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Historical diffusion of nuclear, wind and solar power in different national contexts: implications for climate mitigation pathways

Vadim Vinichenko[1], **Jessica Jewell**[1,2,3], **Johan Jacobsson**[4] **and Aleh Cherp**[5,6,*]

1 Department of Earth, Space and Environment, Chalmers University, Gothenburg, Sweden
2 Centre for Climate and Energy Transformation, Department of Geography, University of Bergen, Bergen, Norway
3 Advancing Systems Analysis, International Institute for Applied Systems Analysis, Laxenburg, Austria
4 Ramboll, Stockholm, Sweden
5 Department of Environmental Sciences and Policy, Central European University, Vienna, Austria
6 International Institute for Industrial Environmental Economics, Lund University, Lund, Sweden
* Author to whom any correspondence should be addressed.

E-mail: cherpa@ceu.edu

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Abstract

Climate change mitigation requires rapid expansion of low-carbon electricity but there is a disagreement on whether available technologies such as renewables and nuclear power can be scaled up sufficiently fast. Here we analyze the diffusion of nuclear (from the 1960s), as well as wind and solar (from the 1980–90s) power. We show that all these technologies have been adopted in most large economies except major energy exporters, but solar and wind have diffused across countries faster and wider than nuclear. After the initial adoption, the maximum annual growth for nuclear power has been 2.6% of national electricity supply (IQR 1.3%–6%), for wind − 1.1% (0.6%–1.7%), and for solar − 0.8% (0.5%–1.3%). The fastest growth of nuclear power occurred in Western Europe in the 1980s, a response by industrialized democracies to the energy supply crises of the 1970s. The European Union (EU), currently experiencing a similar energy supply shock, is planning to expand wind and solar at similarly fast rates. This illustrates that national contexts can impact the speed of technology diffusion at least as much as technology characteristics like cost, granularity, and complexity. In the Intergovernmental Panel on Climate Change mitigation pathways, renewables grow much faster than nuclear due to their lower projected costs, though empirical evidence does not show that the cost is the sole factor determining the speed of diffusion. We demonstrate that expanding low-carbon electricity in Asia in line with the 1.5 °C target requires growth of nuclear power even if renewables increase as fast as in the most ambitious EU's plans. 2 °C-consistent pathways in Asia are compatible with replicating China's nuclear power plans in the whole region, while simultaneously expanding renewables as fast as in the near-term projections for the EU. Our analysis demonstrates the usefulness of empirically-benchmarked feasibility spaces for future technology projections.

1. Introduction

Mitigating climate change requires rapid growth of low-carbon electricity to substitute fossil fuels not only in power generation, but also in industry, transport, and other sectors [1]. In this context, most attention is on wind and solar power, which grow rapidly in the Intergovernmental Panel on Climate Change (IPCC) climate change mitigation pathways [1, 2] and other projections [3–6]. Yet, there are divergent views on whether the current growth of renewables can realistically accelerate to the rates required for mitigation targets [7–10]. Solar and wind could in principle be complemented by another mature low-carbon technology, nuclear power, which currently plays only a minor role in most climate mitigation pathways [1, 2]. In contrast to renewables, there has been little recent analysis of the future potential of nuclear power, beyond the argument that it is declining [11]. The question is which, if any, combinations of these technologies can realistically meet the demand for low-carbon electricity in climate mitigation pathways?

The mainstream tools to answer this question are Integrated Assessment Models or energy system models, which project future deployment of technologies based on their costs, geophysical factors and demand for low-carbon electricity derived from assumed economic development and emissions constraints. Low and declining costs of wind and solar power combined with their low emissions lead them to dominate cost-optimal mitigation pathways as compared to more expensive nuclear power [1]. Yet, there are numerous social factors beyond costs that affect technology diffusion [12–16] such as technology complexity and granularity [17–20], politics [21–23], institutional capacities [24, 25], and social acceptance [26–30]. How might these other factors affect the future growth of renewables and nuclear power? This question is methodologically challenging, because most of these factors are hard to observe and generalize, let alone incorporate into quantitative models [31–33].

An alternative way to inform technology growth in scenarios is to examine historical technological change, which by default aggregates the effects of various socio-economic, political, and other factors [7, 34–39]. A systematic approach for doing that is to use an empirically-benchmarked 'feasibility space' [40, 41], which involves identifying historical 'reference cases' for technology change in climate pathways and comparing the outcomes and conditions of these reference cases to the projected outcomes and conditions in the pathways [40, 42]. This approach assumes that though the future may be different from the past, it will be shaped by similar causal mechanisms, resulting in similar outcomes under similar conditions. Since it is not possible to exactly match conditions in historical analogies and in scenarios, an informative empirically-benchmarked feasibility space includes reference cases representing a wide range of possible conditions, so that their outcomes can be mapped onto the range of outcomes in the 'solutions space' [40] of scenario ensembles. Feasibility in this approach is not binary. Historical precedents should not be seen as demarcating a hard boundary for future growth and the absence of empirical reference cases for a given outcome does not necessarily mean that it is infeasible, but rather that it requires unprecedented effort or new causal mechanisms to bring about.

In this paper we construct empirically-benchmarked feasibility spaces for nuclear, wind and solar power technologies and their combinations by observing their growth in a variety of contexts at the regional and national levels [7, 38] as well as in near-term plans and projections, which complement historical evidence [43, 44]. This allows us to differentiate the effect of **inherent technology characteristics** such as costs [17, 45], lumpiness [18], complexity [20], and safety [11, 19] from the effect of **contextual factors**, such as political motivation and state capacity [16, 19, 46].

We show that historically wind and particularly solar power have diffused more quickly and to more diverse contexts than nuclear power. However, after its initial adoption in a country, electricity generation from nuclear has grown faster than from renewables, while the installed capacity for solar grew faster than for nuclear and wind. The fastest growth of nuclear occurred in the wake of the oil crises in Western Europe in the 1970s and 80s. The European Union (EU) currently plans to expand solar and wind with comparable rates, in part responding to the energy security crisis triggered by the Russia–Ukraine war. We also show that in contrast to historical evidence, climate mitigation pathways envision wind and solar power growing much faster than nuclear. We find that for Asia, achieving the 1.5 °C target would require either replicating the most ambitious EU plans for solar and wind or the growth of nuclear power observed in Western Europe in the 1980s. The growth rates required in the 2 °C-compatible pathways in Asia can be achieved under more realistic assumptions of expanding renewables in line with the near-term IEA projections for the EU and expanding nuclear in line with the nuclear industry's plans in China.

