Physically consistent sectoral pathways for phasing out fossil fuels

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Abstract

The transition away from fossil fuels relies on electricity-producing renewable energy sources. To understand how much electricity is needed to substitute fossil fuels, sectors of the economy being electrified must be analysed discretely, as their suitability for electrification varies significantly. Constructing, operating, and maintaining these renewable power plants requires substantial amounts of energy. Here, we propose a model which calculates the electricity required to electrify each major sector, and quantifies the energy required to deploy the renewable power plants producing this electricity. We apply this model to the European Union across scenarios phasing out fossil fuels by 2035, 2050, 2075, and 2100. We find that transition energy requirements increase with transition speed and that they are greater than the current energy spent on obtaining fossil fuels in all scenarios. We also reveal the energy requirements of each sector, disaggregated into categories (power plants, grid extensions, and end-use devices) allowing for a comparative analysis of their relative significance. We produce quantitative evidence supporting the emerging conceptual consensus that a rapid energy transition will require reallocating significant amounts of energy from other end uses to transition-related uses. This could lead to societal disruptions, as part of some energy-dependent services (e.g., transport, residential heating, manufacturing etc.) will have to be forgone to carve an energy budget for the transition. Our model can provide quantitative insights into the extent of these disruptions, and support policy- and decision-making to mitigate them.

Keywords: energy transition, energy requirements, fossil fuel phase out, physical model, sectoral electrification

Word count: 7997

1. Introduction

The 2023 United Nations Climate Change Conference (COP28) held in Dubai resulted in an agreement among nearly 200 participating parties on "transitioning away from fossil fuels in energy systems, […], so as to achieve net zero by 2050 in keeping with the science". Nevertheless, the majority of parties have yet to set quantified and time-bound targets for phasing out fossil fuels, despite repeated calls for decisive action [1–4]. For example, the European Union (EU) has committed to reducing net greenhouse gas (GHG) emissions by at least 55% by 2030, compared to 1990 levels, and recognizes the need for a global phaseout of fossil fuels in the energy sector well before 2050 [5]. The EU has, however, not yet articulated specific targets for phasing out fossil fuels, despite being one of the most vocal advocates for a stronger international agreement [6].

Phasing out fossil fuels is complicated by the multifaceted and cross-scale nature of the decision-making process, which involves numerous synergies and trade-offs [7,8]. First, opposition may arise from local communities reliant on fossil fuel extraction for economic sustenance [9]. Second, fossil fuel corporations and lobbying groups actively resist strict regulatory measures to safeguard their economic interests [10]. Third, a shift away from fossil fuel dependency threatens substantial financial losses for investors due to stranded assets, necessitating coordinated action among financial and policy stakeholders at both regional and international levels [11,12]. Fourth, concerns related to security and equity are significant, as defining equitable, just, and feasible approaches for fossil fuel phase out involves complex, multi-level considerations [13–17]. Finally, phase-out initiatives may heighten geopolitical tensions, affecting both fossil fuel-producing states [18] and imports-dependent regions, such as the EU, where future energy supply diverges greatly according to targets (Fig. 1).

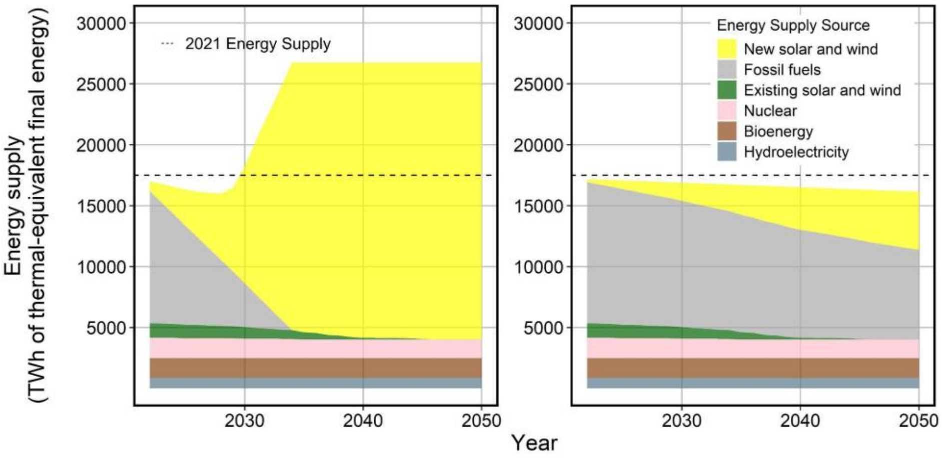

Fig. 1. | Energy supply profile of different energy transition speeds. Examples of future energy supply from 2022 to 2050 in the EU under two fossil fuel phaseout scenarios: 2035 (left) and 2100 (right). Energy supplied by hydroelectricity and bioenergy is assumed to stay constant due to constraining factors explained in section 3.2. Energy supplied by nuclear power plants is assumed to follow announced plant closures, with no new power plants added. Energy supplied by existing solar and wind power plants decreases as they are decommissioned after 25 and 20 years of operation respectively. New solar and wind capacity are installed to meet the energy demand of the services previously met by fossil fuels and decommissioned nuclear, solar, and wind power plants. Sectors are electrified sequentially from most to least suitable for electrification. As a result, the total thermal-equivalent energy production decreases, then increases in the 2035 scenario, whereas only favourable sectors are electrified by 2050 in the 2100 scenario, leading to a steady decrease in thermal-equivalent energy supply.

Alongside geopolitical and socio-economic aspects, phasing out fossil fuels is complicated by the physical challenges inherent to the energy transition. Substantial amounts of energy are required to construct, operate, and maintain a low-carbon energy system [19] and efficiency changes associated with electrification can be positive or negative depending on the sector. Increasing scholarly attention has been directed toward both energy requirements of the transition [19–22] and sectoral changes in final energy consumption linked to services electrification [23–25]. However, most studies focus on either aspect alone, with few providing an integrated analysis, resulting in a loss of critical information for climate mitigation pathways. To bridge this gap, we propose a physically consistent sectoral model designed to estimate the energy requirements for phasing out fossil fuels with sectoral electrification allocation and apply it to the EU context across multiple scenarios.

2. Literature review

2.1. Energy requirements of the energy transition

The energy transition entails a substantial effort to reduce overall energy consumption, improve energy efficiency, and increase the share of low-carbon energy sources in the energy mix. The deployment of infrastructure necessary to achieve those objectives—such as electric vehicles (EVs), wind turbines, and grid expansions—requires significant upfront energy investment, mostly coming from fossil fuels. Conversely, the net energy available to society, defined as the energy supplied after accounting for the energy expended in producing and distributing that energy, is expected to contract – perhaps only temporarily – during the transition[1].

Energy requirements of the energy transition (or net energy available to society) have been estimated through different methods in literature, which could be classified as top-down, hybrid and bottom-up. Top-down methods are mostly used for evaluating energy supply systems at the global or national level, usually through mathematical modelling of energy systems, as explored by Trainer [26], Sers & Victor [27] and Diesendorf & Wiedmann [28], or through data-rich Input-Output tables, such as Fabre [29]. On the other hand, bottom-up methods consist in aggregating process-based production and consumption data of energy resources, usually following a Life-Cycle Assessment (LCA) approach. They have greater accuracy, depending on the data robustness, and greater flexibility to address process-dependent aspects of energy conversion but are limited in scale and scope of analysis [30]. Jacques et al. [31], for instance, relied on detailed bottom-up estimates for the energy requirements of energy resources to assess the macroeconomic and energy consequences of a scenario compatible with the 1.5 °C objective of the Paris Agreement. Hybrid methods are a mix between top-down and bottom-up, designed to overcome limitations and take advantage of strengths of both methodologies [32]. Notable

[1] It is still disputed whether the contraction in net energy available to society holds true when considering the energy supplied after accounting for the energy expended in producing, distributing and *using* that energy [39].

examples are the MEDEAS model [20] or the assessment of the energy requirements and carbon emissions for a low-carbon energy transition from Slameršak et al. [19].

