

Avoiding investment in fossil fuel assets

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2023

Faculty of Engineering

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Original citation:

Kennedy, C. A., Sers, M., & Westphal, M. I. (2023). Avoiding investment in fossil fuel assets. *Journal of Industrial Ecology*, 27(4), 1184–1196.
<https://doi.org/10.1111/jiec.13401>

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Avoiding investment in fossil fuel assets

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Editor Managing Review: Frank Boons

Funding information

Natural Sciences and Engineering Research Council of Canada, Grant/Award Number: Discovery

Abstract

Reducing greenhouse gas emissions requires a transformation of capital assets in the economy, especially those for energy supply. This paper explores the hypothesis that economically efficient decarbonization occurs when the demand for fossil fuels declines at the same rate as their capital assets depreciate. In theory this means that new investments in fossil fuel assets are avoided, but without incurring stranded assets. We examine the practicality of this hypothesis using a biophysical economic model of the US energy supply system, with an example focused on impacts of electric vehicles on the petroleum supply chain. We specifically address two questions: (1) What rate of market penetration for electric vehicles is necessary to avoid investments in the petroleum-related assets? (2) How do the costs of upstream capital assets change with the transformation to electric vehicles? High annual depreciation rates for oil refineries ($\delta = 9.47\%$) and assets for crude oil extraction ($\delta = 8.23\%$) have important impacts on results. To avoid new investment in oil refining assets through widespread electrification of light-duty vehicles, the vehicle stock would need to be transformed in just 4 or 5 years. Under most scenarios, some petroleum pipelines will likely become stranded assets due to their low rate of depreciation ($\delta = 2.48\%$). In some scenarios, additional investments in wind and solar power generation surpass oil and gas extraction for about 5 years during the transformation to electric vehicles. Once built, however, wind and solar capital assets last longer, as shown by their low rate of depreciation ($\delta = 3.26\%$).

KEYWORDS

biophysical economics, capital, decarbonization, depreciation, electric vehicles, energy analysis

1 | INTRODUCTION

Transformation of capital assets that both supply and use energy is at the heart of most strategies for rapidly decreasing global greenhouse gas (GHG) emissions (Bogdanov et al., 2021; Kennedy, 2022; Kennedy & Corfee-Morlot, 2012; Larson et al., 2020). Globally, the International Energy Agency (IEA) estimates that approximately \$370 billion of investments in renewable power generation were made in 2021, which is more than three times that for fossil-fuel-based power generation (Figure 1). Nonetheless, the IEA analysis suggests that clean energy investments still need to double during the 2020s to achieve the 2.0° C climate change ceiling, or triple to fall within 1.5° C. Furthermore, while global investments of ~\$700 billion were projected for renewable and nuclear power generation, and electricity networks in 2021, approximately \$800 billion of

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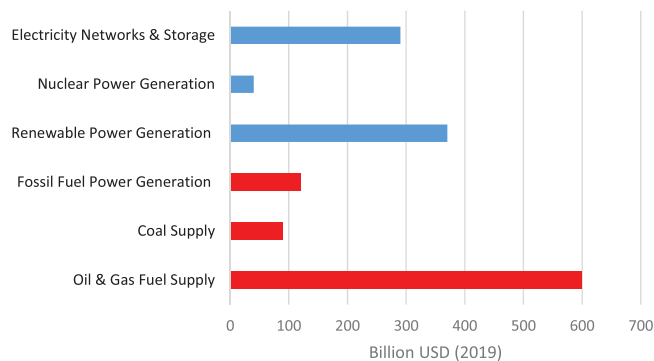


FIGURE 1 Estimates for global energy supply capital investments for 2021, based on the IEA (2021). Underlying data for this figure can be found in Supporting Information S2.

investment was projected for fossil fuel supply infrastructure and power generation. In other words, for every step forward in the transformation of energy-sector supply assets, the world is still taking a larger step backward.

In this paper we explore a climate policy perspective that new investments in fossil fuel assets should be avoided in efforts to curb GHG emissions. We recognize that some fossil fuels will necessarily be used in transforming to a low carbon economy, given that existing fossil fuel assets are locked-in, but the construction of new fossil fuel assets is counter-productive and works against climate change goals. Our arguments are made as much from an economic perspective as an environmental one. Why would societies wanting to reduce GHG emissions as quickly as possible, construct new fossil fuel assets and risk these becoming stranded assets? We hypothesize that economically efficient decarbonization occurs when the demand for fossil fuels declines at the same rate as their capital assets depreciate.

Whilst the goals are broadly the same, the framing of this economic principle for decarbonization is operationally different to other approaches. Most governments would likely seek to grow the economy within agreed climate constraints and commitments, although there are scholars who question whether such green growth is possible (Haberl et al., 2020; Heun & Brockway, 2019; Hicckel & Hallegatte, 2022; Hicckel & Kallis, 2020). The economic principle applied here is slightly more nuanced: to achieve decarbonization of the economy, the stock of fossil fuel assets should be reduced, while continuing to grow the total stock of capital assets in the economy.

Another approach commonly used in integrated assessment models (IAMs) is to seek for lowest cost routes to achieve desired levels of economic growth, subject to climate constraints. Many IAMs used in IPCC reports are set up to resolve scenarios in this way, even if it involves new investment in fossil fuel assets (Gambhir et al., 2019; Westfal, 2021). There are merits to the least cost approach in that it captures the economic conditions faced by the energy supply sector. Nonetheless, there are challenges too. With large uncertainties in future costs of competing energy sources, the IAMs tend to be conservative and project current costs forward with modest degrees of price reductions over time through technological progress. This means that the abrupt changes required to meet climate constraints are essentially delayed until the end period of model simulations. This is seen, for example, by many IAMs overshooting mid-century climate goals in simulations to the end of the 21st century (Rogelj et al., 2018).

Climate policy may also be guided by economic decision making invoking an appropriately established social cost of carbon, SCC (Nordhaus, 2017; Pizer et al., 2014; Wagner et al., 2021). An SCC is also employed in cost-benefit type IAMs such as the DICE model. There are, however, significant challenges with assigning an appropriate value to the social cost given uncertainties in damages and varying arguments on the choice of discount rates (Kaufman et al., 2020; Stern & Stiglitz, 2021; Wagner et al., 2021).

For many years, climate policy analysts have stressed that it is essential for governments to cease subsidizing investments in fossil fuels (Erickson et al., 2020; Global Commission on the Economy & Climate, 2018). While fully agreeing that fossil fuel subsidies should be avoided, we recognize that subsidies are only part of the problem. The greater challenge is that investment in fossil fuel assets continues to be driven by demands for fossil fuels from societal systems including buildings, vehicles, power generation, and industrial processes.

