Complete electrification worsens the net energy prospects of a transition based on wind and solar energy.

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This article is a non-peer reviewed preprint submitted to EarthArXiv.

Title: Complete electrification worsens the net energy prospects of a transition based on wind and solar energy.

Keywords: criticality, deep electrification, energy transition, net energy, energy constraint, physical framework

Abstract

Mitigating climate change largely relies on substituting fossil fuels with low-carbon, electricity-producing energy sources. This mass electrification deeply alters sectoral energy demand, as some sectors can be more efficiently electrified than others. Building transition infrastructure – such as solar and wind farms, grid extensions, and electric vehicles – at a sufficient pace to achieve ambitious transition plans requires significant amounts of energy, potentially causing societal disruptions. We develop a framework to assess how mass electrification will affect transition energy requirements by disaggregating them into sectors and assigning them electrification efficiencies. We apply this model to the European Union (EU-27) under a scenario phasing out fossil fuels by 2050. We find that sectors employed to build transition infrastructure are more difficult to electrify than the economy-wide average. Mass 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, suggesting coal can be a critical material. 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.

As highlighted in literature [10,11], building the renewable power plants, electric grid extensions, and end-use devices required to substitute fossil fuels currently entails using fossil fuels. For example, primary steel used in wind turbines is obtained from iron ore reduced using coal-derived coke in a blast furnace [12], transported using 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. 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 piece of transition infrastructure. It remains uncertain, however, whether this change will increase or decrease transition energy requirements, especially considering the wide range of sector factors quantified (Fig. 3).

This gap results from very few models studying transition energy requirements and changes in energy efficiency caused by electrification simultaneously, except for Capellán-Pérez et al., 2019 [15] and Legendre et al., 2026 [16]. However, this mechanism is not embedded in [16], whilst the electrification efficiency of sectors is not sufficiently disaggregated in [15] to support this analysis. If complete 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 [10,15–21] (see Fig. 1). In addition, as fossil fuel supplies decrease and transition energy requirements persist, transition-related fossil fuel demand could represent a significant share of fossil fuel supply, potentially making them critical materials.

Here, we propose a methodology to address this gap which builds on the model developed by the authors [16]. By breaking down the energy requirements of materials and processes used in the transition into sectors for which we have calculated sector factors, we can quantify how the electrification of sectors affects transition energy requirements. 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.

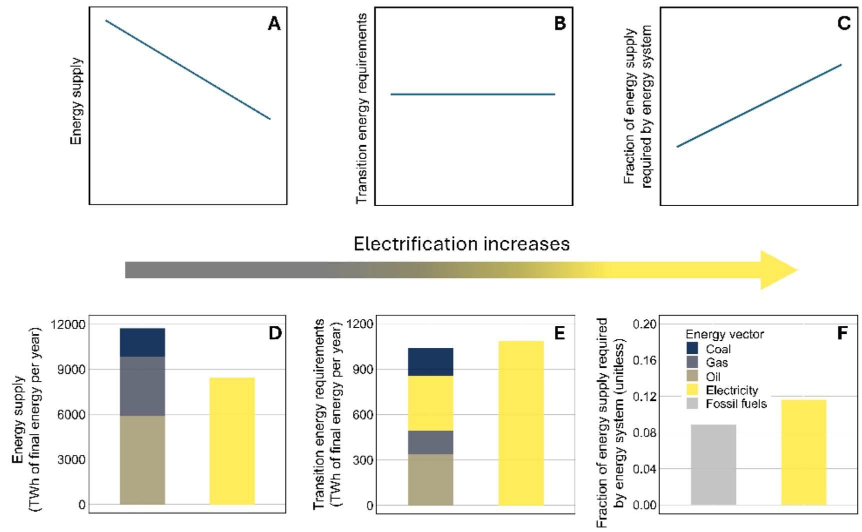

Fig. 1 | Electrification may worsen net energy prospects of the energy transition. Electrification of fossil fuel uses decreases the energy supply required to meet current energy services (A). If the energy required to build transition infrastructure is concentrated in sectors that do not become more 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 [16] 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,

