Net energy analysis reveals sectoral strategies to mitigate derailment risks of electrification.

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Abstract

Mitigating climate change largely relies on substituting fossil fuels with low-carbon, electricity-producing energy sources. Resulting electrification alters sectoral energy demand and efficiency, and therefore also affects the amount of energy required to build energy transition infrastructure such as solar and wind farms, or grid extensions. As these transition energy requirements are significant and potentially disruptive, we develop a framework to assess how electrification will affect these requirements by disaggregating them into sectors and assigning electrification efficiencies to sectors. We apply this model to the European Union (EU-27) under a scenario phasing out fossil fuels by 2050 while maintaining 2021 energy service levels. We find that sectors employed to build transition infrastructure, such as iron reduction or heavy-duty road transport, are more difficult to electrify than the economy-wide average. Electrification therefore increases transition energy requirements relative to supply, exacerbating net energy challenges. We also find that, depending on the order in which sectors are electrified, transition-related demand for coal (linked to steel production for wind turbines) can be significant compared to its supply, and identify solutions to mitigate this criticality. Our results show that improving the electrification efficiency of sectors used in the transition significantly improves net energy prospects, hence we suggest prioritising battery electric trucks and industrial heat pumps over their less efficient hydrogen-powered alternatives. By capturing sector- and vector-specific dynamics, our analysis identifies previously undocumented net-energy challenges and actionable levers to mitigate them. These results highlight the importance of physically consistent transition models to guide the energy transition.

1. Introduction

The energy transition from fossil fuels to low carbon energy sources must proceed swiftly to keep global warming well below 2°C [1]. This endeavour requires coordinated global efforts and is constrained by both physical and social factors. On the social side, countries differ widely in their dependence on fossil fuels [2,3] and in their suitability for renewable energy sources [4–6], making international cooperation and multilateral agreements difficult to establish. Physical challenges range from mitigating the intermittency of solar and wind power plants [7], maintaining grid frequency as momentum-based generation declines [8], and managing the increasing material and energy intensity of the energy sector itself [9,10]. Here, we will focus on physical challenges, specifically the interaction between the evolving final energy mix and the energy requirements of the transition.

Building the renewable power plants, electric grid extensions, and end-use devices required to substitute fossil fuels currently entails using fossil fuels [10,11]. For example, primary steel in wind turbines is obtained from iron ore reduced using coal-derived coke in a blast furnace [12], transported with diesel and heavy fuel oil in heavy-duty trucks and cargo ships, respectively [13,14], and assembled into a turbine using diesel-fuelled cranes and other construction equipment. As a result, a coordinated hand-off between the current fossil fuel-based energy system and the future renewable-based energy system is required to prevent derailment risks [15] caused by fossil fuel shortages. However, the risk of such a shortage, and the potential for industrial electrification to mitigate this risk has not yet been explored.

Substituting all these processes with their electrified versions is likely to change the amount of energy required to build a wind turbine – or any other component of transition infrastructure. It remains uncertain, however, whether this change will increase or decrease transition energy requirements and ultimately affect net energy availability, especially considering the wide range of sectoral electrification efficiencies found (see Fig. 3). If electrification increases the energy efficiency of the overall economy to a greater extent than that of sectors used to build transition infrastructure, then the net energy challenges of the transition will be greater than estimated in previous work [10,16–22] (see Fig. 1). Worsening net energy conditions has been associated with declining socio-economic conditions such as increasing inflation [23], a rise in energy price [24], downward pressure on material prosperity [25], energy firms declining in profitability [19] and economic recession [24,26] and could hence cause societal backlash against the transition, thus representing another derailment risk. It is therefore essential to quantify the severity of these two risks as a first step towards establishing plans to mitigate them.

These two research gaps exist because most existing models study either transition energy requirements or changes in energy efficiency caused by electrification, but do not combine both fields in a single analysis [10,16–20,27–30]. Capellán-Pérez et al., 2019 [21] and Legendre et al., 2026 [22] are exceptions; however, this mechanism is not embedded in [22], whilst the electrification efficiency of sectors is not sufficiently disaggregated in [21] to support this analysis. Here, we propose a methodology to address these gaps which builds on a previous model developed by the authors [22]. By disaggregating the energy requirements of materials and processes used in the transition into sectors and calculating their electrification efficiencies, we can track how electrification shifts transition energy requirements away from fossil fuels and affects their magnitude. Using a physically consistent model, we investigate two research questions. First, we quantify how electrification can affect transition energy requirements. Second, we explore how changing the order of sector electrification may affect the total energy requirements of the transition, and the risk of fossil fuel criticality. Finally, we discuss opportunities to mitigate these derailment risks.

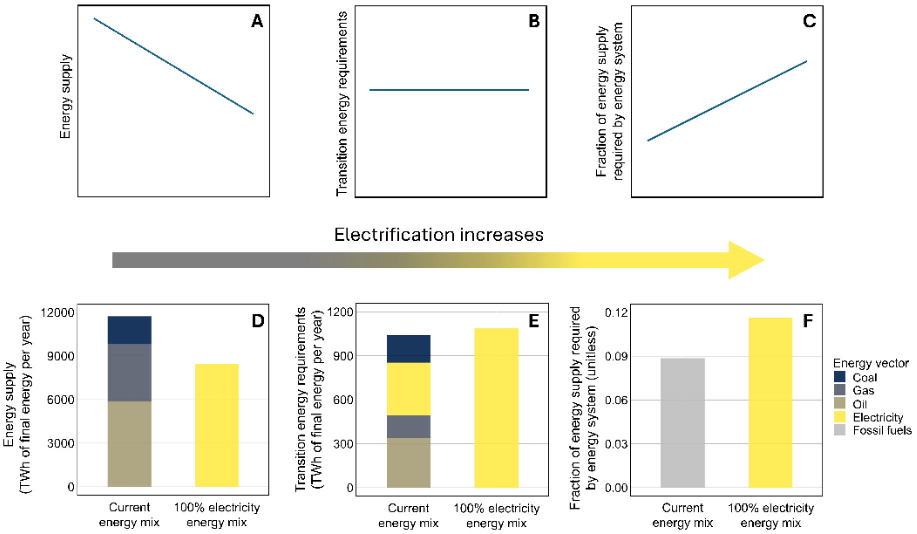

Fig. 1 | Electrification may worsen net energy prospects of the energy transition. Electrification of fossil fuel uses decreases the energy supply required to meet current energy services (A). If the energy required to build transition infrastructure is concentrated in sectors that do not become more efficient with electrification (B), then it will lead to transition energy requirements occupying a greater share of energy supplies (C). Panels D, E and F show corresponding stylised results from two scenarios where the energy supply remains fossil-based, with transition energy requirements met with fossil fuels (left) and the energy supply is 100% electric, and transition energy requirements are met with electrified processes (right).

