Highlights

Techno-economic and carbon-intensity assessment of lignin–methanol oil production for marine fuel applications

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- Chemical process flowsheet model developed for lignin–methanol oil (LiMO) marine fuel production.
- Minimum selling price estimated at £15.76–20.66/GJ across feedstock and scale scenarios.
- Methanol dominates cost and carbon intensity as both solvent and final fuel component.
- Solvolysis yield is the key technical lever for improving waste-lignin economics..
- LiMO is best positioned as a methanol-enhancing blend, not a standalone fuel..

Techno-economic and carbon-intensity assessment of lignin–methanol oil production for marine fuel applications

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Abstract

Maritime fuel decarbonisation requires alternatives compatible with emerging methanol bunkering infrastructure, yet few lignin-derived routes have been assessed at process scale under transparent economic and carbon-intensity metrics. This study evaluates lignin–methanol oil (LiMO)—a blend of crude lignin oil from mild thermolytic solvolysis with methanol—as a methanol-compatible marine fuel pathway. A chemical process flowsheet model was developed for production of 25 wt% LiMO at 200 °C, with techno-economic analysis across technical lignin (Protobind) and pseudo-waste lignin scenarios at pilot and commercial scale. Minimum selling price (MSP), carbon intensity and energy return on investment (EROI) were quantified under UK cost and emission-factor assumptions. MSP was estimated at £15–21/GJ and carbon intensity at 94–105 $kgCO_2e/GJ$; methanol dominated both cost and emissions because it serves as solvent and major fuel component. Ten-fold scale-up reduced MSP by only £0.37–0.65/GJ, reflecting OPEX dominance by methanol and feedstock. Waste lignin improved EROI toward unity (maximum 1.04), but most scenarios remained below net energy breakeven. LiMO is technically viable but should be framed as a methanol-enhancing

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or biomethanol-extending blend rather than a standalone low-carbon fuel. Meaningful improvement requires higher solvolysis yield, heat integration, char valorisation and access to low-carbon methanol and heat.

Keywords: Lignin valorisation, Lignin–methanol oil, Marine fuel, Techno-economic analysis, Methanol, Carbon intensity

1. Introduction

International shipping accounts for approximately 2.9% of global greenhouse -gas emissions and remains heavily dependent on residual fuel oils that are difficult to decarbonise at scale [1]. Regulatory pressure is intensifying: the IMO 2020 global sulphur cap has constrained heavy fuel oil quality, and proposed global measures including carbon pricing on shipping fuels are accelerating interest in alternative marine energy carriers [2, 3]. Among near-term options, methanol is receiving substantial vessel and bunkering investment because it can be handled within evolving dual-fuel engine platforms and port infrastructure [4, 5]. However, neat methanol has a low lower heating value (LHV; ~20 MJ/kg), poor cetane characteristics and high effective fuel cost per unit energy, limiting its appeal as a sole marine fuel without blending or co-firing strategies.

Lignin comprises up to 30% of lignocellulosic biomass and is generated in large quantities from pulp and paper and emerging bioethanol industries [6]. Its aromatic, carbon-dense structure makes lignin an attractive feedstock for liquid fuels, yet conventional pyrolysis and upgrading routes often produce highly oxygenated, acidic oils that require costly hydrotreatment before use [7, 8]. Mild solvolytic depolymerisation in polar solvents offers an alternative that preserves higher-energy aromatic structures at moderate temperature [9]. When methanol is used as solvent, the resulting crude lignin oil (CLO) can be blended directly with methanol to form lignin–methanol oil (LiMO), avoiding hydrogen-intensive upgrading while remaining compatible with methanol marine fuel logistics [10, 11].

LiMO is therefore best understood not as a standalone replacement for conventional marine fuels, but as a methanol-enhancing blend in which lignin oligomers increase energy density, improve ignition-related properties relative to neat methanol and potentially extend limited biomethanol supply [10]. Experimental work has demonstrated engine operability and fuel stability at lignin fractions of 25–30 wt%, with sulphur contents below maritime limits

[10, 12]. What remains unresolved is how feedstock quality, solvolysis yield, methanol price and process scale jointly determine the economic and carbon performance of LiMO production—particularly in a UK context where lignin-rich residues from paper and bioethanol projects may become available [13].

This study addresses that gap through an Aspen Plus techno-economic and carbon-intensity assessment of 25 wt% LiMO production via mild thermolytic lignin methanolysis at 200 °C. The objectives are to: (i) quantify MSP, carbon intensity and EROI for technical lignin and pseudo-waste lignin at pilot and commercial scale; (ii) identify dominant cost and emission drivers; (iii) evaluate sensitivity to yield, ash content, methanol price and recovery efficiency; and (iv) interpret results in terms of LiMO's role as a methanol-extending marine fuel pathway rather than an energy-positive standalone fuel.

2. Background and related work

2.1. Pyrolysis oils

Conventional thermochemical conversion routes, particularly fast pyrolysis, are widely studied for lignocellulosic valorisation. Condensed bio-oils can be obtained at yields up to 80% on a dry feed basis [14], but typically contain high oxygen levels (>30 wt%), substantial water and strongly acidic pH (2–3) [15, 7]. These properties reduce energy density, compromise stability and limit direct use as marine fuels without upgrading. Catalytic hydrodeoxygenation (HDO) can improve properties sufficiently for bunker fuel standards [8], but hydrogen demand and elevated operating conditions dominate costs; techno-economic analyses indicate that even mildly hydrotreated bio-oils remain uncompetitive with conventional fuel oils [8].

Lignin-rich feedstocks offer a structural advantage over whole-biomass pyrolysis because their aromatic framework is naturally more carbon dense. Pathways that preserve rather than fully deoxygenate this structure may therefore deliver fuel blends with higher heating values than typical pyrolysis oils—shifting the design question from extensive upgrading of oxygenated bio-oils toward selective conversion of an underutilised biorefinery residue.

2.2. Lignin solvolysis

Lignin chars readily under conventional pyrolysis conditions, motivating solvolytic depolymerisation. Kleinert and Barth demonstrated lignin-to-liquid (LtL) solvolysis at 380 °C with formic acid, achieving high yields

and HHVs approaching conventional fuel oils [16]. However, formic acid consumption and long reaction times constrain economics, favouring high-value chemical applications over bulk marine fuels. Catalytic hydrogenolysis can achieve high conversion and product HHVs [17], but hydrogen cost, catalyst deactivation and feedstock contaminants (sulphur, alkali metals) limit scalability [18].

Milder non-catalytic solvolysis is more aligned with industrial fuel production. Kouris *et al.* demonstrated thermolytic solvolysis of soda lignin at 200 °C, producing CLO with minimal charring [9]. Selective cleavage of β-*O*-4 linkages, coupled with solvent capping of reactive intermediates, limits repolymerisation; methanol solubilised up to 61 wt% of lignin with low solvent loss. Resulting CLOs have moderate HHVs (~30 MJ/kg) and remain viscous and acidic, but avoid the severity and hydrogen inputs of LtL or HDO routes.

2.3. Lignin–methanol oil

The compatibility between CLO from mild methanolysis and methanol as a marine fuel carrier is increasingly recognised. Methanol's polarity enables blending without further HDO, simplifying the production train relative to drop-in bio-heavy fuel oil pathways. Lazzaro *et al.* showed that a 25 wt% LiMO blend has reduced viscosity compared with heavier CLO blends, enabling pumping under two-stroke marine engine conditions [10]. Kumar *et al.* demonstrated thermodynamic stability at lignin concentrations ≥30 wt%, attributed to methanol–lignin interactions and network formation that resists sedimentation under shear [11].

Combustion studies indicate stable dual-fuel marine operation with a small diesel pilot fraction [10]. LiMO may therefore integrate with developing methanol bunkering infrastructure [4], while mild methanolysis can reduce fuel sulphur content [12, 9]. Commercial demonstrations such as Vertoro's GEM25 (25 wt% lignin) report sulphur below 0.02 wt%, within IMO limits [10].

Thus it follows that conventional pyrolysis oils require substantial upgrading; lignin solvolysis can preserve higher-energy aromatic structures at milder conditions; LiMO may integrate with methanol marine fuel infrastructure—yet the combined effects of feedstock quality, yield, methanol cost and process energy on economic and carbon performance are not well resolved at process scale. This study provides an assessment at process scale.

3. Methodology

3.1. Process modelling

A process flowsheet model was constructed using Aspen Plus V14 for techno-economic analysis (TEA). The model produces 25 wt% LiMO (25 wt% solubilised lignin in methanol), selected as a representative near-term marine blend with minimal upgrading requirements [10]. Reactor conditions were fixed at 200 °C, 55 bar and 30 min residence time, with a lignin:methanol ratio of 1:5 (w/v), consistent with literature reporting favourable yields without char fouling [9].

