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MECHANISM · Energy Systems · Cross-Country Decarbonisation

The Uneven Diffusion of Decarbonisation Technologies: Measures and Stylised Facts

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Abstract

The global energy transition is often interpreted as a single accelerating process. Across countries, it is not. This paper examines the diffusion of decarbonisation technologies across 79 countries between 1965 and 2024 and identifies four stylised facts. Using public Energy Institute energy data and World Bank indicators, this paper develops four measures, namely, deployment level, decarbonisation velocity, carbon lock-in, and transition-path position. First, renewable deployment is both recent and highly concentrated, with most progress occurring after 2000 and in a relatively small group of countries. Second, the pace of decarbonisation varies widely. The frontier economies advance by more than one percentage point annually, whereas the median country progresses by only 0.19 percentage points. Third, carbon lock-in is concentrated in fossil-fuel producers and lower-income economies. Fourth, in 46% of countries, renewable energy expanded alongside rising fossil-fuel consumption between 2010 and 2023, indicating energy addition rather than substitution. These stylised facts provide a comparative framework for understanding why national energy transitions follow significantly different trajectories.

Keywords: energy transition · decarbonisation · technology diffusion · carbon lock-in · modern renewables · cross-country analysis · deployment velocity · addition vs substitution

1. Introduction

The global energy transition is often presented as a single curve bending towards low-carbon energy. At the country level, it looks very different. The diffusion of decarbonisation technologies is uneven, recent, and highly concentrated. A small group of countries is decarbonising rapidly, while many others are making only limited progress. In much of the world, renewable energy is expanding alongside fossil fuels rather than replacing them. Therefore, the global transition is not one transition but many, unfolding at different speeds and along different pathways.

This paper highlights that variation by establishing a set of stylised facts on the cross-country diffusion of decarbonisation technologies. Using public Energy Institute and World Bank data, I

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develop four reproducible measures that capture complementary dimensions of the transition: deployment level, decarbonisation velocity, carbon lock-in, and transition-path position. Together, these measures describe where countries stand, how quickly they are progressing, how strongly they remain tied to fossil fuels, and the pathway their transition is following.

The paper is descriptive. It does not explain why countries differ or estimate the effects of specific policies. Instead, it identifies the empirical regularities that any explanation of the energy transition must account for. The paper's contribution is twofold. First, it provides a consistent framework for measuring decarbonisation across countries and over time. Second, it establishes a comparative empirical baseline that can support future research on the drivers, consequences, and political economy of energy transitions. The analysis also highlights lower-income and fossil-fuel-producing economies, where evidence remains relatively limited and where renewable expansion more often reflects energy addition than fossil-fuel substitution.

2. What Are Measured?

I treat decarbonisation as a diffusion process and measure four complementary dimensions of that process [3]. The first is deployment level, which captures how much of a country's energy system has already shifted towards low-carbon sources. The second is decarbonisation velocity, which measures how quickly that shift is taking place. Countries may reach similar deployment levels but arrive there at very different speeds. The third is carbon lock-in, which captures the extent to which existing fossil-fuel dependence resists change through established infrastructure, institutions, and patterns of energy use [1]. The fourth is transition-path position, which identifies where a country sits along the broad sequence from coal- and oil-based systems towards gas and, ultimately, low-carbon energy. Together, these measures describe not only how far countries have progressed, but also how rapidly they are moving, how constrained they remain by fossil-fuel dependence, and where they are positioned along the transition pathway.

These are measures of technology deployment rather than technological innovation. They capture the adoption and diffusion of low-carbon energy technologies at the country level, not where those technologies are invented or how much research they generate. The distinction is important because deployment and innovation do not necessarily occur in the same places. This deployment perspective provides a consistent basis for comparing national decarbonisation trajectories and establishes an empirical baseline for future causal research.

3. Data and Methods

3.1 Data and the fuel mix

I use primary energy consumption by fuel from the Energy Institute Statistical Review of World Energy for the period 1965–2024. The dataset reports energy consumption in exajoules on a common energy basis. I combine oil, natural gas, coal, nuclear, hydroelectricity, solar, wind, and other modern renewables for each country and year. Country characteristics, including income classification, are obtained from the World Bank World Development Indicators. The final panel covers 79 countries reported individually in the Energy Institute dataset. Smaller economies aggregated into regional totals are excluded because country-level observations are unavailable. To improve the consistency of the low-carbon measures, I validate renewable energy estimates against the World Bank renewable energy series.

