Supplementary Information

A feasible methanol economy for a green future

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Figures and Tables

1. Introduction to the methanol economy

The concept of the methanol economy was first proposed by George A. Olah in 2005 as a means to transition away from fossil fuels by using methanol as a versatile energy carrier and chemical feedstock. To our best knowledge, this work is the first quantification of the methanol economy as a comprehensive climate mitigation strategy, focusing on its deployment in key industrial sectors. For the purpose of this analysis, the methanol economy is defined to include applications in two major sectors: chemicals and transport. Together, these sectors account for approximately 15% of global GDP.[1,2]

- In the chemical sector, six major bulk chemicals were considered: methanol, ethylene, propylene, benzene, toluene, and xylene. Each of these products can be produced through methanol-based pathways and is therefore included within the system boundaries of this study.
- In the transport sector, the scope includes aviation, shipping, and road transport (covering both passenger vehicles and heavy-duty trucks). These sectors collectively represent a significant share of global emissions and economic activity.

Current and projected future demands for these sectors are illustrated in **Fig. S1**, showing trajectories to 2050 under the assumption of continued population and welfare growth. Corresponding numerical data are provided in **Table S1** for the years 2025 and 2050. The 2050 projection is aligned with currently stated policies and assumes ongoing sectoral growth. The demand in each sector was corrected with an additional factor to be in line with current stated policies (1.68 for fuels and 2.36 for chemicals), taken from established literature sources.[3–6]

Finally, this work includes four types of feedstocks, three of which are considered to be sustainable: natural gas, biomass, biomethane, and carbon dioxide from direct air capture (DAC). For biomass and biomethane, the limited availability was considered for the calculations of the environmental and economic impact. Based on literature, 698 bcm of biomethane would be available in 2050. Due to the limited availability of data on this matter, the biomethane potential only includes the world's largest economies, as shown in **Table S2**. The availability of biomass was taken from Huo *et al.*[7] and was found to be around 4.3 Gt per yr by 2050.

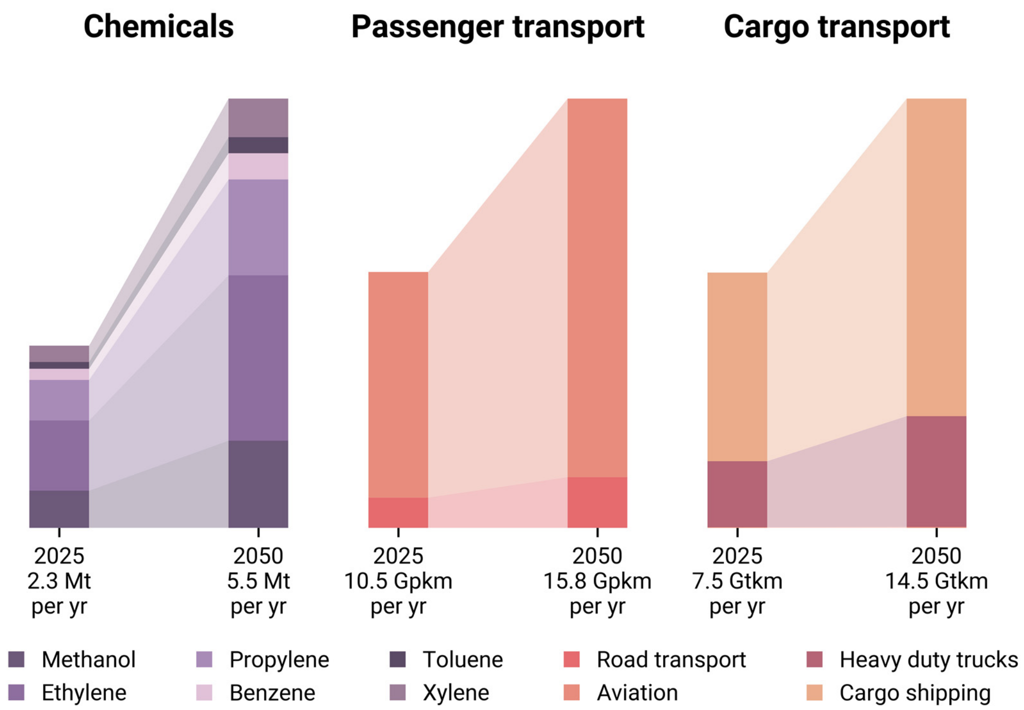

Fig. S1 | Demand for the chemical and transport sectors in 2025 and 2050. The demands are based on the One Earth Climate Model (OECM) and converted to account for growth due to stated policies. Gpkm and Gtkm refer to demand in giga passenger-kilometres and giga ton-kilometres, whereas Mt refers to demand in million tons for chemicals.

Table S1 | Demand for the chemical and transport sectors in 2025 and 2050.

Product	Unit	Base 2025	Stated policies 2050
Passenger aviation	pkm per yr	$4.3 \cdot 10^{12}$	$7.2 \cdot 10^{12}$
Cargo aviation	tkm per yr	$1.8 \cdot 10^{11}$	$3.1 \cdot 10^{11}$
Shipping	tkm per yr	$6.0 \cdot 10^{13}$	$1.0 \cdot 10^{14}$
Passenger car	pkm per yr	$3.2 \cdot 10^{13}$	$5.4 \cdot 10^{13}$
Heavy duty trucks	tkm per yr	$2.1 \cdot 10^{13}$	$3.5 \cdot 10^{13}$
Methanol	Mt per yr	$1.2 \cdot 10^{2}$	$2.9 \cdot 10^{2}$
Ethylene	Mt per yr	$2.3 \cdot 10^{2}$	$5.5 \cdot 10^{2}$
Propylene	Mt per yr	$1.4 \cdot 10^{2}$	$3.2 \cdot 10^{2}$
Benzene	Mt per yr	$3.7 \cdot 10^{1}$	$8.7 \cdot 10^{1}$
Toluene	Mt per yr	$2.3 \cdot 10^{1}$	$5.3 \cdot 10^{1}$
Xylene	Mt per yr	$5.4 \cdot 10^{1}$	$1.3 \cdot 10^{2}$

pkm and tkm refer to demand in passenger-kilometres and ton-kilometres, whereas Mt refers to demand in million tons.

Table S2 | Availability of biomethane. The availabilities are as assumed in this work with respect to the corresponding sources. As data on this subject are limited, the sum of regions was assumed to be the global potential. All values are provided in billion cubic metres (bcm) per yr.

