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Transitioning Away from Oil, with Oil: Quantifying Embedded Oil Demand in the Net-Zero Transition

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Abstract

The prevailing narrative of a net-zero energy system assumes retreat from hydrocarbons. Yet a central paradox remains underexplored: the very technologies designed to displace oil are themselves deeply dependent on it. Renewable energy systems and electric vehicles depend, directly or indirectly, on oil and oil-based products across their supply chain, from extraction and processing to manufacturing. This creates a structural contradiction—oil demand declines in combustion but rises in material form.

We quantify this embedded oil demand using material flow analysis linked to net-zero deployment pathways. Under current production processes, global oil requirements associated with these technologies increase from approximately 2.8 million barrels per day today to around 12 million barrels per day by 2050. A substantial share of this demand is attributable to oil-based materials, particularly petroleum coke and petrochemicals, which are used in critical supply chains for steel, aluminum, silicon, and battery materials. These results indicate a structural shift in oil demand from combustion toward material embedding, suggesting that oil use persists in reconfigured forms even in net-zero energy systems. Explicitly accounting for these material requirements provides a more comprehensive representation of oil demand in energy transition pathways.

Keywords

Oil demand; energy transition; critical minerals;

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Introduction

The global transition away from oil and towards a net-zero emissions (NZE) energy system, driven by the mass deployment of renewable energy and electric vehicles (EVs),[1-3] presents a structural paradox: technologies designed to reduce reliance on fossil fuels require oil-derived inputs for their production and deployment.[4] This raises a broader systems question as the material requirements of the transition may influence the trajectory of non-energy oil demand even in fully decarbonized energy scenarios. In this paper, we examine how oil is utilized across the supply chains of key renewable energy and electric vehicle (EV) technologies and estimate how these requirements scale under net-zero deployment scenarios.

The transition to NZE energy systems is typically modeled as a structural decline in fossil fuel demand. Integrated assessment models (IAMs) and energy system scenarios consistently project substantial reductions in oil consumption, primarily by displacing its role as a fuel in transport, heat, and power generation[1,5-6]. However, these frameworks predominantly treat oil as an energy carrier, while its role as a material feedstock in industrial supply chains is less thoroughly investigated. For instance, oil demand associated with petrochemical and carbon-based inputs in clean energy supply chains is not directly linked to technology deployment in most modeling frameworks.[7-8] As a result, current projections of declining oil demand may not fully reflect the material requirements associated with large-scale deployment of energy transition technologies. In particular, the contribution of oil as a material input is not systematically represented in most energy system projections. This may limit the ability of these models to fully characterize future oil demand and its role in the supply chains of the technologies needed for the energy transition. This has implications for how future energy systems are characterized, particularly in assessing the role of hydrocarbons in large-scale technology deployment.

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A growing body of literature has shown that the energy transition will be considerably more material-intensive than the system it replaces (particularly during the build-out phase)[9-10]. The focus of these studies has generally been on the critical mineral intensity and the potential requirements of the large capacities of renewable electricity generation, electric transportation, and energy storage technologies required for the transition.[11-17] Yet, while these studies quantify the metals required to construct energy transition technologies and systems, they have given comparatively little attention to the role of fossil-derived materials, such as petrochemicals, plastics, and carbon-based intermediates. This is despite the importance of these materials to the production of renewable energy technologies and electric vehicles.[18-22] This raises the question of whether current transition pathways fully capture the extent of hydrocarbon use embedded in these systems. This question has generally been examined from a qualitative perspective, with to date little quantitative research on the question of the volume of hydrocarbons required to produce net-zero energy systems[23-28].

To address this gap, we examine how oil requirements embedded in the supply chains of energy transition technologies scale to system-level demand under net-zero deployment scenarios[29]. We define 'embodied oil' as the total volume of crude oil required across the full supply chain of these technologies. This includes its use as (i) a feedstock for petrochemicals and carbon materials, (ii) an energy source for industrial processes such as heat and transport, and (iii) an indirect input embedded in intermediate materials. Using a bottom-up material flow analysis (MFA) linked to scenario-level deployment pathways, we estimate oil requirements associated with the large-scale deployment of these technologies. This approach complements existing modeling frameworks by explicitly accounting for oil use embedded within material supply chains. Hence, this study provides a framework for explicitly representing oil use as both an energy carrier and a material feedstock within net-zero energy scenarios. In doing so we provide contributions to the literature in two key areas: we provide a quantitative framework for better understanding the size and scope of the

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hydrocarbon industry that will be required to facilitate the creation of a net-zero energy system; and we extend quantitative material analysis of the deployment of renewable energy and electric vehicles (EVs), beyond critical minerals, focusing on oil and petrochemicals as inputs to the myriad of product supply chains required for these technologies.

Results

Across the analyzed technologies and scenarios, three key findings emerge. First, a substantial share of oil demand is embedded in material supply chains rather than direct energy use. Second, petroleum coke constitutes a dominant input across multiple critical materials, particularly in silicon, aluminum, and battery anode production. Third, when scaled to net-zero deployment pathways, these embedded requirements translate into a persistent level of oil demand at the system level, despite the phase-out of oil as a fuel.

Embodied oil requirements for Solar PV. Under current production pathways, solar PV manufacturing requires approximately 900 barrels of embodied oil per MW of installed capacity (Fig. 1a). Most of the embodied oil is used for PV panel production (74%), predominantly in silicon manufacturing for wafers. Oil-based materials are required for the fabrication of silicon carbide and silicon metal, as well as for wafer production itself. 12% of embodied oil is associated with the mounting system, with the vast majority embedded in aluminum production and smaller flows embedded in steel and copper.

Approximately 57% of the embodied oil in solar PV production is utilized in oil-based products (e.g., petroleum products, petrochemicals, and plastics), either used directly or in the manufacturing of other material inputs. A total of 23% is required for other supply chains that were not disaggregated into how oil is specifically used (and therefore is spread over a wide range of inputs - see Methods), ranging from nitrogen to tap water, while 4% is currently used in transport, 10% for electricity, and 3%