Recent analyses suggest that net final energy per capita (producing and distributing phases only, see footnote 1), could decrease by 28–34% by 2030 relative to 2015 under short-term transition scenarios [19], and by 24–31% by 2050 under slower transition pathways [33]. Socio-economic implications of this contraction are analysed, and found to be substantial, with major increases in capital investment, employment and inflation [31,34,35]. In this context, reducing discretionary energy consumption could help prevent the window of opportunity for a just and inclusive energy transition from narrowing significantly due to delays in the transition [36] or fossil fuel resource availability constraints [37–39]. If the feasibility of providing a decent standard of living with significantly less energy than is currently consumed in wealthy nations is substantiated by the literature [30,40], its successful implementation would nonetheless depend on effectively mitigating economy-wide rebound effects [41].

2.2. Sectoral electrification

Several sectors, like domestic heating, or rail transport, benefit from additional efficiency when electrified, however others, like aviation or maritime transport, suffer from the opposite effect and require more final energy for the same service when electrified. Similar to energy requirements, literature on the effect of sectoral electrification on total energy consumption uses three main approaches: top-down, hybrid and bottom-up.

Capellán-Pérez et al. [20] is an example of a top-down approach, as they use ratios of primary to final energy of different energy vectors rather than sectoral electrification efficiency factors to project how the global energy demand could evolve under a "green growth" paradigm. Examples of bottom-up approaches include Grubler et al. [23], Burandt et al. [42] and Milward-Hopkins et al. [30]. Grubler et al. [23] rely on a bottom-up assessment of "activity, intensity and energy demand for four end-use services" to estimate how energy consumption evolves in a scenario featuring strong efficiency improvements. More specifically, they assign electrification efficiencies to sectors which significantly decrease their final energy consumption when electrified, for example land transport (see their supplementary Tables 13, 14 and 21) and cooking (see their supplementary Table 7). Burandt et al. [42] rely on the Global Energy System Model (GENeSYS-MOD) [43] and use ratios representing different technologies' efficiency in providing services with different energy vectors to study the effect of decarbonisation on energy demand. Finally, Milward-Hopkins et al. [30] build on the work of Grubler et al. [23] and Rao et al. [44] to quantify minimum final energy to achieve "decent living standards" (DLS) globally. To this end, they define services required for DLS, assign the most energy-efficient technology available to provide each service, and aggregate all energy needs to obtain total energy demand. Li et al. [45] exemplify a hybrid framework: they use macro-level drivers to forecast service requirements of 47 sub-sectors grouped into four sectors (residence, industry, mobility and services), and assign electricity-based technologies to meet an increasing portion of these services. Additionally, they disaggregate industrial heat requirements into temperature levels, enabling a pinch analysis involving all industrial sectors as well as waste heat from growing data centres and consider the use of heat pumps for low-temperature heat. Another hybrid example is Jacobson et al. [25] which forecasts a penetration rate of "wind-water-sun" energy sources via macroeconomic analysis and multiplies the electrified portion of six sectors' demand by an electricity-to-fuel ratio to determine global final energy consumption.

The impact of sectoral electrification on energy consumption is studied in different depths in literature. For instance, the extent to which final energy consumption is subdivided between final thermal and electrical energy varies greatly. In the previously mentioned works, Millward-Hopkins et al. [30] do not clarify which services are met by which energy carrier, Burandt et al. [42] and Jacobson et al. [25] provide no sources for their electrification efficiency values, while Grubler et al. [23] supply some sources, and Li et al. [45] give sources for most of their values. Furthermore, there remains a large discrepancy in the choice of sectors assessed. Burandt et al. [42] and Li et al. [45] cover the widest range of sectors in a highly disaggregated manner, as they aim to model how the entire energy system of a region changes during an energy transition. However, both exclude maritime transport ([42] instead propose using biofuel, and [45] study a land-locked country), and Li et al. [45] do not consider electrifying aviation. Grubler et al. [23] build a scenario aimed at decreasing final energy consumption and hence only consider electrifying a sector if it would greatly decrease its final energy consumption, leaving out steelmaking, industry energy use, aviation and maritime transport. Jacobson et al. [25] aim to quantify the final energy requirements of a business-as-usual scenario using a nearly fully electrified energy system. Hence, they provide an electrification factor for every sector but aggregate more sectors under one sectoral electrification factor. This leads to some less robust estimations of energy requirements for heterogeneous sectors such as transportation, as shown by the sector factor values of road transport, aviation and maritime transport ranging from 0.29 to 1.84 (see Fig. 3). Millward-Hopkins et al. [30] do not explicitly specify which sectors are electrified, as they do not disaggregate energy consumption beyond final energy, and Capellán-Pérez et al. [20] do not provide electrification efficiency values disaggregated by sector except for road transport.

2.3. Research gap and opportunities

There exists a relatively low number of studies, all very recent, that dynamically assess energy requirements and/or sectoral electrification associated with the energy transition (see Table 1). There furthermore exists a large array of tested scenarios, with slight prevalence of 1.5 °C scenarios, but clear preference for global scale studies. For studies evaluating the energy requirements of the energy transition, there has been a recent and clear shift from a reliance on static estimates of EROI[2] to more consistent dynamic estimates, which testifies to the emerging maturity of the research field. Most energy requirements are computed through bottom-up approaches, with a general partial coverage. All the studies cover power plants and storage, but in the case of the latter, in various ways that all tend to significantly underestimate storage losses compared with more recent literature [46] (see Supplementary note 6 for a summary of literature exploring storage losses). Most studies however devote less attention to grid expansions, which are either built into a static EROI value or added as a factor. Only Sahin et al. [22] and Capellán-Pérez et al. [20] provide an analysis of end-use devices. For sectoral electrification, most studies rely on bottom-up or hybrid approaches with a quasi-full coverage, yet with varying consideration depth. Only one framework assesses the energy requirements and sectoral electrification challenges [20]. However, and although their work has been pivotal in paving

[2] The EROI (Energy Return on Energy Investment) is the ratio between the total energy returned and the total energy invested to accomplish the conversion over the entire life cycle of the system under study [39,98].

the way to an integrated analysis of energy requirements and sectoral electrification, Capellán-Pérez et al. [20]'s estimates of EROI are at the lower end of the range of current values [19,22,47]. Moreover, their consideration of sectoral electrification is limited as they treat all sectors (except road transport) homogeneously, despite significant heterogeneity in sector factor values (see Fig. 3).

While research on the energy transition has been prolific, energy requirements and sectoral electrification challenges have been dealt with less attention and care, despite being called for by the community [48]. As a result, a comprehensive assessment of fossil fuel phase out pathways is still missing. We aim to fill this gap by relying on a physically grounded approach of decarbonization pathways.

Table 1. Selection of the main dynamic frameworks explicitly assessing energy requirements and/or sectoral electrification as part of the energy transition.

