Supplementary Information:
Growth projections of hydrogen electrolysis worldwide with evidence from historical analogs and hindcasting

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Supplementary Methods

S1 – Selection of analogs

We derive a list of historical analogs (Table 1) from the HATCH 2.0[1] dataset for each target technology (solar PV, onshore wind power, hydrogen electrolysis) by systematically repeating three steps for each target technology and analog group ('type of adopter', 'complexity' and 'material use'). Before the steps, we filter by the category 'technology lifetime' and set it to include all analogs with lifetimes ranging from several years to decades. All our three target technologies have expected lifetimes at the scale of multiple years to decades[1–3].

1. We only keep analogs where time series exist in the dataset for at least 50 countries that also have solar PV for higher sample size for our analysis. Similarly, we filter for at least 40 countries for onshore wind power, and 50 for hydrogen electrolysis.
2. We use the three categories 'type of adopter', 'complexity' and 'material use' to identify three groups of analogs. All analogs within one group must fall into the same categorical bin of a group's category than the target technology (S2 – Technology characteristics).
3. To avoid double-counting of technologies, we remove analogs from the filtered analog groups that either comprise more than one technology (i.e., electricity, renewable power, solid biofuels) or are a different unit of an analog that is already in the group (i.e., Hepatitis B first dose vaccine). Further, we remove solar PV from the analogs for solar PV, and onshore wind power from the analogs for onshore wind power to avoid information leakage.

S2 – Technology characteristics

In line with Greene et al.[1], all analogs and target technologies fall into one of three categorical bins per technology characteristic. The type of adopter is either individuals, firms, or both individuals and firms, and has been defined through expert judgement. The complexity based on Malhotra and Schmidt[4] is either simple, i.e., less than 1,000 components, design-intensive, i.e., between 1,000 and 1,000,000 components, or complex, i.e., over a million components. The material use is either low, i.e., less than 0.1 kg per USD, medium, i.e., between 0.1 and 1 kg per USD, or high, i.e., over 1 kg per USD. Based on these criteria, the target technologies fall into the following bins of technology characteristics that we use in step 3 of our selection process (S1 – Selection of analogs, Table 1):

Solar PV (as in HATCH 2.0[1]):

- Type of adopter: Both firms and individuals.
- Complexity: Simple.
- Material use: Medium.

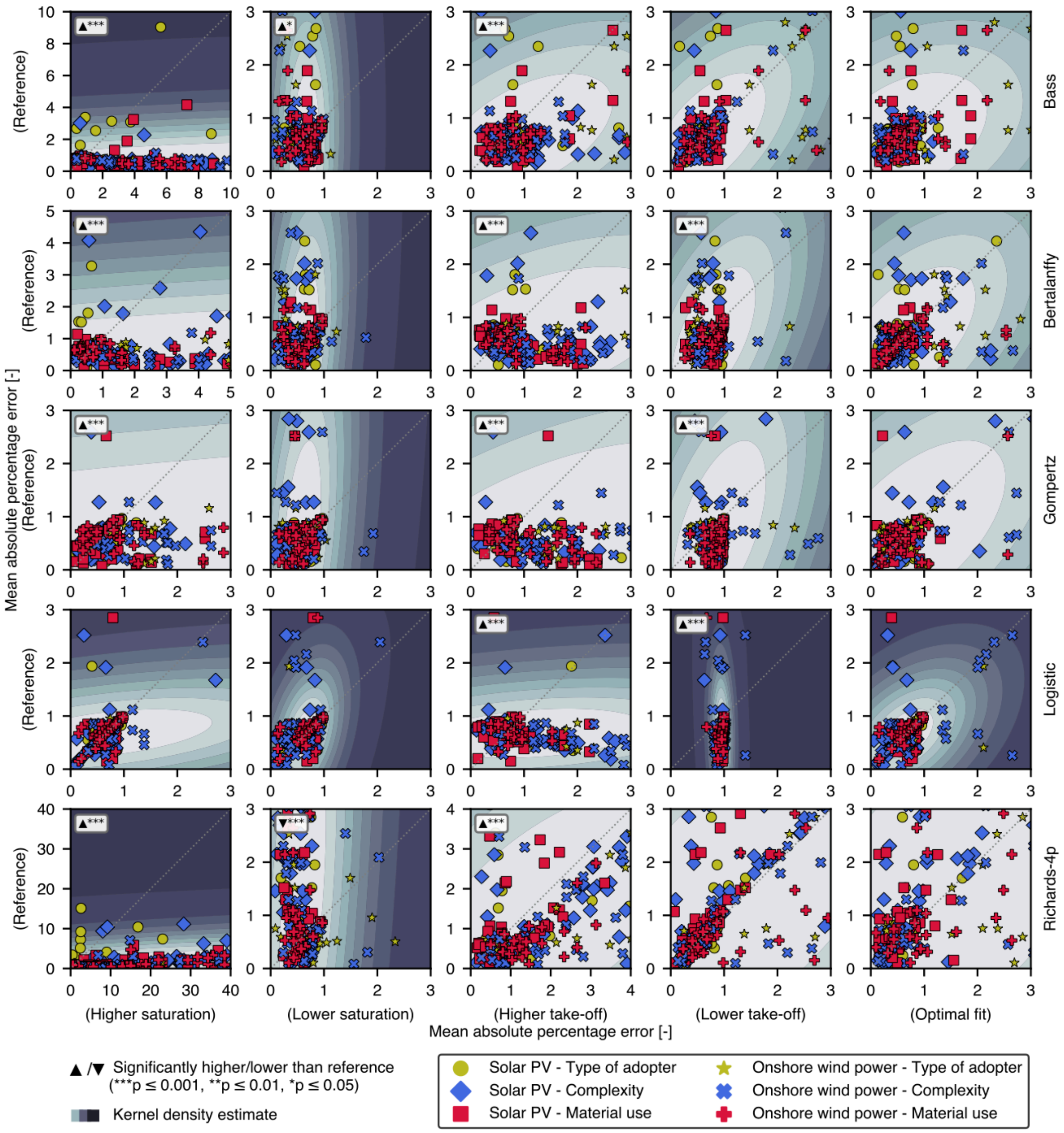
Onshore wind power (as in HATCH 2.0[1]):

- Type of adopter: Firms.
- Complexity: Design-intensive.
- Material use: Medium.

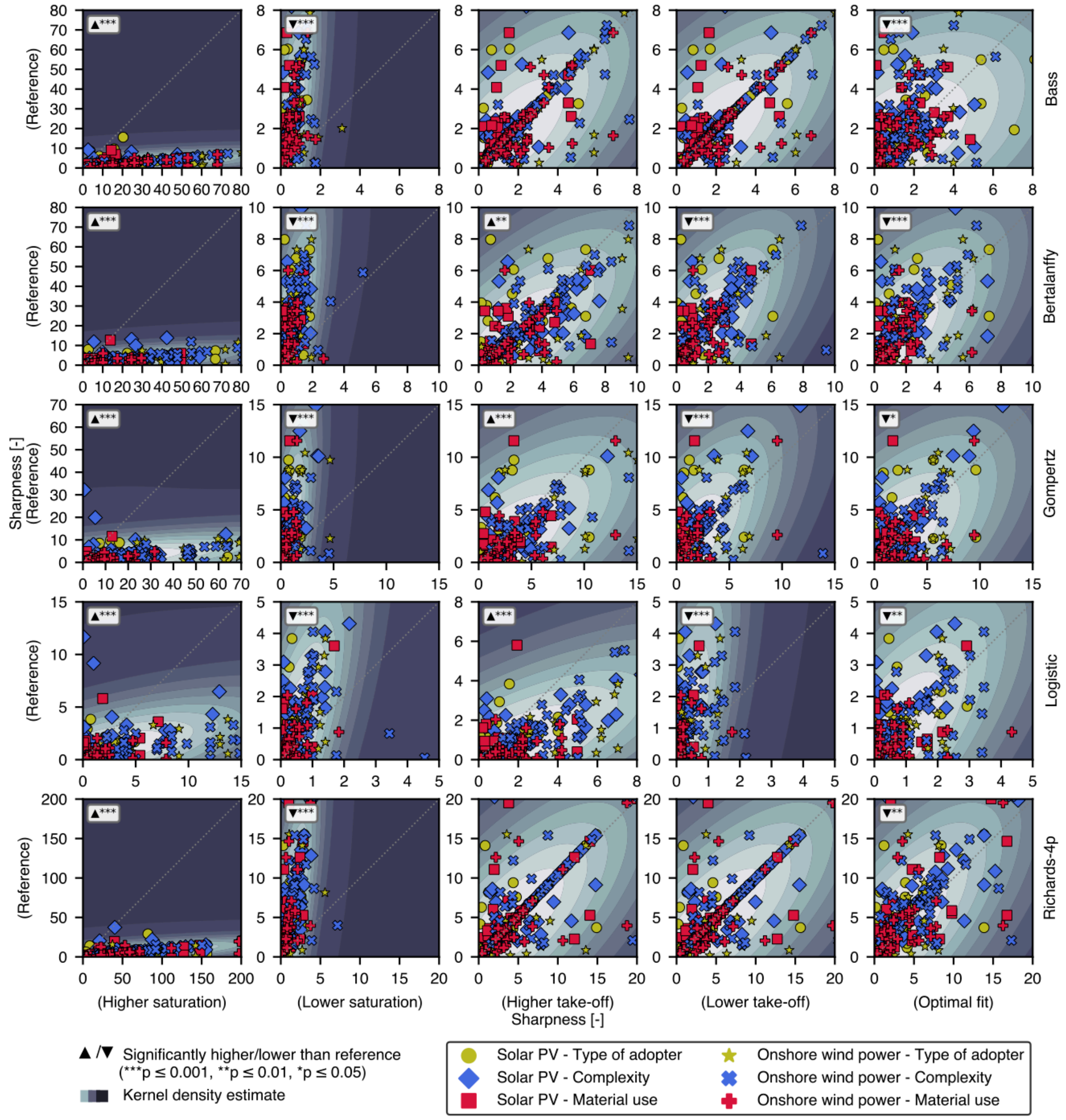
Hydrogen electrolysis:

- Type of adopter: Firms.
- Complexity: Complex. This categorization agrees with similar technologies like biogas and solid biofuels in HATCH 2.0[1].
- Material use: High. This categorization is based on the material intensity of 1.047 kg/USD that we calculate from 7.12 USD/MMBTU[5,6] and conversion[7] with HHV.

