



Universiteit
Leiden
The Netherlands

Prospecting urban mines of fossil fuel-based energy systems in the energy transition

Liang, Y.; Deetman, S.P.; Kleijn, E.G.M.; Wubs, T.; Vuuren, D.P. van; Daioglou, V.; Voets, E. van der

Citation

Liang, Y., Deetman, S. P., Kleijn, E. G. M., Wubs, T., Vuuren, D. P. van, Daioglou, V., & Voets, E. van der. (2025). Prospecting urban mines of fossil fuel-based energy systems in the energy transition. *Communications Earth & Environment*, 6.
doi:10.1038/s43247-025-02518-4

Version: Publisher's Version

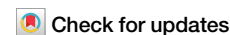
License: [Creative Commons CC BY-NC-ND 4.0 license](https://creativecommons.org/licenses/by-nc-nd/4.0/)

Downloaded from: <https://hdl.handle.net/1887/4287770>

Note: To cite this publication please use the final published version (if applicable).

<https://doi.org/10.1038/s43247-025-02518-4>

Prospecting urban mines of fossil fuel-based energy systems in the energy transition



Yanan Liang¹✉, Sebastiaan Deetman¹, René Kleijn¹, Thijs Wubs², Detlef P. van Vuuren^{3,4}, Vassilis Daioglou^{3,4} & Ester van der Voet¹

The ongoing energy transition from fossil fuels to renewables is increasing the demand for materials, particularly metals. As fossil fuel infrastructure, such as refineries, tankers, pipelines, and ships, is phased out, this obsolete infrastructure could serve as an urban mine, supplying secondary materials like steel, aluminium, and copper. However, the extent to which these materials can meet future needs remains unclear and is often overlooked. Here we develop the global dynamic fossil fuel material model to quantify material stocks embedded in fossil fuel infrastructure and project secondary material availability through 2050 under the Shared Socioeconomic Pathway 2 (SSP2) baseline and 2-degree Celsius (2D) scenarios. Our findings indicate that material demand for new infrastructure continues to grow under the baseline scenario and exceeds recoverable volumes. Even under the 2D scenario, the surplus of recovered metals remains insufficient to meet the growing material requirements of renewable energy technologies.

To prevent further deterioration of the global climate system, the transition of the energy system is becoming increasingly urgent. This transition requires phasing out fossil fuels^{1–5} and expanding sustainable energy sources such as solar and wind power^{6–9}. However, this transition has substantial material implications, as the demand for materials, especially metals, is expected to increase dramatically^{10–17}. A growing body of literature is dedicated to the material requirements of the renewable energy system, indicating that the demand for materials, especially major metals^{18–20} and critical materials^{13,21–24}. Ensuring a stable supply of these materials has become a growing priority for both governments and industries^{25–27}. Most previous studies have adequately considered and evaluated the materials needed to decarbonize electricity generation^{5,18,28–31} and transportation^{30,32–34}. However, less attention has been given to the fate of fossil fuel infrastructure under the energy transition. The phase-out of fossil fuels will not occur immediately³⁵, given their current 80% share of the global energy system³⁶, there will be a gradual shift toward renewables with a declining dependence on fossil fuels. This transition will not only affect fossil fuel demand but also reshape the material use associated with fossil fuel infrastructure, including extraction, processing, storage, and transport^{37–39}. In this study, “fossil fuel infrastructure” refers to physical assets across the fossil fuel supply chain, including coal mining infrastructure, oil and gas platforms,

refineries, gas processing plants, vehicles (e.g., trucks, trains, ships, and tankers), pipelines, and other related structures and equipment^{40–42}. A detailed classification of the infrastructure considered is provided in the Methods section (Fig. 1). Fossil fuel power plants are excluded, as their material composition and decommissioning have already been extensively studied^{30,43}.

Over the past century, a vast amount of fossil fuel infrastructure—including platforms, refineries, pipelines, ships, and tankers—has accumulated worldwide. As fossil fuels are phased out, these assets will become obsolete, making their embedded materials, particularly metals, available for reuse or recycling⁴⁴. However, the quantity, composition, and availability of these materials remain poorly understood.

Currently, there is limited information on the total stock of materials embedded in fossil fuel infrastructure, as well as the flows of new materials entering the system and waste materials leaving it. Furthermore, the impact of the energy transition on these material stocks and flows remains largely unexamined. Despite these knowledge gaps, gaining a deeper understanding of fossil fuel material dynamics could be highly valuable for policymakers and industry stakeholders. Effective decommissioning planning can not only facilitate material recycling and optimize resource allocation but also contribute to the energy transition by mitigating material demand through

¹Institute of Environmental Sciences (CML), Leiden University, Leiden, the Netherlands. ²Delft University of Technology, Delft, the Netherlands. ³PBL Netherlands Environmental Assessment Agency, The Hague, the Netherlands. ⁴Copernicus Institute of Sustainable Development, Utrecht University, Utrecht, the Netherlands.

