2026), Table 1; DNV (2025), Table 3-2; Generation IV International Forum; Deon Policy Institute (2025), Table 3.



Research on advanced reactor technologies is also being conducted in Greece. Kourasis and Petropoulos (2025)[34] investigated the neutronic performance of an alternative ^{11}B-enriched boron carbide coating for TRISO fuel particles, using OpenMC simulations based on a VHTR fuel benchmark. Their findings highlight the importance of coating composition and neutron absorption characteristics in advanced fuel development. Although the study does not address marine reactor qualification, it illustrates relevant domestic research capabilities in the neutronic assessment of advanced nuclear fuel concepts.

To compare the leading reactor options more clearly, Figure 5 presents simplified cross-sectional sketches of the main families discussed in recent maritime studies. The purpose is not to show detailed engineering designs, but to make visible the most policy-relevant differences: the coolant used, the indicative temperature and pressure range, and the reason why recent screening exercises tend to favour lower-pressure concepts over high-pressure water systems.

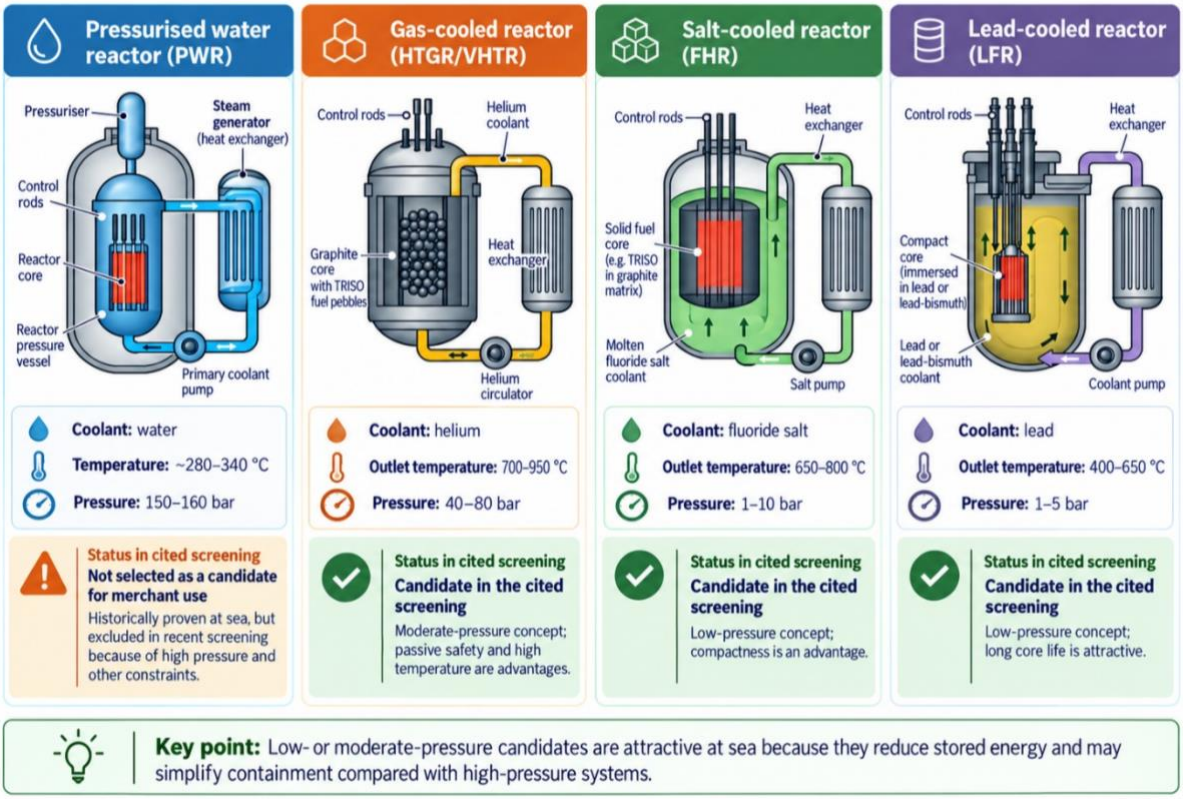


Figure 5: Reactor families considered for maritime use, shown schematically.

"Candidate" refers to the screening by Emblemsvåg et al. (2025) as summarised by Dimopoulos & Vlachou (2026); temperatures for HTGR, FHR and LFR are reactor outlet temperatures. Illustrative comparison of four reactor families frequently discussed for shipping applications: pressurised water reactor (PWR), gas-cooled reactor (HTGR/VHTR), salt-cooled reactor (FHR), and lead-cooled reactor (LFR). The figure highlights the main coolant, indicative temperature and pressure, and each family's status in the cited screening.

[34] I. Kourasis, N. Petropoulos, Evaluation of the neutronic performance of $^{11}B_4C$ as an alternative coating layer in TRISO fuel, 2025, Advances in Nuclear Physics, 31, HNPS2024, doi.

The main distinction in Figure 5 is between historically proven but high-pressure water systems and newer low- or moderate-pressure concepts (HTGRs operate at about 40–80 bar, moderate compared with PWRs; FHRs and LFRs at low pressure) that may simplify containment and reduce some safety burdens. This does not mean that the latter are ready for deployment, but it clarifies why HTGRs, FHRs and LFRs feature prominently in current maritime discussions.[8]

3.4. Small modular reactors and power levels

"Small modular reactor" (SMR) is an industry term for designs of up to about 300 MWe intended for factory-style serial production.[14] Ships need far less power than that. The largest ship installations of propulsion and auxiliary power reach about 100 MW, and earlier DNV work found that about 40 MW may suffice for a 15,000 TEU container ship.[6] A Hyundai KSOE concept for a 15,000 TEU container ship uses a 90 MWth reactor.[14] For the Capesize case in Chapter 4, the reactor must deliver about 38 MWth while the ship is operating.

3.5. Floating nuclear power plants

Floating nuclear power plants (FNPPs) are built in shipyards and towed to where power is needed: remote coasts, ports, industrial sites, desalination plants or offshore installations. The idea is not new: the MH-1A Sturgis floating plant supplied power to the Panama Canal from 1967.[14] Russia's Akademik Lomonosov is the only one in operation today.[14] Westinghouse and Core Power agreed in November 2024 to develop FNPPs based on the eVinci micro-reactor, and Samsung Heavy Industries has completed a conceptual design for a molten salt reactor power barge.[32] Because an FNPP does not propel itself, space and extreme operating conditions are less critical than on a ship, and it may not even have facilities for removing fuel.[6] Chapter 5 discusses the relevance of FNPPs for Greek ports.

3.6. Current projects and actors

Current activity includes reactor developers (Core Power, Westinghouse, Kairos Power, Seaborg, newcleo, Blykalla), shipbuilders (Hyundai KSOE, Samsung Heavy Industries, China's CSSC/Jiangnan) and classification societies (ABS, Lloyd's Register, DNV, Bureau Veritas).[6,14] NuProShip II, funded by the Research Council of Norway, completed a case study in January 2026 showing that a nuclear-powered vessel with dynamic positioning, using a helium gas-cooled reactor, is technically feasible.[35] In Greece, the Deon Policy

[35] VARD, "NuProShip II – Pioneering the future of sustainable Marine Propulsion with Nuclear reactors", press release, 26/1/2026 (accessed 13/10/2026) link.



Institute's 2026 study on floating nuclear plants drew on a research programme with Core Power, the Greek company Athlos Energy and ABS.[12] NTUA's School of Naval Architecture and Marine Engineering is working on nuclear power-cycle design for ships.[8]



4. Benefits and Challenges for Greek Shipping

4.1. Economic Benefits

As per the "Report on the Implications of IMO Net-Zero Framework on Greek Shipping and Economy", below is a **first calculation framework** for a Capesize bulk carrier consuming 18,000 tons of HFO per year. The calculations will examine options like methanol, ammonia and LNG, to compare with an advanced reactor (e.g. MSR/FHR, HTGR or LFR) using U-235 as fuel.

Assuming 275 operating days per year and 25 years of lifetime, the energy demand from 18,000 tons/year HFO (LHV 0.0405 MJ/g = 40.5 MJ/kg) will be:

$$E_{tot} = 18{,}000{,}000\ kg \times 40.5 \frac{MJ}{kg} = 729{,}000{,}000 \frac{MJ}{year}$$

Over 25 years, this will be:

$$729{,}000{,}000 \frac{MJ}{year} \times 25\ years = 18{,}225{,}000{,}000 MJ = 18.225\ PJ$$

4.1.1. Fuel Cost Calculations

4.1.1.1. Conventional Fuels

For the various fuel options to provide the same amount of energy, and using the respective lower heating values the resulting fuel quantities are:

Table 5: Comparison of various conventional fuel options

Fuel	LCV (MJ/kg fuel)	Annual Fuel Quantity (t/year)	Total 25-year quantity (tons)	Mass Ratio to HFO
HFO (VLSFO)	40.5	**18,000**	**450,000**	1.00
LNG (fossil)	49.1	**14,847**	**371,181**	0.82
Ammonia	18.6	**39,194**	**979,839**	2.18
Methanol	19.9	**36,633**	**915,829**	2.04
Note: The comparison is made on equal fuel heating value. Translating it into equal useful ship energy additionally assumes the same conversion efficiency for all fuels; pilot fuel, differences in engine performance and N_2O emissions from ammonia combustion are not modelled.				

Key point: methanol and ammonia require roughly twice the mass of HFO for the same energy content. LNG requires less mass than HFO, but it requires cryogenic storage.

Fuel volume is also a subject for consideration, since fuel storage affects design, range, cargo capacity and arrangement. Thus, using the densities of the various fuel options, the fuel volume equivalents are:



Fuel	Density (ton/m^3)	Annual Fuel Quantity (t/year)	Total 25-year quantity (tons)	Annual Fuel Volume (m3/year)	Volume Ratio to HFO
HFO (VLSFO)	0.98	18,000	450,000	18,367	1.00
LNG (fossil)	0.45	14,847	371,181	32,994	1.80
Ammonia	0.68	39,194	979,839	57,638	3.14
Methanol	0.79	36,633	915,829	46,371	2.52

Ammonia needs more than three times the HFO storage volume for the same energy, before considering tank insulation, containment systems, safety distances, and auxiliary systems. These volumes are annual consumption equivalents, not the tank capacity needed at any one time, which depends on the bunkering interval, endurance and usable tank volume.

Important note: Fuel prices used below are merely working assumptions and not forecasts. Green-fuel prices may change substantially with future availability and production scale; the fixed values are scenario inputs rather than forecasts.

Making some conservative assumptions of fuel prices, the table below illustrates the fuel cost comparison over 25 years.

Table 6: Conventional Fuel cost comparison over 25 years

Fuel	Annual Fuel Quantity (t/year)	Total 25-year quantity (tons)	Assumed price (USD/ton)	Annual Fuel Cost (USD/year)	Total 25-year Cost (USD)
HFO (VLSFO)	18,000	450,000	500	9,000,000	225,000,000
LNG (fossil)	14,847	371,181	750	11,135,438	278,385,947
Green ammonia	39,194	979,839	900	35,274,194	881,854,839
Green/e-Methanol	36,633	915,829	1,000	36,633,166	915,829,146
Note: Green-fuel prices may fall as availability increases; its effect can be gauged from a simple price sensitivity: each USD 100/t change in the assumed price changes the 25-year fuel cost by about USD 91.6 million for e-methanol and USD 98.0 million for green ammonia.					