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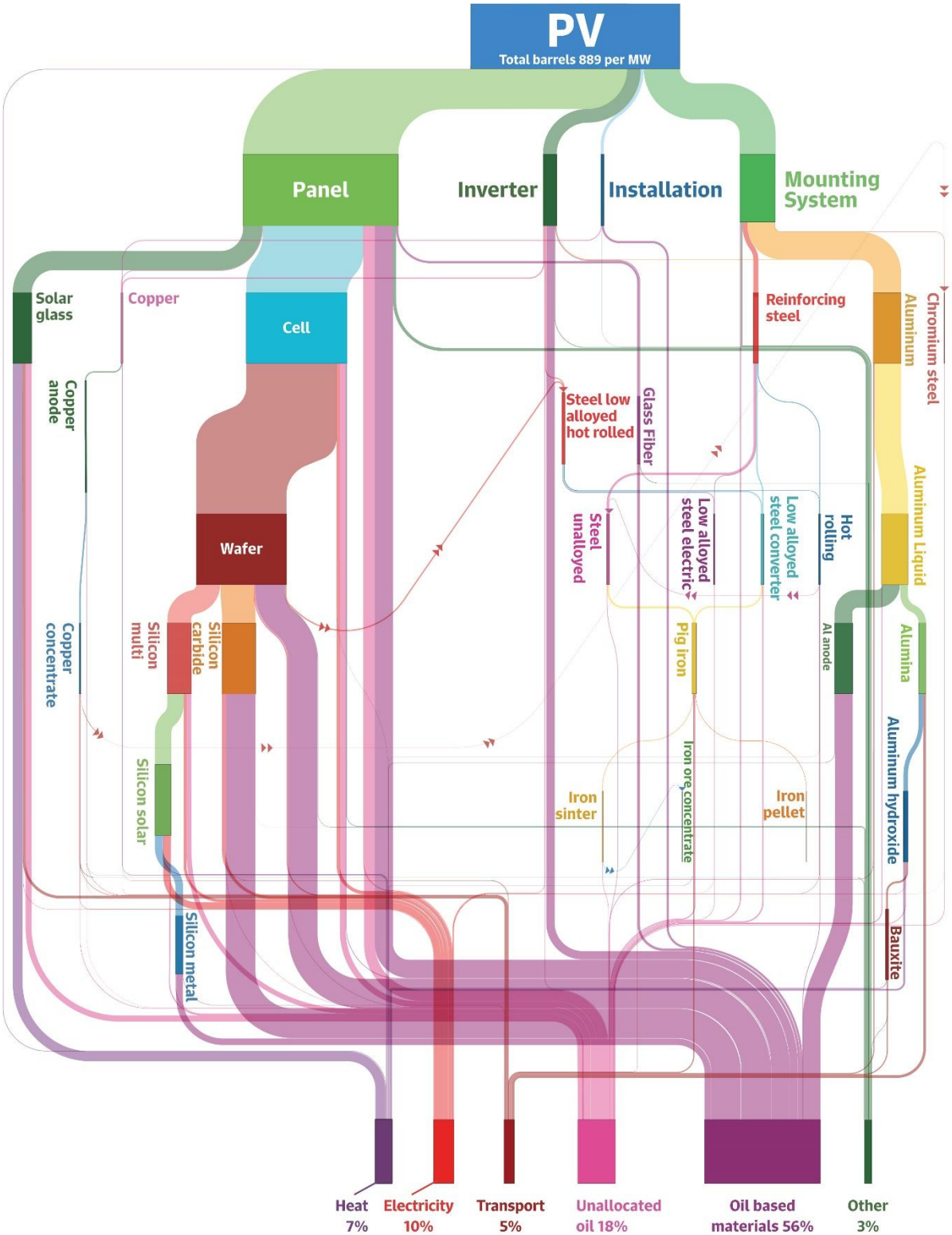
for heat (with the caveat that much of this could change with broader movements away from fossil-fuel usage in these sectors). The remaining 3% is required for physical infrastructure, such as the PV panel and cell factories. In a broader sense, much of this embodied oil requirement is likely to be in other supply chains (such as steel, concrete, and aluminum) for the construction of this infrastructure. However, the supply chains for infrastructure were not further disaggregated.

Further separating the oil-based materials required for solar PV production (Fig. 1b) shows that the largest required share is for petroleum coke (42%). It is used as a reducing agent in the production of silicon carbide and silicon metal for silicon wafers used in PV panels. In addition, it is a key input to anodes used in aluminum production and is generally used for panel mounting systems. Lubricating oil is required for the inverter, and pitch is used in the production of aluminum anode. Petrochemicals such as triethylene glycol, alkylbenzene sulfonate, and dipropylene glycol monomethyl ether are used in silicon wafer production, while isopropanol is used in cell manufacturing. Around a quarter of the oil-based materials are in the form of plastics used to encapsulate and protect the cells (ethyl vinyl acetate), as well as in materials used for handling and storage in wafer production (polyethylene and polystyrene) and in the panel backsheet (polyvinyl fluoride).

This highlights that solar PV deployment is particularly dependent on oil-based material inputs, with petroleum coke playing a central role in both silicon and aluminum supply chains.

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114 (a)



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(b)