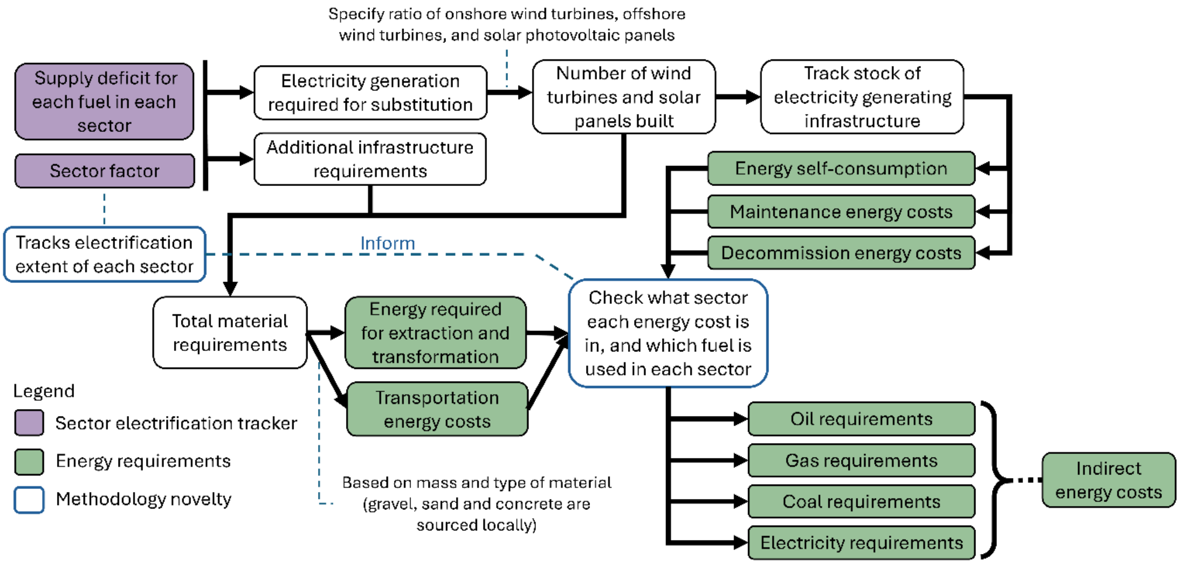

Fig. 2 | Methodology. Summary of the method used to calculate yearly transition energy requirements. The energy supply deficit in each fuel-sector combination is multiplied by the associated sector factor to determine the electricity generation required to substitute these fuels. The capacity of wind 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 [16], 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 sector below:

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

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 [22]), 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 [23]), and the efficiency of electric vehicle chargers is taken as 88%, the higher end of values found by [24]. This results in a sector factor of 0.29.

Compared to our previous work [16], 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.

