Appendix: Key fuel assumptions

Transition Outlook

Modeling shipping's decarbonization potential under four global scenarios



Mærsk Mc-Kinney Møller Center
for Zero Carbon Shipping

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This appendix to the Transition Outlook shows the subset of fuel assumptions that drive most of the simulation's results. All code and assumptions are documented in the GitHub repository for Navigate (https://github.com/zerocarbonshipping/navigate-zcs). All assumptions are illustrative and for analytical purposes only.

We simulate the period 2026-2050 under the four scenarios from the main report:

Coordinated Transition: medium biomass availability, high investment certainty, high hydrogen industrialization

Fragmented Transition: low biomass availability, medium investment certainty, medium hydrogen industrialization

Market-driven Transition: high biomass availability, medium investment certainty, low hydrogen industrialization

Protectionist Transition: low biomass availability, low investment certainty, low hydrogen industrialization

How to read this appendix

We distinguish between two kinds of quantity:

- **Inputs (assumptions).** Values we set directly: feedstock cost and availability, levelized cost of electricity (LCOE), cost of capital (WACC), plant lead time, plant size, build-out pace, and the fossil fuel price and emissions baselines. Each input has a central value and a range that we sample over.
- **Derived assumptions.** Quantities the simulation computes from the inputs but which are not themselves time-stepped decisions: most importantly, the **long-run production cost** and **well-to-wake emissions** of each alternative fuel, which the model builds bottom-up from feedstock, CapEx, financing, etc.

Sampling: We sample whole input *paths* over the timeline, not a fresh independent draw at each time-step. A single sample fixes a consistent trajectory (e.g., one cost-of-capital path), so each assumption keeps its year-to-year shape.

Graph conventions: On the input graphs in this appendix:

- The **solid line** is the central value of the input distribution we specify (the mode of the triangular range).
- **Dotted lines** mark the minimum and maximum of the range we test around that central value.
- We reserve **shaded bands** for the **sampling interval of derived assumptions** (the derived fuel costs and emissions).

In short: *dotted lines = the spread of an input we control; shaded bands = the spread of an output the model produces.*

Notice that the shaded bands do not imply the actual dynamic fuel cost within a given simulation. The lower bound of the shaded bands is the P5 of the cheapest technology in the cheapest scenario, and conversely the upper bound of the shaded bands is the P95 of the most expensive technology in the most expensive scenario. Inside the model, expensive options are assigned lower market share and consequently tend to have no influence on simulation results.

Constant-in-time inputs: Where an input is flat across the whole horizon, we present it as a table rather than a flat line on a graph. Inputs that genuinely move over time keep their graphs.

Introduction

When you read this document, the alternative fuels' emissions may appear low next to emissions numbers for existing alternative fuels. This impression follows from two assumptions:

- We set the GHG price at >380 USD/tCO_2eq, up to the level of 600-800 USD/tCO_2eq.
- We assume the GHG intensity is certified and physically correct, so the model penalizes fuels according to their real physical emissions.

Given this GHG pricing, basically all emissions-reduction measures on upstream emissions are in the money, including paying a premium for low-emissions natural gas for a blue ammonia plant and ensuring biomethane is low-slip, closed-digestate, made with biomass collected by electric trucks, and so on. A world with a GHG price of this size measured against actual physical emissions creates a large incentive to drive emissions down as much as possible, because otherwise the GHG price penalizes fuel consumers.

The high and guaranteed GHG price also impacts other assumptions, such as fuel plant sizes. Hence, only technological considerations limit fuel plant sizes in our analysis; commercial risk does not.

This document includes numbers for available feedstock for shipping, but not numbers for available fuel for shipping. This is because feedstock availability is an input to the model, whereas fuel availability is a dynamic output and thus differs across simulations based on other dynamic results, such as vessel decisions and energy efficiency decisions.

The remainder of the appendix walks through each fuel pathway in turn. It begins with fossil fuels, since they set the baseline that alternatives must compete against, followed by biofuels, blue fuels, and e-fuels.

We consider the following pathways:

Fossil:

- Oil (shared proxy for HFO, LFO, VLSFO, MDO, MGO)
- LNG

Biofuels:

- Biomethane
- Biomethanol (gasification and SMR pathway)
- Bio-ethanol
- Biodiesel

Blue fuels:

- Blue ammonia

E-fuels (multiple pathways of hydrogen produced with alkaline, PEM, and SOEC respectively):

- e-ammonia
- e-methane
- e-methanol
- e-diesel

1. Fossil fuels

1.1 Description of approach

Conventional oil and LNG continue to set the price and emissions baseline that alternative fuels must compete with. Unlike the alternative pathways, both the price and the life cycle emissions of fossil fuels are **exogenous inputs** to the model rather than simulation outputs: fossil fuels involve no new plant to build and no feedstock supply to allocate. We use the same trajectories across all four scenarios. As both price and emissions are flat over the modeled time horizon, we present them as tables.

1.2 Fuel cost

We collect the fuel costs from futures curves and set them at the steady-state value the long-term futures reach, holding them constant across the timeline. The futures curves have short-term fluctuations, but we remove these for simplicity since they have no impact on a transition over 25 years.

Table 1: Market price of oil and LNG, flat over 2026-2050.

Fuel	Market price (USD/t)
Oil	485
LNG	436

1.3 Fuel emissions

Well-to-wake emissions for fossil fuels combine combustion (tank-to-wake) CO_2 with upstream (well-to-tank) CO_2. For LNG, we add methane slip from the upstream process, converting it to CO_2eq using GWP_{100} = 28. All components are constant over the horizon.

Table 2: Well-to-wake life cycle emissions of oil (VLSFO) and LNG, flat over 2026-2050.

Fuel	Life cycle emissions (gCO_2eq/MJ)
Oil	92.1
LNG	76.1

All methane, including LNG, incurs additional emissions from onboard slip in the engines. This number in this section excludes that slip because it depends on the vessel that consumes the fuel.

Impact on the model: The fossil price sets the cost floor that every alternative fuel must beat, and the fossil emissions set the GHG-cost penalty that alternatives avoid. Together, they fix the break-even GHG price at which each alternative becomes competitive, so they anchor the entire fuel-switching result.

2. Biofuels

2.1 Description of approach

We build biofuel costs and emissions **bottom-up** from a feedstock cost, a conversion-process cost, and the cost of capital for new plants. We model low-emissions biofuels by restricting availability to waste and residual feedstocks only (crop residues and used cooking oil). We do not model biofuels derived from first-generation energy crops, consistent with the main report's exclusion of first-generation biodiesel and bio-ethanol.

Although the model supports regional production, we were unable to gather feedstock assumptions at a regional level for biofuels, and therefore set feedstock cost and availability as global values. **Only the WACC is regional** in our biofuel build-up. Biofuel plants use mature technologies and are financed at close to commercial rates, so the WACC has no scenario or uncertainty multiplier on top of the regional spread.

The only input that varies across scenarios is **feedstock availability**, or the share of the global sustainable feedstock pool that we assume reaches shipping in each scenario.

2.2 Fuel costs (derived result)

Figure 1: Total production cost of biomethanol.

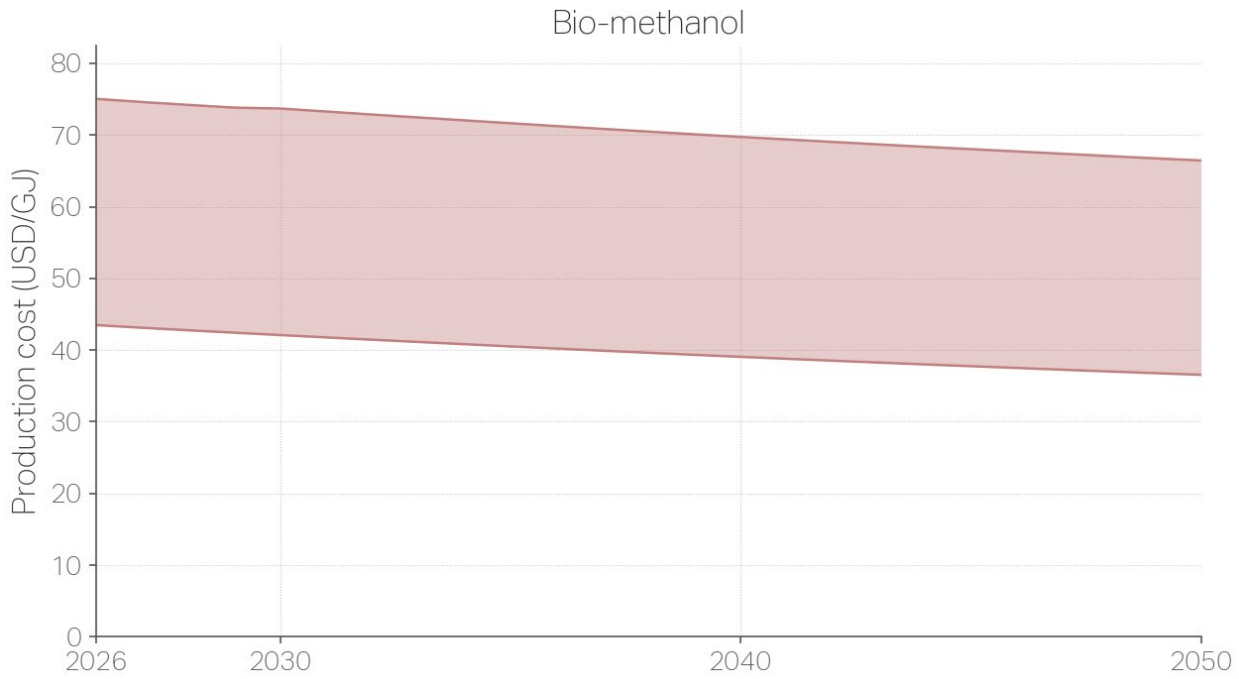


Figure 2: Total production cost of bio-ethanol.