As a cross-check, at the energy-equivalent basis of 41 MJ/kg used for VLSFO under FuelEU, the assumed prices correspond to about USD 1,980 (green ammonia), USD 2,060 (e-methanol) and USD 630 (LNG) per ton of VLSFO-equivalent. DNV estimates carbon-neutral fuels at USD 1,000–2,300 per ton of VLSFO-equivalent and conventional fuel at about USD 500 per ton.[6] The e-fuel assumptions are therefore at the upper end of that range but within it.



4.1.1.2. Nuclear Fuel Cost

Assuming that the HFO engine system converts about 50% of the fuel heating value (LHV) into useful propulsion energy, the nuclear reactor has to produce:

$$729{,}000{,}000\frac{MJ}{year} \times 0.50 = 364{,}500{,}000\frac{MJ}{year} = 11.6MW$$

Respectively, for an illustrative advanced nuclear-electric system with assumed overall thermal-to-useful-energy efficiency of 40%:

$$Required\ nuclear\ thermal\ energy = 364{,}500\frac{GJ}{year}/0.40 = 911{,}250\frac{GJ}{year} = 28.9MW_{th}$$

So, for this vessel case, the rough requirement is about $29MW_{th}$ reactor output on average, corresponding to about $12MW$ average useful propulsion/electric power (these calculations do not cater for weather, maneuvering, auxiliary load, redundancy, and commercial speed requirements. The installed system could be considerably larger).

Note on the power basis. The 11.6 MW and 28.9 MWth above are averages over the whole calendar year (365 days). Because the vessel operates 275 days per year, the average power needed while operating is higher: about 15.3 MW of useful propulsion/electric power and about 38.4 MWth of reactor heat at 40% efficiency. Thermal-to-electric efficiencies are typically in the low thirties per cent and can exceed 40%,[6] while sCO_2 cycles may reach about 45%.[8] At 33% efficiency the annual thermal requirement would be about 1,104,500 GJ (about 46.5 MWth while operating); at 45%, about 810,000 GJ (about 34.1 MWth). The fuel quantities below scale accordingly. These figures are energy-equivalent screening estimates, not installed reactor ratings or design-specific thermal-cycle guarantees; fuel, propulsion and auxiliary loads need separate treatment in a ship-specific design.

The complete fission of 1 kg of U-235 releases[31] roughly:

$$24GWh \sim 86{,}400GJ$$

of thermal energy, so the annual quantity of U-235 that should actually be fissioned would be:

$$\frac{911{,}250}{86{,}400} = 10.55\ kg\ \text{U-235}$$

Over 25 years:

$$10.55 \times 25 \approx 264\ kg\ \text{U-235}$$

To convert MJ to GWd:

$1\ GWd = 1\ GW \times 1\ day = 10^9\ J/s \times 86400\ s = 8.64 \times 10^{13}\ J = 8.64 \times 10^4\ GJ$

Thus, the thermal energy required annually will be:

$$\frac{911{,}250\ GJ}{86{,}400\ s} = 10.55\ GWd$$

And over 25 years:

$$25 \times 10.55\ GWd = 263.67\ GWd$$

Assuming burnup between 50-100 GWd/tHM, the heavy metal requirement will be about 2.6 to 5.3 tHM. This corresponds to initial U-235 content of about:

$$2.6 \times 0.1975 = 0.52\ t\ \text{U-235}$$

to

$$5.3 \times 0.1975 = 1.05\ t\ \text{U-235}$$



(The energy figure has been corrected to be consistent with its source: 24 million kWh × 3.6 MJ/kWh = 86,400 GJ per kg of U-235 fully fissioned.[31] The heavy-metal quantities below are based on burnup and are not affected.)

As mentioned in previous chapters, these quantities describe the heavy metal associated with energy production over 25 years. They do not establish the initial core loading, the residual inventory at end of life or the number and timing of reloads, and the associated fabrication, transport and disposal charges are not priced here.

The mass fissioned (about 264 kg of U-235 over 25 years) is not the reactor's fuel inventory. Real fuel loading depends on enrichment, burnup, neutron economy, reactor design, refueling strategy, reserve margins, and regulatory limits.

- Existing naval nuclear propulsion has often relied on highly enriched uranium to achieve compact cores and long refueling intervals. However, this experience cannot be directly transferred to commercial shipping. Civilian commercial marine reactors would almost certainly be expected to use LEU or HALEU fuel, below the 20% U-235 threshold, because HEU would raise severe safeguards, proliferation, licensing, insurance and port-access issues.
- For cautious calculations, two burn-up values will be used: 50 GWd/tHM as a more conservative estimate, closer to high-end conventional experience, and 100 GWd/tHM, as an optimistic, yet plausible advanced reactor assumption.

Assuming burnup between 50-100 GWd/tHM and HALEU fuel enriched to 19.75% U-235, the heavy metal requirement over 25 years is approximately $2.6\ to\ 5.3\ tHM$, corresponding to initial U-235 content of between $0.52\ to\ 1.04\ t$ U-235. A rough MSR / advanced reactor fuel estimate is presented in the following Table:

Table 7: Rough advanced reactor fuel estimate

Nuclear parameter	Approximate result
Useful propulsion/electric energy needed	364,500 GJ/year
Nuclear thermal energy needed	911,250 GJ/year
Average reactor thermal power	28.9 MWth (calendar-year average); 38.4 MWth while operating
U-235 actually fissioned	10.5 kg/year
U-235 actually fissioned over 25 years	264 kg
Indicative HALEU heavy-metal fuel over 25 years	about 2.6–5.3 tHM
Initial U-235 content in HALEU fuel	about 0.52-1.04 t U-235

Nuclear fuel cost is very uncertain, especially for HALEU. Assuming a price range of 10,000 USD (optimistic, future price) to 30,000 USD (more realistic, present price) per kg



of Heavy Metal, the fuel cost over 25 years will be (for reference, a 2023 Nuclear Innovation Alliance study estimated the production cost of HALEU enriched to 19.75% at about USD 23,725/kgU in oxide form (USD 25,725/kgU as metal), before fuel fabrication, and noted that costs could be higher at small production scale[36]:

Table 8: 25 year nuclear fuel cost estimation

Nuclear fuel price assumption	Annualized fuel cost	25-year nuclear fuel cost
10,000 USD/kgHM	1.1-2.1 million USD/year	26-53 million USD
20,000 USD/kgHM	2.1-4.2 million USD/year	53-105 million USD
30,000 USD/kgHM	3.2-6.3 million USD/year	79-158 million USD
Note: Production-cost estimates, that do not establish a delivered price for finished TRISO or other reactor-specific fuel. Because fabrication, transport and back-end services come on top, the upper end of the range used here should not be regarded as pessimistic.		

4.1.2. Emissions Cost Calculations

Regarding the emissions, the EU approved cost mechanisms are the EU ETS maritime, imposing a cost per ton of reported CO_2-equivalent emissions, and FuelEU Maritime, imposing a penalty if the fuel's yearly well-to-wake GHG intensity exceeds the legal limit. The IMO Net-Zero Framework is not included in the present report because its adoption was adjourned in October 2025 and, after MEPC 84 (April 2026) and ISWG-GHG 22 (September 2026), it is still under negotiation ahead of MEPC 85 (30 November – 3 December 2026). It is therefore not yet an enforceable cost basis.[4,5]

The **EU ETS**[3] now applies to large cargo and passenger ships above 5,000 GT. From 2026, CO_2, CH_4 and N_2O are included, and allowances must cover 100% of in-scope emissions from 2026 onwards, surrendered in the following year (40% of 2024 emissions were surrendered in 2025 and 70% of 2025 emissions in 2026).[3] The *route scope is 100% for intra-EU voyages and port emissions, but 50% for voyages between an EU port and a non-EU port*. **FuelEU Maritime**[37,38] applies from 2025 and sets a well-to-wake GHG-intensity limit, starting with a 2% reduction from the 91.16 gCO_2e/MJ reference value, then tightening in steps to 80% by 2050.

[36] P. White, E. Cothron, Characterizing an Emerging Market for High-Assay, Low-Enriched Uranium Production, Nuclear Innovation Alliance, December 2023 link.
[37] European Union, Decarbonising maritime transport – FuelEU Maritime (accessed 13/11/2026), link
[38] Regulation (EU) 2023/1805 of the European Parliament and of the Council of 13 September 2023 on the use of renewable and low-carbon fuels in maritime transport, and amending Directive 2009/16/EC, link.



Table 9: EU ETS vs. FuelEU mechanisms

Item	EU ETS	FuelEU Maritime
Main purpose	Prices reported ship emissions through EU allowances	Penalizes excess fuel GHG intensity
Main unit	tCO_2eq	gCO_2eq/MJ
Gases	CO_2, CH_4 and N_2O (TtW) starting from 2026	CO_2, CH_4 and N_2O on a well-to-wake basis
GWP for CH_4 / N_2O	28 / 265 (revised MRV Regulation); used here for ETS	25 / 298 (RED II values); used here for FuelEU
Cost formula	ETS cost = tCO_2eq × EUA price	Penalty = FuelEU compliance deficit converted into VLSFO-equivalent energy × €2,400/t VLSFO-equivalent
Route scope	100% intra-EU and port emissions; 50% EU–non-EU voyages	Same general voyage-scope logic
Phase-in	100% of 2026 and later in-scope emissions, surrendered in the following year	Applies from 2025

The following table gives, among others, LCV, well-to-tank factors, CO_2 factors, CH_4 factors, N_2O factors, and methane slip where applicable. These data are taken from EU Regulation 2023/1805[39].

Table 10: Reference list of emission factors

Option	LCV (MJ/kg)	WtT factor used (gCO_2eq/MJ)	TtW factor used			CH_4 / N_2O treatment
			CO_2 (gCO_2/ g fuel)	CH_4 (g CH_4 / g fuel)	N_2O (g N_2O / g fuel)	
HFO	40.5	13.5	3.114	0.00005	0.00018	
LNG, low slip	49.1	18.5	2.750	0	0.00011	LNG diesel slow-speed slip: 0.2%
LNG, higher slip	49.1	18.5	2.750	0	0.00011	LNG Otto slow-speed slip: 1.7%
Fossil methanol	19.9	31.3	1.375	TBM	TBM	
e-methanol	19.9	0 assumed for illustration	1.375	TBM	TBM	RFNBO WtT must be certified; TtW CO_2 still counted in this calculation
Grey ammonia	18.6	121	0	n/a	TBM	N_2O for ammonia ICE is not fixed in the table; result is a minimum estimate

[39] Regulation (EU) 2023/1805 of the European Parliament and of the Council of 13 September 2023 on the use of renewable and low-carbon fuels in maritime transport, and amending Directive 2009/16/EC, link



Green ammonia / e-NH_3	18.6	0 assumed for illustration*	0	n/a	TBM	Assumes certified low-carbon pathway and zero verified N_2O
Nuclear MSR	n/a	0 assumed	0			Not explicitly parameterized in FuelEU Annex II; treated here as zero operational emissions, subject to legal recognition
* For e-fuels/RFNBOs, FuelEU does not simply assign a universal zero value; the well-to-tank value must be calculated/certified under the relevant EU methodology. See also Note ** of Table 13.						

