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Probabilistic feasibility space of scaling up green hydrogen supply

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Abstract

Green hydrogen and derived electrofuels are attractive replacements for fossil fuels in applications where direct electrification is infeasible. While this makes them crucial for climate neutrality, rapidly scaling up supply is critical and challenging. Here we show that even if electrolysis capacity grows as fast as wind and solar power have done, green hydrogen supply will remain scarce in the short term and uncertain in the long term. Despite initial exponential growth, green hydrogen likely ($\geq 75\%$) supplies $< 1\%$ of final energy until 2030 in the EU and 2035 globally. By 2040, a breakthrough to higher shares is more likely, but large uncertainties prevail with an interquartile range of 3.2-11.2% (EU) and 0.7-3.3% (globally). Both short-term scarcity and long-term uncertainty impede investment in hydrogen end-uses and infrastructure, reducing green hydrogen's potential and jeopardising climate targets. However, historic analogues suggest that emergency-like policy measures could foster substantially higher growth rates, expediting the breakthrough and increasing the likelihood of future hydrogen availability.

Introduction

Green hydrogen, defined as hydrogen produced from renewable electricity via electrolysis, and derived e-fuels¹ are critical components of the energy transition², enabling emissions reductions in sectors where direct electrification is infeasible^{3,4} and avoiding sustainability concerns associated with biofuels⁵. These features, plus its versatility, have spurred a recent surge of enthusiasm⁶, policy targets^{7,8}, and investments³. Furthermore, in response to the current energy crisis, an accelerated market introduction of hydrogen is considered a key option to decrease Europe's reliance on fossil fuel imports⁸. Hydrogen therefore plays a central role in facilitating many net-zero emissions scenarios^{9,10} and government plans⁷. Of all ways to produce hydrogen, green hydrogen offers the lowest life-cycle emissions¹¹ and likely lowest long-term mitigation costs¹², making it most suitable for climate neutrality.

While much of the debate and research around hydrogen has revolved around demand-related questions of suitable applications, markets, and sectors¹, the question of supply availability is equally critical. Hydrogen is very valuable for achieving increasingly pressing and legally binding emissions reduction targets^{13,14} as it can provide diverse energy services, ranging from energy storage, long-distance transportation to industry feedstocks³. Due to the substantial size of these hard-to-abate sectors and because virtually all hydrogen production today is fossil^{3,4}, ramping-up green hydrogen supply is urgent¹⁵. Growing awareness that scalability is a critical success factor for climate mitigation technologies has stimulated recent research to apply insights about the pattern^{16,17} and pace¹⁸⁻²⁰ of energy technology diffusion to specific feasibility analyses²¹⁻²³ of ramping-up renewable²⁴⁻²⁹ and phasing-out fossil technologies^{22,30,31} fast enough. However, so far no study has analysed possible expansion

pathways of green hydrogen from electrolysis, a technology in its infancy that needs to experience rapid innovation and deployment to unleash its potential for climate change mitigation¹⁵.

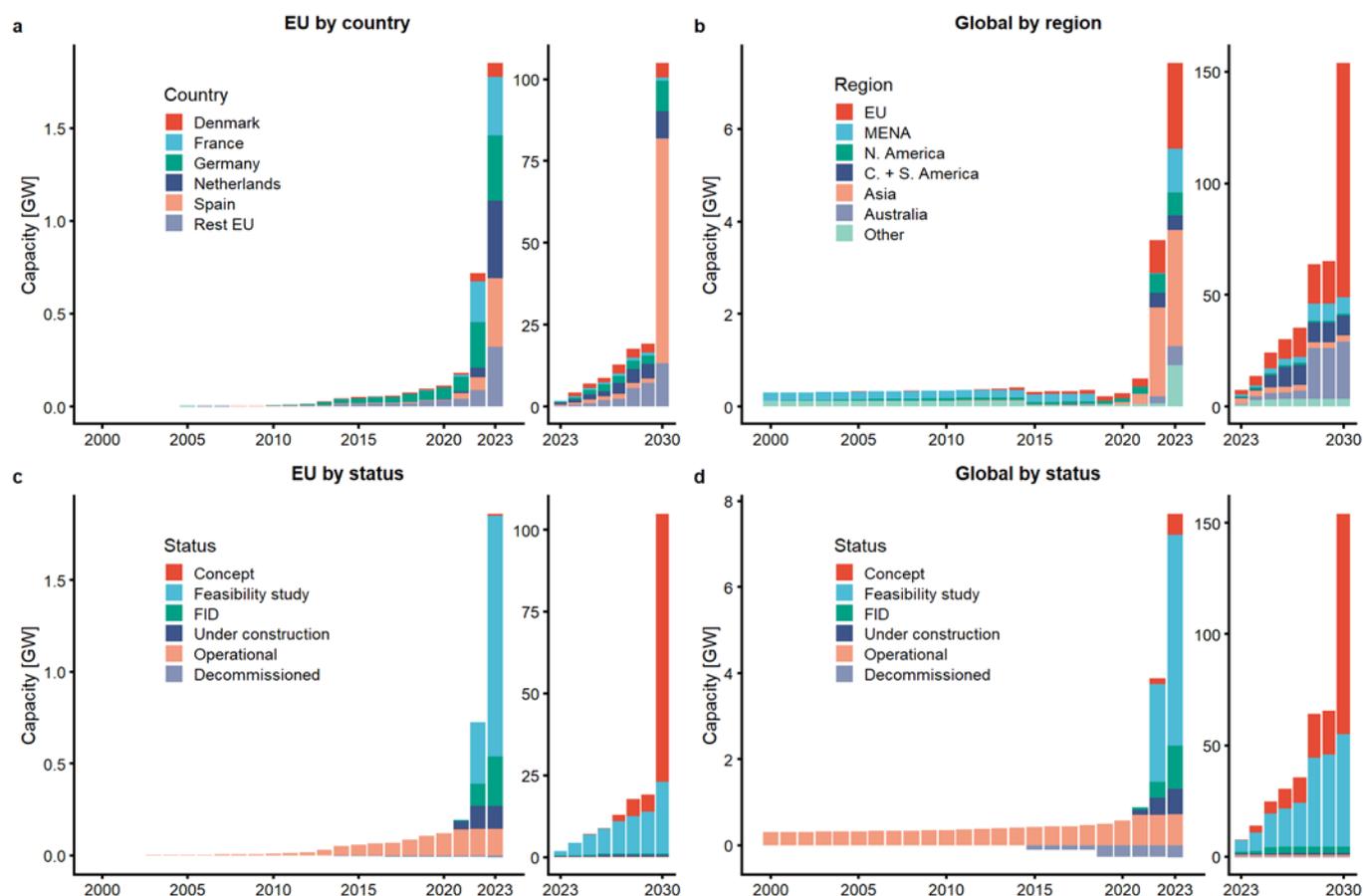


Figure 1: Historical development and future announcements of electrolysis projects. *a,c*, Projects in the EU by country (*a*) and by project development status (*c*). *b,d*, Global projects by aggregated region (*b*) and project development status (*d*). Each panel is split into two parts, showing data from 2000-2023 in the main left-hand part, and 2023-2030 in the smaller right-hand part with a separate axis. Projects without a specified starting date are omitted, which affects 21 GW in the EU and 127 GW globally. In (*a*) and (*b*), decommissioned projects have been subtracted.

Electrolysers are a centerpiece of future green hydrogen supply chains, and their deployment is thus an indicator of the systemic challenges of concurrently ramping-up additional renewable energy capacity, transport infrastructure, and hydrogen end-use applications. In addition, the ramp-up of electrolysers is a key bottleneck in itself. Starting at an estimated 600 MW globally in 2021 (Fig. 1)³² in mostly small and individually manufactured plants (<10 MW), global capacity needs to grow 6,000-8,000-fold from 2021-2050 to meet climate neutrality scenarios compatible with the Paris Agreement^{9,10}. This dwarfs the simultaneously required 10-fold increase of renewable power^{9,10}, which is readily available and cost competitive^{33,34}. While electrolysis project announcements indicate an exponential buildup of momentum in the upcoming years with triple-digit annual growth rates, 80% of additional capacity announced to come online by 2023 is not yet backed by a final investment decision (FID) (Fig. 1c-d). It thus remains unclear how many electrolysis projects will materialise in the short term and whether overall capacity can expand fast enough to meet mid- to long-term hydrogen demands.

Here we analyse the potential deployment of electrolysis capacity for green hydrogen production by combining an S-shaped logistic technology diffusion model¹⁷ with a probabilistic parameterisation based¹⁷ on data from established successful energy technologies: wind and solar power³⁵⁻³⁷. Despite such high growth rates, we find strong evidence of short-term scarcity and long-term uncertainty of green hydrogen supply. This bears a high risk of a substantial gap between likely supply and potential

demand, threatening the outlook of green hydrogen for urgent climate change mitigation. In contrast, if electrolysis capacity were to grow at unconventional growth rates, experienced for some non-energy technologies under special circumstances in the past, it could quickly overcome supply scarcity and secure future green hydrogen availability.

Three uncertain parameters that define the feasibility space

In a finite market, technology adoption starts exponentially but gradually flattens out to follow an S-shaped curve as it approaches saturation (Fig. 2). The theory behind this logistic functional form originates from Roger’s (1962) conception of technology adoption, initiating with a small group of early adopters comfortable with an unfamiliar technology and then proceeding with a much larger group of adopters with lower willingness to pay who wait for lower costs and reliable performance¹⁷. This notion has been developed by transitions theory scholars, for whom the defining characteristic of early adopters is the role of niche markets where unproven technology finds initial markets^{38–40}.

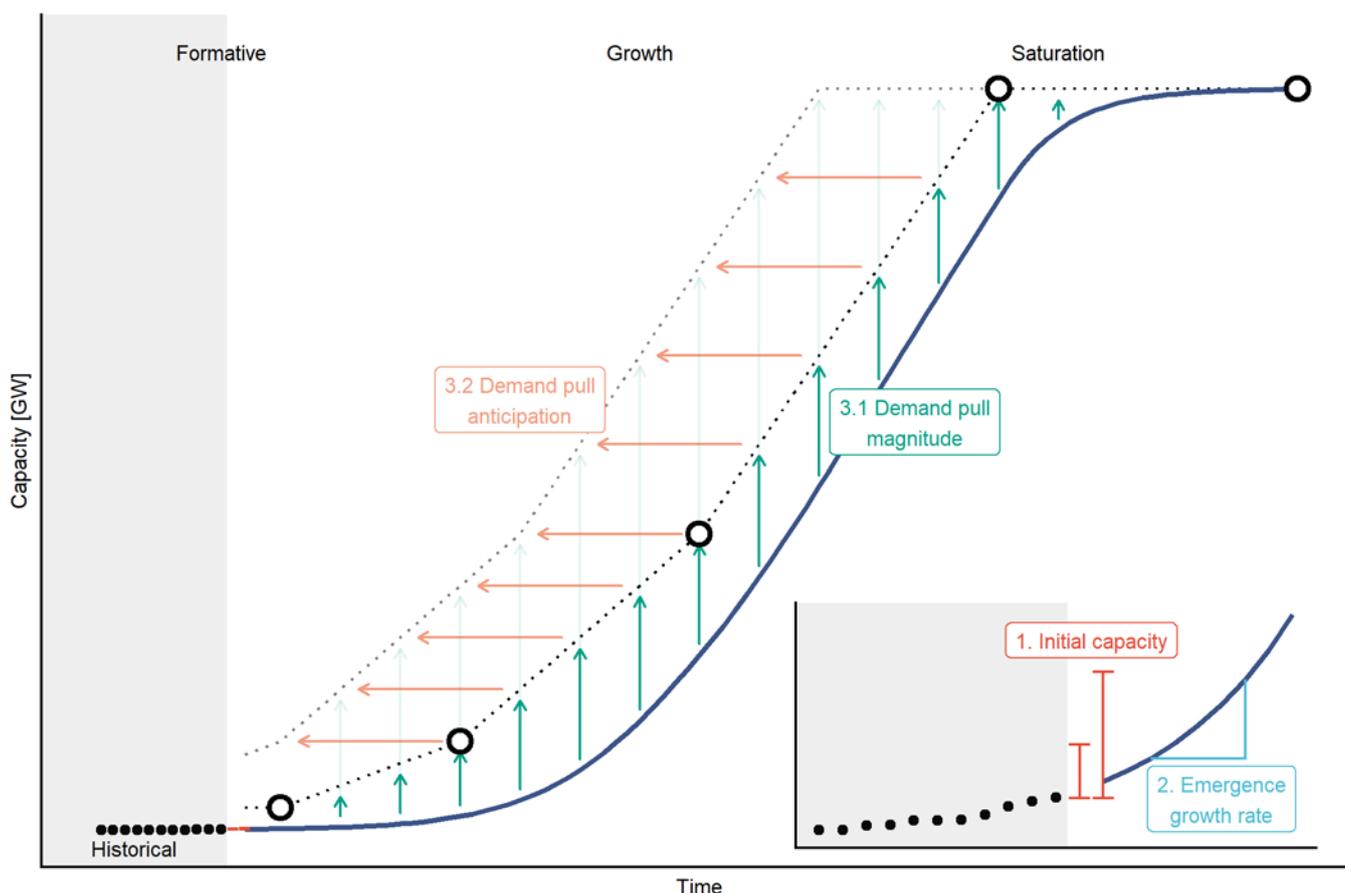


Figure 2: Illustration of the three uncertain parameters of the market ramp-up. In order these are the initial capacity, the emergence growth rate, and the demand pull, for which we distinguish magnitude and anticipation. Black circles indicate electrolysis deployment targets set by policy ambitions or project announcements. The demand pull is indicated by the dotted line and is defined as a piecewise linear function between the deployment targets. Anticipation brings the demand pull forward in time. The solid line indicates a single example path. The probabilistic feasibility space follows from the propagation of the uncertain parameters using a Monte Carlo simulation approach.