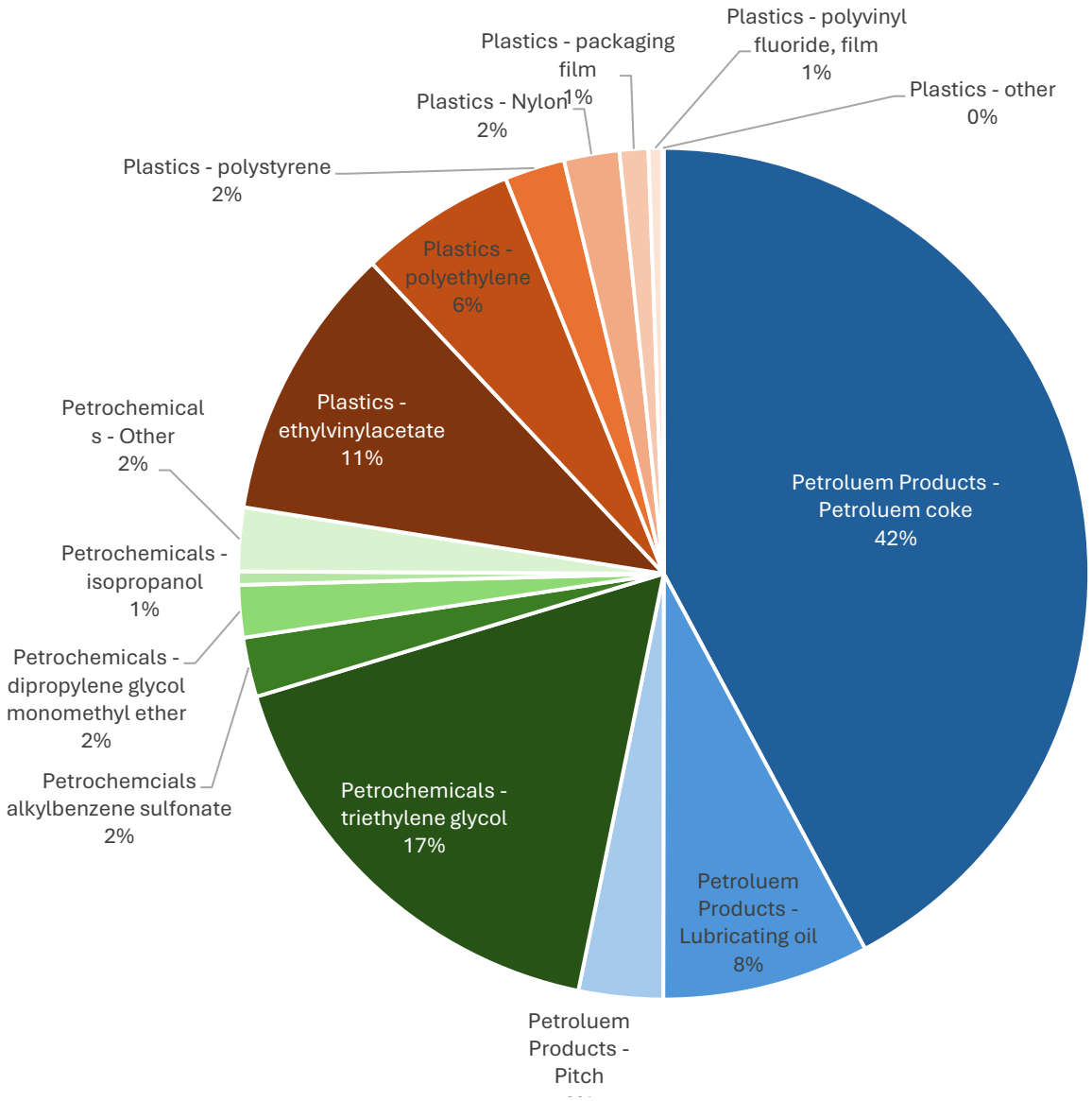


Figure 1 (a): Flow of oil through the supply chain of materials for solar PV (b) Disaggregation of oil-based materials for Solar PV

(a) shows the flow of oil through the supply chain of materials to produce a Solar PV plant (Full details on the specifications of the plant are given in *Supplementary Material*). The size of the arrows shows the scale of embodied oil. Embodied Oil is disaggregated by production stage and through ten material supply-chains before being tracked down to six specific uses:

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heat, electricity, transport, oil-based materials, other and unallocated oil. The scope of each of these categorioes is given in *Methods*.

(b) splits the embodied oil required in the form of oil-based materials for a Solar PV plant into specific products, grouped into three main categories: Petroluem Products (blue), Plastics (orange) and Petrochemicals (green).

Embodied oil requirements for Wind Turbines. Under current production pathways, wind turbine manufacture and installation require approximately 590 barrels of embodied oil per MW. The flow of oil in wind turbine production includes infrastructure for both turbine components and network connections. The majority of embodied oil (around 92%) is used in the construction of the turbine, with only a small share in network connections. The largest oil requirement is embedded in the concrete required for the wind turbines (32%) (Fig. 2a), followed by the fiberglass used in the wind turbine blades (16%), and then in road construction (15%) (based on the assumed road requirement reported by Ecoinvent), steel manufacture (14%), epoxy used in blade manufacture (7%), and copper (7%).

For wind turbines, a smaller share of embodied oil use is in oil-based materials (34%) than for solar PV. In contrast, a larger share is currently used for transportation (24%), chiefly in the supply chain for concrete (41% of transportation needs, with additional requirements for sand and gravel used in its manufacture) due to the weight and volume of the transported material. 21% of embodied oil occurs in supply chains that were not further disaggregated. 10% is required for heat or direct energy use (mainly in clinker production within the concrete supply chain and in road construction), with 6% used for electricity generation and 5% for other infrastructure and processes.

Plastics account for the largest share (45%) of oil-based materials – chiefly, nylon (39%) used in fiberglass production for turbine blades, along with polyethylene, PVC, and synthetic rubber (Fig. 2b). Petroleum products are the next largest (36%), including bitumen (for road construction) and lubricating oil (predominantly in the network connection). Petrochemicals account for the remaining

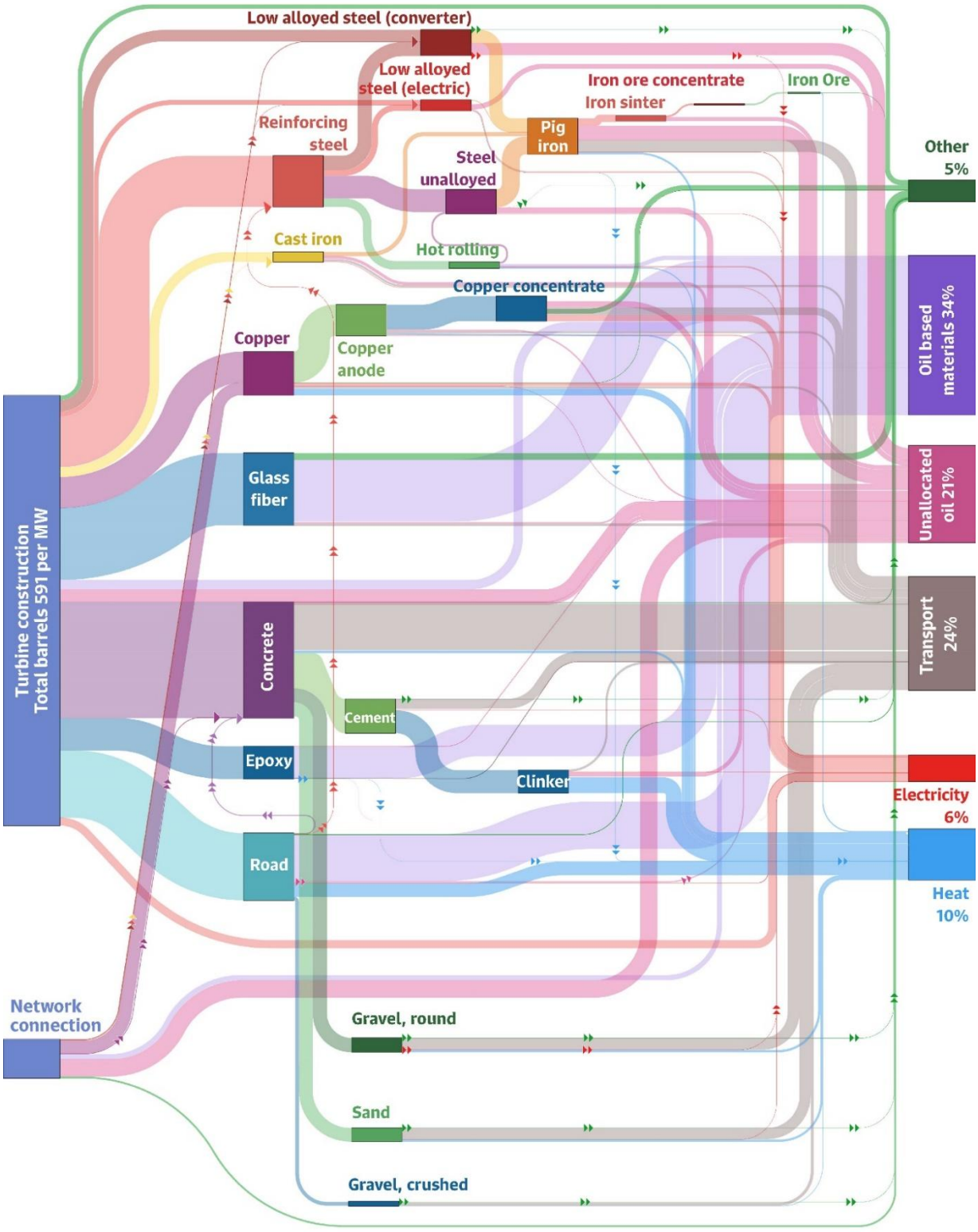
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20%, mostly in the manufacture of epoxy for wind turbine blades (bisphenol and epichlorohydrin). In contrast to solar PV, wind turbine deployment relies more heavily on oil use in transportation and bulk materials such as concrete, reflecting differences in supply chain structure and material intensity.

