Electrification and deep-ocean kelp could cut United Kingdom transport emissions by about 90% for less than the 2026 fuel bill

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Abstract

We apply the same annual, spatial-zone-constrained least-cost transport model used in the accompanying reference analysis to the United Kingdom, changing country-specific demand, fuel-price, power-resource, biofuel and marine-area inputs while leaving the optimisation structure, kelp conversion physics, Grid Harvester model, lifecycle screen, Monte Carlo design and robustness logic unchanged. The UK segment mapping represents 596.0 TWh yr^{-1} of road, off-road, aviation, shipping and rail energy. At today's technology costs the optimised low-carbon energy supply costs €66.2 billion yr^{-1} (about £55.9 billion), slightly below the October 2026 fossil comparator of €68.0 billion (about £57.5 billion), before an estimated central £4.6 billion yr^{-1} electric-vehicle purchase premium.

With the same learning, lower-finance and efficiency levers used in the reference model, annual energy-supply cost falls to €39.5 billion (£33.4 billion), compared with a same-demand October 2026 fossil bill of £54.6 billion. The least-cost case builds 69.5 GW of PV and 39.3 GW of onshore wind, uses 173 TWh yr^{-1} of new electricity, and cultivates 19,470 km^2 of kelp producing 38.9 Mt dry biomass yr^{-1}. Screening well-to-wheel emissions are 21.2 versus 181.8 $MtCO_2e$ yr^{-1}, a 88.3% reduction; the predefined lifecycle-factor range gives 83.5–92.2%.

Across 1,000 Monte Carlo draws, median energy-supply cost is £39.9 billion yr^{-1} (5th–95th percentile £35.8–44.8 billion), and £45.6 billion including vehicle premia. 99.4% of draws remain below the October 2026 fossil comparator after vehicle premia. The result is conditional rather than a forecast: the UK marine areas are transparent screening envelopes, not a permitting-grade GIS inventory, and commercial deep-ocean kelp yield, depth cycling and storm survivability remain the largest physical uncertainties.

Introduction

The United Kingdom is a substantial oil producer but is nevertheless exposed to internationally priced petroleum products. DUKES 2026 reports that the UK was a net importer of petroleum products in 2025, while transport remained the dominant final-energy use. ECUK 2026 reports 55.0 mtoe of transport energy, with road transport 72.4%, air 24.4%, rail 1.8% and water 1.4%; 92.4% of transport final energy remained petroleum. These top-down ECUK totals use accounting boundaries that differ from the product-volume mapping used here, especially for international bunkers, biofuels and non-road fuel, so they are a consistency check rather than an identity with the model total [1,2].

The modelling question is the same as in the reference country case: can an oil-exposed industrial economy supply the transport services represented in the model from low-carbon sources at a cost competitive with fossil fuel, while retaining energy-dense fuels for aviation, shipping and difficult machinery? The supply set includes direct electrification, existing renewable fuels, residue fuels, electrofuels and a complete offshore-kelp chain. Kelp is cultivated without cropland or freshwater; wet biomass is harvested by a cable-guided Grid Harvester and converted without thermal drying through hydrothermal liquefaction (HTL), fermentation plus HTL, or anaerobic digestion [7–14].

The adaptation deliberately preserves the reference model's mechanics. Country-specific changes are confined to UK transport demand, 2025 and October 2026 fossil-price comparators, UK electricity resource

envelopes, renewable-fuel screening caps, the existing nuclear life-extension envelope and North Atlantic marine-area caps. Model costs remain in 2026 euros internally to avoid altering any techno-economic equation; sterling values are display conversions at 1 EUR = £0.8446, the ECB reference rate used for 13 October 2026.

Results

A UK transport-energy balance

The model represents 596.0 TWh yr^{-1}. Road petroleum from DUKES is mapped into 154.3 TWh of petrol light-vehicle demand, 160.1 TWh of diesel light-vehicle demand and 80.0 TWh of heavy-truck and bus demand. A 26.3-TWh off-road agriculture/fishing/machinery screening segment is retained to preserve the reference model's end-use structure. Aviation contributes 142.8 TWh, shipping 28.5 TWh, and rail traction electricity 4.098 TWh [1–3].

Segment	Model energy (TWh yr^{-1})	UK input basis
Petrol, light vehicles	154.3	12.8 Mt petrol; 43.4 GJ t^{-1}
Diesel, light vehicles	160.1	13.4 Mt diesel; 43.0 GJ t^{-1}
Heavy trucks and buses	80.0	6.7 Mt diesel; 43.0 GJ t^{-1}
Off-road/agriculture/fishing	26.3	2.2 Mt screening segment
Aviation	142.8	11.9 Mt; 43.2 GJ t^{-1}
Shipping	28.5	1.8 Mt bunkers + 0.7 Mt domestic/other
Rail traction electricity	4.098	ORR: 4,098 million kWh
Total	596.0	Product-volume model boundary

Marine resource screening

UK waters cover about 885,430 km², of which 722,128 km² are offshore; 38% of all UK waters are within the MPA network [5]. Those figures demonstrate resource scale but do not define developable kelp area. Unlike the reference country's GIS layer, the present UK adaptation uses explicit screening caps so that the solver can be transferred without implying false permitting precision. The caps are 60,000 km² of Atlantic shelf, 40,000 km² of upper slope, and deep-Atlantic bands of 30,000, 70,000 and 120,000 km² at modelled coast-distance bands of 0–100, 100–200 and 200–370 km. Only fractions of those caps are exposed to the optimizer in each scenario.

A permitting-grade UK version would have to intersect high-resolution bathymetry with MPAs and HPMAs, marine plans, Crown Estate and Crown Estate Scotland leases, fishing effort, AIS shipping density and traffic separation schemes, cables and pipelines, defence areas, navigation safety zones, port approaches, seabed rights and ecological constraints. Figure 1 therefore shows screening envelopes, not proposed farm boundaries.