2. Methodology

2.1 Methodology summary

The methodology proposed is summarised in Fig. 2 and builds on that developed by the authors in [22] which aimed to quantify the energy required to produce the renewable energy power plants and associated infrastructure necessary to phase out fossil fuels while maintaining current services. In addition to this, the new methodology enables quantifying the changes in transition energy requirements caused by the inherent electrification of means of producing transition-related infrastructure during the transition. This methodology also enables disaggregating transition energy requirements into major energy vectors (oil,

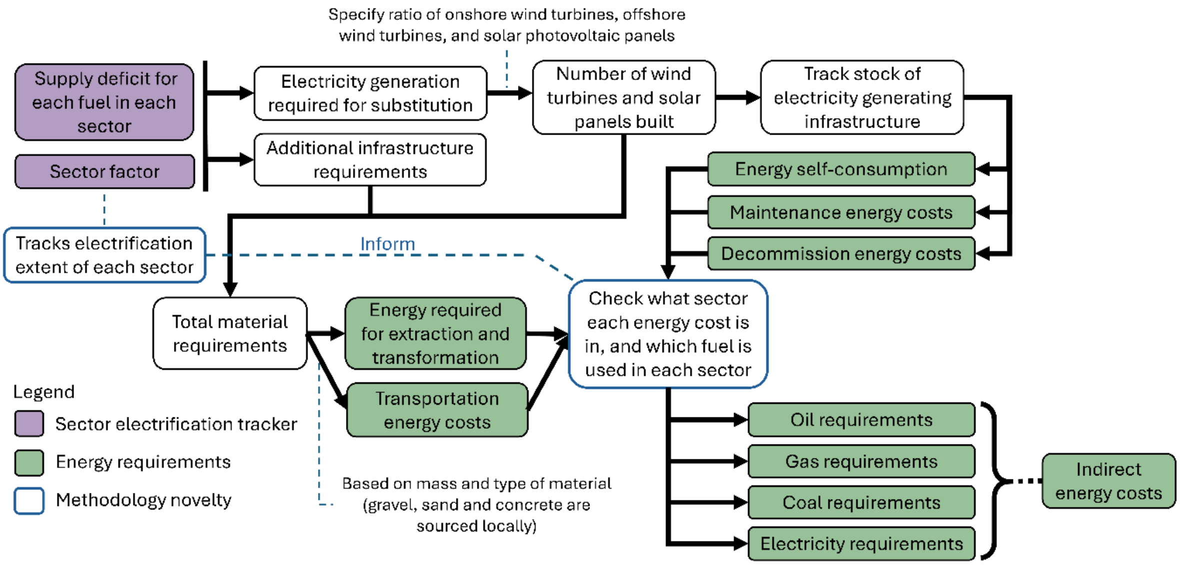

Fig. 2 | Methodology. Summary of the method used to calculate yearly transition energy requirements. The energy supply deficit in each fuel-sector combination is multiplied by the associated sector factor to determine the electricity generation required to substitute these fuels. The capacity of wind turbines and solar panels required to generate this electricity is calculated based on their performance factors. By tracking the stock of electricity generating infrastructure, we estimate the operation-related energy requirements of the stock. For each sector, we quantify the infrastructure requirements for using the electricity generated. We estimate the material requirements of renewable power plants and additional transition infrastructure using life cycle inventory analyses. Each material requirement is multiplied by its corresponding energy intensity broken down into sectors (e.g., iron reduction, industry thermal energy use, etc.) based on a tailor-made dataset to obtain transition energy requirements disaggregated into sectors. Finally, we disaggregate these energy requirements into energy vectors by tracking the extent of electrification of each sector the energy is used in and estimate indirect energy requirements.

gas, coal, and electricity) to identify potential fuel-specific supply and demand challenges. To avoid unnecessary repetition, details of the previously developed methodology are found in [22], and this section focuses on the differences and improvements made over the previous version. We focus on a scenario phasing out fossil fuels by 2050 to represent current net-zero plans, and because it most clearly exhibits the differences in results stemming from the novel methodology developed.

2.2 Estimating sector factors

Substituting fossil fuels in different sectors requires a different amount of electricity per unit of fossil fuel. To accurately account for this discrepancy, we calculate this ratio, called a "sector factor" for each major energy consuming sector of the economy using equation 1,

$$SF_{f,s} = \frac{final\ electrical\ energy\ required\ to\ provide\ service\ (MJ\ of\ electricity)}{final\ thermal\ energy\ required\ to\ provide\ service\ (MJ\ of\ thermal\ energy)}, \text{(Eq. 1)}$$

in which $SF_{f,s}$ is the sector factor for fuel *f* used in sector *s*. Fig. 3.3 summarises the sector factors calculated, and detailed information on how each factor is calculated is provided in supplementary note 1. We provide an example calculation below for the light road transport in equation 2,

$$SF_{LRT} = \frac{final\ electricity\ to\ drive\ BEV\ 100km * \frac{1}{EV\ charger\ efficiency}}{final\ thermal\ energy\ to\ drive\ ICEV\ 100km}, \qquad \text{(Eq. 2)}$$

where SF_{LRT} is the sector factor of the light road transport sector, and "EV charger efficiency" represents the amount of electricity reaching the EV batter divided by the electricity taken from the grid. The final electricity required to drive a battery electric vehicle for 100 km is based on an efficient commercially available vehicle (13.7 kWh, or 49.3 MJ of electricity [31]), the corresponding value for internal combustion engine vehicles is taken as the average value for the EU fleet (6 L of gasoline or 192 MJ [32]), and the efficiency of electric vehicle chargers is taken as 88%, the higher end of values found by [33]. This results in a sector factor of 0.29.

Compared to our previous work [22], we further disaggregate the road transport sector into light and heavy road transport to better capture the effect of electrifying road transport on the transport-related energy requirements of the transition. We also disaggregate the industry energy use sector into "industry thermal energy use" and "construction and mining" sectors because these have markedly different sector factors, and the transition includes a significant amount of energy use relating to soil preparation and mining (as shown in Fig. 4) which is well-represented by this additional sector.

