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# A feasible methanol economy for a green future

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This study quantifies for the first time the methanol economy and includes environmental and cost perspectives toward viable configurations. We developed comprehensive prospective models projected for 2050 including methanol as a substitute for fossil fuels in road and maritime transport, and as a building block for aviation fuels and high-volume chemicals, with carbon sourced from fossil feedstock, biomass, biogas, and atmospheric $CO_2$. Biomass enables negative emissions at an estimated implementation cost of *ca.* 16 USD per person per month, comparable to today's expenditures on fuels and chemicals, but is constrained by availability and ecosystem impacts. Biogas enables net-zero, yet is also supply-limited. Together, these routes could cover only up to 45% of demand. Air-captured $CO_2$ hydrogenation to methanol provides (virtually) unlimited availability and significantly lower emissions while performing well even beyond climate change impacts, but its higher projected cost limits its immediate appeal despite rapid technological progress. Hybrid pathways could bridge these gaps. A bio + fossil mix (45% : 55%) emits only around 34% of a fossil-only system and is deployable today. Substituting fossil carbon with $CO_2$ then unlocks a fully renewable bio + $CO_2$ configuration achieving net-zero at an approximate cost of 32 USD per person per month, one order of magnitude lower than the cost of climate inaction and comparable to the cost of other technological roadmaps designed to implement the Paris Agreement but with greater emission reductions. Bio + fossil thus offers an advantageous transition, while advancing $CO_2$-to-methanol maturity is decisive for a fully renewable methanol economy. Moreover, a regional assessment indicates that emission reductions closely mirror the global average, achieveing net-zero under a bio + $CO_2$-based methanol economy. This work opens new avenues for technological portfolios based on methanol that could be optimised with region-specific data to combat climate change sustainably.

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### Green foundation

1. This work quantifies the potential of methanol as a versatile platform for both chemical and fuel production. We show that certain configurations of the methanol economy can achieve the required emission reductions at costs that remain feasible. The message is clear regarding achieving a fully renewable methanol economy: advancing $CO_2$-to-methanol technologies is central to the field's progress.
2. After two decades of discussion, the methanol economy now has a quantitative backbone. This work demonstrates, with clear metrics, that specific configurations can be favorably evaluated in terms of both environmental and economic grounds, turning a long-debated vision into a measurable opportunity.
3. Beyond further refining our system models, for example by incorporating supply chains and sector coupling, and expanding the spatial and technological scope, the crucial next step is to debate the requirements and first actions toward a methanol economy, identifying critical barriers hampering its full-scale deployment. Such work will sharpen estimates and, more importantly, help transform assessments into practical guidance.

## Introduction

In 2005, George Olah envisioned renewable methanol as a cornerstone of future fuel and chemical production.[1,2] Summarised as the *methanol economy*, this concept leverages the versatility of methanol: it can be used directly as a fuel or as a chemical building block for producing olefins, aromatics, and other high-demand products. By substituting fossil feedstocks with renewable methanol, the methanol economy could transform both the transport and chemical sectors, where crude-oil-derived naphtha, diesel, and kerosene today account for more than 30% of anthropogenic greenhouse gas emissions.[3,4] Unlike pathways designed to meet the Paris Agreement using integrated assessment models (IAMs) or other approaches,[5,6] the methanol economy represents a stand-alone technological vision, with the potential to reshape industrial carbon flows on a global scale while aligning with

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the principles of green chemistry that call for inherently sustainable feedstocks and processes.[7–9]

The feasibility of this concept has not yet been comprehensively assessed, as previous works focused primarily on individual routes rather than providing a holistic view of it. Environmental impacts and economic commitments can only be quantified under this prism precisely under models encompassing the global full life cycle of fuels and chemicals able to include various methanol economy configurations. General analyses have commented on and extended the original concept,[10] with a focus on production routes.[11] Life cycle analyses exist for methanol production[12] and its social aspects.[13] Sectoral studies have examined methanol's relevance for the chemical industry,[14–17] and its suitability as shipping[18–21] and road transport fuel,[22,23] based on the maturity of combustion engines and their reduced emissions,[24] and the production of aviation fuels from methanol, claimed to match the performance of Fischer–Tropsch-derived kerosene.[25–29] Another limitation of these studies (besides focusing on partial aspects of the methanol economy) is that they are often based on static data and fail to analyse prospective scenarios, not accounting for the temporal evolution of impacts associated with anticipated changes in industrial sectors. Hence, the potential broad economic and environmental implications of the methanol economy are poorly understood, and a systems analysis integrating multiple routes and life cycle impacts is missing.

The current global methanol production is around 140 Mt per year, with its main use as a chemical building block.[30] Implementing the methanol economy would thus require increasing this capacity, making the renewable feedstock choice crucial. Originally proposed renewable carbon sources for methanol include biomass, biogas, and $CO_2$.[31,32] Catalytic technologies are either fully or partially applicable to their conversion into methanol. Biomass and biogas routes are well established, since mature technologies can transform both carbon sources into syngas (CO and $H_2$), the feedstock currently used at scale for methanol production. Methanol from these routes is generally referred to as biomethanol. In contrast, combining captured $CO_2$ with green $H_2$ from renewable-powered electrolysis yields e-methanol,[33] a pathway advancing quickly with progress on selectivity and stability.[34] Recent catalytic breakthroughs based on indium or zinc oxides combined with zirconia have given access to new technologies increasingly free from these limitations, some of which are now entering into pilot plant-scale production.[35–40]

This work first defines a general scheme of the methanol economy aimed at maximising methanol's potential, and then quantifies the environmental and economic implications associated with different carbon sources. Our findings show that a fully renewable and viable methanol economy should rely on a combination of biomass, biogas, and $CO_2$ feedstocks, and may achieve net-zero emissions at a cost marginally higher to implementing existing climate strategies designed with IAMs and aligned with the Paris Agreement goals. A transitional solution readily implementable involving the contribution of fossil feedstocks is proposed while the maturity and scale of $CO_2$ hydrogenation to methanol continues to advance.