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Fuel shares are calculated from total primary energy consumption so that they sum to one. To avoid double counting, the aggregate renewables category is adjusted to exclude hydroelectricity, which is reported separately alongside solar and wind. The fossil share is defined as the combined share of oil, natural gas, and coal. The low-carbon share comprises nuclear, hydroelectricity, and modern renewables, while the modern renewable share includes solar, wind, and other non-hydro renewable sources. By construction, the fossil and low-carbon shares together account for total primary energy consumption.

3.2 The four measures

Deployment level is the low-carbon share of primary energy for country i in year t:

$$LC_{i,t} = (\ nuclear + hydro + modern\ renewables\ )_{i,t} / primary\ energy_{i,t} \quad (1)$$

Decarbonisation velocity is the average annual change in the modern-renewable share over 2000 to 2024, in percentage points per year:

$$v_i = slope\ of\ MR_{i,t}\ on\ t,\ for\ t = 2000...2024 \quad (2)$$

Carbon lock-in refers to the persistence of a high fossil-fuel share. It is the recent fossil level scaled down by the pace of its decline, so it is high when fossil dependence is both high and not falling:

$$L_i = fossil\ share_{i,recent} \times (\ 1 - decline\ rate_i\ ) \quad (3)$$

Transition-path position is the combined share of gas and low-carbon energy, which rises as a country moves away from coal and oil:

$$TP_i = (\ gas\ share + low\text{-}carbon\ share\ )_{i,recent} \quad (4)$$

Table 1. The four diffusion measures

Measure	Captures	Construction
Deployment level	How far	Low-carbon share of primary energy
Decarbonisation velocity	How fast	Slope of modern-renewable share, 2000–24 (pp/yr)
Carbon lock-in	How stuck	Recent fossil share scaled by its rate of decline
Transition-path position	Which path	Combined gas and low-carbon share

Computed from Energy Institute fuel-consumption data, 79 countries, 1965–2024.

3.3 Approach

I begin by describing the cross-country distribution of the four measures and how they evolve over time. I then examine cross-country gradients, the persistence of fossil dependence, and whether growth in low-carbon energy is accompanied by declines or increases in fossil-fuel consumption. Finally, I assess whether countries are converging or diverging in their energy transitions by examining the evolution of the cross-country standard deviation of the low-carbon energy share over time.

4. Stylised Facts

Fact 1. Diffusion is recent and concentrated

Modern renewable energy is a recent phenomenon for most countries. Across almost the entire sample period, its share of primary energy remained close to zero. Meaningful growth appears

only after about 2000 and is concentrated in a relatively small group of countries. Even today's frontier economies show little evidence of sustained deployment before the turn of the century. Figure 1 illustrates this pattern by comparing representative frontier economies with large emerging economies. The evidence points to two features of the global transition. First, the diffusion of modern renewables is historically compressed. Most observed deployment has occurred within the past two decades. Second, diffusion is highly concentrated. A small group of countries accounts for much of the observed progress, while most countries remain at early stages of deployment. Therefore, the aggregate transition does not reveal substantial cross-country heterogeneity.

The diffusion curve suggested by global aggregates is, at the country level, a collection of late and uneven take-offs rather than a smooth and broadly shared transition. This distinction matters because countries are often compared as if they were moving along the same diffusion path. The evidence instead suggests multiple diffusion trajectories, with different starting points, speeds, and levels of technological adoption.