In this paper we will bridge between demand-side policies and supply-side goals for reducing GHG emissions. Demand-side policies include measures that restrict GHGs emissions, such as carbon pricing, consumer tax credits, and rebates. Supply-side measures have some distinct advantages, such as low administrative and transaction costs, higher abatement certainty, and overcoming infrastructure lock-in (Green & Denniss, 2018; Piggot, et al., 2020). Here we will show supply-side goals could be introduced at the rate of capital depreciation; and how the demand side would need to respond.

In order to pursue a policy of discouraging investments in fossil fuel assets, it is essential to reduce demand for the energy services that the fossil fuel assets supply—and, moreover, provide equivalent energy services from alternative, carbon-free sources. An example of this—which will be used throughout this paper—is the electrification of light-duty vehicles. With increasing market shares for electric vehicles, demands for refined petroleum products can be reduced, thereby reducing the requirements for a chain of petroleum-related capital assets including oil supply wells, oil pipelines and refineries. Simultaneously, however, new power generation, transmission, and distribution assets are required to provide for the increased electrical demands.

TABLE 1 US energy-sector capital stocks for 2018, and average depreciation and investment from 2014 to 2019. The definition of asset types is given in Supporting Information S1, Section I (stock and investment data is from the US Bureau of Economic Analysis; depreciation rates calculated by authors based on BEA stock and investment data)

Asset type	Capital stock in 2018 (2012\$B)	Average annual depreciation rate 2014–2019 (%)	Average annual depreciation 2014–2019 (2012\$B)	Average annual investment 2014–2019 (2012\$B)
Oil and gas extraction	1630	8.23	136.5	134.8
Coal mining	74	7.92	5.7	6.8
Nuclear fuel	7	50.11	3.3	3.3
Petroleum pipeline	165	2.48	3.8	10.0
Gas structures	417	2.44	9.9	14.5
Petroleum and coal products	218	9.47	20.3	22.0
Electrical power generation (All)	1892	2.45	43.8	87.3
Electrical transmission and distribution	531	5.20	26.1	38.1
Wind and solar power (only)	220	3.26	5.8	22.9

Toward the broader objective of understanding economic transformation without investment in new fossil fuel assets, we explore two narrower questions in this paper:

1. What rate of market penetration for electric vehicles is necessary to avoid investments in the petroleum-related assets?
2. How do the costs of upstream capital assets change with the transformation to electric vehicles?

We focus on the US economy in our analysis, although the methods and findings are transferable to other economies, with adjustments for trade in fossil fuels.

Complexities in answering these questions immediately arise when we take a closer inspection of the energy supply assets in an economy. In any given year there is depreciation of existing energy supply assets in an economy and usually investments in new assets. Table 1 shows, for example, existing capital stocks, depreciation, and new investments in energy supply assets for the United States from 2014 to 2019 (based on US BEA data). Two types of assets: oil and gas extraction (\$1630 billion) and electrical power generation (\$1892 billion), have capital stocks of notably high value, although their investment characteristics are quite different. Oil and gas extraction assets received the greatest average investment (\$135 billion/year from 2014 to 2019), but have a high annual depreciation rate (8.23%/year, 2014–2019) so investments have maintained a relatively constant capital stock for 2014–2019. Electrical power generation assets have a much lower depreciation rate (2.45%/year), so the average annual investment of \$84 billion/year is about double the annual depreciation, leading to a growth in the value of assets. Depreciation rates reflect physical deterioration and obsolescence, but can change gradually over time due to economic conditions, tax laws, and technological change (Giandrea et al., 2021). The high depreciation rates for oil and gas extraction capital are associated with hydrocarbon production decline curves; production often declines steeply when investment stops, as the pressure in the reservoir declines. Amongst the other energy-sector asset types, oil refineries (which account for most of petroleum and coal products manufacturing) have a particularly high depreciation rate of 9.47%/year, driven by the technical requirement to refurbish key units every 5 years. Average annual investment in refineries was only slightly above capital depreciation from 2014 to 2019. For other asset types, including coal mining, petroleum pipelines, gas structures, and electrical transmission and distribution, annual investments have exceeded depreciation of capital.

Aggregate data on capital stocks clearly masks the spatial complexity of fossil fuel assets. The US Energy Information Agency's Energy Atlas provides a richer overview of assets including locations of various types of mines, pipelines, refineries, power plants, and other energy facilities.¹ It depicts, for example, the routes of over 210 natural gas pipeline systems and 400 underground natural gas storage facilities.² Further the EIA details the status of 129 oil refineries (124 in operation) in 30 different states, as of January 1, 2021,³ and planned changes in power plants.⁴ Clearly, there will be spatial variation in future investment and depreciation of energy supply assets. In this paper, however, we restrict the analysis to aggregate national data.

In the following sections we address the core questions by developing a biophysical economic model of the US energy supply system. More broadly, biophysical economic models capture the relationships between capital stocks and energy use in economies (Kennedy, 2020, 2022). The key elements of the current model are: (i) energy balance and loss equations arranged in the form of an energy flow Sankey diagram; and (ii) energy-capital stock relationships for major capital assets. Several scenarios for reduced petroleum demand are investigated based on electrification of