The resulting technology diffusion pathway follows three distinct phases. In the formative phase, policy-backed demonstration projects face technical uncertainty and high costs during the proverbial valley of death⁴¹, leading to slow and unsteady growth⁴². In the growth phase, increasing returns to scale⁴³ and cost-decreasing learning effects⁴⁴ accelerate market adoption. After reaching the maximum rate of expansion, growth starts to slow down as a result of technological, economic and social constraints¹⁷. This marks the beginning of the saturation phase when the final market level is approached. This trajectory characterises all stages of the technology adoption process and is mathematically described by the three-parameter logistic

function (see Methods). Considering the electrolysis market ramp-up, the three parameters initial capacity (timing), emergence growth rate (steepness) and saturation (asymptote), relating to these three stages, are all uncertain and independent. First, the initial capacity is an uncertain parameter as it depends on the possibly strong yet uncertain momentum in the upcoming years, which could propel electrolysis capacity from the formative phase to the beginning of the growth phase and therefore must be included in the analysis. Beyond the evidently speculative nature of projects pending an FID, there are further mutually opposing uncertainties. On the one hand, even projects that have secured an FID might fall behind schedule. On the other hand, data gaps due to additional future projects or missing projects might introduce downward biases. Striking a balance between including near-term momentum and excluding uncertain long-term announcements, we focus on the year 2023 as the “initial year”, as we do not expect any potential new projects to proceed from announcement to operation in less than two years. Fig. 3a-b shows the probability distributions of the initial capacity in 2023, which spans the full range of project announcements, centred around an expected value of realising 30% of projects in the feasibility study category⁴⁵ and assuming that all projects under construction are built in time (see Methods).

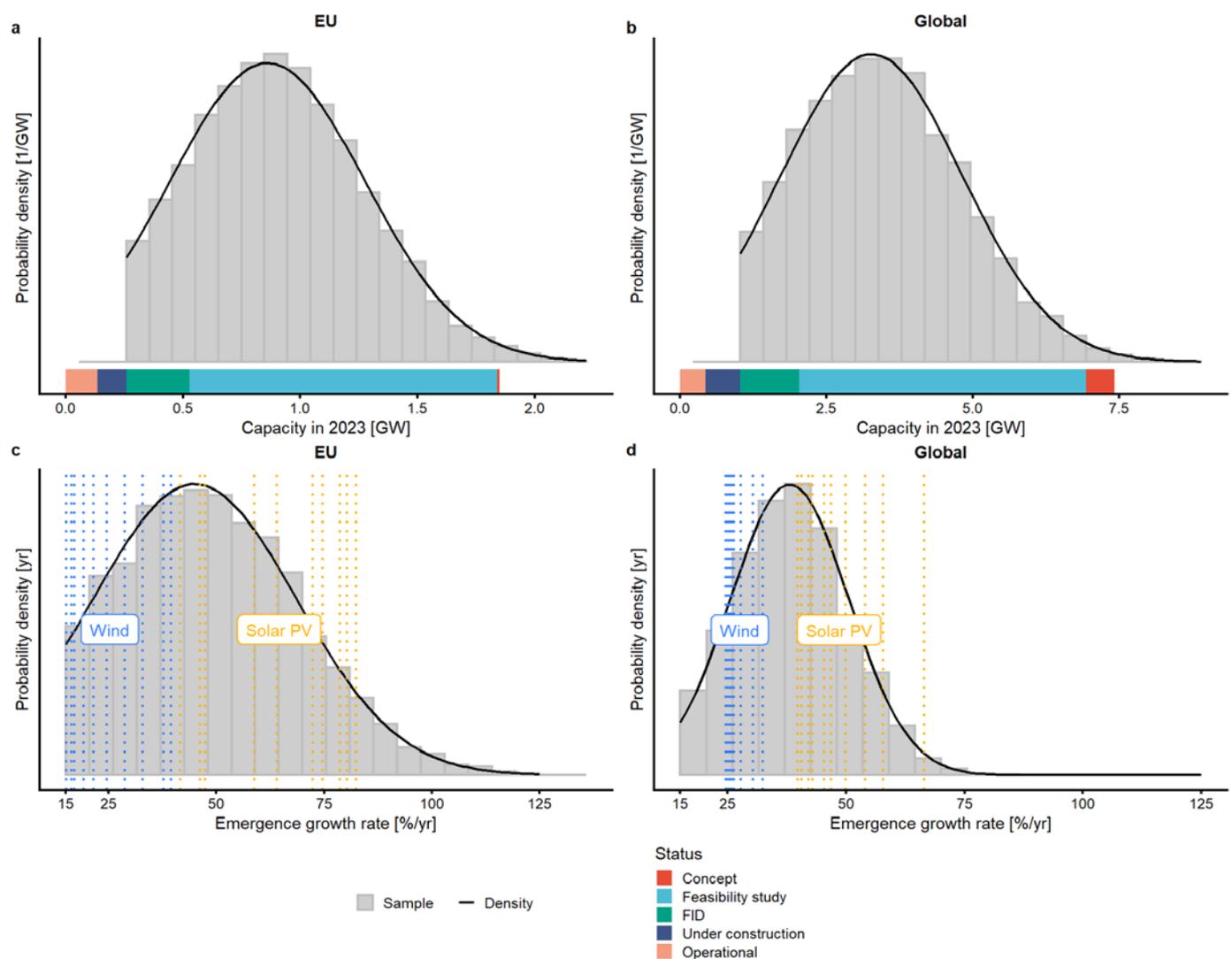


Figure 3: Truncated normal probability distributions of initial capacity in 2023 and emergence growth rates in the conventional growth case. a, b, Initial capacity distributions in the EU (a) and globally (b). The horizontal bars correspond to the 2023 bar in Figure 1c,d, where decommissioned projects have been subtracted from operational projects. **c, d,** Emergence growth rate distributions in the EU (c) and globally (d) based on wind and solar PV in 7-year time slices in the interval 1995–2010 (also see Extended Data Figure 1).

Second, the growth rate is an inherently uncertain function of policy support⁴⁶, technological characteristics⁴⁷ and possible cost reductions⁴⁴, of which the latter are notoriously difficult to predict⁴⁸. As the annual growth rate gradually decreases due to market saturation, we parameterise the emergence growth rate²⁶, which is the maximum annual growth rate that is realised after the formative phase, related to the steepness parameter in the logistic function (see Methods). Unlike previous research, which constructed feasibility spaces by looking at historical precedents of the same technology in different regions^{28,31}, we instead turn to historical precedents of different technologies in the same region. This comparison is necessary because, as long as green hydrogen is uncompetitive⁴⁴, historical growth rates are primarily proxies of past policy support and not necessarily indicative of future potential. In this way, we also abstract from a more granular analysis of factors that influence the pace of technology diffusion in order to construct different scenarios. In the conventional growth scenario, we compare electrolysis with wind and solar power, the historically fastest-growing energy technologies, which now comprise nearly 10% of global electricity generation⁴⁹, during their periods of fastest relative growth, 1995-2010 (Extended Data Fig. 1). Fig. 3c-d shows the corresponding distributions, revealing that solar power grew faster than wind during all 7-year intervals, both in the EU and globally. The distributions are robust to the interval length (Extended Data Fig. 2). Extended Data Table 1 compiles drivers and challenges for higher as well as for lower hydrogen growth rates compared to wind and solar power, such that we carefully conclude that wind and solar PV are a valid initial proxy to derive rough estimates of green hydrogen ramp-up and availability. Later, in the unconventional growth scenario, we compare these growth rates to a broader set of predominantly non-energy technologies.

Third, the final market volume is uncertain as the outcome of the competition among different climate change mitigation technologies remains undecided in many end-use applications⁵⁰. In these applications, hydrogen constitutes a new energy carrier, which implies that not just its supply, but also its demand and infrastructure have to be ramped-up in parallel. In contrast, wind and solar power produced an economic good with existing demand and pre-installed infrastructure, namely electricity. We capture the just-emerging hydrogen market by a steadily-increasing demand-pull and distinguish between its magnitude and anticipation (Fig. 2). We opt for a simple piecewise linear demand-pull function, parameterised on policy targets and announcements in the short- to mid-term and on demand from climate neutrality scenarios in the long-term (see Methods). The demand-pull therefore comprises all factors that increase market opportunities through policies, regulation, and improved competitiveness^{51,52}.

Table 1: Key values of the three uncertain parameters of the electrolysis market ramp-up.

Parameters			EU	Global	Source
1. Initial capacity 2023	Min		0.26 GW	1.02 GW	IEA Hydrogen Projects Database ³⁵ , own market research
	Mean		0.92 GW	3.49 GW	
	IQR		0.65 – 1.16 GW	2.46 – 4.39 GW	
2. Emergence growth rate	Min		15 %/yr	15 %/yr	Historical growth of solar and wind capacity ⁵⁶ (conventional growth case)
	Mean		50 %/yr	39 %/yr	
	IQR		35 – 63 %/yr	31 – 47 %/yr	
3. Demand pull	Magnitude	2024	6 GW	-	EU: Hydrogen strategy ⁷ , RePowerEU Plan ⁸
		2030	100 GW	254 GW	
		2050	500 GW	3600 GW	
	Anticipation		Default: 5 years (Sensitivity analysis: 0 years, 10 years, full anticipation)		Assumptions

The propagation of the uncertain initial capacity and emergence growth rate (Fig. 3) defines a probabilistic feasibility space, under the condition of an increasing policy-backed demand-pull that spurs investment and mitigates financial risks. Table 1 summarises the key model parameters for the electrolysis market ramp up in the EU and globally.

Reconciling different approaches to long-term projections

Our model steers a middle course between two approaches in the recent literature that have analysed growth trajectories of wind and solar power, but arrived at different conclusions regarding their outlook. The first approach relies on fitting growth models with the asymptote as a free parameter that is estimated from historical data if possible^{24,28}. Studies differ in their interpretation of the asymptote as the final market volume²⁴ or as a non-indicative parameter that may be surpassed again later in the diffusion²⁸. While including the asymptote as a free parameter often yields a good fit to data, it comes at the expense of high sensitivity to random fluctuations in the last few data points⁵³, and to the type of growth model used²⁸. A slowdown, which might in hindsight turn out to be just a temporary artefact, for example due to discontinuous policy⁵⁴ or economic crises⁵⁵ (see e.g. Extended Data Fig. 1a), could be misinterpreted as terminal saturation if the asymptote is taken at face value. In that case, this approach risks constraining future conditions to policy-driven historical deployment, which can negatively bias the long-term outlook.

In contrast, the second approach in the literature applies an ex-ante target towards which wind and solar power diffuse from their historical trajectory^{26,27}. While this enables an inter-decadal feasibility analysis under the presupposition that a stated market volume will be attained, it implicitly assumes an existing market with sufficient demand, which technologies can penetrate. This may not be the case for hydrogen because demand-side transformations and infrastructure requirements mean it cannot immediately tap into new markets that are just emerging. In our approach these coordination challenges are summarised by the steadily-increasing demand-pull, which contributes to reconciling the debate on long-term projections of energy technologies, especially for hydrogen, but potentially also for wind and solar power.

Modelling green hydrogen growth using a logistic model that is driven, but also constrained, by an increasing demand-pull leads to an asymmetric S-shaped adoption curve, which approaches the asymptote more gradually than the standard symmetric logistic function. While a similar shape may also be described by the Gompertz model (used in ref²⁸) as another special case of the generalised logistic function (see comparison in Extended Data Fig. 3 and Methods), our model allows for a more precise control of the increasing market volumes, which can be informed by additional information about policy targets, improving cost competitiveness and scenario results.

Electrolysis capacity using growth rates from wind and solar

Fig. 4 shows the probabilistic feasibility space of electrolysis capacity in the EU and globally using a distribution of growth rates assembled from the historical growth of wind and solar power and applying demand-pull anticipation of five years (sensitivity analysis in Extended Data Fig. 4). Three key insights emerge.

First, in the upcoming 1-2 decades, in the first half of the growth phase, electrolysis capacity is likely to remain relatively small compared to both intermediate and final targets as well as to total energy demand. Green hydrogen will thus remain scarce, leading to a large gap between likely supply and potential demand. Another gap exists between likely supply and project announcements (Extended Data Fig. 5). In the EU, neither the 2024 target of 6 GW nor the 2030 target of 100 GW are within reach under conventional growth rates as both fall outside the distribution. The global target of 254 GW by 2030, which ensues from ambitious project announcements³² (Fig. 1d) plus planned EU imports⁸, also lies far beyond the 95th percentile, illustrating the short-term challenges of ramping-up green hydrogen production within the EU and globally.