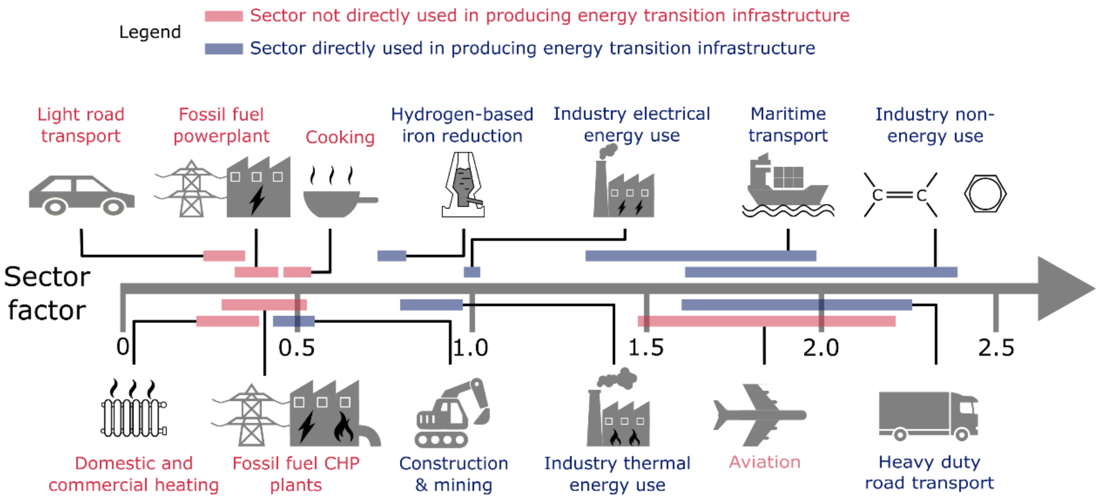

Fig. 3 | Sector factors of the major energy consuming sectors of the economy. The shaded bars represent the likely range (3 standard deviations) of the values given current estimates and the maturity of the technology used. Sectors labelled in blue are directly used in producing and deploying energy transition infrastructure while sectors labelled in red are not. Sectors farther to the right have higher sector factors, meaning they require more electricity to replace one unit of fossil fuel. As many of the blue sectors are on the right, this suggests deep electrification will increase transition energy requirements. All values and sources used are available in supplementary note 1 of this paper and supplementary note 2 of [33].

2.3 Disaggregating the energy required to extract, transform, and transport materials

The material-related energy requirements make up 84% (see supplementary Fig. 2) of the total transition energy requirements and are disaggregated into sectors based on detailed process data. As it would be difficult to find reliable, detailed and representative information for every material used in the energy transition, we obtained this data for the 11 materials and processes representing 90% of the material-related energy requirements. The energy intensities of the remaining materials were taken from [34] and [35] (adjusted to final energy) and were disaggregated into sectors according to the weighed distribution of the other materials. All sources, resulting disaggregation, and explanations can be found in the excel supplementary information. The yearly energy requirements related to the material requirements of the transition are calculated using equation 3,

$$E_{mat,\ s,\ y} = \sum_{m=1}^{m_{max}} M_{m,\ y}\ EI_{m,\ s}, \qquad \text{(Eq. 3)}$$

where $E_{mat,\ s,\ y}$ represents the energy requirements linked to material extraction and transformation in sector *s* for year *y*, $M_{m,\ y}$ represents the mass of material *m* required for year *y*, and $EI_{m,\ s}$ represents the energy intensity of material *m* in sector *s*.

The energy required to transport materials has been updated compared to [33]. We still assign 500 km of heavy-duty road transport and 10,000 km of maritime transport to materials except for gravel, sand and concrete which are sourced locally and hence only require 250 km of heavy-duty road transport as suggested by Kis et al., 2018 [36]. However, the energy required per ton-km of heavy-duty road transport has been revised from 3.5 MJ t^{-1} km^{-1} to 1.2 MJ t^{-1} km^{-1} based on industry data (see supplementary note 2). The specific energy requirements of maritime transport are kept at 0.2 MJ t^{-1} km^{-1}.

2.4 Disaggregating other energy requirements into sectors

Self-consumption, decommission, and maintenance energy requirements are calculated in the same way as described in [22]. Self-consumption is allocated to the industry electricity use sector as it is exclusively in the form of electricity. Maintenance energy requirements are distributed amongst sectors in the same way as that year's material-related energy requirements. This is a simplification as the materials required to maintain renewable energy power plants will not perfectly match those needed to build them. However, since maintenance energy requirements only represent 1% of total transition energy requirements (see supplementary Fig. 2), this does not significantly affect the results. Decommission energy requirements – which represent <0.1% of total energy requirements (see supplementary Fig. 2) – are entirely allocated to the construction and mining sector as the construction vehicles (bulldozers and diggers) used in decommissioning are well-represented by those considered to calculate the sector factor of the construction and mining sector.

2.5 Tracking the extent of electrification of each sector

The methodology presented calculates the amount of electricity generation required to substitute fossil fuels based on which sector these fossil fuels are used in. In doing so, it inherently tracks the amount of fossil fuel removed from each sector. To track the extent of electrification of each sector, we simply subtract the cumulative amount of fossil fuel removed from a sector divided by the total amount of fossil fuel initially used in the sector from unity, as shown in equation 4,

$$EE_{f,\ s,\ y} = 1 - \left(\frac{\sum_{y=1}^{y}\sum_{f=1}^{3} FFR_{f,s,y}}{\sum_{f=1}^{3} FFI_{f,s}}\right), \qquad \text{(Eq. 4)}$$

where $EE_{f,\ s,\ y}$ is the extent of electrification of fossil fuel *f*'s use in sector *s* in year *y* (a fraction between 0 and 1), $FFR_{f,s,y}$ is the amount (in Joules) of fossil fuel *f* removed from sector *s* in year *y*, and $FFI_{f,s}$ is the amount of fossil fuel *f* initially used in sector *s*.