> *"The diffusion curve that the aggregate transition implies is, at the country level, a set of late and uneven take-offs rather than a smooth global shift. "*

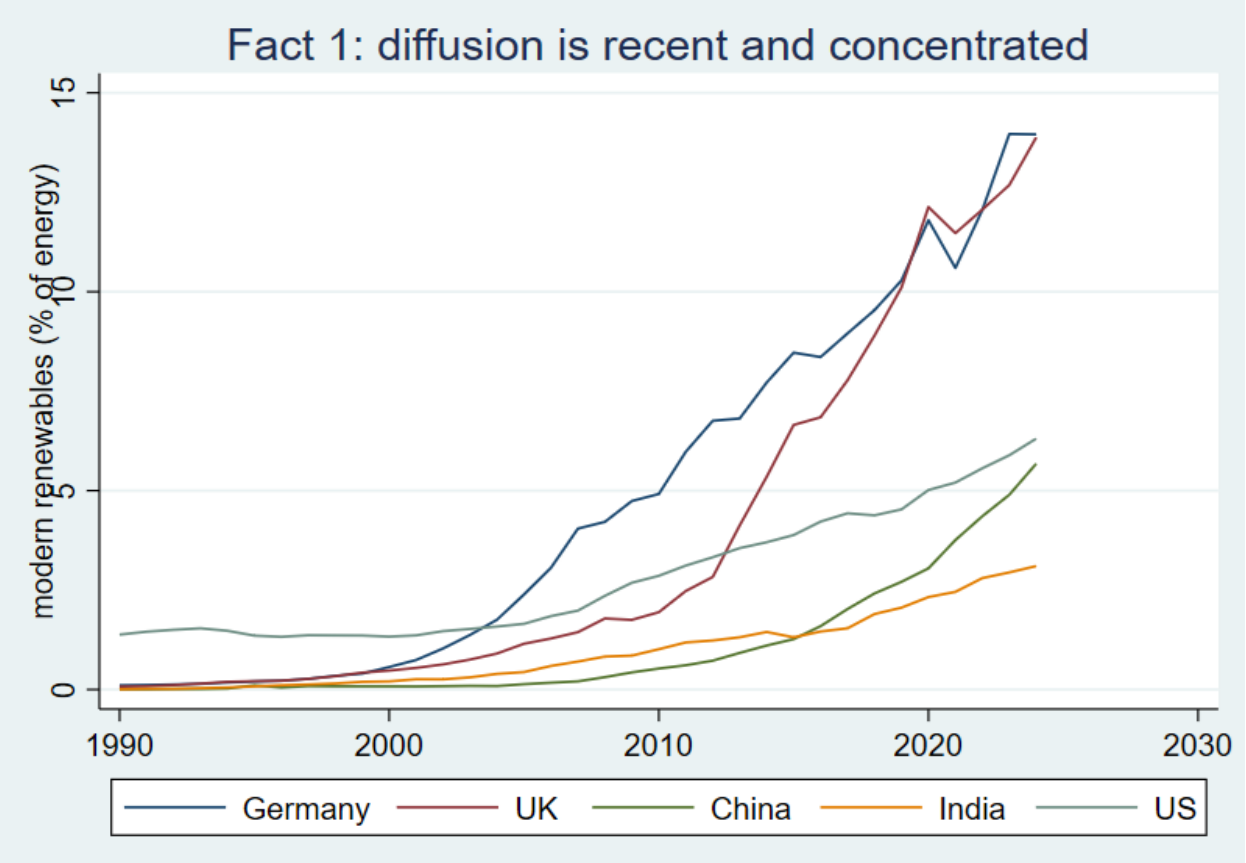


Figure 1. Modern-renewable penetration over time, selected countries, 1990–2024. Modern renewables = solar, wind, and other non-hydro renewables as a share of primary energy. Source: Energy Institute Statistical Review of World Energy.

Fact 2. Diffusion speed is stratified, and the frontier is pulling away

The pace of decarbonisation differs across countries. The distribution of decarbonisation velocity is highly concentrated near zero, with a long upper tail. The median country increases its modern renewable share by only about 0.19 percentage points per year, whereas a small group of frontier economies exceeds one percentage point annually. Most countries are therefore progressing slowly, while a limited number are advancing much more rapidly. This unequal pace is reflected

in the widening dispersion of low-carbon deployment. Between 1990 and 2023, the cross-country standard deviation of the low-carbon energy share increased from 4.0 to 9.7 percentage points, more than doubling over the period [4,5]. Rather than converging towards a common transition pathway, countries are becoming increasingly differentiated in their levels of decarbonisation. The evidence points to a stratified diffusion process. The frontier is pulling away from the majority, suggesting that technological diffusion is reinforcing differences in transition performance rather than narrowing them.