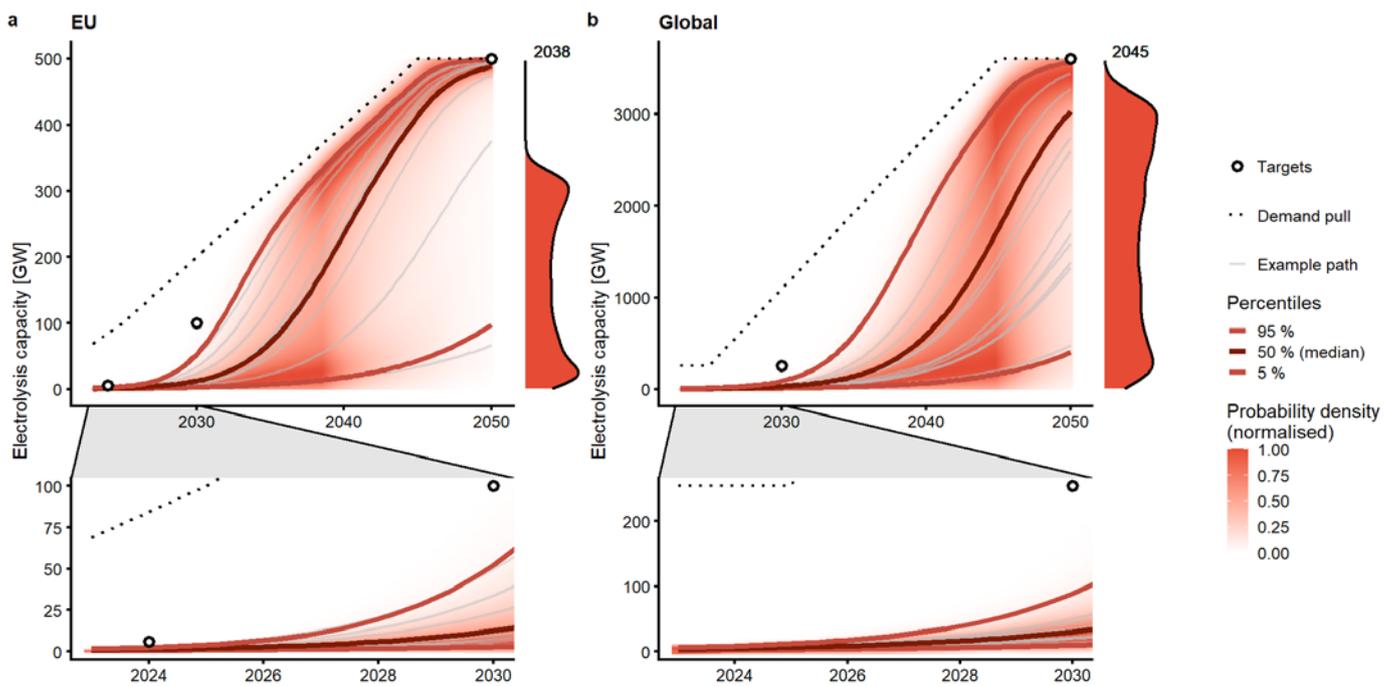


Figure 4: Probabilistic feasibility space of electrolysis growth in the conventional growth case. a, in the EU. b, globally. The colour shade indicates the yearly probability density that results from the uncertainty propagation of the initial capacity in 2023 and the emergence growth rate. Grey lines display random example pathways, illustrating the vast range of plausible outcomes under growth rates similar to wind and solar power. The vertical diagram shows the probability density at the intersection year 2038 in the EU (a) and 2045 globally (b). The results reveal short-term scarcity, with little electrolysis capacity until 2030 (2035) in the EU (globally), and substantial long-term uncertainty, with a wide range of possible electrolysis capacity until 2050.

Second, a breakthrough to high capacities is possible, but both timing and magnitude are subject to large uncertainties. The results reveal a threshold above which the probability distribution flips towards larger values and then follows the linear demand-pull with a few years of delay. For the EU this occurs around 2038, and globally around 2045, which approximately coincides with the years of largest annual electrolysis capacity additions in the midst of the growth phase. This tipping behaviour is a property of the probability space, which combines the information of the pathway ensemble and is thus more relevant to decision makers than individual pathways, which are more continuous and span a larger range. The interquartile range (IQR) of probabilistic electrolysis capacity in 2040 is 94 – 330 GW in the EU (246 – 1121 GW globally), and 412 – 497 GW in the EU (1873 – 3434 GW globally) in 2050, marking the saturation phase. Substantial uncertainty thus prevails for several decades, especially globally.

Third, the propagation of uncertainties not only leads to a tipping point but also to a pronounced bimodal distribution near the tipping point, which has adverse consequences for risk management. This pattern is a direct outcome of the superposition of many S-shaped diffusion curves and occurs despite input parameters that follow a well-defined normal distribution with a clear maximum (Fig. 3). This is because for most of the period, the logistic curve produces low and later high capacities (small annual additions); because of high growth rates the transition phase occurs quickly (large annual additions), and thus the probability of being at an intermediate capacity is low. Using the Gompertz model (see Extended Data Fig. 3), the distribution does not turn visibly bimodal until 2050, but is instead very wide and flat, implying a similarly large risk of the supply-demand gap.

Both short-term scarcity and mid- to long-term uncertainty are robust to the type of growth model used and create challenges for policy makers, system planners, industry, and consumers. Relying on the large-scale availability of green hydrogen could lead to expensive path dependencies or even fossil lock-ins⁵⁶ if supply expansion falls short of expectations. Accounting for these risks likely discourages investments in hydrogen supply, infrastructure and end-use technologies, thus exacerbating short-term

scarcity and mid- to long-term uncertainty. In addition, scarce and uncertain supply complicates and delays required end-use transformation and infrastructure investments. As a consequence, green hydrogen could fail to realise its potential.

There are good arguments both in favour and against the hypothesis that electrolysis could grow even faster than wind and solar power did (see Extended Data Table 1).

Emergency deployment with growth beyond wind and solar

To explore what might be possible with special dedication, coordination and funding, we now parameterise our electrolysis diffusion model with unconventionally high growth rates that have been achieved under specific circumstances in the past (Fig. 5). These include mostly non-energy products in situations of wartime mobilisation (e.g. US aircraft or liberty ships in World War II), of massive public investments and central coordination (e.g. nuclear power in France or high-speed rail in China), or of market-driven deployment of highly modular IT innovations with low coordination requirements (e.g. internet hosts or smartphones).

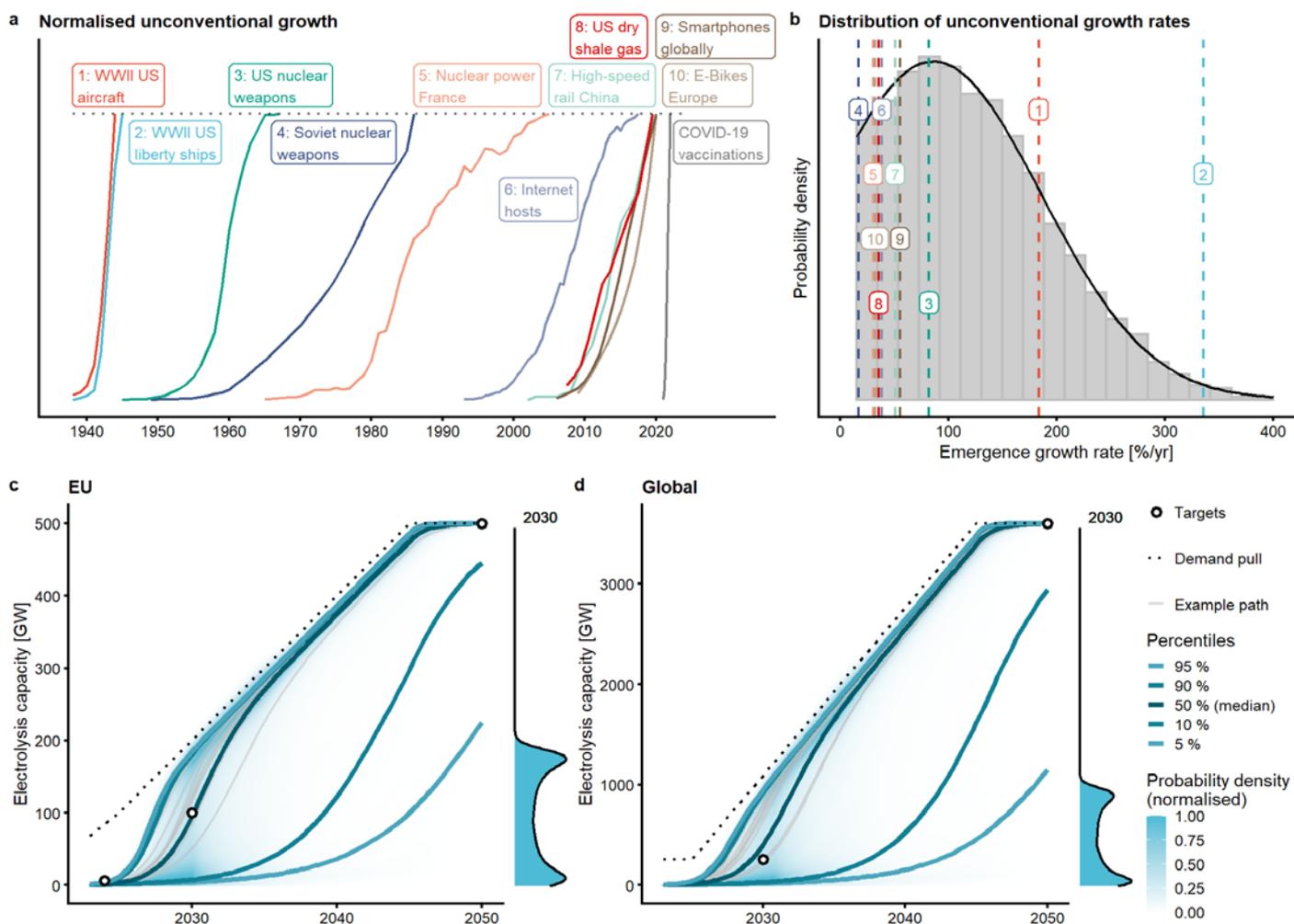


Figure 5: Historical examples of technologies with unconventional growth and probabilistic feasibility space of electrolysis under such growth rates. *a*, Growth pathways of 11 exemplary technologies in different regions from 1938 until today, normalised to their respective maximum level measured in different units (see Methods). *b*, Distribution of emergence growth rates in the unconventional growth case, obtained from fitting logistic curves to the technology pathways in (a). *c-d*, Probabilistic feasibility spaces under unconventional growth rates for the EU (c) and globally (d). The results demonstrate that the ramp-up is substantially expedited compared to the conventional growth case, strongly reducing long-term uncertainty. COVID vaccinations are a case of extremely fast adoption and hence had to be excluded from the distribution.

Fig. 5a shows the normalised historical trajectories of these technologies. In order to cover the full spectrum of associated growth rates, we fit logistic curves and extract the respective annual emergence growth rates. The resulting distribution of unconventional growth rates has a mean value of 126 %/yr, substantially larger than in the conventional growth case (Table 1),

and stretches beyond 300 %/yr (Fig. 5b). Within the analysed data, only US production during World War II (WWII) achieved growth rates above 100 %/yr – except for the number of COVID-19 vaccinations, which far surpass all other technologies such that we exclude it as an outlier with very different circumstances and product characteristics.

For green hydrogen, reaching such unconventionally high growth rates requires policies and regulation to urgently secure business cases by creating, or even guaranteeing, revenue streams through public co-financing or direct investments. If policy makers decide for subsidies, such as co-financing of CAPEX or OPEX, the funding of these programmes would need to reflect the envisaged scale of the hydrogen market ramp-up. There are plans for such instruments for example in the EU, which are yet to be specified and implemented. These comprise carbon contracts for differences, which subsidise additional OPEX of operating industrial processes with green hydrogen (e.g. primary steel via direct reduction), or CAPEX subsidies as part of the EU's "Important Projects of Common European Interest" (IPCEI)⁸. In addition, emergency policies should provide security and coordination along the whole value chain. As hydrogen requires new infrastructure, and as most hydrogen applications are not yet competitive and no hydrogen market exists, policy makers and regulatory agencies should support the coordinated ramp-up of demand, supply and infrastructure together with relevant industry stakeholders. Since hydrogen infrastructures and trade will partly be international, this involves international cooperation.

The resulting probabilistic feasibility spaces show that unconventional growth rates substantially mitigate the issues of short-term scarcity and mid- to long-term uncertainty (Fig. 5c-d, sensitivity analysis in Extended Data Fig. 6). In both regions, EU and global, green hydrogen immediately enters the growth phase, leading to a probability distribution that already tips around 2030 after which the demand-pull acts as the main constraint. In 2030 an even more pronounced bimodal distribution emerges from the simulations, which however also subsides more quickly thereafter. After 2035, the demand-pull, median and 95th percentile are only separated by a very small margin, effectively closing the gap between supply and demand with a high probability. While smaller than before, the 90% confidence interval still indicates a significant spread as small growth rates cannot be ruled out. However, towards 2050 the spread swiftly decreases for the 80% confidence interval, indicating a high probability of mid- to long-term availability.