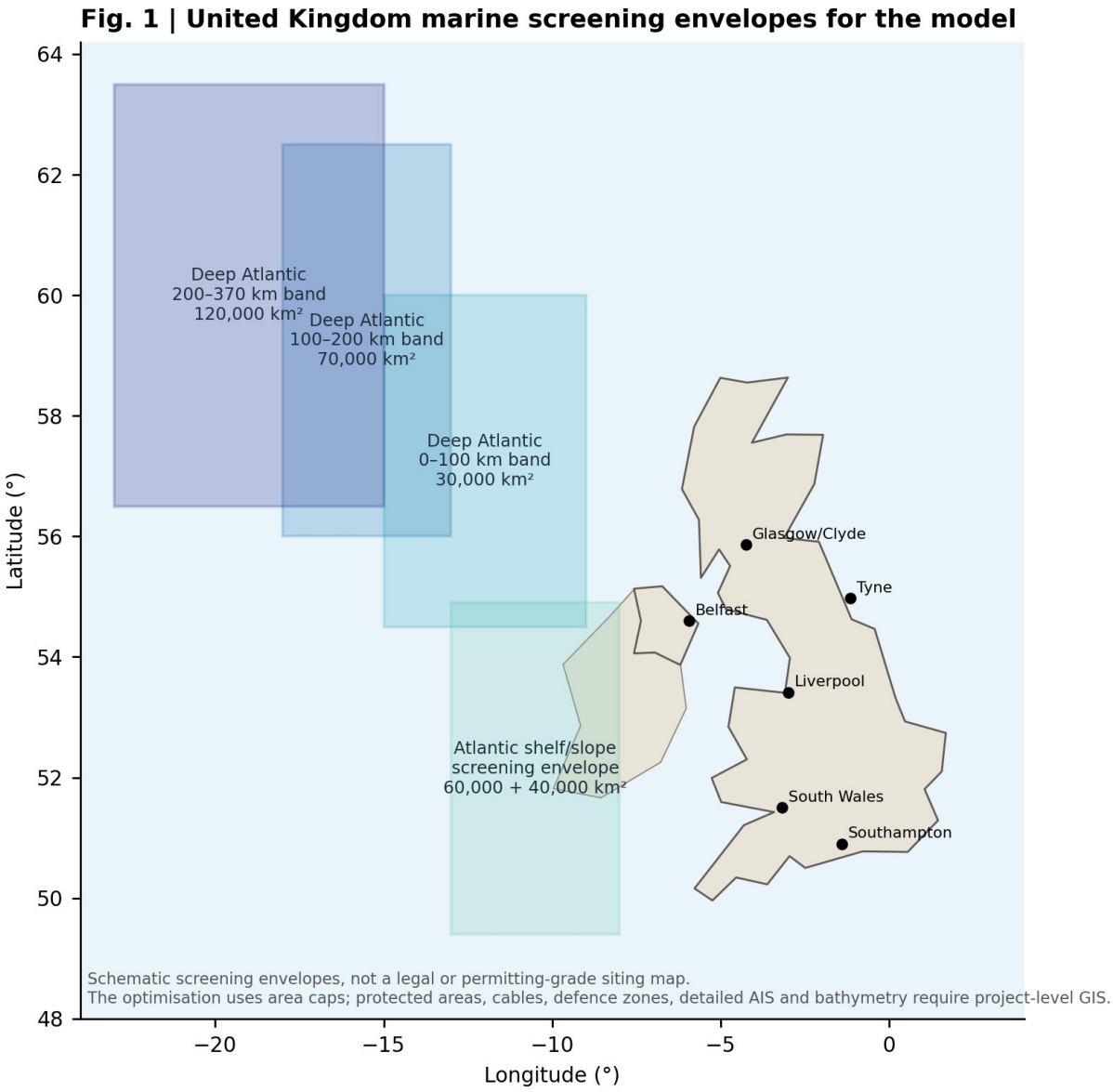

Fig. 1 | United Kingdom marine screening envelopes for the model. The coloured areas are schematic representations of the area caps supplied to the unchanged optimisation-zone structure. They are not legal boundaries or a claim that the full areas are developable. UK waters total about 885,430 km², with 38% within MPAs [5].

Kelp production chain

The farm, nutrient, harvesting and conversion physics are unchanged. Deep-water nutrient supply is compared among depth cycling, solar-pumped pipes, wave pumps and salt-fountain concepts. Depth cycling moves the crop between the illuminated surface layer and the nitracline rather than lifting an enormous water volume, retaining the reference cost advantage [11,15,16]. The model uses 15 t dry ha^{-1} yr^{-1} centrally at current performance and 20 t dry ha^{-1} yr^{-1} in the learning case.

Fresh kelp is represented at 13% dry matter. Thermal drying is energetically unattractive because downstream HTL, fermentation and anaerobic digestion all require a wet feed. Whole-kelp HTL is retained as the lowest-cost direct liquid route; the fermentation-plus-HTL route extracts fermentable carbohydrates before hydrothermal conversion of residues. Fertiliser recovery credits nitrogen, phosphorus and potassium rather than treating nutrients as discarded wastes.