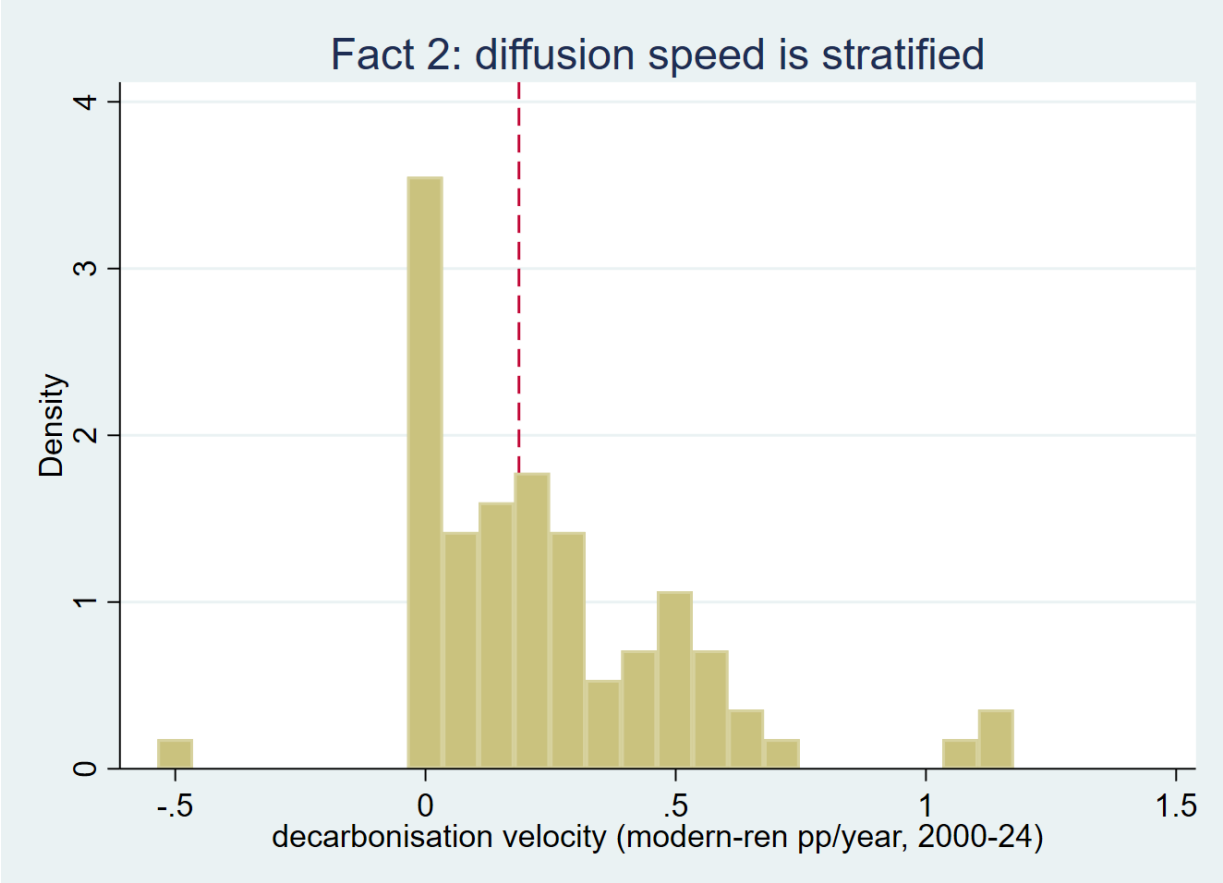


Figure 2. Distribution of decarbonisation velocity across 79 countries, 2000–2024. Country-specific slope of the modern-renewable share in percentage points per year. Median 0.19 pp/yr (dashed red line). Source: Energy Institute Statistical Review of World Energy.