The differences between conventional growth (like wind and solar power) and unconventional growth (emergency-like deployment) become even more apparent in the direct comparison of Fig. 6. In the conventional growth case, the breakthrough year, defined as the year of largest annual capacity additions, in the median occurs around 2040 in the EU and 2045 globally. However, this is again subject to substantial uncertainty with an IQR of 2036 – 2045 in the EU and 2043 – 2049 globally. In contrast, unconventional growth hastens the median breakthrough to before 2035 in both regions, even though uncertainty remains with an IQR of 2029 - 2036 in the EU and 2030 – 2037 globally.

These marked differences in the breakthrough year are also reflected in the electrolysis capacity distributions (Fig. 6c-f and Extended Data Fig. 7). In the conventional growth case, it is likely ($\geq 75\%$) that in 2030 less than 1% of final energy in the EU (less than 0.2% globally) can be supplied with domestic green hydrogen. Under unconventional growth, supply in 2030 spans a wide IQR of 0.8-4.5 % in the EU (0.3-2.1% globally). This also increases the probability of achieving the EU 2030 target of 100 GW to 49%, as opposed to 0.2 % under conventional growth. However, even under unconventional growth rates, ramping-up global electrolysis capacity to 850 GW by 2030 as required by the IEA Net Zero Emissions (NZE) scenario⁹ is unlikely (18% probability), which is also a result of the limited demand-pull at that time (compare Extended Data Fig. 6f).

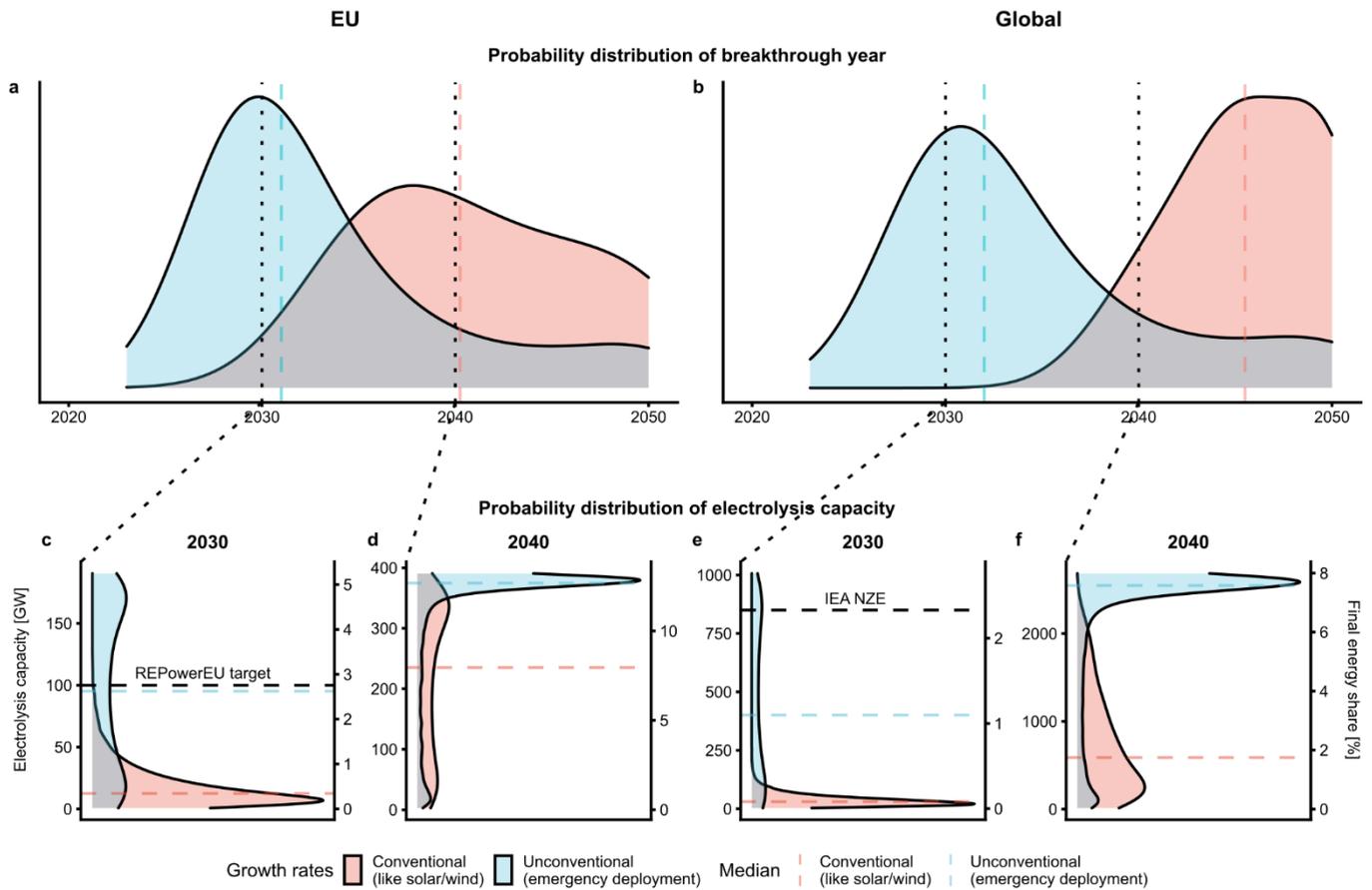


Figure 6: Uncertainty of breakthrough year and electrolysis capacity over time. *a, Breakthrough year distribution in the EU. b, Breakthrough year distribution globally. c,d, Electrolysis capacity distribution in the EU in 2030 and 2040. e,f, Electrolysis capacity distribution globally in 2030 and 2040. In c-f the left axis shows electrolysis capacity (in GW), while the secondary right axis shows the approximate final energy share this capacity could supply domestically (in percent) given total final energy consumption of scenarios that reach net-zero emissions by 2050.*

In the long run, by 2040, large uncertainties dominate in the conventional growth case, illustrated by an IQR of 3.2 – 11.2% in the EU (0.7 – 3.3% globally), which stands in stark contrast to the narrow 11.7 – 12.9% in the EU (6.6 – 7.8% globally) under unconventional growth. The global probability distribution under conventional growth in 2040 is skewed to low capacities, while it is wide and slightly bimodal in the EU. Under unconventional growth, by 2040 the probability distribution is focused at the upper end of the range in both regions and primarily determined by the demand-pull.

Discussion

Despite strong momentum and enthusiasm around green hydrogen, the market ramp-up of electrolysis is a decisive bottleneck on the pathway to climate neutrality. There is also substantial uncertainty about the role and potential of green hydrogen for achieving climate goals: While 1.5°C-compatible pathways presented by the IEA and IRENA foresee a rapid scale-up of green hydrogen, it only plays a limited role in most IAM scenarios assessed by the IPCC (Extended Data Fig. 8). We show that despite exponentially increasing project announcements for the upcoming years, green hydrogen likely ($\geq 75\%$) remains scarce ($< 1\%$ of final energy demand) until 2030 in the EU and until 2035 globally if electrolysis capacity grows similarly to wind and solar power, which have been the biggest success stories of the energy transition so far. This can be explained by the nature of exponential expansion, which includes a flat beginning such that even high annual growth rates take time to translate into noteworthy market shares. However, once the breakthrough occurs it may happen quickly – as was the case for solar power.

For the electrolysis market ramp-up, however, the timing of this breakthrough in terms of largest annual capacity additions is uncertain, but unlikely ($\leq 25\%$) to occur before 2036 in the EU and 2043 globally. We show that the propagation of inevitable

uncertainties associated with both near-term deployment and feasible growth rates leads to uncertain availability of green hydrogen in the mid- to long-term, which implies a substantial risk of a long-term gap between likely supply and potential demand. It is important to note that the probability distributions presented here are conditional on continuous policy support assumed as part of the demand-pull. Even under such policies, uncertainties prevail for decades.

In addition, future short-term scarcity and long-term uncertainty of electrolysis capacity might create additional barriers to electrolysis deployment already today. First, short-term scarcity creates problems due to the threefold coordination challenge of ramping-up hydrogen supply, demand and infrastructure simultaneously, which has been described as a “three-sided chicken-and-egg problem”⁵⁷. The lack of sufficient hydrogen volumes delays both the end-use transformation as well as required infrastructure developments such as the repurposing of existing gas pipelines. Second, long-term uncertainty might deter investors, who could choose to wait for the market to consolidate and for costs to drop (second-mover advantage)⁵⁸. From a policy perspective, relying on the large-scale availability of green hydrogen is therefore a risky bet that, if hydrogen abundance and affordability fail to materialise, may lead to a fossil lock-in due to remaining fossil fuel infrastructure and end-use equipment. As a consequence, under conventional growth like wind and solar power, uncertainties may translate into risks that discourage policy makers and investors such that green hydrogen might fall short of its potential and thus endanger climate targets.

By contrast, policy makers and industry could minimise these risks by fostering rapid investments into green hydrogen supply chains that enable unconventionally high growth rates of electrolysis. In this way the feasibility space would broaden beyond what has been experienced for energy analogues such as wind and solar. This could break the vicious cycle of uncertain supply, insufficient demand and incomplete infrastructure, and turn it into a positive feedback mechanism. Short-term scarcity and long-term uncertainty are two sides of the same coin and could be resolved together. Policies that kick-start a rapid deployment of Gigawatt-scale electrolyzers in the upcoming few years could help to unlock substantial innovation and scaling effects, prompting industries to switch from manual to automated production and thus driving down costs, which would secure expectations and further accelerate growth.

Such unconventional growth could not only allow green hydrogen to meet demand in sectors inaccessible to direct electrification, but in conjunction with expanding renewable electricity, it could keep the window open to reaching a broader and more prominent role of hydrogen in a climate-neutral energy system. However, policy makers should be aware that there remains a risk of overestimating green hydrogen’s potential. While it will be possible to expand the use cases of hydrogen if supply surpasses expectations, in the opposite case, if supply falls short of expectations, it might simply be too late to switch to alternatives. Under these asymmetrically distributed risks policy makers face a twofold problem. On the one hand, they need to accelerate the development of green hydrogen throughout the entire supply chain to foster unconventional growth; on the other hand, they need to safeguard against the inevitable risk of limited availability. Policy makers therefore need to strike a sensible balance between providing regulatory certainty in order to spur green hydrogen investment, while maintaining a realistic judgment on its long-term prospects as well as fostering available and more efficient alternatives such as direct electrification and energy efficiency. Future research should further develop probabilistic decision frameworks⁵⁹ that help enabling urgent technological deployment, while navigating the uncertain feasibility space and associated risks.

Methods

Approach and key input data

We conduct an uncertainty analysis of the market ramp-up and further expansion of electrolysis capacity, in the EU and globally, using a stochastic adaptation of the logistic technology diffusion model. The model accounts for inevitable uncertainties of two

main parameters: the initial electrolysis capacity in 2023, and the annual growth rate, which we parameterise using up-to-date electrolyser capacity data from built, planned and announced projects as well as from empirical data on the growth of successful technologies from the past. We capture the nonlinear propagation of these uncertainties within the logistic diffusion model by a Monte Carlo simulation approach. We further assume a steadily-increasing electrolysis demand-pull driven by continuous policy support and expanding competitiveness of hydrogen applications (Fig. 2). This approach enables us to derive probability distributions of electrolysis capacity deployment over time, which we then interpret as a probabilistic feasibility space of scaling up green hydrogen supply. By design and by necessity, the results do not represent absolute probabilities, but conditional probabilities that are contingent on the assumed demand-pull from policies and markets.

Our analysis relies on global electrolysis projects from the IEA Hydrogen Projects Database³², complemented by our own market research, which we use to parameterise the initial capacity distribution, depending on the project status as explained below.

In order to parameterise the growth rate distribution, we draw on data of historical analogues and distinguish two cases. In the conventional growth case, we assume that electrolysis grows as fast as wind and solar power have during their period of fastest relative growth from 1995 – 2010 (Fig. 3). In the unconventional growth case, we explore the electrolysis market ramp-up under historical growth rates of a wide set of primarily non-energy technologies that grew even faster than wind and solar power (Fig. 5).

For the demand-pull (from policies, regulation, and markets) that drives the technology diffusion, we parameterise its magnitude in time as well as its anticipation by investors. For the EU, in the short term the magnitude is parameterised to the political 2024 target of 6 GW, while the 2030 target of 100 GW follows from the REPowerEU Plan⁸, which foresees the domestic production of 10 Mt of hydrogen, approximately equivalent to 100 GW electrolysis capacity. The long-term demand-pull is set to 500 GW by 2050 as mentioned in the EU Hydrogen Strategy⁷. Globally, the short-term demand-pull magnitude of 254 GW follows from cumulative project announcements of 154 GW by 2030 plus an additional 10 Mt of hydrogen the EU recently announced it plans to import⁸, equivalent to 100 GW of electrolysis capacity. In the long run, we use scenario data of the IEA NZE scenario, which is 3600 GW globally by 2050⁹. The demand-pull anticipation states by how many years these targets, associated policies, and hydrogen competitiveness are anticipated by potential investors, which thus constitutes a measure of both regulatory certainty and investor foresight. Our default assumption is 5 years, while we conduct sensitivity analyses for 0 years, 10 years, as well as a hypothetical case of full anticipation of the long-term market size (Extended Data Fig. 4, Extended Data Fig. 6).