✉ e-mail: y.liang@cml.leidenuniv.nl

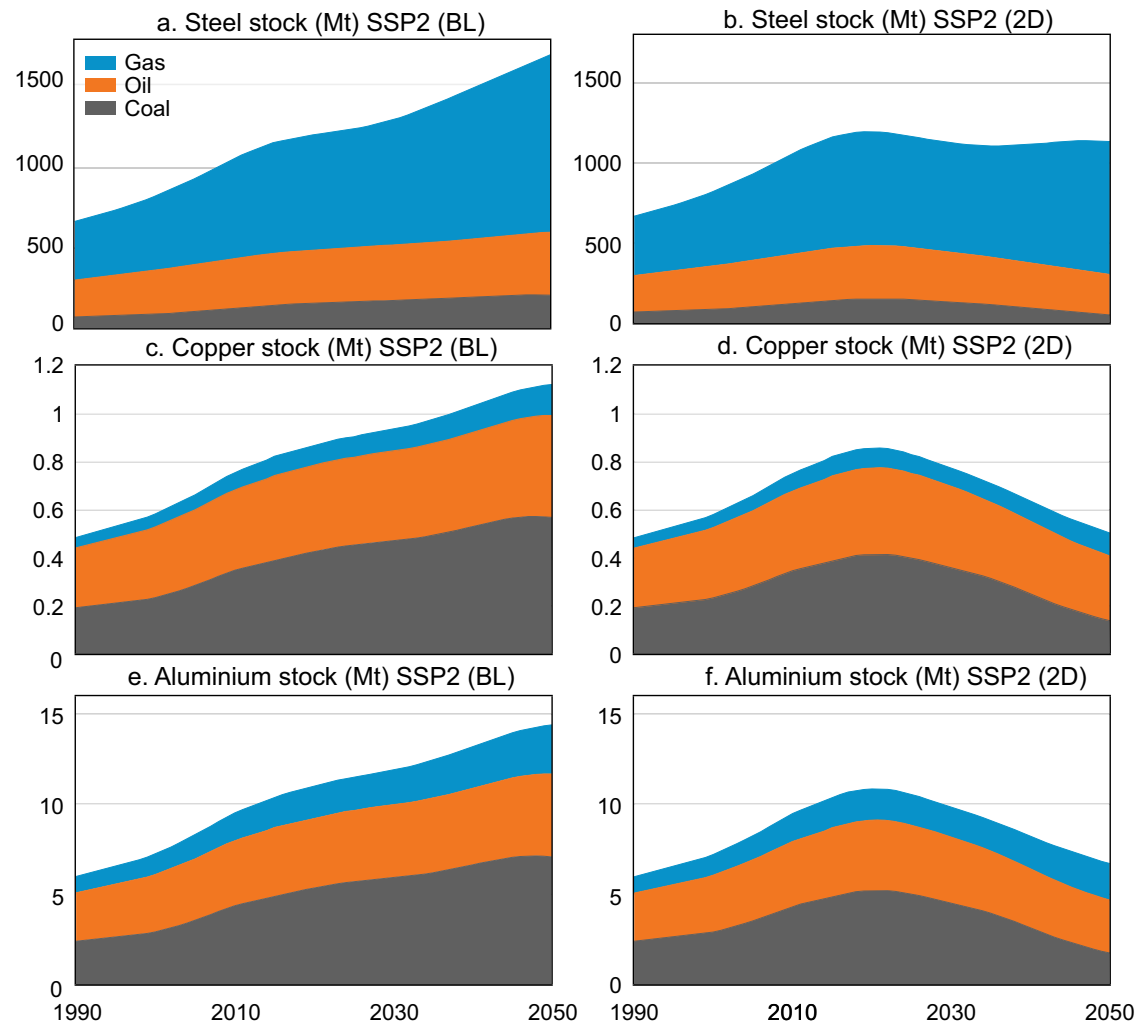


Fig. 1 | Global material stocks in fossil fuel infrastructure from 1990 to 2050 under SSP2(BL) and SSP2(2D) scenarios. The material stocks of steel (a, b), copper (c, d), and aluminium (e, f) are displayed under both the SSP2 (BL) and SSP2 (2D) scenarios.

the repurposing of materials from the existing fossil fuel system for diverse applications. At the very least, such assessments provide critical insights for enhancing global resource efficiency and advancing circular economy policies. To fill this gap, we developed a global dynamic fossil fuel material model (FUMA). It allows for incorporating material-energy feedback into Integrated Assessment Models (IAM), such as the Integrated Model to Assess the Global Environment (IMAGE). The implementation of this model will allow us to assess the dynamics of material stocks and flows within the fossil fuel infrastructure and examine its interaction effect with changes in fossil energy demand. Our analysis aims (1) to quantify the global stock of three major metals (steel, copper, and aluminium) embedded in the fossil fuel infrastructure, (2) to understand the dynamics of material inflows and outflows related to this stock, and (3) to assess the potential of these materials to mitigate the energy transition's material needs. We compare a baseline scenario with a climate scenario, assuming an energy transition in line with the 2-degree Celsius (2D) target as agreed on in the Paris Agreement⁴⁵, based on the IMAGE Shared Socioeconomic Pathway 2 (SSP2)⁴⁶.

Results

Material stock patterns in the development of fossil fuel infrastructure

The material stocks and their development until 2050 in the fossil fuel infrastructure are presented in Fig. 1. Steel is a critical component of all fossil fuel infrastructure. Specifically, the steel stock measured in megatons is

projected to grow. The steel stocks are three orders of magnitude larger than aluminium and copper stocks (For the detailed composition of the individual element stocks in the various infrastructures, please refer to Supplementary Fig. 7).

Under the SSP2(BL) scenario, the steady growth in fossil fuel demand drives a continuous increase in material stocks until 2050, reaching approximately 1700 Mt for steel, 14 Mt for aluminium, and 1.1 Mt for copper. Meanwhile, under the SSP2(2D) scenario, fossil fuel infrastructure stocks were projected to peak around 2022 before gradually declining. This decline is mainly due to a decrease in stocks associated with coal and oil infrastructure. In the SSP2(2D) scenario, natural gas is assumed to serve as a transitional energy source between coal and renewables. This leads to a substantial increase in gas-related infrastructure stocks, particularly for steel (Fig. 1b).

Corresponding to the total stocks, Fig. 2 details the relative share of steel, copper, and aluminium in the global fossil fuel infrastructure. The stock of steel in 2050 in the 2D scenario is slightly above its 2019 value, while the total stock of copper and aluminium shrinks by ~30% compared to 2019. Notably, in 2019, 60% of steel stocks are gas-related, which will further rise to 65% (SSP2(BL)) and 73% (SSP2(2D)) in 2050. Gas pipelines account for most of the steel stock (~70%) in gas-related infrastructure. Unlike steel, the stocks of copper and aluminium are primarily linked to vehicles (trucks, rail cargo and especially ships), with the share of coal stocks currently surpassing those of gas and oil.