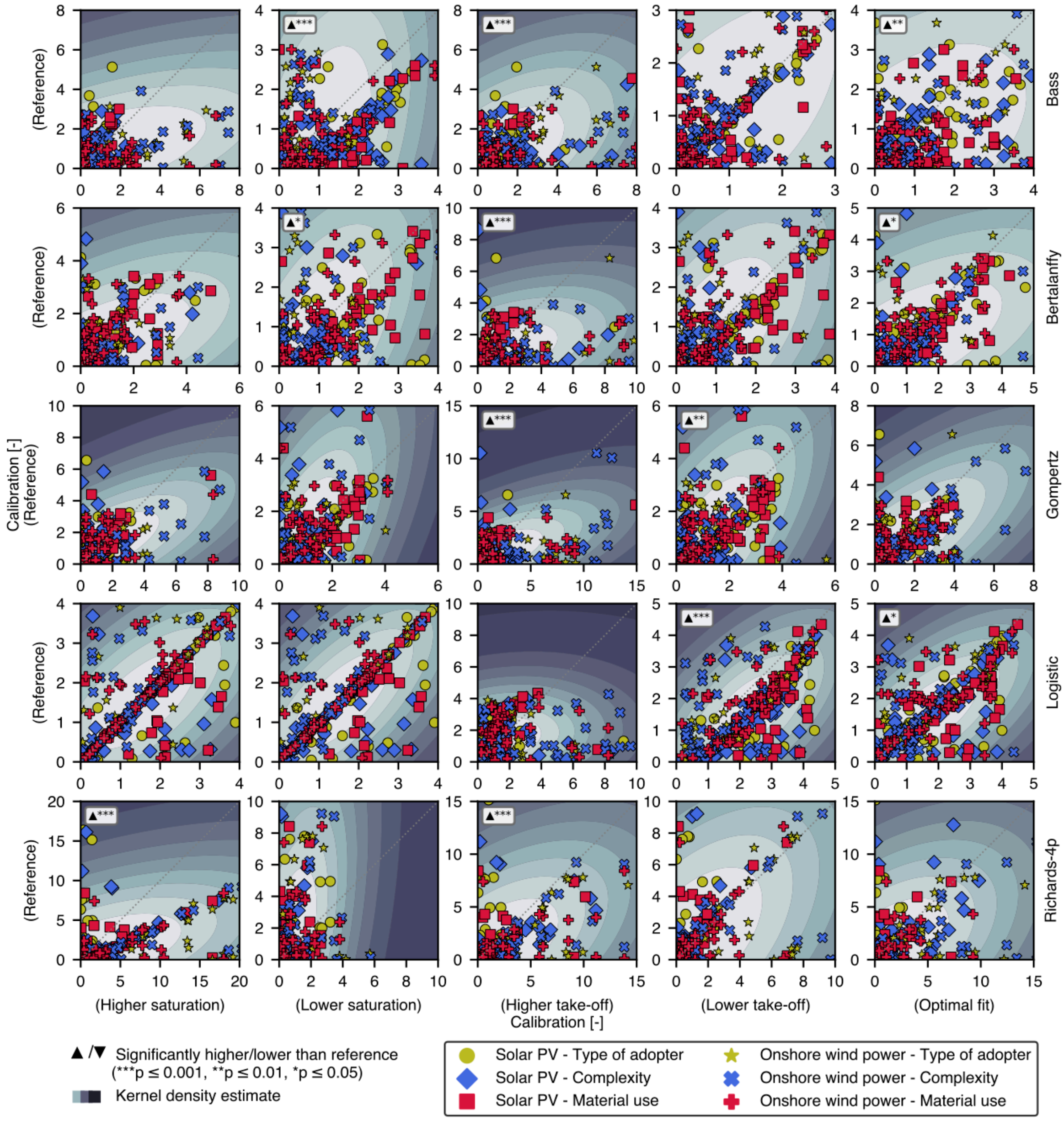
Supplementary Figures



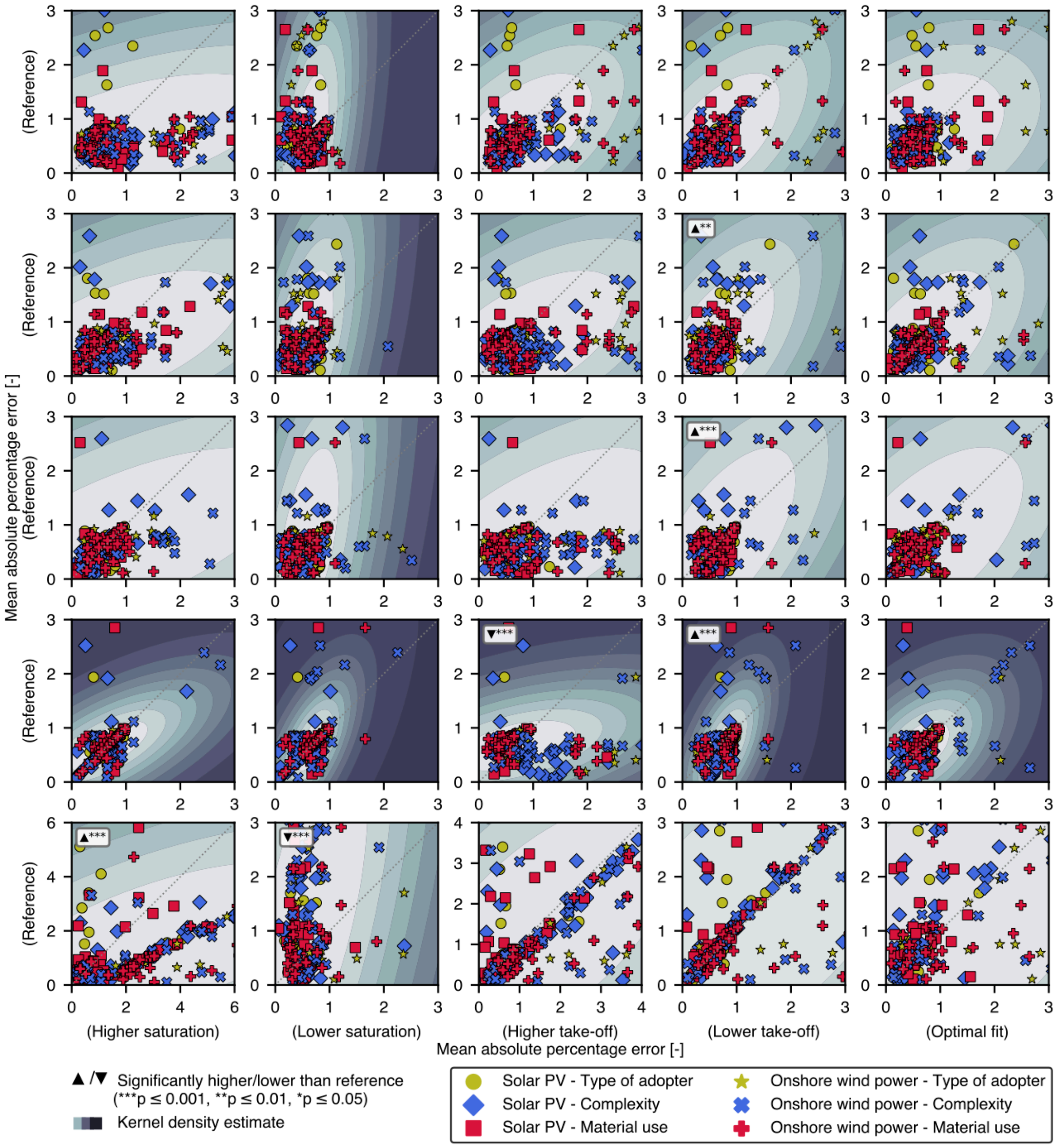
Supplementary Figure 1. Comparison of mean absolute percentage errors (in relative numbers) from out-of-sample testing in hindcasting across all investigated model settings and the reference. Each marker represents one country while colors and shapes of markers distinguish three different groups of analogs and the projected technologies solar PV and onshore wind power, respectively. The higher the mean error, the further away is the median of the projections from the historically observed capacities between the take-off year of a technology in a country and 2023. Each plot compares the reference setting of diffusion attributes (i.e., medium capacity at saturation, medium capacity at take-off, and near-optimal curve fit) per growth model (Bass, Bertalanffy, Gompertz, Logistic, Richards-4p) with changes in diffusion attributes: higher/lower capacities at saturation (i.e., take-off at 0.1%/5% of saturation), higher/lower capacities at take-off (i.e., take-off multiplied by 0.1/5), and optimal curve fits per growth model (Methods). A marker on the diagonal means there is no difference between the reference setting and the change. Arrows indicate with different significance levels from Mann-Whitney U tests if changing diffusion attributes compared to the reference setting leads to higher/lower median mean absolute percentage errors. Color shading shows the density of markers in the plots. For visibility, markers with the highest 25% in mean absolute percentage error lay outside the plots. Figure 2 compares calibration penalties and Supplementary Figure 2 compares sharpness penalties.