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(a)



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(b)

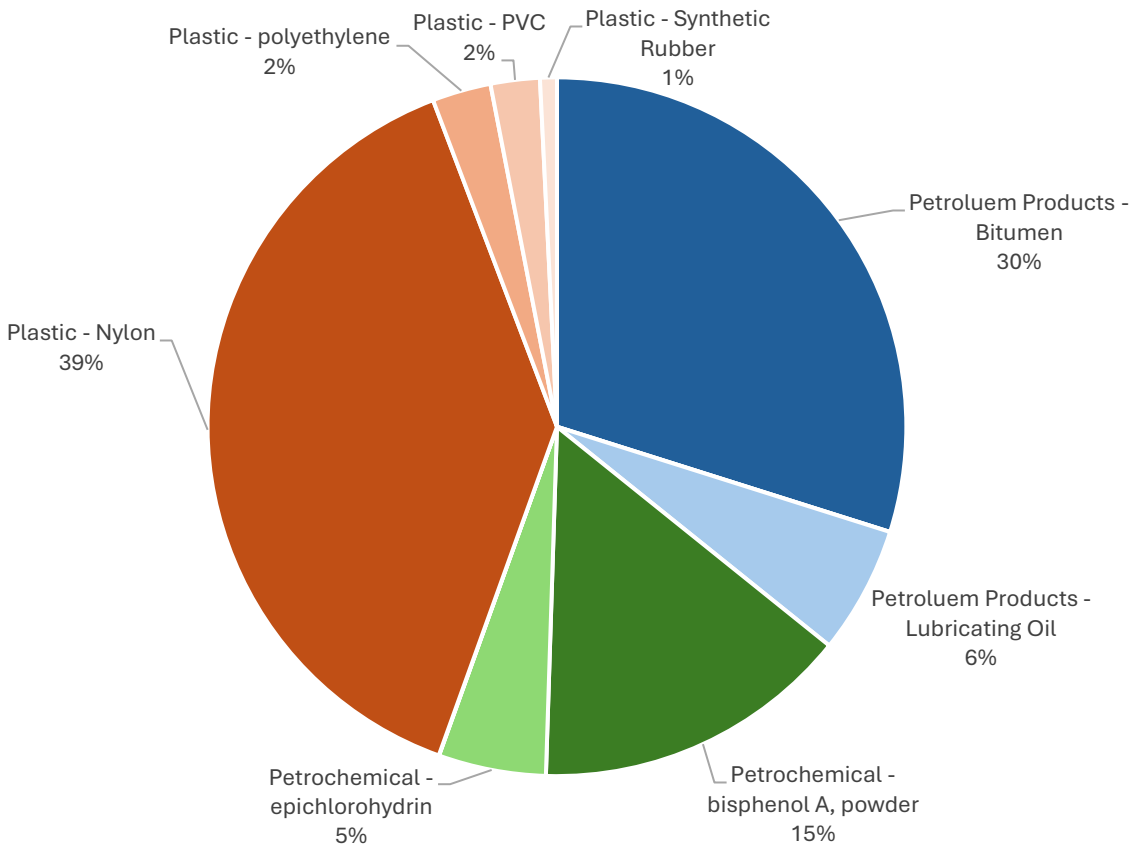


Figure 2 (a) Flow of oil through the supply chain of materials for wind turbines. (b) Disaggregation of oil-based materials for wind turbine production.

(a) shows the flow of oil through the supply chain of materials to produce and intalls a wind turbine (Full details on the specifications of the plant are given in *Supplementary Material*). The size of the arrows shows the scale of embodied oil. Embodied Oil is disaggregated by production stage and through ten material supply-chains before being tracked down to six specific uses: heat, electricity, transport, oil-based materials, other and unallocated oil. The scope of each of these categorioes is given in *Methods*.

(b) splits the embodied oil required in the form of oil-based materials for a wind turbine into specific products, grouped into three main categories: Petroluem Products (blue), Plastics (orange) and Petrochemicals (green).

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Embodied *o*il requirements for LFP batteries and HV transmission. LFP battery production requires approximately 3 barrels of embodied oil per vehicle (assuming an average battery size of 84 KWh), with an additional 4 barrels for the remainder of passenger EVs. Oil-based materials account for 47% of embodied oil requirements, with 27% spread over other material supply chains that were not disaggregated (including the electrolyte and the battery management system). 13% is required for transportation, 4% for heat, 4% for electricity, and 5% for infrastructure and other processes. The majority (80%) of the required oil-based materials are petroleum coke, which is predominantly used in synthetic graphite production for battery anodes. The dominance of petroleum coke in battery production underscores its critical role in synthetic graphite supply chains, linking battery deployment directly to refining by-products.

High-voltage transmission construction requires approximately 230 barrels of embodied oil per kilometer. Oil is required for aluminum production (26%) for cables, steel (13%) for towers, copper (7%) for cables, and concrete (6%) for foundations. The largest share of embodied oil is in oil-based materials (40%), principally lubricating oil and petroleum coke, followed by transportation (32%), mainly in the sand and gravel supply chain. Full details on both LFP batteries and HV transmission are presented in Supplementary Information.