Fact 3. Carbon lock-in concentrates among stuck fossil economies

Carbon lock-in is not evenly distributed across countries. Instead, it is concentrated among a relatively small group of economies that combine persistently high fossil-fuel dependence with little evidence of structural change [6]. Trinidad and Tobago, Turkmenistan, Kuwait, Iraq, and Algeria represent the strongest examples. Their energy systems remain overwhelmingly dependent on fossil fuels, with little sustained decline over the observation period.

At the opposite end of the distribution are countries that have already diversified their energy systems through hydroelectricity, nuclear power, or rapid renewable deployment. These economies exhibit much lower levels of carbon lock-in and greater movement away from fossil fuels. The evidence suggests that carbon lock-in is not a universal characteristic of the global energy transition but a feature of a distinct group of 'stuck' economies. These countries tend to be fossil-fuel producers or lower-income economies. This indicates that the transition challenge is

not simply one of increasing renewable deployment but of overcoming persistent structural dependence on fossil fuels.

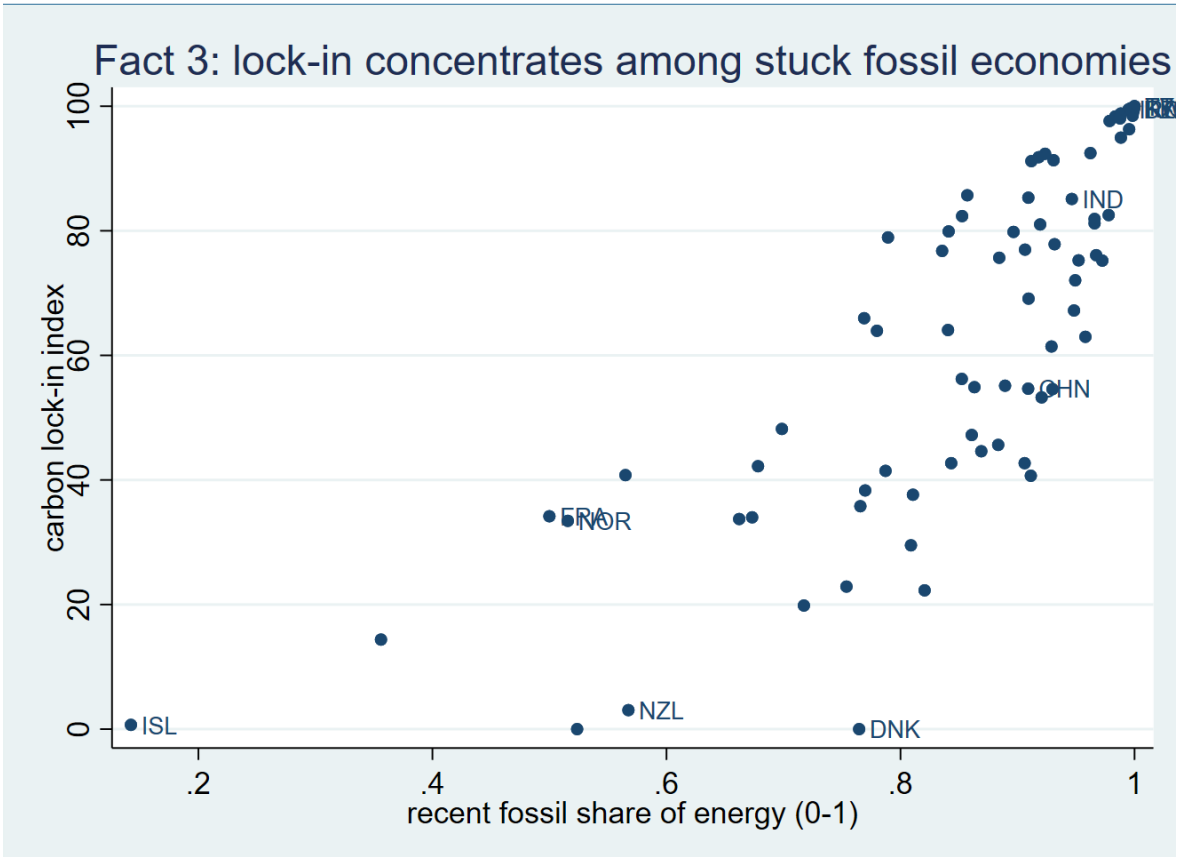


Figure 3. Carbon lock-in index plotted against recent fossil share of primary energy, by country. High lock-in requires both a high fossil share and the absence of decline. Source: Energy Institute Statistical Review of World Energy.