4.1.2.1. EU ETS

A constant EUA price of €75/tCO_2eq is assumed over 25 years. Because no market price can be expected to stay constant for that long, Figure 6 shows how the 25-year ETS cost changes with the EUA price:

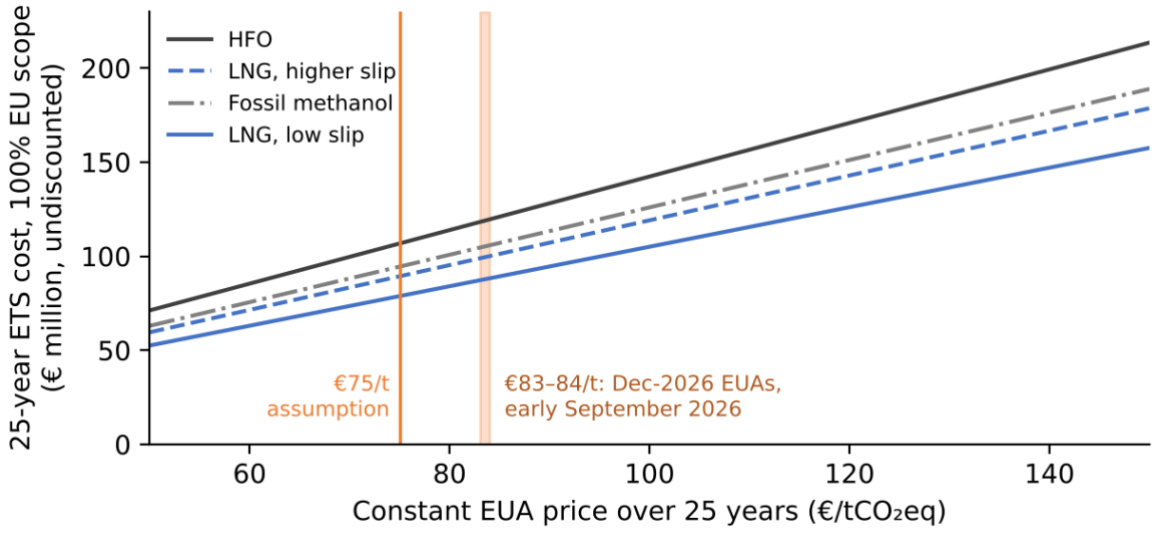


Figure 6: Sensitivity of the 25-year EU ETS cost (100% EU scope, undiscounted) to a constant EUA price.

The vertical line marks the €75/t assumption; the shaded band marks December-2026 EUAs, traded at about €83–84/t in early September 2026. Source: calculations in this chapter, https://tradingeconomics.com/commodity/carbon.

For reference, December-2026 EUAs traded at about €83–84/t in early September 2026.[40] The €75/t assumption is below that dated market observation, without implying a forecast of future EUA prices. Each additional €10/t adds about €14.2 million to the 25-year ETS cost of the HFO case at 100% EU scope. Thus, the emissions cost for the EU ETS over 25 years is presented in Table 11.

[40] S&P Global Commodity Insights, "EU allowances to remain well supported in Q4 but policy risk adds pressure", 3/9/2026 (accessed 13/10/2026) link.

Table 11: Emissions cost for the EU ETS over 25 years

Fuel	Annual Fuel Quantity (t/year)	Annual ETS emissions (tCO_2eq/year)	Annual ETS cost	25-year ETS cost
HFO (VLSFO)	18,000	56,936	€4.27 million/year	€106.75 million
LNG, low slip	14,847	42,012	€3.15 million/year	€78.77 million
LNG, higher slip	14,847	47,629	€3.57 million/year	€89.30 million
Fossil methanol	36,633	50,371	€3.78 million/year	€94.45 million
e-methanol*	36,633	0 (zero-rated)	€0	€0
Grey ammonia	39,194	0**	€0	€0
Green ammonia / e-NH_3	39,194	0**	€0	€0
Nuclear MSR	n/a	0	€0	€0

* Under the EU ETS, RFNBOs (such as e-methanol) that meet the required GHG savings under the Renewable Energy Directive are zero-rated, i.e. no allowances need to be surrendered for their combustion emissions.[3] The e-methanol case therefore assumes certified RFNBO e-methanol. Uncertified e-methanol would instead carry the fossil-methanol values.

** excluding unresolved N_2O

4.1.2.2. FuelEU

FuelEU compares the ship's actual yearly GHG intensity with the legal target. When the actual value is above the target, a penalty applies. Annex IV sets the penalty using €2,400 per ton of VLSFO-equivalent, with 41,000 MJ representing one ton of VLSFO-equivalent energy. The formula used for the following calculations is:

$$\text{FuelEU penalty} = \frac{(G_{actual} - G_{limit})}{G_{actual}} \times \frac{E}{41{,}000} \times 2{,}400$$

Where: $E = 729{,}000{,}000\ MJ/year$. Also, if $G_{actual} \leq G_{limit}$ there is no penalty under FuelEU.

The FuelEU results distinguish an unmultiplied penalty benchmark from a repeated-deficit scenario applying Article 23(2) of the Regulation, under which the penalty of a ship with a compliance deficit in two or more consecutive reporting periods is multiplied by 1 + (n − 1)/10, n being the number of consecutive periods with a penalty. The escalation is linear in n, not compound.[39] The repeated-deficit scenario assumes unchanged fuel use, no pooling or banking, and a penalty in every consecutive year in which the fuel exceeds the GHG-intensity limit. The count starts in the first penalised year of the 2026–2050 horizon: 2026 for HFO, fossil methanol and grey ammonia, 2035 for higher-slip LNG, 2040 for low-slip LNG and 2050 for the e-methanol example (a ship already penalised in 2025 would start 2026 at n = 2). Neither scenario estimates the market cost of buying compliance through pooling, banking, fuel switching or other flexibility measures; these may cost less than repeated penalties, but require separate price and operational



assumptions.[41] The FuelEU calculations use the global warming potentials that FuelEU currently applies (those of the Renewable Energy Directive: CH_4 25, N_2O 298), while the ETS calculations use the values of the revised MRV Regulation (CH_4 28, N_2O 265).[42] With 28/265 instead, the unmultiplied 25-year FuelEU penalty would be about 0.4% lower for HFO but about 2.4% higher for higher-slip LNG (€226.9 million instead of €221.6 million).

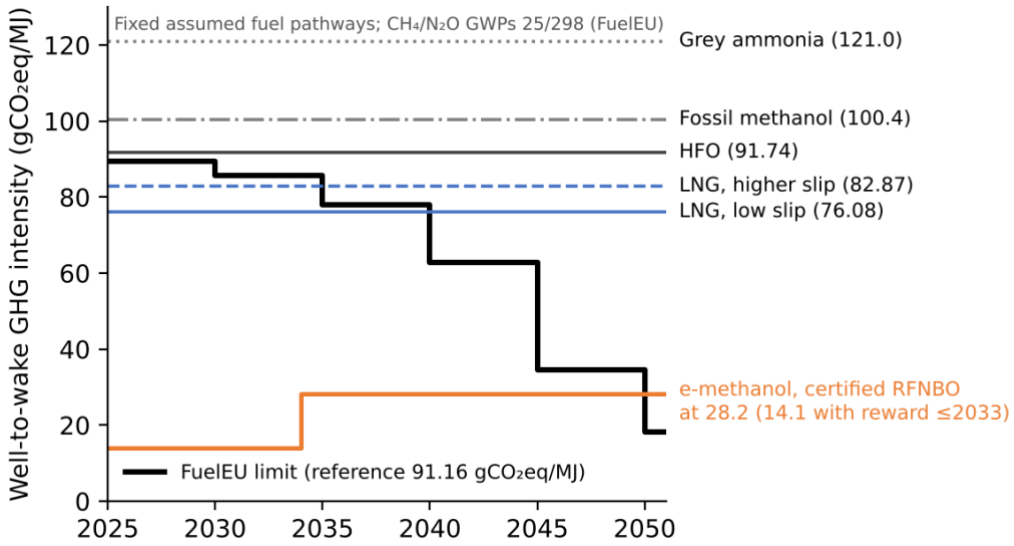


Figure 7: FuelEU Maritime GHG-intensity limits compared with the well-to-wake intensities calculated in this report (GWPs 25/298).

The fuel lines are calculations for fixed assumed fuel pathways, not predictions of future fuel performance.

Having a reference value of 91.16 gCO_2eq/MJ, the legal limits are:

Table 12: Decreasing FuelEU emissions limits

Period	Reduction	FuelEU limit (gCO_2e/MJ)
2026–2029	2%	89.337
2030–2034	6%	85.690
2035–2039	14.5%	77.942
2040–2044	31%	62.900
2045–2049	62%	34.641
2050	80%	18.232

Table 13 presents the FuelEU penalties for the various alternatives: by period for the unmultiplied benchmark, with the 25-year total of the repeated-deficit scenario in the last column. The combined ETS and FuelEU costs are presented in Table 14.

[41] ABS, FuelEU Maritime – Questions & Answers (accessed 13/10/2026) link.
[42] ABS, FuelEU Maritime – FAQs: FuelEU "refers to the GWPs defined in the RED II, 1, 25 and 298 for CO2, CH4 and N2O", which will align with those of the revised MRV Regulation (EU) 2023/957 (accessed 19/10/2026) link.



Table 13: FuelEU penalty table by period — 100% EU scope (unmultiplied penalty benchmark; last column: repeated-deficit scenario with the Article 23(2) multiplier)

Option	GHG intensity (gCO_2eq/MJ)	2026–2029	2030–2034	2035–2039	2040–2044	2045–2049	2050	25-year total, unmultiplied	25-year total with Art. 23(2) multiplier
HFO	91.74	€4.479m	€14.079m	€32.100m	€67.081m	€132.803m	€34.193m	**€284.735m**	**€797.443m**
LNG, low methane slip	76.08	€0	€0	€0	€36.964m	€116.217m	€32.447m	**€185.628m**	**€306.819m**
LNG, higher methane slip	82.87	€0	€0	€12.684m	€51.412m	€124.174m	€33.285m	**€221.555m**	**€459.015m**
Fossil methanol	100.39*	€18.802m	€31.252m	€47.720m	€79.687m	€139.745m	€34.924m	**€352.129m**	**€930.973m**
E-methanol, with RFNBO reward to 2033	14.10 / 28.20**	€0	€0	€0	€0	€0	€15.084m	**€15.084m**	**€15.084m**
Grey ammonia	121.00	€44.667m	€62.263m	€75.927m	€102.450m	€152.282m	€36.243m	**€473.832m**	**€1,172.106m**
Green ammonia	0 assumed†	€0	€0	€0	€0	€0	€0	**€0**	**€0**
Nuclear MSR	0 assumed‡	€0	€0	€0	€0	€0	€0	**€0**	**€0**

* TBM components will have to be added when certified

** Certified RFNBO e-methanol assumed at 28.20 gCO_2eq/MJ, the highest intensity at which a fuel still qualifies as RFNBO (at least 70% GHG saving);[41] a reward factor of 2 applies until 2033 (14.10). The earlier version assumed 34.55/69.10, but a fuel at 69.10 gCO_2eq/MJ would not qualify as RFNBO and would be treated as the least favourable fossil pathway.