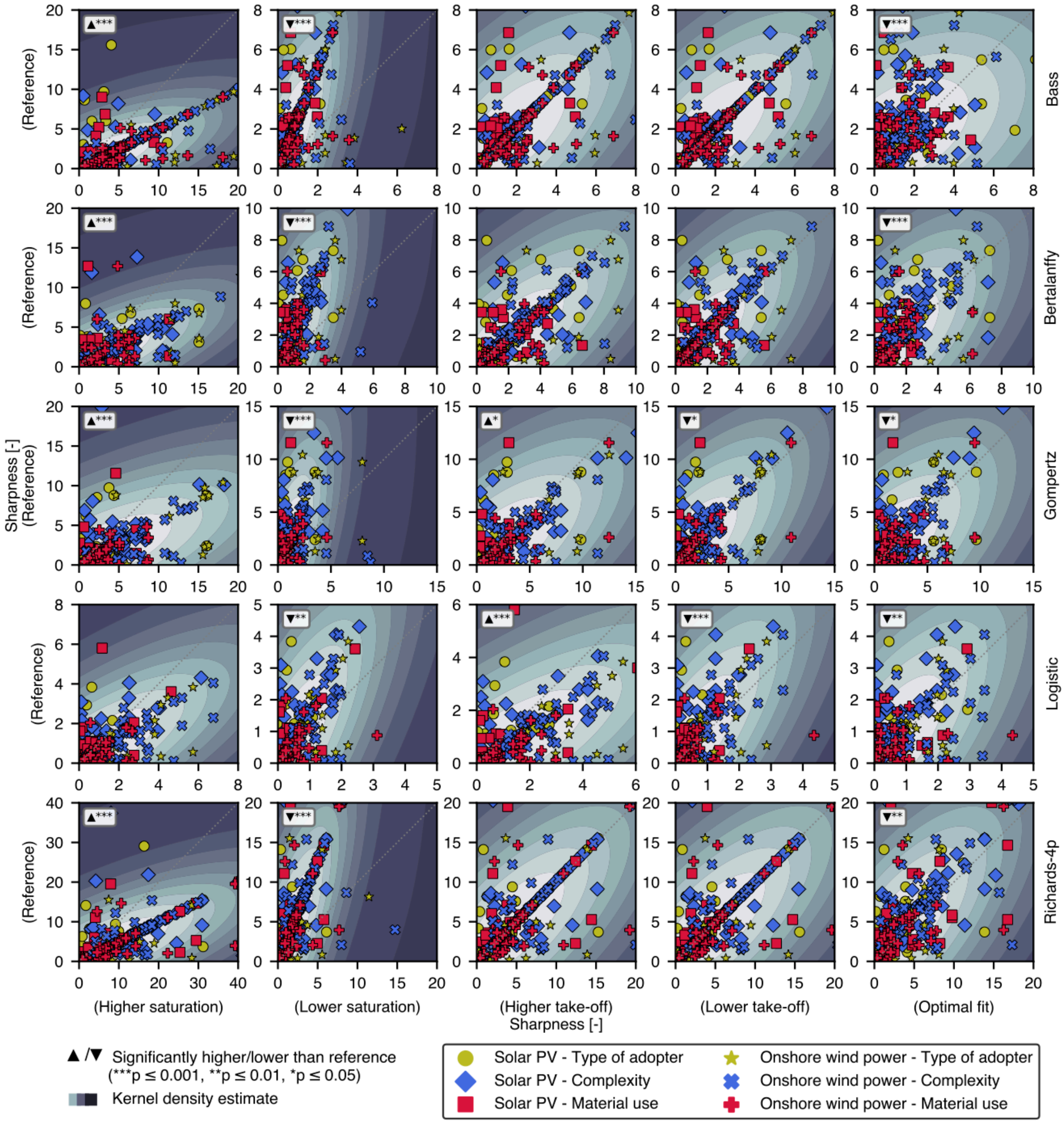
Supplementary Figure 2. Comparison of sharpness penalties from out-of-sample testing in hindcasting across all investigated model settings and the reference. Each marker represents one country while colors and shapes of markers distinguish three different groups of analogs and the projected technologies solar PV and onshore wind power, respectively. The higher the sharpness penalty[65,66], the wider are the probabilistic density intervals of the projections between the take-off year of a technology in a country and 2023. Each plot compares the reference setting of diffusion attributes (i.e., medium capacity at saturation, medium capacity at take-off, and near-optimal curve fit) per growth model (Bass, Bertalanffy, Gompertz, Logistic, Richards-4p) with changes in diffusion attributes: higher/lower capacities at saturation (i.e., take-off at 0.1%/5% of saturation), higher/lower capacities at take-off (i.e., take-off multiplied by 0.1/5), and optimal curve fits per growth model (Methods). A marker on the diagonal means there is no difference between the reference setting and the change. Arrows indicate with different significance levels from Mann-Whitney U tests if changing diffusion attributes compared to the reference setting leads to higher/lower median sharpness penalties. Color shading shows the density of markers in the plots. For visibility, markers with the highest 5% in sharpness lay outside the plots. Figure 2 compares calibration penalties and Supplementary Figure 1 compares mean absolute percentage errors.



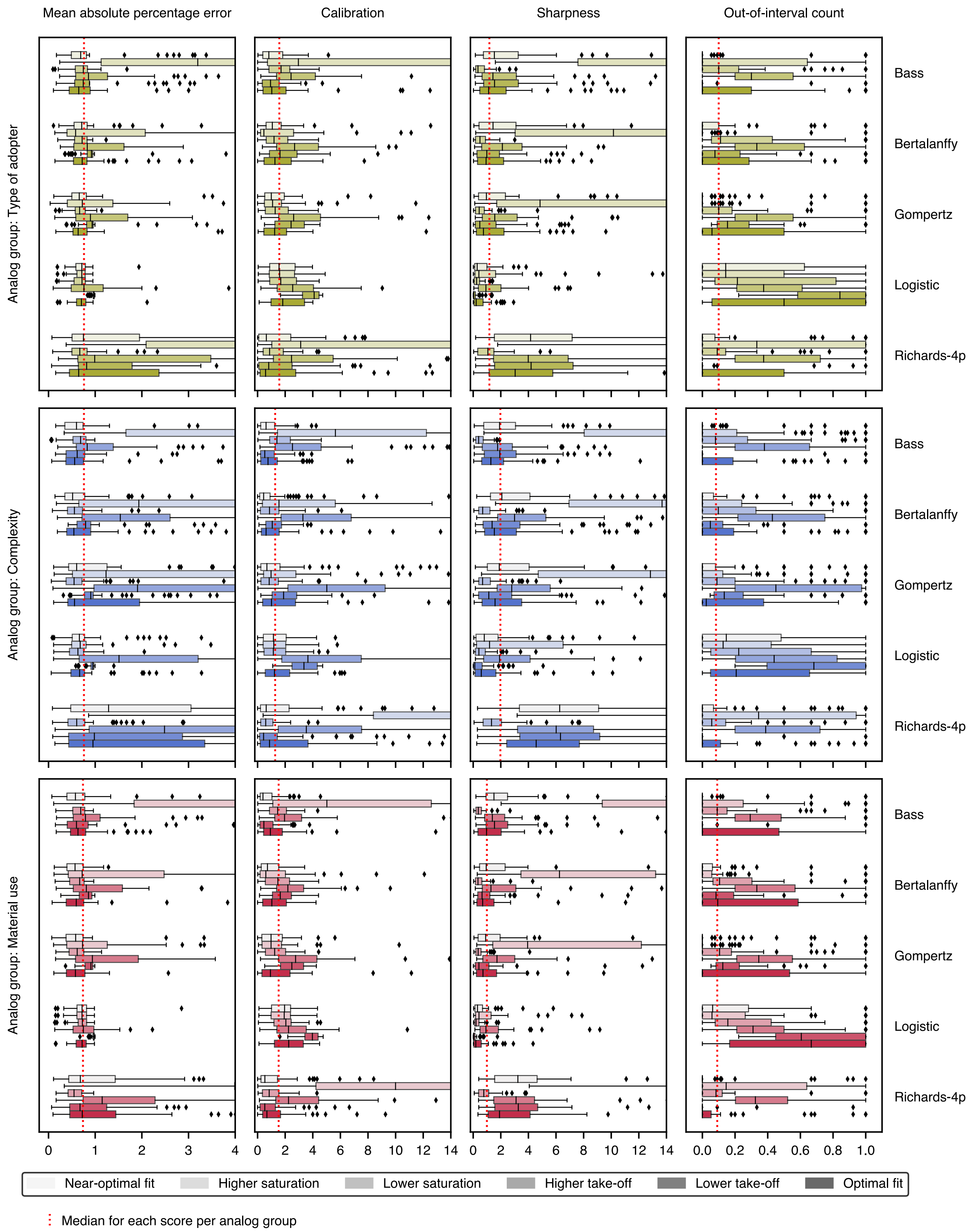
Supplementary Figure 3. Comparison of calibration penalties from out-of-sample testing in hindcasting across all investigated model settings with intermediate capacity changes and the reference. Each marker represents one country while colors and shapes of markers distinguish three different groups of analogs and the projected technologies solar PV and onshore wind power, respectively. The higher the calibration penalty[65,66], the lower the out-of-sample accuracy of the projections between the take-off year of a technology in a country and 2023. Each plot compares the reference setting of diffusion attributes (i.e., medium capacity at saturation, medium capacity at take-off, and near-optimal curve fit) per growth model (Bass, Bertalanffy, Gompertz, Logistic, Richards-4p) with changes in diffusion attributes: higher/lower capacities at saturation (i.e., take-off at 0.5%/2.5% of saturation), higher/lower capacities at take-off (i.e., take-off multiplied by 0.5/2.5), and optimal curve fits per growth model (Methods). A marker on the diagonal means there is no difference between the reference setting and the change. Arrows indicate with different significance levels from Mann-Whitney U tests if changing diffusion attributes compared to the reference setting leads to higher/lower median calibration penalties. Color shading shows the density of markers in the plots. For visibility, markers with the highest 5% in calibration lay outside the plots. Supplementary Figures 4-5 compare mean absolute percentage errors and sharpness.