2. Method

In this paper we empirically analyze the diffusion and growth of three low-carbon energy technologies (LCETs)—nuclear, wind, and solar (PV) power. The main methodological challenge is how to compare growth across technologies, countries, and time periods, given the non-linear and spatially uneven nature of technology diffusion. We follow [7] by measuring two parameters for each technology-country pair: the commercial adoption (take-off) of a given technology and its maximum growth speed along the S-curve (figure 1). The pattern of commercial adoption characterizes spatial diffusion of each technology across countries [7, 19] or its potential to be adopted in different social contexts, while its maximum growth rate characterizes the potential of technology to expand once it has taken off [7]. We systematically explore the adoption and growth of these technologies at the national, regional, and global levels in order to capture a diverse range of conditions for their deployment. We use this analysis to establish reference cases and develop benchmarks

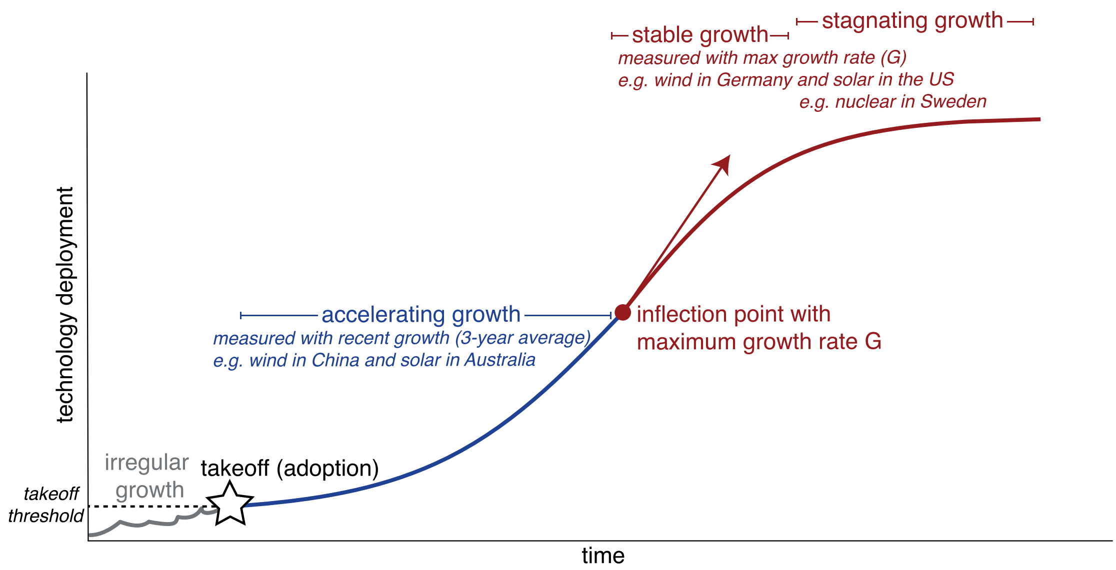

Figure 1. Measuring take-off and maximum growth rate of technology deployment. For each country and region in the sample, we determine whether its use of a particular technology is beyond the formative phase, i.e. has passed the relevant take-off threshold. The growth of technologies before the take-off threshold is likely to be irregular and is not measured. For countries and regions above the threshold, we fit two growth models (logistic and Gompertz) to deployment time series. If the inflection point of the fitted curve is before the end of observations, the growth rate at the inflection point is used as the maximum growth rate for the country-technology pair. If the historical observations end before the inflection point, we use the most recent empirical growth rate averaged over the last three years. See Note S1 and [7] for detail.

for constructing an empirically-benchmarked feasibility space of the future growth of these technologies.

Our national sample includes all countries with total electricity supply >30 TWh/year as of 2020 (67 countries with over 95% of the global electricity production [47], table S1). For adoption ('take-off') of the three technologies, we use technology-specific take-off thresholds [7, 19]. We use logistic regression [48] to test the dependence between technology take-off and characteristics of national context reflecting the institutional capacity and motivation to replace fossil fuels for low-carbon technology adoption.

We measure the maximum growth rates of each technology in the sample countries, selected regions (table S2), and globally by fitting two S-curve growth models—logistic and Gompertz [7]—to power generation and installed capacity data. For cases where the technology has already passed the S-curve inflection point, we calculate the maximum growth rate as the average of the two models (that provide sufficiently similar estimates [7]). For cases where growth is still accelerating, we use the most recent empirical growth rate averaged over the last three years (figure 1). We normalize growth rates to the total electricity supply ('electricity system size') in the year of fastest growth, so the growth rates are expressed as percentage of the electricity system size per year [7] or as capacity per unit of energy (MW/TWh) similarly to [49]. In addition to historical rates, we calculate the growth rates of wind and solar power implied in recent policy proposals and projections [50–53].

We subsequently calculate the maximum 10 year growth rates of the three technologies relative to the electricity system size in the IPCC Sixth Assessment Report (AR6) pathways [1, 2] between 2020 and 2040 (a period comparable with historical experience of significant wind power growth) and compare them to the rates in the reference cases. Finally, we use several combinations of empirical benchmarks derived from reference cases to construct an empirically-benchmarked feasibility space [40] and map the LCETs growth in OECD and Asia in IPCC AR6 pathways onto this space. We focus on the OECD and Asia since they are the world's largest regions with the fastest energy transition growth rates required for mitigation pathways [38].

To validate our method, we use hindcasting to perform a similar analysis with data available in 1974 (for nuclear), 2005 (for wind) and 2015 (for solar). Figure S1 shows that the ranges of maximum national growth rates based even on these early data accurately define the upper bound of LCETs growth rates in 2021 in Asia, Europe, and globally (though nuclear in Europe grew faster for a brief period in the 1980s). In other words, in hindsight, our method works for 47 years for nuclear, 16 years for wind and 6 years for solar, which justifies its applicability for the 15–20 year time horizon up to 2040.

More details on the method are provided in Note S1.