Name	Value
North America[8]	74
European Union[8]	165
China[9]	175
Japan[10]	20
India[11]	125
Russia[9]	70
Brazil[9]	51
South Africa[12]	20

2. Prospective life cycle assessment methodology

2.1. Processes considered

The environmental impact of a methanol economy was calculated based on the technologies that could practically be replaced with a methanol-based solution. For chemicals, this included methanol-to-olefins and methanol-to-aromatics (MTO and MTA, respectively). In road transport and shipping, methanol combustion engines were assumed to replace the current markets. In aviation, methanol was assumed to be converted to kerosene *via* the methanol-to-kerosene technology (MTK).

Methanol employed to produce various products can be obtained from natural gas, biomass, biogas (specifically, using biomethane), used plastics chemical recycling, or CO_2 captured from the atmosphere combined with hydrogen from electrolysis powered by renewable electricity. In our calculations, only the natural gas (fossil), biomass, biogas- and CO_2-based routes were assumed. For this purpose, natural gas reforming to methanol is assumed for the fossil scenario, and biomass gasification to methanol *via* syngas is assumed for the biomass scenario. Biomass was modelled to originate from wheat straw as a benchmark feedstock representing all types of biomass. For the availability, the full 2050 biomass was used, as discussed. Biogas is produced through the anaerobic digestion of biogenic waste material, such as industrial wastewater, sewage sludge, animal manure, agricultural residue crops, and sequential crops as done in previous works.[13] Electrolytic hydrogen is produced through water electrolysis in a PEM electrolyser using renewable energy (for example, onshore wind electricity in this work). CO_2 can be sequestered from the atmosphere through an adsorption-based technology, *i.e.*, direct air capture (DAC). Combining this CO_2 captured from air with hydrogen to produce methanol is referred to as captured CO_2 utilisation scenario.

2.2. Life cycle assessment

We conduct an attributional, prospective life cycle assessment (LCA) following the ISO 14040 and 14044 standards.[14,15] This analysis is structured around the four standardised phases of LCA, as described below. The objective of our work is to evaluate the environmental performance of a future methanol economy, in which renewable methanol substitutes for conventional fossil-based feedstocks and fuels across the chemical and transportation sectors.

2.2.1. Goal and scope

The functional unit considered in this work is the total projected demand for chemicals and fuels in the corresponding year, *i.e.*, 2025 or 2050 across the chemical and transportation sectors. For the chemicals sector, cradle-to-gate system boundary was employed, encompassing all material and energy inputs, as well as associated emissions required to produce olefins and aromatics from methanol. This approach excludes the use phase of chemical products, assuming equivalent downstream applications similar to previous works.[16] For the transport sector, including road, marine, and aviation, a cradle-to-grave system boundary was employed, covering fuel production, combustion, and associated emissions. All calculations are based on global average values. Our results are then compared to three future roadmaps designed to meet three climate scenarios limiting global mean surface temperature (GMST) to 1.5 °C, 2 °C, and 3.5 °C, capturing different levels of decarbonisation by 2050. To model these roadmaps and their implications on the global economy, we apply the *premise* v2.1.3 framework that adjusts existing inventory data from ecoinvent v3.10 to reflect anticipated technological and socio-economic developments.[17] This involves not only modifying technical parameters within primary processes (*e.g.*, efficiencies), but also updating background processes, *e.g.*, to represent a growing share of renewables in electricity mixes. For this purpose, *premise* draws from future economic projections generated by the Integrated Assessment Model (IAM), such as IMAGE.[18]

2.2.2. Life cycle inventories

The life cycle inventories (LCIs) were employed using a combination of literature-based data and existing LCA databases. Business-as-usual fossil-based production of chemicals and fuels is modelled using the ecoinvent v3.10 database. For methanol-based chemical production *via* MTO and MTA, LCI data are derived from the literature.[19,20] For road transport using cars and trucks, inventory data are based on published studies of methanol engine performance, including fuel efficiency, emissions, etc. In the aviation sector, inventory data for MTK process are taken directly from the *premise* framework. Similarly, for methanol-based ships, literature data is used to model the inventories. For methanol production, data for fossil-, biomass-, biogas- and CO_2-based routes are also sourced from literature. The inventories employed in this work are summarised in detail in **Table S3**.

To compute the LCIs, we apply the standard matrix-based formulation of LCA. The inventory vector *g* associated with the functional unit is derived from:

$$g = B \cdot (A)^{-1} \cdot f \qquad (\textbf{Equation S1})$$

where *A* is the technosphere matrix, representing exchanges between economic activities; *B* is the biosphere matrix, linking those activities to environmental flows (*e.g.*, emissions, resource use); *f* is the final demand vector, representing the functional unit (*i.e.*, the demand for business-as-usual chemicals and fuels in 2025 or 2050); and *g* is the resulting inventory vector, quantifying all elementary flows required to satisfy the demand.[21] To model the methanol scenarios, we augment the background matrices to incorporate new methanol production, as well as chemicals and fuels derived from these renewable methanol pathways, resulting in modified matrices *A*' and *B*', and a corresponding inventory vector *g*':

$$g' = B' \cdot (A')^{-1} \cdot f \qquad (\textbf{Equation S2})$$

2.2.3. Life cycle impact assessment

The environmental impacts of the methanol economy are assessed using midpoint and endpoint indicators. GHG emissions are quantified using 100-year global warming potential (GWP) from the IPCC 2021 assessment.[22] Additional endpoint categories, human health, ecosystems quality, and natural resource depletion, are evaluated using the ReCiPe 2016 v1.03 impact assessment method.[23] For a given inventory vector *g* or *g*', representing either the conventional or augmented system, the corresponding environmental impact vector *h* or *h*' is calculated as:

$$h^{(')} = Q \cdot g^{(')} \qquad (\textbf{Equation S3})$$

Here, Q is the characterisation matrix that translates elementary flows into specific impact categories, based on the chosen LCIA method.

2.2.4. Interpretation

Finally, in the interpretation phase, we analyse the results as presented in the **Results and Discussion** section of the main manuscript.

Table S3 | Brief overview of the life cycle inventories used in this work. These include the source and the activity name used in the dataset. Note that the inventories for MTO and MTA include the process energy consumption.