Scenario-level oil demand in 2050. We scale technology-level embodied oil intensities to estimate scenario-level oil demand under the IEA NZE scenario by 2050. Annual oil requirements to deploy the technologies needed for the NZE scenario in 2050, under current production processes and fuel mixes, are over 12 mbd. This is a rise of over 9 mbd compared to what was required to build the same scope of technologies in 2024 (2.8 mbd). We note that this does not necessarily represent oil in addition to current levels, or to any

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other future scenario. Instead, it represents the oil volume required to construct the proposed range and the technology levels needed for a net-zero emissions system using current production processes, thereby highlighting the importance of oil in these supply chains. These results indicate a structural shift in oil demand from combustion toward material embedding. While total oil use in transport and electricity declines, embodied oil requirements increase, leading to a reconfiguration rather than elimination of oil demand in net-zero systems.

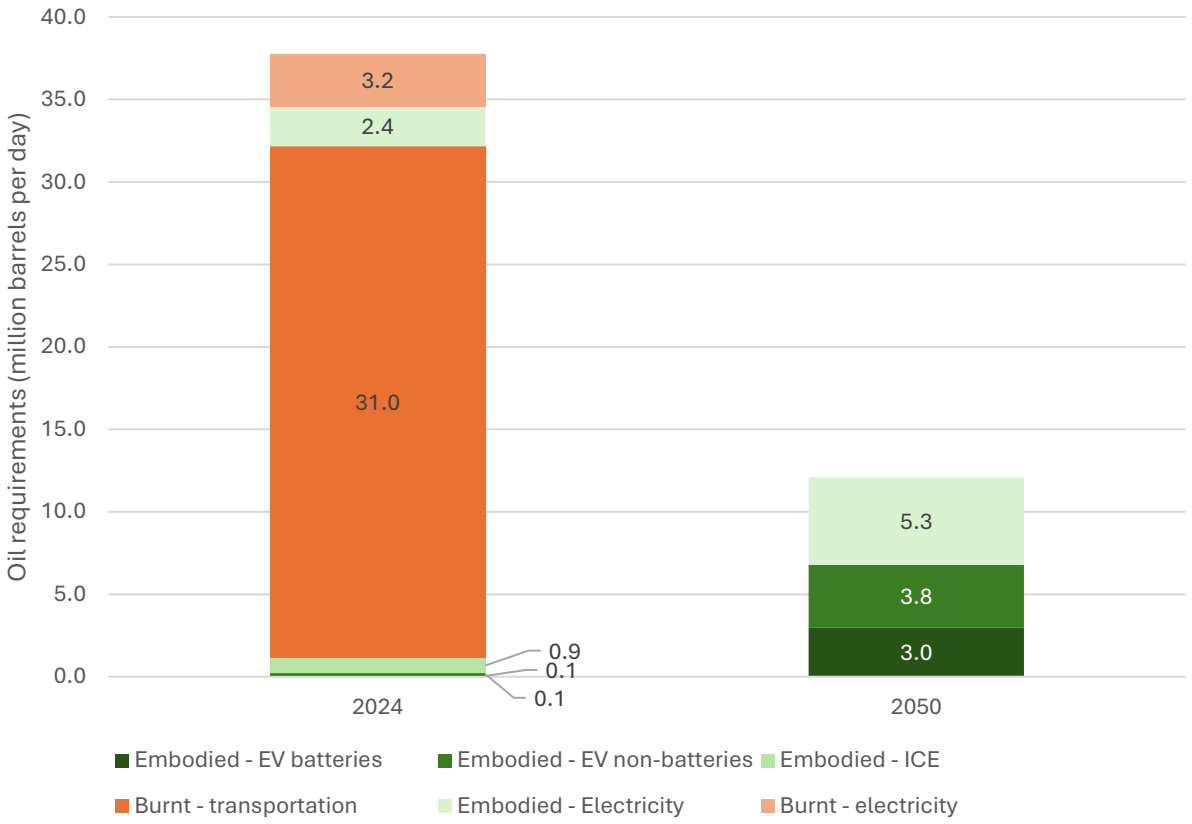
Just over half of the oil required is in the transportation sector, with 25% (3 mbd) used for batteries in transportation (passenger vehicles and trucks) and 31% for EV chassis and drivetrains. Comparatively, electricity generation technologies require less oil: 20% (2.5 mbd) for solar PV and 8% (0.9 mbd) for wind turbines. The infrastructure for transmission and distribution accounts for 13% of oil requirements (or 1.6 mbd). Applying a 20-year infrastructure lifetime produces this estimate. Extending the assumed lifetime to 50 years reduces the calculated oil requirement to 0.9 mbd, due to a reduced number of replacement cycles within the modeled period.

In Fig. 3, we show the estimated oil requirements for a net-zero 2050 energy system in the context of current demand in the electricity and transport sector (details of 2024 oil demand estimation are given in *Methods*). The oil requirements for the road transportation system will fall from over 30 mbd to approximately 7 mbd, with a shift from fuel combustion to embodied oil requirements. For electricity, the electricity system in 2024 has an approximate oil requirement of 5.6 mbd, with approximately 3.2 mbd burnt directly and the remainder embodied in infrastructure. By 2050, this falls to around 5 mbd if directly burned oil is phased

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209 out; however, this decline is offset by larger embodied oil requirements in renewable energy
210 technologies.

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213 **Figure 3. Estimated 2024 and 2050 oil requirements for passenger road transportation**
214 **and electricity.**