Fact 4. Addition, not substitution

In many countries, renewable energy has expanded without reducing fossil-fuel consumption. Between 2010 and 2023, 46% of the countries in the sample (36 of 79) increased their modern renewable share while simultaneously increasing the absolute volume of fossil-fuel consumption. China provides the clearest example. Its modern renewable share increased by more than 4.4 percentage points, yet fossil-fuel consumption rose by 42 exajoules over the same period. India, Indonesia, and Vietnam display a similar pattern.

These countries are undergoing energy addition rather than energy substitution. Renewable energy is meeting part of rapidly growing energy demand, but it is not yet replacing the existing fossil-fuel base. The expansion of clean energy and the continued growth of fossil energy therefore occur simultaneously rather than sequentially. This distinction matters because renewable deployment alone does not necessarily imply decarbonisation. In rapidly growing economies, increases in renewable energy may coexist with expanding fossil-fuel consumption if total energy demand grows faster than the substitution process. Leapfrogging, where low-carbon technologies replace fossil energy before new fossil infrastructure is built, appears to be the exception rather than the dominant pathway.

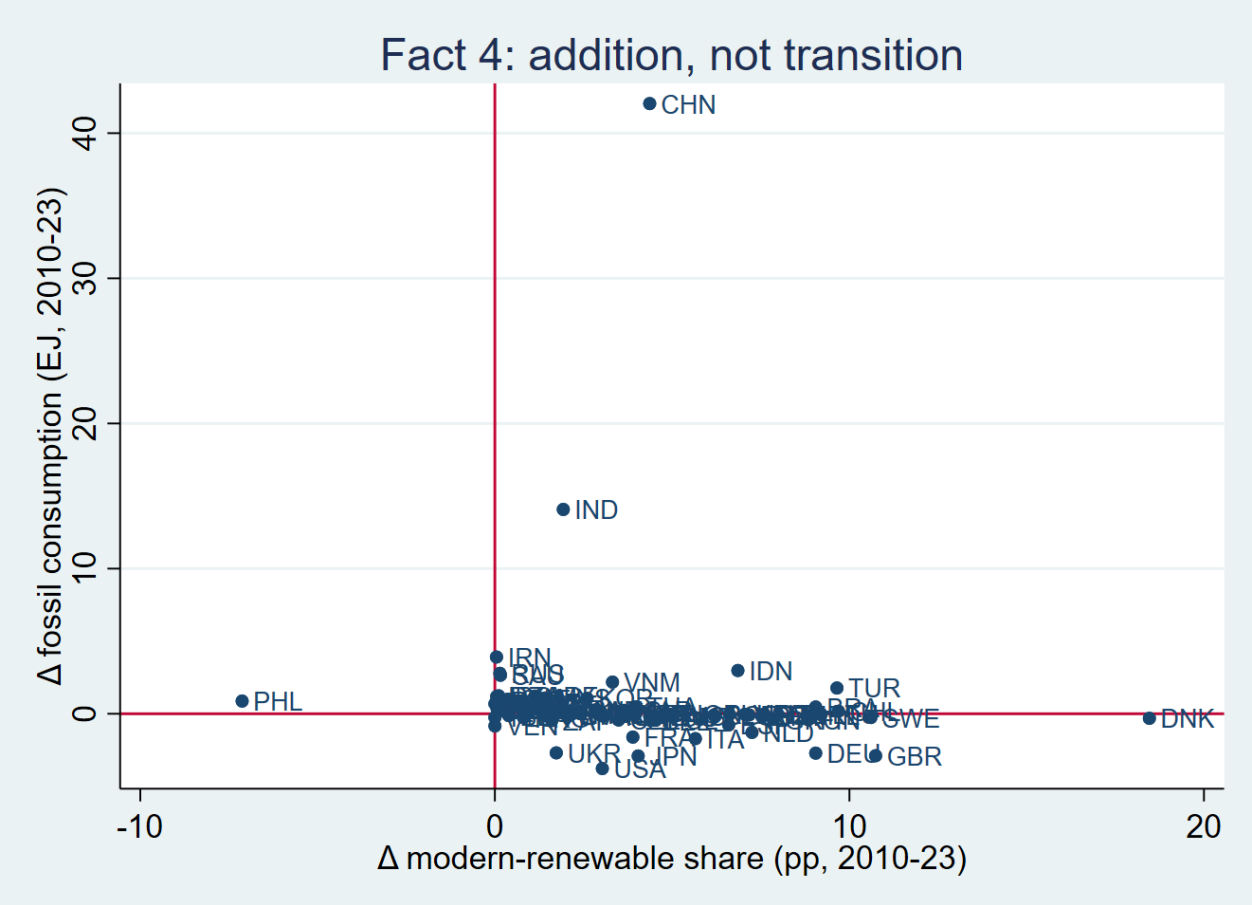


Figure 4. Change in modern-renewable share (percentage points) against change in fossil consumption (exajoules), 2010 to 2023. Upper-right quadrant = addition: renewable share rising while fossil volume also rises. Source: Energy Institute Statistical Review of World Energy.

KEY EMPIRICAL ANCHORS

Velocity median: 0.19 pp/yr (maximum ~1.18, Iceland/Denmark) · Divergence: cross-country SD 4.0 (1990) → 9.7 (2023) · Addition fact: 36 of 79 countries (46%) raised renewable share while fossil volume grew 2010–23 · China: +4.4 pp modern renewables, +42 EJ fossil, 2010–23

5. Discussion

Taken together, the four stylised facts describe a global energy transition that is late, uneven, and increasingly stratified. Modern renewable deployment is concentrated in a relatively small group of countries. Decarbonisation is progressing rapidly at the frontier but slowly across most of the world. Carbon lock-in remains concentrated among a distinct group of fossil-dependent economies, while renewable expansion frequently occurs alongside continued growth in fossil-fuel consumption. Thus, the global transition appears less as a single accelerating process than as multiple national transitions following different trajectories.

The distinction between energy addition and energy substitution is particularly important. In countries such as China, India, Indonesia, and Vietnam, renewable energy is expanding rapidly, yet fossil-fuel consumption continues to grow. These economies are increasing low-carbon capacity without reducing their fossil-energy base. Therefore, their challenge is not renewable