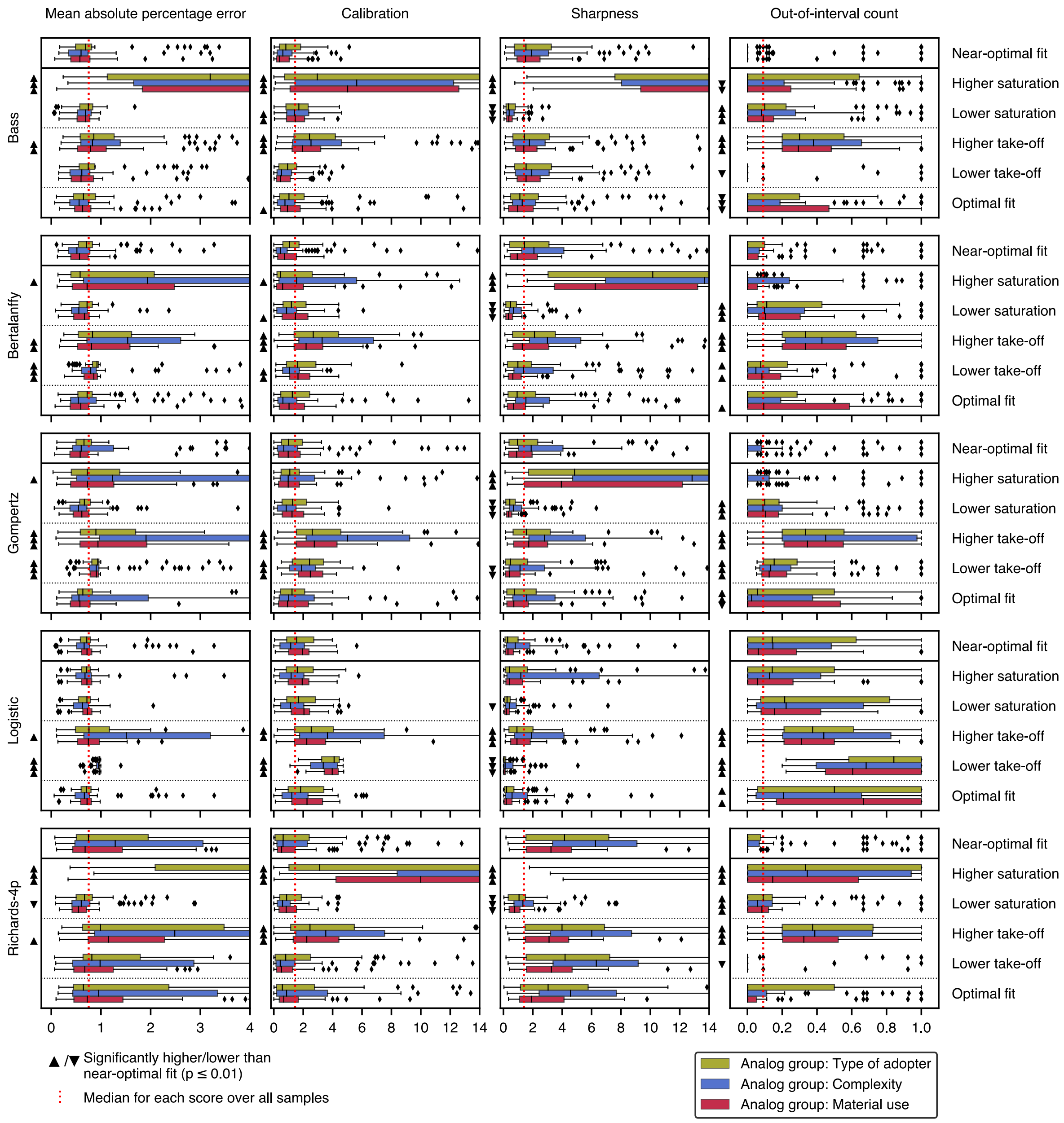
Supplementary Figure 4. Comparison of mean absolute percentage errors (in relative numbers) from out-of-sample testing in hindcasting across all investigated model settings with intermediate capacity changes and the reference. Each marker represents one country while colors and shapes of markers distinguish three different groups of analogs and the projected technologies solar PV and onshore wind power, respectively. The higher the mean error, the further away is the median of the projections from the historically observed capacities between the take-off year of a technology in a country and 2023. Each plot compares the reference setting of diffusion attributes (i.e., medium capacity at saturation, medium capacity at take-off, and near-optimal curve fit) per growth model (Bass, Bertalanffy, Gompertz, Logistic, Richards-4p) with changes in diffusion attributes: higher/lower capacities at saturation (i.e., take-off at 0.5%/2.5% of saturation), higher/lower capacities at take-off (i.e., take-off multiplied by 0.5/2.5), and optimal curve fits per growth model (Methods). A marker on the diagonal means there is no difference between the reference setting and the change. Arrows indicate with different significance levels from Mann-Whitney U tests if changing diffusion attributes compared to the reference setting leads to higher/lower median mean absolute percentage errors. Color shading shows the density of markers in the plots. For visibility, markers with the highest 25% in mean absolute percentage error lay outside the plots. Supplementary Figure 3 compares calibration penalties and Supplementary Figure 5 compares sharpness penalties.



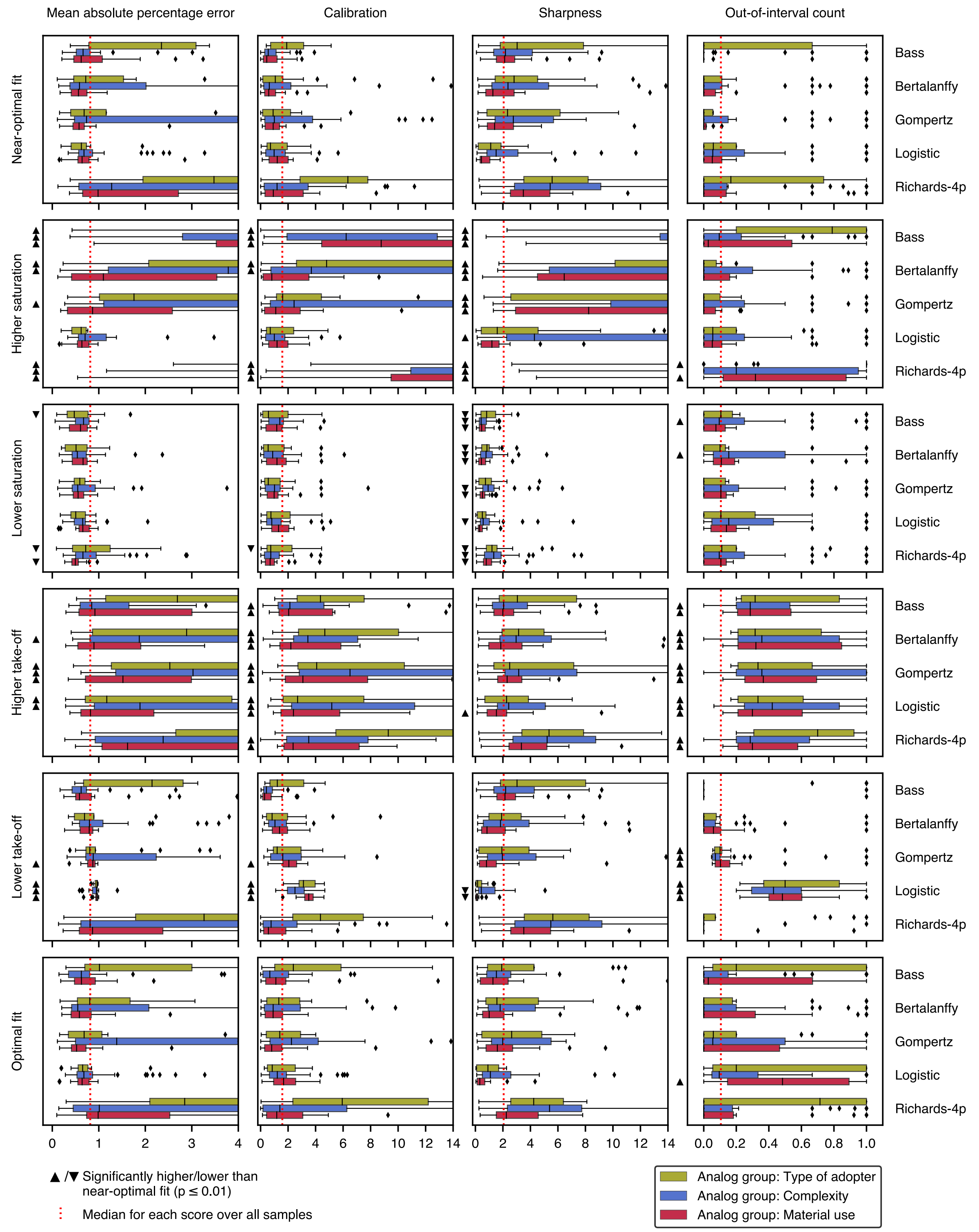
Supplementary Figure 5. Comparison of sharpness penalties from out-of-sample testing in hindcasting across all investigated model settings with intermediate capacity changes and the reference. Each marker represents one country while colors and shapes of markers distinguish three different groups of analogs and the projected technologies solar PV and onshore wind power, respectively. The higher the sharpness penalty[65,66], the wider are the probabilistic density intervals of the projections between the take-off year of a technology in a country and 2023. Each plot compares the reference setting of diffusion attributes (i.e., medium capacity at saturation, medium capacity at take-off, and near-optimal curve fit) per growth model (Bass, Bertalanffy, Gompertz, Logistic, Richards-4p) with changes in diffusion attributes: higher/lower capacities at saturation (i.e., take-off at 0.5%/2.5% of saturation), higher/lower capacities at take-off (i.e., take-off multiplied by 0.5/2.5), and optimal curve fits per growth model (Methods). A marker on the diagonal means there is no difference between the reference setting and the change. Arrows indicate with different significance levels from Mann-Whitney U tests if changing diffusion attributes compared to the reference setting leads to higher/lower median sharpness penalties. Color shading shows the density of markers in the plots. For visibility, markers with the highest 5% in sharpness lay outside the plots. Supplementary Figure 3 compares calibration penalties and Supplementary Figure 4 compares mean absolute percentage errors.