Product	Scenario	Technology	Source
Hydrogen	Captured CO_2	Wind-powered water electrolysis	D'Angelo *et al.*[24]
Methanol	Business-as-usual	Natural gas reforming and coal gasification	ecoinvent v3.10 ('market for methanol')
	Captured CO_2	DAC CO_2 coupled with wind-powered hydrogen from electrolysis	González-Garay *et al.*[25] (using DAC CO_2 inventory extracted from Terlouw *et al.*[26] and electrolysis-based hydrogen extracted from D'Angelo *et al.*)
	Biomethane	Biomethane reforming	ecoinvent v3.10 ('methanol production, natural gas reforming') substituting natural gas with biomethane with carbon capture and storage (CCS) extracted from Istrate *et al.*[13]
	Biomass	Biomass gasification	Liu *et al.*[27]
	Fossil	Natural gas reforming	ecoinvent v3.10 ('methanol production, natural gas reforming')
Ethylene	Business-as-usual	Naphtha cracking and fossil MTO	ecoinvent v3.10 ('market for ethylene')
	Captured CO_2	CO_2-based MTO	Ioannou *et al*. substituting methanol with CO_2-based methanol
	Biomethane	Biomethane-based MTO	Ioannou *et al.*[19] substituting methanol with biomethane-based methanol
	Biomass	Biomass-based MTO	Ioannou *et al.*[19] substituting methanol with biomass-based methanol

	Fossil	Fossil-based MTO	Ioannou *et al*.[19] substituting methanol with fossil-based methanol
Propylene	Business-as-usual	Naphtha cracking and fossil MTO	ecoinvent v3.10 ('market for propylene')
	Captured CO_2	CO_2-based MTO	Ioannou *et al*. substituting methanol with CO_2-based methanol
	Biomethane	Biomethane-based MTO	Ioannou *et al*.[19] substituting methanol with biomethane-based methanol
	Biomass	Biomass-based MTO	Ioannou *et al*.[19] substituting methanol with biomass-based methanol
	Fossil	Fossil-based MTO	Ioannou *et al*.[19] substituting methanol with fossil-based methanol
Benzene	Business-as-usual	Naphtha cracking	ecoinvent v3.10 ('market for benzene')
	Captured CO_2	CO_2-based MTA	Ioannou *et al*.[20] substituting methanol with CO_2-based methanol
	Biomethane	Biomethane-based MTA	Ioannou *et al*.[20] substituting methanol with biomethane-based methanol
	Biomass	Biomass-based MTA	Ioannou *et al*.[20] substituting methanol with biomass-based methanol
	Fossil	Fossil-based MTA	Ioannou *et al*.[20] substituting methanol with fossil-based methanol
Toluene	Business-as-usual	Naphtha cracking	ecoinvent v3.10 ('market for toluene')
	Captured CO_2	CO_2-based MTA	Ioannou *et al*.[20] substituting methanol with CO_2-based methanol

	Biomethane	Biomethane-based MTA	Ioannou *et al*.[20] substituting methanol with biomethane-based methanol
	Biomass	Biomass-based MTA	Ioannou *et al*.[20] substituting methanol with biomass-based methanol
	Fossil	Fossil-based MTA	Ioannou *et al*.[20] substituting methanol with fossil-based methanol
Xylene	Business-as-usual	Naphtha cracking	ecoinvent v3.10 ('market for xylene, mixed')
	Captured CO_2	CO_2-based MTA	Ioannou *et al*.[20] substituting methanol with CO_2-based methanol
	Biomethane	Biomethane-based MTA	Ioannou *et al*.[20] substituting methanol with biomethane-based methanol
	Biomass	Biomass-based MTA	Ioannou *et al*.[20] substituting methanol with biomass-based methanol
	Fossil	Fossil-based MTA	Ioannou *et al*.[20] substituting methanol with fossil-based methanol
Passenger aviation	Business-as-usual	Fossil kerosene from petroleum	ecoinvent v3.10 ('market for transport, passenger aircraft, medium haul' and 'market for kerosene')
	Captured CO_2	CO_2-based MTK	*premise* ('kerosene production, from methanol, hydrogen from electrolysis, CO_2 from DAC, energy allocation') substituting methanol with CO_2-based methanol
	Biomethane	Biomethane-based MTK	*premise* ('kerosene production, from methanol, hydrogen from electrolysis, CO_2 from DAC, energy allocation') substituting

			methanol with biomethane-based methanol
	Biomass	Biomass-based MTK	*premise* ('kerosene production, from methanol, hydrogen from electrolysis, CO_2 from DAC, energy allocation') substituting methanol with biomass-based methanol
	Fossil	Fossil-based MTK	*premise* ('kerosene production, from methanol, hydrogen from electrolysis, CO_2 from DAC, energy allocation') substituting methanol with fossil-based methanol
Cargo aviation	Business-as-usual	Fossil kerosene from petroleum	ecoinvent v3.10 ('market for transport, freight, aircraft, medium haul' and 'market for kerosene)
	Captured CO_2	CO_2-based MTK	*premise* ('kerosene production, from methanol, hydrogen from electrolysis, CO_2 from DAC, energy allocation') substituting methanol with CO_2-based methanol
	Biomethane	Biomethane-based MTK	*premise* ('kerosene production, from methanol, hydrogen from electrolysis, CO_2 from DAC, energy allocation') substituting methanol with biomethane-based methanol
	Biomass	Biomass-based MTK	*premise* ('kerosene production, from methanol, hydrogen from electrolysis, CO_2 from DAC, energy allocation') substituting methanol with biomass-based methanol
	Fossil	Fossil-based MTK	*premise* ('kerosene production, from methanol, hydrogen from

			electrolysis, CO_2 from DAC, energy allocation') substituting methanol with fossil-based methanol
Shipping	Business-as-usual	Fossil shipping fuel from petroleum	ecoinvent v3.10 ('transport, freight, sea, container ship' and 'market for heavy fuel oil)
	Captured CO_2	CO_2-based methanol combusted in shipping engine	Malmgren *et al.*[28] substituting methanol with CO_2-based methanol
	Biomethane	Biomethane-based methanol combusted in shipping engine	Malmgren *et al.*[28] substituting methanol with biomethane-based methanol
	Biomass	Biomass-based methanol combusted in shipping engine	Malmgren *et al.*[28] substituting methanol with biomass-based methanol
	Fossil	Fossil-based methanol combusted in shipping engine	Malmgren *et al.*[28] substituting methanol with fossil-based methanol
Passenger car	Business-as-usual	Fossil fuels from petroleum (96%) and battery electric vehicles (4%)	ecoinvent v3.10 ('market for transport, passenger car with internal combustion engine' and 'market for transport, passenger car, electric')
	Captured CO_2	CO_2-based methanol combusted in car engine	Li *et al.*[29] and Methanol Institute[30] substituting methanol with CO_2-based methanol
	Biomethane	Biomethane-based methanol combusted in car engine	Li *et al.*[29] and Methanol Institute[30] substituting methanol with biomethane-based methanol
	Biomass	Biomass-based methanol combusted in car engine	Li *et al.*[29] and Methanol Institute[30] substituting methanol with biomass-based methanol
	Fossil	Fossil-based methanol combusted in car engine	Li *et al.*[29] and Methanol Institute[30] substituting methanol with fossil-based methanol