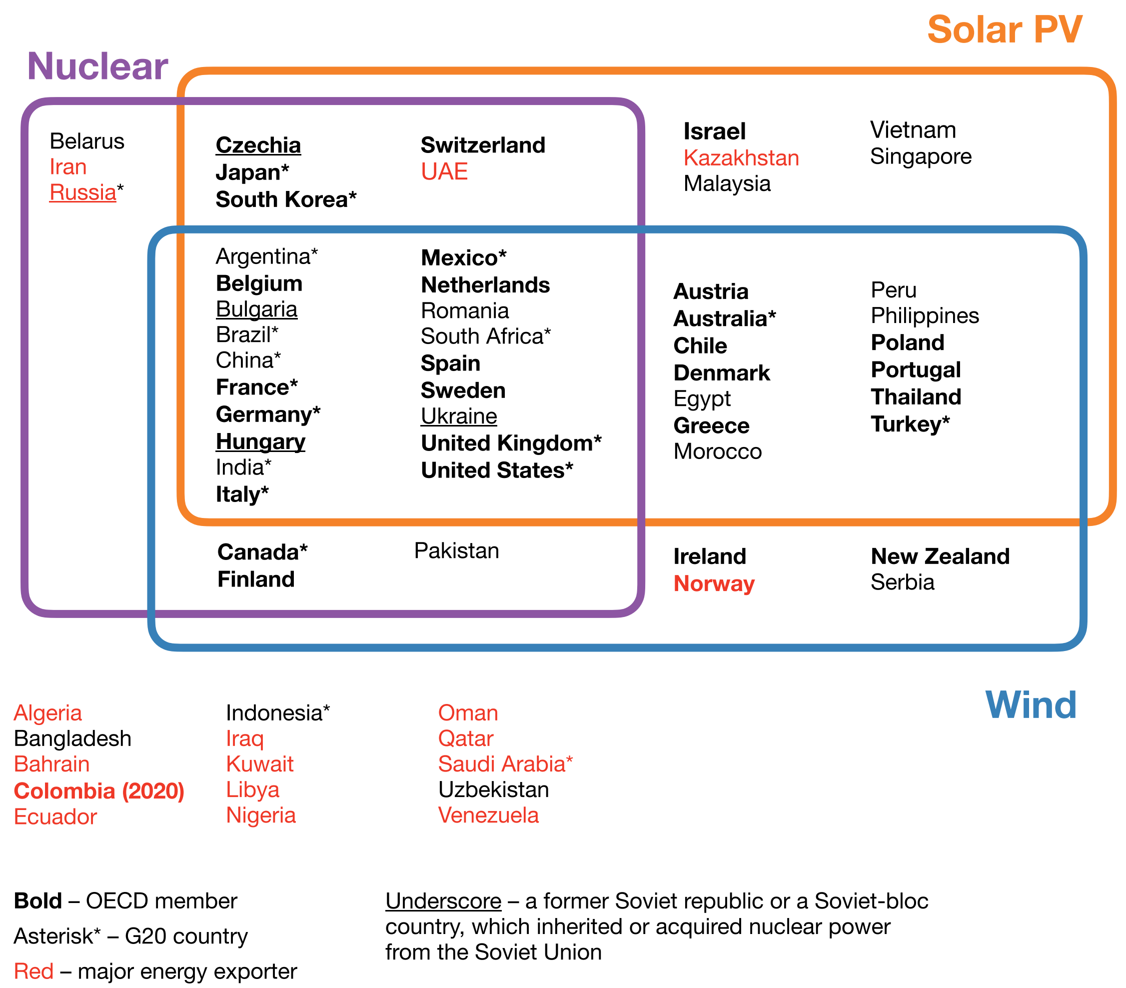

Figure 2. Adoption of nuclear, wind and solar (PV) power. Sample—67 countries with electricity supply >30 TWh per year accounting for over 95% of global electricity supply. See Note S1 for the definition of adoption and variables used to characterize national context.

3. Results

3.1. Solar and wind power diffuse across countries faster and wider than nuclear

To analyze the cross-country diffusion of LCETs we establish whether each technology has been adopted, i.e. completed the formative phase [54] or 'taken off' [7] in a particular country. For nuclear power, we define take-off as when a country has at least one commercial-size reactor (two if the first reactor is small or the delay between the first and the second reactors is very long) [19] and for renewables we define take-off as wind or solar generation exceeding 1% of total electricity supply [7]. In our sample of 67 countries, nuclear power has taken off in 30 countries, wind—in 39, and solar power—in 42 countries. Nineteen countries have adopted all three LCETs, 21—two, and 12—one of them. Among the remaining 15 countries where none of the LCETs have taken off, 12 are major energy exporters (figure 2). Notably, it took 23 years for nuclear to diffuse from two to twenty countries, 15 years for wind, and 10 years for solar power (tables S1 and S3).

Multi-variable regression tests (tables S4 and S5) confirm that major energy exporters are statistically less likely to adopt any of the three LCETs. This aligns with prior studies arguing that large fuel exports reduce both motivation and capacity for adopting low-carbon technologies [7, 19, 46, 55]. Our analysis also shows that larger economies are more likely to adopt nuclear and (with weaker significance) solar. This also echoes prior studies arguing that larger economies may be more suitable for accommodating nuclear reactors [46] and that they may have more capacity for mobilizing resources and attracting investors for emerging energy technologies [7, 19]. We also statistically test four measures of state capacity as potential explanatory variables for adopting low-carbon technologies, including OECD membership and three suitable metrics reviewed in [56]: Government Effectiveness [57], Quality of Government [58, 59], and Hanson and Sigman's index [60], which is a robust predictor of coal phaseout [61]. We detect no effect of state capacity on the adoption of LCETs, which apparently disagrees with prior studies [7, 19, 25]. However, these

Table 1. Summary of national, regional, and global growth rates for generation of nuclear, wind, and solar power.

	Countries					Regions (growth rate)			
			Rate						
Technology	No. where growth was measured[a]	Growth: Acc./Stable/ Stagn.[b]	max	median (IQR)[c]	TMax, median (IQR)[d]	Europe[e]	OECD90	Asia	World (growth rate)
Nuclear	20	3/2/15	9.8% (FR)	2.6% (1.3–6%)	1984 (1980–1985)	3.0%	1.9%	0.4%[f]	1.4%
Wind	35	7/15/13	2.9% (PT)	1.1% (0.6–1.7%)	2016 (2013–2019)	0.9%	0.7%	0.6%	0.7%
Solar PV	24	8/10/6	2.3% (AU[f])	0.8% (0.5–1.3%)	2017 (2014–2018)	0.5%	0.5%	0.7%	0.5%[f]

Notes: See Method and Note S1 for calculation details, tables S6–S8 for growth curve fit parameters. Growth rates are expressed as % of the total electricity supply per year.

[a] The number of countries where a particular technology has taken off and criteria for measuring sustained growth are met (Note S1).

[b] See Note S1 for the growth type classification.

[c] For cases with accelerating growth, average growth rates over the last 3 years are included.

[d] The year where fastest growth is achieved. Countries with accelerating growth are not included in this summary.

[e] Western Europe for nuclear power, EU27 for wind and solar.

[f] Accelerating growth.

studies measured whether stronger state capacity correlates with earlier introduction or higher levels of LCETs, while we measure the correlation of state capacity with whether a particular technology has been adopted in a particular country by now. The divergence of these results may mean that states with stronger capacity introduced renewables and nuclear earlier and thus have achieved higher deployment by now, however, more recently LCETs have expanded to countries with different levels of state capacities. Indeed, we find that countries which by 2009 had adopted wind and by 2015 had adopted solar have stronger state capacity than those which had not adopted the two technologies (table S4). The fact that state capacity is no longer a significant determinant of technology adoption reflects worldwide technology diffusion where state capacity is initially, but no longer a constraint. The main remaining constraint to the adoption of LCETs seems to be presence of major fossil exports, which most likely affects motivation or impedes LCETs through high fossil fuel subsidies typical of such countries [62].

3.2. Nuclear power generation normalized to electricity supply grew faster than solar and wind

We measure maximum growth rates in electricity capacity and generation by each technology in each country where the technology has taken off, selected regions, and the world (Method, Note S1). Maximum growth of nuclear power generation has been faster: median 2.6% of total electricity supply per year (interquartile range 1.3–6.1%/year) as compared to wind—1.1% (0.6–1.7) and solar power—0.8% (0.5–1.3) (tables S6–S8). However, in terms of installed capacity, maximum growth of nuclear (median 3.3 MW/TWh/year (IQR 2.5–9.8)) and wind power (3.6 MW/TWh/year (2.2–5.2)) are similar, while solar (8.2 MW/TWh/year (5.2–12.8)) is more than twice as fast. This is because typical capacity factors of the three LCETs are different: 79% (44%–85%) for nuclear, 22% (12%–27%) for wind, and 11% (10%–17%) for solar (global mean and the range of regional means) [63], which means that more electricity can be generated from the same installed nuclear capacity than from wind and especially solar capacity. For all three LCETs, higher maximum growth rates occur in smaller countries, presumably due to their greater homogeneity and weaker inertia [7, 38, 64] (table 1 and figures 3, S2).