† excluding unresolved N_2O

‡ subject to legal recognition



Table 14: Combined ETS and FuelEU costs (unmultiplied penalty benchmark and repeated-deficit scenario)

Option	25-year ETS cost	25-year FuelEU cost, unmultiplied	Combined, 100% EU scope	Combined, 50% EU scope	Combined with multiplier, 100% EU scope	Combined with multiplier, 50% EU scope
HFO	€106.755m	€284.735m	**€391.490m**	**€195.745m**	**€904.198m**	**€452.099m**
LNG, low methane slip	€78.773m	€185.628m	**€264.401m**	**€132.200m**	**€385.592m**	**€192.796m**
LNG, higher methane slip	€89.304m	€221.555m	**€310.859m**	**€155.429m**	**€548.319m**	**€274.160m**
Fossil methanol	€94.445m	€352.129m	**€446.574m**	**€223.287m**	**€1,025.418m**	**€512.709m**
E-methanol	€0	€15.084m	**€15.084m**	**€7.542m**	**€15.084m**	**€7.542m**
Grey ammonia	€0	€473.832m	**€473.832m**	**€236.916m**	**€1,172.106m**	**€586.053m**
Green ammonia	€0	€0	**€0**	**€0**	**€0**	**€0**
Nuclear MSR	€0	€0	**€0**	**€0**	**€0**	**€0**

4.1.3. CAPEX

Taking as base a new Capesize / Newcastlemax-size bulk carrier ordered now, the newbuilding CAPEX can be approximately estimated as per the following table.

Table 15: CAPEX Estimations for a new Capesize / Newcastlemax-size bulk carrier ordered now

Option	Estimated newbuilding cost	Indicative premium vs HFO	Comment
Conventional HFO / VLSFO eco Capesize	**USD 75–80 million**[43]	baseline	Standard modern Capesize / Newcastlemax-type bulk carrier.
HFO with scrubber	**USD 77-83 million**[44]	+2-3 million	Newbuild scrubber planning allowance; relevant to HSFO use, with scrubber OPEX and washwater requirements excluded from this CAPEX comparison.
LNG dual-fuel	**USD 90–100 million**[45]	+15-25 million	This matches recent large LNG dual-fuel bulker indications around USD 95 million.

[43] C. Jallal, ClarkSea Index rose as world fleet expanded in 2025, Riviera 8/1/2026, link.
[44] Clarkson Research, SO_x Scrubber Payback Analysis, 2017, link.
[45] Himalaya Shipping, Himalaya Shipping Ltd. (HSHP) Announces its Preliminary Results for the Three and Nine Months Ended September 30, 2024, link.



Methanol dual-fuel	**USD 85–95 million**[46]	+10-15 million[47]	Methanol systems are usually simpler than LNG cryogenic systems, but tank volume is much larger than HFO.
Ammonia-ready	**USD 95–105 million**[48]	+20-30 million	Better viewed as "future-proofed," not necessarily ammonia-fuelled from delivery.
Ammonia dual-fuel / ammonia-capable	**USD 110–130 million**	+35-55 million	Still immature commercially; safety systems, tank arrangements and engine availability add uncertainty. Assumed price.
Advanced-reactor nuclear-powered bulk carrier (conceptual)	**USD 300–500 million**	+225-425 million	Not commercially orderable today; conceptual estimate including nuclear island, shielding, electric propulsion, licensing / interface costs and large contingency. [14]

Notes on Table 15

1. As per the Clarksons/Riviera research, the baseline newbuilding price for a conventional Capesize should be assumed to be around USD 75 million. For a large newbuilding, scrubber installation is modelled here as an additional USD 2–3 million; this is a planning allowance, not a Capesize-specific yard quotation, and excludes scrubber OPEX and fuel-spread effects.[49]
2. Himalaya Shipping stated that current newbuilding costs for a dual-fuel Newcastlemax in China were believed to be about USD 95 million. This implies a premium of roughly USD 20 million (25-30%).
3. For an illustrative methanol dual-fuel newbuilding delivered with an operational methanol fuel system, the assumed CAPEX is USD 85–95 million (USD 10–15 million above the HFO reference range). A methanol-ready specification, which only anticipates future conversion, is a different and potentially lower-cost option and is not priced in this row. Methanol storage is less complex than LNG because it does not require cryogenic tanks, but it needs much more tank volume than HFO.[47]
4. The cost of an ammonia-ready Capesize may be broadly comparable to an LNG or methanol-capable newbuilding, around USD 95–105 million, but a genuinely ammonia-fuelled vessel from delivery should be treated as more expensive, approximately USD

[46] A. Čučuk, Deal signed for 3+5 210,000-ton methanol and ammonia reserved bulk carriers, Offshore Energy, 2024, link.
[47] OECD Report, The Role of Shipbuilding in Maritime Decarbonisation,28 April 2025 (accessed 13/11/2026), link.
[48] M.W. Bockmann, Ammonia-ready ships add $22m to newbuilding costs, Lloyd's List, 2022, link.
[49] MJLF & Associates, "A Good Scrub, or Just a Wash?", 18 December 2025 (scrubber installation on larger newbuilds: approx. USD 2–3 million; not a Capesize quotation) link.



110–130 million, because of fuel toxicity, safety zones, ventilation, detection systems, material compatibility, tank arrangements and still-developing engine technology.

Under the present conceptual CAPEX assumptions, nuclear propulsion is (or maybe "will be") by far the most capital-intensive option. Its potential competitiveness depends not on lower construction cost, but on lifecycle economics: avoided fuel expenditure, avoided carbon costs, operational autonomy, possible speed advantages, and the emergence of a specialized licensed nuclear-operator business model.

4.1.4. Decommissioning

For a conventional ship, end-of-life recycling is not usually treated as a major positive cost in the same way as nuclear decommissioning. In many cases, the owner receives scrap value, although this depends on steel price, recycling location, hazardous-material inventory, and environmental standards. However, for the nuclear option decommissioning will be a much larger and more specialized cost because it includes reactor defueling, radioactive waste handling, radiological decontamination, dismantling of the nuclear island, licensing, security, and long-term waste management. The Deon Policy Institute's 2025 report[14] states that nuclear decommissioning costs are often taken as roughly 10–20% of the initial capital cost. Table 16 therefore retains gross, illustrative end-of-life cost allowances for arithmetic comparability. These allowances, especially for LNG, methanol and ammonia systems, are not validated ship-specific net recycling costs; recoverable scrap values are deliberately excluded from every base case. For nuclear, the separate radioactive-waste and licensing obligations remain central.

Table 16: Indicative decommissioning costs for the various fuel options

Option	Gross end-of-life allowance (scenario input)	Notes
HFO	0-5 million USD	Possibly offset by scrap value
LNG dual-fuel	5-10 million USD	Cryogenic tanks and gas systems; *Not reliably quantified; potentially offset by recycling value*
Methanol dual-fuel	0-5 million USD	Possibly offset by scrap value
Ammonia-capable	5-15 million USD	Toxicity-related cleaning, tanks, piping and safety systems
MSR nuclear	40-80 million USD	Final reactor shutdown, removal of nuclear fuel, radiological surveys, decontamination, dismantling of the nuclear island, radioactive waste management, regulatory closure, and then ordinary ship recycling.

4.1.5. Lifecycle perspective

Table 17 brings the previous sections together. It is a simple, undiscounted 25-year sum of newbuilding CAPEX, fuel, EU regulatory costs and decommissioning for the Capesize



case, with euro amounts converted at 1.08 USD/EUR (the 2024 average rate used by DNV) .[6] It is a screening assessment of selected cost components rather than a complete lifecycle business case: crew, insurance, maintenance, nuclear fuel-cycle services not explicitly priced, financing and residual value are not represented. Regulatory costs are shown for the unmultiplied FuelEU benchmark, with the repeated-deficit scenario in the last column. Neither the unmultiplied benchmark nor the repeated-deficit scenario accounts for FuelEU compliance flexibility mechanisms, including pooling, banking of compliance surpluses, or borrowing from future reporting periods. Consequently, the calculated penalties should be interpreted as illustrative regulatory-cost scenarios rather than unavoidable compliance expenditures; the actual cost may be lower depending on the availability and price of alternative compliance arrangements.

The 50% EU-scope values are an assumed effective-exposure sensitivity; an actual EU–non-EU trading pattern includes fully covered EU port energy, so its cost is not automatically half of the full-scope total. Costs are assumed to start in 2026 for comparability, although a nuclear ship, its fuel supply and its licensing could not in practice be available that early.

Three points stand out. First, against the e-fuel options, nuclear fuel savings more than offset its extra CAPEX in this simple sum. Compared with HFO, the outcome depends on how strictly EU rules apply to the ship's trade and on whether repeated FuelEU penalties are assumed. Second, the nuclear range is very wide, and its upper half overlaps with HFO. The result is driven by reactor cost, which no one can yet quote. Third, the comparison is sensitive to the time value of money, because a larger share of nuclear costs is incurred up front (see the discounted results below).

Table 17: Capesize case: indicative undiscounted 25-year cost components (USD million).

Option	CAPEX	Fuel (25 yrs)	EU ETS + FuelEU, unmultiplied (25 yrs)	Decommis-sioning	Total	Total with FuelEU multiplier
HFO (VLSFO), eco Capesize	75–80	225	423 (211)	0–5	**723–733 (511–521)**	**1,277–1,287 (788–798)**
LNG dual-fuel (low slip)	90–100	278	286 (143)	5–10	**659–674 (516–531)**	**790–805 (582–597)**
E-methanol (certified RFNBO)	85-95	916	16 (8)	0–5	**1,017-1,032 (1,009–1,024)**	**1,017-1,032 (1,009–1,024)**
Green ammonia (ammonia-capable)	110–130	882	0	5–15	**997–1,027**	**997–1,027**
Advanced reactor (nuclear)	300–500	26–158	0	40–80	**366–738**	**366–738**

Notes:

- Regulatory costs at 100% EU scope, 50% scope in brackets
- Final column applies the FuelEU Article 23(2) multiplier for consecutive deficits.



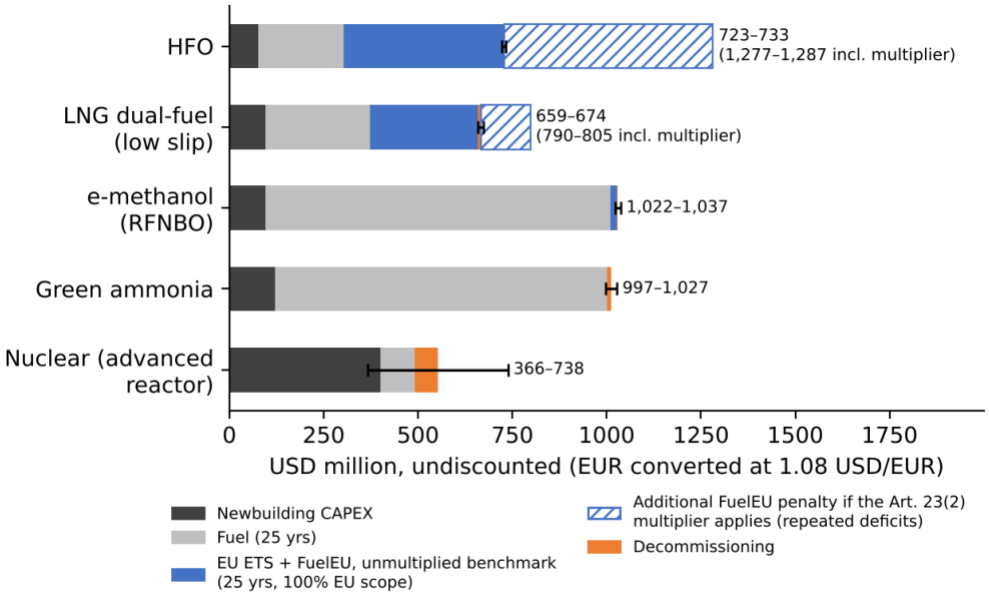


Figure 8: Capesize case: composition of indicative undiscounted 25-year costs (midpoints; range bars show scenario bounds, not statistical confidence intervals).

Blue bars show the unmultiplied FuelEU benchmark; hatched bars show the additional penalty if the Article 23(2) multiplier applies. Crew, insurance, maintenance, financing and residual values are omitted. Source: calculations in this chapter.