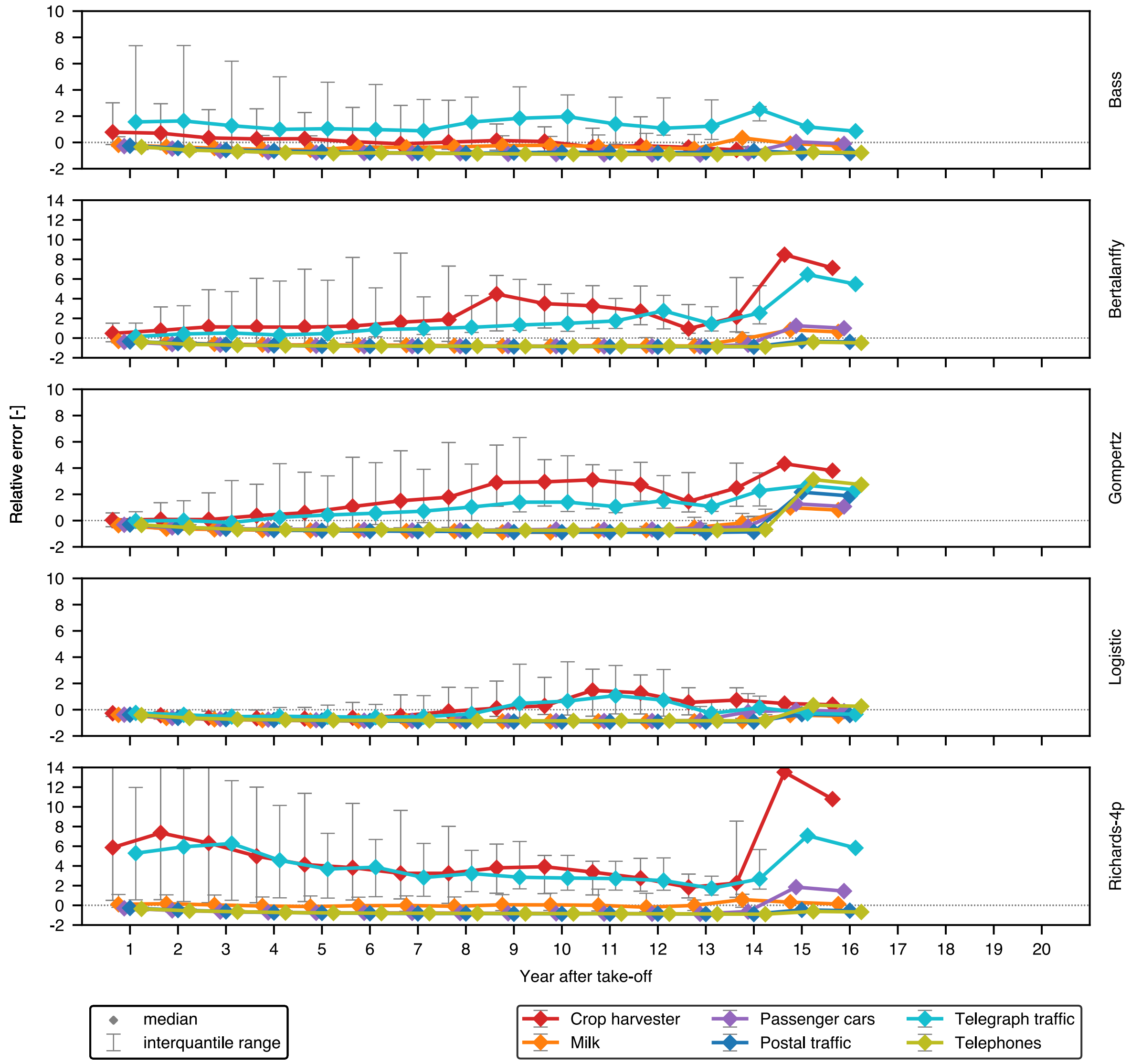
Supplementary Figure 6. Out-of-sample performance scores of projections across all countries of both solar PV and onshore wind power across, grouped by analog group, growth model, and diffusion attributes where near-optimal fit describes the reference. The higher the mean absolute percentage error, calibration penalty, sharpness penalty, or out-of-interval count, the lower the mean out-of-sample performance of the projections between the take-off year of a technology in a country and 2023. The box plots indicate median, first and third quartiles, and whiskers. Single dots are outliers and can lay outside the plot windows. Related to Figure 2.



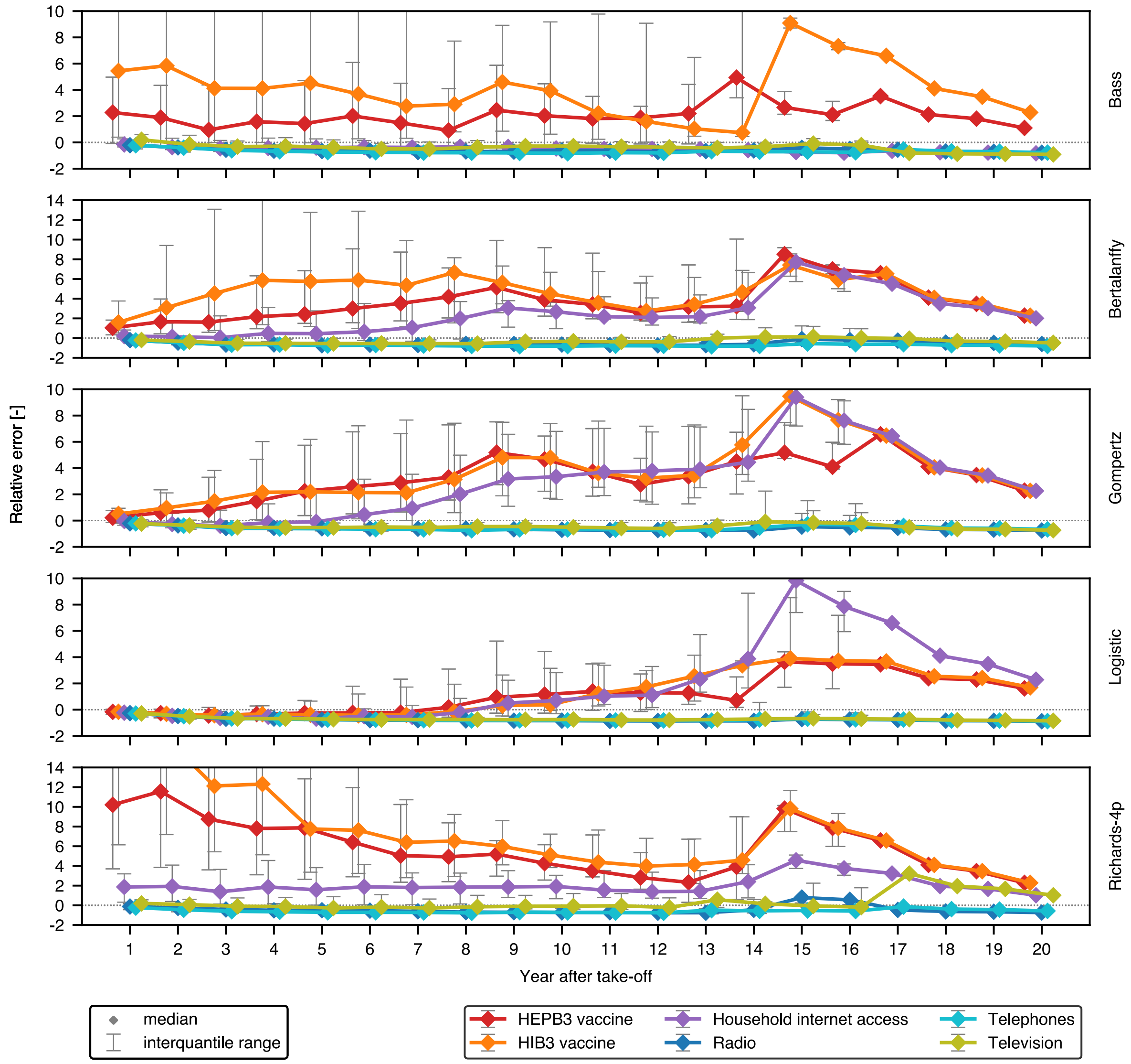
Supplementary Figure 7. Out-of-sample performance scores of projections across all countries of both solar PV and onshore wind power across, grouped by growth model, and diffusion attributes where near-optimal fit describes the reference, and analog group. The higher the mean absolute percentage error, calibration penalty, sharpness penalty, or out-of-interval count, the lower the mean out-of-sample performance of the projections between the take-off year of a technology in a country and 2023. The box plots indicate median, first and third quartiles, and whiskers. Single dots are outliers and can lay outside the plot windows. Arrows indicate if changing diffusion attributes compared to the reference setting (near-optimal fit) leads to significantly higher/lower median scores (p<0.01, Mann-Whitney U test). Related to Figure 2.



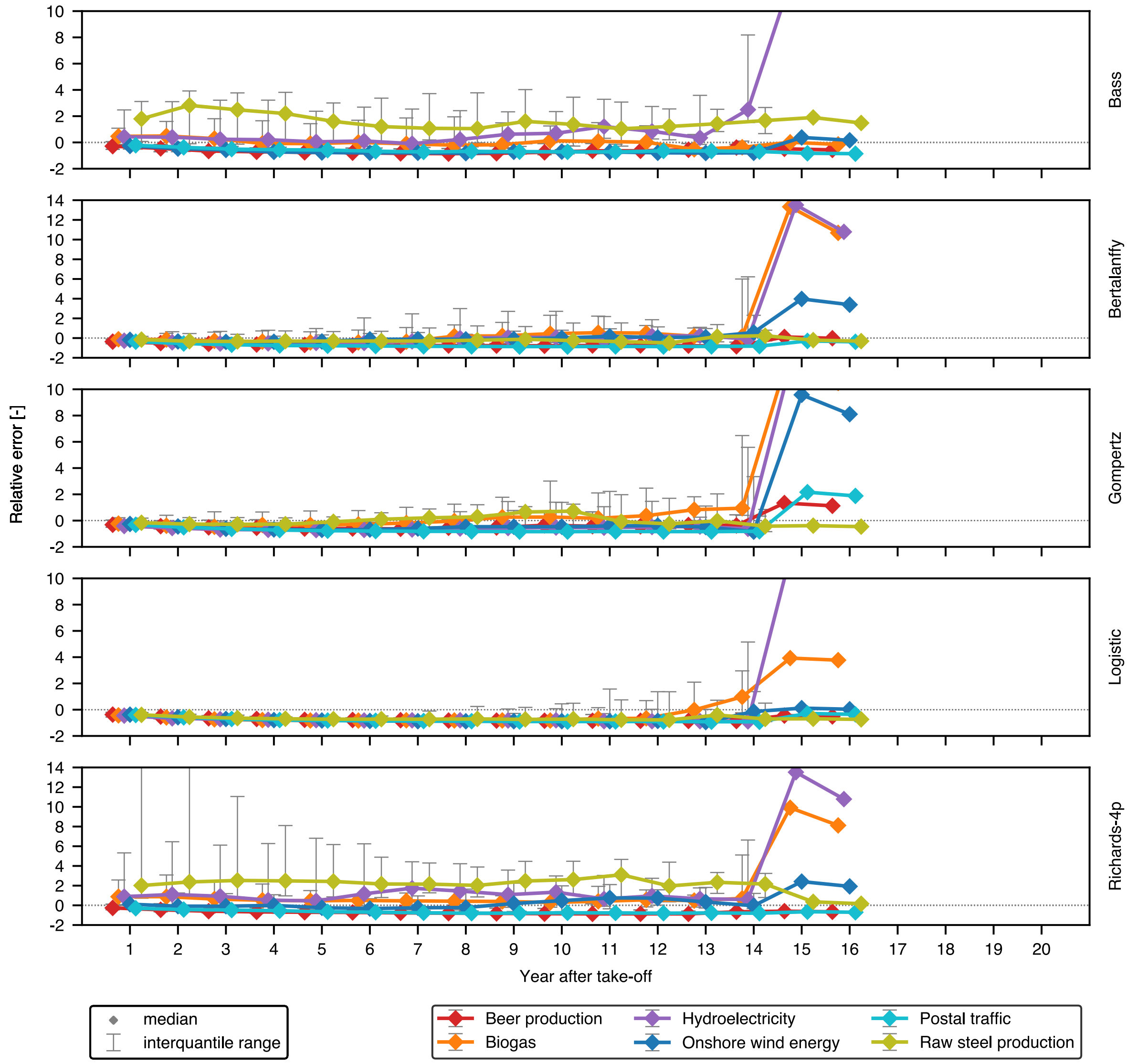
Supplementary Figure 8. Out-of-sample performance scores of projections across all countries of both solar PV and onshore wind power across, grouped by diffusion attributes where near-optimal fit describes the reference, analog group, and growth model. The higher the mean absolute percentage error, calibration penalty, sharpness penalty, or out-of-interval count, the lower the mean out-of-sample performance of the projections between the take-off year of a technology in a country and 2023. The box plots indicate median, first and third quartiles, and whiskers. Single dots are outliers and can lay outside the plot windows. Arrows indicate if changing diffusion attributes compared to the reference setting (near-optimal fit) leads to significantly higher/lower median scores (p<0.01, Mann-Whitney U test). Related to Figure 2.