## Crystallising the methanol economy

As highlighted, the methanol economy remains a broad guiding concept that underscores the versatility of methanol, with no concerted effort yet towards implementation. The shipping sector is the first where initiatives are emerging.[41] Specifically, decades of research on methanol-fuelled vessels have improved understanding of its potential.[42,43] In response to the International Maritime Organisation's carbon reduction targets, global support for methanol as a shipping fuel has expanded, driving new low-carbon methanol plants, often near ports (Fig. 1). Early industry momentum suggests sustainable

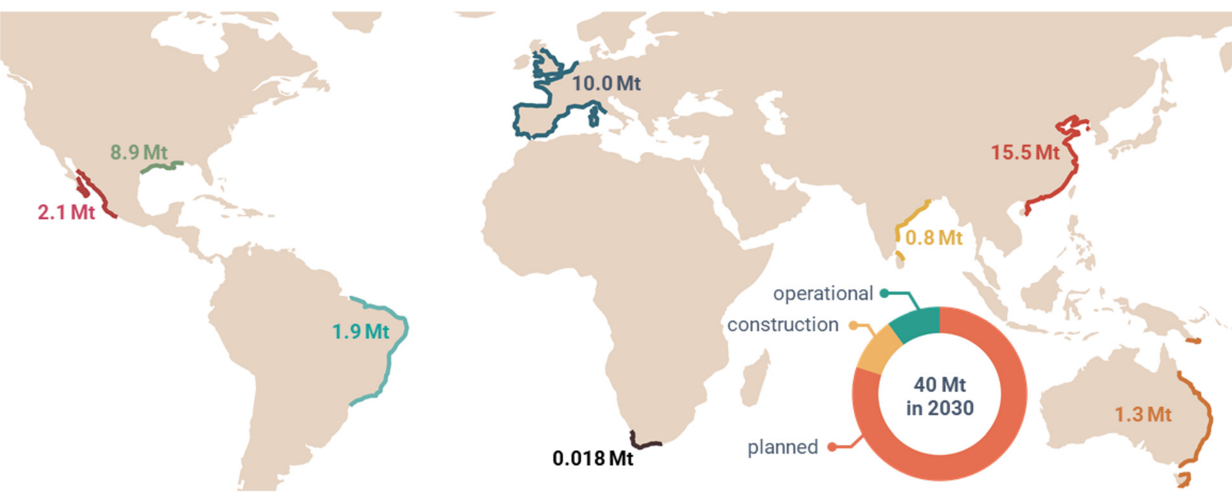


**Fig. 1** The first signs of a methanol-based economy are emerging. Recent advancements in the defossilisation of shipping have increased the focus on methanol as the primary replacement for fossil-based shipping fuels. Consequently, most of the constructed or planned methanol plants are in coastal areas. Europe, China, Australia, India, South Africa, Brazil, Mexico, and the United States (highlighted in the map) are projected to become major industrial methanol hubs by 2030, with total capacity expected to exceed 40 Mt annually.

methanol production could reach 40 Mt per year by 2030, with shipping expected to represent a major share of this demand.[44]

Other recent technological advances are broadening the scope to other industries, opening the door to multiple configurations of the methanol economy.[45–47] Fig. 2 illustrates the structure of the methanol-based economy considered in this study, emphasising the sectors that could realistically function entirely on methanol. In this study, only mid- to high-TRL (technology readiness level) technologies were considered, reflecting mature processes suitable for near-term deployment. Emerging technologies such as direct air capture (DAC) and green hydrogen production currently exhibit lower TRLs.[48] However, since the analysis targets the 2050 timeframe, expected technological advancements and cost reductions are implicitly accounted for in the assessment based on future estimates. The large-scale deployment of emerging technologies, such as green hydrogen production, was assumed feasible by 2050, implying rapid scale-up in the coming years.

In the chemical sector, methanol can replace fossil-derived naphtha as a feedstock for chemicals production.[49] Conventionally, naphtha is cracked into olefins (ethylene, propylene) and aromatics (benzene, toluene, xylene, BTX) for use in solvents, pharmaceuticals, polymers, and dyes. However, existing mid-to-high TRL methanol-to-olefins (MTO) and methanol-to-aromatics (MTA) technologies enable methanol to serve as the primary feedstock for these chemicals, offering well-studied economic and environmental benefits.[50–52]

Moreover, methanol can also play an essential role in the production of sustainable aviation fuels (SAFs). Aviation accounts for *ca.* 2% of global GHG emissions and uses kerosene as main energy carrier.[53] However, renewable methanol can be converted to SAF *via* the high-TRL methanol-to-kerosene (MTK) process, offering a drop-in solution without major system changes.[26] Notably, growing interest in SAF has already led to the first MTK plant investment in the Netherlands.[54]

Methanol can also be utilised as a road transport fuel additive (*e.g.*, M20 blends). Alternatively, internal combustion engines could also fully operate on methanol as fuel, a *modus operandi* called M100 ICEs. In China, engine development has brought M100 engines for both passenger cars and heavy-duty trucks closer to full scale commercialisation.[55] Although already at a high TRL (TRL 8), the technology is relatively new and it will take some time to build the entire value chain.[56]