Other studies reach similar conclusions. In nuclear propulsion systems, the reactor subsystem accounts for about 70–85% of capital cost and fuel for only about 2–3% of lifecycle cost. Published reactor cost estimates range from about 1,500 to 4,000 USD/kWth.[8] For a 33 MW very large ore carrier, a nuclear sCO_2 system breaks even with a biofuel-compliant conventional ship after about 8–10 years.[8] DNV's fleet simulations suggest nuclear remains competitive at reactor costs up to about USD 18,000/kW if shipping reaches net zero by 2050, but not without decarbonisation, where even at USD 8,000/kW nuclear reaches only about 1.4% of fleet energy use.[6] For containerships, nuclear propulsion appears competitive in scenarios with high cruising speeds and favorable reactor CAPEX, and learning from building and operating the first ships could be decisive.[50]

4.1.5.1. Discounted comparison and sensitivity

Because expenditure occurs at different times, the undiscounted sums above cannot by themselves support an investment conclusion. Table 18 therefore shows present values at an illustrative 8% annual discount rate, keeping the simplified costs of Table 17: CAPEX at the start, constant annual fuel and ETS costs, year-specific FuelEU penalties, and decommissioning at the end of year 25. No operating costs, financing fees or residual

[50] G. Locatelli, N. Guglielmetti, G. Dei, V. Skliarenko, "The economics of nuclear propulsion for containerships", Progress in Nuclear Energy, 196 (2026), 106312, doi.



values are added. Costs are held constant in real terms, so the rate is a real discount rate; 8% is an illustration, not a recommended cost of capital, and other rates are covered by the sensitivity analysis below.

Table 18: Capesize case: present value of the Table 17 cost components at an 8% real discount rate (USD million).

Option	PV, unmultiplied FuelEU, 100% EU scope	PV, repeated-deficit scenario, 100% EU scope	PV, unmultiplied, 50% effective exposure	PV, no EU exposure
HFO (VLSFO), eco Capesize	299–304	419–425	235–241	171–177
LNG dual-fuel (low slip)	285–296	308–319	247–258	210–220
E-methanol (certified RFNBO)	478-489	478-489	477-488	476-487
Green ammonia (ammonia-capable)	487–509	487–509	487–509	487–509
Advanced reactor (nuclear)	317–579	317–579	317–579	317–579

Discounting changes the ranking materially. At 8%, the HFO case costs about USD 299–304 million in present-value terms at 100% EU scope (USD 419–425 million in the repeated-deficit scenario) and the low-slip LNG case about USD 285–296 million, against USD 317–579 million for the nuclear case, whose costs are concentrated at the start. The undiscounted result therefore does not establish an unconditional nuclear cost advantage.

Table 19 and Figure 9 turn the question round. They show the nuclear newbuilding CAPEX at which the nuclear option would match the HFO option in present-value terms, for different discount rates, levels of EU exposure, penalty scenarios and annual fuel consumption. Midpoint values are used for the other cost components (HFO newbuilding USD 77.5 million and decommissioning USD 2.5 million; nuclear fuel USD 92 million over 25 years and decommissioning USD 60 million). At 100% EU scope, the break-even CAPEX reaches the assumed USD 300–500 million range only at discount rates up to about 5% with unmultiplied penalties, or up to about 10% if repeated FuelEU penalties are assumed; at 8% it is about USD 253 million with unmultiplied penalties and USD 374 million with the multiplier. With no EU exposure it is only about USD 120–153 million at any rate considered. At the 2018 Capesize average consumption of 10,100 t/year, the break-even values are roughly 30–40% lower than at 18,000 t/year.

Table 19: Capesize case: break-even nuclear newbuilding CAPEX versus HFO in present-value terms (USD million; midpoint values for the other cost components).

Annual fuel and EU exposure	0%	3%	5%	8%	10%
18,000 t/yr, 100% EU scope, unmultiplied	576	400	327	253	221
18,000 t/yr, 100% EU scope, repeated-deficit	1,129	704	534	374	306



Annual fuel and EU exposure	0%	3%	5%	8%	10%
18,000 t/yr, 50% exposure, unmultiplied	364	271	231	190	171
18,000 t/yr, 50% exposure, repeated-deficit	641	423	335	250	213
18,000 t/yr, no EU exposure	153	142	135	126	120
10,100 t/yr, 100% EU scope, unmultiplied	332	247	210	173	156
10,100 t/yr, 100% EU scope, repeated-deficit	642	417	326	240	203
10,100 t/yr, 50% exposure, unmultiplied	213	174	156	137	127
10,100 t/yr, 50% exposure, repeated-deficit	368	260	214	170	151
10,100 t/yr, no EU exposure	94	102	103	101	99

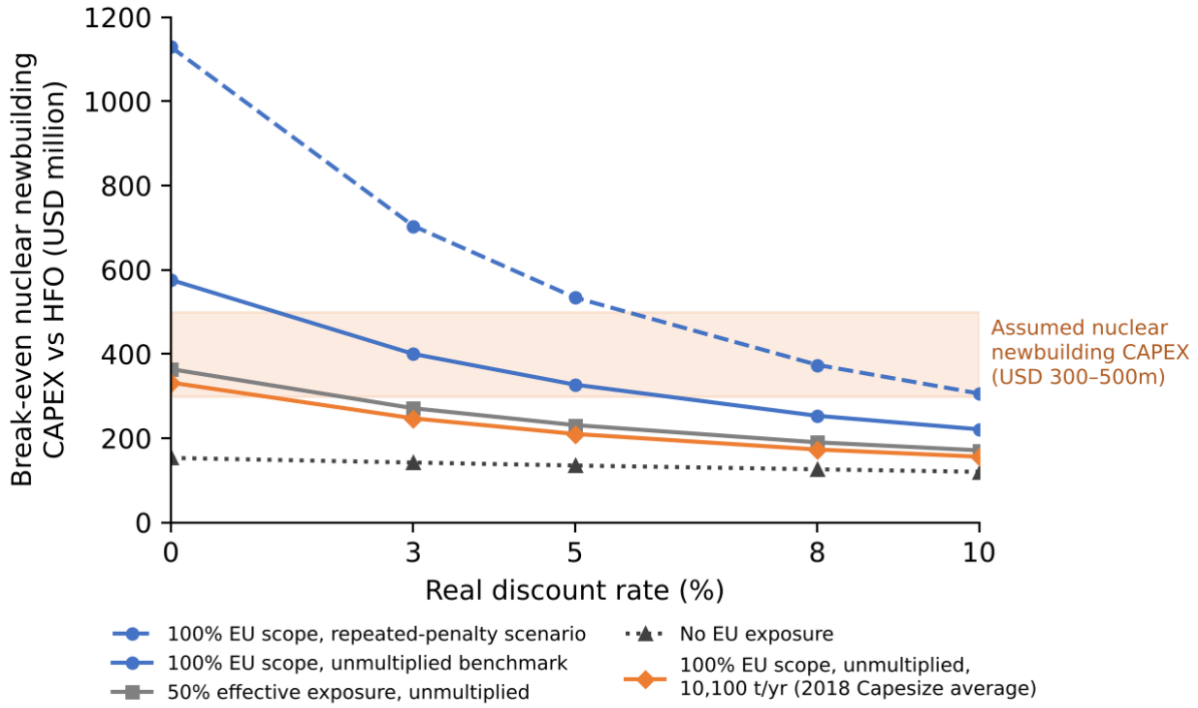


Figure 9: Break-even nuclear newbuilding CAPEX versus HFO as a function of the discount rate, compared with the assumed USD 300–500 million range. Source: calculations in this chapter.

These results indicate that reactor CAPEX, the discount rate, annual fuel consumption and the degree of EU exposure jointly decide the comparison, and that the repeated-penalty and purchased-compliance cases need to be treated separately.

4.1.6. Indicative scaling to other ship types

Table 20 extends the Capesize calculation to other large ship types, using their 2018 average fuel consumption from Table 3, treated as HFO-equivalent, and the same assumptions: 275 operating days, HFO LCV 40.5 MJ/kg, 50% engine efficiency, 40% nuclear thermal-to-useful efficiency, HFO at USD 500/t, EUAs at €75/t, 100% EU scope



and burnup of 50–100 GWd/tHM. Regulatory costs are scaled from the Capesize results in proportion to fuel energy (unmultiplied FuelEU benchmark, with the repeated-deficit total in brackets). Because the IMO totals include auxiliary engines and boilers, applying a single 50% useful-energy factor is a first-order screening simplification. Regulatory costs are not shown for liquefied gas tankers, which burn largely LNG; for these ships, treating the fuel as HFO also understates the energy demand somewhat, because LNG has a higher calorific value.

Table 20: Indicative scaling of the case study to other ship types (25-year values; regulatory costs at 100% EU scope).

Ship type	Fuel (t/year)	Useful power / reactor heat while operating (MW / MWth)	HFO cost, 25 yrs (USD m)	ETS / FuelEU (with multiplier), 25 yrs (€ m)	Nuclear fuel, 25 yrs (tHM)
Capesize (case study)	18,000	15.3 / 38.4	225	107 / 285 (797)	2.6–5.3
Capesize, 2018 average	10,100	8.6 / 21.5	126	60 / 160 (447)	1.5–3.0
Bulk carrier ≥200,000 dwt (VLOC), 2018 average	13,600	11.6 / 29.0	170	81 / 215 (603)	2.0–4.0
Oil tanker ≥200,000 dwt (VLCC/ULCC), 2018 average	19,300	16.4 / 41.1	241	114 / 305 (855)	2.8–5.7
Container ship 14,500–19,999 TEU, 2018 average	31,000	26.4 / 66.1	388	184 / 490 (1,373)	4.5–9.1
Liquefied gas tanker 100,000–199,999 m^3, 2018 average	27,600	23.5 / 58.8	–	–	4.0–8.1

The larger the ship and the more energy it uses, the larger the avoided fuel and carbon costs against which the reactor's CAPEX can be set. This is consistent with the view that the strongest candidates are large, highly utilised ships. On these averages, the reactor heat needed while operating ranges from about 22 MWth for a Capesize to about 66 MWth for a large container ship, well within the power range of small modular reactors (Section 3.4), but below an as-yet-undetermined installed design rating once peak power, margins and availability are considered.

4.2. Operational Benefits

The operational case for nuclear propulsion comes from the fact that, once the reactor is installed, energy is abundant and cheap at the margin.