The configuration comprises three sections (Fig. 2; Table 1): feed preparation and pressurisation (B_1–B_4), solvolysis (B_5), and downstream separation and methanol recovery (B_6–B_9). A heat exchanger (B_3) recovers effluent heat to preheat feed, reducing external heating in B_4. Solids are removed in B_6; flash separation (B_7) controls the final lignin:methanol ratio; methanol is recovered from solid (B_8, 90% base case) and liquid (B_9, 95% base case) streams. A distillation column prevents water accumulation in the recycle loop.

Due to uncertain solvolysis kinetics, the reactor was modelled with an *RYield* block using experimental product distributions for Protobind (PB) 1000 technical lignin [9, 19]. A lumped-parameter framework (Fig. 1) decomposed feed into solubilised lignin, char, insoluble residue, light gases and methanol losses, represented with conventional and non-conventional components using literature elemental analyses [9, 20]. Elemental mass closure was verified via external spreadsheet calculations (Supplementary Information SI-2).

Figs. 3 and 4 show the completed Aspen Plus flowsheet upstream and downstream of filtration.

3.2. Feedstock and yield assumptions

Lignin feed was characterised using ultimate analysis of Protobind 1000 (compositional data in Supplementary Information SI-1). Waste lignin was represented as a less reactive, higher-ash variant of Protobind to isolate yield and ash effects. Feed was modelled on a dry basis; practical feed moisture was assumed at 5% for technical lignin (2–5% for Protobind). For the waste case, an external drying step reduced moisture from 40 to 5 wt% using a 70%-efficient dryer; drying energy was included in process energy and OPEX but excluded from technical-lignin feed cost (assumed pre-dried at purchase). Sulphur was included; nitrogen, chlorine and other trace contaminants were

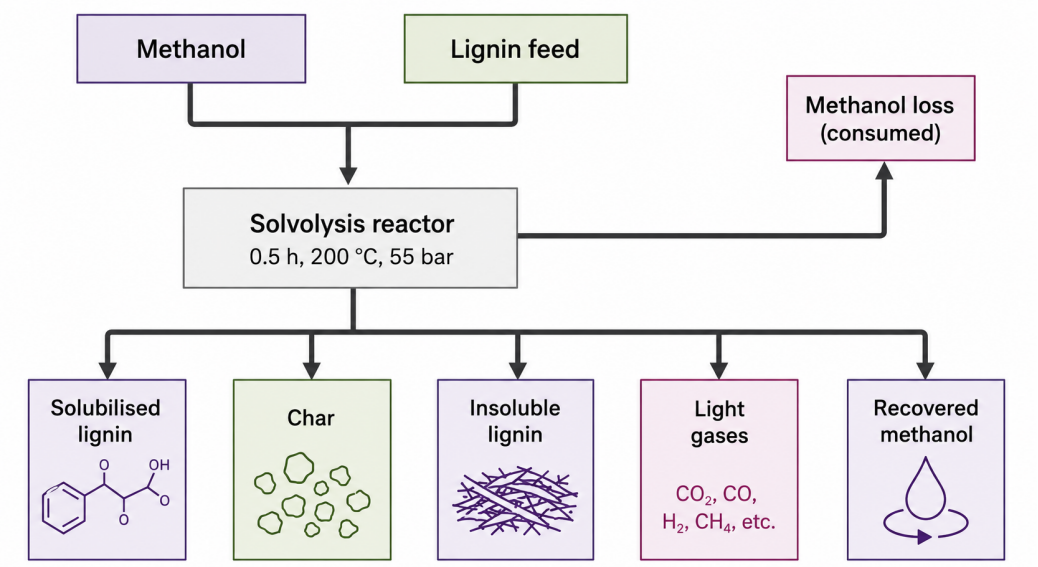

Figure 1: Schematic representation of lumped product streams used in the solvolysis reactor model.

excluded. Total acid number was not modelled but is assumed acceptable for 25 wt% LiMO based on literature [10].

Product yields were taken from Kouris *et al.* [9, 19], with complementary data from patent and paper sources where gaps existed. Fixed methanol consumption of 1.1 wt% (relative to lignin) was assumed. Solubilised lignin HHV was held invariant across cases (~29.7 GJ/t), consistent with mild solvolysis literature on waste residues [20]; performance differences were therefore driven by yield and blend composition rather than product quality shifts.

Ash was treated as inert diluent assigned to the char lump in B_5, with yield fractions adjusted per Supplementary Information SI-2. Char served as a slack variable for elemental closure; char carbon content is likely underestimated and no economic value was assigned to char in the base analysis. Unaccounted lignin mass was assigned to light gases (50% CO_2, 40% H_2O, 10% CO) to close elemental balance [20]. Methanol gaseous losses were neglected based on literature to 300 °C [20]. Mass, elemental and energy balances were verified in Aspen and spreadsheets .

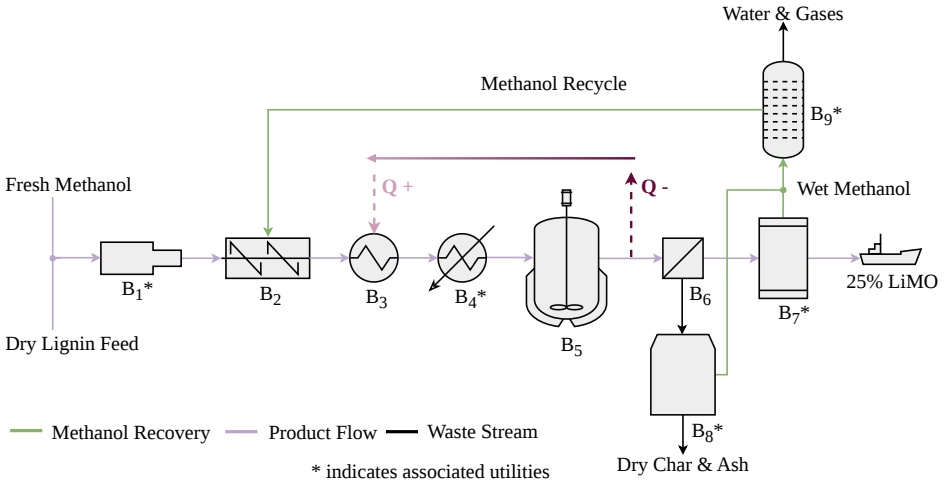

Figure 2: Simplified flowsheet of the LiMO production process. Block labels correspond to Table 1.

3.3. Energy and EROI metrics

Energy return on investment was defined as:

$$\mathrm{EROI} = \frac{E_{\mathrm{LiMO}}}{E_{\mathrm{lignin}} + E_{\mathrm{MeOH}} + E_{\mathrm{process}}} \tag{1}$$

where E_{LiMO} is LiMO energy output, E_{lignin} and E_{MeOH} are lignin and makeup methanol energy inputs, and E_{process} is process and utility energy from drying through final product. Upstream feedstock cultivation and capital embodied energy were excluded. For waste lignin, upstream lignin energy was set to zero per co-product allocation guidelines [21]; drying energy remained in E_{process} for all cases. Fuel energies used LHV. EROI > 1 indicates net positive energy within this boundary.

Process efficiency isolated conversion of feed energy into LiMO:

$$\eta_{\mathrm{process}} = \frac{\dot{m}_{\mathrm{LiMO}}\,\mathrm{LHV}_{\mathrm{LiMO}}}{\dot{m}_{\mathrm{lignin}}\,\mathrm{LHV}_{\mathrm{lignin}} + \dot{M}_{\mathrm{MeOH}}\,\mathrm{LHV}_{\mathrm{MeOH}}} \tag{2}$$

3.4. Economic assumptions

MSP was defined as the fuel price covering annualised capital and operating expenditure per unit of fuel energy output:

$$\mathrm{MSP} = \frac{\text{Annualised CAPEX} + \text{OPEX}}{\text{Annual fuel energy output}} \tag{3}$$

Table 1: Key assumptions and flowsheet detail for Aspen Plus blocks.

Block	Unit operation	Aspen type	Key assumptions	Utilities
B_1	Feed pump	Pump	Lignin–methanol slurry at 25 °C	Electricity
B_2	Mixer	Mixer	Ideal mixing	–
B_3	Heat exchanger	HeatX	Feed preheated to ~150 °C	–
B_4	Heater	Heater	Feed to 200 °C	Steam
B_5	Solvolysis reactor	RYield	Isothermal; literature yields	–
B_6	Solid separator	Sep2	Complete solids removal	–
B_7	Flash separator	Flash2	Controls LiMO blend ratio	Steam
B_8	Solids dryer	Flash2	90% MeOH recovery (base)	Steam
B_9	Distillation	RadFrac	95% MeOH recovery (base)	Steam, cooling
–	Boiler	–	85% thermal efficiency	–

MSP is reported in £/GJ (2026 currency year) on an LHV basis. USD costs were converted at 0.75 £/USD and EUR costs at 0.85 £/EUR where required.