Heavy duty trucks	Business-as-usual	Fossil diesel from petroleum	ecoinvent v3.10 (‘market for transport, freight, lorry, unspecified’, and ‘market for diesel’)
	Captured CO_2	CO_2-based methanol combusted in truck engine	Feng *et al.*[31] substituting methanol with CO_2-based methanol
	Biomethane	Biomethane-based methanol combusted in truck engine	Feng *et al.*[31] substituting methanol with biomethane-based methanol
	Biomass	Biomass-based methanol combusted in truck engine	Feng *et al.*[31] substituting methanol with biomass-based methanol
	Fossil	Fossil-based methanol combusted in truck engine	Feng *et al.*[31] substituting methanol with fossil-based methanol

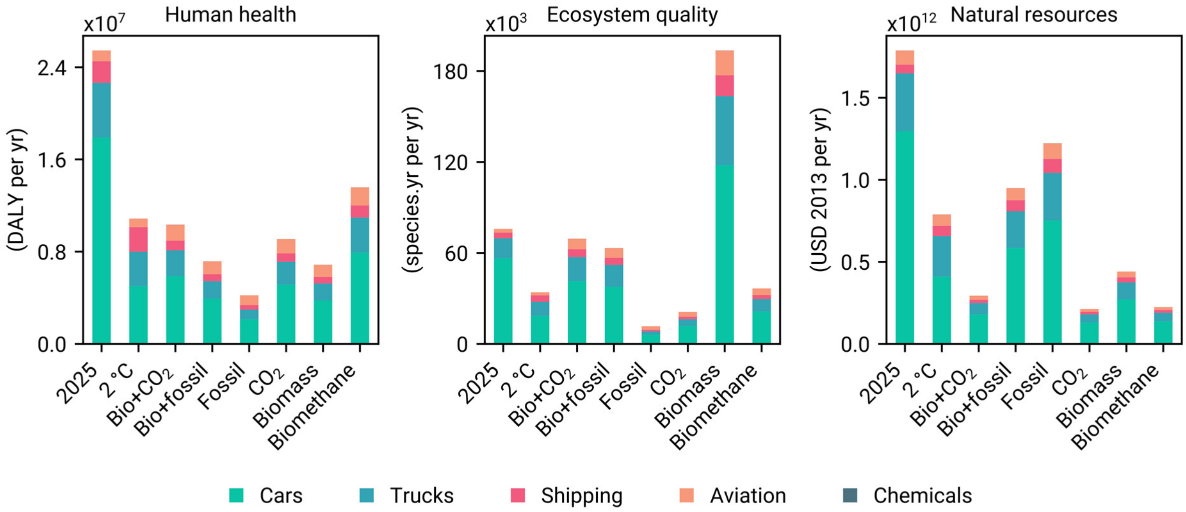

Fig. S2 | Assessment of burden shifting in hybrid methanol economies. In addition to GHG emissions, other environmental indicators such as human health, ecosystem quality, and natural resources are evaluated for three cases: the current scenario (2025), the technological pathway consistent with the Paris Agreement (2°C scenario), and the methanol economy in 2050 (hybrid and individual systems: bio+CO_2, bio+fossil, fossil-based, CO_2-based, biomass-based, and biomethane-based). All indicators are calculated annually based on the total demand in each scenario.