Data handling

We use the IEA Hydrogen Projects Database, which lists 984 global hydrogen projects, of which 886 are based on electrolysis. The database includes the project's development status, technology characteristics, designated end-use applications, and most importantly size as electrical capacity in MW for electrolysis projects. In addition, to ensure the model's initial capacity in 2023 is accurately parameterised, we review all projects with an announced starting year in 2022 or 2023 and an announced size of at least 50 MW. This applies to 49 projects, which we track and include in the GitHub repository (see below). Electrolysis projects with a "DEMO" development status are allocated to the "Operational" and "Decommissioned" status, depending on whether they are still in operation or not. The IEA Hydrogen Projects Database also contains several entries for confidential projects between 2000-2020. We distribute these projects to all regions in proportion to the share of total capacity from other non-confidential projects within that time window, and equally over time.

For the conventional growth case, we use data of installed wind and solar capacity from the BP Statistical Review of World Energy 2021⁶⁰. Solar capacity is available from 1997 onwards in the EU, and from 1996 globally. Wind capacity is available from

1997 in the EU, and from 1995 globally. We fit exponential models to this data in sliding 7-year intervals until 2010, which we use to parameterise the emergence growth rate distribution. This corresponds to the period in which both technologies grew the fastest (Extended Data Fig. 1). The distribution is robust to the choice of the slice length (Extended Data Fig. 2). The emergence growth rate is related to the steepness parameter in the logistic function (see below) and describes the growth rate that is approximately attained in the emergence phase of the technology diffusion when the asymptote is not yet constraining.

Truncated normal distributions

The stochastic uncertainty analysis rests on a Monte Carlo-based simulation approach to randomly sample from probability distributions that reflect the underlying parametric uncertainty. We use normal distributions with lower truncation for both the initial capacity in 2023 and the emergence growth rate.

For the initial capacity distribution, we define the lower truncation a by the capacity of all projects that are already operational or under construction and due to start production in 2023. Given the truncation interval $[a, \infty]$, we thus need to determine the pre-truncation parameters μ (mean) and σ (standard deviation). This leaves two degrees of freedom, for which we impose two conditions. First, we set the post-truncation expected value to the capacity that is equivalent to realising 30% of feasibility study projects, $C_{0.3FS}$. Given ϕ as the probability density function and Φ as the cumulative density function of the normal distribution, the first condition is related to the expected value and reads:

$$E(X) = \mu + \sigma \frac{\phi\left(\frac{a - \mu}{\sigma}\right)}{1 - \Phi\left(\frac{a - \mu}{\sigma}\right)} = C_{0.3FS} \quad (1)$$

Second, we assign a 15 % probability to the option that only those projects that are already backed by an FID, with capacity C_{FID} , are built. Following the truncated cumulative distribution function, the second condition is:

$$F(C_{FID}) = P(X \leq C_{FID}) = \frac{\Phi\left(\frac{C_{FID} - \sigma}{\mu}\right) - \Phi\left(\frac{a - \sigma}{\mu}\right)}{1 - \Phi\left(\frac{a - \sigma}{\mu}\right)} = 0.15 \quad (2)$$

The two equations (1) and (2) form a system of nonlinear equations that we solve numerically to obtain μ and σ . Jointly with the lower truncation value a , this defines the truncated distribution (Fig. 3a-b).

For the emergence growth rate distribution, we first calculate the mean and standard deviation of the 7-year growth rates of wind and solar power in the EU and globally. Subsequently, we apply a lower truncation of 15 %/yr, which thus constitutes the lower boundary of the electrolysis market ramp-up (Fig. 3c-d).

Adapted logistic technology diffusion model

In order to account for the threefold coordination challenge of concurrently ramping-up green hydrogen supply, demand, and infrastructure, we propose an adaptation of the standard logistic technology diffusion model by including a steadily-increasing demand-pull that replaces the fixed final market volume. This accounts for the observation that the market for green hydrogen is just emerging, which stands in contrast to energy technologies such as wind and solar power that were able to tap into the existing electricity market (also see main text). We deliberately do not model market shares, but instead directly describe the growing market volume because the emerging green hydrogen market is not well-described by a substitution of technology shares.

The standard logistic function for the electrolysis capacity $C(t)$ reads

$$C(t) = \frac{C_{max}}{1 + e^{-k(t-t_0)}} \quad (3)$$

where C_{max} is the asymptote, k is the growth constant, t_0 is the inflection point and e is Euler's number of approximately 2.718. This is the solution of the logistic differential equation

$$\frac{dC}{dt} = kC \left(1 - \frac{C}{C_{max}}\right) \quad (4)$$

under the condition that $C(t_0) = C_{max}/2$. Our model idea rests on an adaptation of this differential equation. We turn C_{max} into a time-dependent demand-pull $C_{max}(t)$ and discretise the differential equation, which yields

$$C_{t+1} = C_t + bC_t \left(1 - \frac{C_t}{C_{t,max}}\right) \quad (5)$$

where t denotes time in yearly units, and $b = e^k - 1$ is the annual growth rate. In the Monte Carlo simulation we independently draw a sample ($N = 10,000$) for both the initial capacity C_{2023} and the annual growth rate b , and subsequently feed both into the diffusion equation (5). In order to improve numerical accuracy, we use a quarterly time resolution in the model with a quarterly growth rate of $b_q = (1 + b)^{1/4} - 1$. Further increasing the temporal resolution did not noticeably affect results.

Comparison with Gompertz model

The default logistic function is a special symmetric case of the generalised logistic function

$$C(t) = \frac{C_{max}}{(1 + \nu e^{-k(t-t_0)})^{1/\nu}} \quad (6)$$

with ν as an additional parameter, where the logistic function follows for $\nu = 1$. Another prominent special case of the generalised logistic function is the so-called Gompertz model, which follows as the limiting case for $\nu \rightarrow 0$ and may be written as

$$C(t) = C_{max} e^{-e^{-k(t-t_0)}} \quad (7)$$

or in differential form as

$$\frac{dC}{dt} = kC \ln\left(\frac{C_{max}}{C}\right) \quad (8)$$

where \ln is the natural logarithm and which discretised translates into

$$C_{t+1} = C_t + bC_t \ln\left(\frac{C_{max}}{C_t}\right) \quad (9)$$

Compared with the default logistic function, the Gompertz function is asymmetric and approaches the asymptote much more gradually. Our adaptation of the logistic model with a steadily-increasing demand-pull results in a similar shape, yet one that can be controlled and parameterised more directly using additional information on policy targets and scenario results. Thus, the Gompertz model already includes an asymmetric damping term, so that we only use it with a constant asymptote, $C_{max} = const$. Calculating the Gompertz model together with a non-constant demand-pull would introduce an undesirable superposition of different damping effects.

In contrast to the logistic model in equation (5), the Gompertz model in equation (9) does not simplify for $C_t \ll C_{t,max}$ so that b cannot be interpreted as the emergence growth rate. Instead, we parameterise the Gompertz model such that the initial 7-year growth from 2023-2030 matches the emergence growth rate (see Extended Data Fig. 3). This is in line with our definition of the emergence growth rate, for which we fitted exponential models in moving 7-year windows.

Emergency deployment

To extend the probabilistic feasibility space of electrolysis capacity to emergency deployment, we use a wide dataset of primarily non-energy technologies to parameterise a distribution of unconventional growth rates. This encompasses technologies on both regional and global level, measured in different units, which we normalise by the respective maximum value. All technologies represent stock variables; apart from nuclear power in France and dry shale gas in the US, which are yearly flow variables. In contrast to the conventional growth case, where we used exponential growth rates of wind and solar power to parameterise the emergence growth rate distribution, for the unconventional growth case we fit logistic models (Equation 3), because many technologies have already passed through the entire S-curve (Fig. 5a). After converting the growth

constant k to the annual growth rate b , via $b = e^k - 1$, we re-parameterise the distribution of emergence growth rates (Fig. 5b), draw another sample ($N = 10,000$) and run the Monte Carlo simulation again to obtain the probabilistic feasibility space of Fig. 5c-d.

Final energy shares

We translate electrolysis capacity into corresponding shares of final energy demand that can be supplied under this capacity. This requires assumptions on the electrolysis efficiency and further processing steps, its full-load hours, and final energy demand.

We assume an overall efficiency of 60%, which results from a 60-81% efficiency of electrolyser systems⁶¹ and additional losses due to further processing of some hydrogen into e-fuels¹ as well as losses incurred during transportation, storage and conversion³. Please note that we report shares of hydrogen on the level of final energy, not useful energy. This excludes the efficiency of the end-use application (e.g. a fuel cell), which would further reduce the overall efficiency. Final energy is easier to measure and hence regularly reported by energy system models and frequently taken up by policy makers.

Additionally, we assume that electrolysis runs at 5,000 full-load hours, equivalent to a capacity factor of 57%. Such full-load hours could be realised for example by hybrid solar-wind power plants in several world regions⁶². Furthermore, this assumption is in harmony with the range of 3,000-6,000 full-load hours regarded as cost-minimising using grid electricity⁶¹. In reality, higher full-load hours would reduce the demand-pull for electrolysis capacity as the same hydrogen volume could be produced by fewer electrolysers. While this could slow down the growth of electrolysers, it would not impact the final energy share of hydrogen. On the other hand, higher full-load hours would reduce costs and therefore increase the competitiveness of green hydrogen, spurring investment and growth.

Final energy demand over time is obtained from scenarios that reach climate neutrality by 2050. For the EU, due to the lack of published official modelling results beyond 2030, we use scenarios results of the INNOPATHS project, a recent EU-specific model intercomparison study⁶³. Specifically, we calculate the median of a total of nine scenarios, which originate from three different models (ETM-UCL, PRIMES, REMIND-EU) under three different transformation narratives (New Players 1.5, Incumbents 1.5, Efficiency 1.5). As the results are only available for the EU28, not EU27, and all British Isles (the United Kingdom and the Republic of Ireland) are aggregated into one region (UKI), we approximate the EU27 final energy demand by subtracting the UKI values from the EU28 values. This leads to a slight underestimation of the EU27 value because only the United Kingdom has left the EU. However, as Ireland's final energy demand only accounts for around 1% of that of the EU27, the error is negligible compared to the modelling uncertainty. Global final energy demand is given by the IEA NZE scenario⁹ (variable "total final consumption"), and linearly interpolated if necessary (for 2025, 2035, 2045 in Extended Data Fig. 7).

Comparison with other energy modelling scenarios

In Extended Data Fig. 8 we also provide a comparison of our technology diffusion model results with integrated assessment model scenarios as well as single data points of policy targets, project announcements and further studies. If hydrogen volumes instead of electrolysis capacities are reported, we calculate the corresponding electrolysis capacity using an efficiency of 70% (assuming no additional losses due to transport and and further processing) and 5,000 full load hours.

For the EU we include climate mitigation scenarios from the recently published IPCC AR6 Scenario Explorer and Database, version 1.0 (categories C1, C2, and C3, equivalent to limiting warming to 2°C with a probability of >67%)⁶⁴, approximating the EU with the "Europe" region from the R10 regions dataset, and from the INNOPATHS project (scenarios New Players 1.5, Incumbents 1.5, Efficiency 1.5)⁶³, again approximating EU27 values by subtracting UKI from EU28 (see above). Data from the IPCC SR1.5 is not available for Europe. As an additional point of comparison, we include 2030 and 2050 data points from a

roadmap of the industry association Hydrogen Europe⁶⁵, using the “ambitious” scenario under the assumption that all hydrogen is produced via electrolysis.

Globally, we include climate mitigation scenarios from the IPCC SR1.5 Scenario Explorer, version 2.0 (categories Below 1.5C, 1.5C low overshoot, 1.5C high overshoot, and Lower 2C) and the IPCC AR6, version 1.0 (categories C1, C2, and C3, equivalent to limiting warming to 2°C with a probability of >67%)^{64,66}. In addition, we show the IEA net zero emission (NZE) scenario⁹, the IRENA 1.5°C scenario¹⁰, as well as the “green only” scenario of the Hydrogen Council⁶⁷, a global hydrogen industry association.

Limitations

We focus on the upscaling of electrolysis capacity. However, there are other elements in the supply chain of green hydrogen that could also constitute critical bottlenecks. Of particular concern is the upscaling of technologies to capture atmospheric carbon⁶⁸, especially direct air capture²⁹, for the synthesis of climate-neutral e-fuels, which was however out of scope for this article.

The capacity data of wind and solar power does not include very early upscaling prior to 1995. To parameterise the growth rate distribution, we are therefore limited to the interval 1995-2010, after which growth starts to slow down again. The power of prediction could possibly be improved by including a longer dataset. However, we view 1995-2010 as a valid interval in order to explore the feasibility space of green hydrogen under the assumption that the growth rates observed for wind and solar power in this 15-year time period can be sustained at least as long for electrolysis.

The calculation of final energy shares in the EU leaves out imports from other world regions, which could become substantial in the longer term. An analysis of hydrogen trade was out of scope of this article and final energy shares must be interpreted accordingly.