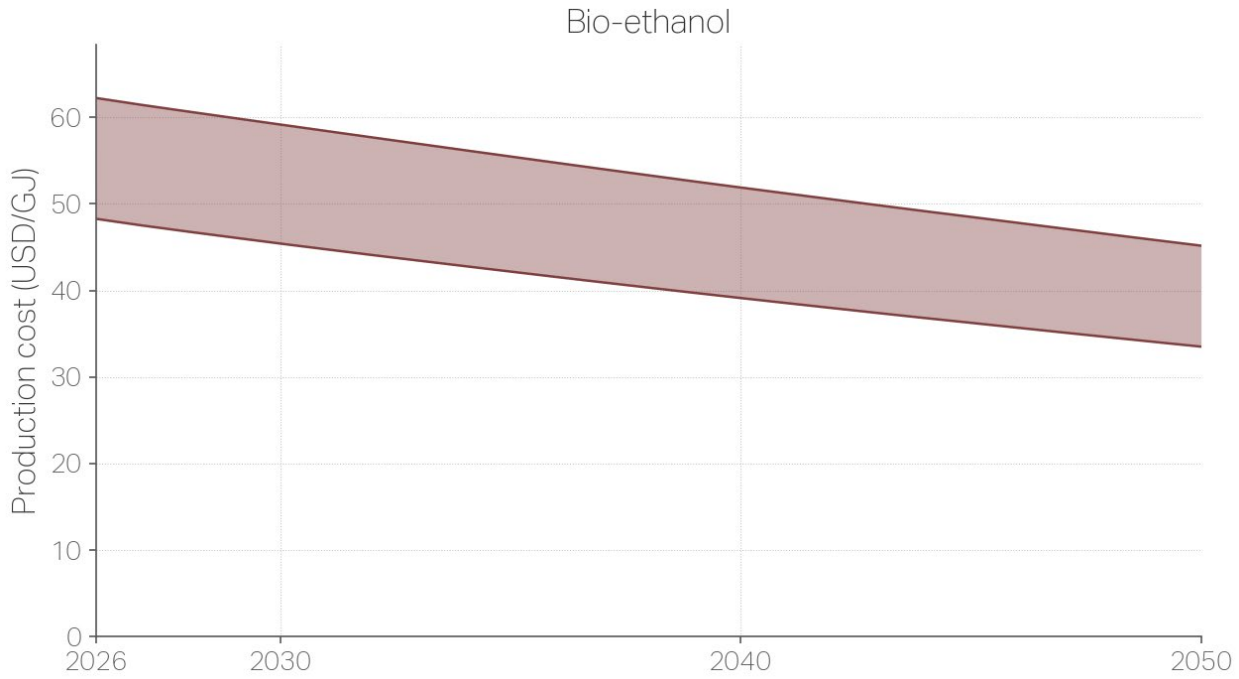


Figure 3: Total production cost of biomethane.

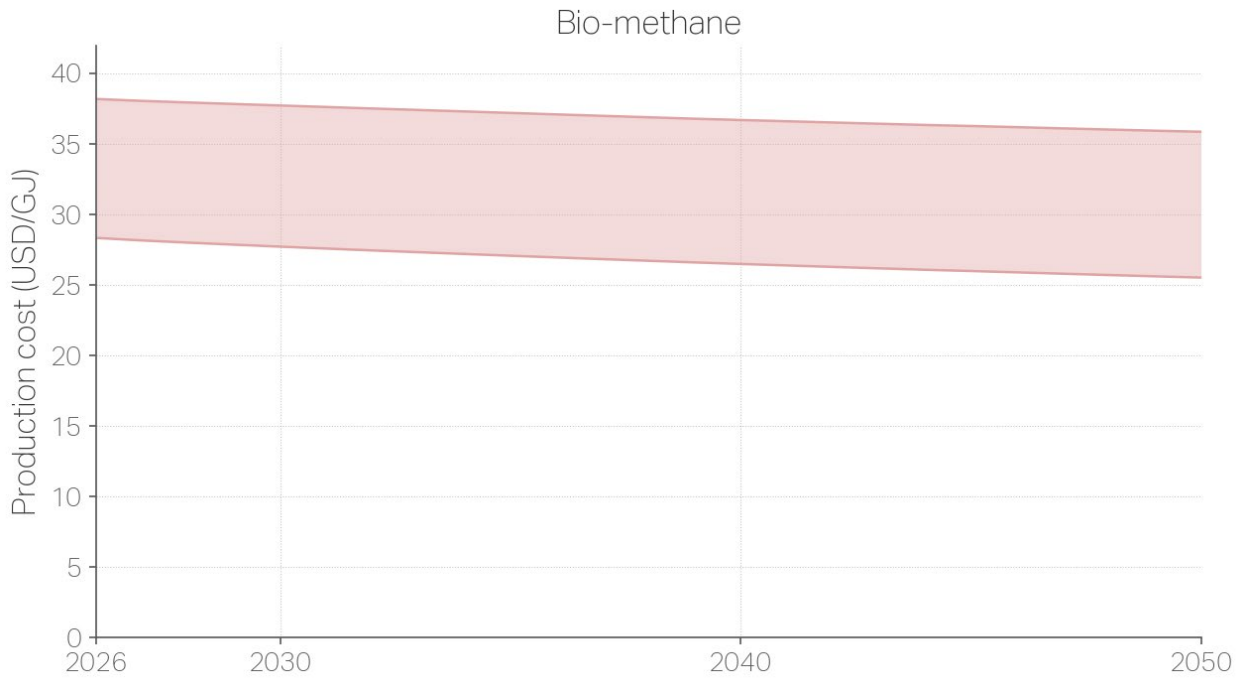
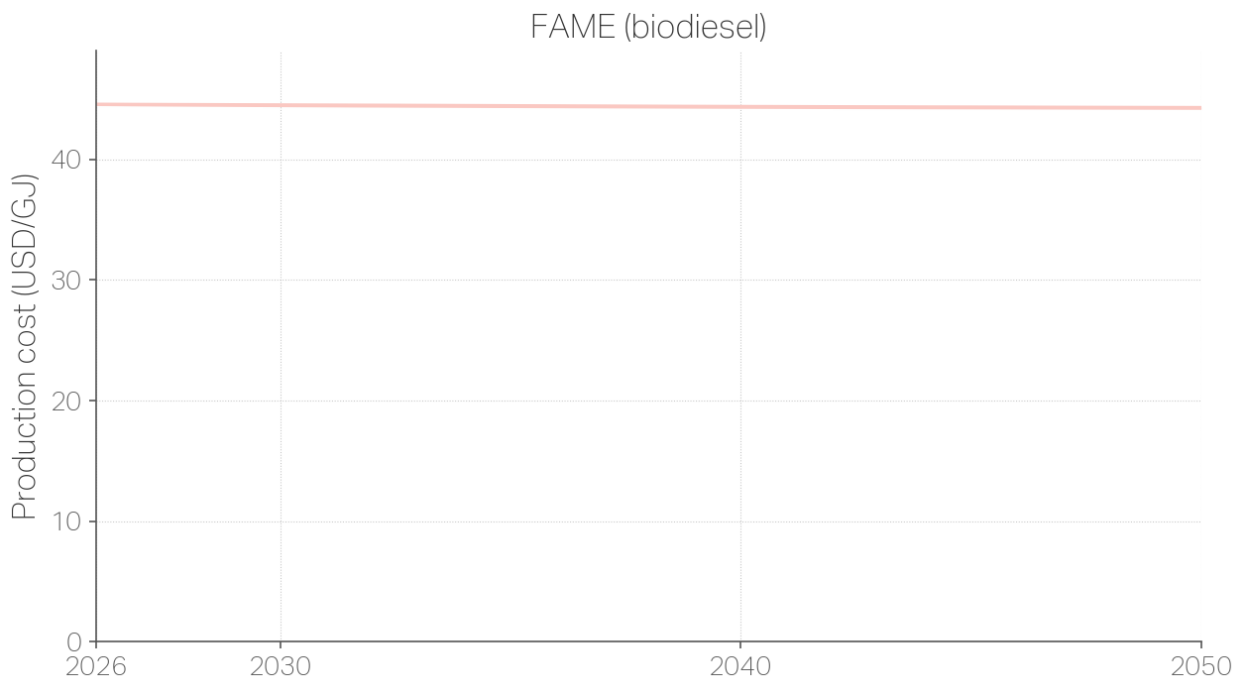


Figure 4: Total production cost of FAME (biodiesel).