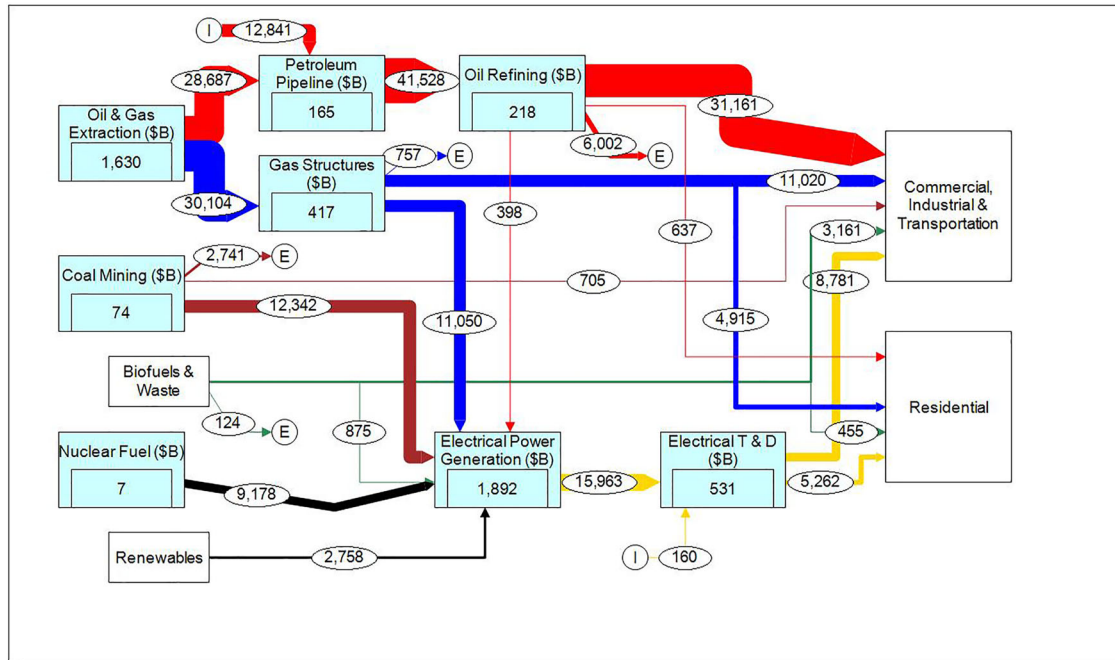


FIGURE 2 US Energy flows (PJ) and energy supply capital stocks (\$billion in 2012 USD) for 2018. Note: useful heat, waste heat and some energy transfers are omitted. Energy data is based on the International Energy Agency energy balance tables; capital assets are calculated from US Bureau of Economic Analysis data (E, export; I, import). Note: Petroleum shown in red; natural gas in dark blue; coal in brown; biomass and waste in green; electricity in yellow.

light-duty vehicles, and different assumptions for US trade of crude oil and refined petroleum. Increased investment in wind and solar power assets is included. Changes in capital investments are calculated relative to the US Energy Information Administration's Annual Energy Outlook projections.

2 | METHOD

2.1 | Data sources

The main methodology of the paper uses: capital stock and investment data from the US Bureau of Economic Analysis (BEA)—see Supporting Information S1, Section I; energy balance data from the IEA (www.iea.org/data-and-statistics); and baseline energy futures projections from the US Energy Information Agency's Annual Energy Outlook 2021 (www.eia.gov/outlooks/archive/aeo21/).

2.2 | Capital–energy relationships for energy-sector assets

The first step of the method involves creation of a Sankey diagram of energy flows for the US economy, integrated with capital stocks of energy-supply assets. Figure 2 shows the flows of crude and refined oil, coal, natural gas, biofuels and waste, and electricity from sources to final demands. The energy flows and processes depicted are based on the IEA's energy balance table for 2018, with some simplification. Energy losses and useful heat are not shown; and end-uses have been aggregated into two categories. The Sankey diagram also depicts eight categories of capital assets; these correspond to processes of energy generation, transformation, and distribution. Ideally it would be desirable to disaggregate some of the categories of capital assets further, for example, separating oil and gas extraction, or different forms of power generation. The categories used, however, are determined by the availability of capital stock and investment data from the US BEA. Values for the capital stocks shown in Figure 2 are detailed further in Supporting Information S1, Section I.

A key assumption of the method is that the size of energy-sector capital stocks (in monetary terms) will be approximately proportional to the quantity of energy they supply in a given year, though only over the long term (decades). This is by no means a perfect assumption; it does not allow for increasing or decreasing economies of scale; nor does it hold up well over the short run (years), during which energy demands can change rapidly, while capital stocks are relatively fixed, or slowly changing. Capacity utilization might, for example, vary substantially during a period of a few years,

allowing for fluctuations in production to occur for a largely fixed capital stock. Examination of time-series data from 1971 to 2018 for capital assets related to crude and refined oils shows the challenges with the assumption in the short run (Supporting Information S1, Section III).

2.3 | Biophysical model

In this section we present the biophysical economic model of the US energy supply system used to explore the scenarios in the following section. First, the model has two energy (E) balance equations given as:

$$E_{OP} = E_{OPE} + E_{LDV} + E_{OT} \quad (1)$$

$$E_{CREF} = E_{CI} + E_{COP} \quad (2)$$

where CI, COP, CREF, LDV, OP, OPE, and OT denote crude imports, domestic crude oil production, crude input to oil refineries, light-duty vehicles, refined oil production, refined oil product exports, and other refined oil use. Two parameters capture energy losses in oil refining (L_{OR}) and electrical transmission and distribution ($L_{T\&D}$) and are specified as follows:

$$L_{OR} = E_{OP}/E_{CREF} \quad (3)$$

$$L_{T\&D} = E_{ELC}/E_{ELP} \quad (4)$$

where ELC denotes electricity consumption and ELP is electricity production. These are based on the IEA's 2018 energy balance for the United States, the parameter values were calculated to be $L_{OR} = 0.9102$; and $L_{T\&D} = 0.8797$. Supporting Information S1, Section IV shows that both parameters have been relatively stable since 1980; slight upward trends can be visually observed, but we do not expect that the processes of oil refining and power distribution will become much more efficient. So using parameter values for 2018 for model simulations to 2040 is reasonable.

Long-term capital stocks are determined from energy flows using the capital-energy ratios for 2018, shown in Table S3. We use the 2018 ratios, rather than time-averaged capital-energy ratios because the latter are less attuned to the capital stocks at the beginning of model simulations; that is, using recent capital-energy ratios avoids excessive capital stock adjustments over the first few years of simulations.

The other key parameters are the annual rates of depreciation for capital stocks, which are given in Table 1. There has been some modest changes to energy-sector depreciation rates over the past 25 years (see Supporting Information S1, Section II), but using average values for 2014–2019 is appropriate given the relative stability of these parameters. Capital stocks (K) and annual depreciation rates (δ) are used to calculate new investment (I) requirements via the following general functional form:

$$I_t = K_{t+1} - K_t(1 - \delta) \quad (5)$$

Application of the model broadly proceeds as follows: (i) either demand-side or supply-side measures lead to exogenous specification of one of the energy variables; (ii) other energy variables are determined from Equations (1) to (4), or are fixed at base scenario values; (iii) capital stocks are calculated from energy variables using Table S3; and (iv) capital investments are calculated from required stocks using Equation (5).

2.4 | Scenarios for reducing oil consumption through electrification of light-duty vehicles

The potential to reduce investments in fossil fuel assets is investigated through several scenarios, all of which entail electrification of light-duty vehicles. Two of the scenarios involve demand-side measures specifying percentage targets for electric vehicle sales (Table 2). The other three scenarios consider supply-side goals which spur electrification of light-duty vehicles through reductions in the availability of refined petroleum. The scenarios are summarized below, with further details in Supporting Information S1, Section V.