CAPEX was estimated from Aspen equipment sizing supplemented by manual reactor and filter estimates. A 75 m^3 stainless-steel-clad reactor was sized from residence time and throughput; commercial scale used five 150 m^3 parallel reactors scaled by a 0.6 power law [22]. Total installed cost used a Lang factor of 4, 10% contingency and 15% working capital [23]. A 20-year lifetime and 10% discount rate gave a capital recovery factor of 0.1174 [24]. CAPEX uncertainty of −30% to +50% was applied in sensitivity analysis [22].

OPEX components and sources are summarised in Table 2. Utilities used UK industrial prices (Quarterly Energy Prices, December 2025) with 2026 climate-change levy rates [25, 26]. Grey methanol was priced at £225/t (~$300/t five-year average); biomethanol sensitivity used £1000/t [27]. Plant uptime was 8000 h/year. Char value was neglected.

3.5. Emission factors and carbon-intensity calculation

Process carbon intensity ($kgCO_2e$ per GJ LiMO) was estimated using the factors in Table 3, applied to lignin, methanol makeup, steam, electricity and cooling within the production boundary. Grey methanol (106.5 $kgCO_2e/GJ$) was the base blending component [30]. Medium-pressure steam was generated from natural gas (0.2027 $kgCO_2e/kWh$); biogas steam (0.02841 $kgCO_2e/kWh$)

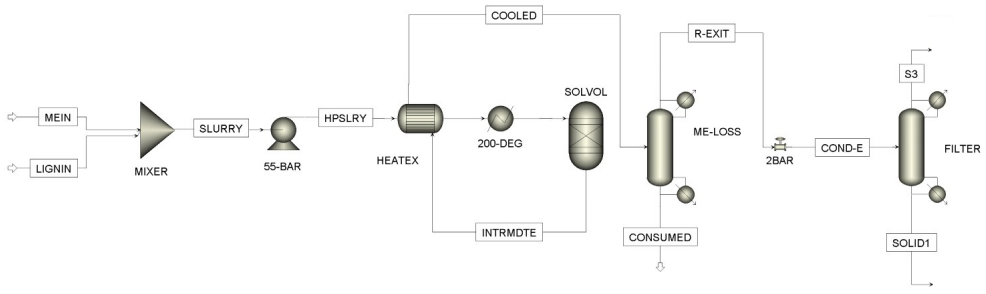

Figure 3: Aspen Plus flowsheet truncated at the filtration step.

was explored in sensitivity scenarios [31]. Waste lignin was assigned zero upstream emissions [21, 32]. This should be interpreted as a process-boundary carbon-intensity assessment rather than a full well-to-wake or cradle-to-grave marine fuel LCA.

3.6. Scenario definitions

Two feedstock scenarios—base (technical lignin) and waste—were evaluated at pilot and commercial (10× throughput) scale (Table 4). Throughputs were set to produce 100,000 and 1,000,000 t/year of solubilised lignin at 8000 h/year operation, defining lignin and methanol flow rates via yield and blend ratio. Sensitivity analysis varied lignin and methanol prices, solvolysis yield, methanol recovery, feedstock ash, biomethanol fraction and steam source.

4. Results and discussion

4.1. Cost and carbon-intensity breakdown

Table 5 and Table 6 summarise the techno-economic and performance results for the four modelled cases. MSP for 25 wt% LiMO with grey methanol ranged from £15.76–20.66/GJ across the four scale–feedstock combinations, exceeding the energy-equivalent cost of grey methanol alone (∼£10/GJ at

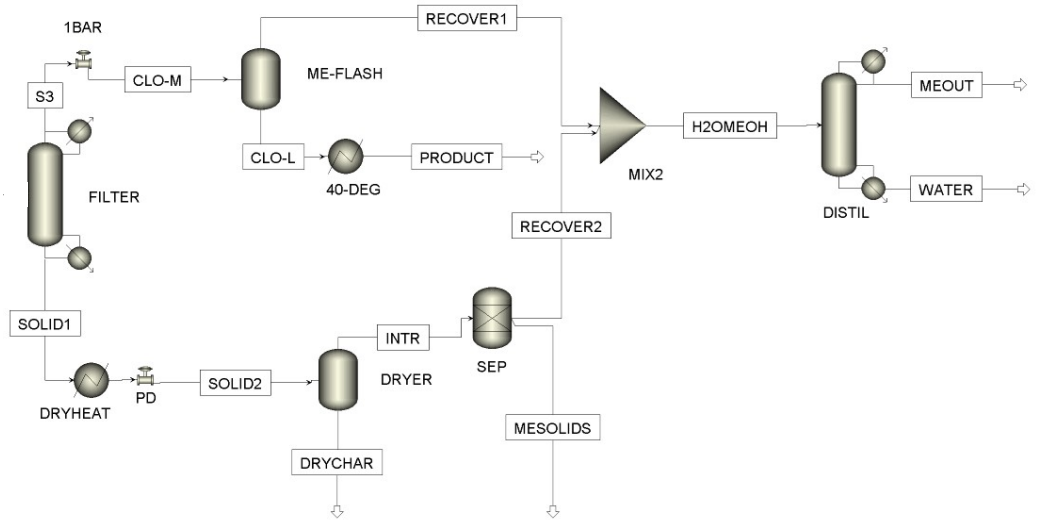

Figure 4: Aspen Plus flowsheet downstream of the filter.

£225/t). This is expected: at low methanol prices, solvolysis adds cost and functions as a fuel-upgrading step rather than a cost-reduction pathway. Even with zero-cost lignin and 60% yield at pilot scale, MSP remained £262/t (∼£12/GJ product), indicating a floor set by methanol and process energy.

The process is OPEX-dominated. Lignin and methanol feedstocks account for the majority of annual operating cost; annualised CAPEX contributes only a small fraction of total cost per GJ. Methanol dominates emissions for the same reason: it constitutes approximately 75 wt% of the final fuel and its makeup carries the grey-methanol carbon intensity, while process utilities contribute secondarily through steam demand.

Carbon intensity (94.7 $kgCO_2e/GJ$ base; 104.5 $kgCO_2e/GJ$ waste) remained close to grey methanol (106.5 $kgCO_2e/GJ$). Assigning zero upstream emissions to waste lignin yielded only modest reduction because lower yield (40 vs. 63.75 wt%) increased methanol circulation, solids handling and steam

Table 2: OPEX components and estimation basis.

Cost component	**Basis**	**Source**
Lignin feedstock	£/tonne	[28, 9]
Methanol	£/tonne	[27]
Steam	£/kWh	[25, 26]
Electricity	£/kWh	[25, 26]
Cooling water	£/m^3	[23]
Labour	Turton correlation	[22]
Maintenance	3% of TCI/year	[23]
Operating supplies	15% of maintenance	[29]
Insurance	1% of TCI/year	[23]
Supervision	15% of labour	[29]

Table 3: Emission factors used in carbon-intensity analysis.

Feedstock/utility	**Basis**	**Value**
Protobind (PB)	$kgCO_2e/kg$	0.5
PB pseudo-waste	$kgCO_2e/kg$	0
Methanol	$kgCO_2e/GJ$	106.5
Biomethanol	$kgCO_2e/GJ$	35
Natural gas	$kgCO_2e/kWh$	0.2027
Biogas	$kgCO_2e/kWh$	0.02841
Electricity	$kgCO_2e/kWh$	0.177

Utility factors are cradle-to-grave. Waste lignin assigned zero upstream emissions per co-product guidelines.

duty for separation and drying. Higher char formation entrained additional methanol, further increasing utility loads.

Table 4: Key parameters for base and waste scenarios (pilot scale; commercial scale = 10× throughput).

Parameter	**Base case**	**Waste case**
Lignin feed	Protobind	PB pseudo-waste
Lignin cost (£/t)	560[a]	45[a]
Methanol cost (£/t)	225 / 1000[b]	225 / 1000[b]
Drying required	No	Yes
Lignin throughput (t/h)	19.6	19.6
MeOH throughput (t/h)	77.5	77.5
Feed ash (wt%)	2	10
CLO yield (wt% lignin)	63.75	40
Char yield (wt% lignin)	23	46.8
B_8 MeOH recovery (%)	90	90
B_9 MeOH recovery (%)	95	95

[a]Sourced from nearby biorefinery with minor transport. [b]Grey / biomethanol sensitivity.