2.3 Fuel emissions (derived result)

Well-to-wake emissions are flat over the horizon and carry no input uncertainty.

Table 3: Well-to-wake life cycle emissions per biofuel from the simulation, flat over 2026-2050.

Fuel	Life cycle emissions (gCO_2eq/MJ)
Biomethanol	8.9
Bio-ethanol	6.7
Biomethane	5.4
FAME (biodiesel)	45.0

2.4 Feedstock cost and availability

The dominant cost and supply constraint on biofuels is the underlying feedstock. We track four inputs: biomass for biogas production, forestry and wood waste, crop residues, and used cooking oil. Costs are global, identical across scenarios, and flat over the horizon, so we tabulate them. Availability is the global pool multiplied by the share we assume reaches shipping (rather than aviation, road, chemicals, or agriculture), and the shipping share varies across scenarios.

Table 4: Global delivered cost of bio-feedstocks used in the simulation, flat over 2026-2050.

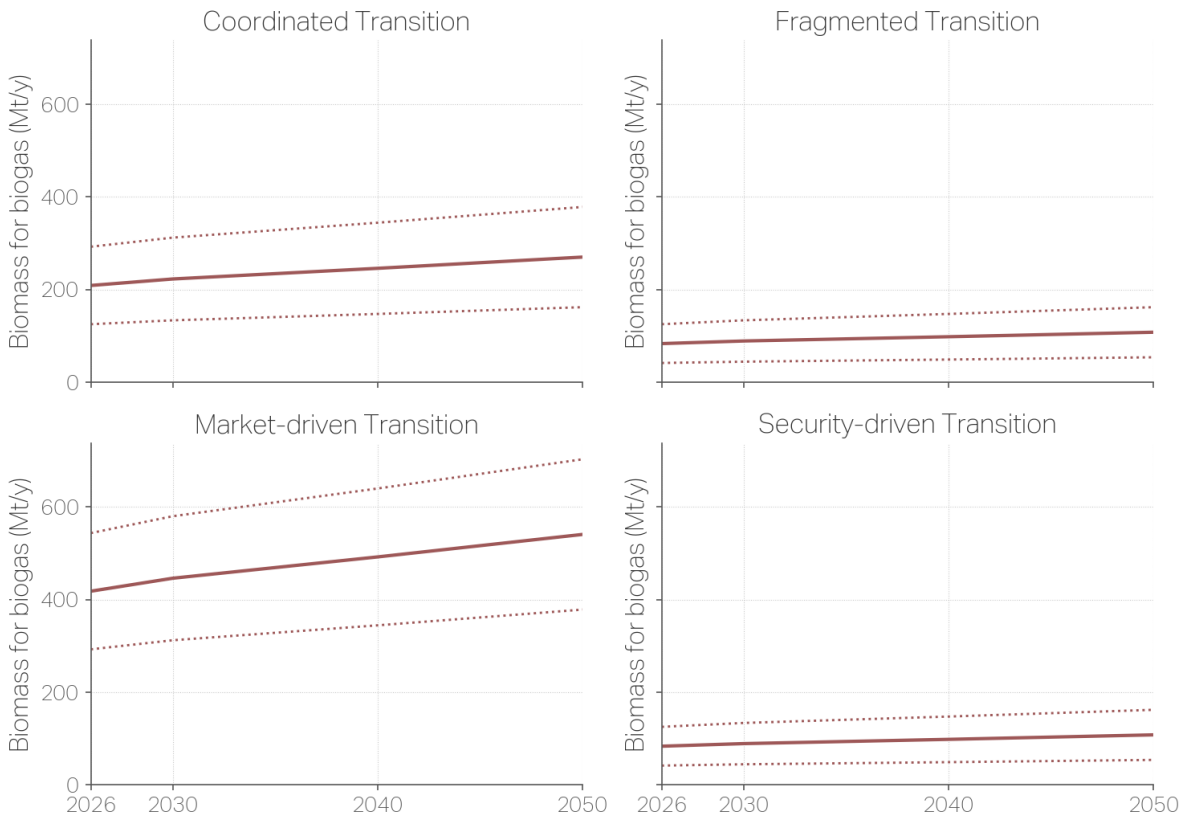
Feedstock	Delivered cost
Biomass for biogas	50 USD/dry t
Forestry and wood waste	65 USD/dry t
Crop residues	60 USD/dry t
Used cooking oil (Europe)	1130 USD/t

Impact on the model: Feedstock cost feeds directly into the derived biofuel production cost (Figures 1-4).

We show availability per feedstock in the following figures. Each figure is a 2×2 grid with one scenario per subplot; the solid line is the central shipping share for that scenario, and the dotted lines span the low and high shares we test around it.

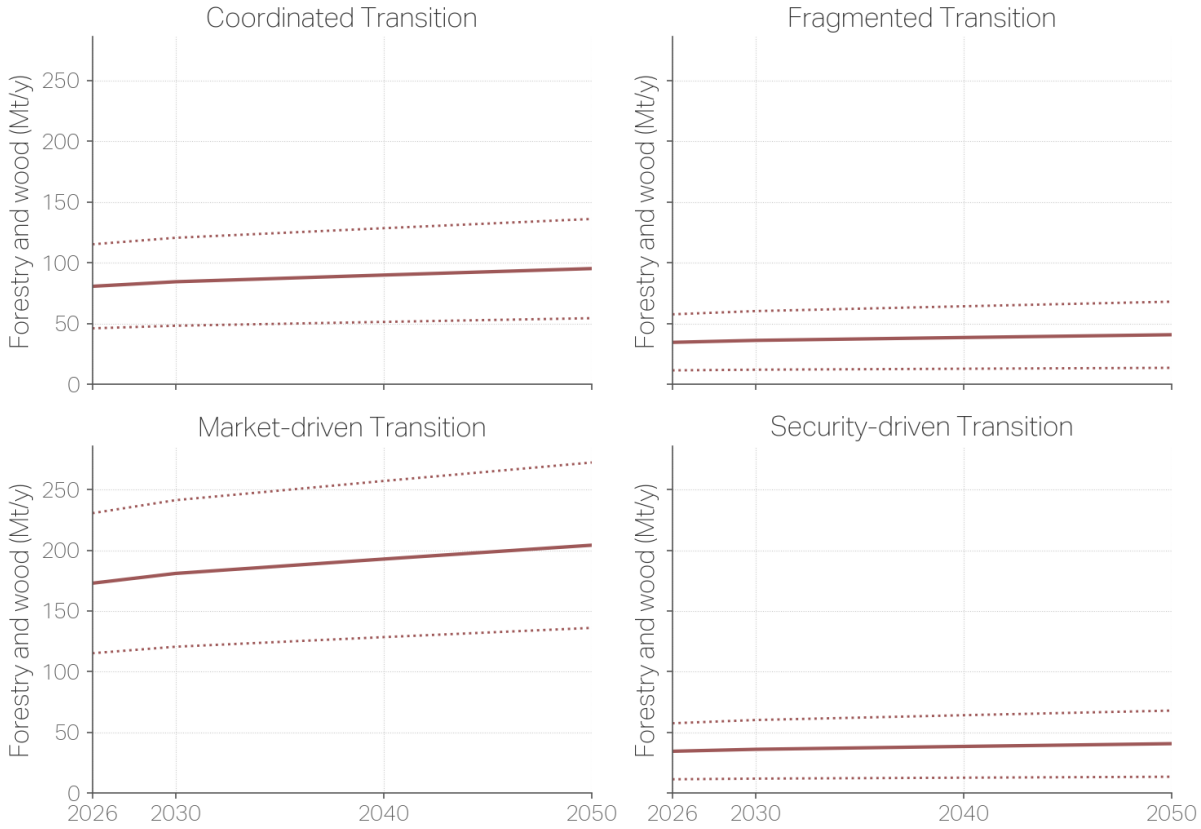
Biomass for biogas

Figure 5: Biogas feedstock available to shipping.



Forestry and wood waste

Figure 6: Forestry and wood-waste feedstock available to shipping.