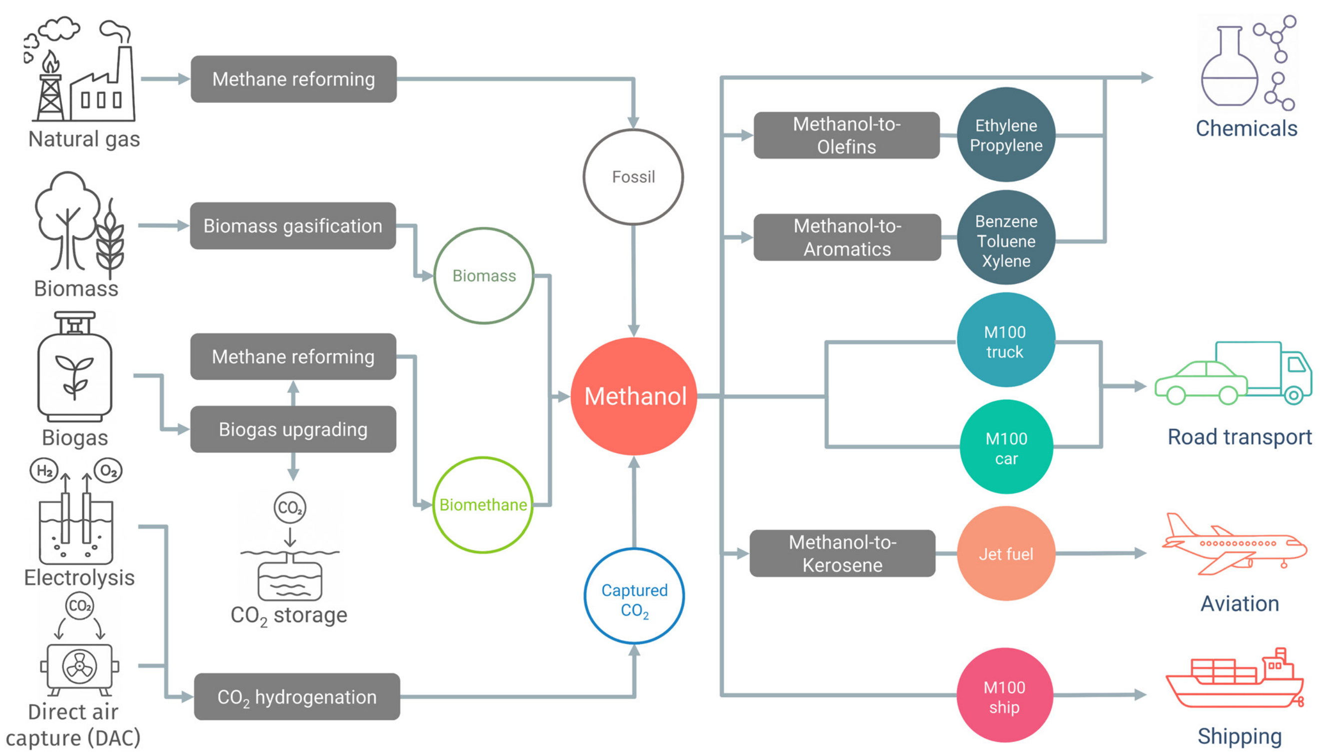


**Fig. 2** Layout of the new methanol structure considered in this work. Methanol can be produced from several pathways: natural gas reforming (fossil scenario), biomass gasification (biomass scenario), biomethane reforming from biogas upgrading (biomethane scenario), and captured $CO_2$ combined with electrolytic hydrogen (captured $CO_2$ scenario). It can replace conventional petrochemical products across various sectors, particularly in chemicals and transport. Using mid-to-high TRL technologies, methanol can be produced and further upgraded into advanced products. In the chemical industry, building-block chemicals such as olefins and aromatics are derived from methanol and used to manufacture a wide range of products, including pharmaceuticals, solvents, and plastics (*e.g.*, polyethylene and polypropylene). In road transport and shipping, engines designed to run exclusively on methanol (commonly referred to as M100 engines) have been developed and successfully tested in recent years. For aviation, methanol can be converted into jet fuel, offering a drop-in solution. All technologies included in the layout of the methanol economy are mid-to-high TRL, and were assumed to have reached maturity by 2050.

M100 engines are however compatible with minimal infrastructure changes, unlike battery electric vehicles (BEVs), which require extensive charging networks and substantial upgrades to the electricity grid.[57,58]

Methanol can be produced from fossil or renewable carbon sources, such as natural gas, biomass, biogas-derived biomethane, and $CO_2$ captured *via* DAC, coupled with hydrogen from water electrolysis powered by renewable electricity (Fig. 2). In the fossil-based scenario, natural gas is steam-reformed into syngas, which is subsequently converted into methanol. This syngas can also be produced through biomass gasification, for example from wheat straw. In contrast, biogas obtained from the anaerobic digestion of biomass is separated into methane and $CO_2$. Similar to the fossil scenario, biomethane can be steam-reformed into syngas for methanol synthesis. Consequently, both biomass-based (during gasification) and biomethane-based (during anaerobic digestion of biomass) processes release a relatively pure stream of $CO_2$, which can be captured using MEA absorption and stored geologically.

The implementation of biomass and biogas-based methanol economics is limited by resource availability, as these feedstocks are typically derived from manure, wastewater sludge, and agricultural and forestry residues, and they face competition from other sectors. Recent studies have attempted to address the limited availability and feedstock scarcity associated with bio-based materials.[59] Our analysis indicates that, combined, biogas and biomass could supply only 45% of the total methanol demand (5522 Mt) (see section S1 and Table S2 of the SI for further details). The remaining 35% of demand would need to be met through fossil methanol derived from natural gas or through $CO_2$-based e-methanol. In the latter case, $CO_2$ captured *via* DAC can be hydrogenated using electrolytic hydrogen to produce methanol (TRL 6–7), with research efforts focussing on direct $CO_2$ conversion.[60,61] Key challenges in utilising $CO_2$ from DAC stem from the substantial energy demand and high associated costs of both DAC and green hydrogen production.[62] Numerous studies indicate that methanol produced *via* this pathway currently faces significant economic constraints, with substantial cost reductions required for it to become competitive by 2050.[63]

Methanol synthesis *via* $CO_2$ hydrogenation is modelled in this work using the commercial Cu–Zn–Al (CZA) catalyst, offering high activity but lower selectivity than in conventional methanol synthesis from CO and $H_2$, its primary industrial application.[34] Although the catalyst cost contributes negligibly to the overall levelised cost of methanol (see section S3 of the SI), emerging systems such as indium oxide-based catalysts show promise for enhancing product selectivity and potentially reducing production costs.[35]

## Methods

The scope of this study is defined in Fig. 2. For a methanol economy based on natural gas, biomass, biomethane, $CO_2$ from air, or in a hybrid configuration, all products are shown on the right. This framework enables an assessment of the maximum environmental and economic potential, assuming full 2050 demand of all the products are met through methanol-based technologies (Table S1 and Fig. S1 of the SI). The study is structured around two primary methodological components: a life cycle assessment (LCA) and a techno-economic analysis (TEA).

First, life cycle inventories (LCIs) for all methanol-based technologies were compiled from literature, shown in Table S3 of the SI. The foreground data models all the methanol technologies and their fossil counterparts. Data for the background system (*i.e.*, emissions of all the activities exchanging mass and energy with the foreground, such as electricity generation) were obtained from the Ecoinvent v3.10 database.[64] The functional unit in this work consisted of the 2050 demand of chemicals and transport (see Table S1 of the SI). This included the projected consumer demand of aviation (both commercial and cargo), road transport in the form of heavy-duty trucks and passenger cars, maritime transport as well as six building block chemicals (methanol, ethylene, propylene, benzene, toluene, and xylene). For transport, the LCA results were calculated on a cradle-to-grave basis, *i.e.*, including the use phase of methanol as fuel. In the chemical industry, the end use of chemicals is often more diverse, making it hard to quantify the associated emissions *a priori* precisely. Note that the end-use phase of all chemicals will nevertheless be the same regardless of the production route (*i.e.*, fossil- or renewable-based); consequently, its modelling would not add any further discriminatory power to the analysis.