Fig. 2 | Kelp production chain and design alternatives

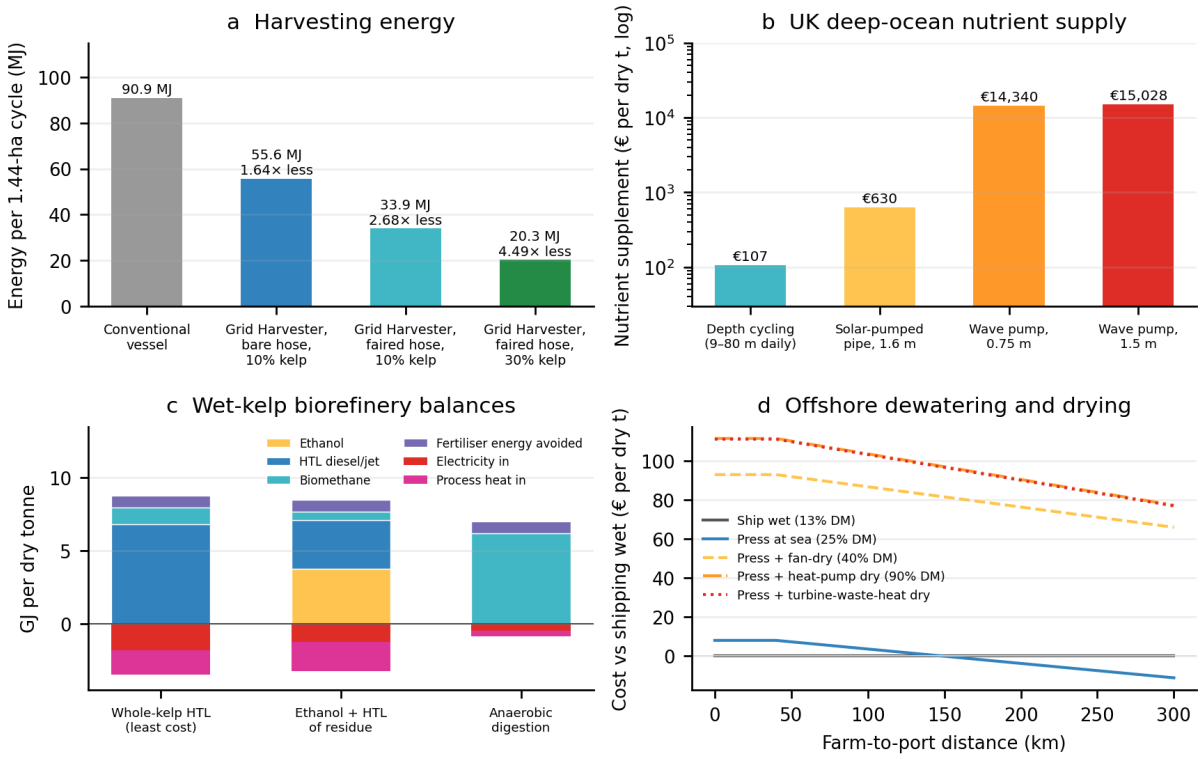

Fig. 2 | Kelp production chain and design alternatives. a, Harvest-cycle energy. b, Deep-ocean nutrient-supply options. c, Wet-kelp biorefinery balances. d, Offshore dewatering and drying relative to shipping wet kelp. The engineering equations and conversion yields are unchanged from the reference model.

Grid Harvester

The Grid Harvester is country-independent. A primary vessel is constrained by a fixed transport cable while a light harvesting head sweeps the crop and moves cut kelp through a suction hose. With the reference 30 m² conventional-vessel resistance area, 85% hose fairing and a 10% kelp slurry, modelled cycle energy is 33.9 MJ for the Grid Harvester versus 90.9 MJ for the conventional vessel, a 2.68× advantage. A conveyor or auger that raises the transport stream to 20–30% kelp lowers the Grid Harvester energy to 23.8–20.3 MJ and raises the advantage to 3.82–4.49×. Grinding at sea consumes more energy than it saves. Turning the harvesting head in place leaves 0.62% of the 1.44-ha farm unharvested, versus 1.49% for the conventional vessel's 90°-turn geometry.