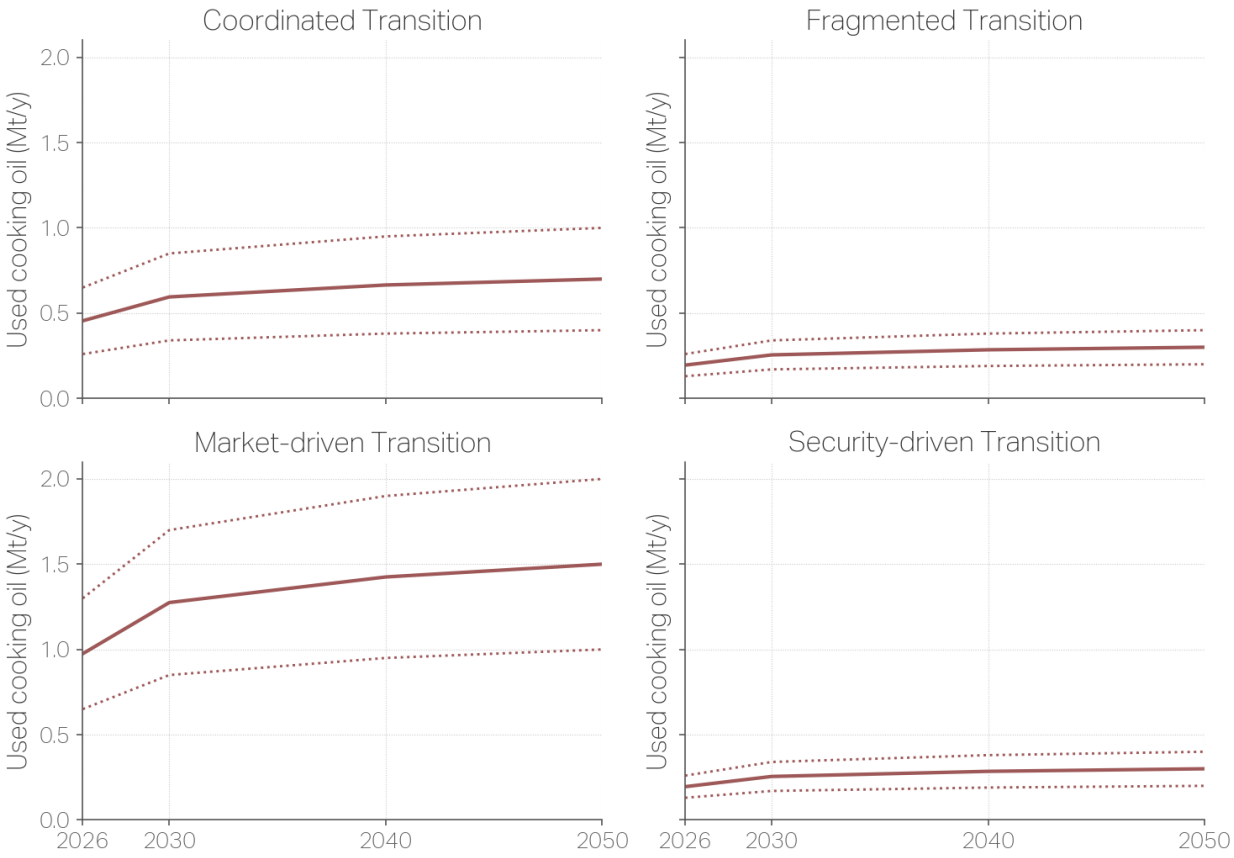
Crop residues

Figure 7: Crop-residue feedstock available to shipping.



Used cooking oil (Europe)

Figure 8: European used cooking oil feedstock available to shipping.

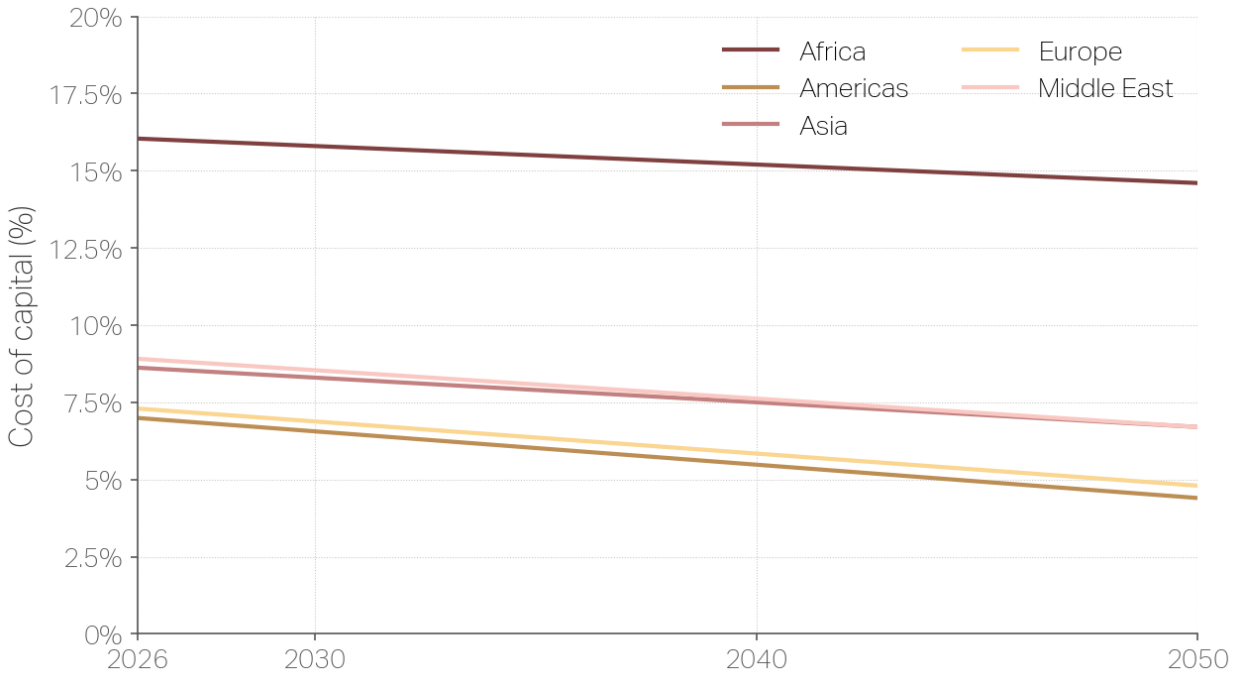


Impact on the model: Feedstock availability caps how much biofuel shipping can access, and consequently how much the fleet can demand before switching to more expensive fuel options. This availability shapes the fuel mix, which in turn shapes the choice of vessels, energy efficiency, and other investment decisions.

2.5 WACC

Biofuel plants use mature technologies and are financed at close to commercial rates. We capture five regions explicitly (Africa, Americas, Asia, Europe, and Middle East) without an additional scenario or uncertainty multiplier.

Figure 9: Cost of capital for new biofuel plants, by region.



Impact on the model: WACC enters the levelized cost of fuel calculation and thus affects the fuel cost directly. Higher WACC raises fuel costs.

3. Blue fuels

3.1 Description of approach

We build costs and emissions for blue fuels **bottom-up** as well. Costs relate primarily to the natural gas going into the plant and its upstream emissions.

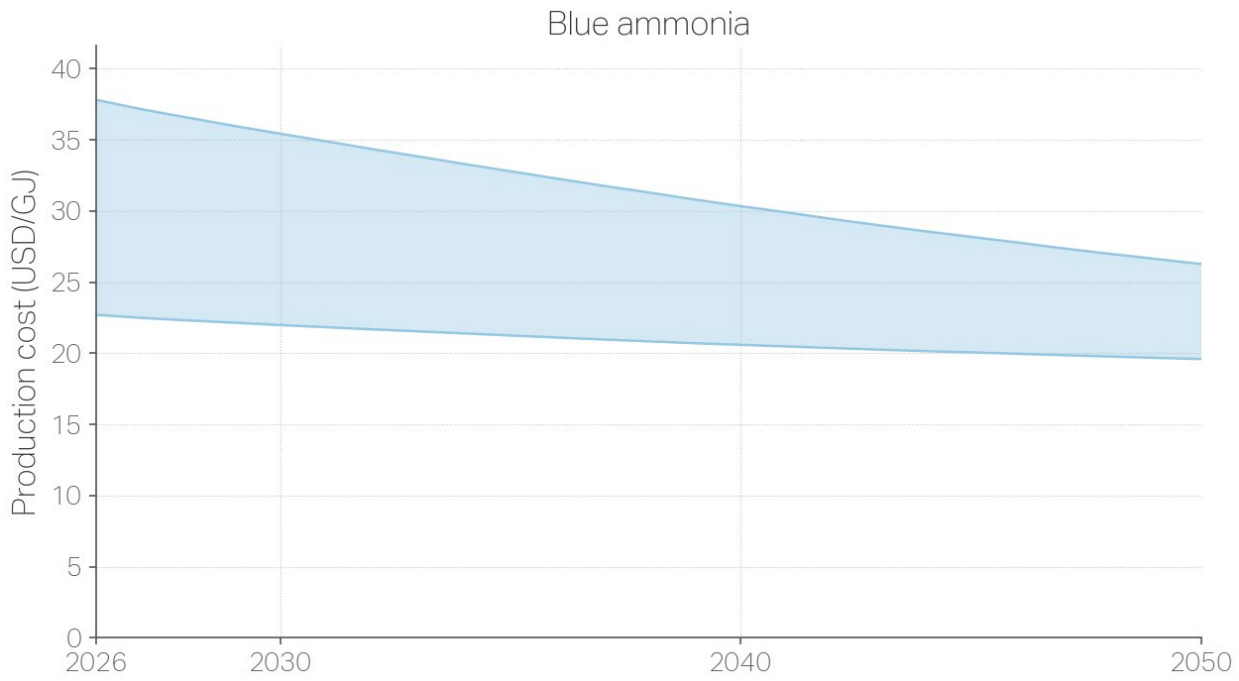
Natural gas is the **feedstock for blue ammonia**. The **WACC** remains regional, since blue-plant financing is close to well-established fossil-fuel financing and reasonable to gather regionally.