Reference	**Scenarios**	**Scale**	**Energy requirements**			**Sectoral electrification**		
			Consideration depth [a]	*Method*	*Coverage* [b]	*Consideration depth* [c]	*Method*	*Coverage*
Sgouridis et al. [49]	Energy scenarios: from 1400 W/cap to 10,000 W/cap	Global	+	Hybrid	P *S*	~	n/a	n/a
King and van den Bergh [33]	3 scenarios: BAU, LCT, CNE	Global	+	Bottom-up	P *S*	~	n/a	n/a
Capellán-Pérez et al. [20]	Green Growth	Global	++	Hybrid & direct physical link	P *G S E*	+	Top-down	Full coverage (35 sectors) with only some sectors having electrification factors
Fabre [29]	IEA and Greenpeace	Global	+	Top-down	P *S*	~	n/a	Power sector only

Slameršak et al. [19]	1.5 °C with negative emissions	Global	++	Hybrid	P *G S*	~	n/a	n/a
Jacques et al. [31]	1.5 °C	Global	++	Bottom-up	P *G S*	~	n/a	n/a
Sahin et al. [22]	9 scenarios ranging from net zero by 2030 (most ambitious) to IEA's STEPS (least ambitious)	Global	++	Bottom up & direct physical link	P S E	~	n/a	Power sector only
Grubler et al. [23]	LED, 1.5 °C	Global	~	n/a	n/a	++	Bottom-up	Full coverage (3 upstream and 4 downstream sectors). Only some sectors are electrified.
Burandt et al. [42]	1.5°C, 2.0°C, and "Low-effort scenario"	National (China)	~	n/a	n/a	+	Bottom-up	Full coverage, except for non-energy use and cargo shipping which are assumed

								to be replaced by biofuels
Jacobson et al. [25]	1.5 °C	Global	~	n/a	n/a	+	Hybrid	Full coverage (6 sectors)
Li et al. [45]	3 scenarios: Moderate, High and Low GDP and population increases	National (Switzerland)	~	n/a	n/a	++	Hybrid	Full coverage (47 sectors)
This paper	4 fossil phaseout scenarios	Regional (EU)	++	Bottom up & direct physical link	P G *S E*	++	Bottom-up	Full coverage (11 sectors)

Note that studies that consider only one challenge and in a stylized way, such as the frameworks of [26–28,30,34,44,50–52] are not included in the table. “Direct physical link” indicates that energy requirement estimates are obtained based on material requirements (obtained from Life-Cycle Inventory data), and the energy intensity of these materials (obtained from LCA data).

[a] Energy requirement consideration depth: not considered: (~), tracked with static, aggregated EROI (+), tracked with variable EROI (++)

[b] Power plants: P, Grid extensions: G, Storage requirements: S, End-use devices: E. *Italic* denotes simplified inclusion of the element.

[c] Sectoral allocation consideration depth: sectoral allocation not explicitly shown (~), sectoral allocation with numbers (+), sectoral allocation with sourced numbers (++)

3. Methods

3.1. Overall methodology

The bottom-up methodology developed in this work centres around tracking the physical (mass and energy) flows resulting from an energy transition as summarised in Fig. 2. We consider scenarios in which services (domestic home heating, industrial activities, transport etc.) are maintained while fossil fuels are phased out. We do not consider the potential for energy efficiency gains in the provision of services outside of those associated with the electrification of services. All energy flows are expressed in final energy rather than primary energy to facilitate comparisons and interpretation, as the latter includes inefficiencies linked to the energy mix of the studied system.

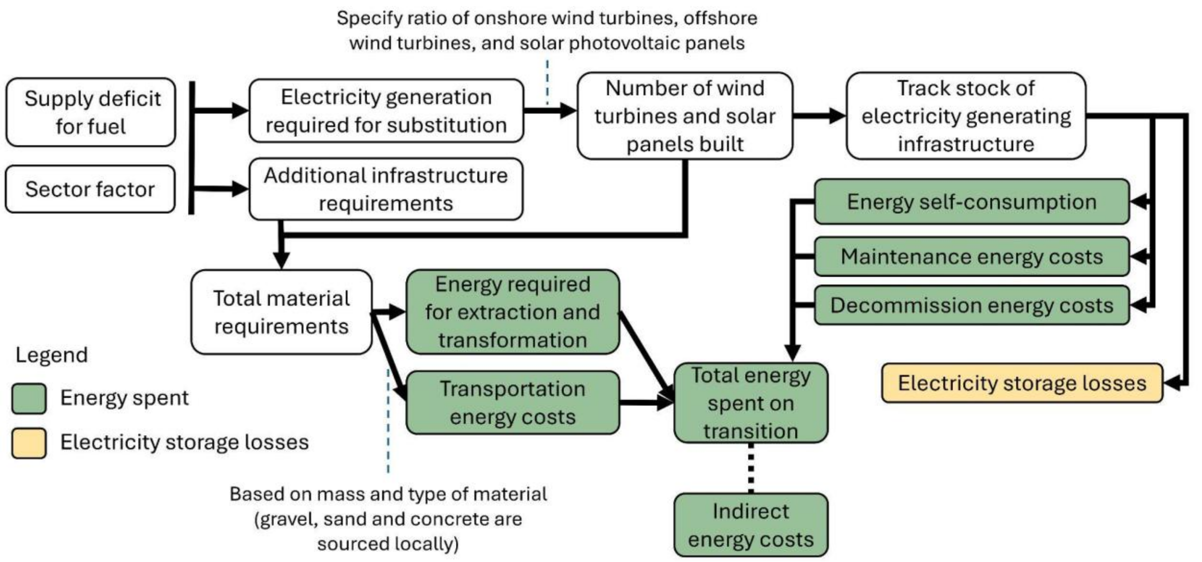

Fig. 2. | Methodology. Summary of the methodology used to quantify the energy requirements of the energy transition each year. For each energy source, we multiply its supply deficit by the corresponding sector factor to obtain the amount of electricity required to substitute its services. We calculate the capacity of solar and wind power plants required to generate this electricity based on their performance factors. For each sector, we quantify the infrastructure requirements for using the electricity generated. Based on life cycle inventory analyses of the power plants and additional infrastructure, we estimate their total material requirements. We multiply each material requirement by its corresponding energy intensity and transportation energy requirements to obtain the energy required to build wind and solar

power plants and additional infrastructure. We track the stock of electricity generating infrastructure to quantify the energy requirements and losses related to energy self-consumption, maintenance, decommissioning, and electricity storage. Finally, the indirect energy costs which cannot be quantified with life cycle assessment methodologies are estimated based on literature. This methodology is repeated for each year of the model.

3.2. Defining scenarios and quantifying an energy supply deficit for each energy source

We start by defining a supply deficit for each fuel. The rate of decline in fossil fuel supply, and its effects on the material and energy requirements of the energy transition is the focus of this study. We consider four linear fossil fuel phaseout scenarios corresponding to increasingly ambitious energy transition scenarios: a phaseout by 2100, 2075, 2050, and 2035 (1.3%, 1.9%, 3.6%, and 7.7% yearly decrease in fossil fuel supply, respectively). The projection used for the rest of the major energy sources in the EU (hydroelectric, nuclear, bioenergy, and existing wind and solar power plants) are common to all four scenarios and summarised below, with more extensive contextualisation of our assumptions on hydroelectricity and bioenergy in Supplementary note 1. The effects of changing their future energy output on the model results are discussed in section 5.3.

Nearly all geographically feasible sites for large hydroelectric dams in the EU are exhausted [53], and climate change will decrease their output potential [54]. However, untapped potential exists in developing run-on-the-river plants [55] and modernizing existing dams [56]. We conservatively assume hydroelectricity production will remain constant.

In the EU, 70% of bioenergy comes from primary biomass, i.e., wood [57], which is sensitive to climate change [58] and competes for land with forests supporting biodiversity and carbon sequestration [59,60], and food production [61]. We assume that bioenergy production will remain constant, aligning with the lower end of estimations made by supply, demand, and IAM scenarios estimates [61–63].

Nuclear power plants in the EU are slow to build (the last two took 16 and 17 years [64]), depend on a limited supply of Uranium-235, and future technologies using Uranium-238 require lengthy development [65]. However, replacing existing nuclear power plants with wind turbines and solar panels leads to higher emissions, constrained energy supply, and increased storage needs [66]. We assume no additional nuclear reactors are built between 2022 and 2050, and that announced reactor closures go ahead, resulting in an 18% decrease in nuclear power supply.

The existing wind turbines and solar photovoltaic panels will be decommissioned at the end of their lifetimes, which is assumed to be 25 and 20 years after they were built, respectively.

As we focus on the energy rather than the emissions aspect of the transition, we consider carbon capture as an ordinary service obtained in exchange for energy, hence an in-depth analysis of its role is outside the scope of this work.