All stated probability distributions are contingent on the demand-pull, which assumes continuous policy support, in particular in the next decade, and an expanding competitiveness of hydrogen due to cost reductions as well as direct and indirect carbon pricing. While we regard this as a necessary assumption because green hydrogen is still at the very beginning of the market diffusion, future research could examine appropriate policy instruments that are capable of realising this demand. This limitation is related to the observation that limited competitiveness of green hydrogen could also reduce the demand-pull, which was however out of scope of this analysis. Another inevitable caveat of our approach is that we need to provide an exogenous long-term demand-pull as an input parameter, thereby enforcing and simultaneously constraining the market ramp-up. Further energy system research is required to improve the estimates of the long-term demand for electrolysis capacity.

Finally, we deliberately do not include an analysis of fossil hydrogen, which can be available earlier than green hydrogen as steam reforming (SMR) of natural gas is an established technology (grey hydrogen). Combining SMR with carbon capture gives “blue” hydrogen with reduced emissions. Fossil hydrogen could play at least a bridging role, which would enable an early ramp up of hydrogen infrastructure and end-use transformation towards hydrogen. However, there are concerns about the life-cycle emissions of blue hydrogen¹¹ and new fossil lock-ins^{69,70}, which could in turn slow down the expansion of lower-emission green hydrogen. In addition, blue and grey hydrogen face competitiveness challenges aggravated by high current natural gas prices¹², which are anticipated to persist at least for a couple of years in the EU, such that grey and blue hydrogen would also require policy support. Further research is required to analyse the balance between taking transitional steps and fostering the mid- to long-term availability of green hydrogen.

Data Availability

All data is publicly available. We use data from the IEA Hydrogen Projects Database³² for electrolysis project capacity, complemented by our own market research and provided in the GitHub repository. Data on wind and solar power capacity is

taken from the BP Statistical Review of World Energy 2021⁶⁰. Data sources for the unconventional growth case are listed in the GitHub repository and include, among others, refs^{76–80}. Final energy scenario data is taken from the IEA NZE⁹ on the global level, and from the INNOPATHS project⁶³ for the EU. Scenario data from the IPCC SR1.5 and IPCC AR6 is available from the respective scenario explorers^{64,66}.

Code Availability

The R model code, including all input data apart from the IPCC scenarios (for Extended Data Fig. 8), is available on GitHub:

<https://github.com/aodenweller/green-h2-upscaling/>

Pre-run simulation results to reproduce all figures are available on Zenodo: <https://doi.org/10.5281/zenodo.6567669>

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Author Contributions Statement

FU and GL suggested the research question. AO and FU jointly conceived and designed the study in consultation with GFN and GL. AO implemented the model and created the visualisations. AO and FU interpreted the results. AO wrote the manuscript with contributions from GFN, MJ and GL. AO and MJ verified and updated relevant electrolysis project announcements. AO collected data for the unconventional growth case.

Competing Interests Statement

The authors declare no competing interests.

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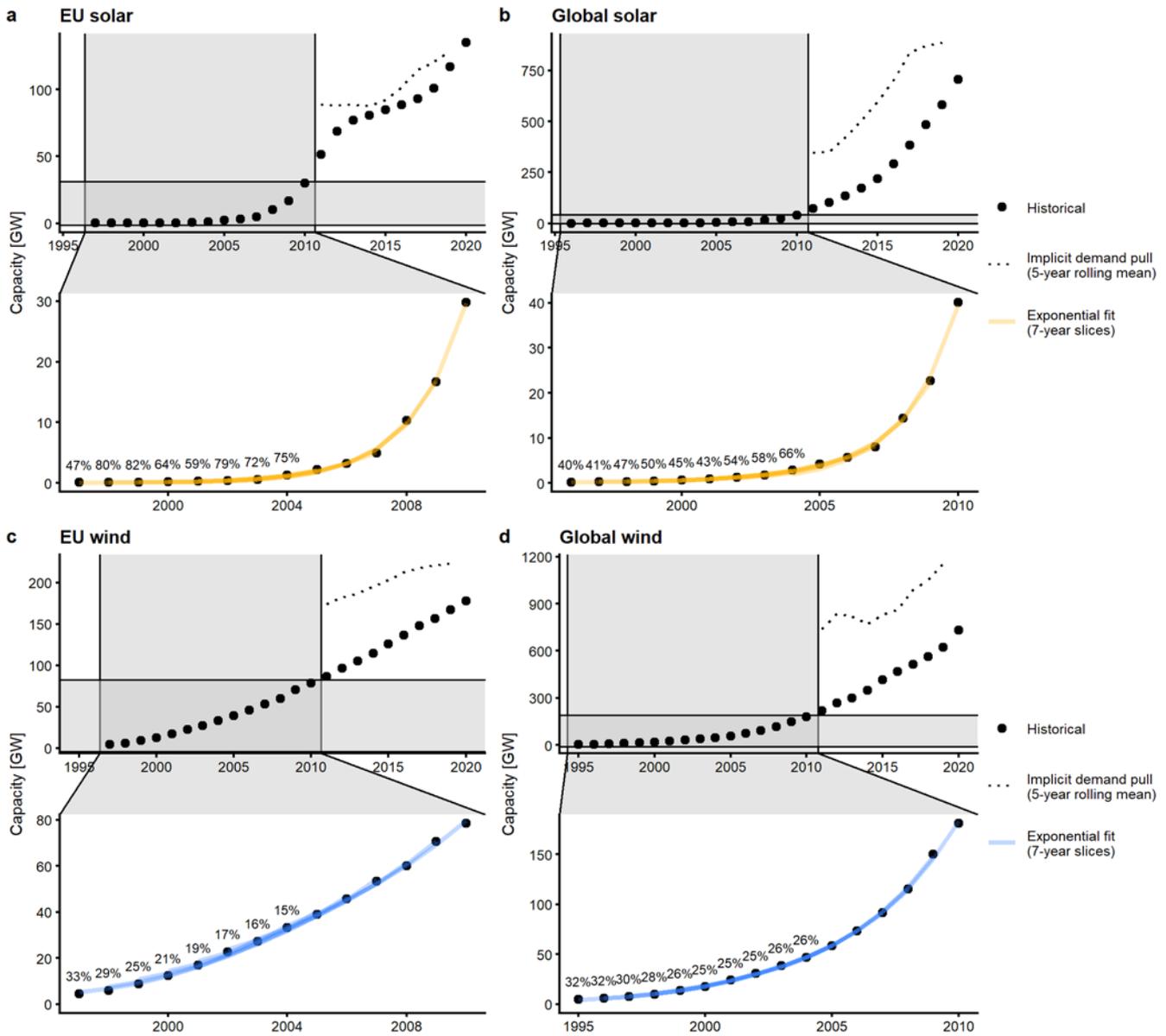
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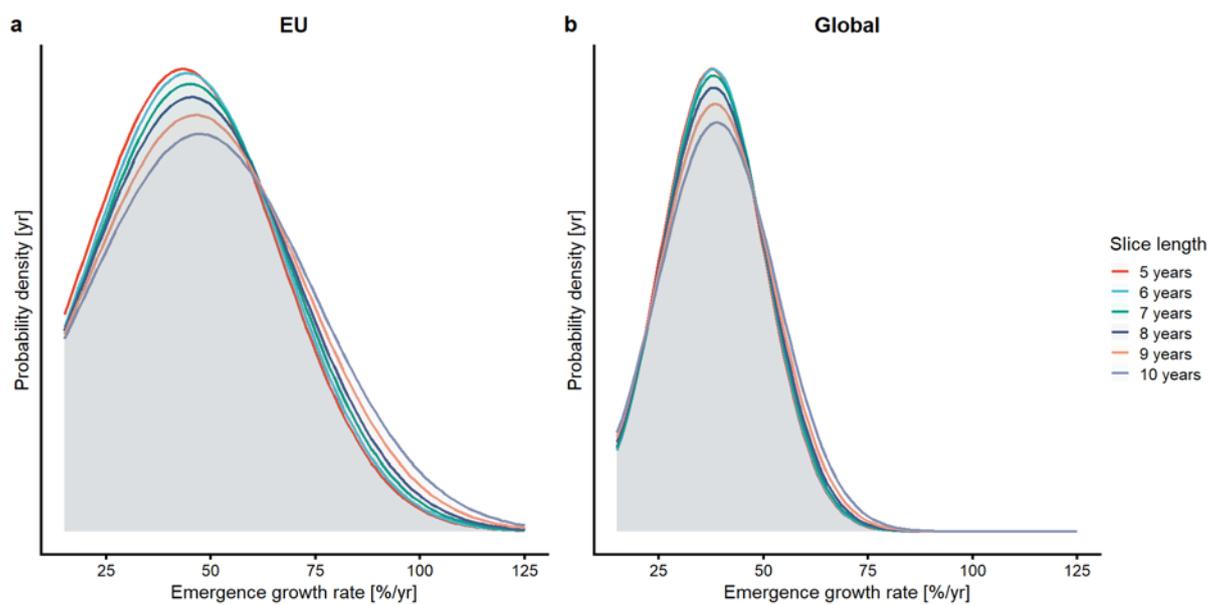
Extended data figures and tables

Extended Data Table 1: List of aspects when comparing potential electrolysis growth to historical wind and solar growth. There are drivers and challenges for higher as well as for lower hydrogen growth rates compared to wind and solar power, such that we carefully conclude that wind and solar PV are a valid initial proxy to derive rough estimates of green hydrogen ramp-up and availability.

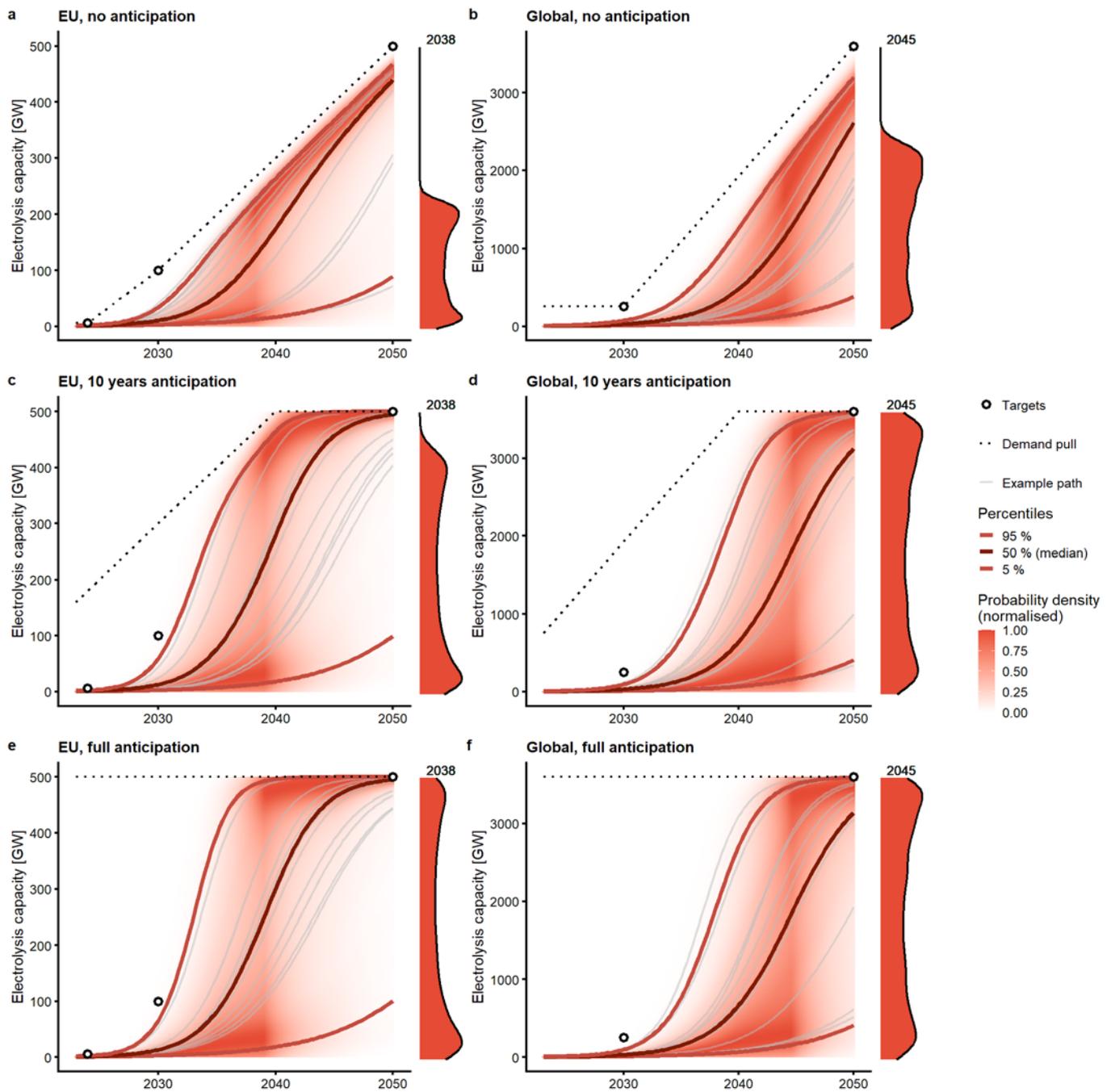
Could electrolysis grow as fast or even faster than wind and solar power during their "boom phase" (1995-2010)?	
Pro	Contra
<p>Urgency to act</p> <p>There is an increasing sense of urgency to ramp-up green hydrogen production volumes, both for climate protection and, especially in the EU, energy security reasons. For example, with the REPowerEU Plan⁸, the EU recently increased its 2030 green hydrogen target by a factor of 2.5. Together with additional policies such as increasing carbon prices, specific subsidies (e.g. CCfDs) and regulations (e.g. e-fuel quotas in aviation) could surpass the effects of the historical support for renewable energies like wind and solar power.</p>	<p>Coordination challenges</p> <p>Hydrogen is a new energy carrier, not an energy source. Hence, the demand side needs to be ramped-up simultaneously with the supply side and new infrastructure. This requires a high degree of coordination and is the main argument behind describing the market ramp-up by an increasing demand pull. The demand for green hydrogen is only just emerging and investors cannot tap into an already existing market. In contrast, wind and solar power produced an economic good, electricity, with sufficient demand and already-existing infrastructure.</p>
<p>Big investors</p> <p>The willingness of big institutional investors and companies to invest into hydrogen could currently be higher compared to the early years of wind and solar power. One reason for this could be company interests to prevent asset stranding of fossil fuel infrastructure, which can partially be repurposed for hydrogen and e-fuels.</p>	<p>International coordination</p> <p>Densely populated countries with limited renewable potentials are planning to import substantial shares of their expected hydrogen demand from countries with better availability of renewable resources. This requires international coordination, most of which is assumed to be on a bilateral basis in the beginning. However, experience shows that large international projects typically have long lead times. Agreeing on a definition of green hydrogen and monitoring compliance poses additional challenges. In addition, exporting countries also require renewable resources for their own decarbonisation.</p>
<p>Societal acceptance</p> <p>In the future, electricity-based energy carriers like hydrogen and e-fuels may be transported over long distances, thereby tapping into large renewable potentials of sparsely populated areas. This potentially alleviates the problem of substantial local opposition to renewable energy developments such as wind farms and power grid expansion, particularly in densely populated areas.</p>	<p>Competition from many sides</p> <p>Green hydrogen faces competition both on the supply side and the demand side of the energy system. On the supply side it competes i) with other applications for renewable electricity, and ii) with other hydrogen production methods such as grey and blue hydrogen. While the opportunity window of fossil hydrogen might be shrinking due to the ongoing energy crisis, the fundamental competition remains. On the demand side, green hydrogen competes not only with fossil fuels, but also with alternative climate mitigation options such as direct electrification, which is more efficient and thus often cheaper, constraining market opportunities for hydrogen. However, wind and solar power also faced intense competition with fossil-based electricity from the very beginning of their industry. In both cases early niche markets provided an important way to avoid direct competition and enabled growth in early years.</p>
<p>Modularity of electrolyzers</p> <p>The empirical record shows that small scale modular (granular) technologies are adopted more quickly and learn faster than large scale technologies⁵⁰. Wind, and even more so solar, are modular technologies. Electrolysers are also modular and could thus grow at fast rates.</p>	<p>Chunky infrastructure</p> <p>Pipelines that are required to transport large quantities of hydrogen at low costs, are large scale, material-intensive and labor intensive. Thus, they are not amenable to rapid learning and adoption. While some natural gas pipelines could be repurposed for hydrogen, this will also take time.</p>