2.6 Calculating dynamic energy requirements of the transition

We define the transition energy requirements calculated using our novel methodology as "dynamic energy requirements" while those calculated assuming the transition energy requirements have identical efficiency gains to the overall economy as "static energy requirements". To calculate the dynamic energy requirements of the transition, we use a three-step process. First, we track the yearly energy requirements of the transition in each sector using equation 5,

$$TER_{s,\ y} = E_{mat,\ s,\ y} + E_{trans,\ s,\ y} + SC_{s,\ y} + E_{maint,\ s,\ y} + E_{decom,\ s,\ y}, \qquad (\mathrm{Eq.}\,5)$$

where $TER_{s,\ y}$ is the total energy requirements in sector *s* for year y, $E_{trans,\ s,\ y}$ represents the energy requirements linked to transporting materials, $SC_{s,\ y}$ represents the energy self-consumption of renewable power plants in sector *s* for year *y*, $E_{maint,\ s,\ y}$ represents the maintenance-related energy requirements in sector *s* for year *y*, and $E_{decom,\ s,\ y}$ represents the decommission-related energy requirements in sector *s* for year *y*. The sources and explanations for the values of $E_{trans,\ s,\ y}$ are found in section 2.3 and supplementary note 2. For $SC_{s,\ y}$ and $E_{maint,\ s,\ y}$, they are found in the excel supplementary information. $E_{decom,\ s,\ y}$ is estimated as 10% of the material-related energy requirements of the power plant based on [37]. Second, we track how much of each energy vector is used to meet transition energy requirements each year using equation 6 for fossil fuels and equation 7 for electricity,

$$E_{total,\ f,\ y} = \sum_{s=1}^{s_{max}} TER_{s,\ y}\left(\frac{IE_{f,\ s}}{IE_{total,\ s}}\right)\left(1 - EE_{f,\ s,\ y}\right), \qquad (\mathrm{Eq.}\,6)$$

$$E_{total,\ e,\ y} = \sum_{f=1}^{3}\sum_{s=1}^{s_{max}} TER_{s,\ y}\left(\frac{IE_{f,\ s}}{IE_{total,\ s}}\right)\left(EE_{f,\ s,\ y}\right), \qquad (\mathrm{Eq.}\,7)$$

where $E_{total,\ f,\ y}$ is the total amount of fossil fuel *f* required by the transition in year y, $IE_{f,\ s,\ y}$ is the initial amount of energy provided by fossil fuel *f* in sector s, $IE_{total,\ s}$ is the total amount of energy initially used in sector s, and $E_{total,\ e,\ y}$ is the total amount of electricity used by the transition in year *y*. Third, we aggregate the energy requirements by vector into final energy using equation 8,

$$E_{total\,final,\ y} = \sum_{f=1}^{3} E_{total,\ f,\ y} + E_{total,\ e,\ y}, \qquad (\mathrm{Eq.}\,8)$$

where $E_{total\,final,\ y}$ is the total energy required by the transition in year y.

2.7 Indirect energy requirements

The direct energy requirements calculated using equation 8 are obtained using a bottom-up assessment and hence are likely underestimated due to truncation errors caused by narrow system boundaries [38–44]. To estimate the truncation error, referred to here as indirect energy requirements, we consulted literature which aims to quantify this error in the context of process-based life cycle assessments [38,44]. As in [22], we use a ratio of "true" energy requirements to estimated energy requirements of 1.3, which means the true energy requirements are 30% larger than the direct energy requirements. The indirect energy requirements are assumed to be spread across sectors and energy vectors with the same distribution as direct energy requirements.

2.8 Uncertainties and sensitivity analysis case studies

The parameters used in this model are all derived from peer-reviewed sources, with most parameters being based on multiple sources. However, there is still uncertainty associated with each parameter. To test the robustness of the model results, we assign an uncertainty in the form of a standard deviation to each parameter based on the certainty of the source(s) used to obtain it (see supplementary Table 3 for mean and standard deviation values used). The model is then run 1,000 times for each case studied, sampling parameter values from a Gaussian distribution, and a 90% confidence interval is shown on every result obtained.

In addition to this, we conduct three sensitivity analysis case studies on parameters that are highly uncertain and parameters of which the value results from engineering or policy decisions that have not yet been taken. (1) Industry thermal energy use can be electrified by using electricity directly, by using green hydrogen, or by using high-temperature heat pumps where applicable. We use three different values for the industry energy use sector factor to represent (i) a neutral mix of technologies as used in the default model, (ii) a mix of technologies with a high penetration of hydrogen use, and (iii) a mix leaning towards a high uptake of heat pumps. (2) The electrification of heavy-duty road transport can be achieved by using either hydrogen fuel cells or batteries to replace diesel tanks. We use two different values for heavy-duty road transport sector factors to represent (i) using fuel cells as in the default model and (ii) using batteries. Note that choosing batteries over fuel cells would result in a significantly lower range, which could exacerbate logistical challenges, and that although batteries represent significant energy requirements in light vehicles, we assume these energy requirements are negligible for trucks due to their high use factor (as a device is used more intensively during its lifetime, its embodied energy diminishes compared to the energy is uses). (3) The length of grid extensions needed to transport the additional electricity generated and deal with the spatial heterogeneity of wind and solar-based generation is subject to significant uncertainty [9,45–47] (see supplementary note 5 of [22]). We assess the impact of the modelling methodology used by producing three scenarios where (i) the grid requirements scale with the gross electricity production as in the default model, (ii) the grid requirements scale with the installed capacity of power plants (as done by [9]), and (iii) the distribution grid scales with installed capacity, and the transmission grid scales with four times the electricity generation (as observed in literature summarised in supplementary note 5 of [22]).

3. Results

3.1 Industrial sectors used to produce transition infrastructure are more difficult to electrify than average.

We summarise the distribution of transition energy requirements among different sectors and energy vectors in Fig. 4 for two illustrative scenarios: one where all infrastructure is built with the current energy mix, and another where all infrastructure is built using electrified processes only.

We observe that 33-35% of the transition energy requirements are in industry electricity use, which does not become more efficient in final energy terms when switching from a fossil fuel to a solar and wind-based energy system. This is mainly due to two materials required by the transition which have electricity-intensive production processes: aluminium, used in solar panel frames and grid transmission lines, and silicon wafers in photovoltaic panels. The sectors which experience efficiency gains with electrification are industry thermal energy use (used widely in production processes), iron reduction (for primary steel production used mainly in wind turbine towers), and construction and mining (used in the mining phase of all minerals, and site preparation for solar plants and wind turbine foundations). On the other hand, heavy duty road transport (used for all materials, but with the bulk of energy demand associated with gravel, sand and concrete transport which make up 65-80% of mass requirements of wind and solar farms), maritime transport (used for all materials), and industry non-energy use (mainly producing plastics used as wire gauges, and other smaller parts) become less energy efficient with electrification. Note that using battery electric trucks would reverse the trend for heavy duty road transport, as seen in sector factor calculations in supplementary note 1 and supplementary figure 3.