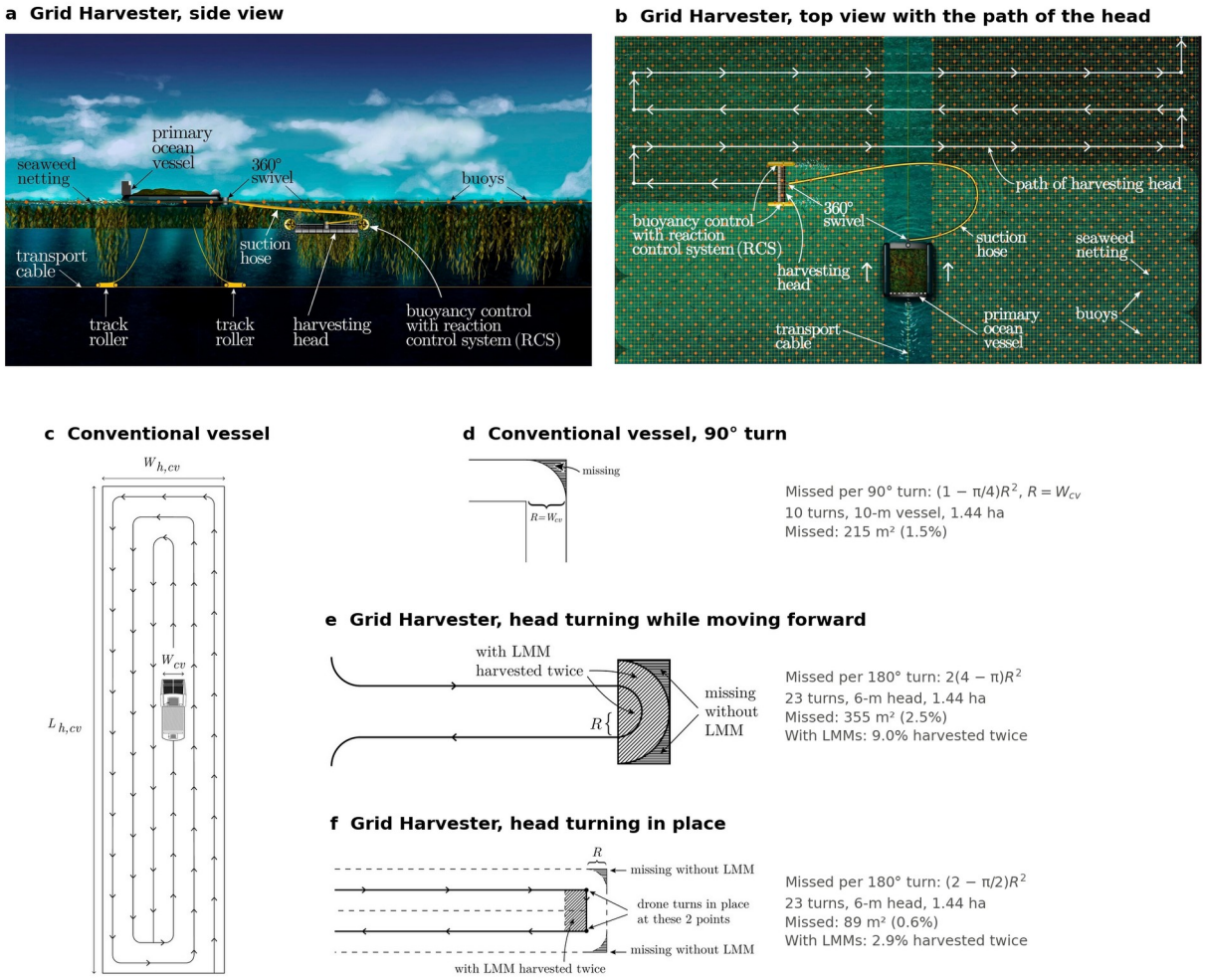

Fig. 3 | The Grid Harvester and conventional-vessel comparison. a,b, Side and top views of the cable-guided system. c–f, path and turning geometries. The image artwork is unchanged because the harvester is not country-specific; the UK adaptation reruns the same drag, pumping, slurry and turning calculations.

The least-cost UK system

Under learning, a 4% cost of capital and the same efficiency/modal-shift levers as the reference case, the least-cost system costs €39.51 billion (£33.37 billion) yr^{-1} before vehicle purchase premia. The same-demand fossil comparator is £54.59 billion at October 2026 prices and £33.20 billion at the 2025 average. The central EV purchase premium is £4.60 billion yr^{-1}, producing a total of roughly £37.97 billion yr^{-1}.

The optimizer directly electrifies both light-vehicle segments, 90% of heavy trucks and buses, and 40% of off-road demand, with methane and a small amount of liquid fuel covering the remaining heavy-duty and off-road constraints. Aviation demand after the efficiency/modal-shift lever is 107.1 TWh and remains a liquid-fuel load. Shipping is split between methane and drop-in liquids in the central least-cost solution. New electricity supply is 173.2 TWh yr^{-1}, supported by 69.5 GW PV, 39.3 GW onshore wind and 0.37 GW of model-equivalent new nuclear capacity; offshore wind is not selected at the assumed cost.

Kelp farms occupy 19,470 km^2 and produce 38.9 Mt dry (300 Mt wet) kelp yr^{-1}, equivalent to 15.3% of transport energy in the model. The fleet requirement is about 300 Grid Harvester units at 416.7 t wet h^{-1} and 2,400 seasonal operating hours. Modelled build capital is €276 billion over 2027–2050, excluding vehicle purchase capital beyond the separately annualised premium.

Fig. 4 | Least-cost low-carbon transport system for the United Kingdom

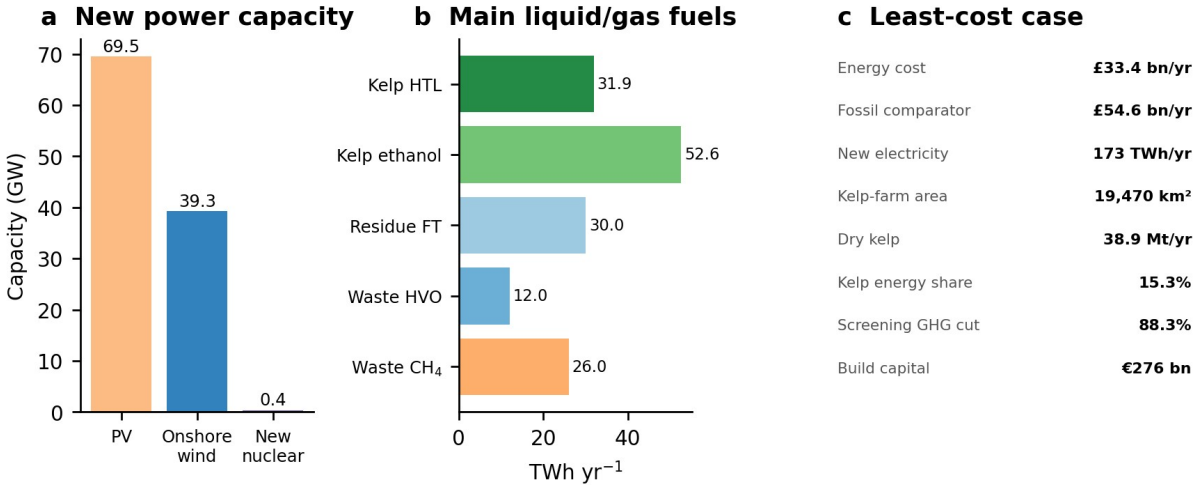

Fig. 4 | Least-cost low-carbon transport system for the United Kingdom. a, New power capacity. b, Principal low-carbon fuel outputs. c, Headline cost, electricity, kelp and lifecycle metrics. The internal optimization remains in euros; sterling is used for headline display.

Cost relative to fossil fuels

At today's technology costs and a 7% cost of capital, energy-supply cost is £55.9 billion yr^{-1} compared with £57.5 billion at October 2026 fossil prices and £34.9 billion at the 2025 average. Including the central vehicle premium raises the today-cost case to £60.5 billion. The learning-only case costs £40.5 billion before vehicle premia, while the full low-cost case falls to £33.4 billion.