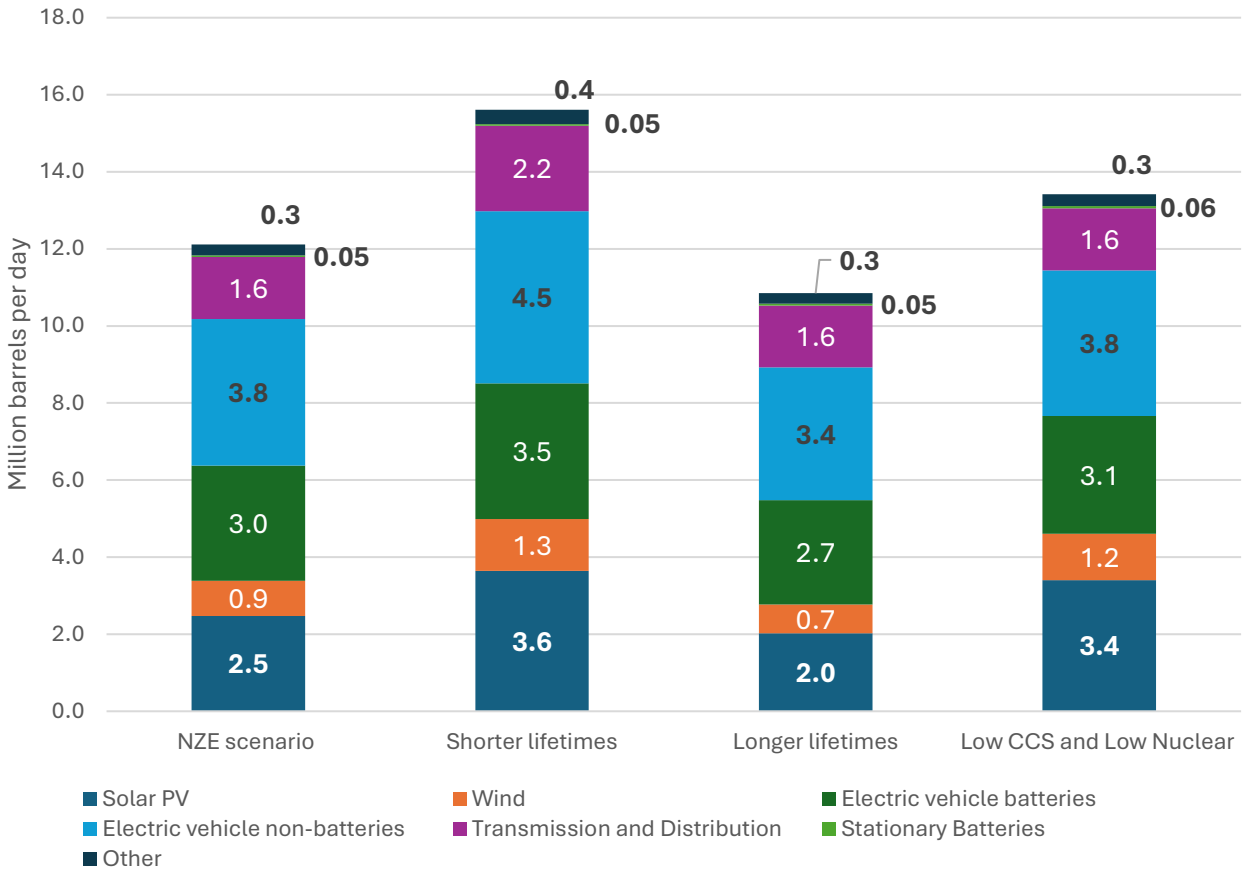
215 The estimated oil (burnt and embodied) for the electricity and transportation sector is estimated for 2024 and for 2050
216 under the IEA's NZE. Oil burnt is shown in orange with embodied requirements in green. 2024 requirements are based on
217 estimations of ICE and EV deployment in 2024 and fuel efficiencies. Details are in *Methods*. 2050 requirements are based
218 on model results and assumed zero combustion of oil in either transportation and electricity.

219 **Sensitivity to lifetimes and deployment scenarios.** While full probabilistic uncertainty
220 analysis is beyond scope, sensitivity to key parameters is assessed to provide bounds on

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estimated oil demand. We test the sensitivity of oil requirements to asset lifetimes and a low carbon capture (LCC) scenario (Fig. 4). Relative to the 2050 reference case (12 mbd), shorter asset lifetimes increase oil demand to almost 16 mbd, largely due to a 47% increase in PV panel output, which raises PV-related oil use by 1.2 mbd. Longer lifetimes reduce demand to 11 mbd, and to 8.3 mbd if transmission, batteries, and vehicles are extended to 50 and 12 years, respectively. Under the LCC scenario, higher deployment of solar PV (+38%) and wind (+32%) increases oil demand to about 13.5 mbd. These results indicate that technology lifetimes are a key driver of long-term oil demand, as shorter replacement cycles substantially increase cumulative material requirements. In contrast, scenario variation has a comparatively smaller effect, suggesting that deployment scale is less influential than asset turnover in determining embodied oil demand.

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233 **Figure 4: Embodied Oil requirements in 2050 under varying scenarios.**

234 Embodied oil requirements in 2050 under four different scenarios are compared and disaggregated based on seven
235 technology categories. Embodied oil requirements in million barrels of oil per day equivalent are shown in the data labels.
236 *NZE scenario* is the IEA NZE scenario. *Shorter lifetimes* is the IEA NZE scenario combined with assumptions that
237 technologies will have shorter lifetimes (details on the specific lifetimes are given in *Supplementary Material*). *Longer*
238 *lifetimes* is the IEA NZE scenario combined with assumptions that technologies will have longer lifetimes (details on the
239 specific lifetimes are given in *Supplementary Material*). *Low CCS and Low Nuclear* is the IEA's alternative net-zero
240 scenario that has lower deployment of CCS and nuclear for electricity generation (full details are in *Supplementary*
241 *Material)*.

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Discussion

This study provides the first quantitative assessment of the scale and composition of oil use embedded in energy transition technologies. By disaggregating oil use across supply chains, we show that a substantial share is attributable to material inputs rather than to direct energy use. This reveals a reconfiguration of oil demand toward material embedding that is not systematically represented in most net-zero modeling frameworks.

Our results indicate a structural shift in oil demand from combustion toward material embedding. While total oil use (for combustion) declines in sectors such as road transport, embodied oil requirements (as chemical products) persist within the supply chains of renewable energy and EV technologies. This suggests that oil demand is reconfigured rather than eliminated under net-zero scenarios. However, the scale of oil required to build the net-zero energy system is small compared to the oil that it is replacing, especially in the road transportation sector. Nonetheless, it highlights the importance of pursuing decarbonization in the oil and oil-based products industries to maintain lower-carbon production during the transition to a broader net-zero energy system.

Petroleum coke accounts for the single largest share of oil-based material use across clean energy technologies. It is primarily used as a reducing agent (carbon source) in the production of silicon metal (for PV), synthetic graphite (for battery anodes), and aluminum (for mounting structures and transmission cables), and it is also used as a heat source in other supply chains (e.g., clinker production for concrete for wind turbine foundations). Its prevalence across these supply chains reflects both its high carbon purity and its role as a low-cost residue from oil refining.

Several substitution pathways for petroleum coke have emerged in the literature, though each comes with technical and economic constraints. In synthetic graphite production, promising alternatives include biomass-derived carbons (via pyrolysis or catalytic graphitization), green needle coke from

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pyrolysis biocrude[30], and recycled graphite recovered from spent lithium-ion batteries[31]. While biomass-to-graphite routes show feasibility at the lab and pilot scales, they are limited by feedstock consistency and high energy inputs[32]. In aluminum production, efforts to replace fossil-based binders and carbon anodes with bio-pitch and biocarbon co-feeds have demonstrated partial substitution potential without compromising electrolytic performance[33]. In the case of silicon metal and silicon carbide production, early studies highlight that biochar and biomass-derived carbon blacks can partially displace petroleum coke, although purity and thermal stability remain key technical hurdles[34-35].

Taken together, these alternatives suggest that a strategic mix of substitution pathways – combining low-carbon energy sources, bio-based feedstocks, recycling, and material efficiency – could significantly reduce dependence on petroleum-coke in energy transition technology supply chains. However, scaling these solutions will require targeted support to overcome technical (e.g., consistency, purity, energy intensity) and economic barriers, and align industrial processes with substitute inputs.