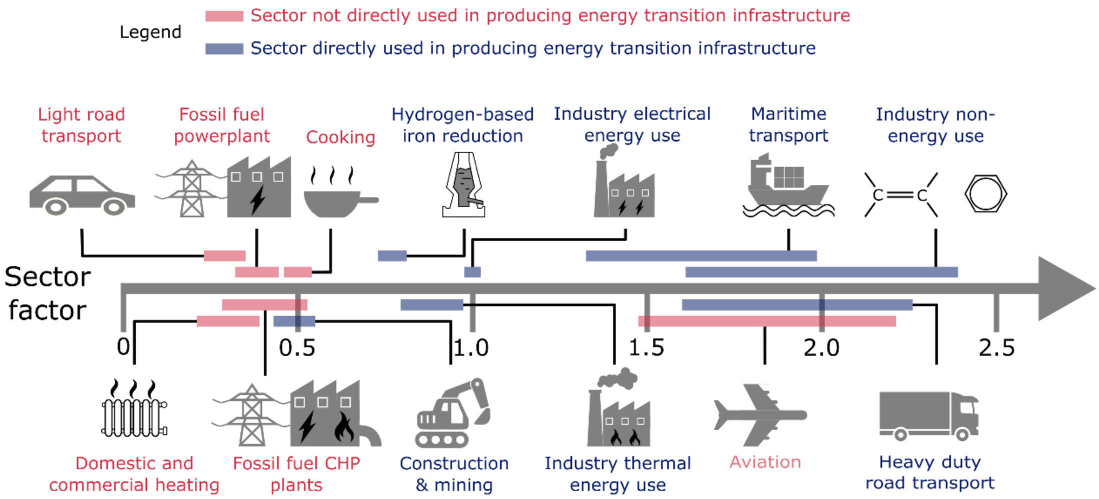

Fig. 3 | Sector factors of the major energy consuming sectors of the economy. The shaded bars represent the likely range (3 standard deviations) of the values given current estimates and the maturity of the technology used. Sectors labelled in blue are directly used in producing and deploying energy 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 [24].

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 [25] and [26] (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 2,

$$E_{mat,\ s,\ y} = \sum_{m=1}^{m_{max}} M_{m,\ y}\ EI_{m,\ s}, \qquad \text{(Eq. 2)}$$

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 [24]. 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 [27]. 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 [16]. 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 3,

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

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 electrify with identical efficiency 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 4,

$$TER_{s,\ y} = E_{mat,\ s,\ y} + E_{trans,\ s,\ y} + SC_{s,\ y} + E_{maint,\ s,\ y} + E_{decom,\ s,\ y}, \qquad \text{(Eq. 4)}$$

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 $E_{trans,\ s,\ y}$, $SC_{s,\ y}$, $E_{maint,\ s,\ y}$, and $E_{decom,\ s,\ y}$ are available in the excel supplementary information. Second, we track how much of each energy vector is used to meet transition energy requirements each year using equation 5 for fossil fuels and equation 6 for electricity,

$$E_{total,\ f,\ y} = \sum_{s=1}^{s_{max}} TER_{s,\ y}\left(\frac{IE_{f,\ s}}{IE_{total,\ s}}\right)\left(1 - EE_{f,\ s,\ y}\right), \qquad \text{(Eq. 5)}$$

$$E_{total,\ e,\ y} = \sum_{f=1}^{3}\sum_{s=1}^{s_{max}} TER_{s,\ y}\left(\frac{IE_{f,\ s}}{IE_{total,\ s}}\right)\left(EE_{f,\ s,\ y}\right), \qquad \text{(Eq. 6)}$$

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 7,

$$E_{total\,final,\ y} = \sum_{f=1}^{3} E_{total,\ f,\ y} + E_{total,\ e,\ y}, \qquad \text{(Eq. 7)}$$

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 7 are obtained using a bottom-up assessment and hence are likely underestimated due to truncation errors caused by narrow system boundaries [28–34]. 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 [28,34]. As in [16], 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 [9,35–37] (see supplementary note 5 of [16]). 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 [16]).

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 silicone 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.