3.3. Quantifying electricity generation required to maintain services

As described in section 2.2, substituting the same amount of a fossil fuel with electricity in a different sector requires a different amount of electricity. We address this sectoral discrepancy by calculating the ratio of final electrical energy required to substitute oil, coal, and gas in each sector they are used based on a literature review. This ratio is called a "sector factor" (SF), defined by 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 summarises the values for sector factors, and detailed explanations and sources for each value are presented in Supplementary note 2, and Supplementary Table 1. The breakdown of fossil fuel use by sectors is obtained from the Eurostat database [57] and is summarised in the excel supplementary information. We now calculate, for each year, the amount of final electrical energy required to provide the services which were previously provided by the fossil fuels phased out and the other power plants which have been decommissioned. For fossil fuels, we multiply the amount of each fossil fuel phased out by the corresponding sector factor as in equation 2,

$$final\ electrical\ energy\ needed\ to\ replace\ fossil\ fuels = \sum_{f=1}^{3} \sum_{s=1}^{s_{max}} FFPO_{f,s}\, SF_{f,s}\, , \text{(Eq. 2)}$$

in which $FFPO_{f,s}$ is the amount of fossil fuel *f* phased out from sector *s*. Fossil fuel sectors are electrified starting with the lowest *SF*, and ending with the highest *SF*. As decommissioned nuclear, photovoltaic, and wind power plants only produce electricity, they have a sector factor of 1.

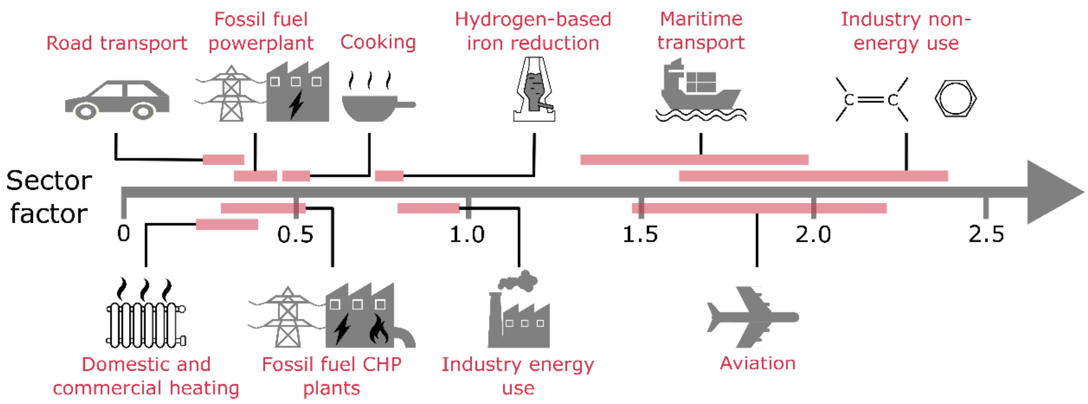

Fig. 3. | Summary of the sector factors calculated. Sectors on the left have lower sector factors, meaning less electricity is required to substitute a unit of fossil fuel in this sector, while sectors on the right have higher sector factors. The shaded bars represent the likely range (3 standard deviations) of the values given current estimates and the maturity of the technology used. Marine transport, aviation and industry non-energy use (i.e., energy carriers that are used as raw materials in production processes, for example chemical feedstock for plastics, lubricants, or asphalt) are based on the least mature technologies, and hence have the largest uncertainties and ranges. All values and sources used are available in Supplementary note 2.

3.4. Installed capacity of renewable energy power plants needed to generate the required electricity

Based on the additional electricity generation required each year, we estimate the capacity of onshore and offshore wind turbines, and solar photovoltaic panels which need to be built each year. This is done based on the performance factors of these renewable power plants, summarised in Table 2. The amount of electricity generated by 1 MW of each power plant in 1 year is calculated using equation 3,

$$YEG_p = CF_p\,(1 - TDL)\,(8760\ hours), \qquad \text{(Eq. 3)}$$

where YEG_p is the yearly final electrical energy generated per MW of capacity of power plant type *p* (in MWh), CF_p is the capacity factor of power plant type *p*, and *TDL* is the transmission and distribution losses in the network. The capacity of each renewable power plant type is hence calculated using equation 4,

$$YIC_p = ES_p\left(\frac{final\ electrical\ energy\ needed\ to\ replace\ fossil\ fuels}{YEG_p}\right), \qquad \text{(Eq. 4)}$$

where YIC_p is the yearly installed capacity of power plant type *p* (in MW), and ES_p is the electricity generation share of power plant type *p*. ES_p is based on the current share of onshore wind, offshore wind, and solar photovoltaic generation in the EU (59%, 8% and 33% respectively).

Table 2. Performance factors used for renewable energy power plants.

Power plant type	Capacity factor (%) [a]	Transmission and distribution losses (%) [b]	Energy self-consumption (% of electricity produced) [c]	Maintenance energy costs (MJ MW^{-1} yr^{-1}) [d]	Lifetime (years) [e]
Solar photovoltaic panel	12.1	6.80	1.0	20002	25
Onshore wind turbine	22.3	6.80	2.8	7175	20
Offshore wind turbine	35.5	6.80	2.0	100097	20

[a] Calculated based on current capacity factors in individual EU countries, weighed by energy demand location (see Supplementary note 3 for more information).

[b] Calculated based on current losses in the EU grid as reported by [57] (see Supplementary note 3 for more information).

[c, d, e] Values obtained based on literature review of life cycle assessment and scientific literature (see excel supplementary information for more information. [d] is expressed in thermal-equivalent MJ.

3.5. Infrastructure required to transport and use the electricity generated

Additional infrastructure is required to transport and use the electricity generated to substitute fossil fuels. We estimate the electricity grid expansions (both transmission and distribution) required to transport the additional electricity generated as a result of deep electrification. We also estimate the material requirements of producing some of the end-use devices required to use electricity instead of fossil fuels. Specifically, we consider EVs and their charging infrastructure due to their exceptionally low usage rates relative to other end-use devices, resulting in a high embodied energy-to-consumption ratio (see Supplementary note 4 for a summary of the usage rates of all end-use devices).

Electricity grid expansion requirements (both transmission and distribution) are estimated as a linear function of the additional electricity they transport each year. A ratio of grid line length (for each power level) to electricity carried per year for the EU is estimated for the year 2013 based on [67] and [68], and is used to estimate the grid requirements for each year using equation 5,

$$Grid_v = Grid_{v,\ 2013}\left(\frac{electricity\ carried\ in\ current\ year\ (TWh)}{electricity\ carried\ in\ 2013\ (TWh)}\right), \qquad \text{(Eq. 5)}$$

where $Grid_v$ is the grid length required for voltage level v, and $Grid_{v, 2013}$ is the grid length for voltage level v in 2013. This leads to a very conservative estimate of additional transmission grid line requirements compared to literature focusing on quantifying this in detail (see Supplementary note 5), hence we carry out a sensitivity analysis on the effect of changing this modelling assumption (see section 3.11).

The number of EVs built each year is calculated as a function of the amount of oil phased out from the "road transport" sector and the EVs decommissioned that year according to equation 6,

$$EV_{count} = ICEV_{count,total}\left(\frac{oil\ phased\ out\ of\ road\ transport\ (TWh)}{total\ oil\ used\ in\ road\ transport\ (TWh)}\right) + EV_{decom.}, \qquad \text{(Eq. 6)}$$

in which EV_{count} is the number of EVs built this year, $ICEV_{count,\ total}$ is the total number of internal combustion engine passenger vehicles in use in 2021 (250,248,653 cars [69]), and $EV_{decom.}$ is the number of EVs decommissioned this year, equal to the number of EVs built one EV lifetime (assumed to be 10 years) prior. We assume that a 4-wheel passenger car is representative of all road vehicles in the EU. This is a simplification, however as they represent nearly 90% of vehicles, it is unlikely to significantly impact the results of the study.