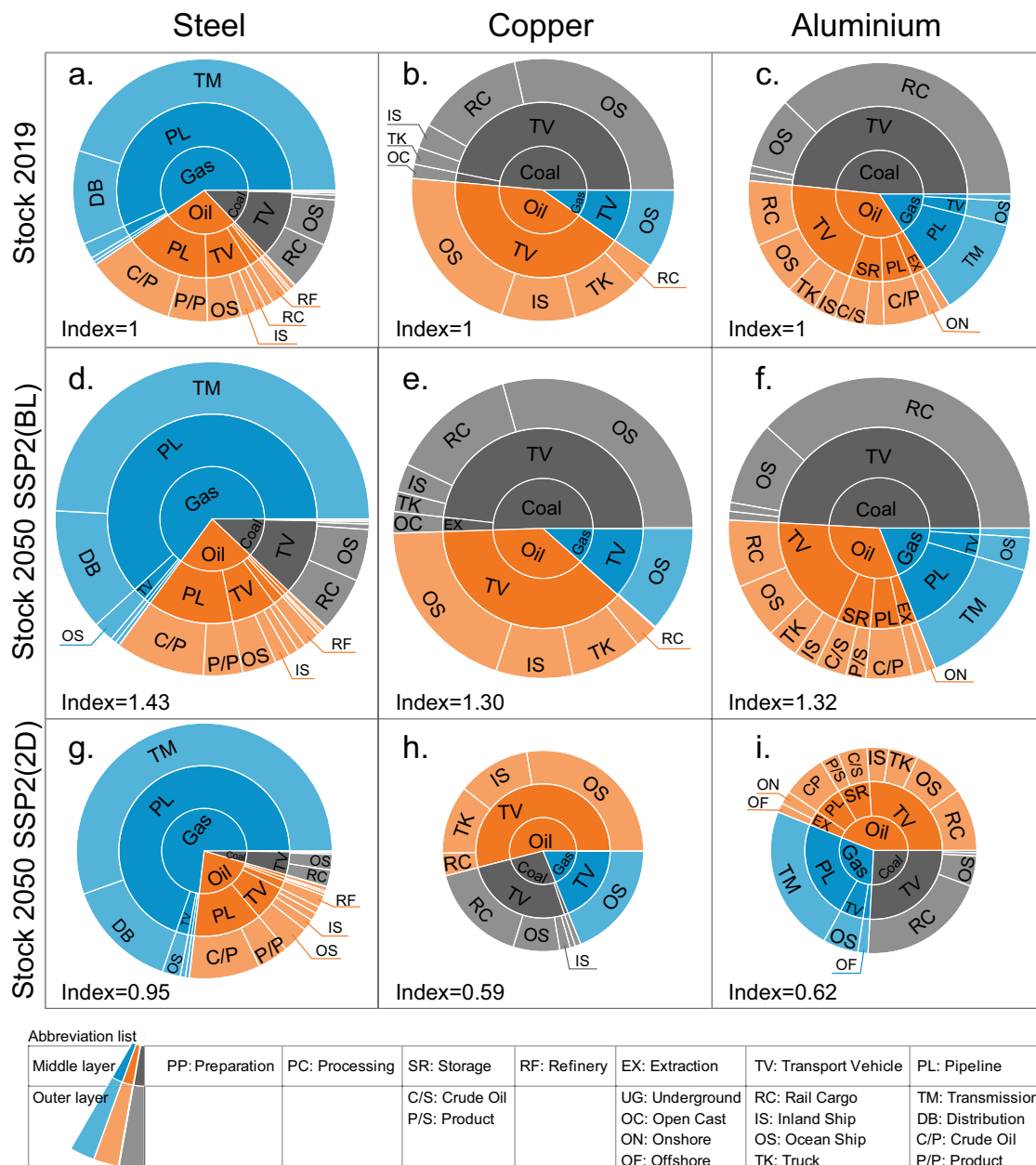


Fig. 2 | Breakdown of material stocks in different fossil fuel infrastructure.

Breakdown of material stocks in different fossil fuel infrastructures in the base year (a–c), the year 2050 under SSP2(BL) (d–f) and SSP2(2D) (g–i) scenarios. Circle areas represent the size of the corresponding material stock. The base year stocks of steel (a), copper (b), and aluminium (c) are set with the index to 1 (stock for 2019 = 1). The inner layer of each circle shows the distribution of material stocks for coal (gray), oil (orange), and natural gas (blue). The middle layer represents the infrastructure

for different phases of each fossil fuel type (including extraction, industrial handling, vehicles, and pipelines). The outer layer represents the subtypes for various infrastructure elements (e.g., offshore/onshore extraction, transmission/distribution gas pipelines, rails/trucks/inland/ocean ships, oil storage, refineries, etc.). Only the major composition elements ($\geq 1\%$) of the infrastructure stock as shown in the figure. The full information is provided in Supplementary Table 12.

The future is expected to witness an upward trajectory of gas-related transportation material stocks, driven by the growing trade volume of liquid natural gas (LNG). The trade of LNG is already increasing, reaching a level comparable to that of gaseous natural gas by 2022⁴⁷. This trend is expected to continue in both SSP2(BL) and SSP2(2D)⁴⁸. For steel, the share of gas in total fossil fuel infrastructure will grow in both scenarios, but most in the SSP2(2D) scenario.

The share of oil increases in both scenarios for copper as well as for aluminium. In absolute terms (Fig. 1), the amounts will grow in the SSP2(BL) scenario but go down under SSP2(2D) assumptions. This indicates that coal is expected to be rapidly phased out and switched to natural gas.

Material requirements, outflows, and surplus

Figure 3 depicts the material demand (inflows) and discarded materials (outflows), which could be regarded as potential secondary material supply under the two scenarios. Here, we present an in-depth examination of these trends, highlighting noteworthy observations regarding the inflows and outflows.

- In both scenarios, the material demand for fossil fuel infrastructure remains substantial through 2050. Under the SSP2(BL) scenario, it continues to grow, whereas in the SSP2(2D) scenario, it declines but remains considerable. The reduction in CO₂ emissions in SSP2(2D) assumes a large-scale deployment of Carbon Capture and Storage (CCS), supporting the continued use of fossil fuel infrastructure.