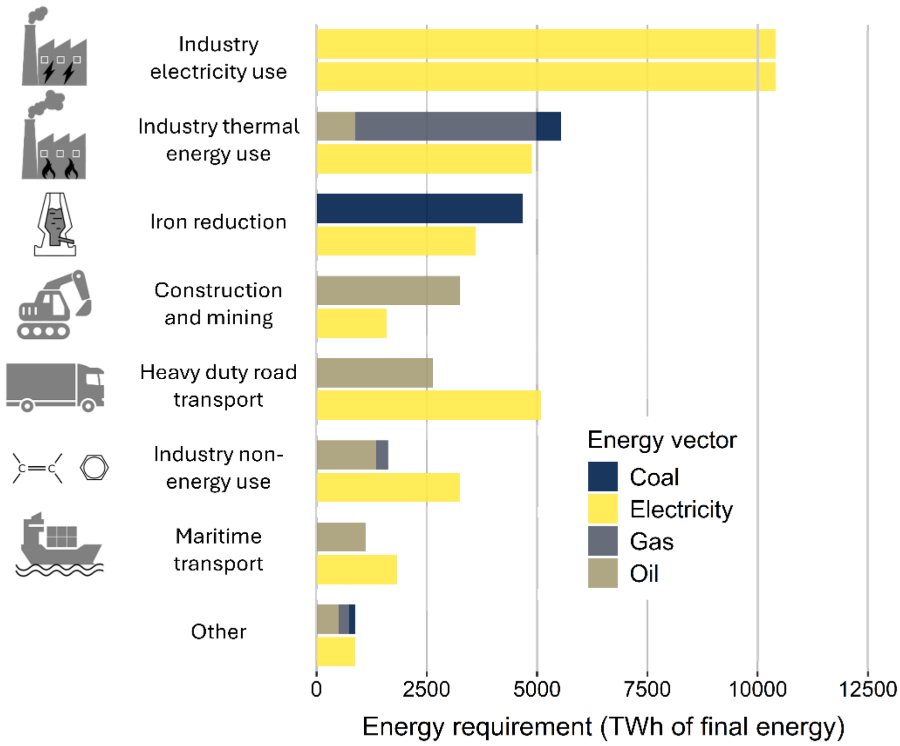

Fig. 4 | Distribution of transition energy requirements amongst sectors. Total energy required by the transition in each sector to phase out fossil fuels by 2050, whilst maintaining all services previously provided by fossil fuels. The top bar indicates the amount of energy required using the current 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).

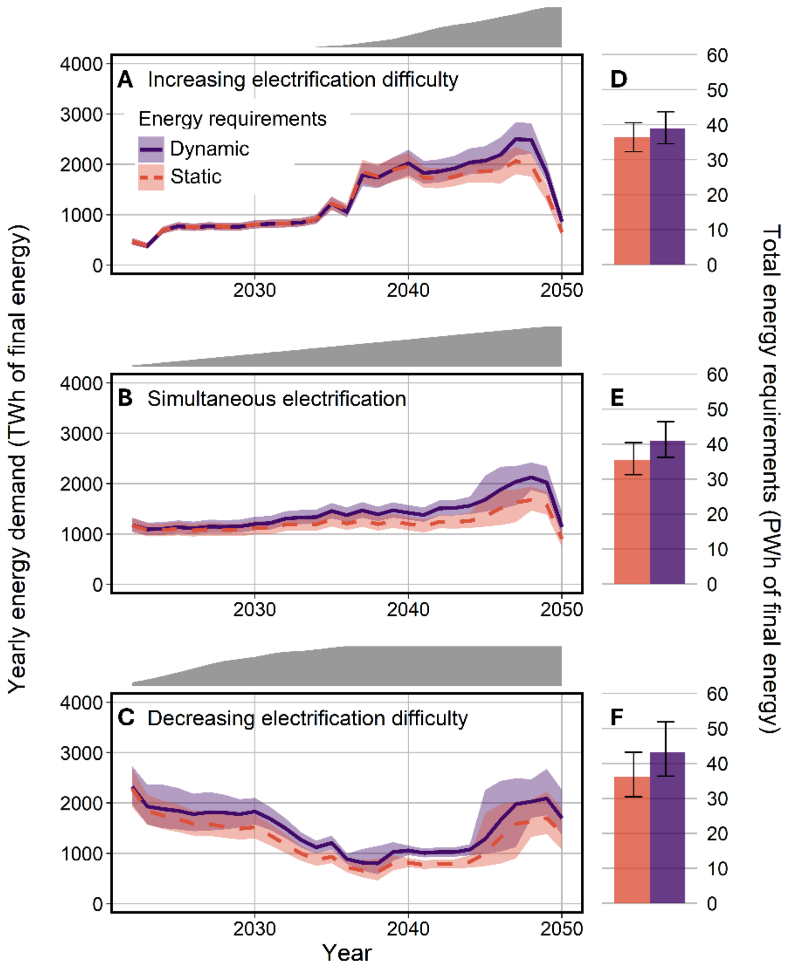

Fig. 4 | Effect of sector electrification order on transition energy requirements. Yearly (A-C) and cumulative (D-F) energy requirements of the transition using a static (red bars and lines) or dynamic (purple bars and lines) modelling methodology. The grey shaded area above each plot represents the 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.