WACC and **plant lead time** are scenario- and uncertainty-dependent: high-infrastructure scenarios pull lead times and financing costs down, while low-infrastructure scenarios push them up. The **reference plant capacity** is uncertainty-dependent (uniform across scenarios).

3.2 Fuel costs (derived result)

Production cost is a derived output and carries P5-P95 uncertainty. The shaded band is the P5-P95 range across samples.

Figure 10: Total production cost of blue ammonia.



3.3 Fuel emissions (derived result)

Well-to-wake emissions are flat over the horizon and carry no input uncertainty (P5 = median = P95), so a table replaces the cost-style graph.

Table 5: Well-to-wake life cycle emissions per blue fuel from the simulation, flat over 2026-2050.

Fuel	Life cycle emissions (gCO_2eq/MJ)
Blue ammonia	17.5

3.4 Feedstock cost and availability

Natural gas is the feedstock for blue fuels. We assume **natural-gas availability is unconstrained** in our scenarios; the binding constraint on blue-fuel deployment is plant build-out, not feedstock supply.

Table 6: Natural-gas feedstock cost (single global value, flat over 2026-2050).

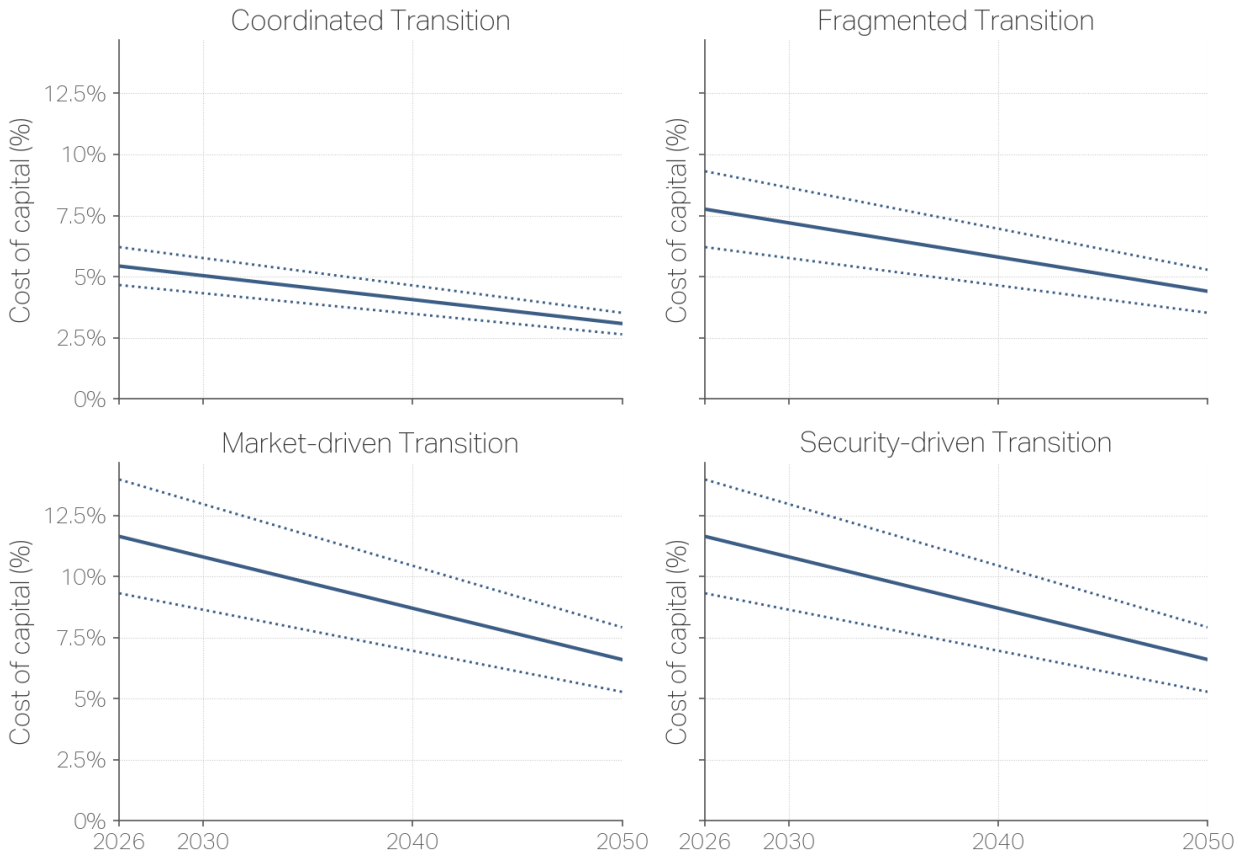
Feedstock	Cost (USD/t)
Natural gas	200

Impact on the model: Natural-gas cost is an important variable-cost term in the derived blue-fuel production cost; its upstream emissions drive the well-to-wake emissions and hence the GHG-cost premium producers pay to source low-emissions gas. Because availability is unconstrained, plant build-out (lead time, WACC, EPC capacity), rather than feedstock, gates uptake of blue fuel.

3.5 WACC

Blue plants are financed at a premium over mature biofuel plants because the technology is first-of-a-kind at commercial scale. We represent the WACC as a single global trajectory (no regionality) with a hydrogen market uncertainty on top. The multiplier moves with the hydrogen-infrastructure axis: scenarios with fast infrastructure build-out get cheaper financing, while scenarios with slow build-out get more expensive financing.

Figure 11: Cost of capital for new blue fuel plants over 2026-2050. One subplot per scenario; the solid line is the central WACC and the dotted lines span the hydrogen-WACC range around it.

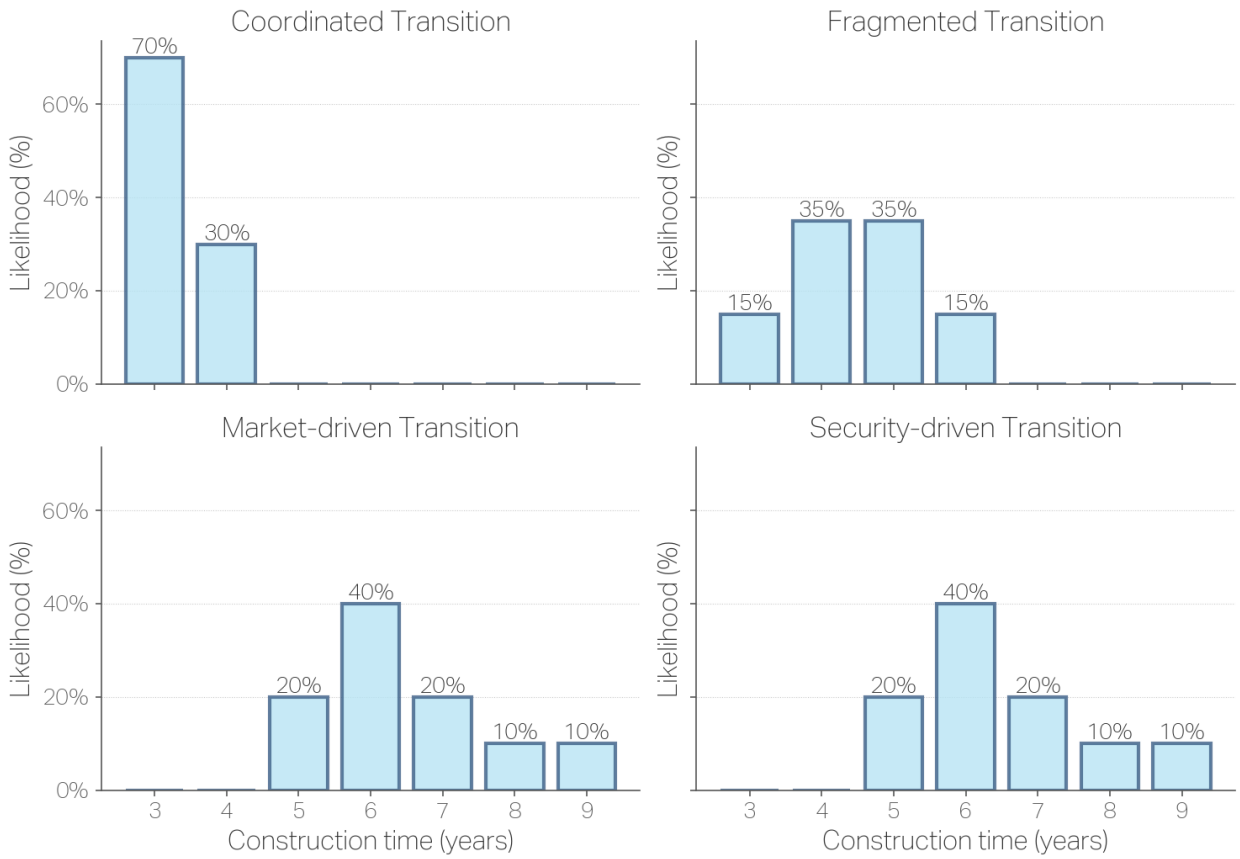


Impact on the model: WACC enters the levelized cost of fuel calculation and thus affects the fuel cost directly. Higher WACC raises fuel costs.