3.6. Total material requirements of the transition each year

The material requirements of the transition are estimated based on the renewable energy power plant and additional infrastructure requirements calculated according to sections 3.4 and 3.5. Each item has an associated material intensity (for example, in kg per MW installed for the power plants, or kg per km for grid lines) sourced from literature. The material intensity of power plants is taken from [70] with some modifications, notably the use of non-stainless steel instead of stainless steel for wind turbine towers. For grid extensions, material intensities are taken from [71] who conducted a review of literature and consulted cable manufacturing companies for additional information. The material requirements for EVs are limited to those absent in ICEVs, as EVs are expected to substitute ICEVs rather than be produced in addition to them. These include materials used in batteries and the additional copper needed for the drivetrain. Material intensities are sourced from [21], specifically for Nickel-Cobalt-Aluminium (NCA) batteries, which consume the least energy to produce. Finally, the materials needed for EV charging infrastructure are accounted for, also using data from [21]. We assume that along the supply chain of each material, there is a loss of material equivalent to 10% of the material found in the final product (based on [72] Table 7). All material intensities are summarised in the supplementary information excel document.

3.7. Energy required to extract, transform, and transport materials

The energy required for extracting and transforming materials is calculated by multiplying the mass required of each material by its corresponding energy intensity. These intensities are derived from recent LCAs or studies specifically quantifying such energy requirements [73–79]. When a source provides data for semi-finished products (e.g., aluminium ingots or copper cathodes), additional literature is used to estimate the energy needed for producing finished products (e.g., aluminium extrusions or copper wires). This tailored dataset enables us to disaggregate final energy requirements into electrical and thermal components for materials accounting for 90% of the total energy demand associated with materials. For the remaining 10%, we use energy intensities from [70] (adjusted to final energy) and assume they share the same thermal-to-electrical energy ratio as the average of the tailored dataset. All values used can be found in the excel supplementary information document. The energy requirements associated with materials can hence be calculated in final thermal-equivalent terms using equation 7,

$$E_{materials,\ th\_eq} = \sum_{m=1}^{m_{max}} M_m\ EI_{th,m} + F_{th,el}\big(M_m EI_{el,m}\big), \qquad \text{(Eq. 7)}$$

where $E_{materials,\ th\_eq}$ is the material-related energy requirements, M_m is the mass required of material m, $EI_{th,\ m}$ is the final thermal energy intensity of material m, $F_{th,\ el}$ is the factor used to convert final electrical energy to final thermal energy (2.5 is used here), and $EI_{el,\ m}$ is the final electrical energy intensity of material m. All energy intensities, sources, and derivations can be found in the supplementary information excel document.

Transporting the materials required for the transition also requires energy in the form of fuel for trucks and cargo ships. To quantify this energy requirement, we apply the method outlined by [80] assigning a transport distance by road and by sea to each material; we assign 250 km of road transport to gravel and concrete/cement, and 500 km of road transport and 10,000 km of maritime transport all other materials. We base the energy requirements per mass transported by road and maritime transport on an analysis by [70], resulting in values of 3.5 MJ t^{-1} km^{-1} and 0.2 MJ t^{-1} km^{-1} respectively. The energy required for transport can hence be calculated using equation 8,

$$E_{transport} = \sum_{m=1}^{m_{max}} M_m(RT_m\ EI_{RT} + MT_m\ EI_{MT}), \qquad \text{(Eq. 8)}$$

where $E_{transport}$ is the final thermal energy required to transport materials, RT_m is the distance material m travels by road transport, EI_{RT} is the energy intensity of road transport, MT_m is the distance material m travels by maritime transport, and EI_{MT} is the energy intensity of maritime transport.

3.8. Energy requirements associated to the stock of electricity generating infrastructure

Some energy requirements are calculated as a function of the stock of electricity generating infrastructure. For example, energy self-consumption for heating the oil in wind turbine gearboxes, or cleaning solar panel surfaces are obtained using equation 9,

$$SC_{total} = \sum_{p=1}^{3} E_{prod.\ p}\, SC_p, \qquad \text{(Eq. 9)}$$

where SC_{total} is the total amount of electrical energy consumed by renewable energy power plants, $E_{prod.\ p}$ is the electrical energy produced by power plant type p, and SC_p is the ratio of electrical energy consumed per electrical energy produced by power plant type p. Values and sources used for SC_p are summarised in the excel supplementary information.

Maintenance energy requirements are calculated similarly, although they are a function of the installed capacity rather than the electrical energy produced by each power plant. They are calculated using equation 10,

$$E_{maintenance,\ total} = \sum_{p=1}^{3} Stock_p\, E_{maintenance,\ p}, \qquad \text{(Eq. 10)}$$

where $E_{maintenance,\ total}$ is the total energy required for the maintenance of the renewable energy power plants, $Stock_p$ is the installed capacity of power plant type p, in MW, *and* $E_{maintenance,\ p}$ is the yearly energy required for the maintenance of 1 MW of capacity of power plant type p. The electrical-thermal split of the maintenance energy requirements is assumed to be the same as that of the corresponding power plant type's material-related energy requirements. All values and sources for $E_{maintenance,\ p}$ are summarised in the excel supplementary information.

The energy required to decommission renewable energy power plants is approximately 10% of the energy required to build them according to [81], hence we assume that it is equivalent to 10% of the material-related energy requirements. The electrical-thermal energy split is assumed to be all thermal energy, as decommissioning typically involves dismantling and transporting power plant parts with diesel-powered construction vehicles (cranes, bulldozers, trucks etc.). We do not consider the decommissioning energy requirements of fossil fuel power plants, nuclear power plants, or other installations replaced by electrified alternatives to be part of the transition energy requirements.

3.9. Electricity storage losses and curtailment

Significant efforts have been undertaken to estimate the electricity storage requirements, electricity losses due to round trip efficiency of storage systems, and levels of curtailment associated with an increasing penetration of intermittent renewable energy power plants [82–85]. These studies report values for the sum of storage losses and curtailment of 1.2% to 10.5% and 7% to 20.4% of power production in scenarios with 80% and 100% penetration of intermittent renewables, respectively. However, they only studied a system over a one-year period, rather than over multiple consecutive years at a time, and do not reflect the case studied in this work (see Supplementary note 6). Smith et al. [46] found that studying time scales shorter than half a century likely leads to a severe underestimation of storage requirements. Using the United Kingdom as a case study, Smith et al. [46] estimated that an electricity system with an 80% penetration of solar and wind lost 23% of its production to curtailment and storage losses on average. In line with this, the share of electricity production lost to storage inefficiencies and curtailment is assumed to increase linearly from 0% to 23% when the penetration of renewables increases from 50% to 80%. We surpass an 80% penetration of solar and wind in some scenarios, hence we likely underestimate these losses.

3.10. Total energy requirements of the transition and indirect energy requirements

The direct energy requirements of the transition are calculated as the sum of energy requirements detailed in sections 3.7 and 3.8. As these result from a bottom-up assessment, they are biased towards underestimating the requirements due to truncation errors arising from narrow system boundaries [30,86]. To quantify the likely truncation error in our result, we refer to recent developments in literature (see Supplementary note 7) aiming to estimate the truncation error found in process-based LCAs, which are comparable to our data sources and bottom-up approach. We use a ratio of "real" energy requirements to "estimated" energy requirements of 1.3, meaning we add 30% to our estimates of both thermal and electrical energy requirements.

The energy required to obtain fossil fuels is estimated and presented alongside the main results of this work in Fig. 4. This is derived by assuming the energy requirements of obtaining fossil fuels decreases linearly with fossil fuel consumption from an initial value sourced from [57]. The value provided by [57] is an underestimation as it only accounts for energy spent within the EU, ignoring energy costs associated with extraction and transport of oil and gas occurring outside the EU.

3.11. Uncertainties and sensitivity analyses

Dozens of parameter and factor values are estimated in this model, usually based on multiple peer-reviewed sources. The confidence in these values is never absolute, and hence an uncertainty is associated with each of them depending on the robustness of the estimation. The robustness of the overall result is tested by running 1,000 simulations in which parameter values are selected based on Gaussian probability distribution functions (see Supplementary Table 7 for mean and standard deviation values used).