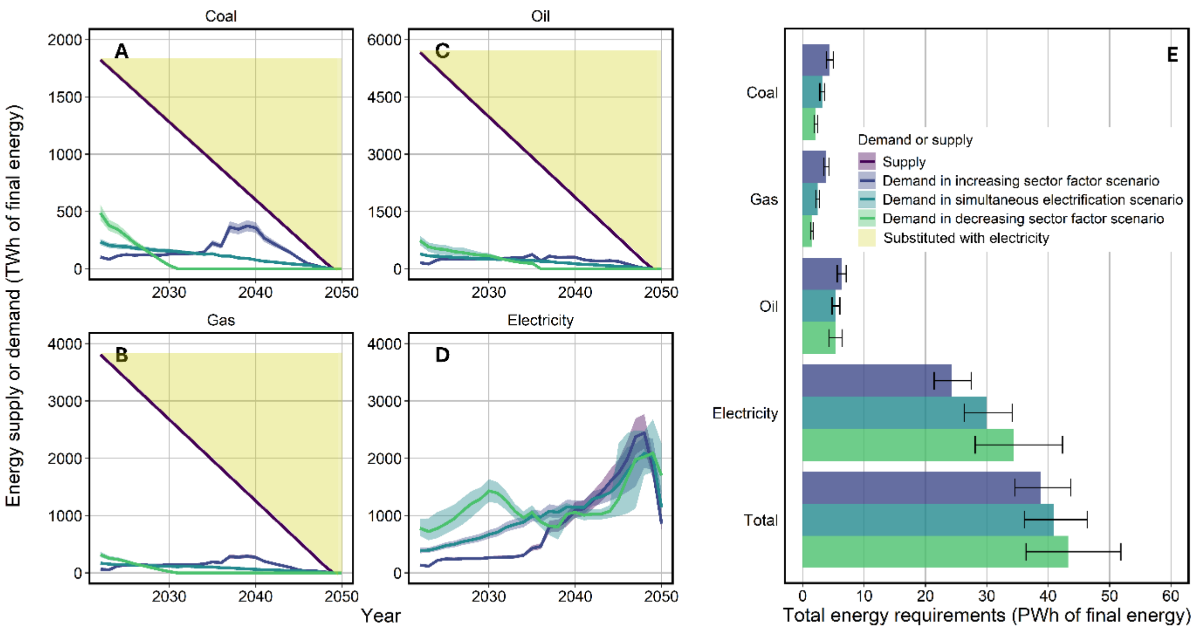

Fig. 6 | Effect of sector electrification order on fossil fuel demand and criticality. Yearly transition-related demand of coal, oil, gas, and electricity (A-D) and cumulative transition-related energy requirements disaggregated by energy vector (E). The shaded regions surrounding the lines and the error 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 Implications of increasing energy requirements for the energy transition

We introduce a methodology that incorporates how the electrification of production processes affects the energy required to produce transition infrastructure. This is achieved by disaggregating the energy requirements of materials and processes needed to build transition infrastructure into specific sectors and estimating how their efficiencies change when electrified.

As the transition energy requirements are concentrated in hard-to-electrify sectors, these requirements increase by 5% under a fully electrified energy mix compared to the current fossil-dominated mix. At the same time, energy supply decreases by 20%, leading to a 31% relative increase in the share of energy supply spent on the energy system during the transition. This divergence between the dynamic and static methodology results is only fully realised once all the sectors that the transition makes use of are electrified, and since these only represent 37% of total fossil fuel energy use, the order in which sectors are electrified determines how much of this divergence is observed during the transition period. Electrifying sectors from easiest to hardest minimises this gap, with the dynamic transition energy requirements only being 7% greater than static ones, while in the simultaneous and hard-to-easy electrification orders they are 15% and 20% greater, respectively (Fig. 5). This highlights that even under favourable sector electrification order, net energy barriers to the transition are still greater than suggested in previous work [10,15,17–21].