The 1,000-draw Monte Carlo median is £39.9 billion yr^{-1} for energy supply and £45.6 billion including vehicle premia. Energy-only costs are below the October 2026 fossil comparator in 100% of draws; with vehicle premia, 99.4% remain below. By contrast, only 0.1% of energy-only draws beat the 2025 fossil bill. The model therefore supports a strong energy-security hedge at 2026 fuel prices but does not imply that the low-carbon system is always cheaper than pre-shock fossil energy.

Fig. 5 | UK system cost relative to fossil fuel

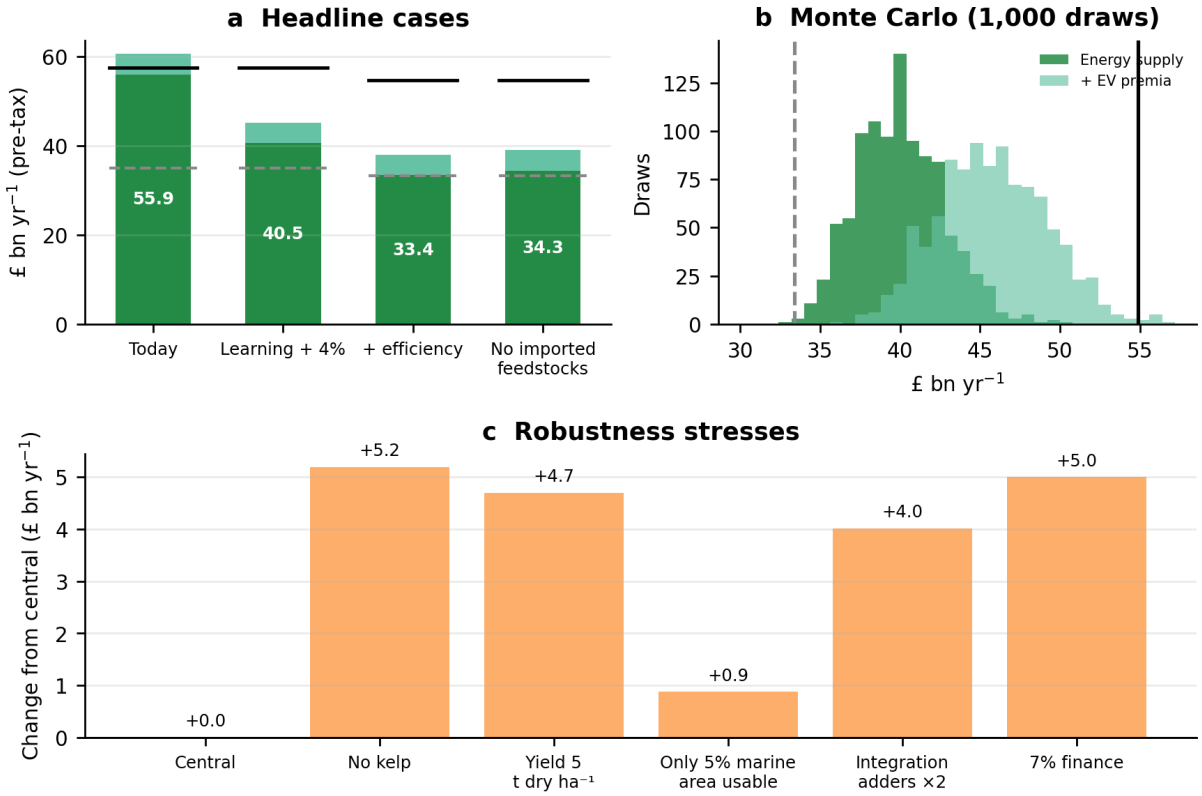

Fig. 5 | UK system cost relative to fossil fuel. a, Headline cases in pounds sterling. b, 1,000 Monte Carlo draws. c, Selected robustness stresses. Sterling conversion is for display only; optimization is unchanged in internal 2026-euro model currency.

Lifecycle greenhouse-gas screening

The lifecycle layer is separate from the economic optimization and uses the same fuel-cycle and generation factors as the reference model. In the central low-cost UK solution, the fossil comparator emits 181.8 $MtCO_2e$ yr^{-1} and the low-carbon system 21.2 $MtCO_2e$ yr^{-1}, avoiding 160.5 $MtCO_2e$ yr^{-1} (88.3%). The predefined low/high factor sets produce a 83.5–92.2% reduction. The Monte Carlo reduction distribution has 5th, median and 95th percentiles of 88.3%, 90.4% and 92.2%.

This remains a screening well-to-wheel/carrier LCA rather than an ISO 14040/44 process LCA. Vehicle manufacture is excluded from both systems, while international bunkers are included when they fall within the model's all-scope boundary. Fuel-cycle factors already embody upstream production energy and are not combined with the electricity-generation factor a second time.