A broader systems consideration is that petroleum coke is co-produced with transport fuels such as diesel, gasoline, and jet fuel through delayed coking processes in oil refining. As long-term global demand for these fuels declines under net-zero scenarios, overall refinery throughput may decrease, potentially affecting the availability and economics of byproducts like petroleum coke. This introduces a planning consideration: future energy technologies may rely on carbon-based materials whose supply is indirectly linked to refining systems that are themselves undergoing transition. This introduces a systems-level constraint where future energy technologies may depend on carbon-based materials whose availability is linked to refining systems undergoing structural decline.

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A fundamental assumption, imposed by limited data, is that current production processes and fuel mixes remain unchanged. In all likelihood, there will be changes in production pathways, material efficiencies, substitution, and recycling rates. Some of these, though not all, will work to reduce oil requirements. This assumption likely overestimates long-term oil requirements, as decarbonization, electrification, and material substitution may reduce oil intensity over time. The results should therefore be interpreted as an upper-bound estimate under current production structures.

In this analysis, we compiled the oil intensity data for approximately a thousand materials and production processes. The future evolution of these production processes under strong climate policy is highly uncertain and largely speculative. Starting to conduct analyses at the individual supply chain level is a vital next step in fully understanding the future dynamics of oil requirements for the manufacture of a global net-zero energy system.

There is a key interlinkage between the oil required to provide electricity for manufacturing renewable technologies (and transmission infrastructure), which, in turn, will be used to produce electricity to produce future renewable technologies. By keeping the oil requirement for electricity generation fixed, we ignore this. However, by disaggregating the oil requirements for technologies such as solar PV and wind turbines into their components, we find that the oil required to produce electricity directly and indirectly accounts for only 6%-10% of total oil requirements. A similar story exists for transportation and heat, although the scope for reducing these oil requirements may be greater.

The endogeneity of the net-zero emissions system and oil requirements for renewable technologies may also work in the other direction. Shifts to electric arc furnaces for steel would reduce emissions, but increase the demand for petroleum coke to produce the anodes required in the process. Even shifts to bio-based plastics may require oil-based products to produce fertilizer inputs. This highlights the dissonance between the efforts to achieve net-zero emissions and the cessation of the

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hydrocarbon industry. Instead, what is required is a pursuit of net-zero, whilst also working to provide lower-carbon-emission materials and production processes for the energy transition.

Ultimately, this paper highlights that a large volume of oil may still be required to produce energy transition technologies, and unless there are fundamental changes to production processes, these requirements are likely to remain, given the intertwining of oil-based products and critical mineral supply chains. The issue of how other models of future oil demand deal with this intertwining between mineral production and oil-based products is unclear, but our paper highlights that there is large potential scope for improving the endogenous nature of future oil requirements and the move to a net-zero energy system.

Our analysis shows that oil use remains embedded within the material supply chains of energy transition technologies, particularly through petroleum coke and petrochemical inputs. While substitution pathways exist, technical and economic constraints limit their near-term scalability. As a result, oil demand in net-zero energy systems is likely to persist in reconfigured forms, shifting from combustion toward material use. Capturing this transition is important for accurately characterizing the role of hydrocarbons in future energy systems.

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Methods

The primary methodology used to estimate the oil requirements of the energy transition - both at the system-wide and individual technology level - is based on Material Flow Analysis (MFA), a widely established modeling framework for quantifying the flows and stocks of materials across systems[36-40]. We implement two complementary MFA-based modeling approaches. The first is a technology-level model that disaggregates oil use across the full supply chain of four key technologies central to the energy transition. The second is a scenario-level model that estimates total oil requirements to deploy a wide basket of technologies required for a net-zero energy system by 2050. Both approaches rely on process-based data from the Ecoinvent database (v3.10) and integrate upstream inputs of oil-derived fuels and materials used across life cycle stages.

Approaches, scope, and system boundary consideration

A critical design question regards the system boundary and scope of the analysis. The main effort is to estimate the embodied oil requirements of the energy system that needs to be constructed to meet net-zero emissions. We aim to capture as much of the infrastructure and architecture as possible for this energy system. The timeframe for this is set to 2050 based on the IEA scenario utilized. Regarding the scope, we define it as the oil required to produce, operate, and dispose of the relevant technologies (as defined by the life cycle inventories (LCI) from the Ecoinvent database). We cover technologies pertinent to electricity generation, electricity storage, transmission, and distribution, as well as some aspects of a net-zero road transportation system. Regarding coverage within these categories, we address different aspects through technology-level disaggregation and scenario-level estimation; therefore, specific technology coverage is discussed in the relevant sections below.

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Technology-level disaggregation

We disaggregated the embodied oil requirements of four key technologies for the energy transition, helping us understand where and how oil is utilized in their supply chains and the oil-based products used. The four technologies selected are:

- Solar photovoltaic panels
- Onshore wind turbines
- Lithium-ion batteries
- High voltage transmission

The preliminary aim of the disaggregation process was to separate out the oil or oil-based product requirements into six ultimate categories. These are:

- ***Transport*** – This includes oil utilized in the transportation of final or input materials, or in the production sites of materials, either directly (e.g., burnt in vehicles) or embodied in the vehicle fleet (e.g., in plastics required to produce those vehicles).
- ***Electricity*** – Covers oil utilized in the production of electricity used across final or input materials – either burnt directly for electricity generation or embodied in the production of electricity generation technologies.
- ***Heat / Energy*** – Oil utilized in the production of heat used across final or input materials – either burnt directly for the generation of heat or embodied in infrastructure for heat generation, or oil used directly burnt for energy – e.g., diesel used to power stationary equipment.
- ***Oil-based materials –*** Oil used to produce oil-based products (such as plastics or petrochemicals) that are either used directly in final products or in the production processes of input materials.

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- ***Other materials*** - Oil embodied in the production process of materials whose supply chains were not followed, as their oil requirements were relatively small.
- ***Other*** – Oil embodied in infrastructure (e.g., factories or mine-sites).

We follow the underlying assumptions in the Ecoinvent database regarding production processes. Therefore, although some of these categories can be produced using other energy sources, or feedstocks other than oil-based products (e.g., transportation via electricity, or petrochemicals using coal or natural gas based feedstocks), we follow the energy sources and production processes given in the databases.

As the technologies covered involve the use of a wide range of materials – either in final production, or across the whole supply chain - we only follow the oil requirements through several key supply chains. The following supply chains were 'followed':

- Ferrous products (e.g., steel alloyed and unalloyed, cast iron)
- Aluminum (inc. aluminum foil)
- Concrete
- Copper (inc. copper foil)
- Glass-fiber
- Lithium
- Graphite
- Silicon
- Sand and gravel
- Solar Glass

These supply chains were selected because they accounted for between 73% to 89% of the oil-based requirements of the chosen technologies.