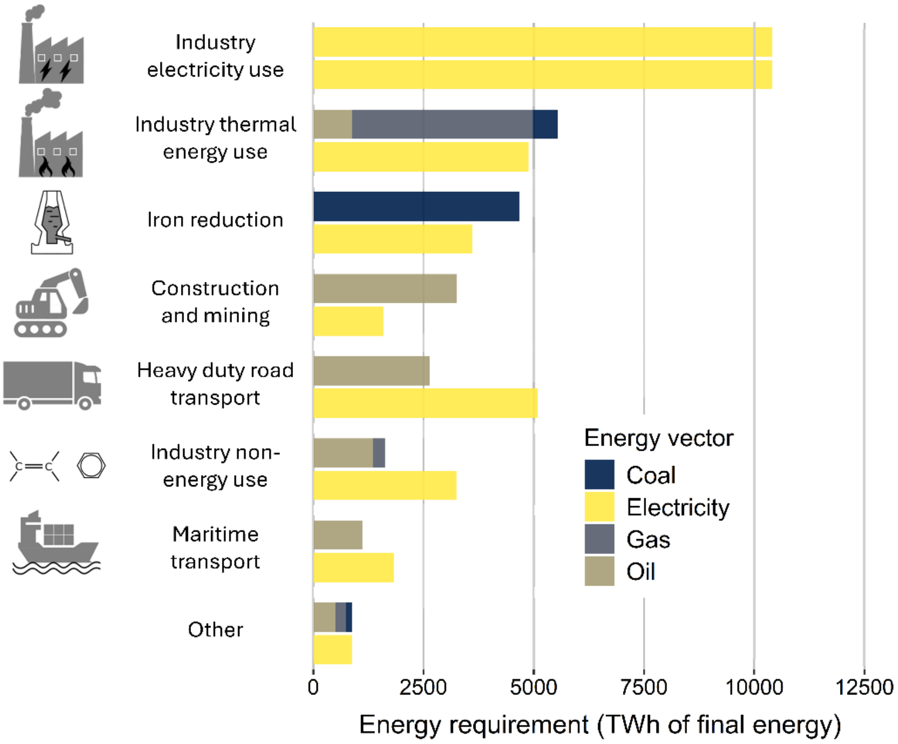

Fig. 4 | Distribution of transition energy requirements amongst sectors. Total energy required by the transition in each sector to phase out fossil fuels by 2050, whilst maintaining all services previously provided by fossil fuels. The top bar indicates the amount of energy required using the current energy mix disaggregated by energy vector, and the bottom bar indicates the amount of energy required if the energy mix is 100% electrical.

3.2 Electrifying transition infrastructure production processes increases total transition energy requirements.

We compare transition energy requirements calculated using the static and the dynamic modelling methods under three scenarios with different sector electrification orders (Fig. 5). In the static methodology results, the three scenarios exhibit two similar trends: first, around 2047, 25 years after the start of the transition, there is an increase in transition energy requirements caused by the need to replace wind turbines built in 2022. Secondly, the transition energy requirements increase gradually as the stock of solar panels and wind turbines grows, leading to higher electricity self-consumption and maintenance requirements.

The different shapes of the three static methodology curves are caused by the order of sector electrification. The model assumes we substitute a fixed amount of fossil fuels each year, hence electrifying a high-sector factor sector requires more wind turbines, solar panels and grid extensions to be built in a year, leading to higher transition energy requirements. Electrifying sectors in order of increasing or decreasing electrification difficulty effectively shifts energy transition requirements later (Fig. 5A) or earlier (Fig. 5C) respectively, while simultaneous electrification spreads the transition energy requirements as evenly as possible (Fig. 5B). Despite all three scenarios having the same stock of solar panels and wind turbines at the end of the transition, building the stock later means it needs to be maintained and operated for less time, and fewer wind turbines are built before 2025 and ultimately need to be replaced within the transition period. As a result, electrifying sectors in order of increasing difficulty leads to the lowest static transition energy requirements, followed by simultaneous electrification and decreasing difficulty. This mechanism affects the dynamic methodology scenarios in the same way as the static methodology.

The divergence between the results of the static and dynamic methodologies increases as sectors directly used to produce energy transition infrastructure are electrified (Fig. 5A-C). This occurs because these sectors have a high – and hence unfavourable - weighted average sector factor of 1.07, compared to 0.80 for the overall economy. As a result, the dynamic methodology always reports higher transition energy requirements than the static methodology, although the difference in cumulative energy requirements of the between the two methodologies varies depending on the order of sector electrification (Fig. 5D-F). When sectors are electrified in order of increasing difficulty (Fig. 5A, D), the sectors used in producing transition infrastructure are electrified later, hence the energy requirement burden is born for fewer years leading to lower overall transition energy requirements. In contrast, electrifying sectors in order of decreasing difficulty causes these sectors to be electrified earlier on, resulting in the energy burden being born for the longest time and requiring the highest transition energy requirements of the scenarios shown (Fig. 3.4B, E). Electrifying all sectors simultaneously leads to the transition energy requirements obtained from both methodologies diverging progressively, and to intermediate cumulative energy requirements relative to the other two scenarios (Fig. 5C, F).