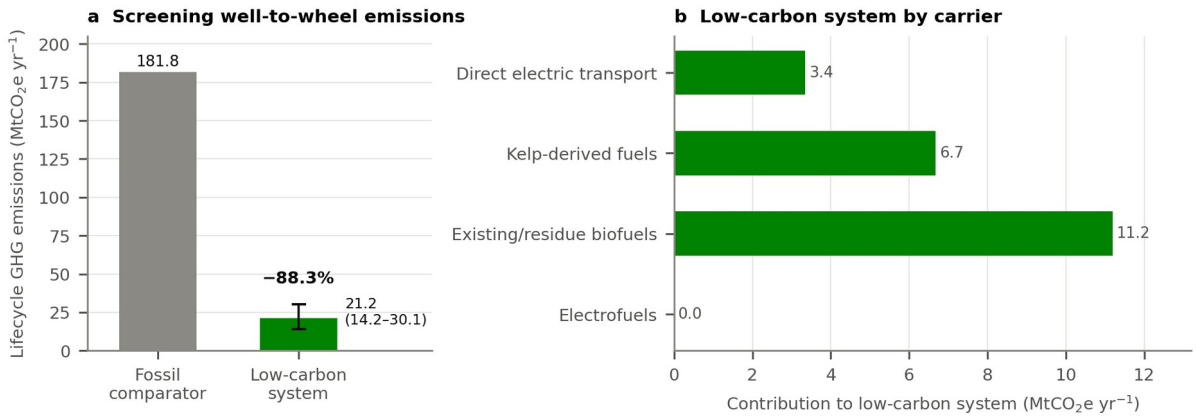

Fig. 6 | Screening lifecycle greenhouse-gas emissions. a, Fossil comparator and central low-carbon system. b, Contributions to the low-carbon result by carrier. This figure is regenerated from the UK solution.

Price stability and import exposure

Between the 2025 average and October 2026 model price sets, the same-demand fossil bill rises by €25.3 billion (about £21.4 billion), or 64.4%. The low-carbon case has about €2.2 billion of internationally traded fuel/feedstock exposure and a corresponding swing of only €1.6 billion (£1.3 billion), about 4.0% of the central low-carbon bill. A no-imported-feedstock variant costs £34.3 billion yr⁻¹ and uses 17,861 km² of kelp.

For the UK, this is better interpreted as exposure to internationally traded petroleum prices than as a claim that all fossil energy is physically imported. The UK produces crude oil but is a net importer of petroleum products [1]. The model's domestic-variant accounting removes imported renewable-feedstock categories and new nuclear, while leaving domestically capitalised electricity, kelp, residues and waste biomethane unchanged.

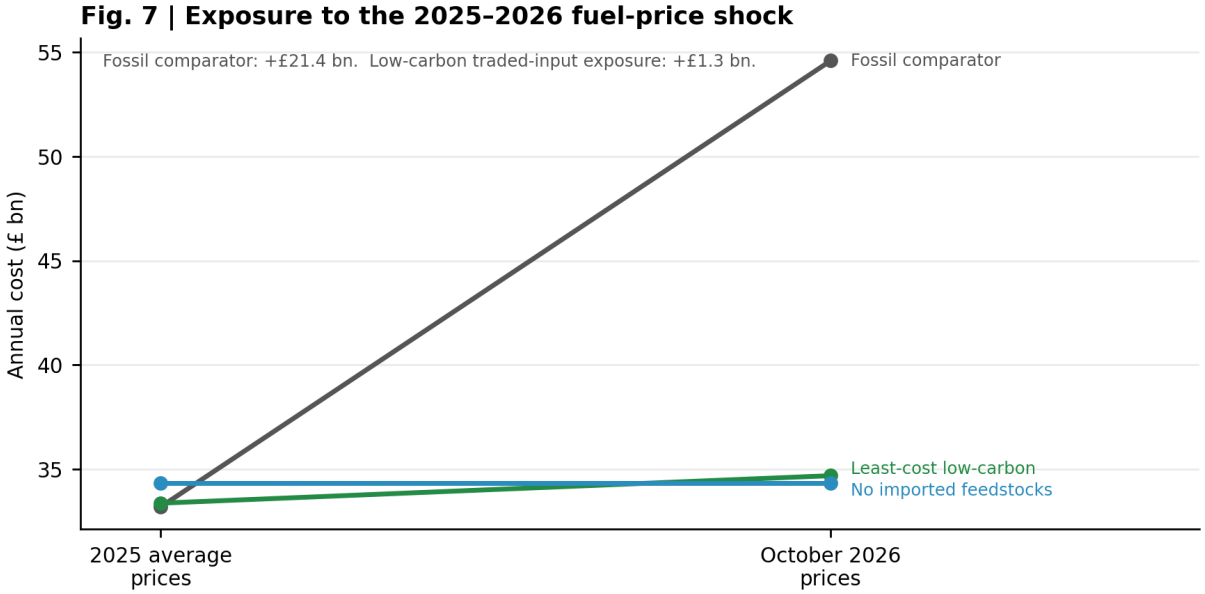

Fig. 7 | Exposure to the 2025–2026 fuel-price shock. The fossil comparator follows the internationally priced fuel set; the low-carbon system is primarily capital-cost driven and therefore less sensitive to the road-fuel price shock.

Robustness and failure modes

Removing kelp entirely raises annual energy-supply cost from £33.4 billion to £38.6 billion, showing that kelp is valuable but not required for mathematical feasibility. Reducing the North Atlantic yield to 5 t dry ha⁻¹ yr⁻¹

raises cost to £38.1 billion. Restricting usable marine screening area to only 5% raises cost more modestly to £34.2 billion because the optimizer substitutes other carriers. Doubling the annual integration/network adders raises cost to £37.4 billion, while retaining a 7% rather than 4% cost of capital raises it to £38.4 billion.

An apparently counter-intuitive feature of the lifecycle results is that the no-kelp sensitivity can have lower screening emissions than the central cost minimum. This occurs because the objective minimizes annual cost, not emissions, and substitutes electricity-based and residue pathways with different screening factors. The result underscores that the ~90% emissions figure is a consequence of the cost-optimal carrier mix under stated factors, not an imposed decarbonisation constraint.