3.6 Plant lead time

Lead times follow the hydrogen-infrastructure axis: faster build-out shifts the distribution to shorter times, while slower build-out widens the distribution and shifts it to longer times. The lead time is a discrete probability distribution over construction years (an input distribution), which we show as a histogram per scenario.

Figure 12: Probability distribution of construction time for a new blue-fuel plant, in years from final investment decision to operation. One subplot per scenario.



Impact on the model: Longer lead times slow the ramp-up of blue-fuel supply and push uptake later. Longer lead times also increase the cost, because the developer pays the CapEx in tranches over the construction period, and longer lead times push out the production year.

3.7 Plant size

Today, blue ammonia is the only blue fuel in scope, and the reference plant capacity is flat over the modeling horizon. We treat the plant-capacity range as an uncertainty (not a scenario lever), so the same low/central/high range applies to all four scenarios.

Table 7: Reference plant size for new blue-ammonia production, flat over 2026-2050.

	Low	Central	High
Blue ammonia (t/d)	2740	4110	5480

Impact on the model: Reference plant size sets how much capacity each build decision adds and drives economies of scale in the derived production cost, where larger reference plants lower the unit cost.

4. E-fuels

4.1 Description of approach

We also build e-fuel costs and emissions **bottom-up**. E-fuels' emissions depend primarily on whether the plant is grid-connected (and so inherits the grid's GHG intensity) or stand-alone with dedicated and additional renewable energy. We assume that all e-fuel plants are stand-alone, so the LCOE is a load-balanced cost from a mix of wind, solar, and battery storage.

Because e-fuels are very CapEx-intensive, we assume producers build them predominantly in areas combining low LCOE with low WACC; the cost is prohibitive in regions with poor financial or technical conditions. We therefore **do not apply regionality to e-fuels** and represent both LCOE and WACC as single global trajectories.

For e-fuels, **WACC** and **plant lead time** are scenario- and uncertainty-dependent (the same hydrogen-infrastructure axis that drives blue fuels). **LCOE**, **reference plant capacity**, and **construction (EPC) capacity** are uncertainty-dependent only.

4.2 Fuel costs (derived result)

Production cost is a derived output and carries P5-P95 uncertainty. We show one figure per e-fuel; the shaded band is the P5-P95 range across samples.

Figure 13: Total production cost of e-ammonia.

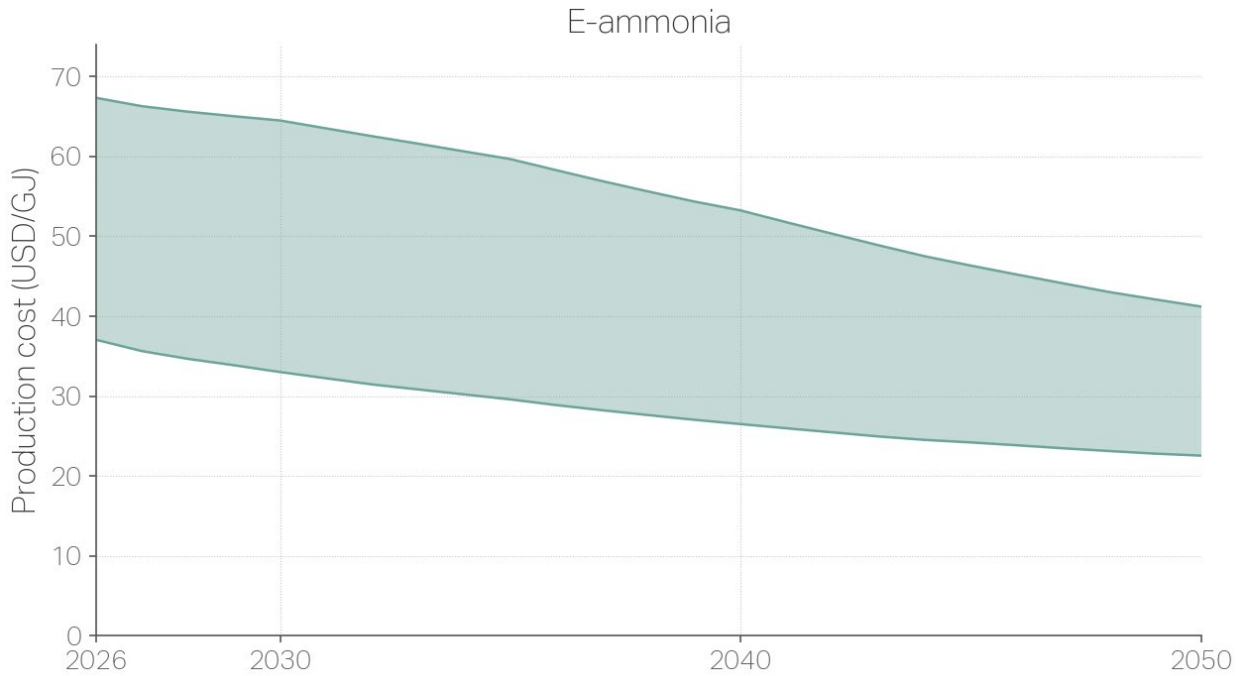


Figure 14: Total production cost of e-methanol.

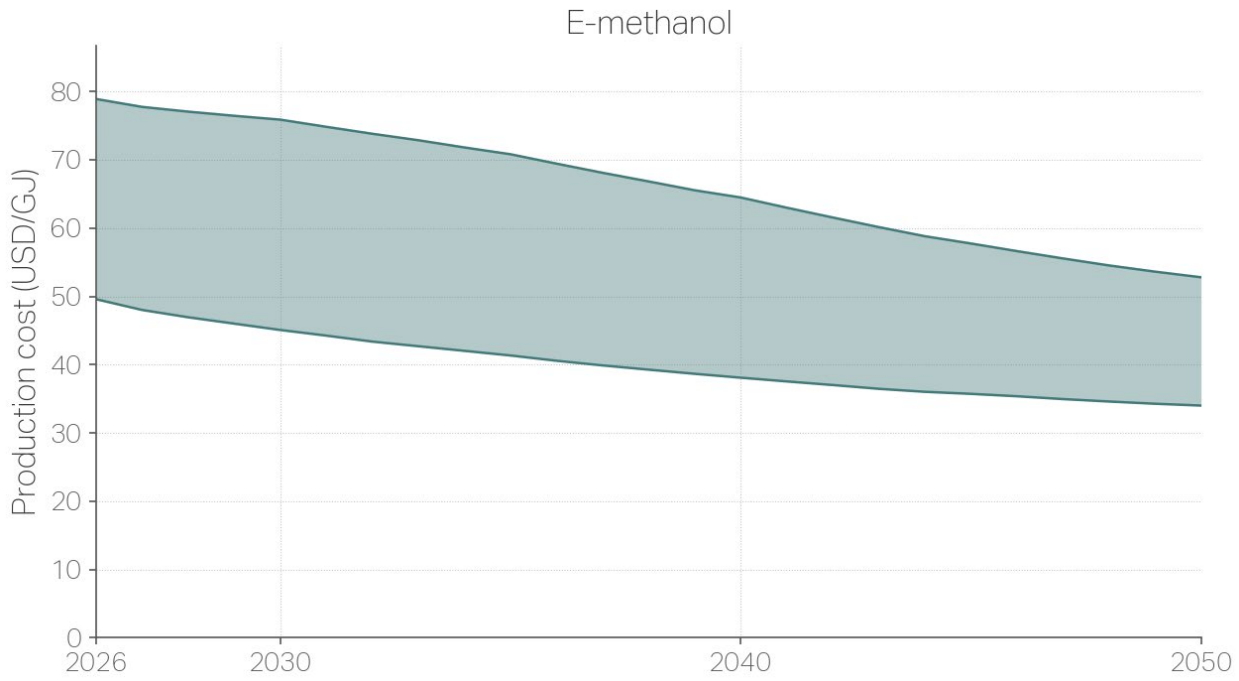


Figure 15: Total production cost of e-methane.