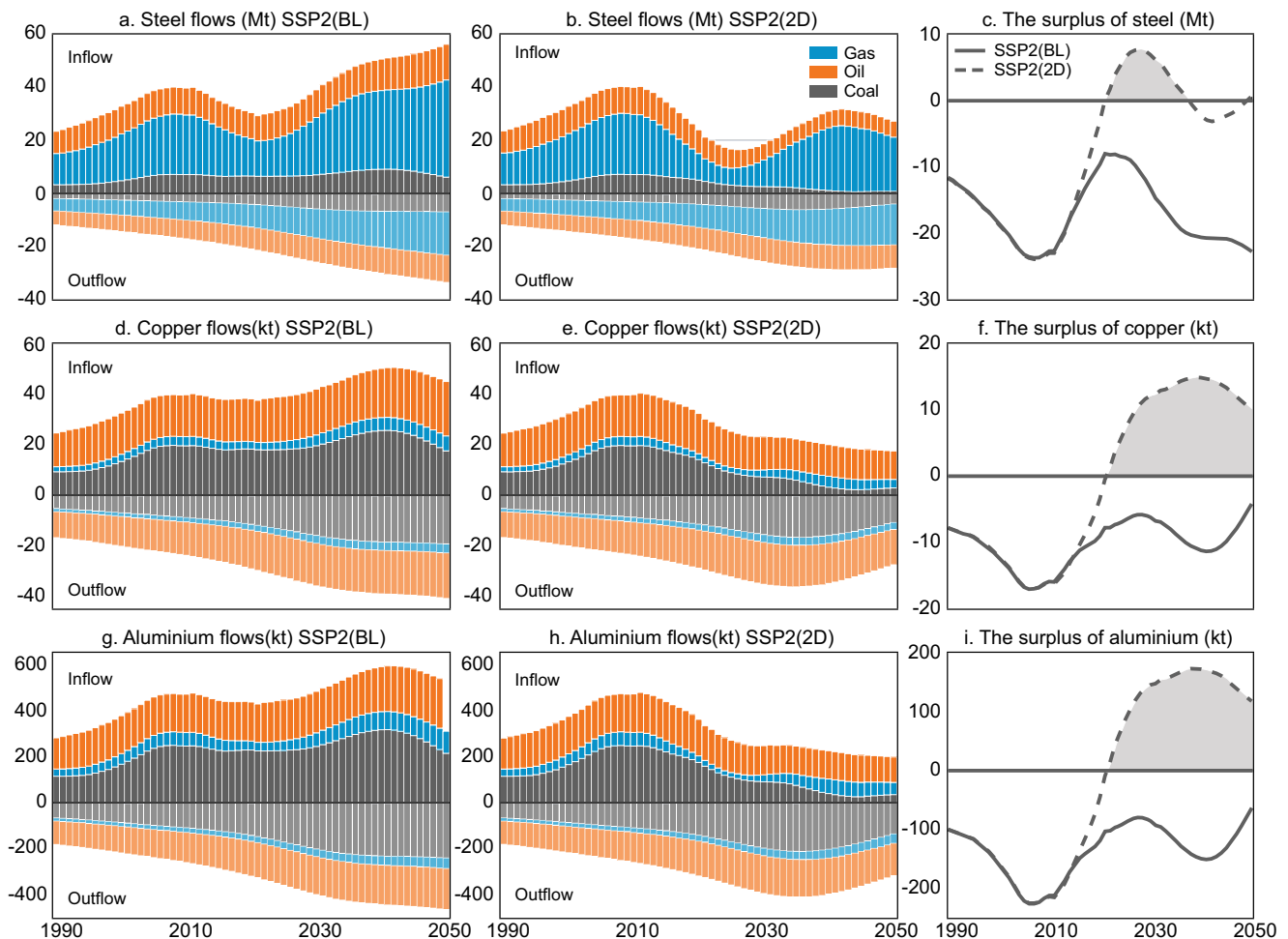


Fig. 3 | Global material flows and the material surplus in fossil fuel infrastructure during 1980–2050 under SSP2(BL) and SSP2(2D) scenarios. The material flows of steel (a, b), copper (d, e), and aluminium (g, h), along with their corresponding

surpluses (c, f, i), are shown. Surplus is defined as the difference between outflows and inflows within the same year, where positive values in the shaded areas indicate that outflows exceed inflows.

Additionally, further adding capital and material stocks used for those CCS installations, as covered by the analysis on material use for electricity generation²⁸.

- The SSP2(BL) scenario fossil fuel system requires more materials than SSP2(2D). The outflows remain smaller than the inflows throughout the whole assessment period. Even assuming all the waste materials will be recycled and used in the same applications, an inflow of virgin materials in the fossil fuel infrastructure is still needed.
- Under the SSP2(2D) scenario, demand for both copper and aluminium peaked around 2022 and then gradually declined. At the same time, these materials will generate annual surpluses until 2050. The cumulative surplus of copper (2022–2050) is ~340 kilotons, which is comparable to the global copper demand for electric vehicles in 2022⁴⁹. Unlike copper and aluminium, steel is expected to experience only a brief surplus before demand rises again after 2030.
- The gas industry will still require an increasing inflow of materials even under SSP2(2D), particularly for the construction of new pipelines, which rely heavily on steel. Over 90% of the cumulative gas-related steel demand from 2020 to 2050 is seen in pipelines. The cumulative demand for steel in natural gas pipelines between 2020 and 2050 is greater than the cumulative steel demand of the coal and oil industries combined over the same period.

Therefore, the availability of secondary materials from the end-of-life fossil fuel infrastructure remains limited in both scenarios until 2050, minimizing its potential contribution to future material demand.

Discussion

Our findings indicate that global stocks of coal-related materials will decline, while stocks of natural gas-related materials will continue to increase until 2050. This shift in material stocks reflects the ongoing transition towards a more sustainable energy landscape. While natural gas has been viewed as a transition fuel due to its lower carbon emissions compared to coal⁵⁰, its continued expansion may slow the decarbonization of energy systems⁵¹. In addition to methane leaks from gas infrastructure^{52–56}, dependence on natural gas infrastructure may create a lock-in effect^{57–59}, where entrenched investments and infrastructure hinder the transformation to renewable energy systems. The phasing out of fossil infrastructure will not advance far enough by 2050 to become a major source of secondary materials. Under SSP2(BL) assumptions, material stock will continue to grow, requiring more materials rather than supplying them. SSP2(2D) scenario, copper and aluminium stocks decline, making some materials available for recycling. However, the projected surplus (outflow minus inflow) in 2050 is only 10 kt of copper and 108 kt for aluminium. When compared to the material demands of renewable energy systems, this volume is marginal: it could supply only 8% of the global aluminium demand and 0.8% of the global copper demand required for wind and solar PV deployment under the SSP2-2D scenario²⁸. In comparison, under the International Energy Agency's (IEA) Net-Zero Emissions scenario, this surplus would meet only 0.2% of the projected 2050 copper demand for these technologies⁶⁰.

Compared to the material demands of renewable energy technologies, the recoverable materials from end-of-life fossil fuel infrastructure are

limited, as demonstrated in our analysis. Additionally, technical constraints further restrict the potential of decommissioned fossil fuel infrastructure in supplying secondary materials. Material losses during collection and recycling, along with technical recycling rates, influence overall material availability^{61–63}. Unlike copper and aluminium, which can be recycled without substantial loss of quality, steel recycling is often constrained by variations in alloy composition and the lack of detailed chemical data, which hinder large-scale recycling efforts⁶⁴. Most steel undergoes a downcycling process, meaning it often fails to meet specifications for high-performance applications due to alloying elements, corrosion, and strength limitations^{65,66}. However, it remains a valuable secondary resource that can be recycled and repurposed for various applications in the global market, contributing to the broader circular economy.

The recyclability of fossil fuel infrastructure varies across different components. Above-ground infrastructure, such as ships and trains, is generally easier to recycle than underground pipelines. Decommissioned underground gas pipelines often remain as hibernating stock without entering the recovery process^{67,68}. Similarly, onshore infrastructure is typically easier to recycle than offshore installations^{69,70}. Offshore structures also require sacrificial anodes made of zinc and/or magnesium, which corrode over time due to seawater exposure and cannot be recycled. Even for the same metal, recycling availability varies widely depending on its form, quality, and location, factors that warrant further investigation.

Certain limitations must be acknowledged. The fossil fuel demand projections used in this analysis are based on IMAGE model data accessed as of January 2024⁴⁶ and subsequent updates are not reflected here. However, the FUMA model framework allows for the integration of the latest data inputs as needed.

Additionally, fossil fuel infrastructure in the real world is more complex than the model assumptions. Some facilities might be co-used by multiple sectors, making their material stocks difficult to attribute to the fossil fuel sector fully. In this study, refineries, processing plants, storage facilities, and pipelines are assumed to be used exclusively for fossil fuels. In reality, some of these assets could be repurposed for biofuels⁷¹, hydrogen⁷², or other industrial applications. For transport vehicles, material stocks are estimated based on the relationship between fossil fuel transport demand and vehicle material stock weight. Here, we assume that all transport materials are exclusively used for fossil fuel transportation. Vehicles used for gas and oil transport are specifically designed to withstand hazardous conditions, including high pressure, flammability, and contamination risks, making repurposing for other types of transportation significantly more challenging⁷³. Additionally, strict safety regulations, material compatibility concerns, and the need for extensive decontamination further restrict their potential for reuse outside the fossil fuel sector^{74,75}. However, some transport vehicles, particularly those used for coal transport, may be repurposed for other energy sectors or general freight.