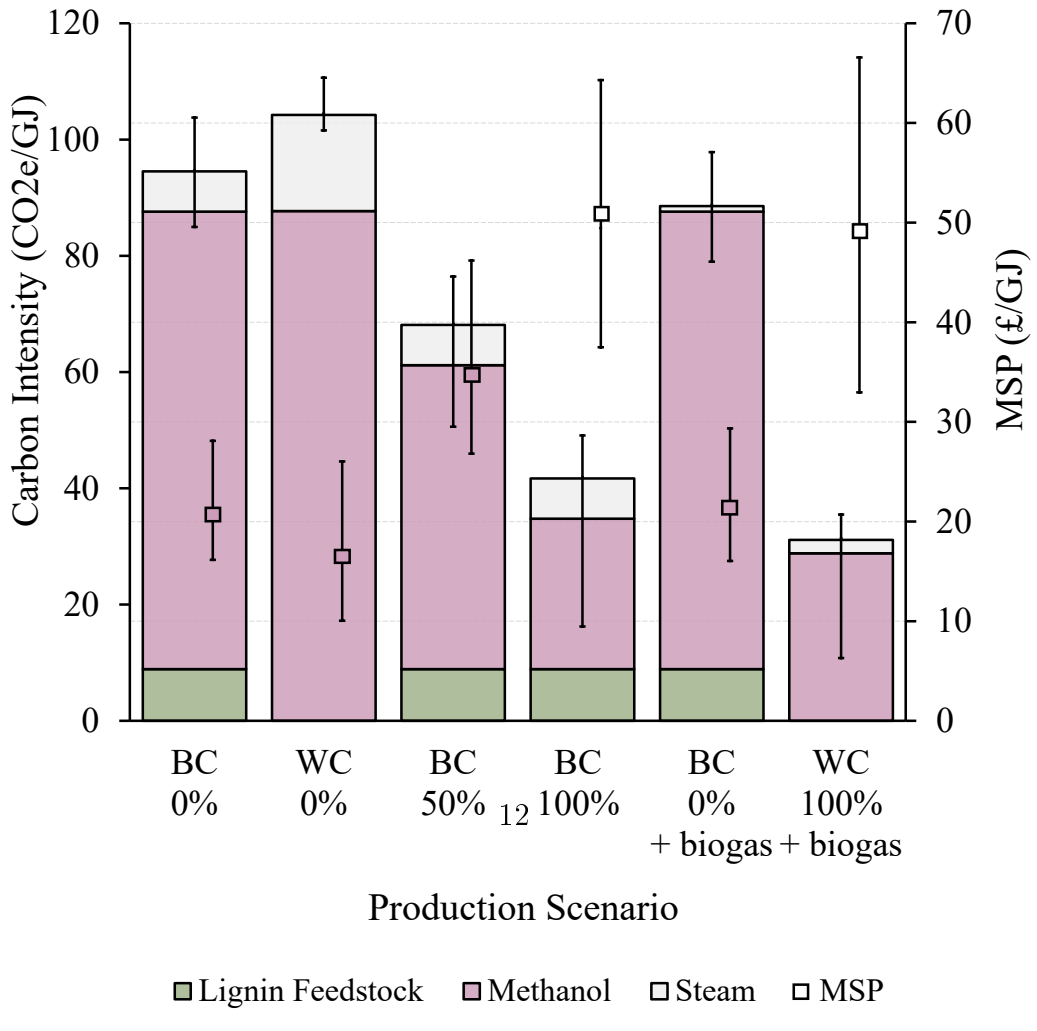

Table 5: Economic results for the four modelled LiMO production cases.

Metric	Pilot base	Scale base	Pilot waste	Scale waste
Capital costs				
Solvolysis reactor(s) [£]	4,890,000	37,164,000	4,890,000	37,164,000
Distillation system [£]	3,980,400	15,845,972	3,980,400	15,845,972
Filter unit [£]	1,500,000	5,971,500	1,500,000	5,971,500
Other equipment [£]	1,706,700	6,794,373	1,706,700	6,794,373
Total FCI [£]	12,077,100	65,775,845	12,077,100	65,775,845
Total CAPEX [£]	15,096,375	82,219,806	15,096,375	82,219,806
Annualised CAPEX [£/yr]	1,772,314	9,652,605	1,772,314	9,652,605
Operating costs				
Lignin feedstock [£/yr]	88,200,000	882,000,000	7,056,000	70,560,000
Methanol makeup [£/yr]	73,500,004	735,000,040	47,174,267	471,742,667
Utilities [£/yr]	15,230,520	152,305,086	24,041,500	240,529,239
Labour + overheads [£/yr]	2,530,000	2,990,000	2,530,000	2,990,000
Total OPEX [£/yr]	179,997,956	1,775,222,151	81,350,622	788,748,932
Cost performance				
MSP [£/tonne]	454.51	446.30	360.94	346.69
MSP [£/GJ]	20.66	20.29	16.41	15.76

Table 6: Energy, carbon and fuel-performance results for the four modelled LiMO production cases.

Metric	Pilot base	Scale base	Pilot waste	Scale waste
EROI [–]	0.73	0.73	0.85	0.85
Process efficiency, η_{process} [–]	0.83	0.83	0.64	0.64
Carbon intensity [$kgCO_2e/GJ$]	94.7	94.7	104.5	104.5
Sulphur content [wt%]	0.1	0.1	0.1	0.1
LHV [GJ/tonne]	22.0	22.0	22.0	22.0

Figure 5 illustrates biomethanol and biogas sensitivity. Methanol makeup dominates emissions; biogas steam reduces intensity most in the waste case where steam demand is elevated. At 100% biomethanol, MSP approaches the assumed biomethanol market value (~£50/GJ) because methanol dominates OPEX—the process acts primarily as an upgrading step. At 60% yield in the waste case, MSP falls to £42.32/GJ, undercutting biomethanol by ~£10/GJ and confirming yield as a critical lever.

Char and insoluble solids remain poorly characterised economically. If valorised as biochar (£400–1000/t), this stream could offset MSP [33]; assigning zero value is conservative.

4.2. Scale-up effects

Tenfold scale-up reduced MSP by only £0.37/GJ (base) and £0.65/GJ (waste), reflecting limited leverage from reduced annualised CAPEX per GJ when feedstock and methanol OPEX dominate. The waste case showed a proportionally larger MSP reduction because lower lignin cost shifted the relative weight of capital. These results caution against assuming that commercial scale alone will close the gap with conventional or neat methanol fuels without concurrent methanol cost reduction or yield improvement. This indicates that process optimisation, yield improvement and process input decarbonisation are more important than scale-up alone.

4.3. EROI and process efficiency

Figure 6 shows EROI sensitivity. Technical lignin cases remain below unity (EROI 0.73) because upstream lignin energy is counted in the numerator boundary. Waste lignin improves EROI to 0.85 at base yield, with a maximum of 1.04 under favourable yield assumptions—but most scenarios remain at or below breakeven. This indicates that the value proposition is not net energy production; LiMO may still be justified if lignin incorporation improves methanol fuel quality (LHV, cetane-related behaviour), extends biomethanol supply or enables use of low-cost waste lignin that would otherwise be discarded.

Treating char as an energy product (LHV 20 MJ/kg) raises waste-case EROI to 1.12, highlighting char characterisation as a priority. Process efficiency η_{process} falls from 0.83 to 0.64 in the waste case due to lower lignin conversion. EROI was unchanged between pilot and commercial scale under current utility-modelling assumptions.

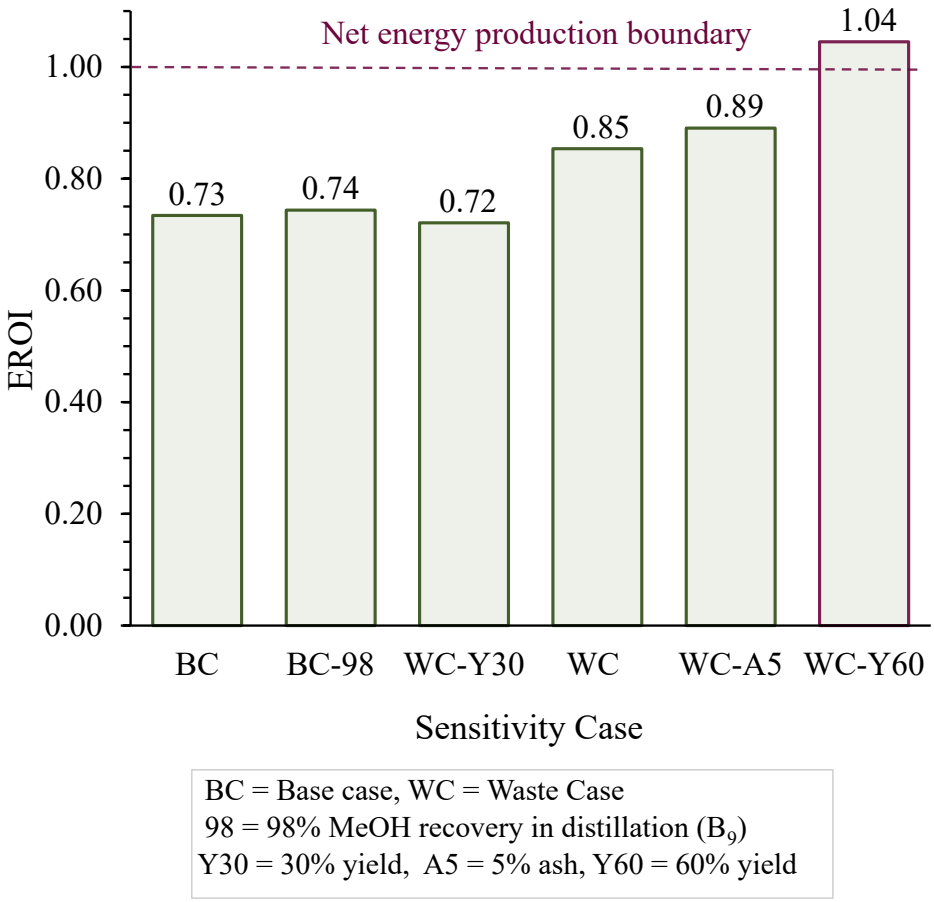

Figure 6: EROI across sensitivity scenarios. Dashed line indicates EROI = 1.