In contrast to many previous works that employ static LCI data reflecting the current economy, this work applies prospective LCA to quantify the projected environmental footprint of the methanol economy. The aim is to estimate the footprint considering expected future changes in socio-economic systems, as represented by IAMs, which can greatly influence the technologies' environmental impact.[65] Specifically, we use the methanol economy projected for 2050 under the RCP6.0 as a reference scenario and compare it with prospective market projections under RCP1.9, RCP2.6, and RCP6.0, which are based on roadmaps designed to be consistent with global mean surface temperatures increases of 1.5 °C, 2 °C (aligned with the Paris Agreement), and 3.5 °C, respectively. The prospective markets resulting from these scenarios were fully integrated with the foreground and background systems using *premise* v2.1.3 (see section S2 of the SI for further information).[66] Climate change impacts, *i.e.*, GHG emissions were calculated based on the IPCC 2021 method, while other environmental impact categories, such as human health, ecosystem quality, and natural resources, were assessed using the ReCiPe 2016 v1.03 method.[67,68] All calculations were performed for each RCP and each impact category for the year 2050.

The environmental assessment was followed by a techno-economic analysis (TEA). For 2050, the cost calculations consider both operating expenditures (OPEX) and capital expenditure (CAPEX) up to the final consumer products. OPEX included heating, electricity, and the cost of raw materials

(Tables S6 and S7 of the SI), while CAPEX encompassed the cost of the necessary methanol production plants, as well as MTO, MTA, and MTK facilities (Tables S4 and S5 of the SI).[69,70] Assuming that only marginal system changes would be required in a methanol economy, no costs for retrofitting existing value chains were included.

Subsequently, the TEA and LCA results were combined to calculate the marginal cost of abatement (MCoA) for each sector. The future costs of a methanol-based economy for each sector were compared with the current market prices of the products demanded. The ratio of the difference in cost to the difference in overall GHG emissions was used to determine the MCoA on an industry basis. The total cost was then compared with other mitigation pathways to contextualise its competitiveness. A full description of the methodology employed in this work is provided in the SI.

# Results and discussion

**Biomass- and biomethane-based methanol economies can achieve net-zero emissions**

In Fig. 3, we show the reduction by 2050 in climate change impacts, *i.e.*, GHG emissions, for the different carbon feedstocks proposed in the original methanol economy concept, compared to the conventional fossil business-as-usual scenario in 2025. The feedstocks considered for the methanol economy are natural gas-based fossil (Fig. 3a), captured $CO_2$ (Fig. 3b), biomass with $CO_2$ storage (Fig. 3c), and biomethane with $CO_2$ storage (Fig. 3d).

Currently, the combined overall GHG emissions for the chemicals and transport sectors are estimated at 16.5 Gt $CO_2$-equivalent ($CO_2$e) annually in 2025. Supply in each sector is assumed to be fully replaced by methanol-based alternatives

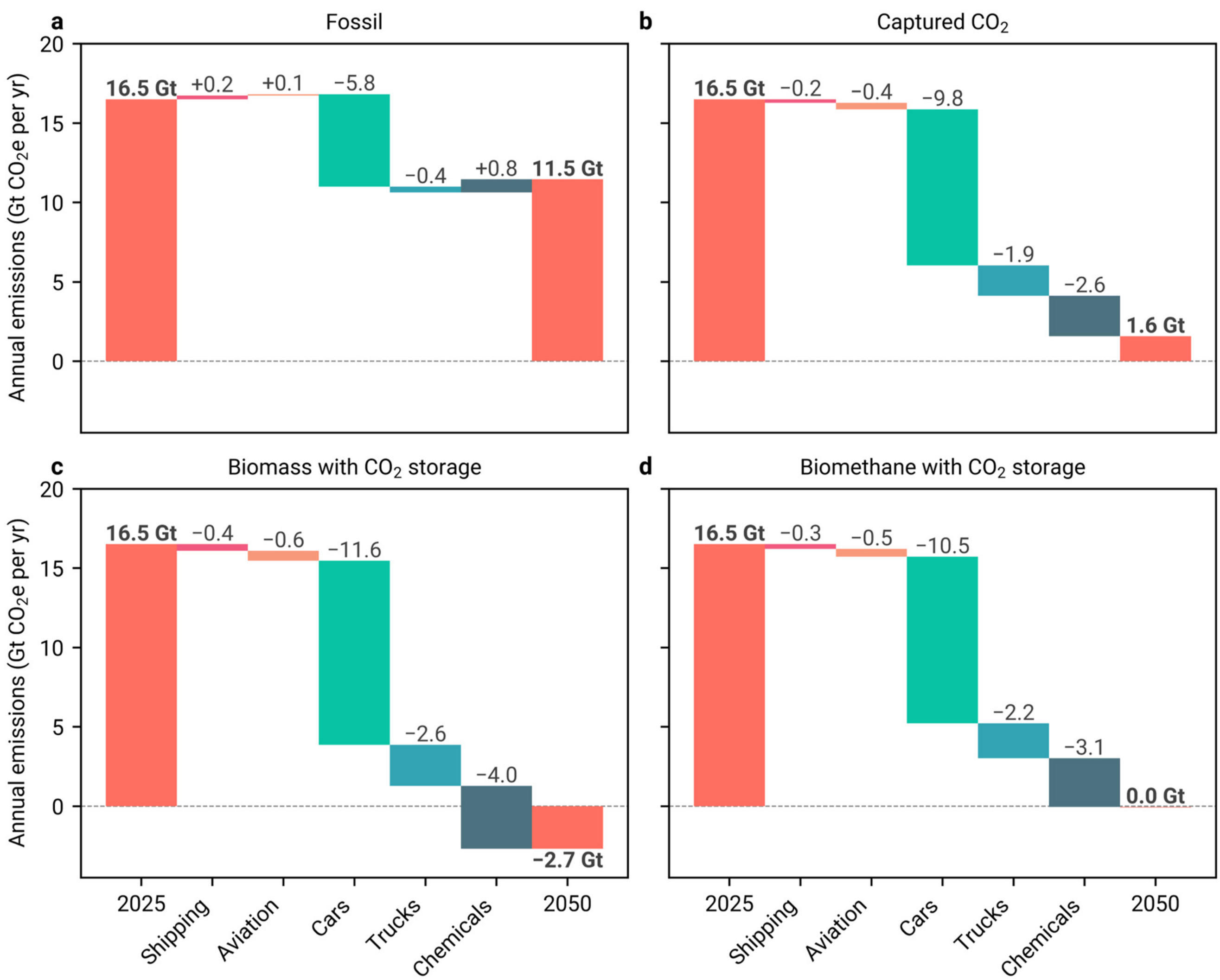


**Fig. 3** Bio-based methanol economies are the best performing in terms of GHG emissions. Potential reductions in GHG emissions across various sectors, shipping, aviation, road transport, and chemicals, by 2050 under (a) natural gas-based fossil, (b) captured $CO_2$ utilisation, (c) biomass with $CO_2$ storage, and (d) biomethane with $CO_2$ storage scenarios, respectively. The baseline (16.5 Gt $CO_2$e per year) represents the 2025 markets, indicating the starting point for a methanol-based economy.