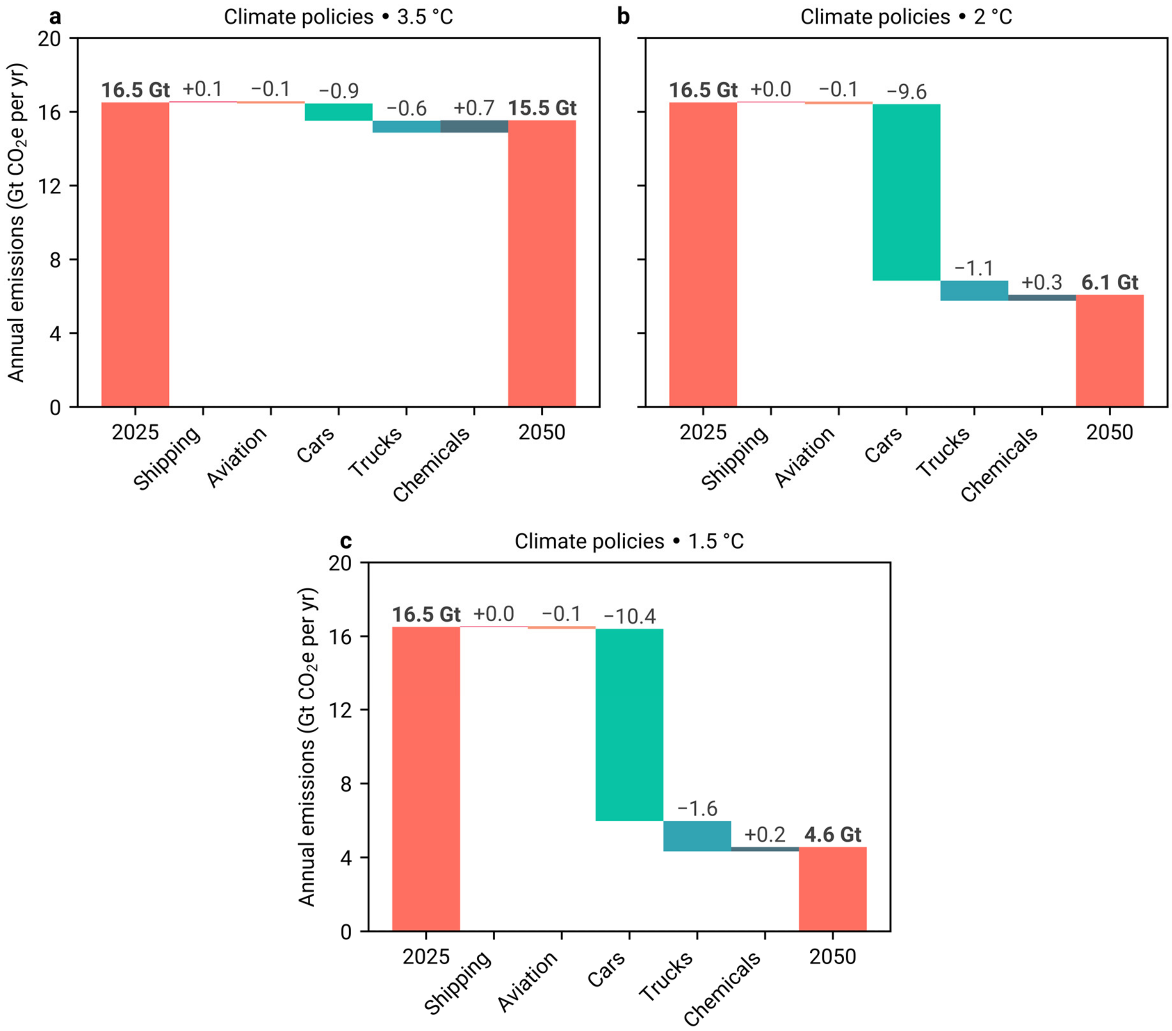

Fig. S3 | Climate change impact of climate policies reaching 3.5, 2, and 1.5 °C targets. The results show the change in climate change impact when following an alternative pathway than the methanol economy (as shown in **Fig. 3** of the main manuscript). The 2°C scenario is in line with the climate target set out by the 2015 Paris Agreement.

3. Assumptions and limitations of the study

- The life cycle inventories developed for this study were based on data from the ecoinvent database, assuming the cut-off system model.[32] The most relevant datasets were selected without further modification. A global system boundary was assumed. Regional variations in inventories were not considered; instead, global averages were applied.
- The numerical results presented in this work are partly dependent on the assumptions embedded in the integrated assessment model (IAM) used. Background inventories were sourced from ecoinvent and combined with the *premise* Python package to generate prospective scenarios.[33] As IAMs are based on computable general equilibrium (CGE) models of the global economy, they may not accurately capture the effects of sudden disruptions in supply and demand, such as those arising from geopolitical events or market shocks.[34]
- For the assessment of green hydrogen production, proton exchange membrane (PEM) electrolysers powered by wind-derived renewable electricity were considered in the environmental impact and cost calculations.
- The cost of the methanol economy was calculated from the feedstock up to the use phase. For chemicals, no end-of-life costs or externalities were included, as they would be the same across scenarios and therefore add no further discriminatory power. In transport, no system costs were assumed. For these sectors, eventual changes to infrastructures were neglected and fall outside of the scope. Transport of products from production plants to the consumer level was neglected in the cost calculations. This simplification provides an upper bound on the real costs of the biomethane and biomass scenarios, leading to lower abatement costs than expected.
- The cost of the technologies included in this work assume the most recent data. For current costs, average values of the time period 2021–2025 were used. For prospective costing, literature values based on exhaustive techno-economic modelling were used to provide some insight into future cost developments of the methanol economy. See **Table S6** for further details.
- In the road transport sector, the ecoinvent markets for passenger cars and heavy-duty trucks were used in 2025. For passenger cars, the 2025 market consisted of 96% internal combustion engines, for which only gasoline was assumed. The residual 4% of demand was met through batteries.[33] In 2050, 100% of the passenger cars were assumed to run on methanol, in order to calculate the full potential. For heavy-duty trucks, diesel was assumed as single fuel in 2025, which was replaced by methanol in 2050.
- Literature data were used to calculate the total cost of implementing technological roadmaps to meet the targets of the Paris Agreement.[35] To compare the costs of this IAM scenario with the cost of the methanol economy, the literature cost obtained for the IAM scenario was downscaled to the chemical and transport sector using the ratio of gross value added (GVA) of these sectors over the global GVA.[36] More precisely, the footprint of the scenarios is computed following a bottom-up approach by combining literature data with ecoinvent data. The costs of the methanol scenarios are also computed in a similar (bottom-up) way, considering the costs of the technologies and aggregating them to derive the cost of the said scenarios. However, this approach could not be followed for obtaining the cost of the IAM scenarios modelled by *premise*, as some bottom-up data are unavailable. Consequently, for the cost of the IAM scenarios, we follow a top-down approach,

assigning a share of the total cost of the scenario, which is reported elsewhere,[35] to the sectors investigated in this work, as explained above.

- In this work, methanol production was modelled using the commercial $Cu/ZnO/Al_2O_3$ (CZA) catalyst. Alternative catalyst systems, such as indium oxide-based formulations, may offer enhanced performance characteristics, including higher selectivity and conversion rates. However, these systems currently exhibit shorter operational lifetimes, and further research is needed to assess their technical robustness and economic feasibility. Assuming a cumulative methanol production of approximately 45,000 metric tons per m^3 of catalyst (based on Clariant's MegaMax 800 catalyst), this corresponds to an additional cost of about 0.0005 USD per kg of methanol produced.[37] Given that this cost is negligible compared with the current market price of methanol (0.55 USD per kg), catalyst costs were considered insignificant in the overall assessment. Nevertheless, improvements in catalyst lifetime and selectivities would further enhance process economics over the 20-year project duration.
- This study focuses exclusively on methanol production, as transport and storage costs are considered negligible in comparison. Recent estimates in the literature indicate that methanol transport costs can reach up to 0.01 USD per kg, while storage costs are approximately 0.005 USD per kg.[38,39] When compared with the fossil-based market price of roughly 0.55 USD per kg, these contributions are negligible.[40] Furthermore, as this study does not explicitly consider the spatial distribution of production and demand, the analysis is confined to the production stage.
- We quantify region-specific impacts by accounting for regional variability in all technosphere flows, such as electricity mixes. The most suitable datasets matching the regional scope of our analysis are selected, particularly focussing on the United States, China, and Europe. In cases where data for a particular country or region are unavailable, global or "rest of the word (RoW)" inventories are used instead.