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deployment itself but the point at which renewable growth becomes large enough to displace fossil fuels rather than simply meet rising energy demand. Identifying the conditions under which this shift occurs is an important question for future research. The measures developed here, especially decarbonisation velocity and carbon lock-in, provide a consistent empirical basis for investigating that transition.

The evidence also highlights growing differences in national transition pathways. The emergence of a rapidly advancing frontier alongside a large group of slow-moving economies raises questions about the conditions that accelerate or constrain diffusion. Likewise, the concentration of carbon lock-in among fossil-producing and lower-income economies points to the importance of structural factors that lie beyond the scope of this paper. Institutional capacity, dependence on fossil-fuel revenues, access to finance, industrial structure, and political commitment are all plausible explanations, but the descriptive evidence presented here cannot distinguish between them.

The findings also have implications for how the global energy transition is monitored. Aggregate indicators, such as the global renewable share or total installed low-carbon capacity, provide an incomplete picture because they average across countries following very different pathways. They also obscure the distinction between renewable energy that replaces fossil fuels and renewable energy that simply accommodates additional demand. The measures proposed here are intended to make these differences visible. Rather than offering a new explanation of decarbonisation, they provide a common empirical tool for describing how national energy transitions differ in level, speed, persistence, and pathway. That empirical baseline provides a foundation for future research on the drivers, consequences, and political economy of global decarbonisation.

6. Conclusion

The global energy transition is not a single curve but a collection of national transitions unfolding at very different speeds. Here, I measured the diffusion of decarbonisation technologies across countries along four complementary dimensions. I showed that it is recent, stratified, diverging, and, in much of the world, additive rather than substitutive. Together, these measures provide a consistent basis for comparing national decarbonisation trajectories and identifying the empirical regularities that future research should explain.

Author Contributions and Declarations

Competing interests: The author declares no competing interests.

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