Disaggregating transition energy requirements into energy vectors (Fig. 6) shows that the easy-to-hard electrification order leads to the strongest fossil fuel criticality, although this remains weak except for coal. In this electrification order, the largest fraction of coal, oil, gas, and electricity supply required by the transition is 60%, 24%, 21%, and 27%, respectively, peaking between 2040 and 2047. Because these fractions remain relatively low, the net energy advantages of electrifying sectors from easiest to hardest outweigh the criticality risks incurred, with two exceptions. First, the iron reduction sector, which represents only a quarter of total coal consumption in the EU but makes up a disproportionate fraction of transition coal requirements (86% of transition coal requirements in 2040, when peak criticality occurs), should be electrified in the first half of the transition. Second, while the sector factor of fossil fuel-based electricity generation is generally low, replacing fossil power plants with solar and wind energy significantly increases the fraction of electricity generation from intermittent sources. As this may disproportionately increase storage losses, it could be advantageous to delay their substitution.

Sensitivity analyses on key modelling assumptions highlight that opting for technological choices with higher efficiency has strong net energy benefits, and that developing better electricity grid models will improve transition energy requirement studies. Improving the efficiency of a technology electrifying a sector used to build transition infrastructure has a triple effect on net energy. First, this decreases the amount of electricity production needed to phase out fossil fuels, so less renewable power plants and grid extensions need to be built, reducing transition energy and material requirements. Second, a more efficient electrified sector reduces the energy requirement per unit of transition infrastructure built. Third, as the fraction of electricity produced with intermittent sources and the total electricity production fall, storage losses are also expected to fall.

Over the transition period, using more efficient battery electric trucks rather than hydrogen fuel cell trucks reduces total transition energy requirements by 13% when electrifying all sectors simultaneously (see supplementary Fig. 3F). Similarly, prioritising heat pumps for industrial thermal energy use over electric boilers could decrease transition energy requirements by 6%, whereas using hydrogen boilers increases them by 11% (see supplementary Fig. 3D). Finally, we find that if grid requirements scale with installed capacity rather than electricity production (as in [9]), this increases transition energy requirements by 13%; if further to this, transmission grid requirements are quadrupled compared to the base case (as observed in [35–37]), this rises to 25% (supplementary Fig. 3E). Grid requirement changes therefore introduce significant uncertainty in our results, suggesting that more advanced grid models such as [35–38] could support a more robust assessment.

As the transition scenarios presented here involve a high penetration of intermittent renewable energy sources into the electricity production mix (>80%), electricity will need to be stored to guarantee reliable supply. This will lead to storage losses due to the round-trip efficiency of storage devices as well as curtailment losses when electricity cannot be economically stored. Based on previous work, these are likely of a similar magnitude to transition energy requirements and hence play a significant role in the net energy challenges of the transition (see supplementary note 6 of [16] summarising findings of [7,36,39–44]). This suggests integrating energy system models capable of quantifying these losses and transmission grid expansion requirements into a physically consistent framework would significantly improve the robustness of results obtained.

4.2 Implications 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 [45]. 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. [21] assumed one unit of primary thermal energy converts to 0.4 units of electricity, while Capellán-Pérez et al. [15] 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 [16] 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. Presently, only easy-to-electrify sectors (e.g., lighting, residential/commercial heating, light road transport, and rail transport) have undergone substantial electrification, hence the appropriate ratio is closer to Sahin et al. [21]'s suggestion. As the transition progresses, the relevant factor will change based on how much energy is used in each sector, the technologies adopted for electrification, and their extent of deployment.