All of the scenarios beyond a base case involve additional investments in electricity sector assets to power a growing fleet of electric vehicles. Based on Figure 3 of Hou et al. (2021), one unit of electrical power supply is required for each 4.5 units of gasoline or diesel avoided by electrification of vehicles. The model captures the additional investments in electrical power generation and electrical transmission and distribution required to meet the increased electrical power demand. In all scenarios, 80% of the increased power generation is assumed to be provided by additional wind and solar assets, with the remaining 20% of the increase being similar to the current mix (i.e., including some nuclear, hydro, and fossil fuels). While some studies suggest that 100% of US electricity could be provided by wind, solar, and hydropower (Jacobson et al., 2015), others indicate there

TABLE 2 Scenarios for changes to US petroleum supply chain based on assumptions about electric vehicle uptake (demand-side scenarios) or depreciation rates for different capital assets (supply-side scenarios), and the EIA's Annual Energy Outlook 2021. Red denotes exogenous scenario drivers; orange denotes endogenous quantities determined by the model. Further description of the scenarios is given in Supporting Information S1, Section V

SCENARIO	Refined petroleum			Crude oil and gas			Natural gas and natural gas liquids
	Fuel use by light-duty vehicles	Other domestic use of refined fuels	Export of refined fuels	Domestic refining of fuels	Import of crude oil	Domestic crude oil extraction	
Base	EIA Annual Energy Outlook 2021	EIA Annual Energy Outlook 2021	EIA Annual Energy Outlook 2021	EIA Annual Energy Outlook 2021	EIA Annual Energy Outlook 2021	EIA Annual Energy Outlook 2021	EIA Annual Energy Outlook 2021
Demand-side measures							
EVs at 50% of new sales in 2030	Based on EVs at 10% of new sales in 2026 rising to 100% in 2035	EIA Annual Energy Outlook 2021	EIA Annual Energy Outlook 2021	Calculated from energy balance	EIA Annual Energy Outlook 2021	Calculated from energy balance	EIA Annual Energy Outlook 2021
EVs at 100% of new sales from 2025	Linear decline over 12 years from 2025	EIA Annual Energy Outlook 2021	EIA Annual Energy Outlook 2021	Calculated from energy balance	EIA Annual Energy Outlook 2021	Calculated from energy balance	EIA Annual Energy Outlook 2021
Supply-side goals							
Constrained refining #1	Calculated from energy balance	EIA Annual Energy Outlook 2021	EIA Annual Energy Outlook 2021	Declines at rate of oil refinery depreciation	EIA Annual Energy Outlook 2021	Calculated from energy balance	EIA Annual Energy Outlook 2021
Constrained refining #2	Calculated from energy balance	EIA Annual Energy Outlook 2021	Declines at rate of oil refinery depreciation	Declines at rate of oil refinery depreciation	EIA Annual Energy Outlook 2021	Calculated from energy balance	EIA Annual Energy Outlook 2021
Constrained extraction	Calculated from energy balance	EIA Annual Energy Outlook 2021	Declines at rate of oil refinery depreciation	Calculated from crude oil supply	EIA Annual Energy Outlook 2021	Declines at rate of extraction depreciation	EIA Annual Energy Outlook 2021

are additional technical challenge, higher costs, and land-use pressures when intermittent renewables are used for over 80% of supply (Clack et al., 2017; Williams et al., 2021). The cost and impacts of electricity storage facilities, new regulations, and dynamic pricing systems are beyond the scope of the model scenarios.

The base case scenario uses forecasted levels of energy supply and demand from the US EIA's Annual Energy Outlook (2021 version). The Energy Outlook provides fairly conservative energy projections, which include relatively little electrification of vehicles and only modest changes to energy supply assets.

All of the other scenarios follow the energy requirements of the base case up until year 2025, before substantial abrupt changes to electric light-duty vehicles are introduced. Using 2025 as the effective start of the scenarios avoids some of the immediate rebound from the Corona-virus-induced economic shock of 2020; and, arguably, is a year by which major rollout of electric vehicles in the United States is viable given the robust state of the technology. The long-run geopolitical impacts of the war on Ukraine are not considered.

The first scenario (50% EV 2030) is based on the proposed US policy-supported target of the Biden Administration that electric vehicles will account for 50% of new light-duty vehicle sales by 2030 (Table 2). Fuel used by light-duty vehicles is specified exogenously in this scenario, with quantities of petroleum processed in oil refineries and extracted domestically calculated by the model (Table 2). The drop in demand for petroleum products and upstream crude oil leads to reduced capital needs for petroleum-related assets, which are also resolved using the model. The capital requirements for petroleum-related assets in this scenario still, however, necessitates new investments as determined by Equation (5).

The second scenario is more ambitious. The scenario (100% EV 2025) considers a policy mandating that all light-duty vehicle sales must be electric vehicles from 2025. Given that the average lifespan of a light-duty vehicle in the United States is about 12 years,⁵ the scenario entails replacement of 8.3% of all fossil fuel powered light-duty vehicles in the US stock with electric vehicles every year starting from 2025. This scenario involves demand-side measures, with model calculations conducted in a similar direction to the first scenario.

The other three scenarios involve supply-side goals that are explicitly tied to depreciation rates of petroleum supply assets. In the two constrained refining scenarios, the stock of oil refinery capital assets is allowed to decline at its normal depreciation rate, starting in 2025, without new investment. The scenario does not necessarily need to be interpreted too strictly; modest expenditures on essential maintenance might continue, but the broad overall strategy is to hold back from further investment in fossil fuel infrastructure. Given the linear form of the assumed energy–capital relationship, it follows that the production of refined petroleum assets also decreases at the same rate as the depreciation of oil refinery assets (9.47%). In constrained refining scenario #1, all of the reduced supply of petroleum products is assumed to be achieved by electrification of domestic light-duty vehicles. Whereas in constrained refining scenario #2, US exports of refined petroleum products are additionally assumed to decline at the same rate as the depreciation of oil refinery assets. Thus the two constrained refining scenarios cover a range between no change in refined petroleum exports and a rapid reduction in exports of petroleum products. In the constrained *extraction* scenario, the domestic production of crude oil is considered to decline at the same rate as the depreciation of oil and gas extraction assets. The scenario assumes that assets required for crude oil extraction depreciate without new investment, starting in 2025.