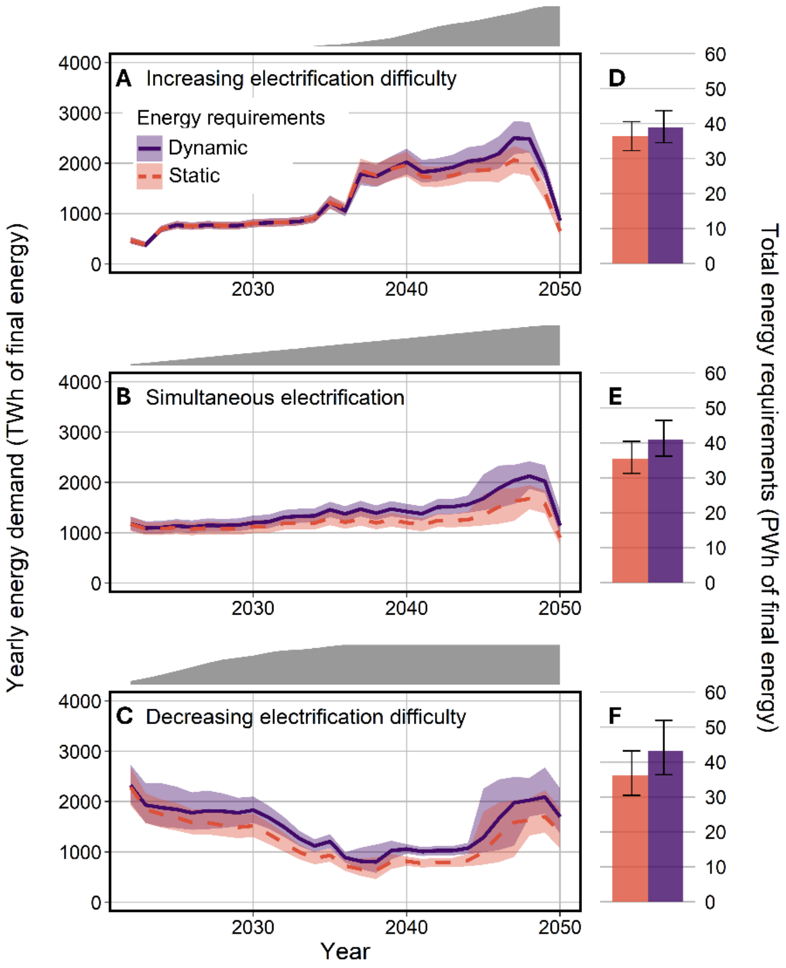

Fig. 4 | Effect of sector electrification order on transition energy requirements. Yearly (A-C) and cumulative (D-F) energy requirements of the transition using a static (red bars and dashed lines) or dynamic (purple bars and lines) modelling methodology. The grey shaded area above each plot represents the overall progression of electrification in sectors directly used to produce transition infrastructure. The shaded regions surrounding the lines and the error bars on the bar charts represent 90% confidence intervals based on 1,000 simulations with parameter values sampled from normal distributions.

3.3 Fossil fuel supply tensions can be mitigated through selecting the order of sector electrification.

When sectors directly used in producing transition infrastructure are electrified, the energy requirements of the transition are shifted from fossil fuels to electricity (Fig. 4). We show this on a continuous timeline in Fig. 6A-D. In Fig 6A-C, we see that for the decreasing sector factor scenarios, fossil fuels are phased out from transition energy requirements by mid-transition and hence show the lowest transition fossil fuel requirements (Fig 6E). In the other two scenarios, they are required all throughout the transition. As a result, electricity requirements are much higher for the decreasing sector factor scenario for the first half of the transition (Fig. 6D). Only the coal requirements in the increasing sector factor scenario come close to their respective supply, indicating criticality, while all other energy vectors and scenarios exhibit low criticality.

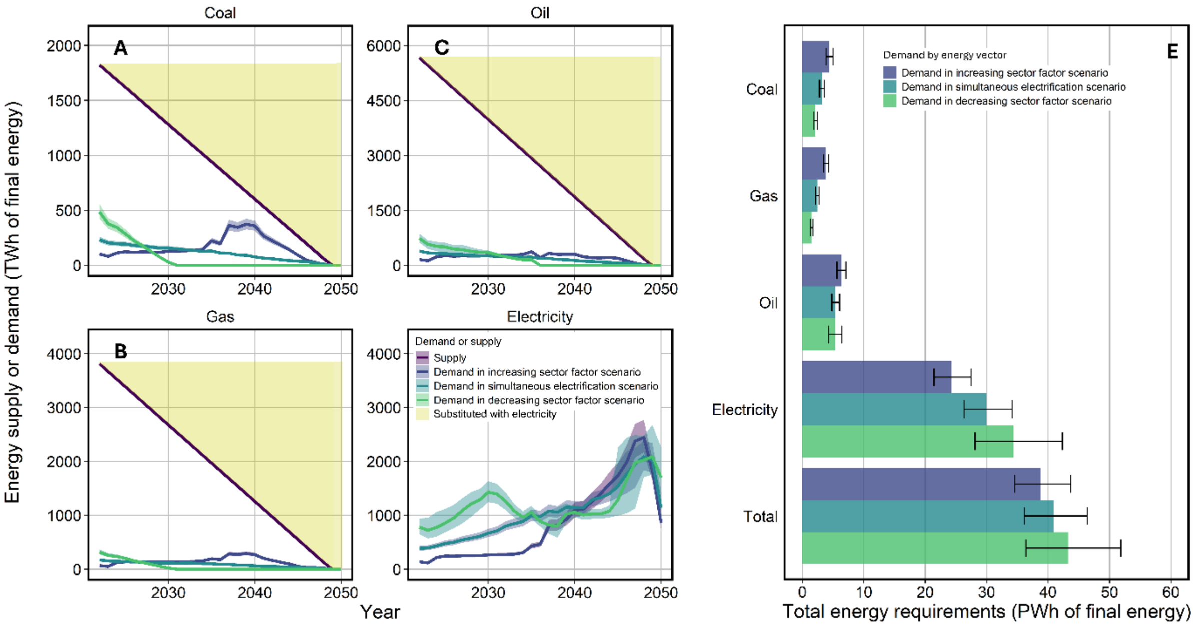

Fig. 6 | Effect of sector electrification order on fossil fuel demand and criticality. Yearly transition-related demand of coal, oil, gas, and electricity (A-D) and cumulative transition-related energy requirements disaggregated by energy vector (E). The shaded regions surrounding the lines and the error bars on the bar charts represent 90% confidence intervals based on 1,000 simulations with parameter values sampled from normal distributions.

4. Discussion

4.1 Mechanisms governing effects of electrification on transition energy requirements and fossil fuel dependence

There are multiple mechanisms shaping the evolution and magnitude of transition energy requirements, which we unpack here. First, our model assumes a fixed quantity of fossil fuels is substituted with electricity each year, hence yearly additional electricity production – and the associated amount of transition infrastructure and energy requirements – is determined by the sector factor of the sectors being electrified that year. As a result, transition energy requirements in the increasing electrification difficulty scenario (Fig. 5A) and the decreasing electrification difficulty scenario (Fig. 5C) are concentrated at the end and start of the timeline, respectively, while the simultaneous electrification scenario (Fig. 5B) shows a more even distribution with an upward trend caused by maintenance and self-consumption energy requirements increasing with the stock of renewable energy power plants (see supplementary Fig. 2B).

Second, the divergence between the two methodologies in Fig. 5A-C occurs when sectors used by the energy transition are electrified. This is because the "dynamic" methodology effectively captures the changing efficiency of, for example, maritime transport used to ship materials required by the transition as a result of electrification, whereas the "static" methodology assumed this process electrifies with the same efficiency as the average sector (0.8 units of electricity per unit of thermal energy). The sectors used by the transition are more difficult to electrify than average (1.05 units of electricity per unit of thermal energy), hence the dynamic methodology shows consistently higher transition energy requirements with the divergence occurring at the end and start of the transition in Fig. 5A and 5C, respectively, while progressing gradually in Fig. 5B.