Beyond recycling, repurposing fossil fuel infrastructure presents an alternative pathway. One example is converting decommissioned gas pipelines into hydrogen pipelines^{72,76,77}, which could extend the lifetime of certain infrastructure while supporting the clean energy transition.

However, notable challenges remain due to the distinct properties of hydrogen compared to natural gas, including issues like steel embrittlement and leak detection, which are not investigated in this study^{78,79}. Further research is needed to determine viable pipeline components for repurposing, along with appropriate technologies and costs. Moreover, repurposing comes with trade-offs, as it may delay material recovery through recycling. A careful evaluation of material efficiency and long-term sustainability is essential to balance these approaches⁸⁰.

Ultimately, a substantial amount of material will continue to be required for fossil fuel infrastructure through 2050 under both the SSP2(BL) and SSP2(2D) scenarios. This indicates that much of the material embedded in fossil fuel infrastructure will remain in use and unavailable as a secondary resource during this period. Therefore, accelerating the transition to renewable energy and reducing fossil fuel dependence could not only

decrease the demand for new fossil infrastructure but also improve the availability of secondary materials within the system.

Methods

System definition

FUMA is one of the dynamic MFA modules attached to the IMAGE model⁴⁶ used to support climate policies^{81,82}. Similar models have been developed for buildings^{83,84}, for the electricity system²⁸, and vehicles⁸⁵. These models are summarized as IMAGE-MAT⁸⁶, use socio-economic and technological information from the IMAGE model and translate that in several steps to material flows and stocks. FUMA does the same for the fossil fuel infrastructure.

The main novelty of FUMA is the incorporation of the IAM, such as IMAGE, into the dynamic MFA model. We use the material-specific data for fossil fuel infrastructure and make the connection with the fossil fuel demand projections from IMAGE. We employ FUMA to assess the use of several major metals: steel, copper, and aluminium. This study covers the main stages of the fossil fuel supply chain, from extraction and industrial processing to distribution^{40,41}. Figure 4 provides a schematic overview of the modelling approach and system boundaries, where the dashed box represents the excluded processes, and the solid boxes indicate the included system components. Specific modelling steps and components are detailed in the Supplementary Method.

Model description

The analysis presented is based on the FUMA model framework, which starts with a base year (2019) of fossil fuel demand and proceeds to calculate the required scale and functioning of operational infrastructure (including extraction, industrial processing, and transport) to meet that demand.

A linear scaling approach is applied to project fossil fuel use in two scenarios from the IMAGE model, deriving the required global infrastructure stocks over time. Subsequently, by employing stock-driven modelling routines^{85,87,88}, FUMA translates IMAGE's projected fossil fuel demand data⁸¹ into a demand for in-use infrastructure stock. This process enables the production of new infrastructure and the demolition of obsolete infrastructure. Additionally, it involves creating connections with materials intensity data and involving the normally distributed lifetime functions, enabling the calculation of materials stock and flow.

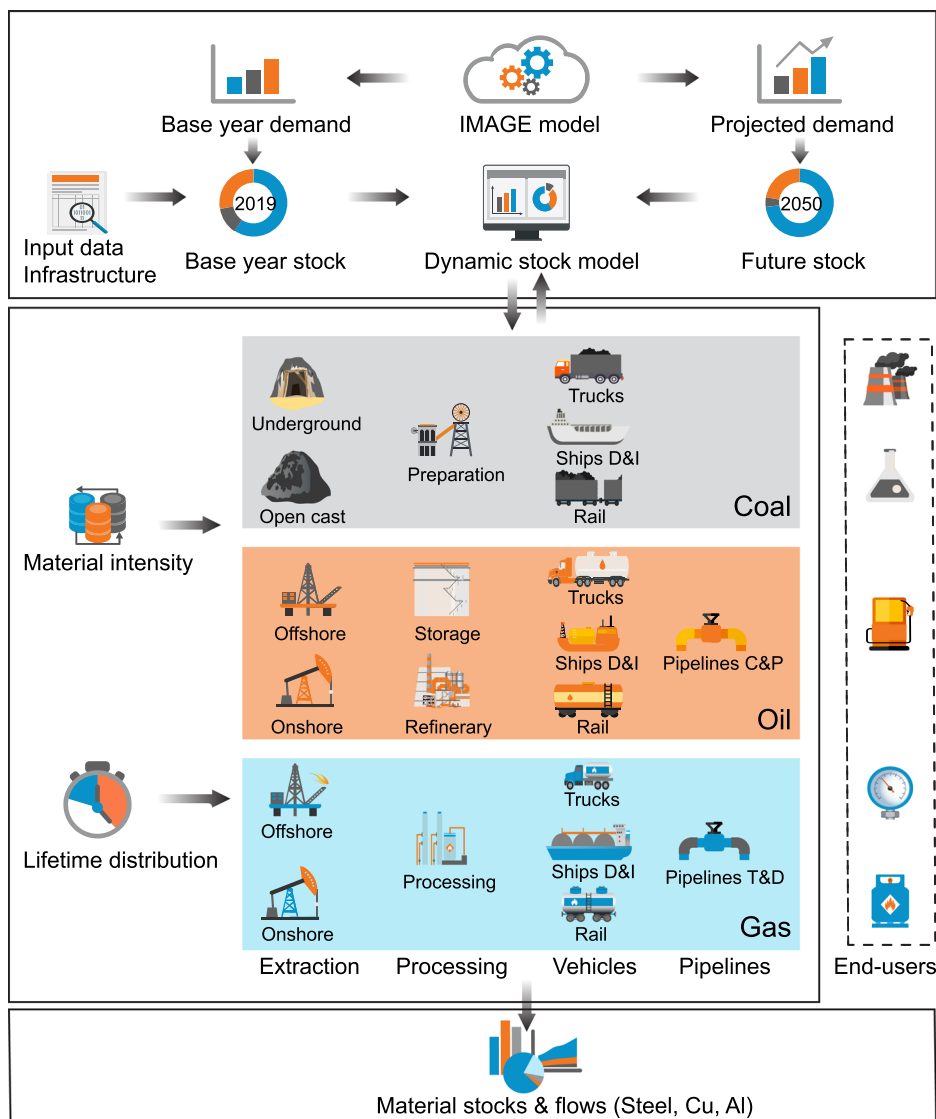
Scenario construction

The annual fossil fuel demand under different scenarios was derived from the IMAGE model⁸¹. We present a baseline scenario (BL) that is consistent with the “Middle of the Road (Medium challenges to mitigation and adaptation)” second shared socioeconomic pathway (SSP2) - SSP2(BL), which describes a development consistent with intermediate challenges for both adaptation and mitigation^{82,89,90}. Besides, to examine the impacts on fossil fuel material demand under different climate targets, we compared the SSP2(BL) scenario with a programmed mitigation pathway that meets the target of limiting global warming to below 2-degree above pre-industrial levels, still in line with SSP2: the SSP2(2D) scenario. We divided the final energy categories into eleven direct fossil fuel end-users. The related Sankey diagrams and interpretations to elaborate on this allocation are included in Supplementary Fig. 6.