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The disaggregation process followed the following steps:

- The oil requirements for each technology were disaggregated between those used in electricity, heat, transport, materials, and other (e.g., factories).
- Materials were split between supply chains to be 'followed'; oil-based materials (e.g., plastics, petrochemicals); and other materials.
- Oil requirements for other materials and oil-based products were assigned to their relevant categories.

For the supply chains to be followed, the primary materials were disaggregated in the same manner, with oil requirements for electricity, heat, transportation and other separated, and materials split between secondary materials to be followed (based on size of oil requirement), other materials (materials with small overall oil requirements not followed further), and oil-based materials. This process required the collection of oil content of 962 materials and processes.

Oil content of technologies:

The embodied oil requirements relating to the technologies were based on the LCI of oil requirements given in the Ecoinvent database. The LCI provides crude oil requirements over the entire life cycle of technology. We used the boundary scope of technology construction, rather than operation. This may understate the oil requirements of some technologies (such as wind turbines) that may require oil-based products in their operation (lubricating oil). We utilize the oil content for technologies as given in the Ecoinvent database. This information captures current (or as recent as Ecoinvent records) production processes, inclusive of electricity mixes, energy input mixes, and recycling rates. We thus capture the oil requirements based on current production patterns and technology. Shifts in how materials are produced and transported, as well as the types of energy used to generate heat or electricity, would therefore change these requirements. However, we acknowledge that this

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assumption is a limitation, but it avoids additional uncertainty about speculating on the future and provides a starting point for the oil requirements that would result without action across a wide range of supply chains. Through the disaggregation of oil requirements (discussed below), we start to examine the potential for oil-based products to be substituted (or indeed for other materials to substitute for oil-based products) in the production of renewable energy.

For some of the technologies covered (e.g., solar PV, wind turbines, lithium-ion batteries), multiple data points are available across different sizes, types, production locations, and chemistries. These differences can be substantial - for example, onshore wind turbines have oil requirements 150% greater than offshore (predominantly due to assumed requirements for road development). We outline these differences in Supplementary Information. We simplify by selecting single technology choices where differences in oil requirements occur. For example, we make the simplifying assumption that all wind deployment is onshore, with the oil requirement based on 4.5 MW turbines. Similarly, we assume that all lithium-ion batteries use lithium iron phosphate cathode chemistry. Full details of these assumptions are given in the Supplementary Information.

Scenario-level estimation

Our second approach is a top-down analysis using scenario-level data for a wide range of technologies combined with estimates of total oil requirements across the life cycle of the technologies. We utilize a dynamic MFA model to estimate global oil requirements for renewable energy deployment between 2025 and 2050. The model builds on similar structures in the literature[11-16,41].

The model is based on three broad groups of inputs: installed capacities of electricity generation, storage, transmission, and distribution, and transportation technologies; the oil requirements of these technologies; and the estimated lifetimes of these technologies. We follow the same

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assumptions embedded in the model, relating to oil content discussed above, and those related to the scenario and lifetimes discussed below.

Scenarios and technology lifetimes

As discussed, we cover four broad categories of technologies within the scenario-level analysis. Within these categories, we include the oil requirements of the following technologies in this analysis:

- Electricity generation technologies:
    - Photovoltaic solar
    - Wind turbines
    - Hydroelectric plants
    - Nuclear power plants
    - Gas turbines (Due to lack of available data, we do not include carbon capture, storage, and sequestration infrastructure in the analysis.)
- Electricity/energy storage
    - Stationary batteries
    - Electrolyzers
- Transmission and distribution
    - High voltage transmission
    - Medium voltage transmission
    - Low voltage distribution
- Road transportation
    - Passenger electric vehicle batteries

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- Passenger electric vehicle glider and drivetrain
- Electric vehicle chargers
- Electric truck batteries

We utilize two different technology deployment scenarios, both drawn from the IEA[9]

- Net-zero emission scenario (NZE) that outlines a global energy system that would achieve net-zero CO2 emissions by 2050
- Low CCUS (LCC) scenario – which meets the same criteria as NZE, but where no fossil fuel-based CCUS projects are developed beyond those already under construction or under development.

The deployment of the relevant technologies is shown in Supplementary Information. For some technologies, the deployment metrics in the IEA scenarios do not align with the relevant oil requirements metrics; therefore, additional assumptions are necessary. Specifically, the IEA reports vehicle battery deployment in terms of kWh. Thus, assumptions on battery size were required to convert these into the number of vehicles (for passenger cars). An average battery size of 84 kWh per passenger vehicle was assumed based on data from BNEF[42]. Additionally, the IEA reports transmission and distribution as a total length. An assumed split between high, medium, and low voltage.

It should be noted that the premise of the NZE is a fundamental change in the global energy system, along with shifts in industrial sectors and production processes. For this analysis, we focus on the former – the mass deployment of renewable energy and electric vehicles (and associated infrastructure). As a starting point, we focus on the former (energy technology deployment), whilst keeping the latter (industry and production processes) fixed at current baselines. We do this as our focus is on oil requirements, rather than any associated emissions. Through the second step of

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disaggregation of oil requirements, we can then examine where (and where not) decarbonization of those requirements is required and/or possible.

A critical factor in determining the oil requirements for the scenario is the predicted lifetime of the technologies. This defines how often technologies need to be replaced to meet the required installed capacities. One key challenge in estimating these parameters is that these technologies are in constant development, with changes in design, chemical compositions, and utilization. Also, the mass deployment of solar panels, wind turbines, and EVs is still in its infancy, and thus, the actual lifetimes of these technologies across geographies and climatic conditions are still being determined.

To capture these elements, we use the predicted lifetimes embedded in the Ecoinvent database for the relevant technologies as a baseline. However, to capture the uncertainty in this factor, we also present results from two other scenarios – one where lifetimes are shorter (from 14 to over 40% depending on technology) and one where lifetimes are longer (from 14 to 50%). Full details of these lifetimes are in Supplementary Information.

2024 oil demand estimation

Demand for oil in transportation in 2024 is based on an assumed new vehicle production of 92.5 million in 2024 (from OICA), with 11 million electric vehicles[43-44]. We take oil consumption in 2024 in the passenger road from the calculations of total oil demand and oil by sector from the IEA[45]. For 2024 oil demand from electricity demand we use 2024 installed capacity from the IEA[1] and estimate that 3.2 mb/d of oil is burned directly for electricity, based on 757 TWh of oil-fired generation in 2024 and an assumed heat rate of 9 MMBtu per MWh.

Supplementary Information is available for this paper. Correspondence and requests for materials should be addressed to Dr Timothy Laing.

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