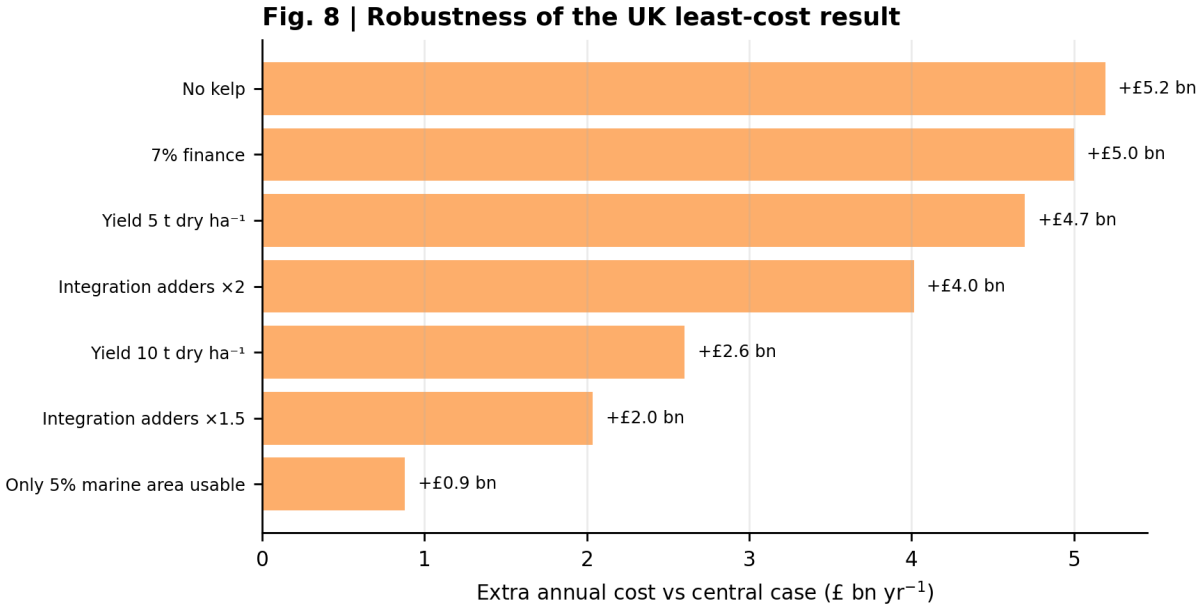

Fig. 8 | Robustness of the UK least-cost result. Bars show extra annual energy-supply cost relative to the central low-cost solution under selected structural and parameter stresses.

Discussion

The UK adaptation reproduces the principal qualitative result of the reference model: electrification dominates where batteries are efficient, while a smaller pool of low-carbon molecules is reserved for hard-to-electrify demand. The UK case is not a simple rescaling of the reference country. Higher aviation energy, a different road-fuel split, a substantial existing nuclear fleet, no CSP option, UK renewable-fuel supply, and different marine and electricity resource caps change the optimum. The least-cost UK solution uses less kelp area than the unconstrained learning case because efficiency and modal shift reduce liquid-fuel demand and the optimizer can choose among kelp, residues and waste-derived fuels.

The result also illustrates why the Grid Harvester should not be sold primarily as an energy-saving device. Its per-tonne energy saving is small at system scale; its potential value is throughput, automation and the ability to follow a fixed farming grid without carrying the entire harvested load around the field. The decisive kelp uncertainties remain biomass yield, structure cost, daily depth-cycling reliability, mooring and hose behaviour in storms, ecological compatibility, nutrient dynamics, and wet-biomass conversion performance at commercial scale.

UK marine consenting is a central limitation. JNCC reports 38% MPA coverage across UK waters [5], but MPA status alone neither proves nor excludes compatibility with a specific aquaculture technology. The screening areas in this paper are therefore capacity constraints for a technology-and-cost experiment. Before any siting conclusion, a full GIS should be rebuilt with UKHO/Marine Management Organisation/Marine Scotland/DAERA marine-plan and navigation data, Crown Estate leasing data, detailed AIS and VMS fishing effort, protected features, seabed infrastructure and engineering bathymetry.

The annual linear programme does not establish 8,760-hour adequacy. Variable-renewable integration and network requirements are represented by adders and stressed up to 2×. A subsequent UK power-system version should couple the transport solution to hourly or sub-hourly dispatch, storage, interconnection, flexible electrolysis, seasonal fuel storage and regional network reinforcement. Similarly, the screening LCA should be replaced by a process-resolved ISO-compatible assessment if the technology advances beyond concept and pilot stages.

Methods

Optimisation structure

The model is an annual linear programme solved with SciPy/HiGHS. Decision variables allocate each transport segment among allowed end-use technologies and build or use energy-supply pathways sufficient to satisfy carrier balances. The objective is annualised pre-tax energy-supply cost. Vehicle purchase premia are calculated separately so the energy result and the capital transition premium are visible rather than conflated.

Each fossil-energy segment has conversion ratios and maximum shares. Light petrol vehicles require 0.31 MWh of direct electricity per MWh of fossil energy replaced; light diesel vehicles 0.375; battery-electric heavy vehicles 0.53 with a 90% share cap; electric off-road machinery 0.45 with a 40% cap. Methane and liquid alternatives remain available where electrification is limited. Aviation requires jet-compatible liquid fuel. Shipping can use methanol, ammonia, methane or drop-in liquid fuel. Rail electricity is supplied directly.

Electricity and heat

UK resource inputs retain the reference cost structure but use UK screening capacity factors and caps: PV €33 MWh^{-1}, 11.5% capacity factor and 250-GW cap; onshore wind €45 MWh^{-1}, 30% and 120 GW; floating offshore wind €100 MWh^{-1}, 45% and a 20,000-km^2 screening envelope at 5.5 MW km^{-2}; CSP is disabled; existing nuclear life extension is €60 MWh^{-1}, 88% and 5.9 GW; new nuclear is €120 MWh^{-1} at 90%. New nuclear can also provide process steam with 0.30 MWh of electricity forgone per MWh thermal. Flexible and direct electricity receive the same network/integration adders as in the reference model.