Base year and future material stock and flow calculation

We access the material composition data and the lifetime data for the fossil fuel infrastructure from the background reports of Ecoinvent3.8⁹¹. The base year data of fossil fuel demand is sourced from IMAGE. These datasets are used to calculate material intensity per unit of activity across different stages of the fossil fuel supply chain, such as fuel extraction, gas processing, and refining. Additionally, we derive the transport stock demand for fossil fuels in the base year by combining the transport turnover demand (ton-kilometer per unit of fossil fuel, tkm/kg or tkm/m³) with data on the weight of different transport vehicle modes. This allows us to estimate the total

Fig. 4 | System definition of the global fossil fuel infrastructure and the framework of FUMA. D&I domestic and international transport, C&P crude oil and products, T&D transmission and distribution.



transport demand weight across various vehicle types⁸⁵. Next, we determine the stock of materials in the vehicles based on the fraction of the weight of materials in the different vehicles⁸⁵. In addition, for oil and gas, we calculate the pipeline stock in kilometers of pipeline length in the base year, 2019. This includes categorized length calculations for natural gas transmission and distribution pipelines and crude oil and petroleum product pipelines. (Supplementary Tables 9 and 10). To eliminate the geographical mismatch of energy production and consumption, the base year fossil fuel infrastructure stocks have been redistributed based on the regional share of global fossil fuel demand so that final fossil fuel consumption drives the requirement for fossil fuel infrastructure elements.

From the base year infrastructure stock and the projected energy demand in IMAGE⁴⁶, we then derived the fossil fuel infrastructure stock yearly. The dynamics of fossil fuel infrastructure using a stock-driven approach are based on references^{85,87,88}. We assess the demolition from the existing fossil fuel infrastructure stock using a lifetime model based on documented lifetime distributions⁹². Then, the construction can be calculated using the basic mass balance (inflow = outflow + Δ stock). Using material intensity data for specific infrastructure elements, we calculate the corresponding material flows and stocks. A detailed description of the model, the data used, and assumptions, as well as numerical results, is provided in the Supplementary Methods.

Data availability

The project energy demand data under different climate scenarios are sourced from the IMAGE model: <https://www.pbl.nl/en/image/data>. The processed data used to generate the figure are available at Zenodo via the following link: <https://zenodo.org/records/15072780>.

Code availability

The scripts and data used to run the FUMA model are available on Zenodo: <https://zenodo.org/records/15072780>.

Received: 11 October 2024; Accepted: 26 June 2025;

Published online: 08 July 2025

References

- Welsby, D., Price, J., Pye, S. & Ekins, P. Unextractable fossil fuels in a 1.5 °C world. *Nature* **597**, 230–234 (2021).
- Trout, K. et al. Existing fossil fuel extraction would warm the world beyond 1.5 °C. *Environ. Res. Lett.* **17**, 064010 (2022).
- van Asselt, H. & Newell, P. Pathways to an International Agreement to Leave Fossil Fuels in the Ground. *Glob. Environ. Politics* **22**, 28–47 (2022).
- Gielen, D. et al. World energy transitions outlook: 1.5 °C pathway. (2021).