In addition to an uncertainty analysis, we conduct sensitivity analyses to assess the effect of 4 major assumptions in the model. (1) The effect of a full hydrogen economy on the energy requirements of the transition is tested by using an alternative set of sector factors corresponding to using hydrogen in residential heating, commercial heating, industry energy use (e.g., hydrogen boilers instead of electric boilers), and road transport (fuel-cell vehicles instead of BEVs) summarised in Supplementary note 2. (2) The assumption regarding grid expansions requirements is tested by (i) scaling the grid line requirements with installed capacity rather than the electricity generated (similarly to [87]), and (ii) multiplying the grid line requirements of the base case by 4 (to match transmission requirements estimations mentioned in Supplementary note 5). (3) As the industry energy use sector has one of the least robust sector factors, we test the effect of changing it to a sector factor corresponding to a high rollout of high temperature heat pumps, as well as a fully hydrogen-based industry heat system. (4) Finally, we present the main results assuming all sectors are electrified simultaneously rather than consecutively.

4. Results

4.1. Energy requirements for fossil fuel phase out

Total energy requirements of the transition for the four transition scenarios are shown in Fig. 4, and put in comparison with electricity storage losses, and energy spent on fossil fuels in the EU. First, we can observe that in all scenarios, transition energy requirements become larger than the energy required to obtain fossil fuels at the starting year. Secondly, phasing out fossil fuels faster leads to a higher peak in transition energy consumption, and total energy spent on the transition. Thirdly, in the scenarios which phase out fossil fuels (Fig. 4A; 4B), transition energy requirements increase until fossil fuels are phased out, then drop as the stock of renewable energy power plants stabilises. Finally, Fig. 4A indicates that after fossil fuels are phased out, transition energy requirements associated to the maintenance, energy self-consumption, decommissioning and replacing of solar panels and wind turbines after 2040 are still significantly larger than the energy required to obtain fossil fuels was in 2021. Supplementary Fig. 4 shows that material-related energy requirements are one order of magnitude greater than transport and self-consumption-related requirements, and two orders of magnitude greater than maintenance and decommission-related requirements.

Storage losses, which result from deepening penetration of intermittent power plants (up to 90% of electricity generation in the scenarios of Fig. 4A and 4B), are similarly significant to transition energy requirements, reaching 2462 TWh of electricity (or 6155 TWh of thermal-equivalent final energy) per year. At first, storage losses evolve on a similar timeline to transition energy requirements because the latter indicates additional intermittent electricity production, which the former depends on. After fossil fuels are phased out, however, storage losses remain constant, as they depend on the stock of electricity generating infrastructure, which no longer changes once the transition is achieved.

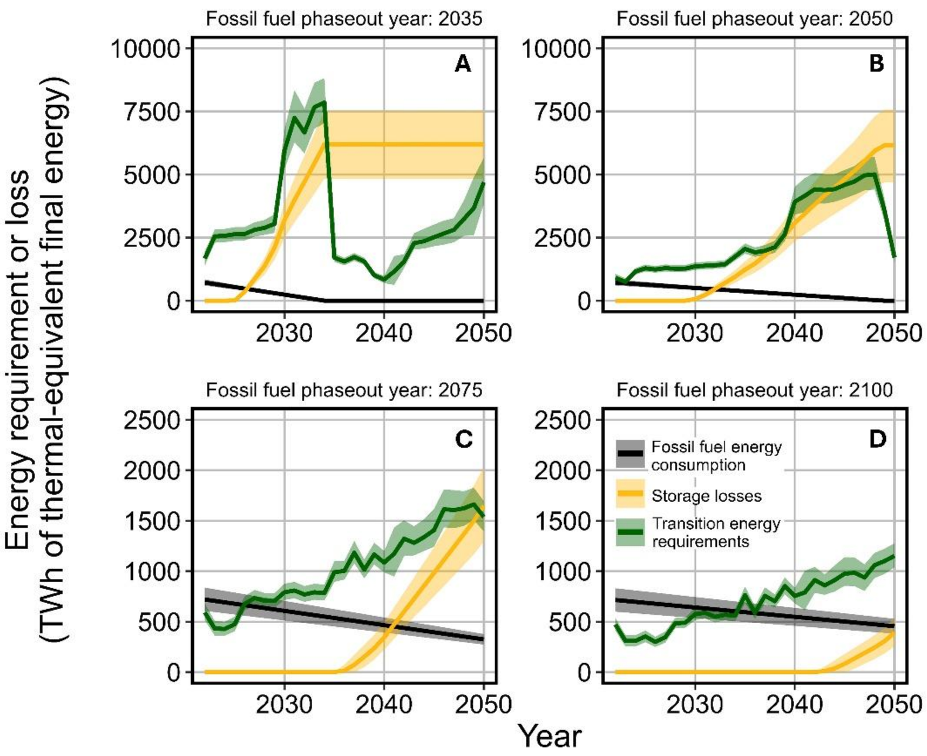

Fig. 4. | Faster energy transitions have higher energy requirements. Summary of the energy requirements associated with an energy transition phasing out fossil fuels in 2035, 2050, 2075 and 2100 (panels A, B, C and D respectively). The electricity storage losses resulting from the increasingly intermittent electricity production are shown in yellow, while the rest of the energy requirements detailed in Fig. 2 are shown in green. The energy expenditures associated with fossil fuels are shown in black for comparison. The shaded regions surrounding the lines represent 90% confidence intervals based on 1,000 simulations with parameter values sampled from normal distributions. Note the change of scale between the top two figures and the bottom two figures.

4.2. Sectoral electrification efforts

To assess the transition energy requirements, we broke them down by sector, and further disaggregated them by power plants, grid extensions, and end-use devices for the 2050 scenario (Fig. 5). Notably, road transport requires the most energy (26%), followed by industry non-energy use (22%), together comprising 48% of the total. End-use devices for road transport (vehicles, chargers, and dedicated grid extensions) represent nearly 70% of its energy requirements, indicating a substantial energy investment is required to enable consumption of electricity in this sector. The grid extensions required by sectors typically represent 11% of their total energy requirements, except for road transport (3%), and electricity generation (0%) demonstrating that they are smaller but significant. Across all sectors 0.72 units of electrical energy are needed to replace each unit of fossil fuel thermal energy.

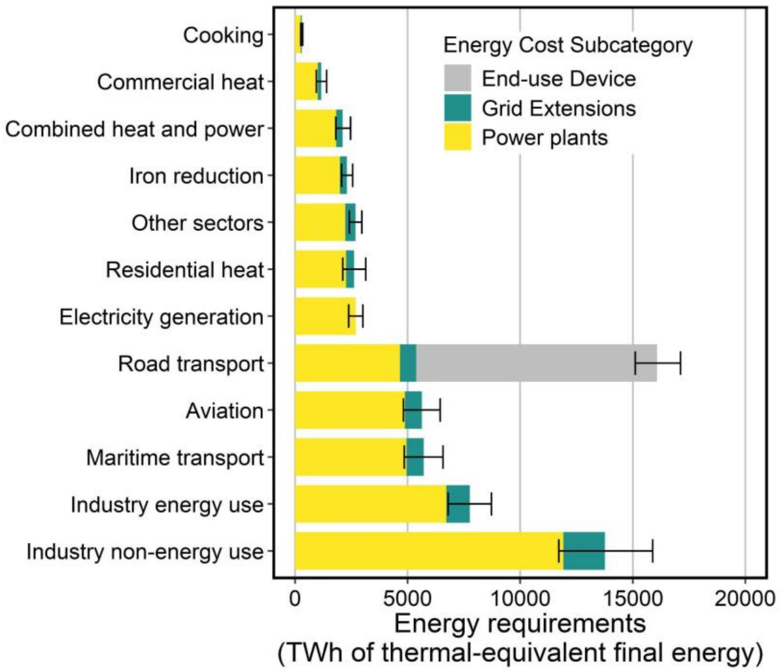

Fig. 5. | Energy requirements disaggregated by sector and type. Energy required to electrify each sector by 2050, disaggregated into power plants (yellow), grid extensions (green), and end-use devices (grey). End-use devices were quantified only for road transport (see Supplementary note 4). Grid extensions are unnecessary for electricity generation, as replacing thermal plants with renewables does not increase total electricity production. Error bars show the 90% confidence interval for total energy requirements, based on 1,000 simulations with parameter values sampled from normal distributions. The analysis assumes simultaneous sector electrification to avoid penalizing sectors electrified earlier.