3 | RESULTS

Given the high rate of depreciation of oil refinery assets, the main results show that the electrification of light-duty vehicles would need to occur relatively quickly in order to avoid further investments in refineries. If domestic light-duty vehicles were the only driver of decreases in demand for petroleum products (constrained refining scenario #1), then electrification of the entire vehicle fleet would occur within just four years (by 2029 in Figure 3a). If declining exports also contribute to decreased oil refining—without oil refinery investment—then the electrification of light-duty vehicles would occur over 5 years. Both of these scenarios are much more rapid than the case of just electrifying new light-duty vehicles sold after 2025 (100% EV 2025 scenario), or the proposed policy of reaching 50% EVs in new sales by 2030 (50% EV 2030). So under optimal conditions—with demand for refined oil products declining at the rate of oil refinery depreciation—it would be necessary to transform the existing vehicle fleet on the road and not just rely on sales of new light-duty vehicles.

Under the current plan of EVs reaching 50% of new vehicle sales in 2030, light-duty vehicle fuel use—and hence GHG emissions—will only be 12.5% lower than the base case. Under the 100% EV 2025 scenario, light-duty vehicle fuel use in 2030 would be 42% below base. Neither of these demand-side scenarios are as ambitious as the supply-side scenarios, all of which see elimination of fossil fuels by light-duty vehicles at or before 2030 (Figure 3a).

Substantial new investments in electrical power generation would be required to support the electrification of light-duty vehicles. The rate of such new investments (Figure 3b) clearly corresponds to the rate of vehicle electrification. Under the assumption that all the incremental power is provided 80% by wind and solar, then new investments could peak at as high as \$200 billion in 2026. This is the case with the most rapid electrification of vehicles (constrained refining scenario #1). Note that Figure 3b only shows incremental new investments in power generation associated with the electrification of light-duty vehicles—and these peak when the transformation of the vehicle stock is most rapid. With slower rates of electrification, new power generation investments would peak at just over \$140 billion (constrained refining scenario #2; and constrained extraction scenario) or close to \$60 billion under the two demand-side scenarios. The size of these estimated investments should

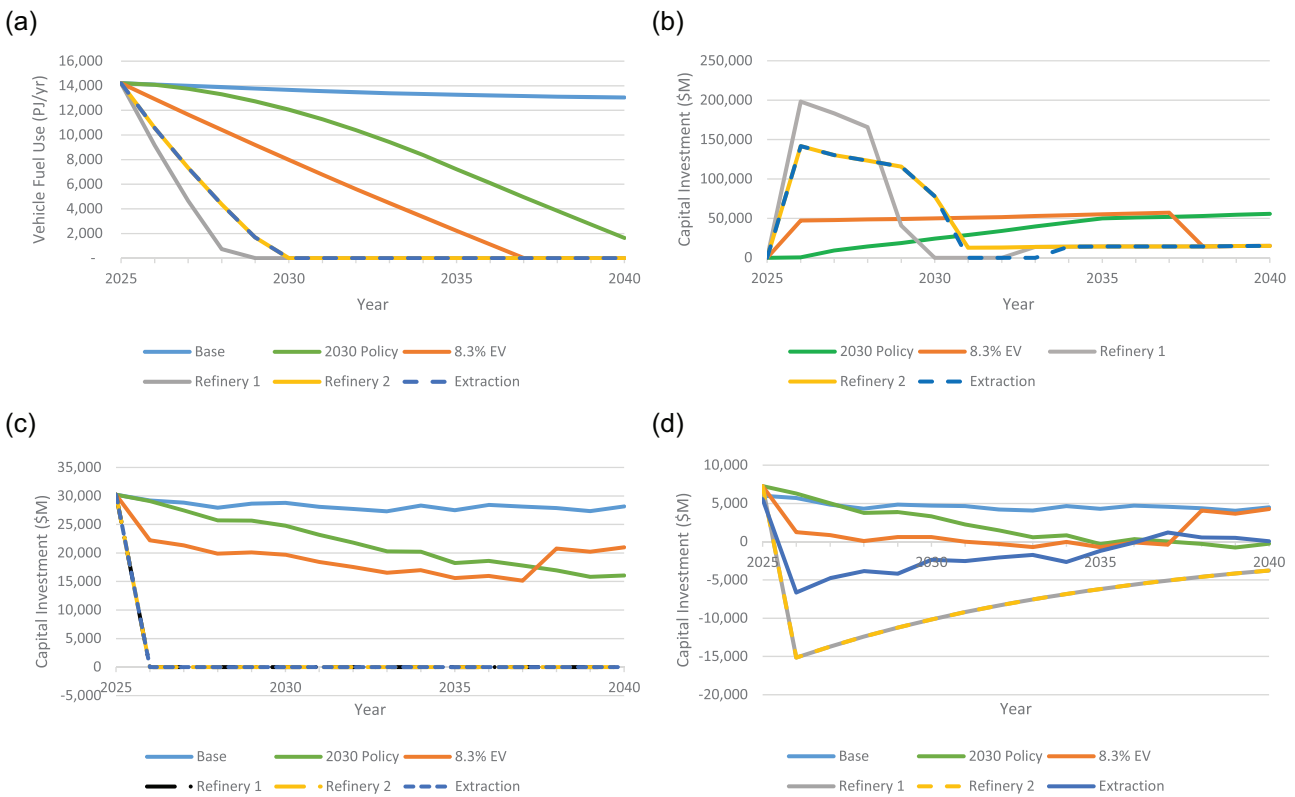


FIGURE 3 Results for five scenarios of electrification of light-duty vehicle in the United States, 2025 to 2040: (a) Fuel use by light-duty vehicles; (b) Capital investment in additional wind, solar, and other power assets; (c) Capital investment in oil refineries; (d) Capital investment in petroleum pipelines. Note that the negative investment for pipelines in (d) is an indication that these are becoming stranded assets, and are losing value faster than their normal rate of depreciation. Information on the model used to generate this figure can be found in Supporting Information S2.

be treated cautiously, however, as they rely on relatively rough approximation of long-term capital-energy relationships, as discussed in the methodology.

The widely differing rates of depreciation amongst the types of energy supply assets (Table 1) has an important implication on the potential for fossil fuel assets to become “stranded” under electrification. Oil refinery assets, depreciating at 9.47% per year, are far from become stranded assets in the two demand-side scenarios, with substantial investments continuing (Figure 3c). Petroleum pipelines, however, have a much lower depreciation rates at 2.48% (Table 1). Under the three most rapid electrification scenarios (constrained refining #1 and #2; and constrained extraction), the results show there would be periods of substantial negative investment in petroleum pipelines (Figure 3d). This essentially means that some pipelines could become stranded assets because the long-term value of the energy services they provide is declining faster than their rate of depreciation. In practice, these assets could be sold off below their book value in some form of resale market, or possibly repurposed for other uses, such as transportation of other fluids. Even in the two slower electrification scenarios—based only on transforming new vehicle sales—there is potential of some minor stranding of petroleum pipeline assets when the vehicle stock becomes fully electric.