The fastest historical national growth for nuclear power (9.8%/year) was in France, a relatively large economy. A few other countries expanded nuclear at around 6%/year and the highest regional rate (3%/year) was observed in Western Europe. For most countries in our sample (15 out of 20), the fastest growth of nuclear power occurred in the late 1970s or the 1980s—in the wake of the oil crises. Currently nuclear power in those countries is stagnating or even declining [11], although some of them have started to consider re-starting nuclear construction (table S9). In Asia, nuclear power is currently growing at an accelerating rate, and China has plans for its further expansion [65, 66]. However, the growth of nuclear in Asia is slower than the current growth of solar or wind power and the historical growth of nuclear in Europe and OECD.

For wind and solar, the highest historical *national* rates are 2.9%/year and 2.3%/year respectively, but in large countries and regions (above 1000 TWh, approximately the size of Japan) the growth has been under 1.1%/year. The highest *regional* rates for wind and solar were observed in the EU (0.9%/year and 0.5%/year respectively). The fastest growth was in the second half of the 2010s, however in several countries

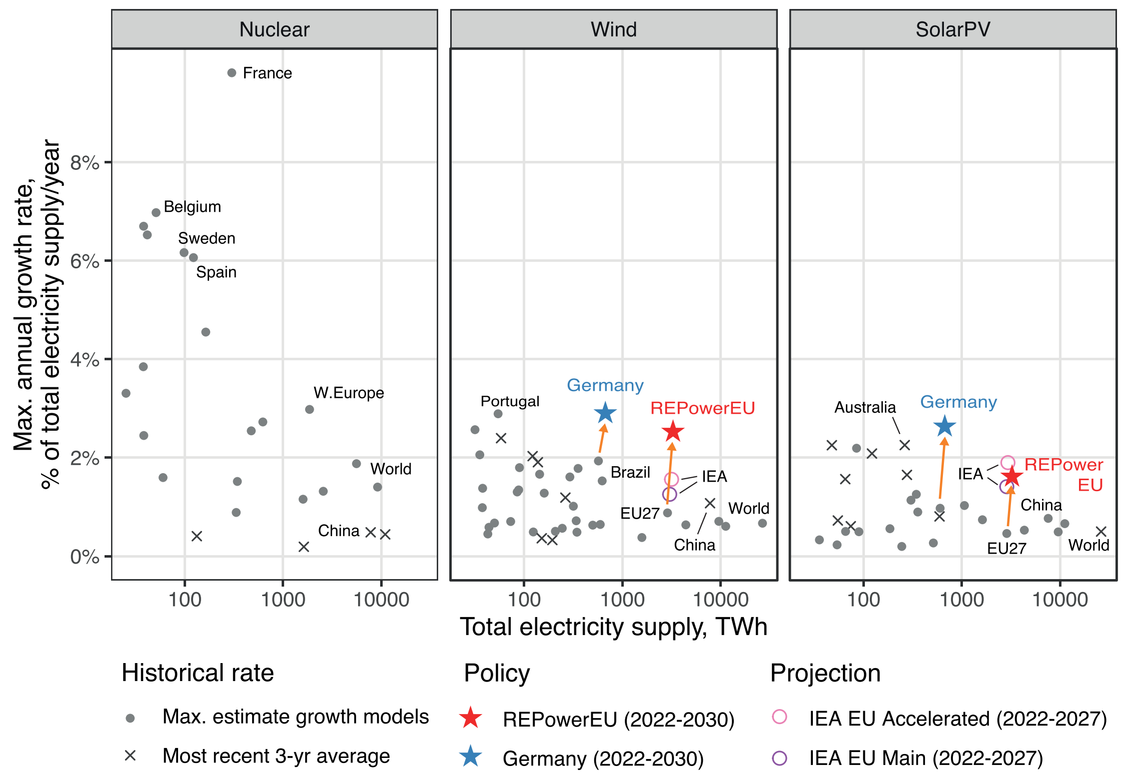

Figure 3. Maximum growth rate of electricity generation by low-carbon technologies vs. total electricity supply. Growth rates estimated by growth models for stable and stagnating growth (Note S1) are shown by solid circles and recent 3 year average growth rates for accelerating countries—by crosses. Historical growth rates are higher for nuclear, but recent plans and projections for wind and solar in the EU and Germany (stars and hollow circles) approach these rates for large systems.

(8 for solar and 7 (including China) for wind), growth is still accelerating. Solar is also accelerating globally (table 1).

3.3. Following the recent energy crisis, EU plans and projections envision faster growth of wind and solar, comparable to the growth of nuclear in the 1980s

In May 2022, aiming to achieve the net-zero emission target and phase-out the dependence on fossil fuels imports from Russia, the European Commission proposed the REPowerEU plan [50], which proposes to reach 45% of renewable energy in the total final energy consumption by 2030 (as compared to 32% in the 2018 Renewable Energy Directive [67] and 40% under the 2021 'Fit for 55' package [68]). The Commission's working document detailing the proposal [69] provides estimates of renewable power capacity in 2030 necessary to reach these goals: 592 GW and 510 GW of solar PV and wind power respectively. Using recent capacity factors and installed capacity data, if wind and solar PV grow linearly in the EU27, wind would need to grow 2.6%/year relative to the electricity supply and solar PV would need to grow at 1.6%/year relative to the electricity supply between now and 2030 (Note S1).

At the time of writing, the REPowerEU proposal has not been approved. However, in March 2023 negotiators from the European Parliament and the Council agreed on a binding target of 42.5% (which is half-way between Fit for 55 and REPowerEU), retaining 45% as aspiration [70]. Although the agreement does not include renewable power targets, the implied growth can be estimated at 2.4%/year and 1.5%/year (relative to the electricity supply) for wind and solar respectively, based on the assumptions that the capacity targets are likely to be halfway between the REPowerEU and the Fit for 55 proposals. The required growth of solar power is consistent with the IEA near-term (until 2027) projections [51], but the required growth of wind power is much faster than both the Main and the Accelerated case in these projections (figure 3, table 2).

Thus, the growth of solar and wind power in current EU plans is historically unprecedented for continental-size electricity systems and close to the fastest rates in individual countries. The planned growth of each technology is still lower than the fastest growth of nuclear power observed in Western Europe (3%) (figure 3). However, the growth of wind and solar power would need to take place simultaneously rather than asynchronously as historically. Among the EU countries, Germany has

Table 2. Growth rates implied in near-term plans and projections. See Method and Note S1 for calculation details.