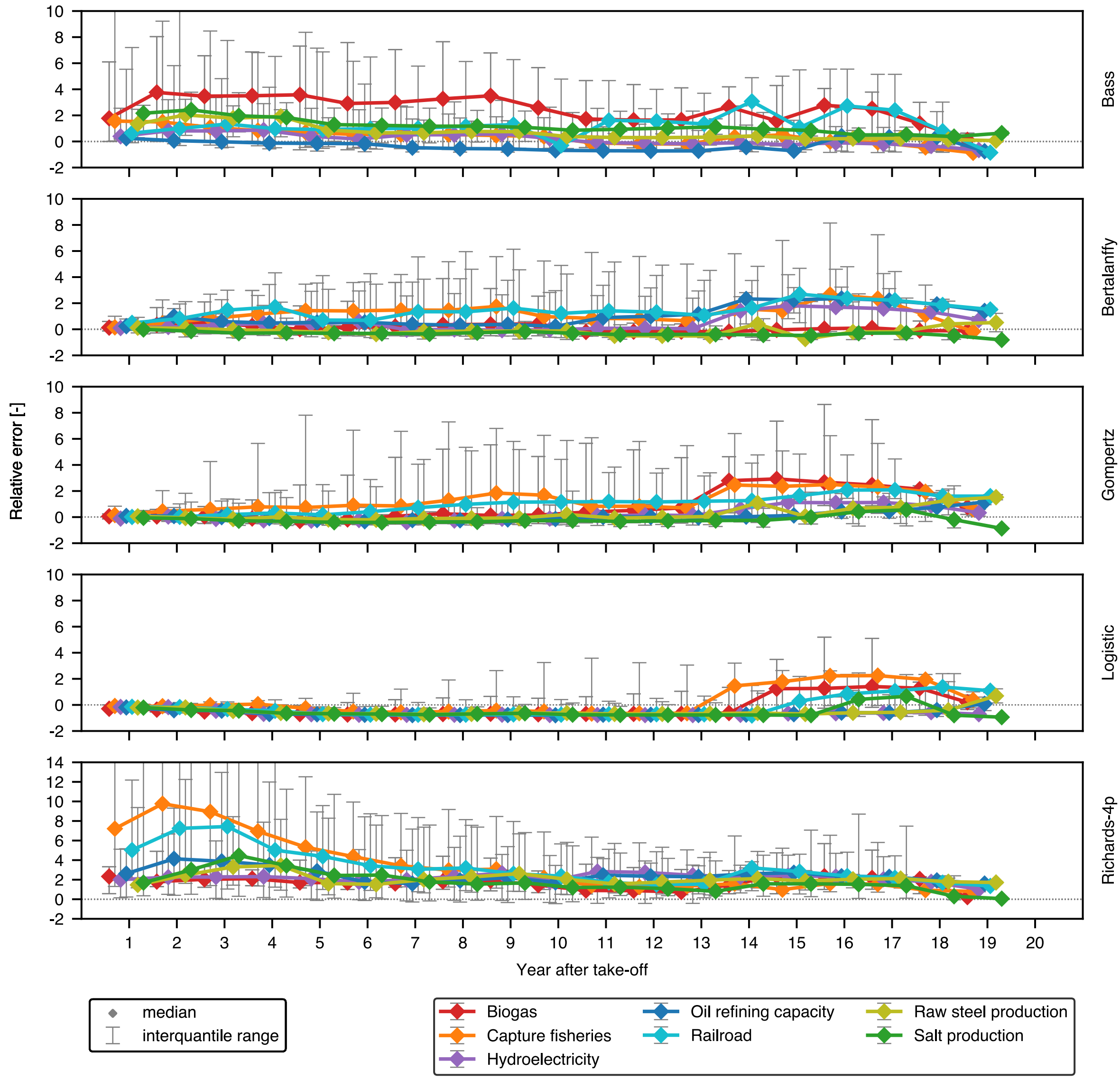
Supplementary Figure 9. Median relative errors with interquartile ranges for projections of growth models based on single analogs across all countries for solar PV. The analogs are part of the group with same type of adopter (Table 1). The higher the magnitude of the error, the further away is the projected capacity of solar PV from the historically observed capacity. If projected capacities are higher than the corresponding observations, errors are positive. The projected capacities are estimates of a deterministic projection using the substitution model and growth parameters from optimal fits of a growth model to the historical time series of an analog. Supplementary Figures 10-11 show percentage errors for other analogs. Supplementary Figures 12-14 show percentage errors for onshore wind power. Related to Figure 3.



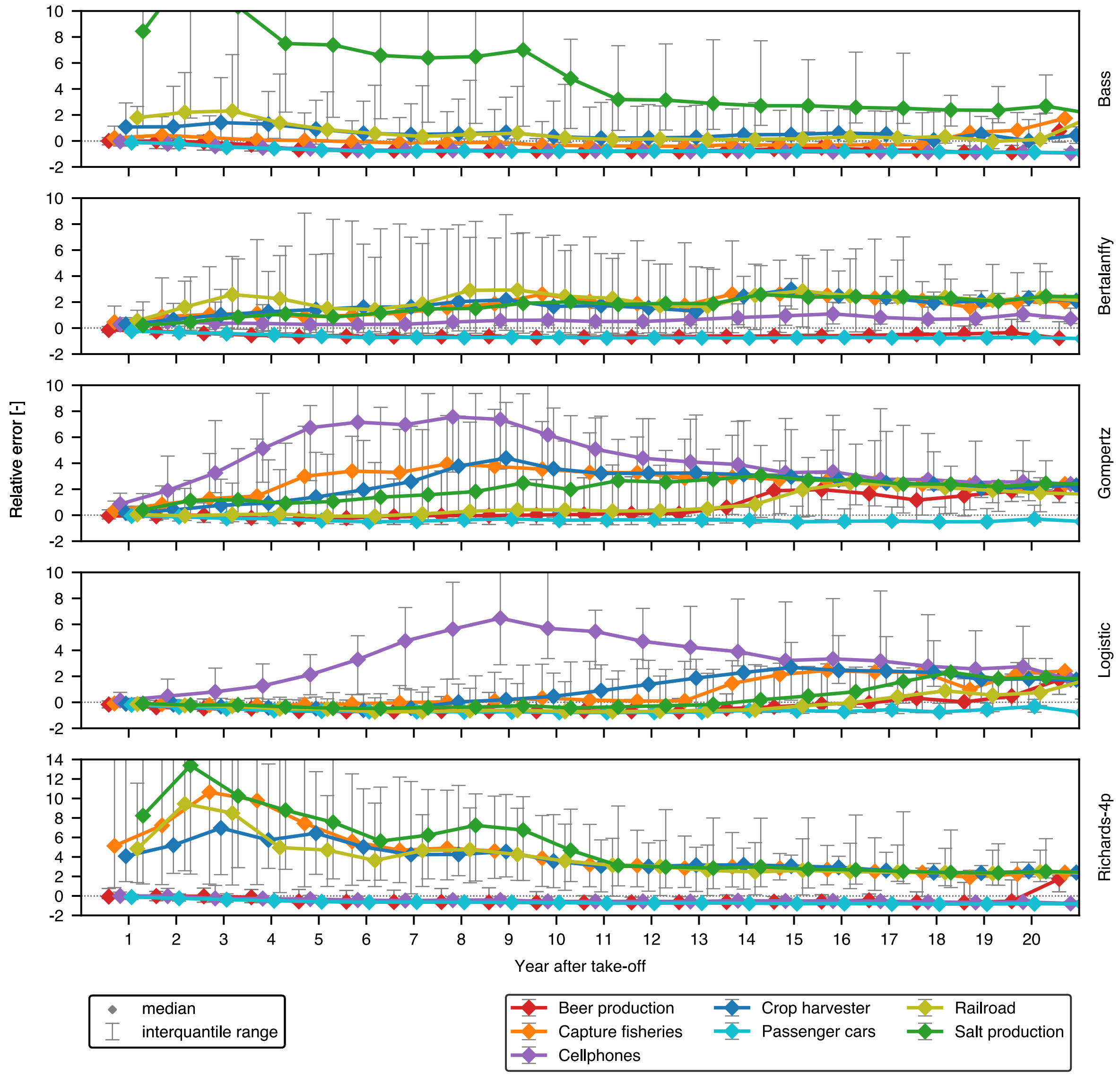
Supplementary Figure 10. Median relative errors with interquartile ranges for projections of growth models based on single analogs across all countries for solar PV. The analogs are part of the group with same magnitude of complexity (Table 1). The higher the magnitude of the error, the further away is the projected capacity of solar PV from the historically observed capacity. If projected capacities are higher than the corresponding observations, errors are positive. The projected capacities are estimates of a deterministic projection using the substitution model and growth parameters from optimal fits of a growth model to the historical time series of an analog. Supplementary Figures 9 and 11 show percentage errors for other analogs. Supplementary Figures 12-14 show percentage errors for onshore wind power. Related to Figure 3.