Further insights are gained by examining the investment implications of the individual scenarios, while noting the impacts of assumptions about trade in crude oil and petroleum products. In the 50% EV 2030 scenario, the increased investment in power generation and transmission and distribution is offset by the decline in investment in assets for oil and gas extraction (which decline from ~\$250 billion in 2025 to ~\$130 billion; Figure 4a). This decline occurs with the assumption that US crude oil imports remain unchanged from the base case. It could also be reasonably assumed that some or all of the reduced crude oil demand is met through a decrease in imports, which would result in a smaller decrease in investment in domestic crude extraction. Fuller resolution of crude oil imports versus domestic production lies beyond the analysis conducted here.

In both of the constrained refining scenarios (e.g., Figure 4b), the magnitude of the investment in wind and solar and other power generation surpasses oil and gas extraction for a few years. The reduction in oil and gas investments in these scenarios likely overshoots what is viable in curtailing crude oil production—and would impact natural gas liquid and natural gas production. So in practice, some reduction in crude oil imports would have to occur in order to achieve the large decrease in oil refining in these scenarios.

An important observation in Figure 4b,c, is that the additional investments in wind and solar power (plus 20% other), and electrical transmission and distribution, substantially decline after the approximately 5-year period of transforming to electric vehicles. (Note the model is only capturing

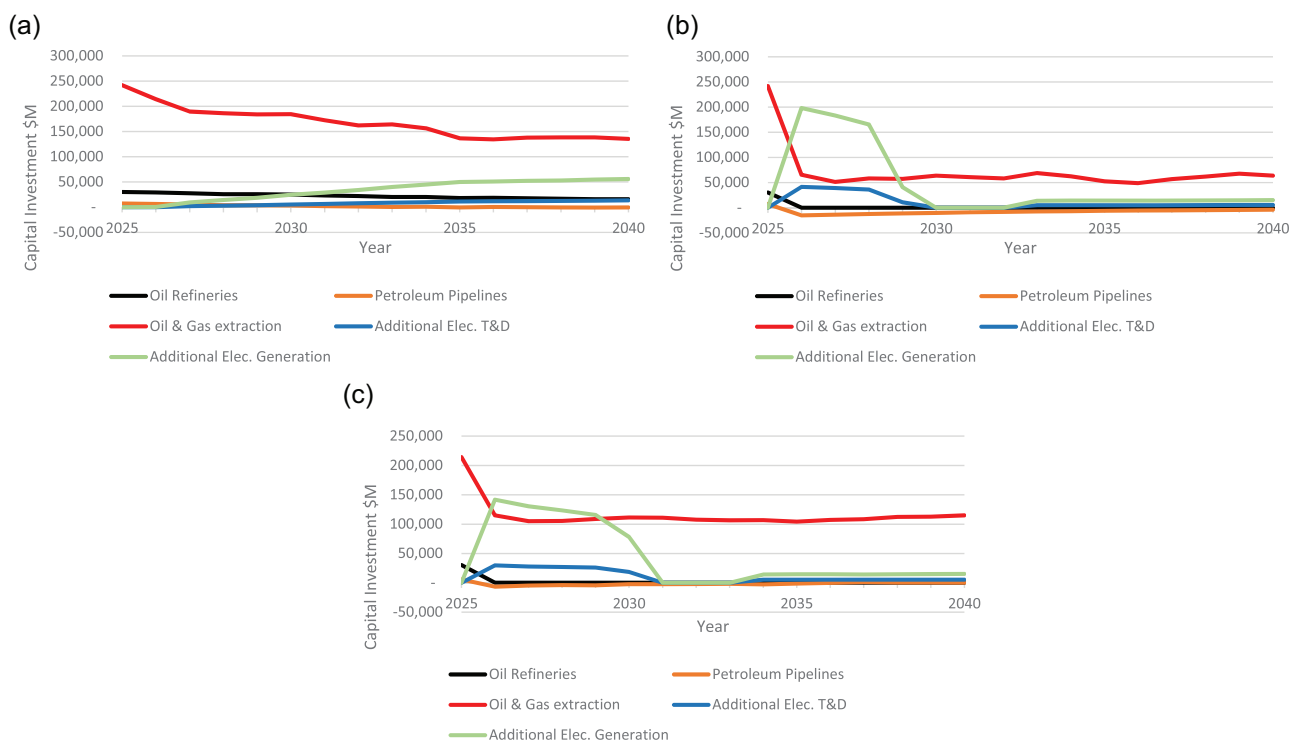


FIGURE 4 US capital investments in petroleum assets and incremental electrical power assets, 2025 to 2040, under three of the scenarios: (a) 50% EV 2030 (EVs reach 50% of new vehicle sales by 2030); (b) constrained refining #1; and (c) constrained extraction. Information on the model used to generate this figure can be found in Supporting Information S2.

incremental wind and solar investments from electrification of light-duty vehicles; further wind and solar investments can be expected under overall power sector decarbonization.) The rates of capital depreciation play a notable role in the investment dynamics. Wind and solar depreciate at the relatively low rate of 3.26%/year (Table 1); so once built, relatively low levels of future investment are required to maintain the capital stock. Similar arguments apply to electrical transmission and distribution assets that depreciate at 5.2%. The greater durability of power sector assets versus petroleum supply assets, other than pipelines, enhance their sustainability, beyond providing a backbone to a carbon-free energy system.

4 | DISCUSSION

The analysis conducted above has a variety of policy implications ranging from broad economic principles for decarbonization to finer details on the importance of capital depreciation rates, and approaches to accelerating the electrification of vehicles. Before turning to these, it should be recognized that the methods employed are fairly broad-brush, employing simple models that miss many finer details of conventional economic models. The energy–capital stock relationships have limitations and are approximate. Nonetheless, the main findings from the analysis relate to the dynamics of the transformation of the capital stock, which are largely dependent on the established depreciation rates and the energy Sankey diagram.