5. Grubert, E. Fossil electricity retirement deadlines for a just transition. *Science* **370**, 1171–1173 (2020).
6. Cherp, A., Vinichenko, V., Tosun, J., Gordon, J. A. & Jewell, J. National growth dynamics of wind and solar power compared to the growth required for global climate targets. *Nat. Energy* **6**, 742–754 (2021).
7. Wang, Y. et al. Accelerating the energy transition towards photovoltaic and wind in China. *Nature* **619**, 761–767 (2023).
8. Goldschmidt, J. C., Wagner, L., Pietzcker, R. & Friedrich, L. Technological learning for resource efficient terawatt scale photovoltaics. *Energ. Environ. Sci.* <https://doi.org/10.1039/d1ee02497c> (2021).
9. Pryor, S. C., Barthelmie, R. J., Bukovsky, M. S. & Leung, L. R. Climate change impacts on wind power generation. *Nat. Rev. Earth Environ.* **1**, 627–643 (2020).
10. World Bank Group. *The Growing Role of Minerals and Metals for a Low Carbon Future*. world Bank <https://doi.org/10.1596/28312> (2017).
11. Graedel, T. E., Harper, E. M., Nassar, N. T. & Reck, B. K. On the materials basis of modern society. *Proc. Natl. Acad. Sci. USA* **112**, 6295–6300 (2015).
12. Gielen, D. & Lyons, M. Critical materials for the energy transition. *Technical paper. IRENA (International Renewable Energy Agency)* (2021).
13. IEA. *The Role of Critical Minerals in Clean Energy Transitions*. IEA <https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions/executive-summary> (2021).
14. Wang, P., Wang, H., Chen, W.-Q. & Pauliuk, S. Carbon Neutrality Needs a Circular Metal-Energy Nexus. *Fundamental Res.* <https://doi.org/10.1016/J.FMRE.2022.02.003> (2022).
15. Herrington, R. Mining our green future. *Nat. Rev. Mater.* **6**, 456–458 (2021).
16. Gielen, D. & Lyons, M. *Critical Materials for the Energy Transition: Rare Earth Elements* (2022).
17. Raw materials for a truly green future. *Nat. Rev. Mater.* **6**, 455–455 (2021).
18. Liang, Y., Kleijn, R., Tukker, A. & van der Voet, E. Material requirements for low-carbon energy technologies: A quantitative review. *Renew. Sustain. Energy Rev.* **161**, 112334 (2022).
19. Lennon, A., Lunardi, M., Hallam, B. & Dias, P. R. The aluminium demand risk of terawatt photovoltaics for net zero emissions by 2050. *Nat. Sustain.* <https://doi.org/10.1038/s41893-021-00838-9> (2022).
20. Limited quantity and quality of steel supply in a zero-emission future | Nature Sustainability. <https://www.nature.com/articles/s41893-022-01025-0>.
21. Wang, P. et al. Critical mineral constraints in global renewable scenarios under 1.5 °C target. *Environ. Res. Lett.* **17**, 125004 (2022).
22. WWF. Critical materials for the transition to a 100 % sustainable energy future contents. **76** (2014).
23. Olivetti, E. A., Ceder, G., Gaustad, G. G. & Fu, X. Lithium-Ion Battery Supply Chain Considerations: Analysis of Potential Bottlenecks in Critical Metals. *Joule* **1**, 229–243 (2017).
24. Liang, Y., Kleijn, R. & van der Voet, E. Increase in demand for critical materials under IEA Net-Zero emission by 2050 scenario. *Appl. Energy* **346**, 121400 (2023).
25. Sprecher, B. & Kleijn, R. Tackling material constraints on the exponential growth of the energy transition. *One Earth* **4**, 335–338 (2021).
26. Lee, J. et al. Reviewing the material and metal security of low-carbon energy transitions. *Renew. Sustain. Energy Rev.* **124**, 109789 (2020).
27. Nassar, N. T. et al. Evaluating the mineral commodity supply risk of the U.S. manufacturing sector. *Sci. Adv.* **6**, eaay8647 (2020).
28. Deetman, S., de Boer, H. S., Van Engelenburg, M., van der Voet, E. & van Vuuren, D. P. Projected material requirements for the global electricity infrastructure – generation, transmission and storage. *Resour., Conserv. Recycling* **164**, 105200 (2021).
29. Li, F., Ye, Z., Xiao, X., Xu, J. & Liu, G. Material stocks and flows of power infrastructure development in China. *Resour., Conserv. Recycling* **160**, 104906 (2020).
30. Kalt, G., Thunshirn, P., Krausmann, F. & Haberl, H. Material requirements of global electricity sector pathways to 2050 and associated greenhouse gas emissions. *J. Clean. Prod.* **358**, 132014 (2022).
31. Wang, S. et al. Future demand for electricity generation materials under different climate mitigation scenarios. *Joule* <https://doi.org/10.1016/j.joule.2023.01.001> (2023).
32. Carmona, L. G., Whiting, K., Haberl, H. & Sousa, T. The use of steel in the United Kingdom's transport sector: A stock–flow–service nexus case study. *J. Ind. Ecol.* **25**, 125–143 (2021).
33. Greim, P., Solomon, A. A. & Breyer, C. Assessment of lithium criticality in the global energy transition and addressing policy gaps in transportation. *Nat. Commun.* **11**, 1–11 (2020).
34. Baars, J., Domenech, T., Bleischwitz, R., Melin, H. E. & Heidrich, O. Circular economy strategies for electric vehicle batteries reduce reliance on raw materials. *Nat. Sustain.* **4**, 71–79 (2021).
35. World Energy Investment 2022 – Analysis. IEA <https://www.iea.org/reports/world-energy-investment-2022>.
36. IEA. *World Energy Outlook* (2022).
37. Le Boulzec, H. et al. Dynamic modeling of global fossil fuel infrastructure and materials needs: Overcoming a lack of available data. *Appl. Energy* **326**, 119871 (2022).
38. Smith, C. J. et al. Current fossil fuel infrastructure does not yet commit us to 1.5 °C warming. *Nat. Commun.* **10**, 1–10 (2019).
39. Fricaudet, M., Prakash, V., Sohm, S., Smith, T. & Rehmatulla, N. Fossil fuel carrying ships and the risk of stranded assets (2024).
40. Coburn, T. C. Oil and Gas Infrastructure. *The Oxford Handbook of Energy Politics* 98–124 <https://doi.org/10.1093/oxfordhb/9780190861360.013.2> (2021).
41. American Petroleum Institute. Natural Gas Infrastructure. <https://www.api.org/news-policy-and-issues/natural-gas-solutions/natural-gas-infrastructure> (2025).
42. EIA. Coal mining and transportation. <https://www.eia.gov/energyexplained/coal/mining-and-transportation.php> (2025).
43. Kalt, G. et al. Material stocks in global electricity infrastructures – An empirical analysis of the power sector's stock-flow-service nexus. *Resour., Conserv. Recycling* **173**, 105723 (2021).
44. Griffiths, S., Sovacool, B. K., Kim, J., Bazilian, M. & Uratani, J. M. Decarbonizing the oil refining industry: A systematic review of sociotechnical systems, technological innovations, and policy options. *Energy Res. Soc. Sci.* **89**, 102542 (2022).
45. Adoption of the Paris Agreement. Proposal by the President. | UNFCCC. <https://unfccc.int/documents/9064>.
46. PBL. The 2021 SSP scenarios of the IMAGE 3.2 model. PBL Netherlands Environmental Assessment Agency <https://www.pbl.nl/en/publications/the-2021-ssp-scenarios-of-the-image-32-model> (2021).
47. Statistical Review of World Energy | Energy economics | Home. bp global <https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html>.
48. Sarraf, D. & Dale, S. B. P. *Energy Outlook* (2023).
49. IEA. Critical Minerals Data Explorer. <https://www.iea.org/data-and-statistics/data-tools/critical-minerals-data-explorer> (2023).
50. Bistline, J. E. T. & Young, D. T. The role of natural gas in reaching net-zero emissions in the electric sector. *Nat. Commun.* **13**, 4743 (2022).
51. Kemfert, C., Präger, F., Braunger, I., Hoffart, F. M. & Brauers, H. The expansion of natural gas infrastructure puts energy transitions at risk. *Nat. Energy* **7**, 582–587 (2022).
52. Omara, M. et al. Methane emissions from US low production oil and natural gas well sites. *Nat. Commun.* **13**, 2085 (2022).
53. Zimmerle, D. J. et al. Methane emissions from the natural gas transmission and storage system in the United States (File