Electrifying the sectors used to produce transition infrastructure shifts the transition energy requirements from fossil fuels to electricity, hence the order in which sectors are electrified dictates the transition's reliance on fossil fuels. These sectors are harder to electrify than average, hence electrifying sectors from easiest to hardest leads to the transition using the largest amount of fossil fuels, whilst simultaneous electrification results in moderate fossil fuel usage, and electrifying sectors from hardest to easiest minimises fossil fuel usage (Fig. 6E). As electrifying sectors from easiest to hardest concentrates the transition energy requirements later in the transition, and this is also when fossil fuel supplies are the lowest, it leads to the largest share of available fossil fuels being required by the transition (Fig. 6A-C). This fraction is generally low, except for coal in the increasing electrification difficulty scenario, where transition coal requirements reach 60% of available coal (Fig. 6A), mainly due to its use in iron reduction and to a lesser extent industry thermal energy use (see Fig. 4). Natural gas follows a similar pattern to coal due to its extensive use in industry thermal energy use, while oil is used in several sectors with a wide range of sector factors, making its transition-related use less sensitive to electrification order (see Fig. 4).

4.2 Anticipating derailment risks associated with transition energy requirements

Our findings suggest it is likely that during an ambitious energy transition, net energy availability will decrease at least temporarily, however understanding the mechanisms governing this enables identifying opportunities to mitigate these challenges. If we allow net energy to decrease unchecked, the consequences of this – which include increasing inflation, energy prices, and general price levels, decreasing material prosperity and potentially an economic recession – could lead to social backlash, slowing down the deployment of non-fossil sources. This would be highly undesirable as it would force us to rely longer on fossil fuels which are becoming more sparse and harder to extract and process [48,49] (and recently, transport due to conflicts near the Strait of Hormuz), which would weaken the resilience of the energy system and make it all the more difficult to allocate a significant part of our energy supply to deploying renewable energy sources. System-level net energy will decrease in part because the energy required by fossil fuels will persist proportionally to their consumption and hence overlap with transition energy requirements which are paid "upfront", causing the energy requirements of two systems to be born without increasing energy supply (as in Fig. 4 of Legendre et al., 2026 [22]). It must be noted that remaining in a fossil-fuel dominated system poses more certain threats to long-term energy availability than transitioning to more sustainable sources. This is due to two factors: their exhaustible nature forcing an eventual terminal decline in supply [50–52] and their decreasing energy return on investment linked to the use of increasingly hard-to-obtain resources [48,49]. It is therefore essential that we anticipate these net energy challenges and mitigate derailment risks which could slow down the substitution of fossil fuels by sustainable energy sources [15].

We identify several opportunities to mitigate these derailment risks based on our results and discuss additional measures qualitatively. First, based on Fig. 5D-F, we find that electrifying sectors in order of increasing difficulty leads to lower transition energy requirements. This is not observed in the static methodology, highlighting the importance of our novel methodology. Second, we find that choosing technologies which electrify sectors employed in deploying transition infrastructure more efficiently decreases transition energy requirements through two mechanisms: (i) the resulting decrease in electricity demand decreases the amount of power plants and grid extensions required and (ii) when these sectors are electrified, less energy is needed to deploy each unit of transition infrastructure. Favouring battery electric trucks over hydrogen fuel cell trucks and industrial heat pumps over electric boilers decreases transition energy requirements by 13% and 6% respectively, while opting for hydrogen boilers leads to an 11% increase (see supplementary Fig. 3). Applying targeted sufficiency to sectors which are hard to electrify and have low social value could also play a significant role. For example, decreasing the size of individual electric passenger vehicle batteries from 60 kWh to, on average, 30 kWh could reduce total transition energy requirements by approximately 10% (due to the energy intensity of battery production) while a 30% gain in energy efficiency in these lighter vehicles could lead to a further 3% decrease. Converting aircraft class seating arrangements to all-economy could reduce aviation emissions (and hence energy demand) by 26-57%, which would decrease total transition energy requirements by approximately 2-5% [53]. Decreasing the amount of energy allocated to aviation could further reduce transition energy requirements with manageable social impacts as 1% of the global population is responsible for 50% of commercial aviation-related greenhouse gas emissions [54]. By decreasing the total electricity production required, these two types of opportunities also decrease the penetration of intermittent renewable electricity sources, which would decrease storage infrastructure requirements, curtailment losses, and storage losses [7], further improving net energy prospects.

When the total energy requirements of the energy systems increase past those of the current fossil fuel energy system, this excess energy will need to be taken from an existing sector and reallocated to sectors used to produce transition infrastructure (such as those in Fig. 4). To mitigate backlash risks, we suggest this energy should be taken in priority from sectors providing non-essential products. This is more feasible in the global north, which could cut its energy consumption by 75% without compromising on “decent living standards” than in the global south, which needs 74% of its current energy consumption to meet the same standards [55]. If some energy still needs to be taken from more essential sectors, such as mobility to access work, education, healthcare and other essential goods and services, or domestic heating, one solution would be improving the energy efficiency of these essential sectors through developing more energy efficient public transport, private vehicles, and insulating buildings. By reducing the energy required to provide essential services, a larger energy budget could be carved out for the energy transition without risking social backlash.

In addition to net energy challenges, the energy transition requires a coordinated handoff from the fossil fuel system to the renewable-based system, as deploying transition infrastructure will continue to require fossil fuels during the transition. The increasing electrification scenario minimises transition energy requirements but leads to the highest dependence on fossil fuels (Fig. 5D-F, Fig. 6E). This is not inherently problematic but does lead to the transition requiring a significant share (60%) of available coal supply towards the end of the transition, making the transition more sensitive to supply shocks, which is particularly significant since the EU imports 60% of its hard coal [56] which is used to make coke for iron reduction. This vulnerability can be mitigated by electrifying iron reduction earlier in the transition when coal is more abundant. As iron reduction has a sector factor of 0.77, it would also decrease transition energy requirements by producing iron more efficiently for a longer part of the transition. A similar strategy could be applied to the industry thermal energy use sector, specifically for natural gas, and would prove doubly effective if more efficient heat pumps are used over electric boilers.