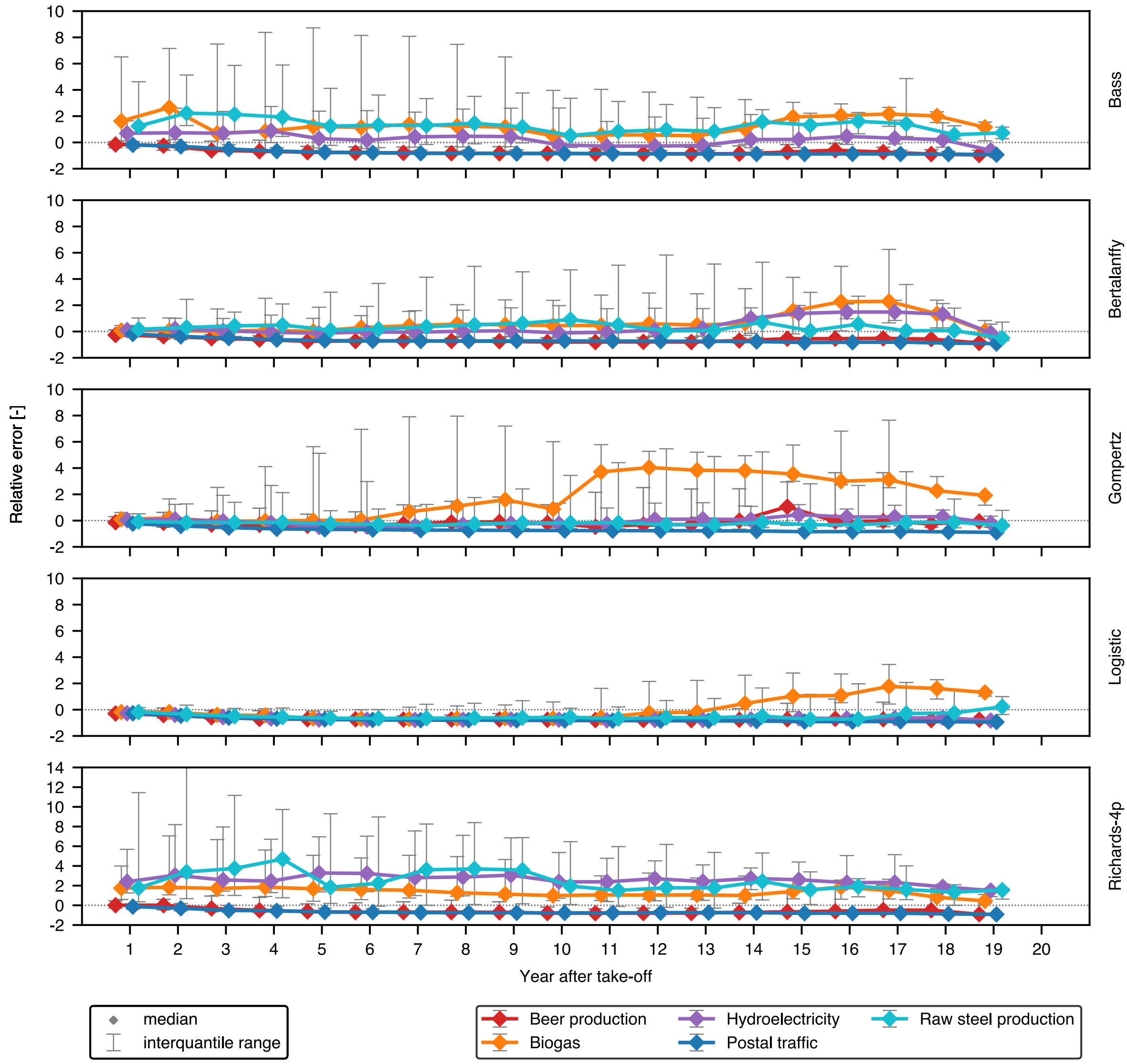
Supplementary Figure 11. Median relative errors with interquartile ranges for projections of growth models based on single analogs across all countries for solar PV. The analogs are part of the group with same magnitude of material use (Table 1). The higher the magnitude of the error, the further away is the projected capacity of solar PV from the historically observed capacity. If projected capacities are higher than the corresponding observations, errors are positive. The projected capacities are estimates of a deterministic projection using the substitution model and growth parameters from optimal fits of a growth model to the historical time series of an analog. Supplementary Figures 9-10 show percentage errors for other analogs. Supplementary Figures 12-14 show percentage errors for onshore wind power. Related to Figure 3.



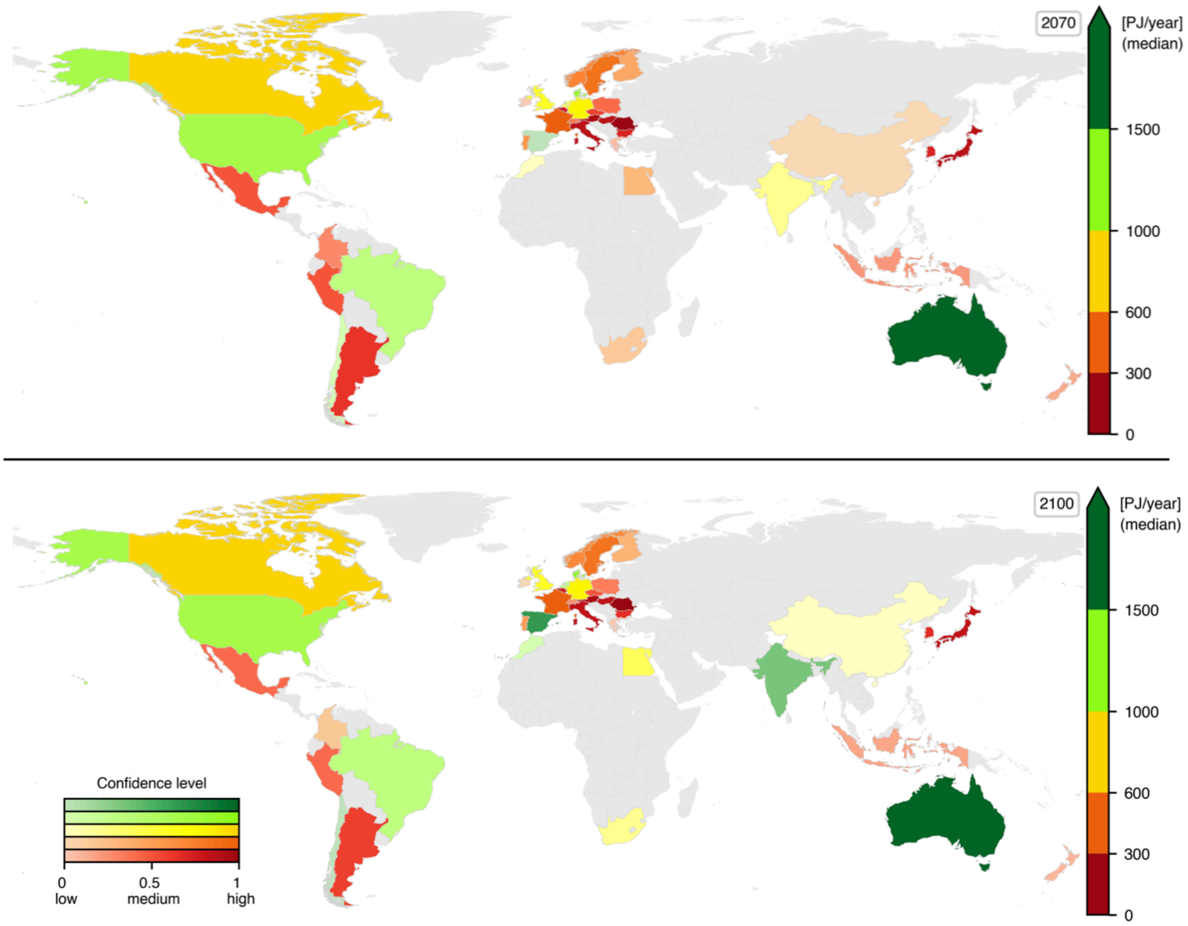
Supplementary Figure 12. Median relative errors with interquartile ranges for projections of growth models based on single analogs across all countries for onshore wind power. The analogs are part of the group with same type of adopter (Table 1). The higher the magnitude of the error, the further away is the projected capacity of onshore wind power from the historically observed capacity. If projected capacities are higher than the corresponding observations, errors are positive. The projected capacities are estimates of a deterministic projection using the substitution model and growth parameters from optimal fits of a growth model to the historical time series of an analog. Supplementary Figures 13-14 show percentage errors for other analogs. Supplementary Figures 9-11 show percentage errors for solar PV. Related to Figure 3.



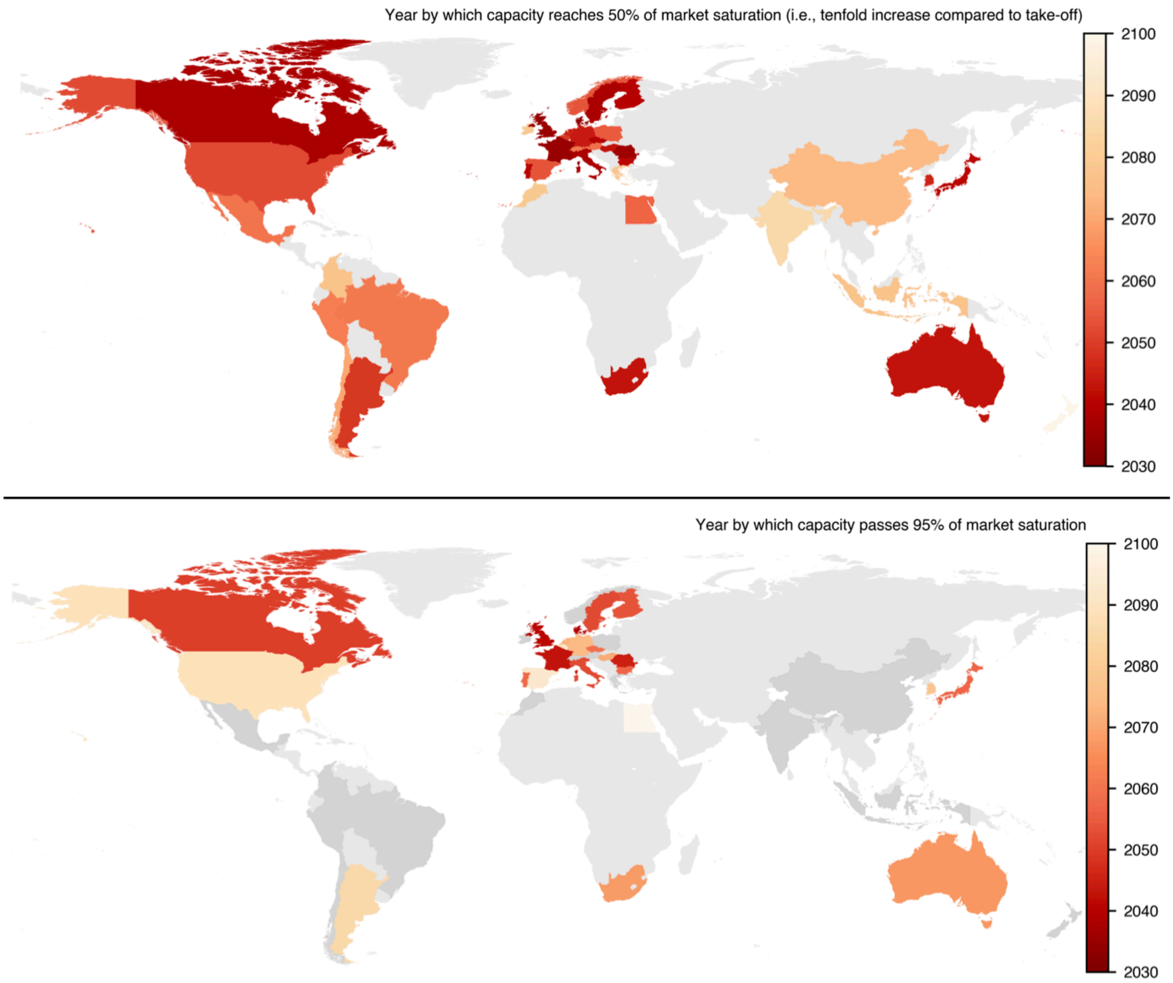
Supplementary Figure 13. Median relative errors with interquartile ranges for projections of growth models based on single analogs across all countries for onshore wind power. The analogs are part of the group with same magnitude of complexity (Table 1). The higher the magnitude of the error, the further away is the projected capacity of onshore wind power from the historically observed capacity. If projected capacities are higher than the corresponding observations, errors are positive. The projected capacities are estimates of a deterministic projection using the substitution model and growth parameters from optimal fits of a growth model to the historical time series of an analog. Supplementary Figures 12 and 14 show percentage errors for other analogs. Supplementary Figures 9-11 show percentage errors for solar PV. Related to Figure 3.