 

by 2050. Our results forecast that a methanol economy based on biomethane and biomass, both coupled with geological $CO_2$ storage, can achieve net-zero or even negative residual GHG emissions. In contrast, $CO_2$-based methanol yields around 1.6 Gt $CO_2e$ annually. On the other hand, a fossil methanol economy, using natural gas as feedstock, results in 11.5 Gt $CO_2e$ per year, which, while higher than other renewable carbon scenarios, is still lower than the conventional 2025 case.

Across all scenarios, the sector-based analyses in Fig. 3 show that the largest mitigation potential lies in road transport and the chemical industry. By switching predominantly fossil fuel combustion engines in 2025 to M100 passenger cars and heavy-duty trucks in 2050, up to 11.6 and 2.6 Gt $CO_2e$ per year could be saved, respectively. Demand for methanol as a passenger-car fuel would depend on how effectively existing BEV mandates reduce ICE vehicle stock. These mandates differ by jurisdiction: Europe pushes for an almost fully electric fleet by 2050 (95%), whereas the United States and China have more conservative targets of around 60%.[71] These mandates matter, as they could potentially limit the demand for M100 engines. To gain clear insights into the potential of a methanol economy against BEV mandates, as well as other policies aiming to achieve the targets set out by the Paris agreement, a broader assessment of the impact of M100 passenger cars within the automotive sector is required. Our findings suggest that the methanol economy has significant potential to complement BEV mandates, as discussed in a later section.

In a methanol economy, the chemical industry would also see a significant reduction in GHG emissions. This is primarily due to the use of renewable carbon as feedstock, *i.e.*, biogenic carbon in bio-based scenarios (biomass and biomethane) as well as captured $CO_2$ in the carbon capture and utilization scenario.

While Fig. 3 illustrates the full potential of a specific methanol economy reliant on a particular carbon source, such an analysis is limited by the scarcity of bio-based resources, as discussed earlier. In this work, we estimate that meeting the chemical and fuel demand by 2050 would require approximately 5522 Mt of methanol annually. Based on biomass and biomethane availability estimates reported in the literature (see section S1 of the SI), we project that about 45% of this demand could be met using bio-based routes. Therefore, although bio-based routes are the most favourable alternatives in terms of GHG emissions, a methanol economy solely reliant on them is infeasible, highlighting the need for hybrid solutions to satisfy future demand. This limitation is discussed in more detail in the following sections, and additional information on the availability of biogenic carbon feedstocks is provided in section S1 of the SI.

### Minimal collateral environmental damage

The environmental impact of a methanol economy in terms of GHG emissions clearly underscores the need to consider methanol in climate strategies. However, climate change is not the only relevant indicator for environmental sustainability. The phenomenon of mitigating environmental harm in one category while creating new problems in others is known as burden shifting. To address potential burden shifting, it is also necessary to study the impacts of all scenarios on human health, ecosystem quality, and natural resources, which can be calculated for 2050 using the same general assumptions as those applied to climate change impacts. Our results, presented in Fig. 4, show that, compared with the conventional

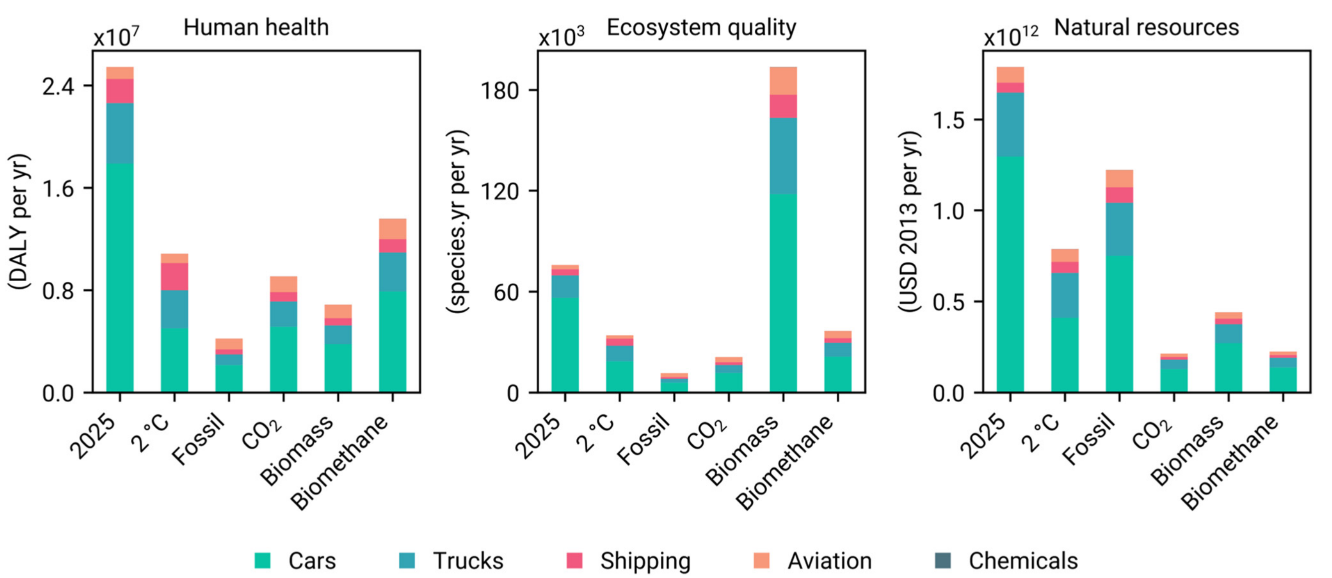


Fig. 4 Assessment of potential burden shifting for the methanol economy. Besides GHG emissions, other environmental indicators, including human health, ecosystem quality, and natural resources, are assessed for the current scenario (2025), the technological roadmap to meet the Paris Agreement (2 °C scenario), and the methanol economies (fossil, $CO_2$, biomass and biomethane-based) in 2050. These indicators are calculated annually based on the total demand in each scenario, representing the absolute endpoint impacts per functional unit across feedstock scenarios.

2025 scenario, there is no immediate risk of significant burden shifting in any of the methanol economies considered (*i.e.*, fossil, $CO_2$, biomass, and biomethane), except for the ecosystem quality impact category in the biomass scenario. In this case, extensive land use exacerbates ecosystem quality by causing biodiversity loss and habitat damage.