- Modeling_EST_Suppl_Info_-_Final3b.docx) S1 1 Supporting Information for 2 Methane emissions from the natural gas transmission and storage system in the.
54. Alvarez, R. A. et al. Assessment of methane emissions from the U.S. oil and gas supply chain. *Science* **361**, 186–188 (2018).
 55. Balcombe, P., Brandon, N. P. & Hawkes, A. D. Characterising the distribution of methane and carbon dioxide emissions from the natural gas supply chain. *J. Clean. Prod.* **172**, 2019–2032 (2018).
 56. Gordon, D. et al. Evaluating net life-cycle greenhouse gas emissions intensities from gas and coal at varying methane leakage rates. *Environ. Res. Lett.* **18**, 084008 (2023).
 57. Davis, S. J., Caldeira, K. & Matthews, H. D. Future CO₂ Emissions and Climate Change from Existing Energy Infrastructure. *Science* **329**, 1330–1333 (2010).
 58. Pfeiffer, A., Hepburn, C., Vogt-Schilb, A. & Caldecott, B. Committed emissions from existing and planned power plants and asset stranding required to meet the Paris Agreement. *Environ. Res. Lett.* **13**, 054019 (2018).
 59. Yang, S., Hastings-Simon, S. & Ravikumar, A. P. Pipeline Availability Limits on the Feasibility of Global Coal-to-Gas Switching in the Power Sector. *Environ. Sci. Technol.* **56**, 14734–14742 (2022).
 60. IEA. *Global Critical Minerals Outlook 2024*. <https://www.iea.org/reports/global-critical-minerals-outlook-2024> (2024).
 61. Raabe, D., Tasan, C. C. & Olivetti, E. A. Strategies for improving the sustainability of structural metals. *Nature* **575**, 64–74 (2019).
 62. Manager. Recycling Rates of Metals (2017).
 63. Reck, B. K. & Graedel, T. E. Challenges in Metal Recycling. *Science* **337**, 690–695 (2012).
 64. Mulvaney, D. et al. Progress towards a circular economy in materials to decarbonize electricity and mobility. *Renew. Sustain. Energy Rev.* **137**, 110604 (2021).
 65. Helbig, C. et al. A terminology for downcycling. *J. Ind. Ecol.* **26**, 1164–1174 (2022).
 66. Watari, T., Hata, S., Nakajima, K. & Nansai, K. Limited quantity and quality of steel supply in a zero-emission future. *Nat. Sustain* **6**, 336–343 (2023).
 67. Global socioeconomic material stocks rise 23-fold over the 20th century and require half of annual resource use. <https://www.pnas.org/doi/10.1073/pnas.1613773114>.
 68. Streeck, J., Wiedenhofer, D., Krausmann, F. & Haberl, H. Stock-flow relations in the socio-economic metabolism of the United Kingdom 1800–2017. *Resour., Conserv. Recycling* **161**, 104960 (2020).
 69. Sommer, B. et al. Decommissioning of offshore oil and gas structures – Environmental opportunities and challenges. *Sci. Total Environ.* **658**, 973–981 (2019).
 70. Melbourne-Thomas, J. et al. Decommissioning Research Needs for Offshore Oil and Gas Infrastructure in Australia. *Front. Mar. Sci.* **8**, 711151 (2021).
 71. Su, J., van Dyk, S. & Saddler, J. Repurposing oil refineries to “stand-alone units” that refine lipids/oleochemicals to produce low-carbon intensive, drop-in biofuels. *J. Clean. Prod.* **376**, 134335 (2022).
 72. Jayanti, S. E.-P. Repurposing pipelines for hydrogen: Legal and policy considerations. *Energy Rep.* **8**, 815–820 (2022).
 73. Pharris, T. & Kolpa, R. *Overview of the Design, Construction, and Operation of Interstate Liquid Petroleum Pipelines*. (2008).
 74. IMO. *Fourth IMO GHG Study 2020 Full Report* (2021).
 75. Mokhtab, S., Mak, J. Y., Valappil, J. V. & Wood, D. A. *Handbook of Liquefied Natural Gas*. (Gulf Professional Publishing, 2013).
 76. Potential role of natural gas infrastructure in China to supply low-carbon gases during 2020–2050 - ScienceDirect. <https://www.sciencedirect.com/science/article/pii/S0306261921012927>.
 77. Lipiäinen, S., Lipiäinen, K., Ahola, A. & Vakkilainen, E. Use of existing gas infrastructure in European hydrogen economy. *Int. J. Hydrogen Energy* (2023) <https://doi.org/10.1016/j.ijhydene.2023.04.283>.
 78. Raj, A. et al. Evaluating hydrogen gas transport in pipelines: Current state of numerical and experimental methodologies. *Int. J. Hydrog. Energy* **67**, 136–149 (2024).
 79. Télesy, K., Barner, L. & Holz, F. Repurposing natural gas pipelines for hydrogen: Limits and options from a case study in Germany. *Int. J. Hydrog. Energy* **80**, 821–831 (2024).
 80. Invernizzi, D. C. et al. Developing policies for the end-of-life of energy infrastructure: Coming to terms with the challenges of decommissioning. *Energy Policy* **144**, 111677 (2020).
 81. Stehfest, E., van Vuuren, D., Bouwman, L. & Kram, T. *Integrated Assessment of Global Environmental Change with IMAGE 3.0: Model Description and Policy Applications*. (Netherlands Environmental Assessment Agency (PBL), 2014).
 82. Riahi, K. et al. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Glob. Environ. Change* **42**, 153–168 (2017).
 83. Deetman, S. et al. Modelling global material stocks and flows for residential and service sector buildings towards 2050. *J. Clean. Prod.* **245**, 118658 (2020).
 84. Marinova, S., Deetman, S., van der Voet, E. & Daioglou, V. Global construction materials database and stock analysis of residential buildings between 1970–2050. *J. Clean. Prod.* **247**, 119146 (2020).
 85. Deetman, S. P. Stock-driven scenarios on global material demand: the story of a lifetime. (Leiden University, 2021).
 86. United Nations Environment Programme, I. R. P. Global Resources Outlook 2024 - Bend the trend: Pathways to a Liveable Planet as Resource Use Spikes (2024).
 87. Pauliuk, S. & Heeren, N. ODYM-An open software framework for studying dynamic material systems Principles, implementation, and data structures. <https://doi.org/10.1111/jiec.12952>.
 88. Deetman, S., Pauliuk, S., Van Vuuren, D. P., Van Der Voet, E. & Tukker, A. Scenarios for Demand Growth of Metals in Electricity Generation Technologies, Cars, and Electronic Appliances. *Environ. Sci. Technol.* **52**, 4950–4959 (2018).
 89. harrisson, thomas. Explainer: How ‘Shared Socioeconomic Pathways’ explore future climate change. *Carbon Brief* <https://www.carbonbrief.org/explainer-how-shared-socioeconomic-pathways-explore-future-climate-change/> (2018).
 90. Fricko, O. et al. The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century. *Glob. Environ. Change* **42**, 251–267 (2017).
 91. Wernet, G. et al. The ecoinvent database version 3 (part I): overview and methodology. *Int. J. Life Cycle Assess.* **21**, 1218–1230 (2016).
 92. Müller, E., Hilty, L. M., Widmer, R., Schluep, M. & Faulstich, M. Modeling Metal Stocks and Flows: A Review of Dynamic Material Flow Analysis Methods. *Environ. Sci. Technol.* **48**, 2102–2113 (2014).

Acknowledgements

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 101056868. Yanan Liang would like to thank the China Scholarship Council (No. 201908510229).

Author contributions

Y.L. wrote the original draft, conducted data collection, contributed to the development and design of the methodology, software, and code, performed formal analysis and data visualization, and revised the manuscript. S.D. contributed to the conceptualization of the study, contributed development and design of the methodology, software, and code, provided input on data visualization, and edited and reviewed the manuscript draft. R.K. participated in the conceptualization of the study, provided input on data visualization, edited and reviewed the manuscript draft, and supervised Y.L. T.H. assisted with data collection, methodology development, and contributed to the code. D.V. and V.D. provided the IMAGE data and modelling resources and contributed to the explanation of

the database. E.V. participated in the conceptualization of the study and methodology design, provided input on visualization, edited and reviewed the manuscript draft, and supervised Y.L.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at

<https://doi.org/10.1038/s43247-025-02518-4>.

Correspondence and requests for materials should be addressed to Yanan Liang.

Peer review information *Communications Earth & Environment* thanks Jordan Calderon, Sherif Khalif and the other, anonymous, reviewer(s) for their contribution to the peer review of this work. Primary Handling Editors: Sadia Ilyas and Martina Grecequet. [A peer review file is available].

Reprints and permissions information is available at <http://www.nature.com/reprints>

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by-nc-nd/4.0/>.

© The Author(s) 2025