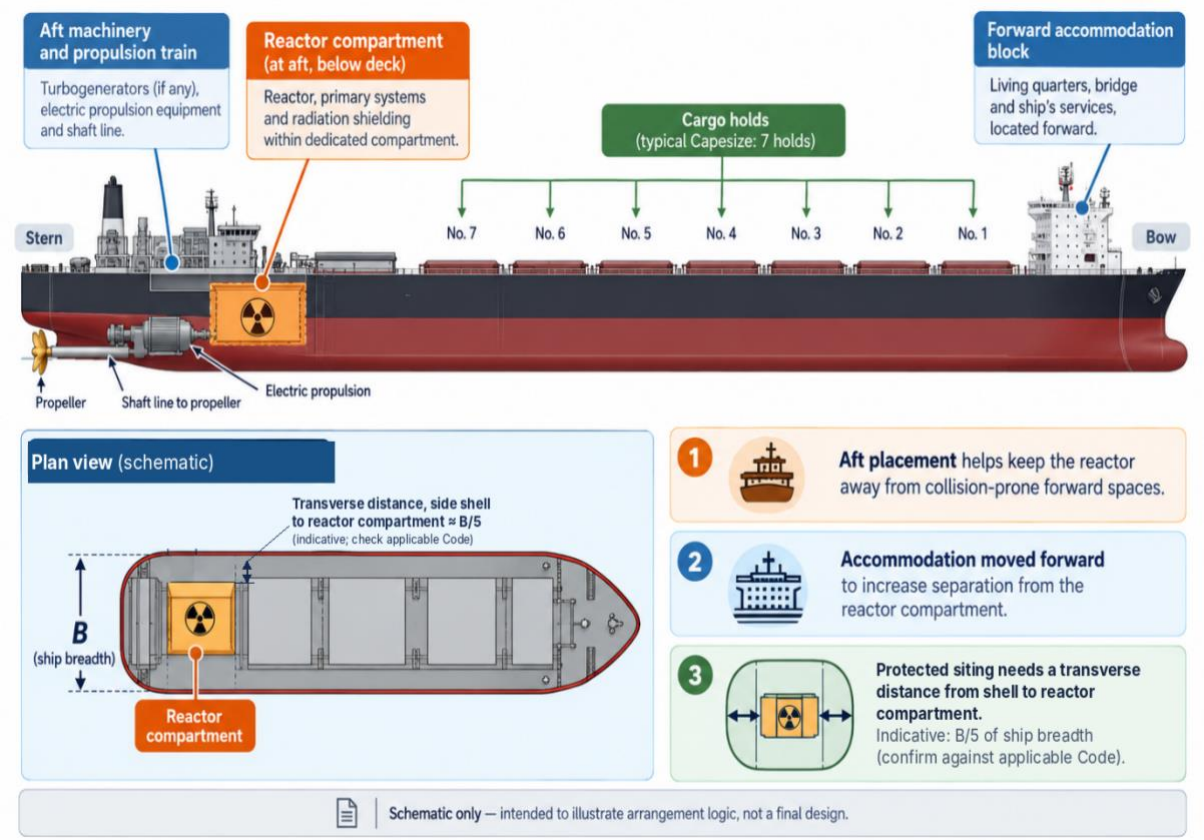


Figure 10: Illustrative (conceptual) arrangement of a nuclear propulsion plant in a Capesize bulk carrier.

Simplified schematic showing a possible aft reactor compartment, forward accommodation block, electric propulsion arrangement, and an indicative transverse protected-siting distance of B/5 (one-fifth of ship breadth) between the side shell and the reactor compartment, shown in a schematic plan view. Neither aft reactor placement nor forward accommodation is a universal requirement, and the applicable siting distance should be checked against the IMO Nuclear Code, which is under revision. The figure is illustrative only and not a final ship design.

A nuclear-powered merchant ship would not simply replace an engine with a reactor and leave the rest of the vessel unchanged. Reactor shielding, compartmentalisation, propulsion architecture and survivability requirements affect the overall arrangement of the ship. Figure 10 shows, in schematic form, the type of layout often discussed in conceptual studies for a large bulk carrier. In such layouts, accommodation and navigation spaces are typically moved forward and the nuclear island retained aft.[8] The arrangement shown illustrates why nuclear propulsion is more feasible on large ships than on small ones. Large hulls provide the space needed for shielding, protected siting and separation between the reactor compartment and accommodation.

4.2.1. Higher speed and more voyages

In a conventional ship, fuel consumption rises steeply with speed. DNV notes that many vessels now sail below their design speed because of GHG regulations. A nuclear vessel could operate at design speed without regulatory penalties, because nuclear fuel costs are low compared with CAPEX.[6] The historical ships already showed that the cost



penalties of high-speed operation in oil-fired ships do not apply to nuclear ships.[16] Hyundai KSOE calculations for a 15,000 TEU container ship with a 90 MWth reactor show speed rising from 20 to 25 knots. A typical voyage would shorten from 54–70 to 40–56 days, allowing 15–17 instead of 10–12 voyages per year.[14] Designing for higher speed does require more installed power and a stronger hull, shaft and propeller, which raises CAPEX.[6] How much speed is worth depends on the segment. It is clearest in liner trades and less certain in tramp bulk markets, where freight rates and port waiting times set the pace.

4.2.2. Refueling intervals

Ships are normally dry-docked every five years, and DNV considers five years the minimum desirable refuling interval.[6,14] Today's land-based PWRs refuel about every two years, with outages of up to two months. Some Generation III+ designs aim for 4–5 years, and liquid-fuel concepts promise up to 20 years of operation.[14] At sea, the older Russian Arktika-class icebreakers refuel every 3–4 years, while the newer Project 22220 icebreakers with RITM-200 reactors are quoted at 6–7 years.[32] Refuling takes about 6–8 weeks and can only be done by licensed personnel at certified yards.[14]

4.2.3. Avoided bunkering and fuel-supply risk

A nuclear ship does not depend on the availability of new alternative fuels in each port, and leasing a reactor at a known cost can remove the risk premium of uncertain future fuel prices.[8,6] The trade-off is a new dependence on a small number of nuclear fuel suppliers and licensed yards (Section 4.4).

4.2.4. Cargo capacity

Without fuel tanks or a main engine, space can be freed for cargo. In the Hyundai KSOE 15,000 TEU concept, about 800 additional TEU could be carried.[14] On the other hand, the reactor compartment, shielding and collision protection impose their own constraints. IMO Nuclear Code, currently under revision mandates that the nuclear installation must lie at least one-fifth of the ship's breadth from each side, and concept drawings often omit essential support systems.[14] DNV therefore assumes equal cargo capacity for nuclear and conventional ships in its cost studies.[6]

4.2.5. Power for ports

A nuclear ship can also supply electricity to shore while it is at berth. A simulation of a container ship with a lead-cooled fast reactor found avoided emissions of 25.0 kt CO_2 per



year at sea and a further 17.1 kt per year during port stays, including electricity sold to the onshore grid. Electricity revenues were €2.13 million per year, and the minimum payback was 6.4 years.[51]

4.3. Strategic Benefits

4.3.1. Shaping the international rules

The IMO has started revising SOLAS Chapter VIII and the 1981 Nuclear Code. The revision is meant to make the Code technology-neutral and goal-based and to align it with current IMO instruments (MARPOL, STCW, the Hong Kong Convention) and IAEA standards.[19] The work plan approved at MSC 111 (May 2026) foresees finalisation of the revised Code in 2030.[7,52] Greece is the largest shipowning nation and has a history of defending its own maritime positions in the IMO, including against common EU positions.[21] That gives it both the standing and the incentive to engage in this work in the IMO, NEMO and IAEA processes. Port access, liability and how flag states and port states share responsibility will all be decided there. Greece could also use its role in the IMO and its mediating position between the IMO and the EU to shape the wider debate, including through MEPC.[14]

4.3.2. Know-how, universities and research

Greece has a small but real nuclear knowledge base. It includes experience in operating and decommissioning the research reactor at NCSR "Demokritos", the subcritical reactor of NTUA's nuclear technology department, and the Greek Atomic Energy Commission (EEAE).[14] Greek engineers are active in the field: two of the four authors of the Deon study work at Core Power and ABS.[14] NTUA's School of Naval Architecture and Marine Engineering is publishing on marine nuclear power cycles,[8] but also the School of Mechanical Engineering of NTUA as well as other universities are active. Strengthening these institutions, and adding basic nuclear content to merchant navy training, would build the human capital that any later deployment needs.[14]

4.3.3. Shipyards

Greek ship repair activity fell from 1,575 ships in 2000 to 339 in 2013, then recovered to about 651 ships in 2023. Repaired capacity fell from 16 million GRT in the early 2000s to 4 million GRT in 2016 and has since recovered to about 8 million GRT.[14] US efforts to

[51] G. Barone, A. Buonomano, G. Del Papa, C. Forzano, G.F. Giozio, R. Maka, G. Russo, A. Palombo, "Nuclear lead-cooled fast reactor (LFR) for naval propulsion and shore connection: An energy, economic and environmental analysis", Applied Thermal Engineering (2025), 127354, link.
[52] ClassNK, "IMO MSC 111" session summary (13–22 May 2026) (accessed 13/10/2026) link.



rebuild Western shipbuilding and reduce reliance on Chinese yards could create openings for allied countries in parts of the nuclear-maritime supply chain.[14] Fuel handling and refueling would require specially licensed nuclear facilities.[6] Realistic early roles for Greek yards are therefore in conventional repair, hull and non-nuclear systems, with nuclear-licensed activities as a longer-term option.

4.3.4. Port-energy business models

FuelEU obliges container and passenger ships to use shore power at major EU ports from 2030.[8] Deon's 2026 study found no fundamental barriers to floating nuclear power plants in Greece and identified maritime applications as a possible entry point for a gradual national strategy (Chapter 5).[12]

4.3.5. Energy security

Nuclear propulsion reduces dependence on emerging alternative-fuel supply chains.[8] It also creates a new dependence. HALEU is currently supplied mainly by Russia's TENEX, which makes it scarce in the West, and Western nuclear fuel supply chains are limited and under pressure as they reduce reliance on Russian enrichment.[14,6] For Greece, energy security is therefore an argument for allied supply-chain cooperation, not for nuclear by itself.

4.3.6. Positioning

Taken together, these strands would let Greece act as an early, serious participant in clean-shipping technology without hosting nuclear ships prematurely. The Prime Minister has already stated that Greece intends to lead on the shipping dimension of nuclear energy, separately from any domestic role.[22]

4.4. Challenges

The obstacles to maritime nuclear power are numerous, but they are not all of the same kind. Some concern reactor technology and fuel supply, others are regulatory, commercial or societal. Figure 11 groups the principal barriers identified in this report and shows, at a glance, why the challenge is broader than engineering alone.





Figure 11: Main barriers to the use of nuclear power in Greek shipping.

Overview of the principal barriers identified in this report, grouped into technology, regulation, commercial factors and society. The figure highlights the report's central finding that the hardest barriers are institutional and commercial rather than purely physical. Licensing lead times range from 5–10 years for familiar concepts to 15–20 years for new concepts in less-prepared settings, and engineering maturity has not yet been demonstrated for any merchant design.

The figure reinforces an important conclusion of the report: the critical barriers are not the basic physics of propulsion, but the supporting framework around it. Licensing, liability, port access, insurance, financing and public acceptance are likely to determine the pace of any future deployment more than reactor thermodynamics. For Greece, this implies that early preparation should focus as much on institutions and governance as on technology monitoring.

4.4.1. Licensing framework

Under the United Nations Convention on the Law of the Sea (UNCLOS), nuclear-powered ships enjoy, in principle, the same rights of innocent passage and freedom of navigation as conventional vessels, subject to additional precautionary requirements. However, SOLAS Chapter VIII and the 1981 Code of Safety for Nuclear Merchant Ships (Resolution A.491(XII)) were developed primarily around pressurised water reactor (PWR) technology.[6] Their application to advanced reactor concepts therefore presents significant regulatory challenges. Until the revised Code is adopted (currently planned for 2030), approval of new designs may require alternative-design procedures, while bilateral arrangements may also be necessary to facilitate access to foreign ports.[6,7]



Licensing is not a single approval granted by one authority. It is a multi-layered process involving both nuclear and maritime institutions, with potential iterations whenever design modifications affect safety assessments, classification requirements or port-entry conditions. A reactor requires authorisation from a competent national nuclear regulator, while the flag State must have the legal framework and technical capacity to certify a nuclear-powered merchant ship. Classification societies contribute through their technical rules, design assessments and verification activities, whereas the IMO and IAEA provide the international regulatory and safety frameworks within which national authorities operate.[6] Figure 12 illustrates the responsibilities and interactions of these organisations, highlighting why the licensing process is more complex than that of a conventional merchant vessel.