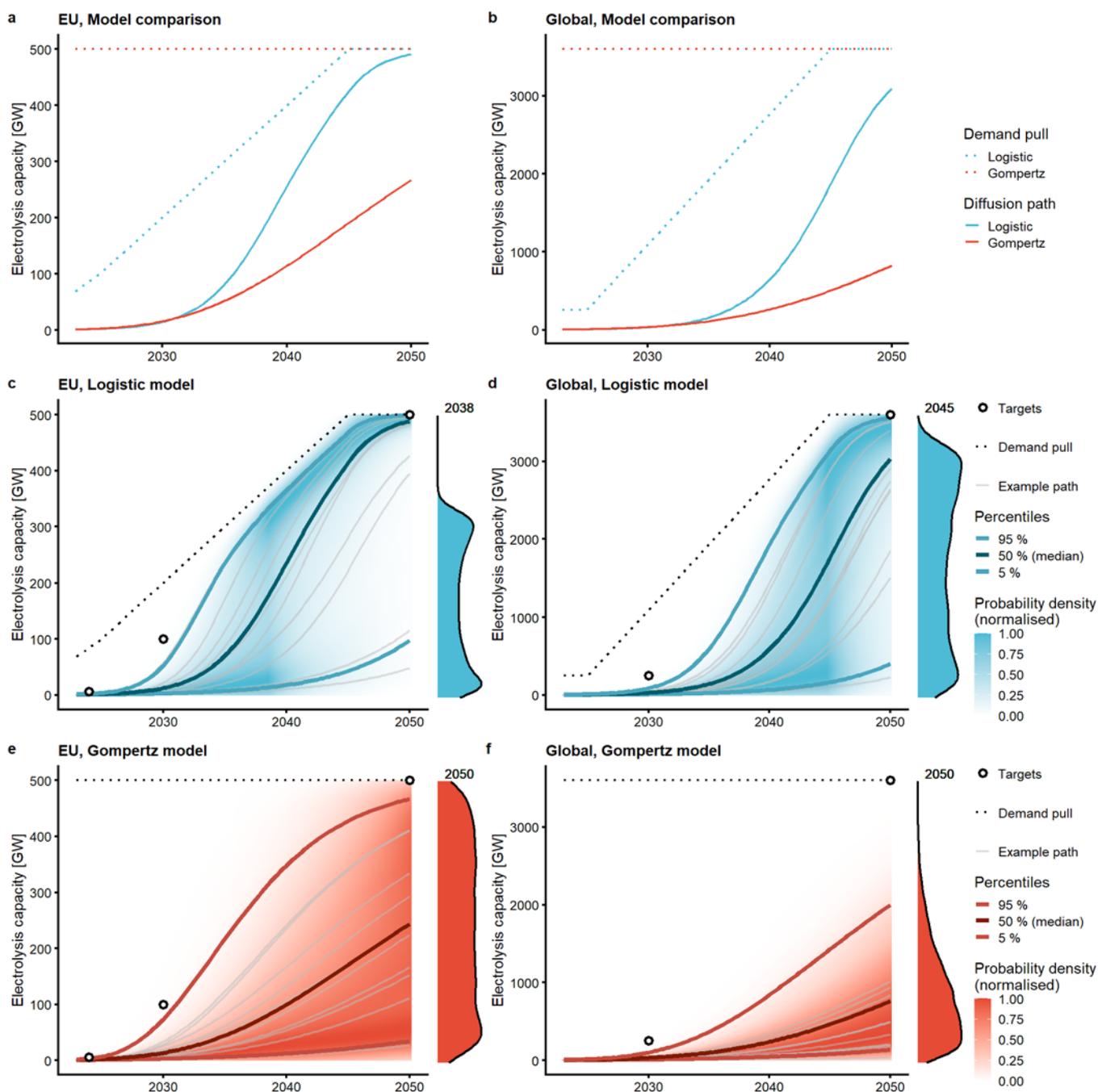
Extended Data Figure 1: Historical capacities and exponential growth rates of solar and wind power. **a**, Solar power in the EU, **b**, Solar power globally, **c**, Wind power in the EU, **d**, Wind power globally. The zoom panel displays the period of fastest growth until 2010, from which we estimate exponential growth rates in 7-year slices. The percentage values indicate the corresponding growth rate for the subsequent 7-year period. These growth rates define the emergence growth rate distributions in Figure 3c-d. To illustrate the idea of our adapted logistic technology diffusion model, we also calculate the implicit demand pull from 2011-2020 (dotted line, 5-year rolling mean) that replicates the historically observed capacities based on the average emergence growth rate taken from the 1995-2010 interval (see Equation 5). The approximately linear shape of the implicit demand pull demonstrates that this is a well-founded assumption, which we therefore also apply to the analysis of electrolysis capacity upscaling.



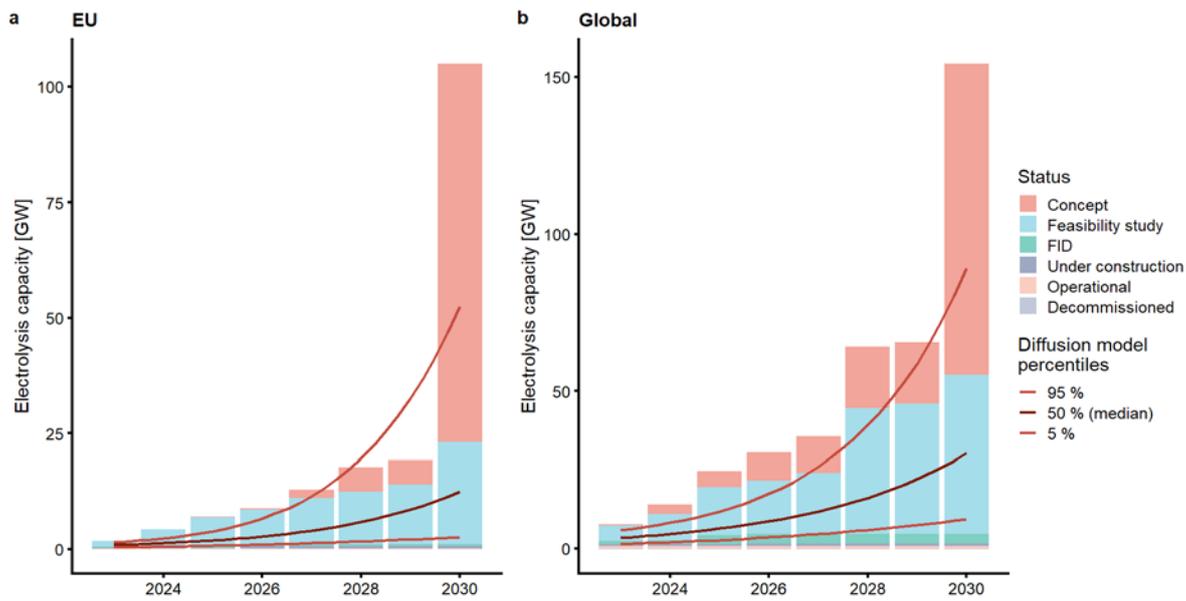
Extended Data Figure 2: Emergence growth rate distributions in the conventional growth case under varying slice lengths of the underlying solar and wind power fit. *a*, in the EU, *b*, globally. The distributions are relatively robust to the length of the time slice that underlies the estimate of the exponential growth rate. We therefore use the intermediate 7-year slice length, which also corresponds to the 2023-2030 time window that is of particular concern for 2030 policy targets as the model starts in 2023.



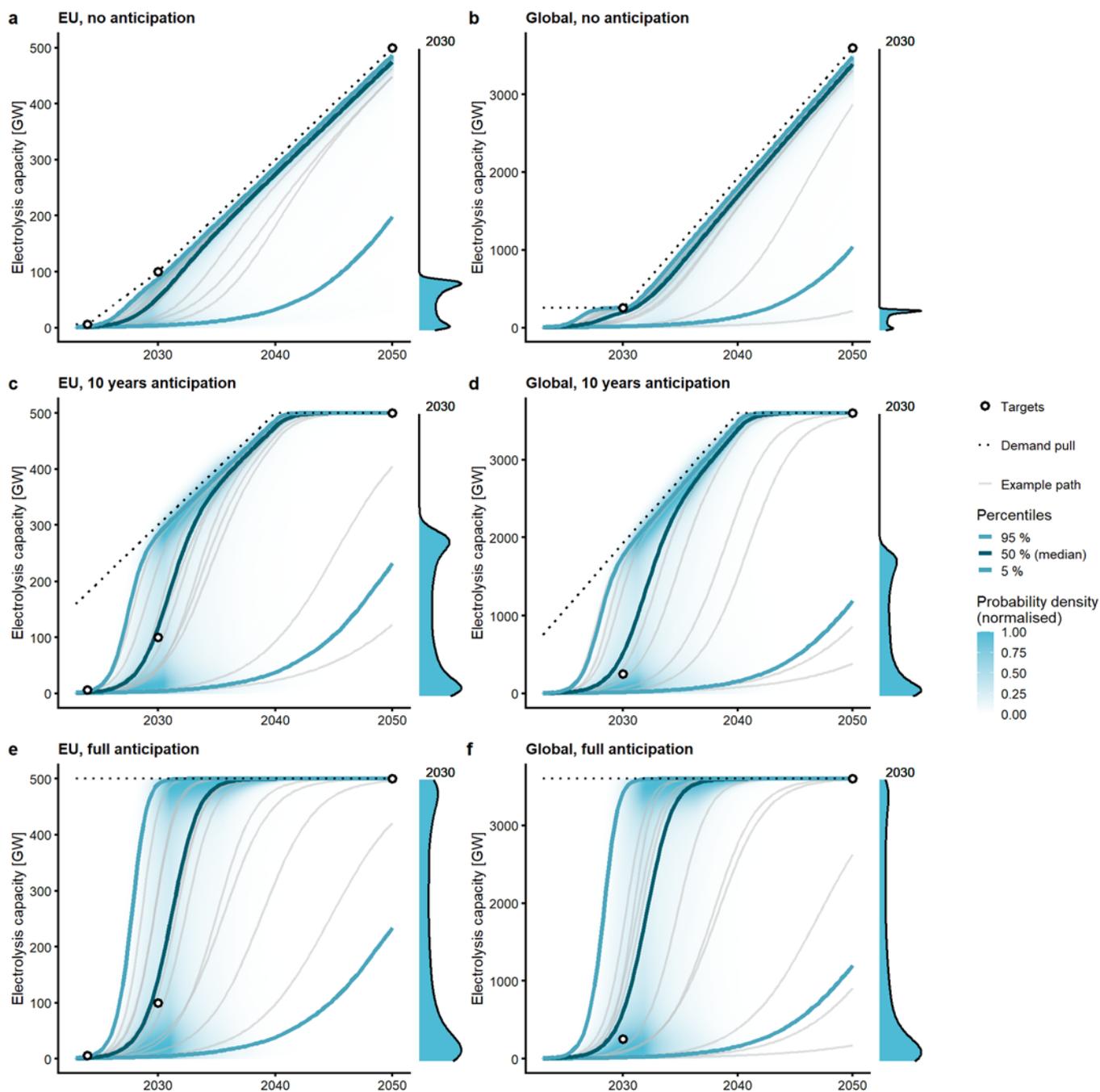
Extended Data Figure 3: Sensitivity analysis of probabilistic feasibility spaces for the conventional growth case under varying demand pull anticipation levels. a,c,e, EU with no anticipation, 10 years anticipation, and a hypothetical case of full anticipation of the long-term market size, respectively. b,d,f, globally. Both short-term scarcity and long-term uncertainty are robust to the level of demand pull anticipation. However, in the long-term capacity deployment is higher under full anticipation of the demand pull (i.e. the default logistic function), especially in the EU, which has higher growth rates than globally.