4.3 Implications of dynamic methodology results for net energy research

A persistent methodological challenge in net-energy analysis arises from the need to compare energy sources of different forms, such as electricity and heat, using a conversion factor [57]. This is particularly relevant when estimating the energy return on investment (EROI) of energy technologies that produce electricity – such as wind turbines, solar panels, nuclear power plants or hydroelectric dams – but require both electrical and thermal energy to build. Previous studies assumed very different, static conversion factors. Sahin et al. [20] assumed one unit of primary thermal energy converts to 0.4 units of electricity, while Capellán-Pérez et al. [21] and Slameršak et al. [10] assumed that final thermal and final electrical energy are equivalent.

The framework we present addresses this discrepancy by deriving a physically grounded conversion ratio. Once all sectors have been electrified, we find that, on average, 0.80 units of final electrical energy are needed to substitute one unit of fossil fuel-based final thermal energy. This is slightly higher than the value of 0.72 found in [22] because heavy road transport is considered separate from light road transport in this paper and has a worse sector factor. However, if battery electric trucks are considered instead of hydrogen fuel-cell trucks, this value decreases to 0.73. We suggest that the appropriate ratio depends on the context studied and should be calculated based on which sectors are electrified, and with what technology.

As our results indicate that the electrification of sectors leads to changes in the amount of energy needed to produce materials used in transition infrastructure, the denominator of an EROI calculation (the amount of energy required to obtain a unit of energy) must be dynamic. We find that obtaining materials for onshore wind turbines, solar panels, and offshore wind turbines with a fully electrified mix requires 8%, 8%, and 11% less final energy, respectively, than with the current mix. This reflects offshore wind turbines relying most heavily on steel production, which electrifies efficiently (see Fig. 3), whereas the energy requirements of solar panels and onshore wind turbines are distributed towards harder-to-electrify sectors. The overall increase of transition energy requirements is driven by the inefficient electrification of maritime and heavy-duty road transport. These insights indicate the transition itself will change the energy requirements of transition infrastructure, and therefore the static "cumulative energy demand" approach used by previous studies [16–21,58] is not appropriate for scenarios where electrification expands to sectors used in deploying transition infrastructure. Given that the dynamic methodology finds higher transition energy requirements, previous work is also likely to underestimate these requirements. A robust physical framework capable of reflecting this dynamic system is therefore indispensable to net energy analysis in a transition context.

4.4 Limitations and future research opportunities

Despite improving on previous approaches to estimate transition energy requirements, this study retains several limitations, which we outline below alongside avenues for future research.

We use static values for several parameters that may be better described by dynamic values, such as the energy efficiency of services, their demand levels, the performance factors of renewable power plants, and their material requirements. The model also has a limited scope and hence cannot consider how climate change will affect bioenergy and hydroelectricity supply, or how the recycled content of materials will evolve. Finally, we do not use a full energy system optimisation model (ESOM) to estimate the grid extension requirements or storage losses arising from the increasing electricity production from intermittent sources (see section 5.3 of [22] for a detailed discussion of how these limitations can affect the results).

Beyond these methodological and scope-related constraints, broader system-level dependencies must also be considered. Although we estimate how much transition energy requirements increase once fossil fuels are completely phased out, this does not mean that the supply chains of transition infrastructure are made independent of fossil fuels. For example, helium, a by-product of natural gas [59], is used in the manufacture of semi-conductors [60], which are essential for making the inverters required by solar and wind farms [61]. As a result, if global natural gas production is stopped, essential components of a solar- and wind-heavy grid risk becoming unavailable. Such supply chain dynamics are beyond the scope of this work, but identifying them is essential to understanding and overcoming obstacles to the transition

Finally, future work could go beyond estimating sector- and energy vector-level transition energy requirements in two ways. First, as oil and coal are not homogenous vectors, and different subcategories of these fossil fuels can only be used in specific sectors (e.g., gasoline and bitumen are not interchangeable, and neither are bituminous and sub-bituminous coals) further disaggregating their supply and transition-related demand could highlight other barriers. Second, because establishing industrial capacity and training a specialised workforce can take decades, quantifying these needs would clarify when such efforts must begin. This would enable plans for deploying infrastructure and restructuring the workforce to be made ahead of time, helping to prevent these factors from becoming bottlenecks for the transition.

5. Conclusion

We introduce a framework that disaggregates the energy required to build transition infrastructure by sector and energy vector, revealing how these requirements evolve as electrification progresses. Our framework captures more complex dynamics through which the transition will affect net energy availability and the broader economy than aggregated net energy analysis [16–21]. This enables identifying side effects of an ambitious transition which could lead to social backlash and poses derailment risks [15], as well as opportunities to mitigate these effects. Our results show that these dynamics lead to stronger net energy constraints than previously documented. These constraints are dependent on the order in which sectors are electrified. Starting from the easiest-to-electrify and ending with the hardest-to-electrify results in the lowest energy requirements. However, it leads to a high supply tension for coal, hence we suggest the prioritising electrifying the coal-intensive iron-reduction process (whether via hydrogen direct reduction [62,63] as assumed here, or using different methods as described in [64]) to mitigate this. We identify three mechanisms through which improving the electrification efficiency of a sector used to produce transition infrastructure improves net energy prospects and quantify two of these impacts. As we find them to be significant, we support prioritising battery electric trucks and high-temperature heat pumps over hydrogen fuel cell trucks and hydrogen boilers.

Beyond these sector- and vector-specific findings, the transition and the electrification associated with it will significantly change how goods and services that are essential to the global economy are produced (steel, concrete, fertilisers, plastics, and goods transport [65], which make up more than 15% of current energy expenditure [66]). The amount of energy needed to provide them will change to different extents, likely affecting how they are used in the global economy. Alongside increasing the amount of energy spent maintaining the energy system, this is likely to deeply affect the energy system and the economy it underpins. This highlights the importance of continuing the shift towards using physically consistent frameworks to support transition planning. This is crucial given the increasing risk of fossil fuel depletion [48,49], and even more so in regions highly dependent on imports such as the EU, which imports 90% of its oil [67] and gas [68] consumption, and 60% of its hard coal consumption [56].

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Author Contributions

UVL: Conceptualisation, Methodology, Formal Analysis, Writing - Original Draft, Visualization; LD: Writing - Original Draft, Writing - Review & Editing, Supervision; PBP: Conceptualization, Writing - Review & Editing, Supervision

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Conflicts of Interest declarations

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All data and supplementary information will be made available upon request. The code used for the model will be made available upon request.

Declaration of AI use

We have used AI-assisted technologies for spellchecking and as inspiration for rewording individual sentences. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication

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