Region/ country	Source	Plan/projection	Installed capacity in 2022, GW	Planned or projected capacity, GW	Plan or projection year	Generation growth rate implied in the target, % of TES per year
EU27	Wind	REPowerEU	204	510	2030	2.6%
		IEA Accelerated		316	2027	1.6%
		IEA Main		290	2027	1.2%
	Solar PV	REPowerEU	198	592	2030	1.6%
		IEA Accelerated		471	2027	1.9%
		IEA Main		396	2027	1.4%
Germany	Wind	RE Act, Offshore Wind Act (2022)	66	145	2030	2.9%
	Solar PV	RE Act (2022)	67	215	2030	2.6%

Table 3. Empirical benchmarks for combined LCET growth compared with the maximum 10 year LCET growth rates in IPCC AR6 mitigation pathways for OECD and Asia (2020–2040). The rows represent empirical benchmarks for the combined growth of wind and solar, and the columns—of nuclear power. Each cell indicates the combined growth of all three LCETs (bold numbers) as well as the closest temperature outcome(s) that corresponds to the IPCC AR6 pathways with similar combined growth of LCETs (med.—median, max.—maximum, Q1 and Q3—first and third quartile of the pathways in the respective temperature category), see figures 4, S3.

Wind + solar growth	Nuclear growth: 0% (no growth)	Nuclear growth: 1% (China's nuclear industry's plans to 2035)	Nuclear growth: 3% (max. regional growth rate—Western Europe in the 1980s)
1.3% (close to the current growth in Asia)	**1.3%** OECD: ≈med. 3 °C Asia: <Q1 3 °C	**2.3%** OECD: ≈med. 2 °C Asia: between med. 3 °C–2.5 °C	**4.3%** OECD: >med. 1.5 °C Asia: ≈med. 2 °C, <Q1 1.5 °C
3% (Q3 of national rates, aver. of 2022–27 IEA projections for EU)	**3%** OECD: >med. 2.0 °C Asia: >med. 2.5 °C	**4%** OECD:≈med. 1.5 °C Asia: ≈med. 2 °C, <Q1 1.5 °C	**6%** OECD: >Q3 1.5 °C Asia: >med. 1.5 °C
4.2% (implied by REPowerEU)	**4.2%** OECD: >med. 1.5 °C Asia: ≈med. 2 °C, <Q1 1.5 °C	**5.2%** OECD: >Q3 1.5 °C Asia: ≈Q3 2 °C, <med. 1.5 °C	**7.2%** OECD: ≈max. 1.5 °C Asia: ≫Q3 1.5 °C

legislated similarly ambitious growth in the amendments to the Renewable Energy Act and Offshore Wind Act adopted in the summer of 2022 [52, 53], which explicitly define renewable energy capacity targets for 2030 implying growth rates at 2.9%/year and 2.6%/year for wind and solar respectively. These rates are still unprecedented for renewables in large countries like Germany, but were observed for nuclear power in the past.

3.4. Climate mitigation pathways require expanding LCETs in Asia as fast as in the EU's renewables plans while simultaneously developing nuclear

Based on the historical growth rates of the three technologies combined with plans and projections for wind and solar in the EU and Germany, we define benchmarks for future growth (table 3). The three benchmarks for combined wind and solar power include 1.3% per year (the current growth in Asia and OECD), 3.0%/year (the third quartile of the historical national growth rates, and the average of the IEA Main and Accelerated scenarios for the EU); and 4.2%/year (the rate implied in the REPowerEU). The three benchmarks for nuclear include no growth; 1%/year (consistent with China's plans for 2035 reported by nuclear industry's sources [65, 66]); and 3.0%/year (the highest regional growth observed in Western Europe in the early 1980s).

The total growth in low-carbon technologies in different combinations of these empirical benchmarks (table 3) can be compared with the fastest 10 year growth of solar, wind and nuclear power (which collectively account for approximately 90% of low-carbon electricity additions in IPCC AR6 pathways) between 2020 and 2040 (table S10, figure S4). In 1.5 °C- and 2 °C-consistent pathways, the main global growth of LCETs is concentrated in Asia reflecting the critical role of this region in global decarbonization [38] (solar grows faster in the Middle East and Africa region, but this region is only about 1/5th of Asia). Based on the combination of its size and transition rates, OECD remains the 2nd most important region in terms of fossil fuel phase-out [38] and low-carbon electricity growth in the pathways.

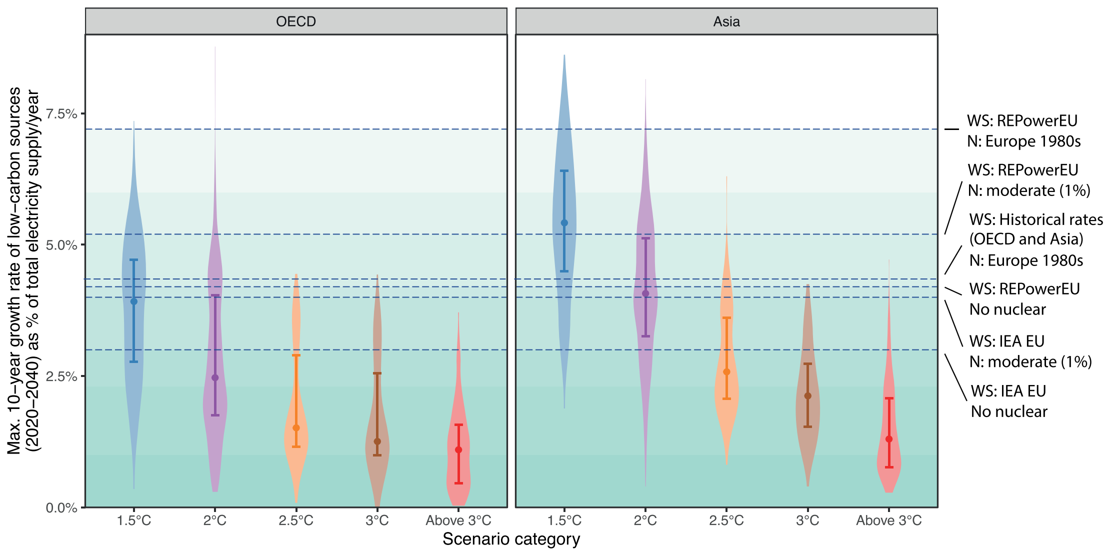

Figure 4. Empirically-grounded feasibility benchmarks and growth rates of low-carbon sources in the IPCC AR6 pathways for OECD and Asia. The violins show the density of maximum 10 year growth rates of LCETs (nuclear + wind + solar) in the IPCC pathways for OECD and Asia under various temperature outcomes between 2020 and 2040 (Note S1). Error bars and dots—IQRs and medians across the respective temperature category. Horizontal lines show selected combinations of empirically grounded benchmarks (table 3), 'WS'—wind and solar power combined, 'N'—nuclear power. See figure S3 for the depiction of all benchmarks.