4. Techno-economic analysis

This section outlines the methodology followed for the techno-economic assessment (TEA) conducted in this study. The TEA consisted of three stages:

- Estimation of capital (CAPEX) and operational expenditures (OPEX) for each process at the global scale using literature-based cost correlations.
- Calculation of the total system cost of transitioning to a methanol economy under defined conditions.
- Integration of TEA and LCA results to determine the marginal cost of abatement (MCoA) for each sector.

As described in the section on life cycle assessment (LCA), process-level mass and energy balances were used to develop life cycle inventories (LCIs). These LCIs provided the necessary input-output data for each production pathway. Based on this information, both CAPEX and OPEX were estimated for the reference year 2023. The scaling of each process was determined by final consumer demands, as specified in **Table S1**.

For aviation, the demand was converted into a required annual production requirement from kerosene. Using the LCI for aviation, this allowed for calculations on the required scale of the MTK process. In road transport and shipping, high-purity methanol was assumed as the direct fuel in the combustion engines. The total demands from **Table S1** were therefore converted into the sectoral methanol demand. For the chemical industry, the LCIs for the methanol production, MTO, and MTA provided the required methanol production values. The methanol demand in all sectors combined gave the total size of the methanol economy, for which the cost results were calculated.

4.1. Capital expenditure

Methanol production requirements from all end-use sectors were aggregated to determine the total annual production volume. Capital costs were estimated using the non-linear scaling correlations available in the literature, originally calibrated to 2014 cost data.[41] The cost of each process follows a correlation of the form:

$$C_i = \left(\frac{S}{S_0}\right)^n \times C_0 \qquad (\textbf{Equation S4})$$

where:

- S is the required production scale;
- S_0 is the reference scale;
- C_0 is the cost at S_0;
- n is the scaling exponent.

The cost C is valid for 2014 and converted to 2023 values using the ratio of the Chemical Engineering Plant Cost Index (CEPCI) for both years. Following the original work, the total plant costs (TPC) is computed from the sum of the unit costs above considering the balance of plant cost (BOP), often 20% of the above cost that is added to account for additional necessary expenditures to run the plant (*e.g.*, utility plants). Additionally, indirect costs (IC), accounting for engineering, are included, which adds a factor of 32%. The calculation of the TPC is reflected in **Equation S5**:

$$TPC = \sum_i C_i \times (1 + BOP) \times (1 + IC) \quad \textbf{(Equation S5)}$$

where:

- C_i is the 2023 cost of a given process i;
- BOP is the balance of plant, an estimate of the total outside battery limits.
- IC are the indirect costs, and estimate of engineering start-up, royalties, and other factors.

The total plant cost (TPC) was subsequently annualised through **Equation S6** to provide the total annualised cost of the scenario.[42] This calculation ensures project financing is taken into account by including an interest rate and investment payoff period.

$$TAC = ACCR \times TPC + OPEX \quad \textbf{(Equation S6)}$$

where:

- TAC is the total annualised capital cost;
- TPC is the total plant cost in 2023;
- ACCR is the annual capital charge ratio, derived from the interest rate and investment horizon;
- OPEX is the operational expenditure, as explained in the next section.

The ACCR was calculated for a fixed interest rate and investment payoff period, following **Equation S7**:

$$ACCR = \frac{i \times (1 + i)^n}{(1 + i)^n - 1} \quad \textbf{(Equation S7)}$$

where:

- i is the interest rate;
- n is the number of years of compound interest.

All assumptions, parameters, and economic inputs used to compute the TAC are listed in **Tables S4** and **S5**.

Table S4 | Capital expenditure input data. The mass balance data in kg feed per second were extracted from the inventories. Literature data and correlations were used to calculate the overall 2014 CAPEX for each scenario.[41] The results were adjusted to 2023 using the CEPCI factor. Olefins to middle distillate was used as a reference for the MTK process, in which methanol is converted to olefins first through the MTO process. To yield kerosene, these olefins are reacted to the middle distillate fraction and separated into valuable products. All production scale values (S, S_0, and S_{max}) are in kg per sec. S_{max} is the upper limit for which the correlations are valid.

Process	S	S_0	S_{max}	C_0 [2014 M$]	n	C [2014 M$]
WGS	225000	150	250	3.69	0.67	4500
Methanol synthesis	130000	36	350	8.09	0.65	13000
MTO	42000	11	100	3.42	0.65	6200
MTA	39000	11	100	5.71	0.65	970
Olefins to middle distillate	300	11	100	3.42	0.65	44
Methane reformer	58000	12	35	30.22	1.00	140000
Biomass gasifier	230000	18	33	54.34	0.77	606000

Table S5 | Operational data used for the techno-economic analysis.

Description	Unit	Value
Operating hours	h per yr	8000
Interest rate[43]	%	10
Loan payback period	yr	20
ACCR	-	0.12
CEPCI 2014[44]	-	576.1
CEPCI 2023[44]	-	800.8
Balance of plant (BOP)[41]	-	0.20
Indirect costs (IC)	-	0.32

4.2. Operational expenditure

Table S6 lists the feedstock and utility prices used to calculate the operational expenditure (OPEX) for each process. These include:

- Biomethane used as a carbon source in biogenic methanol production.
- Biomass converted to syngas through gasification.
- Hydrogen produced through PEM electrolysis, powered by renewable electricity from wind turbines.
- Natural gas as fossil feedstock, converted to syngas through steam methane reforming;
- CO_2 captured via direct air capture (DAC).
- Natural gas for process heating.
- Grid electricity used for all remaining power demand.

All utility and feedstock prices were taken from literature sources and reflect the best available data for the reference year 2025. Where applicable, price variability and future market trends were considered to define upper and lower bounds for each input. These bounds were subsequently used to capture uncertainty in the result for total cost and marginal cost of abatement (MCoA), as shown in a later section.

OPEX calculations included both variable costs, such as feedstocks, electricity, and other utilities and, fixed operational costs, such as labour, maintenance, and overheads. For the chemical and transport sectors, current (fossil-based) fuel and chemical product prices were used to benchmark against a methanol-based economy. These prices were sourced from recent market analyses and techno-economic studies, as listed in **Table S7**. Given the volatility of global markets, price fluctuations were accounted for by defining a baseline, high, and low scenario based on literature values for each commodity based on historic market prices. These were used to evaluate the sensitivity of the total system cost and the marginal cost of abatement to market dynamics, as discussed in the next section. While infrastructure and distribution costs were excluded from the calculations in this work, their potential influence was acknowledged in the broader discussion of system-level limitations (**Section 3** of the SI).