4.3. Full hydrogen economy case study

We explore the effect of using hydrogen as an energy vector whenever possible, rather than when it is necessary (e.g., for iron reduction, aviation and maritime transport) to simulate a “full hydrogen economy scenario” (Fig. 6). Using hydrogen increases the sector factors of all concerned sectors significantly: cooking, commercial heating, residential heating, road transport, and industry energy use see their sector factors increase 2.6, 4.8, 4.8, 2.9, and 1.6-fold respectively. The total energy requirements across sectors increase dramatically from 62,850 to 82,560 TWh of thermal-equivalent final energy. This excludes end-use devices from the full hydrogen economy case due to data limitations, hence underestimating its transition energy requirements. Most notably, the share of energy requirements for domestic and commercial heating increases from 6% to 22%. The increased electricity production required to use hydrogen also increases electricity storage losses by 44% once the transition is complete. This hydrogen-centric approach to the transition results in an energy system with substantially more energy requirements and storage losses than the base case while providing the same services. Finally, the substitution rate of fossil fuel thermal energy by electricity increases to 1.1, making electricity less useful, on average, than thermal energy.

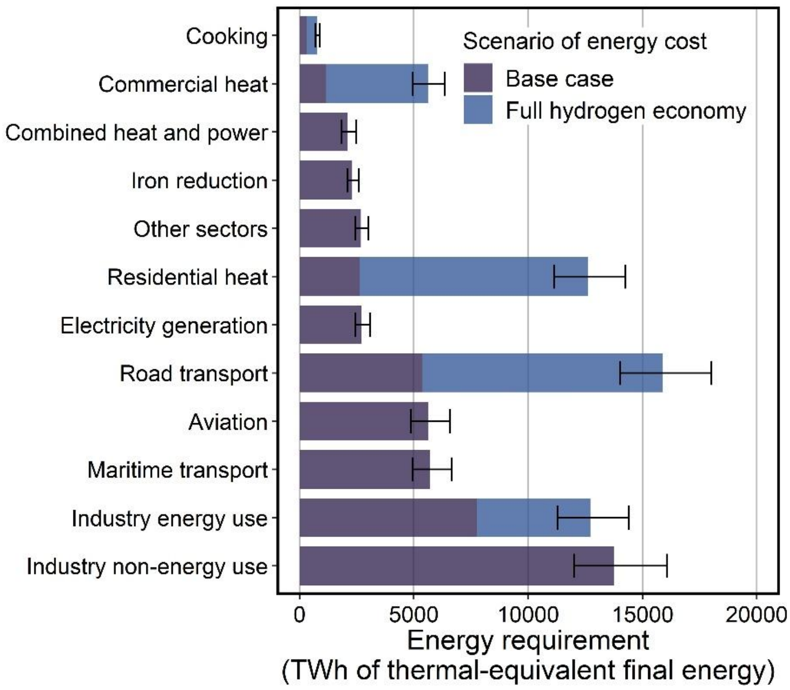

Fig. 6. | Changes in energy requirements of sectors when using hydrogen as the default energy carrier. The results presented are for a 2050 fossil fuel phase-out with simultaneous sector electrification. Energy requirements represent power plants and grid extensions only; end-use devices are not considered (see Results section 4.3). The "Base case" represents the results shown in Fig. 5. The "Full hydrogen economy" bars represent the additional energy requirements when using hydrogen as

an energy vector in a sector. Error bars show the 90% confidence interval for total energy requirements, based on 1,000 simulations with parameter values sampled from normal distributions.

4.4. Sensitivity analyses

Each model parameter was assigned a Gaussian probability distribution, and 1,000 simulations were conducted for each scenario, resulting in a distribution of results summarised as a 90% confidence interval in Fig. 4-6. Yearly transition energy requirements vary by ±10-12% until 2039, increasing to ±15-20% from 2040 onwards as uncertainty in the lifetime of wind turbines and solar panels starts affecting results. Storage losses vary consistently by ±21-24% throughout the transition. Sector-specific energy requirements vary by ±8-32% with lower uncertainties for sectors using established electrification technologies (e.g., heat pumps in residential heating), and higher uncertainties for those relying on novel or undeveloped technologies (e.g., hydrogen-fuelled planes).

Several sensitivity analyses were conducted to estimate the impact of key assumptions in the model. Based on the results summarised in Table 3, the largest contributor to uncertainty is changes to the grid extension requirements (Supplementary Fig. 1). Changing the sector factor of industry energy use to reflect a deeper penetration of high-temperature heat pumps or hydrogen (Supplementary Fig. 2), or changing the sectoral electrification from sequential to simultaneous led to smaller changes in transition energy requirements (Supplementary Fig. 3) For the 2075 and 2100 scenarios, the increase due to simultaneous sectoral electrification is significantly larger, but this is due to different sectors being electrified during the study period (as opposed to the same sectors in different orders for the 2035 and 2050 scenarios), which makes the results incomparable. Supplementary Table 6 summarises additional data output of the sensitivity analyses, including peak transition energy requirement, peak storage losses, and total storage losses.

Table 3. Sensitivity analysis results. The relative change in total transition energy requirements observed in each sensitivity analysis compared to the base case for the corresponding fossil fuel phaseout scenario (2035, 2050, 2075 or 2100) is shown. The full hydrogen economy case study and the grid expansion requirement sensitivity analyses show the most significant increases in energy requirements. Significant increases are observed for the 2075 and 2100 simultaneous sector

electrification scenarios because different sectors are electrified during the study period compared to the base case; the difference would be smaller had the study period extended to the respective fossil fuel phaseout dates. n/a values are shown when the model results were not generated because they would not lead to meaningful comparisons.

Sensitivity analysis	Differences in transition energy requirements for scenario			
	2035	2050	2075	2100
1. Full hydrogen economy case study	+36%	+37%	n/a	n/a
2.1 Grid expansion scales with installed capacity	n/a	+18%	n/a	n/a
2.2 Grid expansions quadruple	n/a	+34%	n/a	n/a
3.1 Industry uses hydrogen	n/a	+5.3%	n/a	n/a
3.2 Industry uses heat pumps	n/a	-2.0%	n/a	n/a
4 Simultaneous sector electrification	+6.1%	+7.9%	+53%	+58%

5. Discussion

5.1. Energy requirements for phasing out fossil fuels

We present a physically consistent framework for the energy transition featuring disaggregated sectoral electrification to estimate the energy requirements of the transition across four scenarios in an EU case study. We find that faster transition scenarios demand greater energy reallocations – that is, taking energy which used to serve a final end-use unrelated to the energy sector, and spending it on the energy transition instead. In a scenario which phases out fossil fuels by 2035, the combined transition energy requirements and storage losses peak at 14,005 TWh of thermal-equivalent final energy – over 80% of the EU's current energy supply. Distributing the transition requirements evenly would reduce the peak to 60%. For the 2050 scenario, we find that both values are lowered to 64% and 50% respectively. Whilst these results do not suggest such scenarios would be physically impossible – the energy required does not surpass the energy available in any given year – it would require significant planning to implement and raises concerns about potential societal disruptions in the fastest cases. Furthermore, using hydrogen in sectors where it is unnecessary would increase peak energy requirement of the transition, exacerbating the associated societal disruptions.