In an ambitious, yet arguably feasible, scenario when all of Asia expands nuclear at the rate envisioned in the Chinese nuclear industry's plans and simultaneously expands renewables at the rate projected by the IEA for the EU, it would grow LCETs similarly to the median in 2 °C-consistent pathways. Achieving the median growth envisioned in 1.5 °C-consistent pathways would require expanding renewables as fast as proposed in REPowerEU while still expanding nuclear. If nuclear does not grow, the 1.5 °C-compatible trajectory becomes essentially unattainable, unless the whole of Asia expands renewables faster than REPowerEU and most of the individual countries. Even achieving the median 2 °C-compatible growth would be challenging without nuclear as it would require Asia to expand renewables faster than all historical rates and as fast as planned in REPowerEU. If nuclear does not grow in Asia and renewables grow with more realistic rates (as in the near-term IEA-projections for the EU) the total growth of LCETs will match the median of the 2.5 °C-compatible scenarios (figure 4, table 3).

In OECD, the growth of LCETs envisioned in the mitigation pathways is less ambitious than in Asia. The median LCET growth across 1.5 °C-consistent pathways can be achieved either without any nuclear growth if the ambitious REPowerEU rates are implemented not only in the EU but across OECD or with moderate nuclear growth and IEA-projected renewable growth for the EU. The median 2 °C- consistent growth is attainable with the IEA-projected wind and solar and without nuclear (figure 4).

3.5. Climate mitigation pathways envision the growth of renewables similar to historical growth of nuclear and vice versa

The median regional growth rates of solar and wind in IPCC pathways are well above historical rates in large countries or regions. For example, the median rates (IQR) for solar and wind growth in 1.5 °C-consistent pathways in Asia are 2.8%/year (1.8–3.3%/year) and 2.3%/year (1.4–2.8%/year) respectively (figure 5, table S10). In contrast, for nuclear power, the typical growth rates in pathways are significantly *lower* than the fastest national, regional or even global growth rates observed historically. For example, nuclear power growth rates in Asia are 0.8%/year (0.3–1%/year) (figure 5, table S10). Moreover, for China, most pathways envision the total nuclear capacity in 2035 (median of 138 and 88 GW for 1.5 °C and 2 °C-consistent pathways respectively) that is lower than the plans recently discussed by China's industry (180 or 200 GW) [65, 66]. All in all, the growth of nuclear power in pathways is similar to historical growth of renewables and vice versa (figure 5).

The benchmarks for the growth of LCETs can be used to construct an empirically-benchmarked feasibility space where exceeding the combinations of high growth benchmarks signifies more feasibility challenges (figure 6). Subsequently, the maximum rates in IPCC AR6 1.5 °C- and 2 °C-consistent pathways, forming a stylized 'solution space' [40, 71] can be mapped onto this feasibility space (figure 6). The majority of mitigation pathways envision unprecedented rates of wind and solar deployment in Asia and

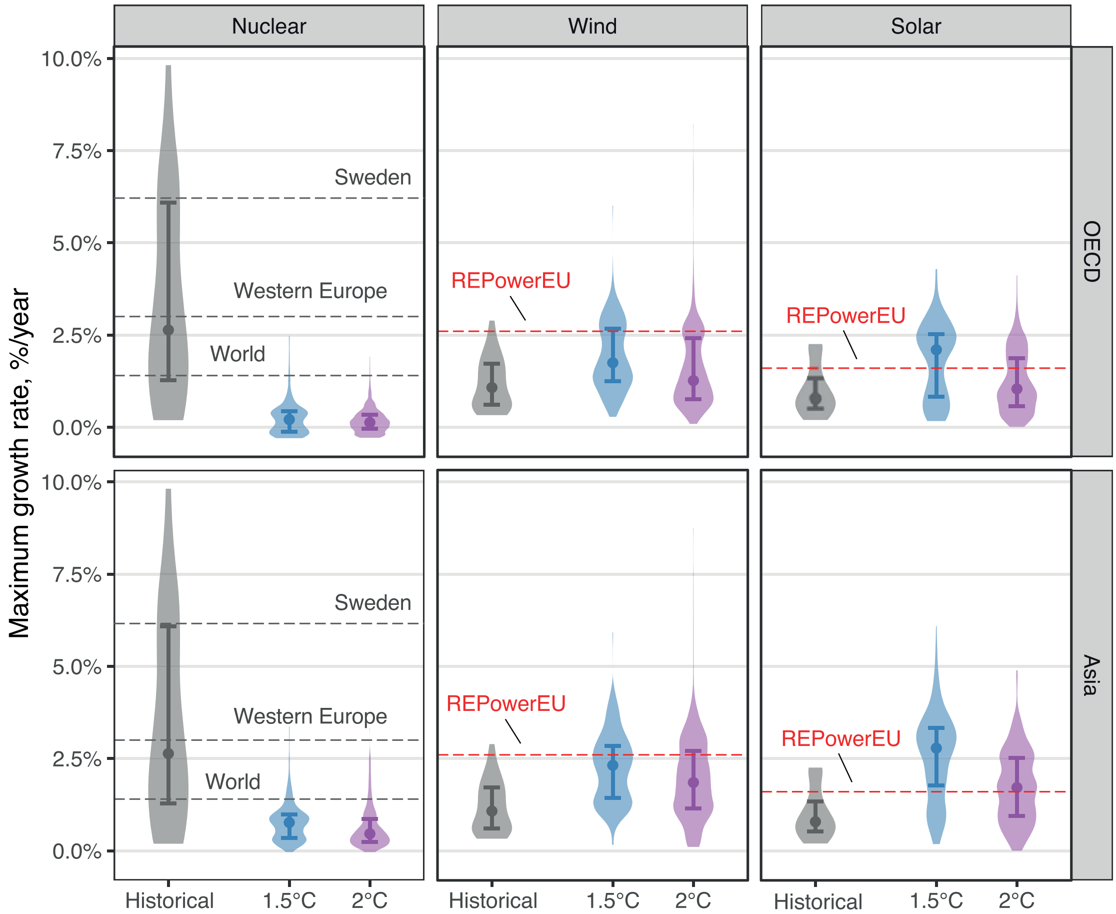

Figure 5. Comparison of maximum historical national, regional and global (for nuclear) growth rates, REPowerEU, and rates for OECD and Asia in the 1.5 °C and 2 °C-consistent IPCC AR6 pathways. Grey violins—density of maximum historical national growth rates. Colored violins—densities of 10 year maximum growth rates in 1.5 °C and 2 °C-consistent pathways for OECD and Asia between 2020 and 2040. Error bars—IQRs of the respective rates; dots—medians. Dashed lines—relevant benchmarks (historical rates or targets). See figure S4 for rates in pathways for all regions.

modest rates of nuclear power deployment (see also figure 5), though there are pathways that stay within the empirically observed rates for both nuclear and renewables. The scenario solution space for OECD is much closer to the empirical evidence, especially for 2 °C-consistent pathways (figure 6).