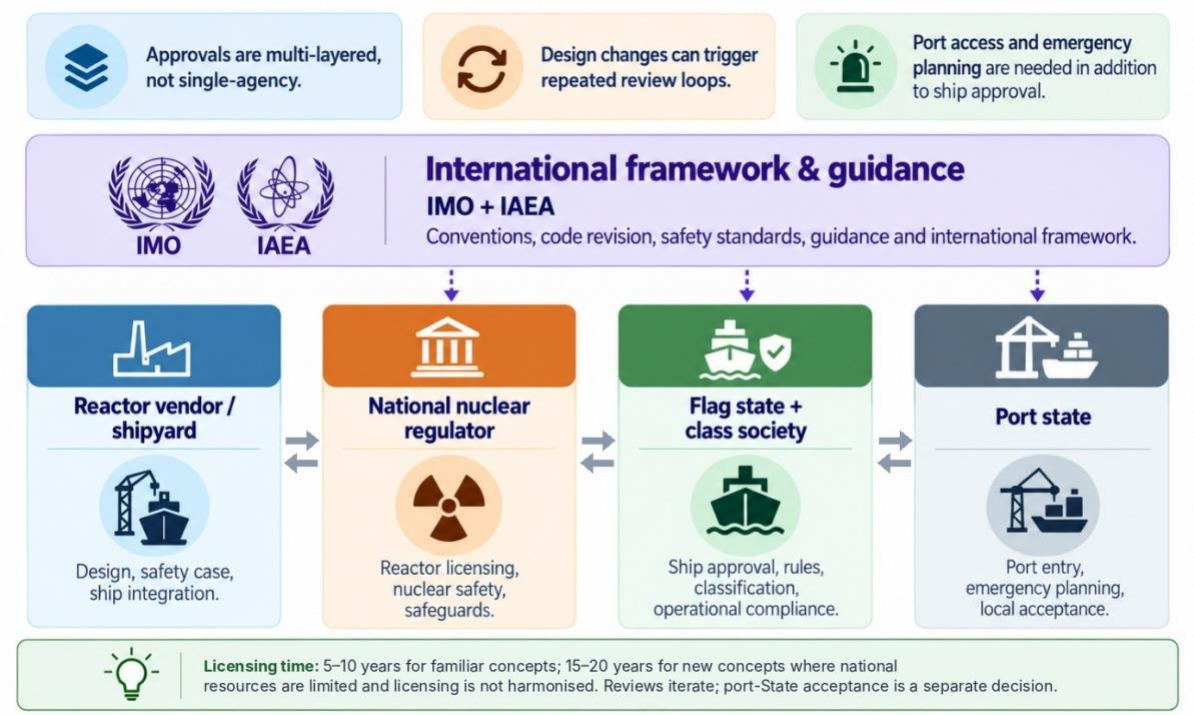


Figure 12: Regulatory responsibilities and approval framework for a nuclear-powered merchant ship.

Simplified representation of the principal organisations involved in maritime nuclear propulsion, from reactor design and national nuclear regulation to flag-State certification, classification and port-State acceptance. The IMO and IAEA provide international instruments, standards and guidance rather than ship-specific licences. Two-way arrows indicate iterative review between the parties; port-State acceptance is a separate decision, not an automatic consequence of flag-State and class approval. Source: Adapted from DNV (2025) and IMO (2026).

The complexity helps explain the long timescales associated with licensing nuclear-powered merchant ships. DNV estimates that licensing may take 5–10 years for established reactor technologies and 15–20 years for new technologies, particularly where national regulatory resources are limited or licensing systems are not harmonised.[6] Moreover, approval by the flag State does not automatically guarantee access to foreign ports, where additional national requirements and emergency preparedness arrangements may apply.



For Greece, these considerations are particularly important. The operation of nuclear-powered vessels under the Greek flag would require a clear regulatory framework, an appropriately defined mandate for the Hellenic Atomic Energy Commission (EEAE), and substantially strengthened institutional and technical capacity.[14] Even if commercial deployment is not envisaged in the near term, early engagement with international rulemaking, regulatory cooperation and institutional capacity-building would allow Greece to prepare for potential future applications while protecting the operational flexibility of its merchant fleet.

4.4.2. Port access and emergency planning

Experience with the first merchant nuclear ships showed that port and canal access may be difficult and restricted.[16] Coastal states may impose non-discriminatory safety requirements and regulate access to their ports, including emergency preparedness measures.[6] Many countries, Greece among them, have legislation or bilateral agreements for nuclear-powered military vessels, but not for commercial ones. The first commercial nuclear ships will therefore probably trade between countries with established nuclear regulators under bilateral agreements.[14] Land-based plants have emergency planning zones several kilometers wide, which would be difficult in dense ports and canals. Some Generation IV designs aim for zones limited to the site boundary, and NuScale has already received US approval for a reduced zone.[14]

One potential approach to overcoming port-access restrictions is the development of Pink Corridors: designated shipping routes connecting ports that cooperate in establishing the regulatory, safety, security and operational conditions necessary to accommodate nuclear-powered merchant vessels. Such corridors could provide a practical pathway for early commercial deployment by concentrating regulatory preparation, emergency planning and infrastructure requirements on a limited number of participating ports.

A first initiative was announced in September 2026 by Lloyd's Register, A.P. Moller–Maersk and the ports of Felixstowe (UK) and Charleston (USA)[53,54]. The project examines the requirements for a hypothetical nuclear-powered container ship operating between the two ports, including nuclear safeguards, ship security, cyber resilience, emergency response, insurance and regulatory alignment. It remains an exploratory project rather than an approved or operational shipping corridor.

[53] Lloyd's Register, Pink Corridor project to explore safety requirements of nuclear-powered transatlantic container shipping route, Press Release 2 Sept 2026 (accessed 13/11/2026), link.
[54] World Nuclear News, Project to consider trans-Atlantic nuclear-powered cargo ships (accessed 13/11/2026), link.





Figure 13: "Pink Corridor" (illustrative) between the ports of Felixstowe (UK) and Charleston (USA).[53]

Pink Corridors could initially favour vessels operating on predictable, fixed routes, particularly container ships under long-term service arrangements. Their relevance to tramp shipping is more complicated, since bulk carriers and tankers require greater flexibility in selecting ports and changing trading patterns. **For Greek shipping, therefore, the development of an international network of nuclear-ready ports may ultimately be as important as the availability of commercially viable marine reactors**.

4.4.3. Spent fuel and radioactive waste

Storage and disposal of spent fuel are fundamental to the credibility of the supply chain, and the requirements depend on reactor and fuel type. They must be addressed before any operating license is granted, and an interim storage facility is a prerequisite for a commercial nuclear fleet.[6] Greece has no nuclear power programme, so the back end of the fuel cycle would have to be provided by the reactor supplier or operator, or through international arrangements.

4.4.4. Safeguards and non-proliferation

All nuclear material is subject to IAEA safeguards. For the merchant reactor concepts assessed here, the analysis assumes LEU or HALEU fuel enriched to less than 20% U-235. This design assumption reflects non-proliferation, safeguards and commercial-acceptability considerations; it should not be read as a universal prohibition of civilian use of highly enriched uranium, which some civilian maritime reactors have used.[6] An international system for accountancy and control of mobile reactors still has to be established.[6] A Greek deployment would require a defined safeguards, accountancy and physical-protection framework for the reactor and its fuel throughout construction, operation, transport and the back end of the fuel cycle. As a non-nuclear-weapon state under the NPT, Greece would apply full safeguards to any nuclear ship or floating plant



under its control. NEMO and the IAEA held their first joint workshop on safeguards for maritime nuclear systems in March 2025.[14]

4.4.5. Security and piracy

Maritime installations must be designed against collision, grounding and sinking, as well as sabotage, terrorism and piracy. They need remote monitoring, secure communications and rigorous cybersecurity.[6] Early nuclear ships would probably be restricted to routes with lower piracy risk.[14] For a fleet that trades globally, that is a commercial limitation in itself.

4.4.6. Insurance

P&I club rules exclude nuclear risks arising from the fuel of a nuclear-powered entered ship (see, for example, The Swedish Club's rules).[11] Nuclear insurers and the maritime insurance market do not yet share a common framework, although discussions have begun.[14] Without a liability cap, insurance could become prohibitively expensive for operators.[10] It is significant that NuProShip planned to bring insurance companies into its second phase.[18]

4.4.7. Liability

There is no global liability framework for operators of civil nuclear-powered ships. The 1962 Convention on the Liability of Operators of Nuclear Ships was signed by a few countries but never entered into force, and it cannot be ratified in its present form. Its definition of "nuclear damage" does not cover environmental damage, and its limits are expressed in gold.[10] Flag-state certification must consider adequate liability cover.[6] A modern liability regime, or bilateral arrangements in the meantime, is therefore a precondition for commercial trading.

4.4.8. Public acceptance

Acceptance will depend on public confidence as much as on technical performance.[6] The Deon Policy Institute's 2026 study found social acceptance of nuclear energy in Greece to be low compared with other countries and called for more public education and engagement.[12] Its survey evidence is more nuanced than a single acceptance figure: in a survey conducted by Athlos Energy in August 2025, 30.3% of respondents supported nuclear energy and 42.8% opposed it, while about 49.6% expressed positive views of nuclear propulsion for large commercial vessels and 48.6% of floating nuclear power plants.[13] Attitudes therefore differ between applications and should not be equated.



Acceptance is likely to be most restrictive for passenger ships such as cruise ships, despite their otherwise favourable technical profile.[8]

4.4.9. Crew and training

Nuclear ships require specialised education in nuclear engineering, radiological safety and system operation, beyond traditional marine engineering skills.[8] The Savannah needed more than three times the crew of a conventional ship, and keeping nuclear manning small remains a largely unaddressed issue.[6] The nuclear roles needed include senior reactor operators, reactor operators, nuclear material control and accounting staff, and security personnel. Regulators may initially require more operators and less automation than designers propose.[14] The IMO revision aims to align the Nuclear Code with STCW.[19]

4.4.10. Fuel supply chain

Many new designs need HALEU, for which the West currently depends on limited supply. Production capacity is being developed in the US, and costs are high.[14,36] Export controls and sanctions affect both the front and the back end of the fuel cycle.[6]

4.4.11. Financing and business model

Conventional ship finance, built on low CAPEX and fuel-driven operating costs, is poorly suited to nuclear ships. Long-term power purchase agreements, leasing or “energy-as-a-service” models, public–private partnerships and state guarantees may be needed.8 Under nuclear law, a licensee must hold long-term responsibility for the reactor, its fuel, waste and decommissioning. No shipping company currently meets these criteria, so the first ships are likely to involve licensed nuclear operators, for example in a “power-by-the-hour” arrangement.[6,14] How such ships could be sub-chartered or resold is still unresolved.[14] For Greek owners, whose business model relies heavily on chartering and sale-and-purchase, this is a central issue.



5. Benefits for Greek Ports and Maritime Infrastructure

This report focuses on long-distance shipping, but nuclear technology could affect Greek ports in three ways: as a source of power, as a source of clean fuels, and as host to visiting nuclear ships.

5.1. Shore power and floating nuclear power plants

From 1 January 2030, container and passenger ships moored at the major EU ports covered by the Alternative Fuels Infrastructure Regulation must connect to onshore power supply (OPS) for all their electrical needs at berth. From 2035 the obligation extends to other ports where OPS is available, unless the ship uses an approved zero-emission technology.[39] Projects to supply cleaner shore-side electricity at Piraeus and Heraklion have already been funded.[14] Large ports will therefore need substantial, firm low-carbon power.