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. To illustrate how this impacts net energy analysis, we provide an example using wind turbines and solar panels. We find that obtaining materials for onshore wind turbines or solar panels generating 1 TWh of electricity per year with a fully electrified mix requires 8% less final energy than with the current mix. For offshore wind turbines, the decrease is larger, at 11%. This reflects that offshore wind turbines rely most heavily on steel, which is currently produced using coal in processes that become more efficient when electrified, whereas the energy requirements of solar panels and onshore wind turbines are slightly skewed towards harder-to-electrify sectors. 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 [15,17–21,46] is not appropriate for scenarios with deep electrification. A robust physical framework capable of reflecting this dynamic system is indispensable to net energy analysis in a transition context.

4.3 Implications of dynamic methodology findings for energy transition research

Disaggregating transition energy requirements by sector and by energy vector reveals complexities that aggregated net energy analyses cannot capture. Because this approach also shows that higher energy requirements are likely, it is even more crucial to represent them in transition models. Our methodology provides greater granularity than studies using "primary" and "final" energy stages as the results do not need to be presented in an aggregated form using semi-arbitrary conversion factors to assess net energy. This framework enables more detailed discussions on the net energy consequences of the transition, such as the likelihood of energy supply stress in specific fuels (Fig. 6A-D) and the saturation of specific sectors by transition needs (supplementary Fig. 2). As more specific insights are obtained, the energy-related barriers to the transition can be described more precisely and support more targeted policy recommendations, as in section 4.1. Therefore, we believe that future research on transition scenarios should adopt similar physically grounded frameworks.

More broadly, the amounts of energy required to obtain different products crucial to the global economy (e.g., steel, concrete, plastics, fertilisers, and goods transport [47], which make up >15% of current energy expenditure [48]) will change in differing magnitudes and directions under a full energy transition based on electrification. Hence, a transition model without a robust physical framework describing these changes will be unable to accurately depict the future physical world. Such models risk internal inconsistencies between the available energy supply, the energy invested in building the energy system itself, and the residual energy available for other sectors [46]. Policies derived from such analyses may thus be based on physically infeasible situations, undermining their effectiveness. On the other hand, a model with a physical framework can highlight physical barriers to the transition and inform policies to address them. Overall, we encourage the ongoing move away from non-physical transition models towards physical models capable of describing the changes brought by mass electrification, as the former's usefulness is undermined by the transition itself [46,49]. This will enable better transition planning and minimise the risk of unforeseen bottlenecks.

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 2.5.3 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 [50], is used in the manufacture of semi-conductors [51], which are essential for making the inverters required by solar and wind farms [52]. 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

This study introduces a framework that disaggregates the energy required to build transition infrastructure by sector and energy vector, revealing how these requirements evolve as electrification progresses. This captures more complex dynamics through which the transition will affect net energy availability and the broader economy than aggregated net energy analysis [15,17–21]. 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 iron-reduction process (whether via hydrogen direct reduction [53,54] as assumed here, or using different methods as described in [55]) to mitigate this. Similarly, it may be sensible to substitute fossil fuel power plants later than implied by the easy-to-hard electrification order, as this could prevent storage losses from rising too rapidly. 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 mass electrification associated with it will significantly change how goods and services that are essential to the global economy are produced (steel, plastics, fertilisers, concrete, and goods transport [47]). The amount of energy needed to produce them will increase to different extents, likely affecting how they are used in the global economy. Alongside the increasing 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 [56,57], and even more so in regions highly dependent on imports such as the EU, which imports 90% of its oil [58] and gas [59] consumption.

Acknowledgements

The authors are grateful to participants to the seminar "From Modelling to Strategic Decision-Making Facing Planetary Boundaries: Issues and Challenges of a Multi-Disciplinary Approach" (Les Houches, June 23-28, 2024) for fruitful comments on the work conducted. We also sincerely thank the researchers who have made their data publicly available as online supplementary information.

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

Financial support

UVL thanks the EPSRC for funding their PhD studentship (grant number EP/T51780X/1). LD thanks the Erling-Persson Family Foundation for funding the research.

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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