4.4. Sensitivity analysis

Base-case MSP sensitivity (Fig. 7) confirms methanol and lignin price as primary drivers, with approximately linear yield effects through increased methanol circulation and steam demand at low conversion. Methanol recovery variations in B_8 and B_9 have limited impact because the dominant methanol "loss" is intentional retention in the final LiMO product.

In the waste case (Fig. 8), methanol price remains dominant but yield becomes the leading secondary factor—the main opportunity for cost reduction when lignin is low cost. Ash content further compounds cost through yield dilution and increased solids handling.

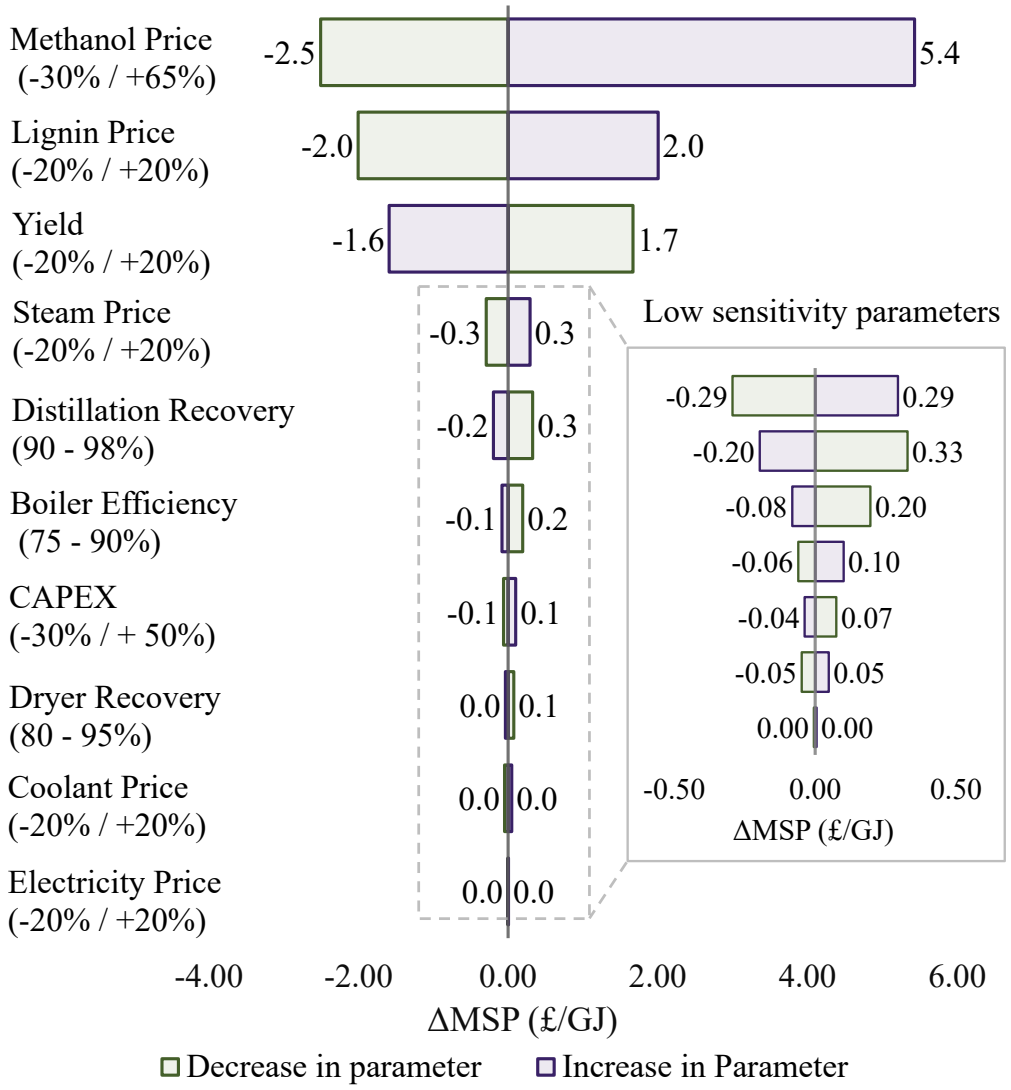

Figure 7: Sensitivity of base-case MSP to parameter uncertainty. Low-sensitivity parameters use a secondary axis.

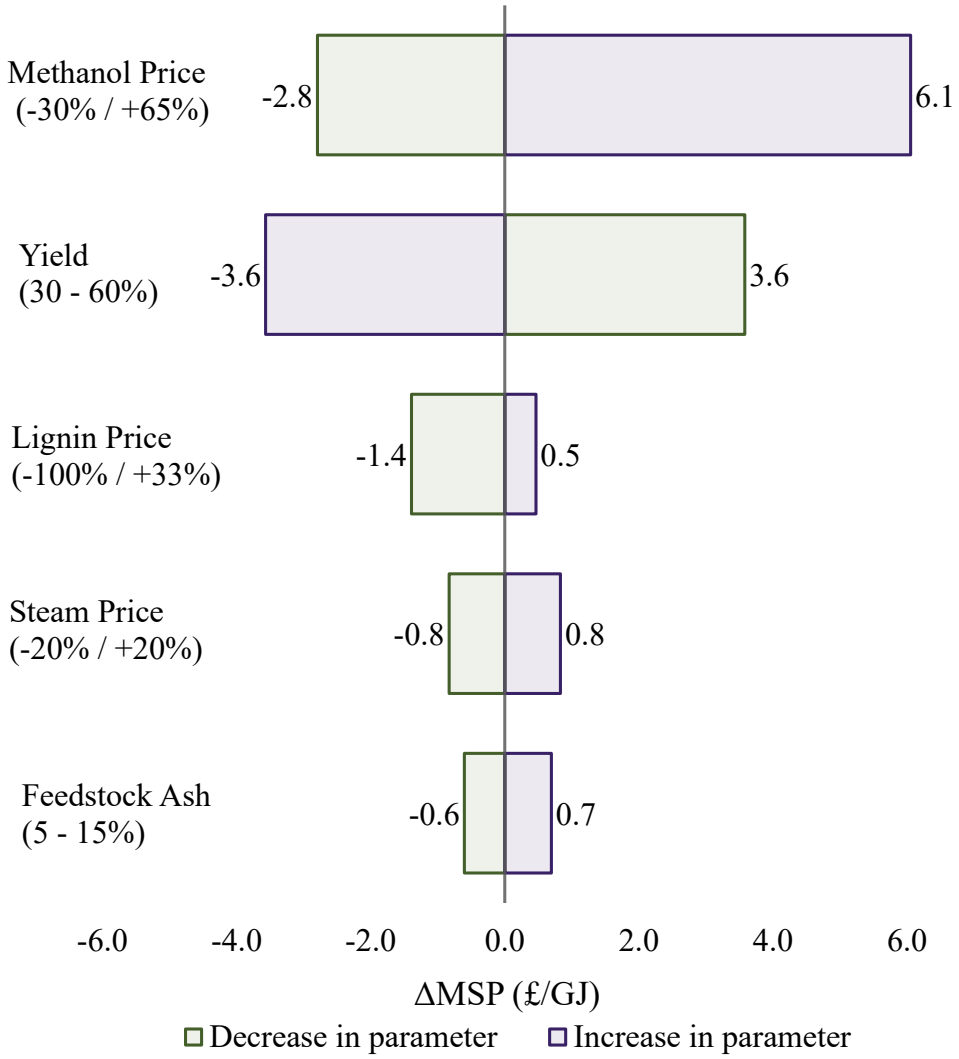

Figure 8: Sensitivity of waste-case MSP to key parameters including feedstock ash. Lignin price varied within waste-feedstock cost uncertainty.

Table 7: Literature cost estimates for hydrochar and comparator biochar market prices.