We also reveal the energy required to electrify each sector, enabling us to identify trends and opportunities for facilitating the transition. We find that decreasing the usage of a sector's product is more impactful when it has a higher sector factor. For example, decreasing the demand of the aviation or non-energy use sectors by 1 TWh of final fossil fuel energy eliminates an energy investment of 12 or 13 TWh respectively, compared to 2 TWh for the residential heating sector. Symmetrically, investing 1 TWh of energy into electrifying residential heating displaces a total of 7.2 TWh of fossil fuels compared to 1.2 and 1.1 TWh for aviation and non-energy use. Assuming that efficiency measures are being deployed in all sectors, this suggests that other demand reduction methods, such as sufficiency, should preferably be directed towards high-factor sectors, such as non-energy industrial use, aviation, maritime transport, etc., where co-benefits could be further multiplied [88–90].

Regarding other sectors, we support [21] in finding that the construction of EV batteries and charging infrastructure requires more energy than building the renewable energy power plants which power them. This suggests that the road transport sector has a unique opportunity to reduce its transition energy requirements in using smaller vehicles as this would decrease both end-use devices and – assuming smaller vehicles are more efficient – power plant and grid extension energy requirements. Decreasing the number of EVs required by increasing car sharing would also be beneficial, assuming rebound effects are mitigated [91,92].

We find that using hydrogen increases energy requirements of the energy transition across all sectors and increases energy-related societal disruptions. Hence, we believe that any economics-based argument in favour of using hydrogen as an energy vector should be complemented with an assessment of the additional energy and material requirements it entails. In an alternative scenario including growth in energy demand met by renewable power plants, transition energy requirements and storage losses would increase compared to the case presented and conversely decrease if energy demand gradually decreased.

5.2. Implications for energy transition research

Current literature on the energy transition is predominantly shaped by economics-based models that do not comprehensively account for physical flows and, consequently, overlook the challenge of energy requirements and sectoral electrification [39]. Based on a physically consistent approach, we show that energy needs have major socio-economic implications and suggest ways to account for them consistently in future research.

First, the amount of electricity required to substitute fossil fuels on the energy supply side should be based on the sectors fossil fuels are removed from. Current publications tend to consider a static, although varying value for this substitution rate, leading them to suggest different amounts of renewable energy power plants are required to phase out the same amount of fossil fuels, resulting in different transition energy requirements. For example, Sahin et al. [22] consider that one unit of primary fossil fuel energy is replaced by 0.4 units of electricity (in their Supplementary Table 1), while Capellán-Pérez et al. [20] (based on the explanation of g^{syst} and g^{tech}) and Slameršak et al. [19] (based on their supplementary Figure 7), assume that final energy is equivalent whether it is thermal or electrical energy.

Second, we suggest that studies systematically clarify system boundaries when it comes to assessing the energy requirements of the transition. As we have summarised in Table 1, power plants, grid expansions, storage losses, and end-use devices have been considered in different combinations and depths in literature, which complicates comparing results between studies.

Third, when addressing energy transition requirements, we call to either present thermal and electrical components separately, or to use a dynamic substitution factor that mirrors changing average electricity-heat substitution rates as sectors are electrified. In literature, energy requirements are treated in two main ways. The first is to present them in final terms, in which case electricity and heat are assumed to be equivalent [20]. The second is to convert all types of energy requirements into a single type using a set of conversion factors, as done in [22], and this work.

5.3. Limitations and future development

Although our methodology improves some aspects of transition energy requirement estimations, it faces several limitations. Below, we summarise these limitations, their likely impacts, and future development opportunities to address them.

The first set of limitations results from treating some parameters as static rather than dynamic. First, we do not consider improvements in the energy efficiency of providing services (e.g., home insulation reducing energy consumption, or energy requirements of processes involved in deploying renewable energy power plants decreasing, etc.). This leads us to progressively overestimate electricity demand and transition energy requirements over time. Secondly, we assume that demand for services remains constant, which could over- or underestimate electricity demand and transition energy requirements, depending on factors such as economic growth, demand-side solutions, and the rebound effect. Thirdly, we consider that performance factors and material requirements of renewable energy power plants remain constant, although these are expected to evolve and improve their net energy characteristics [93]. The projected efficiency gains in the optimistic "450 ppm" scenario of Steffen et al. [93] would only decrease energy requirements of wind turbines and solar photovoltaic panels by 14% and 31% by 2040 (compared to financial cost reductions estimations of 62% and 75% [94]), respectively, without necessarily affecting the energy requirements of grid extensions or end-use devices, or storage losses. As a result, the performance factors and material intensities reflecting these improvements are represented in the 90% confidence intervals in Fig. 4-6. Finally, we use static values for the specific energy requirements of fossil fuels, even though they increase with cumulative extraction for oil and gas [37,38]. This leads us to underestimate the energy spent on fossil fuels in Europe, particularly in the 2075 and 2100 scenarios.

The second set of limitations stems from our study's scope. We cannot quantify the recycled fraction of material supplies, which affects their energy intensities, because we do not model material demand of non-transition end-uses (e.g., construction, data centres, etc.), or primary material supplies.

Instead, we assume that transition material requirements are met in addition to other uses, meaning their energy intensity corresponds to primary material supplies. Although biomass and hydroelectricity energy supplies are affected by climate change [58,95,96], we do not model these interactions. Finally, high-temporal-resolution electricity generation models (e.g., [97]) provide more accurate estimates of grid extension requirements, storage losses, and their variations based on the relative share of different electricity generation technologies, but developing and using one is far beyond the scope of this work.

Future opportunities to improve the model require more interdisciplinary research. Integrating dynamic material flow analysis to quantify recycled material availability, using high-temporal-resolution electricity generation models for better storage and grid requirement estimations, and applying climate-biomass-hydrology nexus analyses to improve bioenergy and hydroelectricity modelling are key areas for future development. A further opportunity identified involves assessing how the electrification of production processes influences the transition's energy requirements. This could be achieved by tracking the extent of electrification of sectors and disaggregating transition energy requirements into sectors.

6. Conclusion

The energy transition needs significant deployment of wind and solar power plants, in turn requiring materials, and energy to extract and transform these materials into energy infrastructure. Accurately quantifying this amount of energy is crucial to identifying potential physical barriers to the energy transition and devising plans to overcome them. To this end, we propose a physically consistent model quantifying the energy required to build renewable energy power plants, along with the necessary grid extensions and end-use devices needed to phase out fossil fuels across all sectors. We apply this model to four fossil fuel phaseout scenarios (2035, 2050, 2075, 2100), as well as a case study on the use of green hydrogen as an alternative energy vector to electricity.

We find that transition energy requirements increase with transition speed and that they are greater than the current energy spent on obtaining fossil fuels in all scenarios. By tracking the requirements of each sector, we find that road transport requires the most energy to electrify (26% of total energy requirements), closely followed by industry non-energy use (22%). Further disaggregating these requirements by category – power plants, grid extensions, and end-use devices – reveals that grid extensions make up 11% of the total (increasing to 35% depending on modelling assumptions), and that end-use devices account for nearly 70% of road transport energy requirements, highlighting their significance. Finally, we estimate that using hydrogen as an energy vector whenever possible – rather than when necessary – increases total energy requirements by 31% and storage losses by 44%.

Our findings align with the emerging consensus on net energy [39] indicating that a rapid energy transition (by 2035 or 2050) will require reallocating significant amounts of energy from other end uses to the transition. This could lead to societal disruptions, as we would have to spend less energy on some services (e.g., transport, residential heating, manufacturing, etc.) to carve an energy budget for the transition. Within the EU and globally, significant disparities exist in how much energy populations can spare, due to differences in the share of energy used for discretionary purposes. The energy transition will affect everyone, albeit unevenly, whether it is fast (as explained above) or slow (due to the consequences of climate change), and hence the path forward must be built with these two forces – among others – in mind. Better quantifying the energy requirements of the transition will facilitate planning these trade-offs and complementing energy analysis with multidisciplinary research on material flow analysis, climate-energy system interactions, and electricity systems will yield more robust and comprehensive results.

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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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