Other than the aforementioned scenario, an extended analysis shows that, compared to current levels (labelled 2025 in Fig. 4), impacts are significantly reduced in both the technological roadmap aimed at reaching the 2 °C target by 2050 (labelled 2 °C in Fig. 4) in line with the Paris Agreement, as well as in all methanol economy pathways. By 2050, compared to the 2 °C scenario, the biomethane-based methanol economy shows minimal burden shifting in the human health and ecosystem quality categories, whereas the biomass-based economy shows burdens shifting only in the ecosystem quality category. This is primarily due to the increased use of biogenic feedstock, which places additional pressure on ecosystems, while particulate matter emissions contribute to impacts on human health.[72]

In the natural resources impact category, the methanol economy exhibit impacts approximately three times lower than those of the 2 °C scenario by 2050, except in the fossil methanol case. This difference is attributable to two primary factors. First, the 2 °C scenario, which relies on results from IAMs, assumes extensive electrification of the road transport sector, requiring extraction of scarce materials such as lithium and rare earth elements. Second, the 2 °C pathway does not fully phase out fossil fuels, in contrast to the complete fossil fuel substitution assumed for the methanol economy in this work.

Current impacts show much higher results (*i.e.*, in the 2025 scenario), underscoring the environmental threat posed by crude oil and its derivatives and highlighting the urgent need to address the triple planetary crisis—climate change, biodiversity loss, and pollution and waste.

Across the environmental indicators, passenger cars contribute the most in each scenario, consistent with the climate change impact results shown in Fig. 3. For biomass- and biogas-based methanol, Fig. 4 shows some potential burden shifting. Notably, these results account for the full cradle-to-wheel scope for transport and cradle-to-gate scope for the chemicals value chain, excluding minor potential contributions such as methanol transport and storage.[73] Further details are provided in section S3 of the SI.

### Hybrid methanol economies can meet climate targets

As highlighted, bio-based routes face limited availability despite their advantageous environmental performance, (Fig. 3) whereas the unlimited $CO_2$ route still requires further development, which contributes to its currently higher implementation costs. A combination of these routes could therefore offer a well-balanced renewable configuration with both environmental and economic advantages in the midterm. In parallel, the strategic integration of fossil and bio resources in the short term may give access to an interim solution.

Fig. 5 shows the average results for the two hybrid methanol economies. The left pane presents a bio + $CO_2$ configuration comprising 20% biomethane, 25% biomass, and 55% $CO_2$, while the right pane shows a bio + fossil one with 20% biomethane, 25% biomass, and 55% fossil-based methanol. The bio + $CO_2$ scenario results in net-zero emissions overall, enabling a fully renewable methanol economy. In this hybrid economy, a 20% biomethane share (exhausting the full projected biomethane availability) and a 25% biomass mix were considered to minimise burden shifting compared with purely biomass-based routes, particularly in the ecosystem quality impact category (as shown in Fig. S2 of the SI).

Nonetheless, as current production levels of methanol from captured $CO_2$ are relatively low, the bio + fossil scenario could serve as a viable intermediate solution, exhibiting 5.6 Gt $CO_2e$ per year in 2050. Fossil methanol is a mature technology that could be deployed as an interim pathway while the $CO_2$ scenario reaches a higher TRL. Moreover, this hybrid methanol economy, similar to the bio + $CO_2$ scenario, shows minimal burden shifting (see Fig. S2 of the SI).

In addition to achieving a significant reduction in emissions, these pathways also outperform technological roadmaps designed to meet the Paris Agreement's 2 °C target (see Fig. S3 of the SI for a sector-wise breakdown). The bio + $CO_2$ and bio + fossil methanol economies show 5.9 and 0.5 Gt $CO_2e$ lower residual emissions per year, respectively, compared to the roadmap for the 2 °C scenario. Under the 2 °C scenario, most of the reduction in impacts is attributed to the decarbonized electricity mix.[65] We recall that emissions for this scenario were derived from pathways based on IAMs, which project the market and energy system changes needed to achieve the 2 °C target. Further details are provided in section S2 of the SI.

The methanol economy and the IAMs technological roadmaps to meet the Paris Agreement are, however, not mutually exclusive. Defossilisation of the electricity grid would further benefit the methanol economy, so methanol could have a more prominent role toward 2050, further reducing residual GHG emissions. We performed the same analysis for scenarios consistent with limiting global temperature increases to 3.5 °C and 1.5 °C, respectively. Results for these pathways, including sectoral breakdowns and mitigation potential, are provided in the SI (Fig. S3).

Under the 2 °C scenario, global BEV mandates are assumed to accelerate electric vehicle deployment, covering over 70% of road transport demand. Our results indicate that BEV-based systems outperform M100 engines in ecosystem quality (Fig. 4) with methanol engines based on $CO_2$ or biogas exhibiting lower impacts on human health and resource depletion, as BEVs rely on the extraction of scarce materials. A comparison of climate change impacts (Fig. S3 of the SI) reveals that the 1.5 °C scenario, representing an almost fully electrified fleet, achieves a similar GHG reduction to a fully biomethane-based methanol economy (Fig. 3d). While further comparative assessments of BEVs and M100 vehicles are needed, our results identify methanol cars as a viable and complementary low-carbon alternative.

Finally, the results shown in Fig. 5 correspond to a global methanol economy. However, as biogenic feedstock would become a scarce commodity, regions might focus more on

 