4. Discussion

Our analysis of historical growth as well as near-term plans and projections contributes to the debate on the effect of technology characteristics, such as cost and granularity, vis-à-vis the effect of national contexts on the speed of energy transitions [19]. First, we provide new evidence concerning the speed of deployment of granular vs. lumpy technologies [7, 18]. On the one hand, more granular wind, and especially solar power, diffuse faster and wider between countries than nuclear power (figure 2, tables S1–S3). Furthermore, whereas the size of the economy constrains the diffusion of nuclear power, the effect is weaker for solar and absent for wind. All LCETs, irrespective of their granularity, are rarely introduced by major energy exporters, which might signal the importance of political factors for the diffusion of these technologies. On the other hand, once a technology has taken off in a particular country, region, or globally, the generation of lumpy nuclear power has typically grown faster relative to the electricity supply than wind, which in turn grew faster than even more granular solar.

The key arguments for the faster growth of granular technologies are better access to investment capital, as well as faster experience accumulation leading to faster learning and cost decline [18]. While the costs of solar and wind have been declining much faster than the costs of nuclear did [4, 72] we find that renewables still grow slower than nuclear in the 1980s. This finding not only supports the argument in the literature [23, 26, 27, 73–77] that costs are not the single factor driving the growth of policy-driven and socially-embedded technologies, but it goes further by quantitatively demonstrating that more expensive technologies can in fact grow faster. One possible

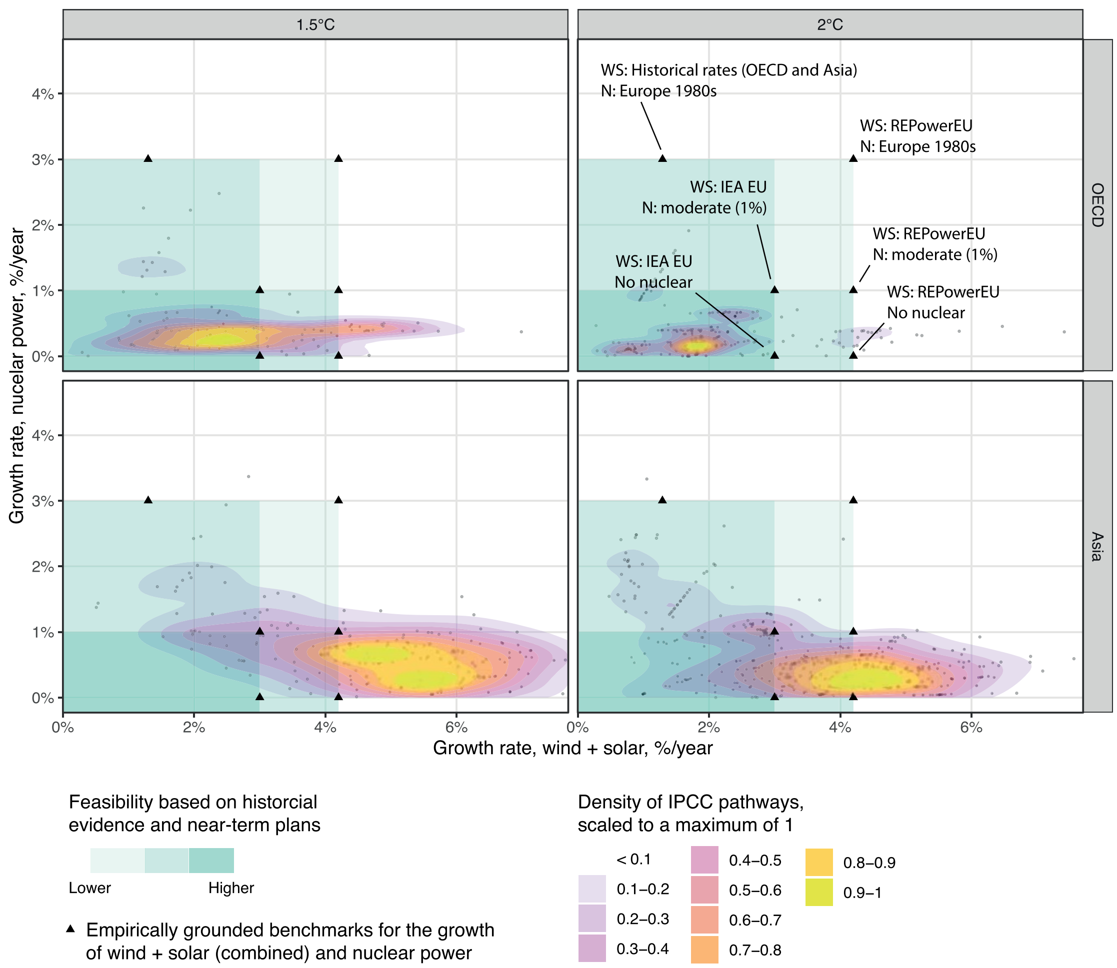

Figure 6. The empirically-benchmarked feasibility space and the solution space for nuclear, solar and wind power in the IPCC AR6 pathways for OECD and Asia. Horizontal axis—growth rates of combined wind and solar power ('WS'); vertical axis—growth rates of nuclear power ('N'). Dots—combinations of maximum growth rates in individual 1.5 °C (left panel) and 2 °C-consistent (right panel) pathways between 2020 and 2040. Multi-colored shading—estimated density of the pathway rates. Green shading—feasibility zones based on empirical benchmarks from historical evidence and near-term plans and projections (table 3). Triangles—combinations of empirically grounded benchmarks (same as in figure 4, see also table 3).

explanation for the faster historical growth of nuclear power is that in case of policy-driven technology expansion it is easier for the state to plan and manage the deployment of a lumpy technology, which involves fewer projects and actors than granular technologies. In terms of political economy, fewer actors also comprise a concentrated interest group, which can be more influential in stimulating supportive state action [78].

Our findings on faster historical growth of nuclear power differ from those by Lovins *et al* [17], who report faster growth of renewables. This is because Lovins *et al* used absolute values, whereas we normalized growth to the electricity system size. In the mid-1980s when nuclear experienced its fastest growth, the global electricity system was two and a half times smaller than today, so the same absolute growth rates meant higher normalized rates. The use of normalized rates is better suited for comparing technology growth across countries or over time and is the established practice in assessing feasibility of technology deployment in scenarios [34, 35, 40]. We also believe that our normalization base is more relevant than other normalization bases such as the population size [79] or GDP [35] for analyzing decarbonization because it captures the dynamics of substituting fossil fuels with low-carbon sources as a percentage of the electricity system size.

Secondly, we demonstrate how the effects of technology characteristics can be disentangled from those of the context for the purpose of empirical feasibility benchmarking. For example, prior literature attributed the rapid growth of nuclear power to the unique political context of the post-WWII period or massive state support rather than to specific features of nuclear technologies [17, 54]. Likewise, the growth of renewables has been explained in terms of socio-political drivers and barriers rather than inherent characteristics of wind and solar power [73, 80]. By systematically measuring growth of all three technologies in all large countries we overcome a limitation of pairwise comparisons of country/technology combinations, which leads to confusing the differences between technologies and national contexts [17]. In other words, analyzing the entire ensemble of national and regional cases of growth for each technology means we avoid 'cherry-picking' [17] and leverage the variety of contexts into a range of reference cases necessary for constructing a feasibility space [40]. We further expand the range of empirically observed conditions by complementing historical observations with near-term plans and projections. Adding the EU's renewables targets [50] to our reference cases is especially important since they provide a particularly elegant 'natural experiment' [40, 81] which fills a gap in historical observations: the growth of granular technologies in wealthy democracies expecting booming electricity demand under an energy security threat.

