Physically consistent sectoral pathways for phasing out fossil fuels

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Overview

Alongside geopolitical and socio-economic impacts, phasing out fossil fuels is complicated by the physical challenges inherent to the energy transition. The energy transition requires a substantial amount of energy to construct, operate, and maintain a low-carbon energy system, much of which is currently derived from fossil fuels (Slameršak et al., 2022). A further challenge arises in the sectoral allocation of electrification efforts, as certain sectors are more amenable to transformation due to the efficiency gains associated with electrification. Increasing scholarly attention has been directed toward both the energy requirements of transition plans (e.g., Capellán-Pérez et al., 2019; Pulido-Sánchez et al., 2022; Slameršak et al., 2022) and the changes in final energy consumption linked to the electrification of services (e.g., Grubler et al., 2018; Jacobson et al., 2022). However, most studies focus on either aspect alone, with few providing an integrated analysis, resulting in a loss of critical information for making climate mitigation pathways operational. To bridge this gap, we propose an energy 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 scenarios phasing out fossil fuels by 2035, 2050, 2075 and 2100.

Methods

The bottom-up methodology developed in this work centres around tracking the physical (mass and energy) flows resulting from an energy transition, using the European Union from 2021 to 2050 as a case study. First, we quantify the infrastructure (power plants, electric grid extensions, and end-use devices) required to replace fossil fuels with electricity. Secondly, we estimate the quantity of materials necessary to build this infrastructure and calculate the energy needed to extract, transform, and transport these materials. Thirdly, we track the energy required to operate and maintain the stock of renewable energy power plants, as well as the losses arising from an electricity system with a very high penetration of intermittent power plants. Finally, we evaluate the robustness of the results using several sensitivity analyses.

To quantify the infrastructure requirements, we start by calculating sectoral electrification efficiencies for all major sectors in which fossil fuels are used. Using these values, we quantify the electricity required to substitute the fossil fuels phased out each year. Based on the additional electricity generation required each year, we estimate the capacity of onshore and offshore wind turbines, and solar photovoltaic panels needed each year. This is done based on the performance characteristics (e.g., capacity factors, grid transmission losses, ageing losses, etc.) of these renewable energy power plants in the specific region they are built. The grid expansions necessary to transport the additional electricity resulting from electrification are conservatively estimated by assuming the total grid requirements scale with total electricity production. We also quantify the amount of "end-use devices" required to use the additional electricity, such as electric vehicles and their associated charging stations.

The yearly material and energy requirements of these transition scenarios are obtained by quantifying the total amount of materials necessary to build the power plants, grid extensions, and end-use devices required based on life cycle inventory databases. Next, we obtain the energy required to extract, transform, and transport these materials by multiplying the mass of each material by its corresponding energy intensity. These intensities are derived from recent life cycle assessments and studies specifically modelling such energy costs. By tracking the stock of solar photovoltaic panels and onshore and offshore wind turbines, we estimate the energy required to operate and maintain them. We quantify the losses arising from the round-trip efficiency of electricity storage devices based on the total stock of electricity-generating infrastructure, and the share of intermittent power sources.

To evaluate the robustness of the main results, we carried out 100,000 simulations with randomised parameter values sampled from normal distributions, and 90% confidence intervals were derived. We also tested the effect of key assumptions on the total energy requirements of the transition, including the use of hydrogen rather than electricity as an energy vector, and empirical representations of different grid expansion requirement models.

Results

Our results indicate that, first, in all scenarios, transition energy requirements become larger than the energy required to obtain fossil fuels was before the transition started. Secondly, phasing out fossil fuels faster leads to a higher peak in transition energy requirements, and total energy spent on the transition. Thirdly, in the scenarios which phase out fossil fuels completely (2035 and 2050), transition energy requirements increase until fossil fuels are phased out, then drop as the stock of renewable energy power plants stabilises. Finally, the 2035 scenario demonstrates that after fossil fuels are phased out, transition energy requirements associated to the decommissioning and replacing of solar panels and wind turbines after 2040 are still significantly larger than the energy required to obtain fossil fuels ever was. We find that storage losses are of a similar significance to transition energy requirements. The largest source of uncertainty in the transition energy requirements came from the grid expansion requirements, increasing transition energy requirements by 18-34% compared to our base case depending on modelling methodology.

We also find that across all sectors, the replacement rate of fossil fuel energy by electricity is 0.71 units of electrical energy for each unit of fossil fuel thermal energy. In the case study where green hydrogen is used in all possible sectors (e.g., including residential heating, cooking, road transport), this replacement rate increases to 1.1, making electricity less useful, on average, than thermal energy.

Conclusions

We concur with the emerging consensus that an energy transition must be fast enough to avert catastrophic climate change, but that a much faster shift will divert energy from potentially essential current uses to the transition, risking societal disruptions. In addition to this, we conclude that sectoral disaggregation is essential to make physically consistent transition plans, as ignoring it may lead to an underestimation of the total electricity requirements, and in turn of the scale of renewable energy power plants needed to phase out fossil fuels. Decisions regarding the use of hydrogen in various sectors have a significant impact on the total amount of renewable energy power plants needed, and in turn on the feasibility of the transition in terms material supplies, and energy requirements. Finally, more extensive grid requirement modelling is necessary in energy transition research to enable more accurate and robust scenario analysis.

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