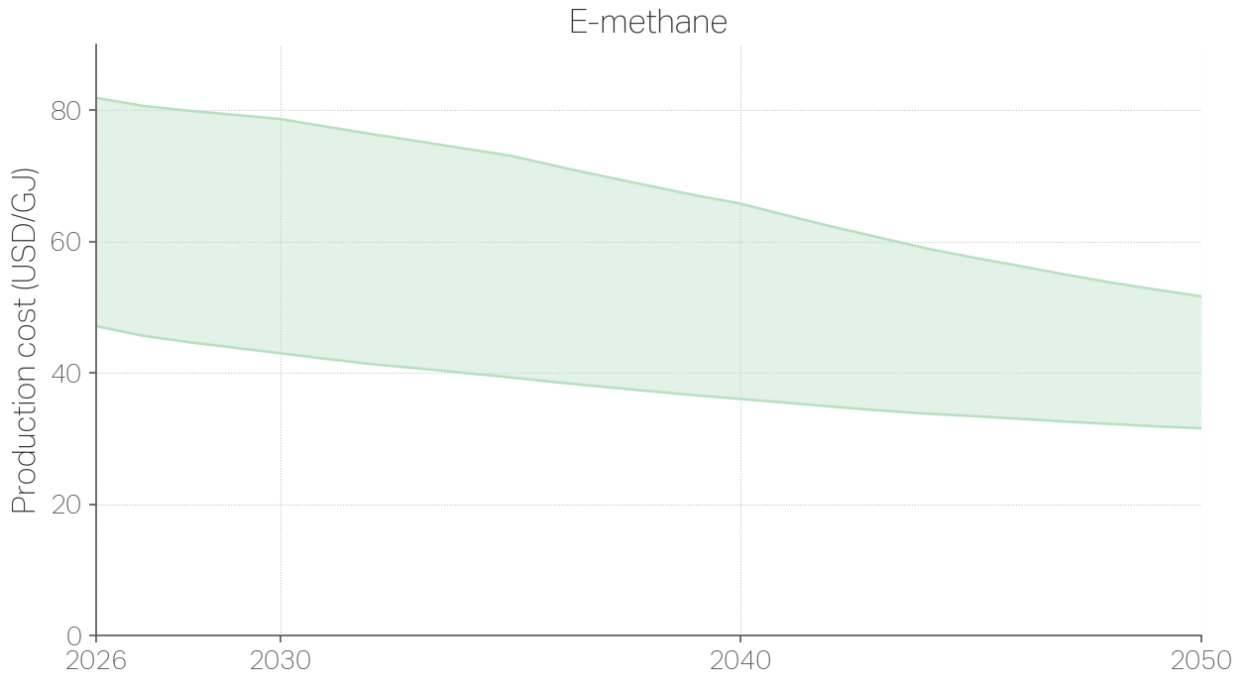
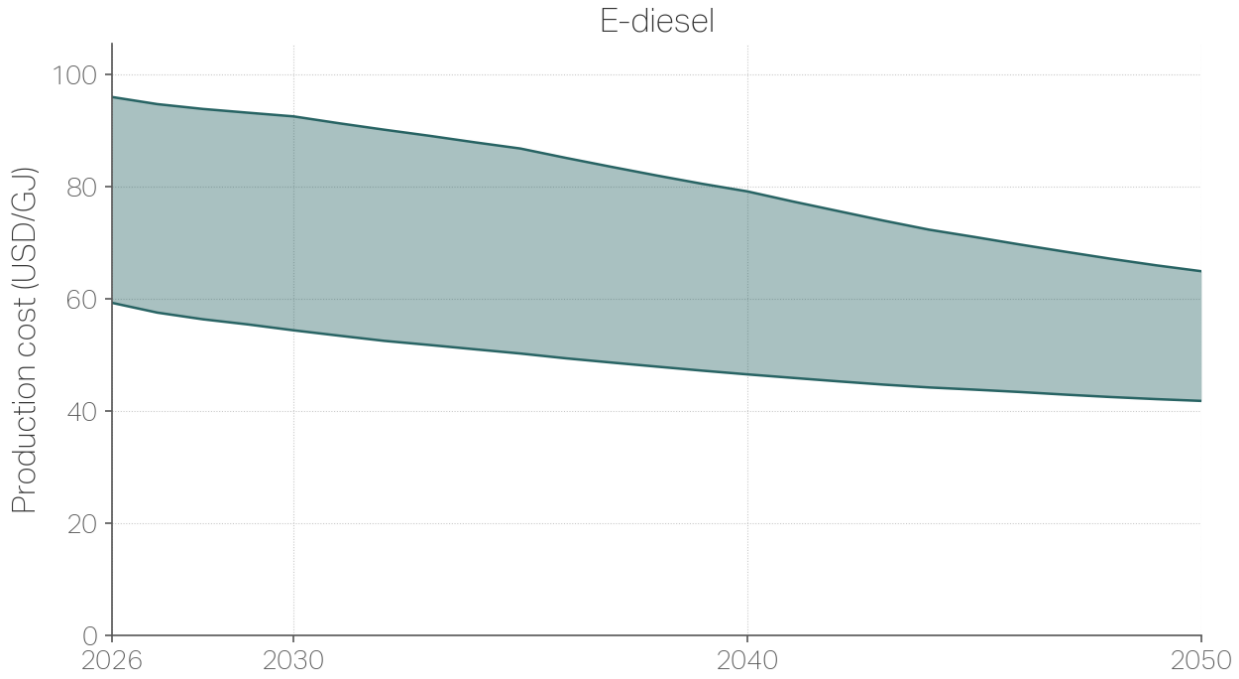


Figure 16: Total production cost of e-diesel.



4.3 Fuel emissions (derived result)

Well-to-wake emissions are flat over the horizon and carry no input uncertainty (P5 = median = P95), so a table replaces the cost-style graph.

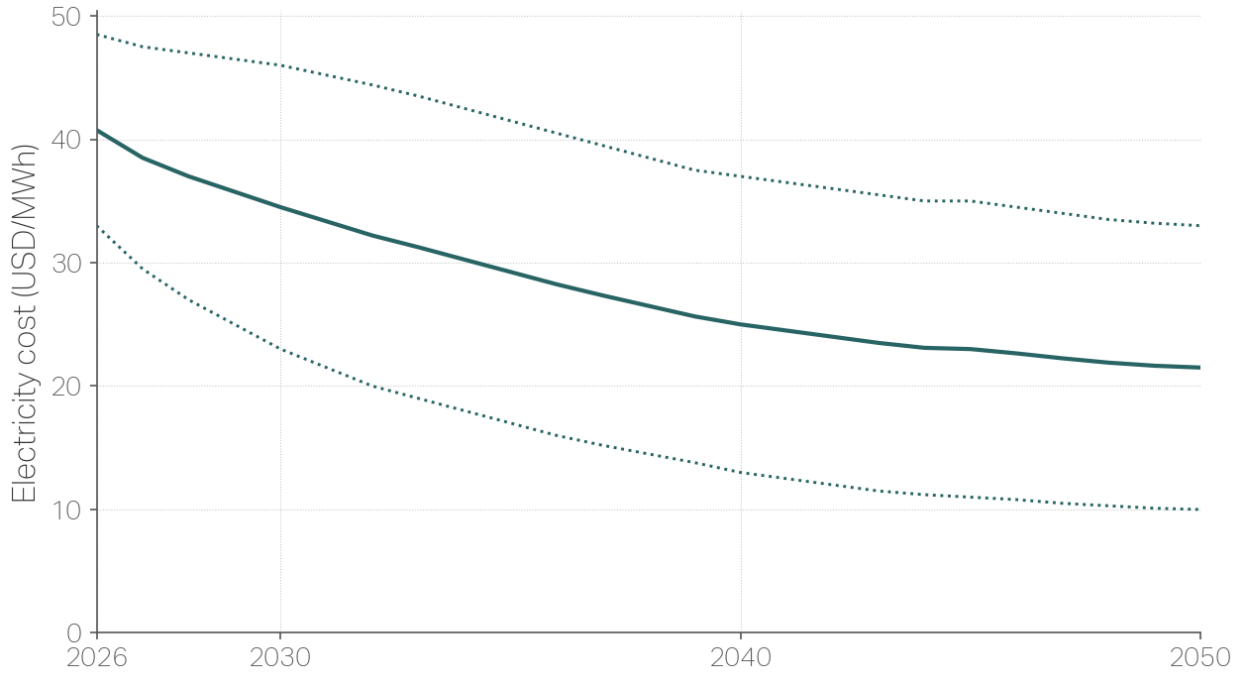
Table 8: Well-to-wake life cycle emissions per e-fuel from the simulation, flat over 2026-2050.

Fuel	Life cycle emissions (gCO_2eq/MJ)
E-ammonia	2.0
E-methanol	2.0
E-methane	4.0
E-diesel	2.0

4.4 Feedstock cost and availability

E-fuel production draws on two feedstocks: renewable electricity (the dominant variable cost) and biogenic CO_2 (the carbon input for e-methanol, e-methane, and e-diesel). We place new e-fuel capacity at renewable-energy hotspots with the lowest delivered cost of renewable power.

Figure 17: Levelized cost of electricity at e-fuel production hotspots. The solid line is the central trajectory; the dotted lines span the optimistic (low) and conservative (high) trajectories.



Biogenic CO_2 cost is global, identical across scenarios, and flat over the horizon, so we tabulate it.

Table 9: Biogenic CO_2 cost (global, flat over 2026-2050).

Feedstock	Cost (USD/t)
Biogenic CO_2	150

Figure 18: Biogenic CO_2 supply available to shipping (global availability × the assumed shipping share). One subplot per scenario; the solid line is the central shipping share for that scenario, and the dotted lines span the low and high shares we test around it.