Source	**Value (GBP/t)**	**Basis**	**Key assumptions**
Hydrochar – Production cost / Breakeven price / MSP			
Nadarajah et al. (2024), *Waste Manag.* [34]	57–102	MSP vs. market comparable	Fe-doped Rice straw engineered hydrochar for water treatment adsorbent
Saba, McGaughy & Reza (2019), *Energies* [35]	80–88	Breakeven price	Co-HTC of coal & miscanthus, 110 MWe coal-plant fuel-blend scale
Lucian & Fiori (2017), *Energies* [36]	133–170	Production cost / breakeven	Pelletized hydrochar from grape marc/compost, 9,300 t/yr plant
Mazumder et al. (2020), *Biomass Conv. Biorefin.* [37]	45–53	Breakeven cost	Co-HTC of coal waste & food waste
Biochar – Realised market prices / Breakeven cost			
UK Biochar Demonstrator (industry survey) [33]	400–1000	Wholesale product price	UK wholesale price range for farmers, virgin-wood and mixed-feedstock biochar
Shackley et al., *Carbon Manag.* [38]	−148–389	Breakeven cost	UK Full chain: feedstock to field-spread, net of electricity/gate-fee revenue; negative = profit-making

The solid char produced during mild solvolysis was not characterised in this study. Given its formation through a low-temperature, solvent-based

process, it may be more analogous to hydrochar than to conventional biochar produced by pyrolysis. Although established markets exist for biochar, wider evidence on the current and future market value of hydrochar remains limited. Presented in Table 7 is a summary of published hydrochar MSPs, production costs and breakeven prices, together with biochar values for comparison. The reported hydrochar values were used as conservative estimates for the potential value of the untreated solvolysis char in the sensitivity analysis and as such they should not be interpreted as confirmed sale prices for this material. Nevertheless, further upgrading or functionalisation could increase its value towards that of commercial biochar or other higher-value carbon products. However, this would introduce additional capital and operating costs, and further experimental characterisation and process modelling would be required to determine the resulting effect on LiMO MSP.

Presented in Figure 9 is the pilot-scale LiMO MSP for the technical- and pseudo-waste-lignin cases across the assumed range of char values. The results indicate that char valorisation could reduce LiMO MSP more substantially than a tenfold increase in plant throughput. For technical lignin, an assumed char value of approximately £90/t reduces the pilot-scale LiMO MSP to £20.29/GJ, equal to the MSP obtained through tenfold scale-up without char revenue. The apparent benefit is considerably greater for the pseudo-waste-lignin case because the lower LiMO yield was modelled as a corresponding increase in char production. This result is therefore particularly sensitive to the assumed product distribution and should be regarded as illustrative rather than a reliable cost projection until the char yield, composition and potential applications have been experimentally established.

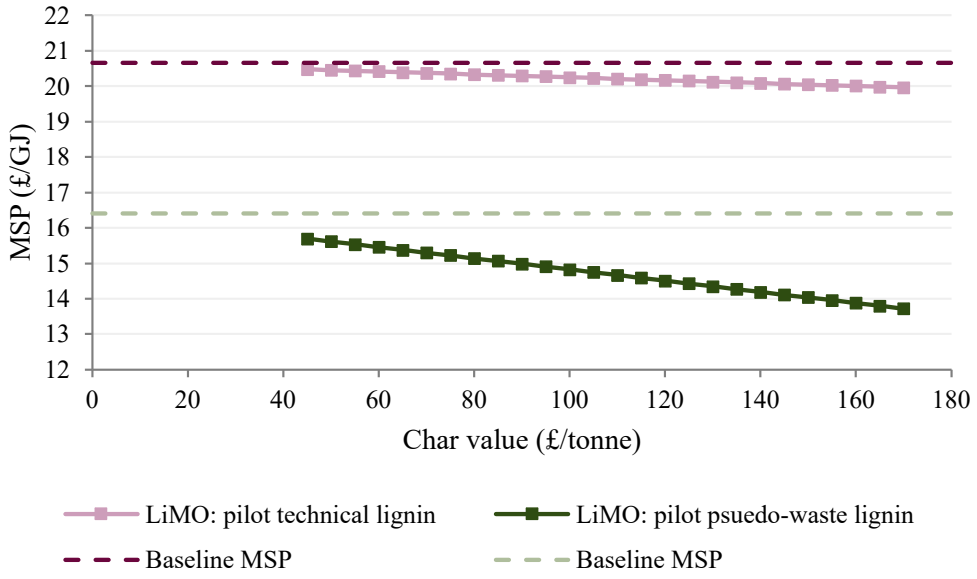

Figure 9: Plot of LiMO MSP over a range of estimated solvolysis char sale values at pilot scale.

4.5. Implications for marine methanol fuels

The economic position of LiMO depends strongly on the comparator used. Relative to low-cost fossil methanol, the LiMO pathway incurs an economic penalty because the solvolysis process adds feedstock, utility and capital costs to a product that remains predominantly methanol by mass. However, the more relevant long-term comparison for marine decarbonisation is with renewable methanol production routes rather than with unabated fossil methanol alone.

Table 8 and Figure 10 compare the LiMO MSP calculated in this study with representative production-cost ranges reported for fossil methanol, biomethanol and e-methanol. IRENA reports indicative current production costs of approximately USD 100–250/t for fossil methanol, USD 320–770/t for biomethanol and USD 800–1600/t for e-methanol [39]. Using the exchange-rate assumption adopted in this study and an LHV of 19.9 GJ/t for neat methanol, these correspond to approximately £3.8–9.4/GJ, £12.1–29.0/GJ and £30.2–60.3/GJ, respectively. More recent process-specific studies similarly demonstrate substantial variation between renewable methanol path-

ways. Rajaee *et al.* reported a minimum levelised cost of fuel of EUR 21.56/GJ (£18.33/GJ) for an integrated biomass-to-methanol configuration incorporating solid-oxide electrolysis [40], while Galimova *et al.* estimated a representative levelised e-methanol cost of EUR 172/MWh_{LHV}, equivalent to EUR 47.8/GJ (£40.63/GJ) or approximately EUR 960/t (£816/t) [41].

Against these benchmarks, the LiMO MSP range of £15.76–20.66/GJ lies above the reported cost range for low-cost fossil methanol but within the broad cost envelope reported for biomethanol. It is also below many reported current estimates for e-methanol production. The lowest-cost LiMO case, based on commercial-scale processing of pseudo-waste lignin, achieves an MSP of £15.76/GJ, while the commercial technical-lignin case has an MSP of £20.29/GJ. This comparison indicates that the additional processing required to incorporate lignin does not necessarily place LiMO outside the cost range of renewable methanol fuels, particularly where low-cost lignin residues are available.

This finding supports the positioning of LiMO as a methanol-enhancing or methanol-extending pathway rather than as a direct replacement for conventional marine fuel. In the modelled 25 wt% blend, lignin-derived material displaces a proportion of the methanol requirement while increasing the LHV of the final fuel to approximately 22 GJ/t, compared with approximately 19.9 GJ/t for neat methanol. Where sustainable lignin residues are available at low cost, the process could therefore extend constrained supplies of biomethanol or e-methanol while increasing the energy transported per unit mass of methanol-compatible fuel.

The comparison should nevertheless be interpreted with caution. Published methanol cost estimates are derived using different geographical boundaries, plant capacities, feedstock assumptions, electricity prices, financing conditions and definitions of production cost. The comparison in Table 8 is therefore intended to establish the broad economic position of LiMO rather than demonstrate direct cost-equivalence between individual projects. Moreover, the grey-methanol LiMO scenarios modelled here retain a carbon intensity close to that of conventional methanol. Economic competitiveness alone therefore does not establish environmental benefit; meaningful decarbonisation requires the use of low-carbon methanol and low-carbon process heat, as demonstrated by the sensitivity analysis in Figure 5.

For maritime applications, LiMO may consequently be most attractive where three conditions coincide: low-cost lignin residues are locally available, low-carbon methanol supply is constrained or expensive, and the res-

ulting fuel-property improvements provide operational value. The present analysis does not assign an economic premium to potential improvements in volumetric energy density, ignition behaviour, combustion characteristics or fuel handling. Establishing these benefits through engine testing and fuel-standard compliance assessment will therefore be essential to determine whether LiMO can command value beyond its energy-equivalent MSP.

Table 8: Indicative production-cost benchmarks for methanol pathways and the LiMO minimum selling prices calculated in this study. External ranges are broad benchmarks; system boundaries, plant scales, geographical assumptions and economic methodologies differ between sources. USD values converted at 0.75 £/USD; EUR values at 0.85 £/EUR; methanol LHV = 19.9 GJ/t.