Table S6 | Data on feedstock and utilities cost, including upper and lower bounds.

Name	**Unit**	**Average**	**Lower**	**Upper**
Hydrogen[45]	USD per kg	3.500	2.400	4.600
DAC CO_2[45]	USD per kg	0.123	0.092	0.392
Biomethane[13]	USD per MMBtu	24.400	17.350	31.180
Biomass[46]	USD per tonne	200	100	300
Natural gas feedstock[47]	USD per MMBtu	10	2.5	18.5
Heating[48]	USD per GJ	3.500	1.750	5.250
Electricity[49]	USD per kWh	0.096	0.048	0.144

Table S7 | Business-as-usual market prices for chemicals and fuels in 2025.

Name	Unit	Average	Lower	Upper
Kerosene[50]	USD per litre	0.960	0.800	1.100
Diesel[51]	USD per litre	0.912	0.650	1.400
Shipping fuel[52]	USD per kg	0.533	0.400	0.650
Gasoline	USD per litre	0.920	0.670	1.320
Methanol[53]	USD per kg	0.550	0.350	0.780
Ethylene[54]	USD per kg	0.954	0.600	1.340
Propylene[55]	USD per kg	0.865	0.750	0.990
Benzene[56]	USD per kg	0.901	0.490	1.110
Toluene[57]	USD per kg	0.682	0.400	0.900
Xylene[58]	USD per kg	0.600	0.400	1.000

4.3. Total cost

Table S8 shows the total cost results of the methanol economy for the scenarios assumed in this work (biomass, biomethane, captured CO_2, fossil, and a bio+fossil). The total values in trillion USD per year were the resulting sum of CAPEX and OPEX. The variability in cost of the input parameters (see **Table S6**) allowed for a sensitivity analysis, shown in **Table S8** as the upper and lower bounds.

To contextualise the results of the methanol economy, the total current cost of the chemical and transport sectors was estimated using market prices for fuels and products, as listed in **Table S7**. This provided a baseline for a comparison with the projected costs of a methanol-based economy. Additionally, the cost of the technological roadmap aimed at achieving the Paris Agreement's 2 °C climate target was used as a reference point (refer to **Fig. S2**). The total global cost of meeting this target, as reported in the literature, was downscaled to the chemical and transport sectors using the gross value added (GVA) ratio of these sectors relative to total global GVA.[36] This proportional approach provided a benchmark cost of established climate strategies, as discussed earlier.

For the calculation of the monthly cost of these proposals per capita (**Fig. 6** in the main manuscript), the total cost was divided by the total global population as expected in 2050 (9.8 billion).[59] The cost of other technologies, services, and industrial policies were taken from literature and converted to a monthly cost using the same methodology.

Table S8 | Total cost results. Cost results for each methanol economy scenario, the current industries, and the cost of defossilising these industries to meet the targets set out in the Paris Agreement. All costs are reported in trillion USD per yr.

Scenario	**Average**	**Lower**	**Upper**
Biomethane	3.28	2.33	4.19
Biomass	1.93	0.96	2.88
CO_2	4.88	3.36	8.08
Fossil	1.34	0.34	2.49
Bio+CO_2	3.82	2.55	6.00
Bio+fossil	1.88	0.89	2.93
2025	2.62	1.86	3.75
2°C policies	2.39	1.80	2.98

4.4. Marginal cost of abatement

The final step of the analysis combined the outcomes of the life cycle assessment (LCA) and techno-economic assessment (TEA) in order to quantify the marginal cost of abatement (MCoA) for different sectors. This indicator allows for a direct comparison of decarbonisation potential and economic feasibility between fossil- and methanol-based alternatives. The MCoA was calculated according to **Equation S8**:

$$MCoA = \frac{C_{MeOH} - C_F}{E_F - E_{MeOH}} \qquad \text{(\textbf{Equation S8})}$$

where:

- C_F: current market cost of the fossil-based product or service (USD per unit);
- C_{MeOH}: equivalent cost under a methanol-based replacement (USD per unit);
- E_F: associated GHG emissions from current fossil-based operations (kg CO_2e per unit);
- E_{MeOH}: GHG emissions from methanol-based alternatives, accounting for production, use-phase, and residual impacts (kg CO_2e per unit).

This expression yields the cost per tonne of CO_2 equivalents (CO_2e) avoided and forms the basis for comparison across multiple use cases and end-use sectors. An MCoA below zero indicates that the methanol-based alternative is not only cleaner but also economically favourable under the given assumptions. Equal to the calculation of the environmental and economic results individually, three transition pathways to a methanol economy were evaluated:

- Biomethane-based methanol economy;
- Captured CO_2 utilisation-based methanol economy;
- Biomass-based methanol economy

Sector-specific MCoA values are provided in **Tables S9**, **S10**, and **S11** for each scenario. To address model uncertainty, a sensitivity analysis was performed. For these calculations, the upper and lower bounds of critical input parameters such as feedstock cost and energy price, as found in literature, were used. The corresponding variation in MCoA outcomes provided insights into the robustness of the economic-environmental trade-offs under alternative assumptions and policies. These results can be used to identify priorities for cost-effective decarbonisation through methanol substitution and to highlight the viability of different methanol production routes.

Table S9 | Marginal cost of abatement results for biomethane scenario. All abatement costs are reported in USD per ton CO_2e.

Name	Average	Lower	Upper
Chemicals	137.8	0.2	267.7
Shipping	372.0	169.7	573.8
Aviation	114.7	–26.4	257.1
Heavy duty trucks	–21.1	–244.9	130.7
Passenger cars	8.0	–88.36	81.6
Total	51.5	–72.6	150.4

Table S10 | Marginal cost of abatement results for captured CO_2 utilisation scenario. All abatement costs are reported in USD per ton CO_2e.

Name	Average	Lower	Upper
Chemicals	312.1	98.7	723.3
Shipping	817.6	440.6	1639.6
Aviation	348.8	109.5	848.9
Heavy duty trucks	99.1	–195.5	485.4
Passenger cars	70.5	–52.8	256.9
Total	144.5	–23.4	413.8

Table S11 | Marginal cost of abatement results for biomass scenario. All abatement costs are reported in USD per ton CO_2e.