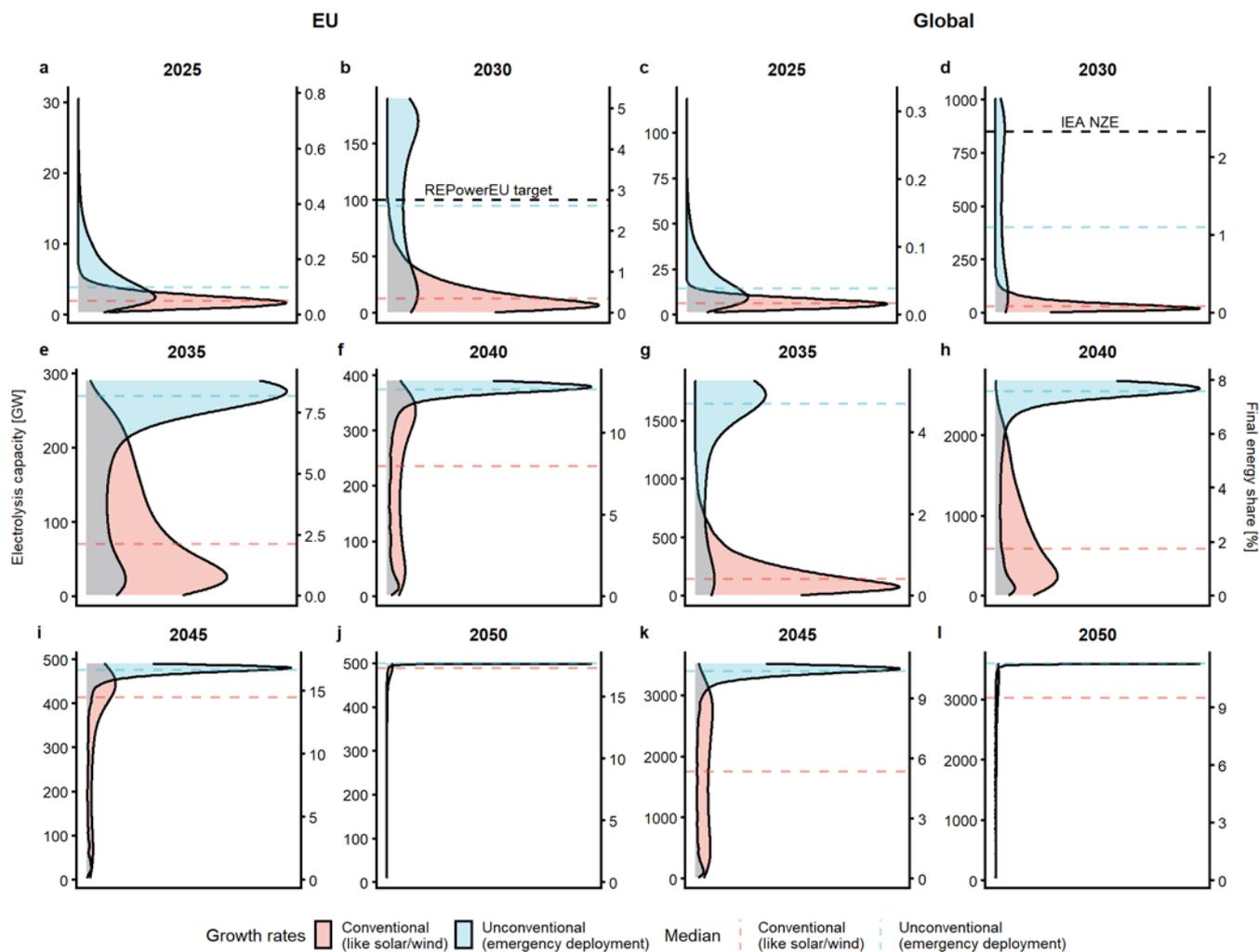
Extended Data Figure 4: Comparison between the adapted logistic model and the Gompertz model. **a,b**, Comparison of the logistic model with increasing demand pull and the Gompertz model with full demand pull for the mean parameter specification of the initial capacity in 2023 and the emergence growth rate, for the EU (a) and globally (b). The Gompertz model is parameterised so that the growth within the initial 7-year period from 2023-2030 corresponds to the emergence growth rate, which is in line with the parameterisation of the conventional growth case (see Methods). **c,d**, Probabilistic feasibility space of the adapted logistic model for the EU (c) and globally (d). These panels are a copy of Figure 4 and included here only for comparison. **e,f**, Probabilistic feasibility space of the Gompertz model, leading to a much earlier damping of the market ramp-up than in c-d. This implies a substantially reduced long-term availability and illustrates the broad methodological difficulties of long-term projections. Nevertheless, our two main conclusions are robust as the Gompertz model also reveals short-term scarcity and long-term uncertainty of green hydrogen supply. While both models lead to an asymmetric adoption curve that approaches the asymptote more gradually than the default logistic function, our adapted logistic technology diffusion model allows for a more precise control of the increasing market volume that can be informed by additional information about policy targets and scenario results.



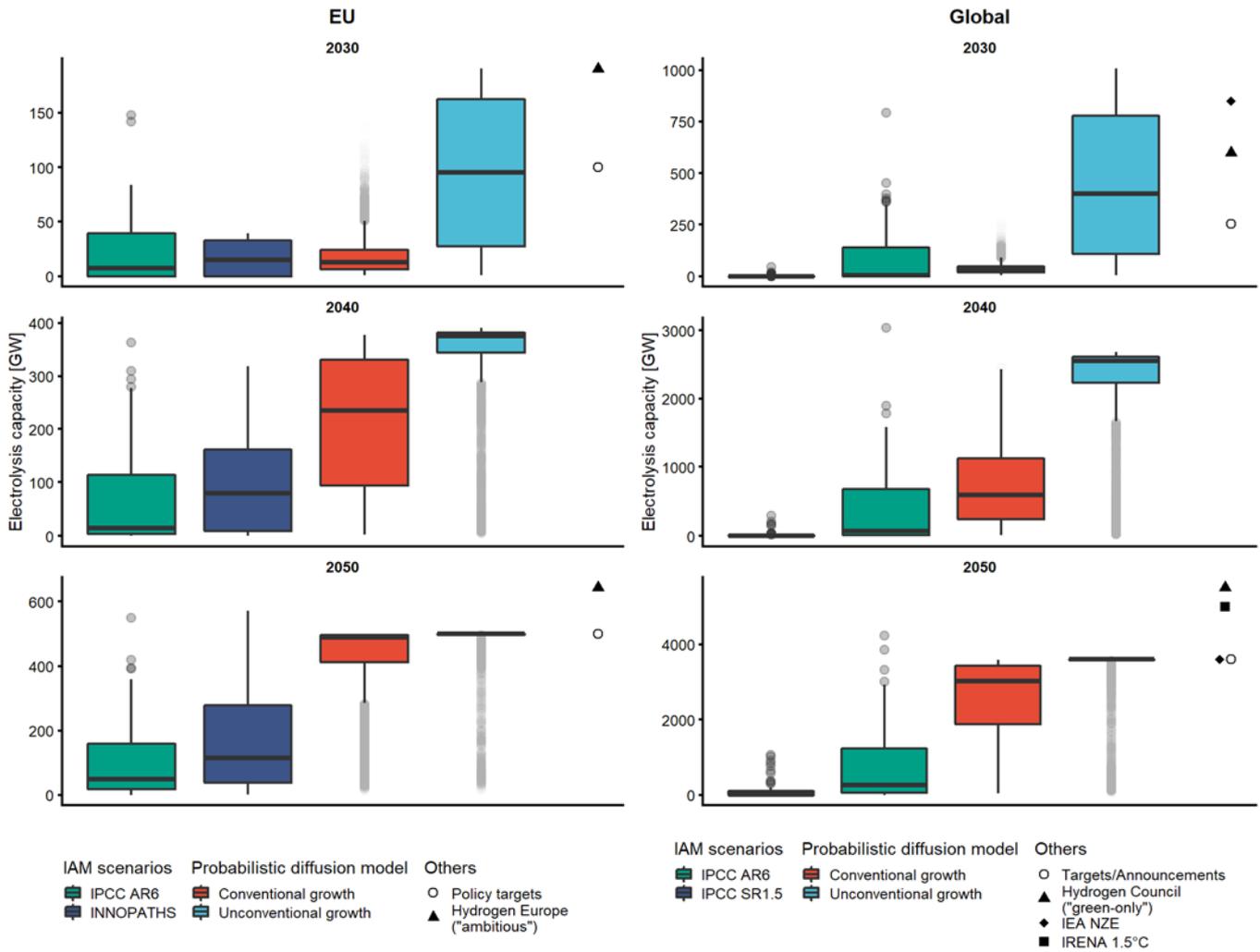
Extended Data Figure 5: Comparison of conventional growth percentiles with project announcements until 2030 for validation. a, in the EU. b, globally. Both panels show the conventional growth case (like wind and solar) with five years demand pull anticipation, similar to Figure 4. In both regions, cumulative project announcements surpass the median of the diffusion model results at all times. This is in line with the observation that the vast majority of announcements are fundamentally uncertain as they are not backed by a final investment decision yet. The comparison between the results of our probabilistic technology diffusion model and the cumulative project announcements demonstrates the plausibility of our modelling approach.



Extended Data Figure 6: Sensitivity analysis of probabilistic feasibility spaces for the unconventional growth case under varying demand pull anticipation levels. a,c,e, EU with no anticipation, 10 years anticipation, and a hypothetical case of full anticipation of the long-term market size, respectively. b,d,f, globally. In both regions, short-term scarcity can be overcome to an even greater extent under full anticipation of the demand pull. Notably, under unconventional growth rates and full demand pull anticipation, short-term uncertainty results as indicated by the marginal distributions in 2030. As the probabilistic feasibility space is primarily determined by the demand pull level after 2030 in both regions, under full demand pull anticipation the saturation market volume is reached already around 2035 with a high probability in both regions.



Extended Data Figure 7: Probability distribution of electrolysis capacity in 5-year time steps between 2025-2050. a,b,e,f,i,j, in the EU, c,d,g,h,k,l, globally. This diagram is an extension of Figure 6c-d with additional years (2025, 2035, 2045, 2050). The left axis shows electrolysis capacity in GW, the right axis the corresponding final energy share that can be supplied with this capacity. In 2025, green hydrogen supply is minimal in terms of the final energy share in both regions and largely irrespective of the growth rate. In 2035, unconventional growth rates enable a final energy share that is almost 4 times larger than under conventional growth rates in the EU, and more than 10 times larger globally. In 2045, and even more so in 2050, the demand pull acts as the main constraint such that the differences between conventional and unconventional growth rates become smaller again.



Extended Data Figure 8: Comparison of probabilistic diffusion model with IAM climate mitigation scenarios, targets, and further studies. In both the EU and globally, IAM scenarios tend to use (far) less green hydrogen than envisaged by policy targets or other studies such as by Hydrogen Europe, the Hydrogen Council, the IEA, or IRENA. This is especially true for the global IPCC SR1.5 scenarios, which contain hardly any hydrogen produced via electrolysis. Most of all, this comparison demonstrates that the awareness of hydrogen's critical importance for climate change mitigation and potential for technological learning is just emerging and already acknowledged by the IEA and IRENA. However, this awareness has not yet penetrated into the IAM community, even though electrolysis capacity deployment levels in climate mitigation scenarios have increased from the IPCC SR1.5 to the IPCC AR6 globally, as well as from the IPCC AR6 to the more recent EU-focused INNOPATHS scenarios. We believe that our analysis can help to parameterise plausible expansion pathways of green hydrogen for climate change mitigation scenarios in IAMs. Note that in the long run the technology diffusion pathways are asymptotically constrained by the exogenously assumed final market volume (see Table 1). The long-run capacity levels achieved in reality may exceed this level.