The specific strategy investigated in this paper—of decreasing demand for fossil fuels at the same rate as fossil fuel assets depreciate—has some appeal from an economic efficiency perspective. Essentially, the strategy seeks to make use of existing capital stocks, without leaving them stranded. There are several challenges to this approach, however. First, it could reasonably be argued that stocks of fossil-fuel-based capital assets should be abandoned more quickly if this is necessary to prevent catastrophic climate change. As shown by the results here, at least for the case of petroleum supply assets, the rates of capital depreciation are so high that it would be hard to replace them any faster. With crude oil extraction assets physical deteriorating or becoming obsolescent at 8.23% per annum and petroleum refining assets depreciating at 9.46% per annum, demand for petroleum would have to decline very rapidly to leave these assets stranded. The only exception is the case of petroleum pipelines; with a depreciation rate of just 2.48% per annum these are far more prone to becoming stranded assets. Thus, arguably, new investment in petroleum pipelines should be rigorously avoided. The variation in capital depreciation rates between different asset types along the petroleum supply chain illustrates that there are practical challenges in applying the strategy of phasing out assets at their natural depreciation rates. Nonetheless, in this case the petroleum

TABLE 3 Use of petroleum products for US transportation in 2018 (derived from Tables 4–6: Energy Consumption by Mode of Transportation, United States Department of Transportation, Bureau of Transportation Statistics, <https://www.bts.gov/content/energy-consumption-mode-transportation>)

Vehicle type	Energy use (PJ)
Light-duty vehicle, short wheel base and motorcycle	11,690
Light-duty vehicle, long wheel base	4723
Trucks (single-unit 2-axle 6-tire or more)	2042
Combination truck	3851
Bus and transit	413
Rail	540
Marine	1011
Aviation	1978

pipelines are a smaller component of the supply chain assets, valued at \$165 billion in 2018, which is an order of magnitude smaller than oil and gas extraction assets (\$1630 billion in 2018; Table 1).

The speed of widespread adoption of electric light-duty vehicles implied by the scenarios in this paper is far more rapid than current policies support. Under the most aggressive scenarios, electrification of US light-duty vehicles would begin in 2025, with the entire fleet transformed by 2030. This is starkly different to the commitments made at the United Nations Framework Convention on Climate Change Convention of Parties 26 by 30 nations and 6 automobile manufacturers to stop making fossil fueled light-duty vehicles by 2040.⁶ The United States was not one of the signatories to the COP 26 agreement. Nonetheless, it can be seen from our analysis that the current commitments essentially support continued investment in petroleum supply chain assets up to 2040 and for many years beyond.

In the United States, the stock of light-duty electric vehicles⁷ continues to steadily increase, reaching 1.8 million vehicles in 2020, but only 2% of new car sales were electric in 2020 (IEA, 2022). There are many policy issues with the rollout of electric vehicles in the United States. At the federal level, US fuel economy regulations (Corporate Average Fuel economy standards) have not had a strong positive impact on electric vehicles. However, 14 states have followed California's lead and adopted stricter low-emission vehicle (LEV) criteria pollutant and GHG emission regulations. California has also issued an executive order requiring that by 2035 all new car and passenger light truck sales be zero-emission vehicles (IEA, 2022). In 2021, the Biden Administration did announce a target of 50% electric vehicle sales by 2030 (The White House, 2021). Two of the biggest barriers remain cost and charging infrastructure. In general, electric vehicles are expected to reach costs parity in most markets by the late 2020s (BNEF, 2021). The recently passed Infrastructure Investment and Jobs Act allocates \$7.5 billion for charging infrastructure (Infrastructure Investment & Jobs Act, 2021), although to even support 100% electric vehicle sales by 2040 in this country may require investments of \$28 billion from 2021 to 2030 in non-home chargers (Bauer et al., 2021).

Another aspect of the scenario results requiring discussion is the role of international trade. The United States might reduce its need for fossil fuel assets by both reducing its export of refined petroleum and substituting imported crude in place of domestic production. There are possible constraints in that the United States tends to export lighter shale oils, because its refineries are geared to process heavier oils. Moreover, such changes have a negative impact on the US trade balance, and would only involve minor reductions in domestic GHG emissions, so are unlikely to be pursued through policy. The dynamics of global petroleum trade are to some degree outside of US policy. If trading partners, in particular Mexico, Canada, and Brazil, reduce their requirements for US refined petroleum products through their own electric vehicle policies, this helps with reducing investment in US fossil fuel assets. An alternative perspective might be that in phasing out oil refining, the United States would prioritize its own needs and rapidly seek to reduce exports. Still, as we saw in constrained refining scenario #2, the impacts of exports are modest.

More substantial and prolonged reductions in fossil fuel assets would require US policies beyond those supporting electrification of light-duty vehicles. Automobile use can be reduced through mass transit, and modal shift to non-motorized transport, aided over longer time scales by densification and changing urban form. Many of the other transportation modes, such as trucks and airplanes are harder to electrify due to their higher power intensities, although some technological progress is being made. After light-duty vehicles, trucks and airplanes are the next highest modes of transportation energy consumption, using approximately 4900 and 2000 PJ of petroleum products in 2018 (Table 3). Beyond transportation, over 2500 PJ of petroleum products are used by industry, residential, commercial and agricultural sectors; and approximately 5000 PJ for non-energy use (based on IEA energy balance table for United States). Reducing demand for refined petroleum products from these uses beyond transportation may be essential for sustaining a decline in the stock of fossil fuel assets.

If demand for petroleum in the United States can be reduced at rates similar to the depreciation of the main petroleum supply assets (oil wells and refineries), the supply of crude oil to the US economy could reduce by about 90% by mid-century (Figure 5). Such a reduction would be far greater than is observed with the IAM GCAM under either a 1.5°C climate change constraint at 2100, or business-as-usual. It should be noted that GCAM, like other IAMs, stays within 1.5°C, in part by relying on negative emissions technologies to offset continued direct CO₂ emissions,