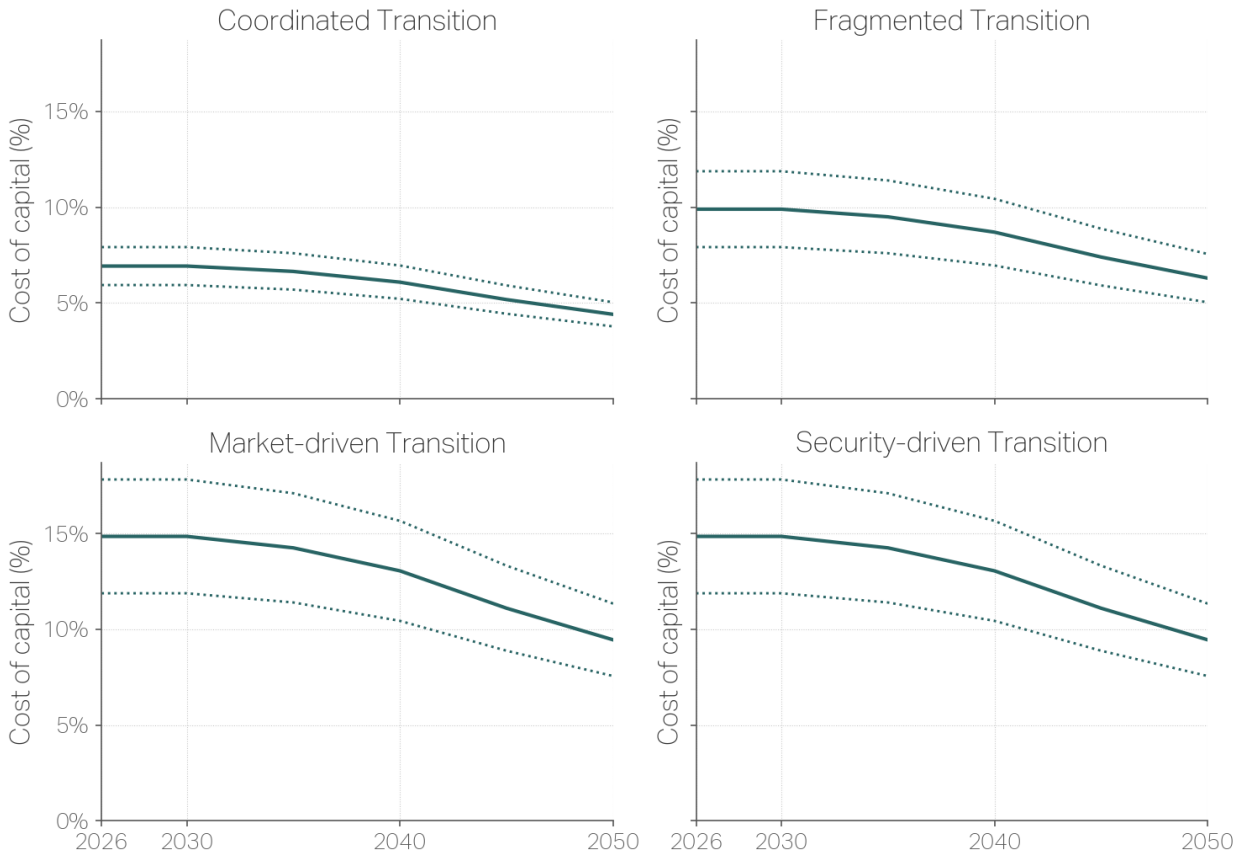


Impact on the model: LCOE is the dominant variable cost in the derived e-fuel production cost, so the LCOE trajectory largely sets when e-fuels become competitive. Biogenic CO_2 cost adds to the cost of the carbon-containing e-fuels (e-methanol, e-methane, e-diesel) but not e-ammonia, and the biogenic CO_2 supply to shipping caps how much carbon-containing e-fuel shipping can source.

4.5 WACC

E-fuel plants are financed at the same first-of-a-kind premium as blue plants. We represent the WACC as a single global trajectory (no regionality) with a hydrogen market uncertainty on top.

Figure 19: Cost of capital for new e-fuel plants over 2026-2050. One subplot per scenario; the solid line is the central WACC and the dotted lines span the hydrogen-WACC range around it.



Impact on the model: WACC enters the levelized cost of fuel calculation and thus affects the fuel cost directly. Higher WACC raises fuel costs.

4.6 Plant lead time

E-fuel lead times are blue lead times plus one year: the same uncertainty distribution shifted by a year of additional first-of-a-kind risk and moving with the same hydrogen-infrastructure axis across scenarios.

Figure 20: Probability distribution of construction time for a new e-fuel plant. One subplot per scenario.



Impact on the model: Longer lead times slow the ramp-up of e-fuel supply and push uptake later. Longer lead times also increase the cost, because the developer pays the CapEx in tranches over the construction period, and longer lead times push out the production year.

4.7 Plant size

The reference plant capacity differs by fuel type: e-ammonia and e-methanol coincide with blue ammonia, while we scale e-methane and e-diesel relative to them. We treat the plant-capacity range as an uncertainty (not a scenario lever), so the same range applies to all four scenarios. Because it is flat over time, we tabulate it.

Table 10: Reference plant size by e-fuel type, flat over 2026-2050.

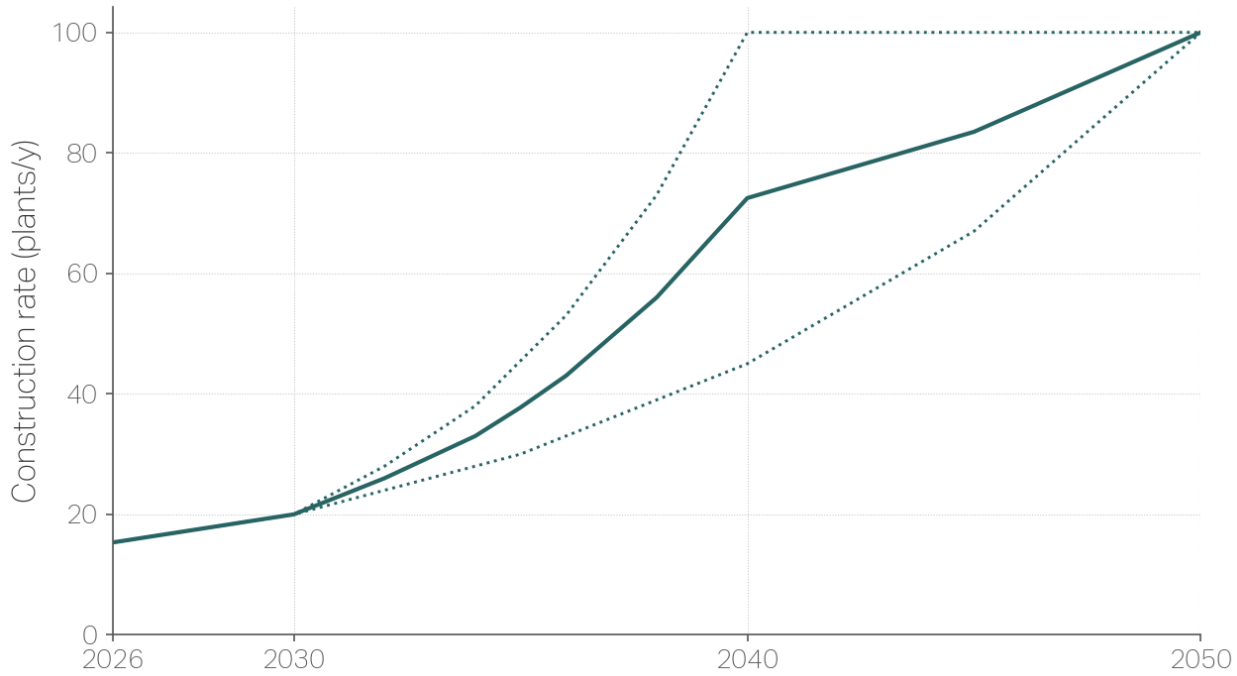
Fuel	Low (t/d)	Central (t/d)	High (t/d)
E-ammonia	2740	4110	5480
E-methanol	2740	4110	5480
E-methane	1397	2096	2795
E-diesel	1041	1562	2082

Impact on the model: Reference plant size sets how much capacity each build decision adds and drives economies of scale in the derived production cost, where larger reference plants lower the unit cost.

4.8 EPC build-out pace

Construction capacity for new e-fuel plants is a global EPC constraint **shared with blue plants**: the two compete for the same engineering, procurement, and construction resources. The pace is uncertainty-dependent and does not vary by scenario.

Figure 21: Maximum global construction rate for new e-fuel and blue-fuel plants. The solid line is the central trajectory; the dotted lines span the slow (low) and fast (high) build-out trajectories.



Impact on the model: EPC capacity is a hard ceiling on how fast the industry can build new blue- and e-fuel plants in aggregate. When demand for new capacity exceeds the EPC ceiling, the model rations build-out between blue and e-fuel plants, so this pace can bind even when economics are favorable at the level of an individual plant.

Abbreviations

CapEx	Capital expenditure
EPC	Engineering, procurement, and construction
FAME	Fatty acid methyl esters
gCO_2eq	Grams CO_2 equivalent
GHG	Greenhouse gas
GWP_{100}	Global warming potential (100 years)
HFO	Heavy fuel oil
LCOE	Levelized cost of electricity
LFO	Light fuel oil
LNG	Liquefied natural gas
MDO	Marine diesel oil
MGO	Marine gas oil
PEM	Proton exchange membrane
SMR	Steam methane reforming
SOEC	Solid oxide electrolyzer cell
tCO_2eq	Tonnes CO_2 equivalent
USD	United States dollars
VLSFO	Very low-sulfur fuel oil
WACC	Weighted average cost of capital