Fuel pathway	**Reported cost**	**£/GJ**	**Source**
Grey (fossil) methanol	USD 100–250/t	3.8–9.4	[39]
Biomethanol	USD 320–770/t	12.1–29.0	[39]
Biomass-to-methanol with SOEC	EUR 21.56/GJ	18.33	[40]
E-methanol	USD 800–1600/t	30.2–60.3	[39]
European e-methanol	EUR 960/t	40.63	[41]
LiMO: pilot, technical lignin	£454.51/t	20.66	This study
LiMO: commercial, technical lignin	£446.30/t	20.29	This study
LiMO: pilot, pseudo-waste lignin	£360.94/t	16.41	This study
LiMO: commercial, pseudo-waste lignin	£346.69/t	15.76	This study

5. Limitations and further work

This yield-based Aspen model provides a transparent first-order TEA but carries important limitations. Waste lignin yields and product distributions are extrapolated from technical lignin data and require experimental validation. Feedstock moisture effects are simplified via a fixed drying step; alternative water-management strategies could alter energy demand. Gaseous product speciation is assumed and may be incomplete, though gas-phase emissions are minor relative to methanol and steam. Char composition and valorisation potential are uncertain; assigning zero value biases MSP and EROI conservatively. Methanol consumption was held constant at 1.1 wt% despite likely feedstock dependence. Electricity demand was tied primarily to pumping and may underestimate solids-handling loads, particularly for high-ash feeds. Pinch analysis and detailed heat integration were not undertaken. A kinetic reactor model would improve scale-up confidence.

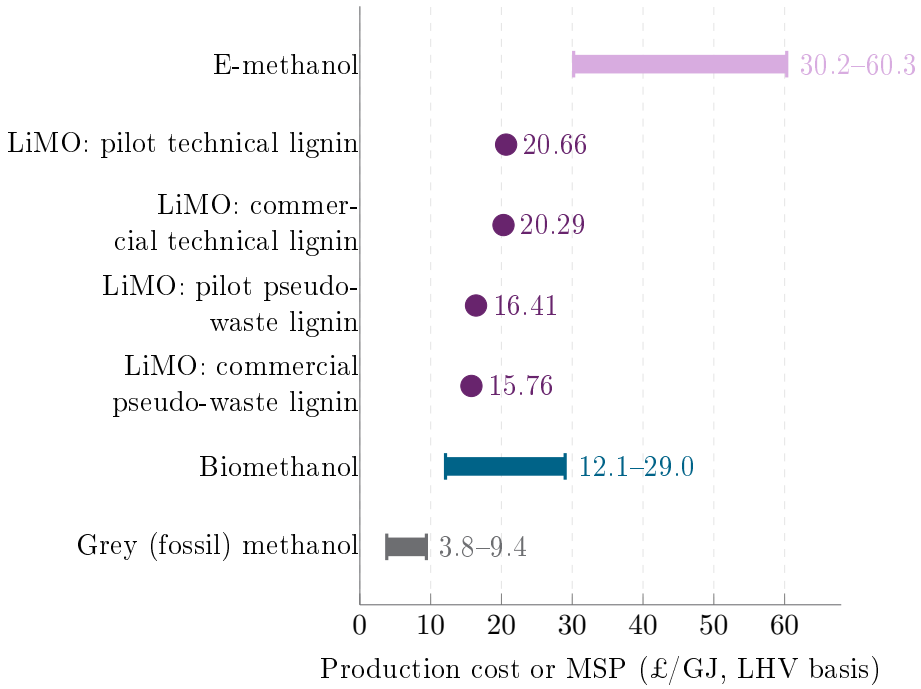

Figure 10: Comparison of LiMO minimum selling prices with indicative production-cost ranges for grey (fossil) methanol, biomethanol and e-methanol. Methanol production-cost ranges are based on IRENA [39]. LiMO values are calculated in the present study. External values are broad benchmarks rather than directly harmonised techno-economic comparisons.

Future work should prioritise: (i) experimental methanolysis of UK-relevant waste lignin streams with full product and char characterisation; (ii) pinch analysis and utility optimisation; (iii) evaluation of higher lignin blend ratios toward bio-heavy fuel oil applications; (iv) engine testing of fuel properties (viscosity, stability, combustion) under representative marine conditions; and (v) integration scenarios with low-carbon methanol and renewable process heat.

6. Conclusions

This study presented a techno-economic and carbon-intensity assessment of 25 wt% lignin–methanol oil production via mild thermolytic solvolysis for UK marine fuel applications. The principal conclusions are:

- LiMO production is technically feasible under the modelled conditions (200 °C, 55 bar, 25 wt% lignin blend) using an Aspen Plus flowsheet with literature-based yield distributions.
- MSP is estimated at £15.76–20.66/GJ (£346.69–454.51/t) across pilot and commercial scenarios with technical and pseudo-waste lignin.
- Carbon intensity remains close to grey methanol (94.7–104.5 $kgCO_2e/GJ$ vs. 106.5 $kgCO_2e/GJ$ for grey methanol) unless low-carbon methanol and low-carbon process heat are used.
- Methanol dominates both cost and emissions because it is simultaneously solvent, recovered recycle stream and major final-fuel component.
- Feedstock quality and solvolysis yield are critical: the waste case demonstrates improved economics but higher carbon intensity when yield falls to 40 wt%.
- LiMO should be viewed as a methanol-enhancing or biomethanol-extending route, not automatically as a standalone sustainable marine fuel; EROI remains near unity in most scenarios (0.73–0.85 base range; maximum 1.04 under favourable waste-lignin assumptions).
- Further work should prioritise waste-lignin experimental validation, product and char characterisation, heat integration, higher blend ratios and engine/fuel-property testing.

Nomenclature

Abbreviations

CLO	Crude lignin oil
CAPEX	Capital expenditure
CCS	Carbon capture and storage
EROI	Energy return on investment
FCI	Fixed capital investment
GHG	Greenhouse gas
HDO	Hydrodeoxygenation
HFO	Heavy fuel oil
HHV	Higher heating value
IMO	International Maritime Organization
LCA	Life cycle assessment
LHV	Lower heating value
LiMO	Lignin–methanol oil
LtL	Lignin-to-liquid
MSP	Minimum selling price
OPEX	Operating expenditure
PB	Protobind
SI	Supplementary information
SMF	Sustainable marine fuel
TEA	Techno-economic analysis
TCI	Total capital investment
UK SHORE	UK Shipping Office for Reducing Emissions

Symbols

Symbol	Definition	Unit
C_1	Reference equipment cost	£
C_2	Scaled equipment cost	£
E_{LiMO}	Energy output of LiMO product	GJ
E_{lignin}	Energy input associated with lignin feed	GJ
E_{MeOH}	Energy input associated with makeup methanol	GJ
E_{process}	Process and utility energy input	GJ
i	Discount rate	–
$\dot{m}_{\mathrm{LiMO}}$	Mass flow rate of LiMO product	kg h^{-1}
$\dot{m}_{\mathrm{lignin}}$	Mass flow rate of lignin feed	kg h^{-1}
$\dot{M}_{\mathrm{MeOH}}$	Mass flow rate of makeup methanol	kg h^{-1}
n	Project lifetime	years
S_1	Reference equipment size or throughput	variable
S_2	Scaled equipment size or throughput	variable
η_{process}	Process energy efficiency	–

Chemical formulae

CO	Carbon monoxide
CO_2	Carbon dioxide
H_2O	Water
MeOH	Methanol

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Declarations

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary information

Detailed Aspen flowsheet diagrams, elemental mass balances, compositional data, ash and yield adjustment methods, energy balance tables, equipment sizing calculations, full CAPEX/OPEX breakdowns and sensitivity-analysis data are provided in Supplementary Information SI-1 through SI-4.

References

[1] I. M. Organisation, Fourth greenhouse gas study 2020, https://www.imo.org/en/ourwork/environment/pages/fourth-imo-greenhouse-gas-study-2020.aspx, accessed: 2025-12-23.

[2] I. M. Organisation, Imo 2020 – cutting sulphur oxide emissions, https://www.imo.org/en/mediacentre/hottopics/pages/sulphur-2020.aspx, accessed: 2025-12-23.

[3] I. M. Organisation, Imo approves net-zero regulations for global shipping, https://www.imo.org/en/mediacentre/pressbriefings/pages/imo-approves-netzero-regulations.aspx, accessed 2025-12-26.

[4] Clarksons, Green technology tracker: Record investments in alternative fuel, https://www.clarksons.com/home/news-and-insights/2025/green-technology-tracker-record-investments-in-alternative-fuel/, accessed: 2026-01-10 (2025).
URL https://www.clarksons.com/home/news-and-insights/2025/green-technology-tracker-record-investments-in-alternative-fuel/

[5] Ansuman Ghosh, Rising interest in methanol as ship fuel, https://www.ukpandi.com/news-and-resources/news/article/articles/2023/rising-interest-in-methanol-as-ship-fuel/, accessed: 2026-03-26 (2026).

[6] R. Abolore, S. Jaiswal, A. Jaiswal, A comprehensive review on sustainable lignin extraction techniques, modifications, and emerging applications, Industrial Crops and Products 235 (2025) 121696. doi:https://doi.org/10.1016/j.indcrop.2025.121696.