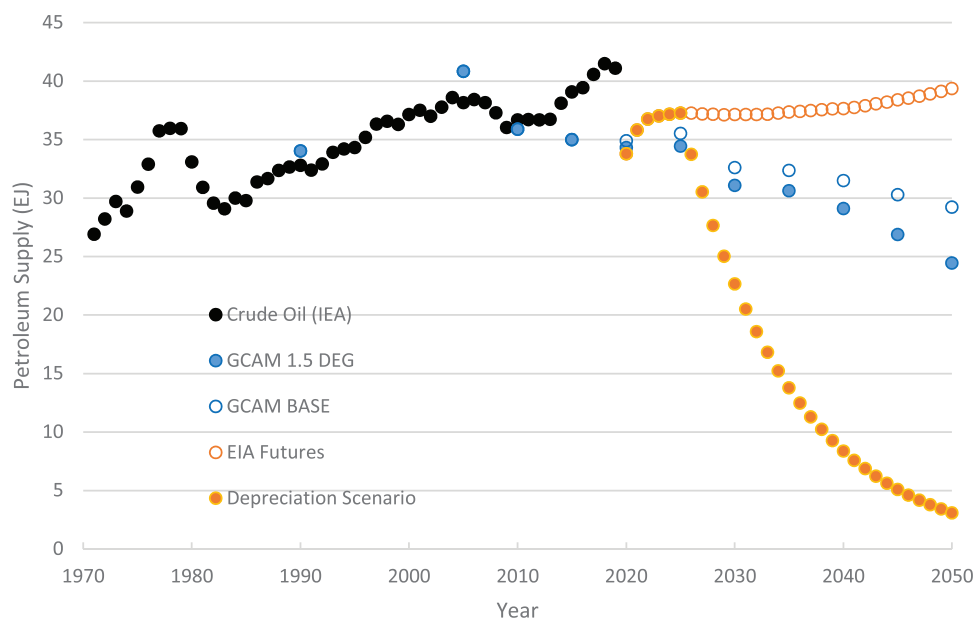


FIGURE 5 US supply of crude oil to 2050: Comparison of the extraction depreciation scenario against the EIA Annual Energy Outlook and two GCAM scenarios with and without a 1.5°C climate change constraint a 2100. See Supporting Information S1, Section VI for further details of the GCAM scenarios. Underlying data for this figure can be found in Supporting Information S2.

such as bio-energy carbon capture and other CO₂ removal from land use and land use change (Rogelj et al., 2018). (See Supporting Information S1, Section VI for more on the GCAM simulations.) Converse to both the asset depreciation scenario and the GCAM scenarios, the EIA's Annual Energy Outlook expects the supply of crude to the US economy to increase by mid-century.

5 | CONCLUSIONS

The key contribution of this paper lies in exploring decarbonization from the novel perspective of capital-stock depreciation dynamics. Using a tractable biophysical model, we have bridged supply-side and demand-side considerations showing both how upstream fossil fuel assets would change as the result of aggressive electrification of light-duty vehicles, and in reverse, calculating the magnitude at which such a transformation of the light-duty vehicle fleet would need to occur based purely on supply-side characteristics. Our novel methodology could also be used to explore transformation of other capital assets in the economy toward deep decarbonization. Importantly, by focusing our exploration of decarbonization on the depreciation dynamics of fossil fuel assets, the decarbonization strategies presented here are those that (excepting pipelines) straddle the line between a future characterized by the existence of stranded assets, and one in which fossil fuel assets are retired before the end of their operational lifespans.

As noted in the previous section, allowing fossil fuel assets to decrease at their depreciation rates implies immense declines in the capacity to provide fuels; however, the logic for how such a result might occur is subject to substantial complexities. On the one hand, we might imagine that sufficiently robust demand driven changes for fuels could lead to the scenario in which no new fossil fuel capacity is required and demand for fuels declines commensurately with the fossil fuel asset depreciation rate. Put differently, a straightforward mechanism to reduce investment in fossil fuel assets is to reduce the demand for the energy they supply. The mechanisms to enable a decline, or complete cessation, in investment in new fossil fuel assets, when considered from the supply-side perspective, might include a cessation of federal oil and gas leases on federal lands, and off-shore areas.

Reducing, or even eliminating, investment flows for new fossil fuel assets would occur in the cases that either the financing for such investment simply becomes unavailable (e.g., divestment policies or the restriction of loans from financial institutions) or that investments in non-fossil-fuel energy assets become sufficiently more attractive to displace fossil fuel investment entirely. While no mechanism is explicitly stated in the refinery and extraction scenarios, they are both characterized by an immediate drop in fossil fuel asset investment (refineries, pipelines, and extraction), and a transient increase in incremental wind and solar investment. Whether it be by restriction or induced by incentives, such as the clean energy tax credits in the Inflation Reduction Act (US House of Representatives, 2022), the supply-side scenarios indicate that a very substantial redirection of energy investment occurs in order to accommodate the depreciating fossil fuel assets. Furthermore, while no legal or process barriers are present to the building of new wind, solar, and electrical T&D assets in the model, the rate at which the scenarios indicate such assets would have to come

online presents significant problems in practical contexts. Put differently, achieving no new investment in fossil fuels while simultaneously building out compensatory renewable capacity requires both bringing said capacity online and integrating it into existing electrical grids very rapidly.

Realizing the principle of no new fossil fuel investment while avoiding either the problem of stranded assets or inefficient early retirement of fossil fuel assets requires designing demand-side policies based on the supply-side characteristics of fossil fuel assets; equivalently, this amounts to the statement that analysis of supply- and demand-side policies cannot occur in isolation. For the transformation to occur at the relatively fast rate demanded by the depreciation rates of fossil fuel assets raises several important questions concerning feasibility and points to areas of necessary further research. Principally interesting is whether the redirection (and possible upscaling) of energy investment toward renewable capacity, and the speed at which planning, legal, and logistical barriers to such new capacity construction can be surmounted actually occur can match the relatively rapid rates prescribed by the fossil fuel asset depreciation rates.

Ultimately the success of the pathways investigated in this paper would require these conditions be met, as otherwise a mismatch between demands and supply capacities for fossil fuels and electric power could arise. What we have shown are the existence of monetary and physical capital-stock and investment pathways predicated on the efficient phase out of fossil fuel assets. Whether such pathways can be realized is dependent on a large number of policy and financial considerations beyond the scope of this paper; however, what is clear from the analysis undertaken here is the important role that capital-stock dynamics play.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Supporting Information S2 contains data for the figures, plus spreadsheets for model simulations.

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NOTES

¹<https://atlas.eia.gov/>

²https://www.eia.gov/naturalgas/archive/analysis_publications/ngpipeline/index.html

³Energy Information Administration (EIA), Refinery Capacity Report, June 2021, <https://www.eia.gov/petroleum/refinerycapacity/>

⁴https://www.eia.gov/electricity/annual/html/epa_04_05.html

⁵<https://www.energy.gov/eere/vehicles/articles/fotw-1198-august-9-2021-average-age-us-light-duty-vehicles-reached-new-high>

⁶<https://www.gov.uk/government/publications/cop26-declaration-zero-emission-cars-and-vans/cop26-declaration-on-accelerating-the-transition-to-100-zero-emission-cars-and-vans#fn:1>

⁷Both battery electric and plug-in hybrid vehicles.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Kennedy, C. A., Sers, M., & Westphal, M. I. (2023). Avoiding investment in fossil fuel assets. *Journal of Industrial Ecology*, 27, 1184–1196. <https://doi.org/10.1111/jiec.13401>