Name	**Average**	**Lower**	**Upper**
Chemicals	13.6	–97.0	120.7
Shipping	99.6	–45.1	248.3
Aviation	–27.8	–139.2	87.7
Heavy duty trucks	–108.1	–298.3	23.6
Passenger cars	–44.5	–132.4	24.2
Total	–20.4	–128.6	67.9

5. Regional analysis of the methanol economy

This section provides additional context for the results presented in the main manuscript. Since all scenarios were evaluated at a global scale, potential regional differences, both in challenges and opportunities, may not have been fully captured. To address this, the analysis here focuses on the three largest economies: the United States, China, and the European Union, which currently account for approximately 16%, 18%, and 15% of global GDP, respectively.[60] This section presents an assessment of the regional bio-based methanol production potential, along with a regionalised life cycle analysis (LCA) based on the utilisation of each region's full bio-based potential.

5.1. Regional bio-based methanol potential

Table S12 presents the methanol production potential from biomass (agricultural and forestry residues) and biogas across the three regions and compares these values with the projected 2050 methanol demand in each region. The global 2050 methanol demand was allocated to the United States, China, and the European Union based on their expected shares of global GDP in 2025, as reported in the literature.[60]

The results indicate that the total availability of biogenic feedstocks across all three regions falls short of the corresponding scaled-down methanol demand. Therefore, in all three regions, a methanol-based economy cannot be established without incorporating CO_2-based pathways for methanol production.

Table S12 | Regional potential of biomass- and biogas- based methanol in the United States, China, and the European Union. The results are based on literature data, see **Table S2**. The values are reported in Mt per yr.

Type	**United States**	**European Union**	**China**
Biogas	113	253	268
Biomass	531	152	199
Total methanol demand	884	828	994

5.2. Regional climate change impacts of a methanol economy

Finally, regional LCA results were calculated under the assumption of full utilisation of bio-based methanol, with any remaining demand met through CO_2-based methanol. **Fig. S4** presents the current GHG emissions for the defined functional unit in each region, along with the projected emission reductions across sectors under a fully implemented methanol economy scenario.

The results reveal a consistent trend across all three regions, closely aligning with the global average. The most substantial emission reductions occur when fossil-fuel-based combustion engines in passenger cars and trucks are replaced with M100 engines. It should be noted that existing EV mandates in these regions will already accelerate the decarbonisation of these sectors. Nevertheless, the findings highlight the full potential of a methanol-based energy system, leveraging each region's bio-based resources while meeting residual demand through CO_2 utilisation pathways, to achieve near-net-zero GHG emissions across all assessed regions.

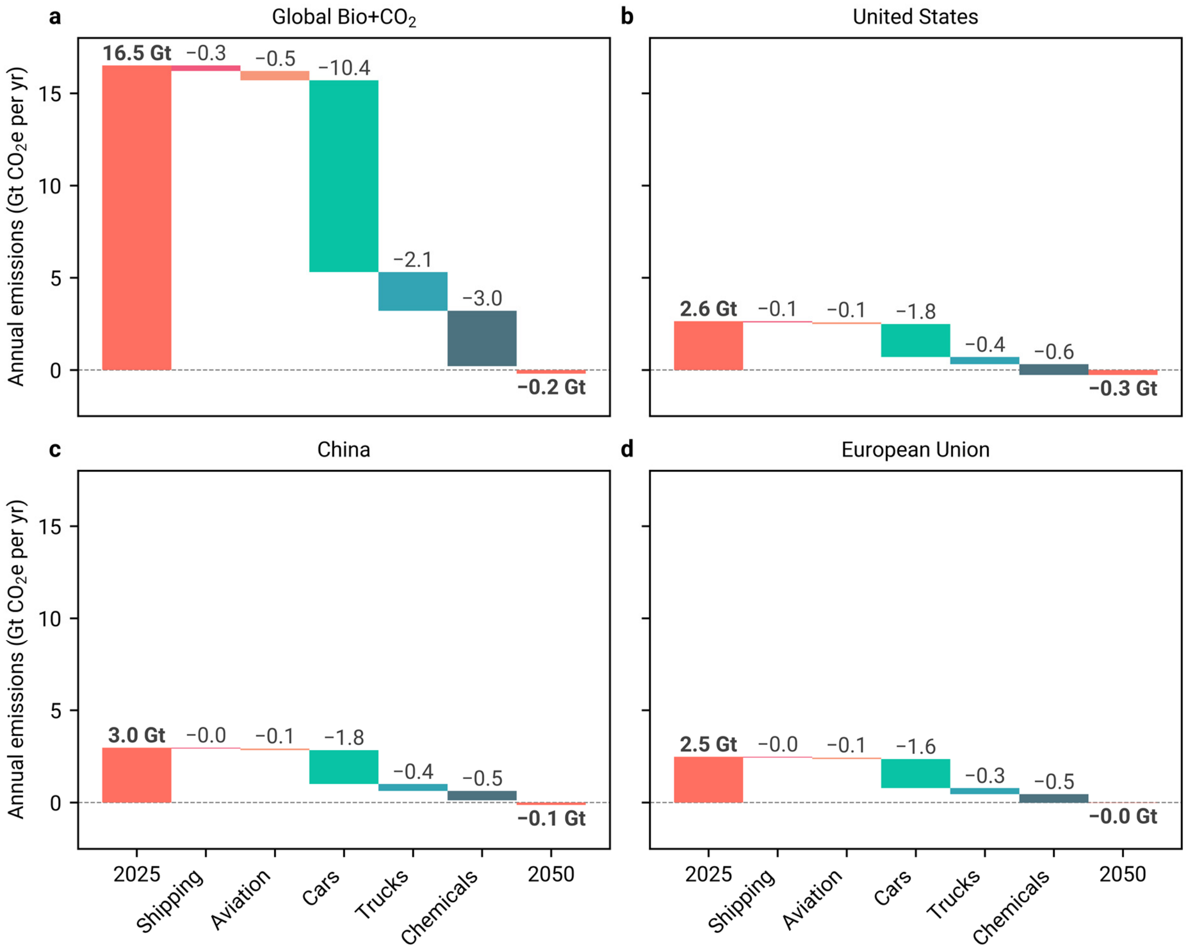

Fig. S4 | Regional climate change impacts. The results present the change in climate change impact derived from a regional LCA for a bio+CO_2 hybrid economy, based on the biogenic feedstock availabilities shown in **Table S12**, while the remaining demand is met through CO_2-based methanol. This analysis incorporates region-specific LCIs and adjusts methanol demand according to each region's projected contribution to global GDP in 2025.

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