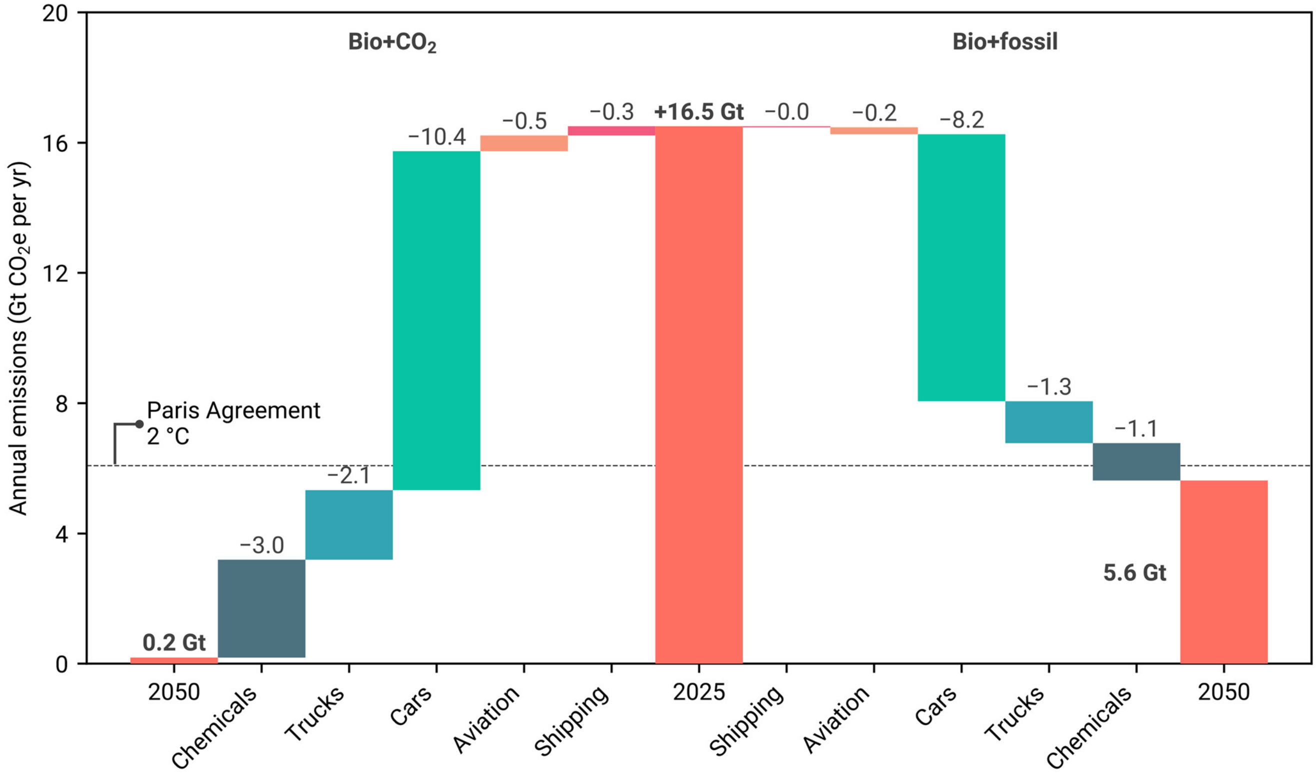


**Fig. 5** GHG emission impact of hybrid methanol economies. The climate change impact of two methanol economies was assessed. The left pane shows the impact of an bio + $CO_2$ economy based on biomass (25%), biomethane (20%), and captured $CO_2$ (55%). The bio + fossil configuration to the right assumes the same fraction of bio-based methanol, but fills the residual demand (55%) with methanol from natural gas.

meeting domestic demand, guided by targeted policies. Therefore, a regional assessment was performed for the United States, China, and Europe, which together account for around half of global GDP (section S5 of the SI). In this assessment, we assume that each region fully exploits its potential of biogenic carbon feedstock from biomass and biogas, with any residual methanol demand met through $CO_2$-based methanol (Table S12 of the SI). Emission reduction patterns closely follow the global average, with road transport, particularly M100 engines, providing the largest gains (Fig. S4). This comparison highlights that, while the global methanol economy benefits from aggregated resource availability, regional implementation depends on balancing domestic feedstock with $CO_2$-based methanol for net-zero emissions.

### Implementing the methanol economy comes at a low per capita cost

To enable a more precise evaluation of the overall impact of the methanol economy, it is essential to contextualise economic implications. The left panel of Fig. 6 shows the total cost of each scenario in 2050, alongside current spending on chemicals and fuels based on 2025 demand. Total system costs increase from approximately 2.6 trillion USD in 2025 to between 2.0 and 4.3 trillion USD annually by 2050 under the hybrid methanol economy scenarios, compared with 2.4 trillion USD annually under the technological roadmaps developed with IAMs to meet the Paris Agreement's 2 °C climate target (see section S4 of the SI for details on the calculations for the 2 °C scenario). Nonetheless, the methanol economy results in residual emissions that are up to 5.9 Gt $CO_2e$ lower than those under the 2 °C roadmaps. This indicates that, although the methanol economy entails higher costs, it offers significantly greater mitigation potential. Numerical values for all scenarios are provided in Table S8 of the SI.

Total cost rises by 2050 compared to 2025, but so does the population and thus demand for chemicals and fuels. Consequently, the total average monthly cost of the methanol economy was calculated at 16 USD per capita for the hybrid bio + fossil and 32 USD per capita for the bio + $CO_2$. These results were calculated accounting for the total projected global population by 2050, expressed in 2025 USD (see section S4 of the SI). Similarly, the monthly cost of the roadmaps designed to meet the Paris Agreement target is 20 USD per capita but results in higher residual GHG emissions. These values are substantially lower than the estimated monthly cost of climate inaction, projected to reach 320 USD per capita by 2050, reflecting the resulting damages from natural disasters and climate change.[74] The cost of implementing a methanol economy is comparable, for example, to a monthly streaming subscription or to that of the Apollo space program, approximately 10 USD per month per American citizen. Space exploration was supported by strong public and political backing as