Kelp farms and nutrients

Legacy solver zone keys are retained to guarantee the same code path. UK North Atlantic shelf, slope and deep zones replace the country-specific reference zones; warm-water placeholder zones have zero UK area. Farm costs include structure, maintenance, seeding, harvesting, transport and nutrient strategy. Deep-water options are depth cycling, solar-pumped upwelling, tested/scaled wave pumps and salt-fountain pumping. The optimizer selects the least-cost allowed method for each zone and distance band.

Biorefineries and preprocessing

Three refinery routes are available: whole-kelp HTL; fermentation of mannitol, laminarin and an alginate fraction followed by HTL of residue; and anaerobic digestion. The learned case reduces refinery capital cost by 30% and permits full alginate utilization. Offshore preprocessing options are wet shipment, pressing, fan drying, heat-pump drying and a turbine-waste-heat sensitivity. Because wet downstream routes require slurry, removed water must ultimately be restored, so drying is credited only with transport/ensiling savings and charged its energy/capital cost.

Learning, finance and efficiency levers

The low-cost pathway applies the same sequence of levers as the reference analysis: kelp biomass cost decreases from €300 to €200 per dry tonne; yield rises from 15 to 20 t dry ha^{-1} yr^{-1}; deep structures become cheaper; alginate utilization and HTL yield improve; refinery cost falls 30%; the optimizer gains free route and heat-source choice; cost of capital falls from 7% to 4%; demand is reduced through efficiency/modal shift; and the liquid-only rule is removed. The final least-cost case then allows the optimizer to choose the kelp share rather than requiring kelp to supply all liquids.

Vehicle premia

Incremental EV purchase prices are annualised over 15 years at 4% and allocated per unit of fossil energy replaced. The UK screening distances are 11,500 km yr^{-1} for cars, 20,000 for vans and 75,000 for heavy trucks. Central purchase premia remain €1,000 per car, €2,000 per van and €30,000 per heavy truck. The resulting central annual premium is €5.45 billion (£4.60 billion), split between €4.46 billion for cars/vans and €0.99 billion for heavy trucks/off-road machinery.

Monte Carlo

One thousand draws use the same triangular-distribution design: cost of capital 3–4–7%; biomass cost €150–220–600 per dry tonne; North Atlantic yield 5–15–22 t dry ha^{-1} yr^{-1}; deep-structure factor 1.05–1.15–1.60; depth-cycling capital €0.3–0.7–3.0 million km^{-2}; HTL and methane-yield uncertainty; alginate utilization; PV and wind costs; biofuel prices; electrofuel and refinery costs; fertilizer prices; aviation and shipping demand; wind-assist limit; vehicle premia; and lifecycle factors. In 10% of draws deep-ocean kelp is disabled, representing structural non-deployment or failure. Fossil prices are not sampled; each draw is compared with fixed 2025 and October 2026 price sets.

Lifecycle accounting

The screening lifecycle layer uses the same central factors as the reference model: 92 gCO_2e MJ^{-1} for fossil road fuels, 89 for fossil jet and 93.3 for fossil marine fuel; 22 gCO_2e MJ^{-1} for offshore macroalgal fuels, 25 for existing/residue biofuels, 12 for low-carbon electrofuels and 3.2 for renewable ammonia; and cradle-to-grave generation factors for PV, wind and nuclear. Low/high factor sets are propagated as a sensitivity. Vehicle manufacture is excluded from both sides.

Fossil price comparators and sterling display

The internal October 2026 UK road-fuel comparator is reconstructed from DESNZ pump prices after removing 20% VAT and the applicable fuel duty, then converted to euros. Aviation and marine values preserve the same wholesale-proxy convention as the reference model. The 2025 average set is a lower-price baseline. Because the optimizer uses euros, the £0.8446 per euro conversion is applied only after solution and cannot change the selected technology mix.

Limitations

- The model is annual, not hourly. Integration and network adders are stress-tested but do not prove firm capacity or transmission feasibility.
- The UK marine-area caps are screening assumptions, not a high-resolution GIS inventory and not a statement that the coloured map areas are developable.
- The 2.2-Mt off-road segment is a model-preserving screening input; UK official transport accounting uses different boundaries for agriculture, fishing and non-road machinery.
- Deep-ocean kelp yield, depth cycling, storm survival, mooring fatigue, hose/slurry rheology and large-scale alginate fermentation are extrapolated from limited evidence.
- The Macrocystis depth-cycling literature is not direct commercial validation for UK Saccharina, Laminaria or Alaria systems.
- Costs are pre-tax energy-supply costs. They exclude changes in fuel-duty revenue, stranded refining assets, detailed distribution-network reinforcement and most transition-policy costs.
- Lifecycle results are screening estimates, not an ISO 14040/44 process LCA.

Data and code availability

The UK adaptation package accompanying this manuscript contains the complete numerical model, UK country-input note, deterministic outputs, 1,000 Monte Carlo draws, robustness results, lifecycle outputs, Grid Harvester calculations, manuscript figures and Source Data workbooks for the regenerated quantitative

figures. The solver structure and engineering modules are the same as in the supplied reference model. A public UK repository URL and permanent archive identifier should be added before journal submission.

Use of AI tools

Anthropic Claude assisted with code development and debugging, drafting, and code-based generation of quantitative figures. No generative-AI image tool was used to create the Grid Harvester artwork or other manuscript images. All system-design choices, model assumptions, code outputs, references and scientific conclusions remain the responsibility of the authors.

Acknowledgements

None.

Author contributions

J.B. conceived the study, designed the Grid Harvester and kelp-biorefinary concept, developed and executed the energy-system modelling framework, analysed the results and wrote the manuscript. C.P. designed and wrote the code for the Grid Harvester model. P.V.B. prepared the Grid Harvester illustrations. C.P. and P.V.B. reviewed the manuscript. All authors should confirm the final UK adaptation before submission.

Competing interests

The authors declare no competing interests.

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