[7] A. Bridgwater, G. Peacocke, Review of fast pyrolysis of biomass and product upgrading, Biomass and Bioenergy 38 (2012) 68–94, overcoming Barriers to Bioenergy: Outcomes of the Bioenergy Network of Excellence 2003 – 2009. doi:https://doi.org/10.1016/j.biombioe.2011.01.048.

[8] X. Chen, M. A. Arellano-Treviño, K. A. Orton, A. Dutta, C. Mukarakate, K. Iisa, E. C. Tan, Sustainable marine fuel production through mild hydrotreating of catalytic fast pyrolysis bio-oil, Fuel 398 (2025) 135455. doi:https://doi.org/10.1016/j.fuel.2025.135455.

[9] P. D. Kouris, D. J. G. P. van Osch, G. J. W. Cremers, M. D. Boot, E. J. M. Hensen, Mild thermolytic solvolysis of technical lignins in polar organic solvents to a crude lignin oil, Sustainable Energy Fuels 4 (2020) 6212–6226. doi:10.1039/D0SE01016B.

[10] M. Lazzaro, P. Sementa, F. Catapano, C. Tornatore, et al., Investigation of liquid lignin-methanol blends under realistic two-stroke marine engines conditions, SAE Technical Paper 2023-24-0085, SAE International (2023). doi:10.4271/2023-24-0085.

[11] S. Kumar, J. Risbo, J. J. K. Kirkensgaard, Y. Cabrera Orozco, Leo and limo fuels: Structural and rheological characterization of solvolytically fractionated lignin dispersed in alcohols, ACS Sustainable Chemistry & Engineering 10 (39) (2022) 13156–13164. doi:10.1021/acssuschemeng.2c04017.

[12] S. Constant, H. L. J. Wienk, A. E. Frissen, P. d. Peinder, R. Boelens, D. S. van Es, R. J. H. Grisel, B. M. Weckhuysen, W. J. J. Huijgen, R. J. A. Gosselink, P. C. A. Bruijnincx, New insights into the structure

and composition of technical lignins: a comparative characterisation study, Green Chem. 18 (2016) 2651–2665. doi:10.1039/C5GC03043A.

[13] LanzaJet, The future of sustainable aviation fuel (saf) in the uk., https://www.lanzajet.com/speedbird, accessed: 2026-03-26 (2026).

[14] A. Bridgwater, G. Peacocke, Fast pyrolysis processes for biomass, Renewable and Sustainable Energy Reviews 4 (1) (2000) 1–73. doi:https://doi.org/10.1016/S1364-0321(99)00007-6.

[15] H. Ben, F. Wu, Z. Wu, G. Han, W. Jiang, A. J. Ragauskas, A comprehensive characterization of pyrolysis oil from softwood barks, Polymers 11 (9) (2019) 1387. doi:10.3390/polym11091387.

[16] M. Kleinert, T. Barth, Towards a lignincellulosic biorefinery: Direct one-step conversion of lignin to hydrogen-enriched biofuel, Energy & Fuels 22 (2) (2008) 1371–1379. doi:10.1021/ef700631w.

[17] B. Zhang, W. Li, X. Dou, J. Wang, L. Jin, A. T. Ogunbiyi, X. Li, Catalytic depolymerization of kraft lignin to produce liquid fuels via ni–sn metal oxide catalysts, Sustainable Energy Fuels 4 (2020) 1332–1339. doi:10.1039/C9SE01089K.

[18] K. Ye, Y. Liu, S. Wu, J. Zhuang, A review for lignin valorization: Challenges and perspectives in catalytic hydrogenolysis, Industrial Crops and Products 172 (2021) 114008. doi:https://doi.org/10.1016/j.indcrop.2021.114008.

[19] P. Kouris, M. D. Boot, E. J. M. Hensen, H. Oevering, A method for obtaining a stable lignin: polar organic solvent composition via mild solvolytic modifications, WO Patent 2019/053287 A1, international Publication Date: March 21, 2019 (2019).

[20] J. B. Nielsen, A. Jensen, L. R. Madsen, F. H. Larsen, C. Felby, A. D. Jensen, Noncatalytic direct liquefaction of biorefinery lignin by ethanol, Energy & Fuels 31 (7) (2017) 7223–7233. doi:10.1021/acs.energyfuels.7b00968.

[21] British Standards Institution, Environmental management. life cycle assessment. requirements and guidelines, Standard, BSI, London, UK, incorporating amendments A1:2018 and A2:2020 (2006).

[22] R. Turton, R. C. Bailie, W. B. Whiting, J. A. Shaeiwitz, Analysis, Synthesis, and Design of Chemical Processes, 3rd Edition, Prentice Hall, 2009.

[23] G. Towler, R. Sinnott, Chemical Engineering Design: Principles, Practice and Economics of Plant and Process Design, 3rd Edition, Elsevier, 2021.

[24] Penn State College of Earth and Mineral Sciences, Eme 460: Georesources evaluation and investment analysis, accessed: 2026-04-19.
URL https://courses.ems.psu.edu/eme460/node/652

[25] Department for Energy Security and Net Zero, Quarterly Energy Prices: September 2025, Official statistics, HM Government, accessed: 2026-01-15 (Sep. 2025).
URL https://www.gov.uk/government/statistics/quarterly-energy-prices-september-2025

[26] HM Revenue & Customs, Climate Change Levy rates, https://www.gov.uk/guidance/climate-change-levy-rates, accessed: 2026-01-15 (2024).

[27] Argus Media, Argus methanol: Issue 26-46, Tech. rep., Argus Media group, London, UK, daily/Weekly Price Assessment Report (3 2026).
URL https://www.argusmedia.com/en/commodities/methanol

[28] Sustainability Directory, Lignin-rich feedstocks, https://energy.sustainability-directory.com/term/lignin-rich-feedstocks/, accessed: 2026-04-08 (2026).

[29] M. S. Peters, K. D. Timmerhaus, R. E. West, Plant Design and Economics for Chemical Engineers, 5th Edition, McGraw-Hill Education, New York, NY, 2003.

[30] Methanol Institute, Carbon footprint of methanol, Tech. rep., Methanol Institute, accessed: April 14, 2026 (1 2022).
URL https://methanol.org/wp-content/uploads/2022/01/CARBON-FOOTPRINT-OF-METHANOL-PAPER_1-31-22.pdf

[31] Department for Energy Security and Net Zero, 2025 government greenhouse gas conversion factors for company reporting, Tech. rep.,

HM Government, accessed: April 14, 2026 (6 2025).
URL https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2025

[32] C. Moretti, B. Corona, R. Hoefnagels, I. Vural-Gürsel, R. Gosselink, M. Junginger, Review of life cycle assessments of lignin and derived products: Lessons learned, Science of The Total Environment 770 (2021) 144735. doi:10.1016/j.scitotenv.2021.144735.

[33] The Biochar Demonstrator, Information for farmers, accessed: Jul. 18, 2026 (2025).
URL https://biochardemonstrator.ac.uk/info-for-farmers/

[34] K. Nadarajah, O. M. Rodriguez-Narvaez, J. Ramirez, E. R. Bandala, A. Goonetilleke, Lab-scale engineered hydrochar production and techno-economic scaling-up analysis, Waste Management 174 (2024) 568–574. doi:10.1016/j.wasman.2023.12.024.

[35] A. Saba, K. McGaughy, M. T. Reza, Techno-economic assessment of co-hydrothermal carbonization of a coal-miscanthus blend, Energies 12 (4) (2019) 630. doi:10.3390/en12040630.

[36] M. Lucian, L. Fiori, Hydrothermal carbonization of waste biomass: Process design, modeling, energy efficiency and cost analysis, Energies 10 (2) (2017) 211. doi:10.3390/en10020211.

[37] S. Mazumder, P. Saha, K. McGaughy, A. Saba, M. T. Reza, Technoeconomic analysis of co-hydrothermal carbonization of coal waste and food waste, Biomass Conversion and Biorefinery (2020). doi:10.1007/s13399-020-00817-8.

[38] S. Shackley, J. Hammond, J. Gaunt, R. Ibarrola, The feasibility and costs of biochar deployment in the UK, Carbon Management 2 (3) (2011) 335–356. doi:10.4155/cmt.11.22.

[39] International Renewable Energy Agency, Methanol Institute, Innovation outlook: Renewable methanol (2021).

[40] F. Rajaee, G. Guandalini, M. C. Romano, J. Ritvanen, Techno-economic evaluation of biomass-to-methanol production via circulating fluidized

bed gasifier and solid oxide electrolysis cells: A comparative study, Energy Conversion and Management 301 (2024) 118009.

[41] T. Galimova, M. Fasihi, D. Bogdanov, G. Lopez, C. Breyer, Analysis of green e-methanol supply costs: Domestic production in europe versus imports via pipeline and sea shipping, Renewable Energy (2025). doi:10.1016/j.renene.2024.122336.