Floating nuclear power plants are one possible long-term source. The Deon Policy Institute's 2026 study, the first of its kind for Greece, assessed FNPPs with a PESTLE framework. It found "no fundamental barriers to implementation" and concluded that "the challenge is not one of feasibility, but of framework development". It also found that Greek policy, legal and regulatory frameworks do not yet substantively address nuclear energy or FNPPs, that limited domestic nuclear experience is a technical obstacle, and that financing and economic viability remain open questions. Its recommendation was a gradual, institutionally organised strategy with maritime applications as a possible entry point.[12] Russia's Akademik Lomonosov shows that the concept works in practice, and ABS has published class requirements for nuclear power systems on vessels, barges and offshore units.[14]

5.2. Nuclear energy for marine fuel production

Reactors can provide both electricity and high-temperature heat for hydrogen, ammonia and methanol production.[14] A Greek case study of liquid "pink" hydrogen from SMRs for maritime use found a levelised cost of €6.64/kg at an SMR CAPEX of €10,000/kW, too high to compete with diesel under current conditions. Viability would require carbon costs of at least €0.387/kg and diesel prices above €0.70/L, and fewer than 1,000 SMR units (77 GW) would then suffice for economies of mass production. With lower carbon and fuel prices, more than 10,000 units (770 GW) would be needed, which the authors consider



impractical.[55] Nuclear-based fuel production for Greek ports is therefore a long-term option that depends heavily on carbon prices.

5.3. Hosting nuclear ships

If commercial nuclear ships are to call at Greek ports, the port regulatory framework will need adapting, as it must for any new fuel.[14] That means emergency planning, port-entry procedures and coordination between the port authority, the Hellenic Coast Guard and the EEAE. Refuling and the handling of fresh and spent fuel would be confined to specialised, licensed yards and ports.[6] US and French nuclear aircraft carriers already visit Greek waters, so there is relevant operational experience to draw on.[14]

Participation in future Pink Corridor initiatives could offer Greece an opportunity to develop regulatory expertise, strengthen cooperation between port authorities and nuclear regulators, and position selected Greek ports within emerging nuclear-powered shipping networks. Initial involvement need not entail immediate acceptance of nuclear-powered vessels. Feasibility studies, bilateral cooperation and participation in international pilot projects could help establish the requirements for future port readiness.

The June 2026 Rotterdam study[56,57], undertaken by Lloyd's Register, CORE POWER, Maersk and the Port of Rotterdam Authority, provides a relevant precedent. It found that existing port safety and risk-management frameworks could offer a starting point for assessing nuclear-powered commercial vessel calls, provided that nuclear-specific requirements were incorporated. **A comparable assessment could help determine whether any major Greek port could eventually participate in a Pink Corridor**.

5.3.1. Environmental radiation monitoring and emergency preparedness

The potential accommodation of nuclear-powered merchant vessels or floating nuclear power plants would also require an appropriate environmental radiation monitoring framework. Greece possesses relevant scientific experience in this field. Research conducted at the Nuclear Engineering Laboratory of NTUA includes gamma-spectrometric analysis of environmental samples, atmospheric radionuclide monitoring,

[55] E. Pompodakis, T. Papadimitriou, "Techno-Economic Assessment of Pink Hydrogen Produced from Small Modular Reactors for Maritime Applications", Hydrogen, 6(3) (2025), 47 doi.
[56] Lloyd's Register, Rotterdam study sets out pathway for nuclear-powered commercial ship port calls, Press release 11 June 2026 (accessed 13/11/2026), link.
[57] CORE POWER, CORE POWER, Maersk, LR and the Port of Rotterdam publish study on port calls for nuclear ships, Press Release 13 June 2026 (accessed 13/11/2026), link.



and investigations into the influence of natural radioactive background on measurement sensitivity[58,59,60].

Related investigations have also addressed the distribution of natural and artificial radionuclides in marine sediments of the North Aegean Sea.[61] These studies demonstrate relevant measurement and analytical expertise, although they do not constitute an operational monitoring system specifically designed for nuclear-powered shipping. Any future port-hosting arrangement would require a dedicated assessment of baseline radiation levels, monitoring objectives, detector capabilities, environmental sampling protocols and emergency response requirements.

5.4. Short-sea and coastal shipping

For Greek domestic ferries, electrification is the more relevant pathway. The ELECTRA-GR project found that fully electrifying the Salamis–Perama route would cut about 900 t CO_2 per year, with a 15-year net present value of €1.6 million. Hybrid conversion of the lower-traffic Chios–Oinousses route would cut 85 t per year but has a negative net present value (−€1.69 million). The main obstacles are port infrastructure, regulatory gaps and limited industrial readiness.[9] This supports the conclusion that nuclear is relevant to Greece's deep-sea fleet, not to its coastal services.

[58] M.J. Anagnostakis, Environmental radioactivity measurements and applications – Difficulties, current status and future trends, Radiation Physics and Chemistry 2015, 116, pp. 3-7, doi.
[59] K. Kanoutos, N. Petropoulos, M. Anagnostakis, Radon progeny monitoring outdoors using multiple NaI detectors, Journal of Environmental Radioactivity 2026, 298, 108099, doi.
[60] I. Mitsios, N. Petropoulos, M. Anagnostakis, Influence of short lived radon and thoron progeny on the γ-spectroscopic analysis of low activity environmental and aerosol samples, Radiation Measurements 2024, 174, 107105, doi.
[61] I. Mitsios, F. Pappa, D. Patiris, P. Rouni, M. Anagnostakis, C. Tsabaris, In Depth Analysis of a Sediment Core from North Aegean Sea, Advances in Nuclear Physics 2022, 28, HNPS2021, doi.



6. Conclusions – Roadmap

Nuclear propulsion is a credible long-term option for selected large, highly utilised vessels, particularly where trading patterns and contractual arrangements support recovery of substantial capital investment. The present assessment supports continued technical and institutional preparation, but does not establish a universal cost advantage or an immediately deployable business case. Greece's next steps should concentrate on regulatory capacity, international rulemaking, design-specific feasibility studies and commercial arrangements for fuel supply, liability, insurance and decommissioning. Participation in pilots should follow evidence that these requirements can be met, rather than a calendar target alone.

Nuclear power cannot be an immediate replacement for conventional marine fuels across the Greek-owned fleet. However, it may become a strategic option for specific high-energy maritime applications, especially large long-distance vessels and port-energy systems. Greece's main opportunity is to prepare early: by building regulatory expertise, participating in international rule-making, supporting research, assessing port and shipyard implications, and ensuring that Greek shipping remains influential in the next technological cycle of maritime transport.

Greek shipping could benefit from nuclear power not only through possible future fuel-cost savings and zero-carbon propulsion, but also through strategic positioning: influence over emerging regulations, participation in new maritime energy value chains, modernization of ports and shipyards, and protection of Greek shipping competitiveness under stricter decarbonization rules.

6.1. Roadmap

6.1.1. Phase 1: Knowledge and monitoring, 2026–2027

Create a Greek working group on nuclear maritime applications. Monitor IMO, IAEA, ABS, Lloyd's Register, CORE POWER, Maersk, NYK, Hyundai KSOE, Westinghouse, Seaborg and other actors. Build on the inter-ministerial committee approved in July 2026[15], give it an explicit maritime work stream, and also follow NEMO, DNV and the IMO SDC correspondence group on nuclear power.[7] Map existing Greek academic and research capabilities relevant to maritime nuclear applications.

Responsible institutions (proposed): Inter-ministerial committee on nuclear energy, with a maritime work stream led by the Ministry of Maritime Affairs and Insular Policy; EEAE; NTUA and other universities; the Union of Greek Shipowners. **Decision gate:** a maritime work stream with a mandate and resources is in place, and a gap analysis of Greek legislation and institutional capacity has been completed.



6.1.2. Phase 2: Regulatory preparation, 2027–2030

Review Greek law on nuclear-powered commercial vessels entering Greek ports. Develop emergency planning and port protocols. Prepare national positions for the IMO revision of SOLAS Chapter VIII and the Nuclear Code, which is planned for finalisation in 2030,[7] and for a modern nuclear-ship liability regime. Strengthen the Hellenic Atomic Energy Commission. This effort should also draw upon existing academic expertise in nuclear engineering, reactor physics and radiological monitoring. Research conducted at NTUA demonstrates relevant capabilities in advanced nuclear fuel assessment, thermal-hydraulic safety analysis and radiation measurements.[34,58,62] Recent work on the educational reuse of NTUA's subcritical MAGNOX graphite pile could also contribute to nuclear engineering education and personnel training.[63]

Responsible institutions (proposed): Ministry of Maritime Affairs and Insular Policy (including the Hellenic Coast Guard and the Greek delegation to the IMO); EEAE; Ministry of Environment and Energy. **Decision gate:** draft legal provisions for the port entry of commercial nuclear ships and a funded EEAE mandate exist, and Greek positions have been submitted to the IMO revision of the Nuclear Code.

6.1.3. Phase 3: Port and shipyard feasibility studies, 2028–2032

Assess Piraeus, Heraklion, Alexandroupoli and Greek shipyards as potential sites for nuclear-related port energy services, repair capacity, or support infrastructure.

Responsible institutions (proposed): Port authorities of the candidate ports and Greek shipyards, with EEAE, the Hellenic Coast Guard and universities. **Decision gate:** site-specific feasibility, emergency-planning and cost studies show at least one viable application with identified financing.

6.1.4. Phase 4: Participation in international pilots, 2030–2035

Greek shipowners, universities and regulators could participate in international demonstration projects without Greece necessarily hosting nuclear vessels immediately. Projects such as Norway's NuProShip show how shipowners, yards, class, universities and the maritime regulator can work together in such consortia.[18] Greek participation in international Pink Corridor initiatives should also be explored, initially through regulatory

[62] E.D. Poulopoulou, N.M. Lymperea, A.A. Nikoglou, N.P. Petropoulos, An experimental study of the bottom flooding rewetting front velocity on a hot vertical rod at low flowrates and atmospheric pressure; assessment of linear and non-linear modelling and of RELAP5-3D/ver4.3.4 predictions, Nuclear Engineering and Design (2024), 427, 113431, doi.

[63] I.D. Kourasis, V. Theos, M.I. Savva, W.J. Mohammad, S. Chatzidakis, N.P. Petropoulos, Neutronics Modeling of NTUA's Subcritical MAGNOX Graphite Pile in View of its Redeployment as a Reactor Mock-Up for Educational Purposes. Nuclear Science and Engineering (2026), 1–22. doi.



cooperation and port-readiness assessments, and subsequently through potential pilot routes involving Greek-controlled vessels or selected Greek ports.

Responsible institutions (proposed): Greek shipowners and the Union of Greek Shipowners, universities and classification societies, with the flag administration and EEAE. **Decision gate:** an international pilot with a defined reactor design, licensing route, fuel supply, insurance and liability arrangements is available, and a design-specific feasibility study supports Greek participation.

6.1.5. Phase 5: Commercial adoption, post-2035

Greek shipping may adopt nuclear propulsion selectively where it is commercially, legally and socially acceptable.

Responsible institutions (proposed): Shipowners and licensed nuclear operators, with flag-State and port-State authorities. **Decision gate:** the revised IMO Code is adopted, liability and insurance frameworks are in place, and a design-specific business case holds under discounting and realistic EU exposure.