The context of REPowerEU is somewhat similar to that of Western Europe in the 1970s and 80s, when the region experienced both increasing demand and energy insecurity. Interestingly, the planned growth of renewables is comparable to the historical growth of nuclear observed under the same conditions, while being much faster than historical growth of renewables that occurred under different conditions. This may indicate that the context plays at least as important a role as inherent technology characteristics in defining the speed of energy transitions.

We show how empirical reference cases of national and regional growth of low-carbon technologies can provide benchmarks for global pathways. First, we observe that the fastest growth occurs in smaller systems (figure 3), which means that empirical observations from larger countries and regions are most appropriate benchmarks for global or regional growth in pathways. Second, we observe that the fastest growth of both nuclear and renewables occurs in advanced economies under expanding electricity demand and energy security threats, a context that combines high capacities and high motivation for energy transitions. The importance of the energy security motivation is also confirmed by our findings that major energy exporters are laggards in adopting LCETs. We also use the evidence that the growth of solar and wind power is typically not faster in latecomers than in early-adopters [7]. Therefore, under the most favorable assumptions we can expect that the growth of wind and solar power in Asia in 2020–2040 could be similar to what is envisioned in REPowerEU for 2020–2030, while the growth of nuclear could be similar to its growth in Western Europe in the 1970s–1980s. Under more realistic assumptions, only slower growth rates would be reached. Among other things, these assumptions presume that nine large Asian economies which so far adopted none or only one or two of the LCETs (figure 2) will be able to adopt all three, which seems to be plausible in light of our findings on technology adoption. Comparing the plausible combinations of the empirical benchmarks to the growth of LCETs in IPCC AR6 pathways, we argue that more ambitious climate targets would require both deployment of renewables historically observed in 'crisis-driven' political contexts in advanced economies, and non-trivial deployment of nuclear power.

We further show that there is a mismatch between the growth of low-carbon technologies in climate mitigation pathways and historical experience. The fast growth of renewables in the pathways is similar to the historical growth of nuclear power, while the slower growth of nuclear is similar to the historical growth of renewables. This mismatch is most likely driven by significant decline in costs of wind and solar and stagnating costs of nuclear in the models underlying the scenarios. However, models and scenarios would better reflect empirically observed mechanisms [12, 82] if they also incorporate non-cost factors prominently shaping historical experience. Finally, we show how empirically-grounded benchmarks can be used to construct a feasibility space for simultaneous deployment of nuclear and renewables and how the 'solution space' from the IPCC mitigation pathways can be mapped onto the feasibility space for identifying more feasible scenarios.

There are limitations to our method which call for caution in the interpretation of our findings. First, there are obvious limits of extrapolating historical observations to the future where the circumstances could be dramatically different. We partially address this limitation through hindcasting (figure S1), which justifies using our estimates in the 15–20 years time-horizon until 2040. In addition, we supplement historical observations with more ambitious benchmarks derived from IEA near-term (5 years) projections and plans in Germany and the EU. Yet, there still may be a possibility that an unprecedented combination of factors such as declining costs of renewables, energy security threats, and uniquely strong climate policies can lead to faster transitions in Asia than those historically observed in Europe, Germany, and other front-runner countries. To disregard this possibility might mean unreasonably deprioritizing scenarios or policy measures which are not in line with historical experience and other empirical benchmarks. We therefore recommend two guiding principles of interpreting our results. First, feasibility assessment should not be treated as binary [40, 41], which means that unprecedented outcomes are not necessarily infeasible. However, as a rule of thumb achieving such outcomes would require more efforts than achieving outcomes with multiple empirical precedents drawn from diverse contexts. Secondly, policy makers or scenario developers planning or projecting unprecedented outcomes need to explain *why* the future will be different from the past, in other words, what kind of unprecedented mechanisms would cause these unprecedented outcomes.

5. Conclusion

The debate on which technologies can deliver the fastest decarbonization is mainly focused on technology characteristics such as cost, complexity, and safety. Yet, societal contexts, such as national capacity and motivation matter at least as much, and therefore historical analogies of projected technological expansion should be drawn from a wide variety of socio-economic and political conditions. Here we show that in favorable contexts, nuclear power generation grew faster than solar and wind, though the use of nuclear has remained limited to large countries. This contrasts the widespread narrative that nuclear power cannot be expanded fast, but also stresses the historical conditions for its rapid growth in Western Europe in the 1970s–1980s: growing industrialized economies responding to energy security shocks.

With respect to demand growth and energy security, the current situation in Europe is similar to the 1970s and the 1980s, when nuclear power grew fastest. This might explain why several European countries including Sweden, the Netherlands, Poland, France, Hungary, Czechia and the UK are seeking to build more nuclear power (table S9). More remarkably, energy insecurity and the prospects of demand growth are triggering unprecedented plans for renewables in the EU and Germany, requiring faster growth than anything previously observed in any large country and nearly matching the historical growth of nuclear power. This observation echoes the analogies between the efforts required to achieve climate goals and war-like policy measures [83–85].

These precedents of rapid growth of low-carbon technologies provide hope for faster decarbonization of electricity in Asia, the most critical region for global emission reductions. With respect to low-carbon electricity growth, as in some other decarbonization areas [44, 64], climate mitigation pathways assume larger effort in Asia than in OECD. We show that it could be feasible to stay on track to the 2 °C target if both renewables and nuclear in Asia grow with ambitious yet empirically realistic rates which replicate the EU's projections for renewables and China's plans for nuclear.

Our analysis demonstrates the potential to use empirically-grounded benchmarks for informing climate mitigation scenarios through systematically constructed feasibility spaces. The empirically-benchmarked feasibility spaces could be used in conjunction with other feasibility assessment methods, including those based on models and detailed analysis of concrete barriers and driving forces [14, 15]. There is an extensive research agenda to understand whether and if so to what extent specific causal mechanisms such as cost declines of renewables, stronger climate policies (for example the US Inflation Reduction Act), and energy security crises accelerate energy transitions. The existing, largely qualitative, research in this area should be supplemented by comparative and quantitative studies using systematic metrics of the speed of technology diffusion proposed in this paper. This approach to feasibility assessment can be expanded to more technologies and eventually contribute to making transparent and realistic assumptions in climate mitigation pathways.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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Conflict of interest

The authors declare no conflict of interest.

Ethical statement

This research does not involve human participants or animal experimentation.

ORCID iDs

Vadim Vinichenko https://orcid.org/0000-0001-7135-2618
Jessica Jewell https://orcid.org/0000-0003-2846-9081
Aleh Cherp https://orcid.org/0000-0002-9299-9792

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