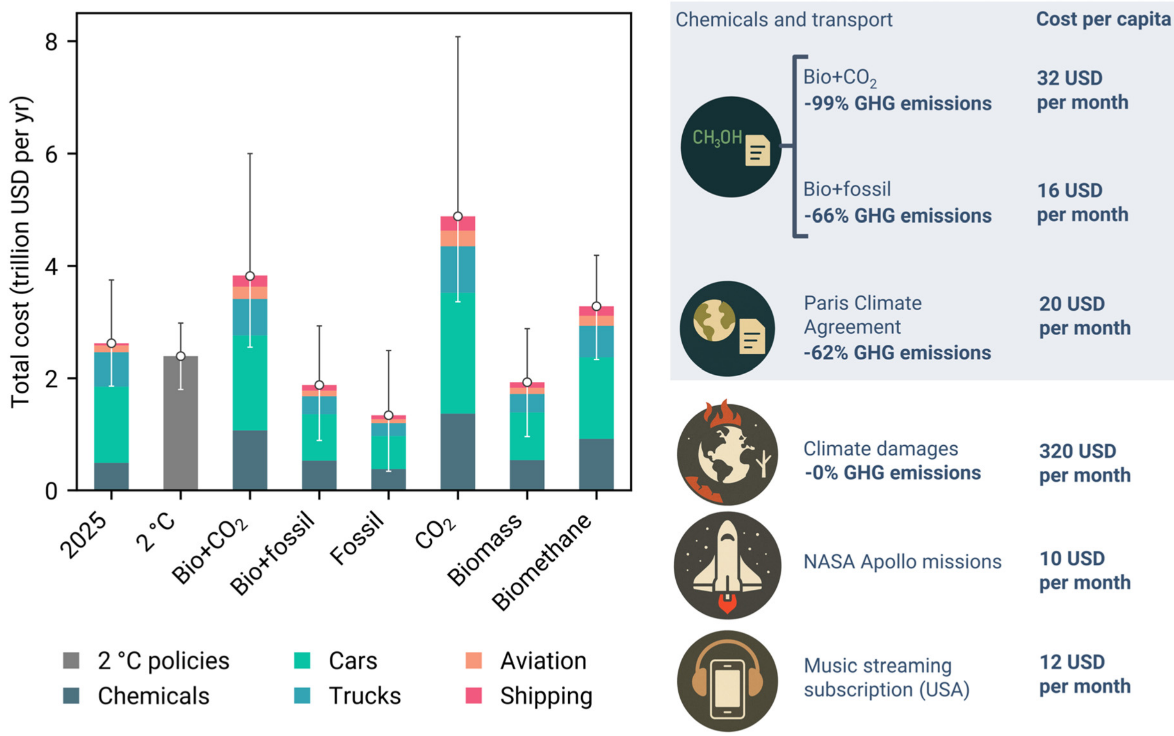


**Fig. 6** Annual costs of implementing the methanol economy. The total cost is compared with current spending on fuels and chemicals, as well as with estimates from technological roadmaps targeting the Paris Agreement's 2 °C climate goal. GHG emission reductions are significantly higher in the hybrid methanol economy scenarios than in the Paris Agreement scenario, as shown in Fig. 5. The figure also illustrates the variability in cost, primarily driven by uncertainties in feedstock prices, both at present and in the future (see section S4 of the SI for further details). Current costs are based on average market prices from 2021 to 2025, as extracted from the literature. Costs for the 2 °C climate goal were downscaled to the chemical and transport sectors using a top-down allocation of literature-reported costs. See section S3 of the SI for further details.

part of a bold industrial policy. A comparable investment could similarly make the methanol economy a viable strategy for mitigating the damaging effects of climate change.

Finally, the marginal cost of abatement (MCoA) was calculated for each sector of the methanol economy (according to eqn (S8) of the SI), quantifying the additional cost per unit of emissions avoided by the methanol-based alternative compared with the business-as-usual case. Three standalone methanol economies were assessed: biogas, biomass, and captured $CO_2$ utilisation (see section S4 of the SI). Across all three scenarios, consistent trends were observed. Road transport exhibited the lowest MCoA, followed by the chemical industry, aviation, and shipping. In contrast, MCoA for shipping was substantially higher. Nevertheless, shipping has attracted attention as a methanol-end use sector, with high TRL technologies and supportive regulations outweighing the higher MCoA (Fig. 1). Detailed numerical results for the MCoA are provided in Tables S9–S11 of the SI.

## Conclusions

This study quantifies for the first-time, to our best knowledge, configurations of the methanol economy and identifies viable technological roadmaps using comprehensive prospective models of the fuel and chemical sectors projected for 2050 from environmental and cost angles. The scope covers replacing fossil fuels with methanol in road and maritime transport, and its role as a chemical building block for aviation fuels and the largest-volume carbon-based chemicals. Fossil, biogas, biomass, and $CO_2$ captured from the air are considered as carbon sources, in line with Olah's seminal vision.

The biomass-based scenario with $CO_2$ storage achieves negative emissions at an implementation cost of *ca.* 16 USD per person per month—lower to today's spending on fuels and chemical sector combined—outperforming all other sustainable feedstocks. However, limited availability and impact on ecosystems restrict its scalability. The biogas (*i.e.*, biomethane reforming) pathway can deliver net-zero emissions with negligible additional environmental impacts, but is also constrained by availability. Together, biomass and biogas could meet only *ca.* 45% of the carbon needs. Air-captured $CO_2$ hydrogenated to methanol offers (virtually) unlimited availability and near net-zero emissions without added environmental burdens, but its projected cost (around 41 USD per person per month) detracts from its attractiveness despite the rapid maturation of the technology.

To bridge these gaps, we explore hybrid systems. A bio + fossil configuration (45%/55%) can be implemented immediately using mature technologies, achieving residual emissions compatible with those of the technological roadmaps designed to meet the Paris Agreement at around 16 USD per person per month. The future replacement of fossil carbon with $CO_2$ leads to a bio + $CO_2$ configuration (45%/55%) capable of net-zero emissions at approximately 32 USD per person per month, comparable to the estimated cost of pathways that seek to meet the Paris Agreement but with greater emissions reductions. Crucially, accelerating the maturity of $CO_2$-to-methanol technologies will be decisive in realising this transition. Across all scenarios, implementation of the methanol economy for road transport yields the largest impact reduction potential—nearly two-thirds of emission reductions—followed by chemical production, while aviation and shipping contribute more modest benefits. We thus propose a phased implementation roadmap: road transport → chemicals → aviation → shipping, which could complement other technological strategies in portfolios optimised based on region-specific data.

It must be acknowledged that some of the configurations explored here may clash with policy choices already locked in across certain regions. As earlier described, Europe, for instance, has committed to an electric vehicle trajectory, leaving little space for large-scale methanol-based road transport.[75] In such settings, full implementation is unlikely. But in other parts of the world, where pathways remain open and critical decisions have not yet closed the door, the methanol economy could become a powerful alternative. Overall, this analysis highlights a broader lesson: locking in a single transition strategy too early risks discarding viable options. In the spirit of Olah's vision, the transition should remain open to multiple parallel routes, not only to safeguard flexibility, but also to maximise the chances of meeting global climate goals more sustainably, where methanol could play a key role.

## Author contributions

HK: conceptualisation, methodology, visualisation, formal analysis, writing – original draft, writing – review, and editing; AN: conceptualisation, methodology, visualisation, formal analysis, writing – original draft, writing – review, and editing; AJM: conceptualisation, visualisation, validation, writing – original draft, writing – review and editing; GG-G: conceptualisation, validation, writing – original draft, writing – review and editing, supervision, and project administration; JP-R: conceptualisation, validation, writing – original draft, writing – review and editing, supervision, and project administration.

## Conflicts of interest

There are no conflicts to declare.

## Data availability

The data presented in the figures of this paper are publicly available *via* Zenodo (https://doi.org/10.5281/zenodo.17044021). The background LCI datasets used in this study are available in the Ecoinvent v3.10 (cut-off system model) database under the accessible link (https://ecoinvent.org). Other supporting data are available from the corresponding authors upon request.

Supplementary information (SI) containing an extended description of the methodology of the life cycle, technoeconomic, and regional analyses is available. See DOI: https://doi.org/10.1039/d5gc04615g.

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