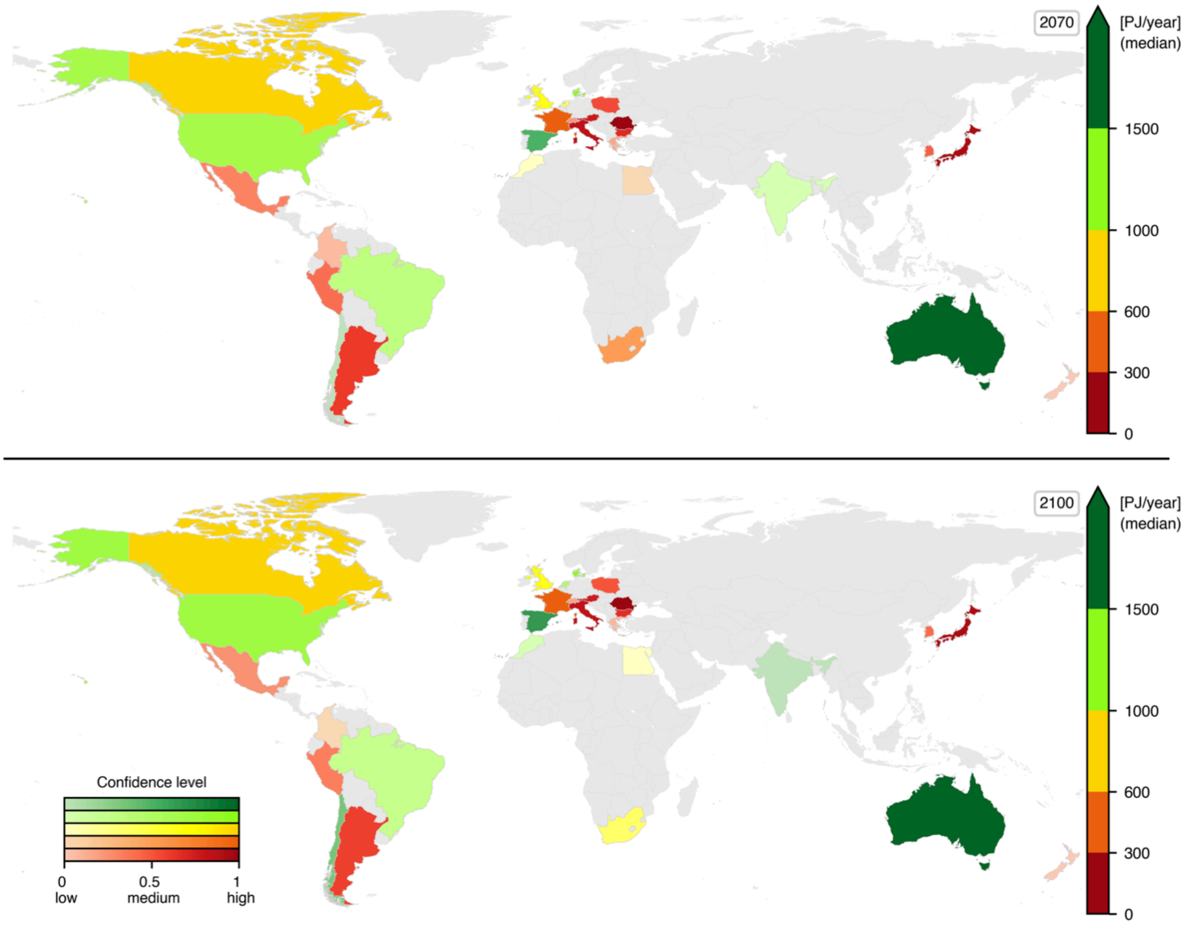
Supplementary Figure 14. Median relative errors with interquartile ranges for projections of growth models based on single analogs across all countries for onshore wind power. The analogs are part of the group with same magnitude of material use (Table 1). The higher the magnitude of the error, the further away is the projected capacity of onshore wind power from the historically observed capacity. If projected capacities are higher than the corresponding observations, errors are positive. The projected capacities are estimates of a deterministic projection using the substitution model and growth parameters from optimal fits of a growth model to the historical time series of an analog. Supplementary Figures 12-13 show percentage errors for other analogs. Supplementary Figures 9-11 show percentage errors for solar PV. Related to Figure 3.



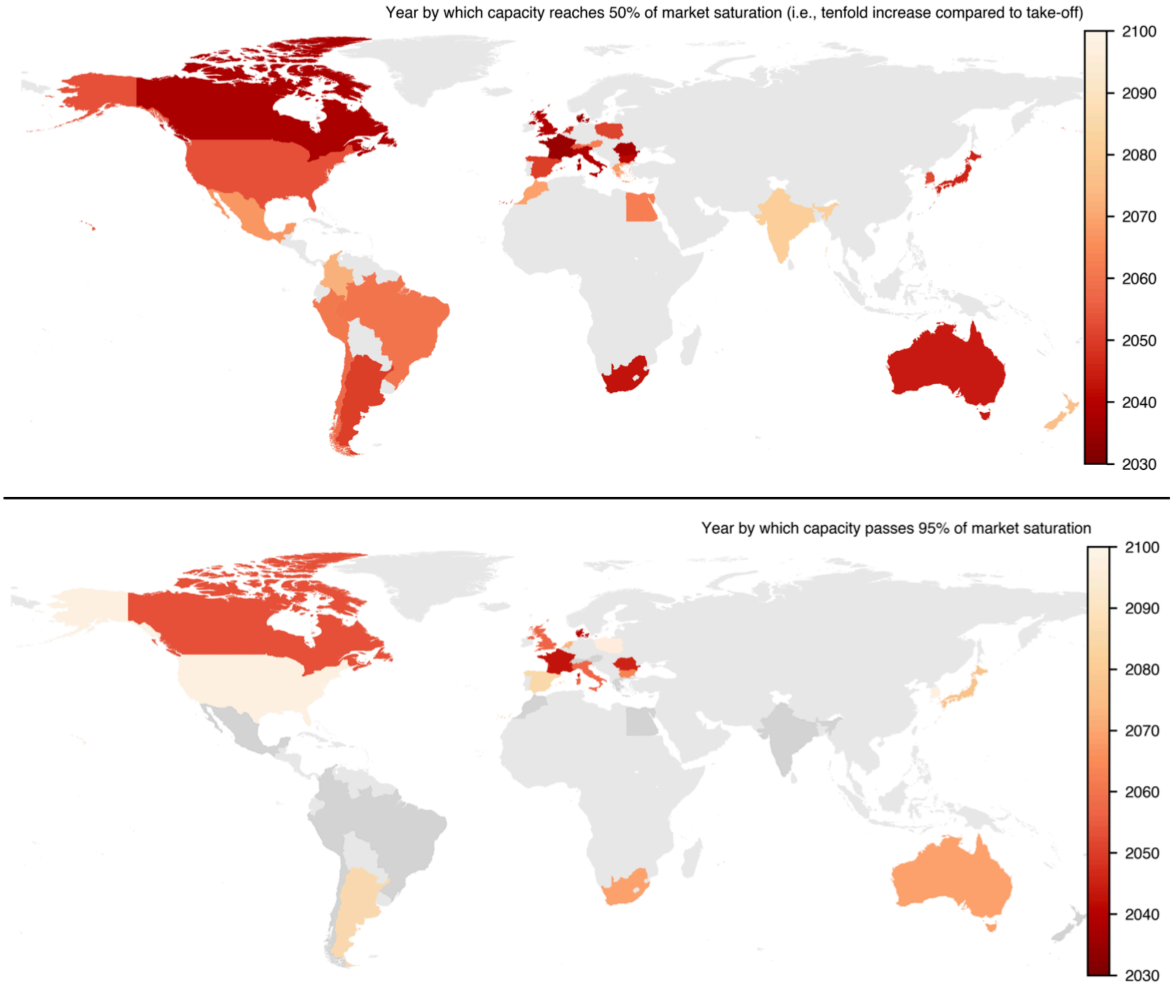
Supplementary Figure 15. Projected median capacities of hydrogen electrolysis with confidence levels per country in 2070 and 2100. The projections are weighted projections of all analog groups (Table 1). The darker the shading, the higher is the confidence level the projected capacity. The confidence level[8] represents the width of a projection in the selected year. Countries in grey have no projections. Geographic boundaries come from Opendatasoft[9]. Related to Figure 4.



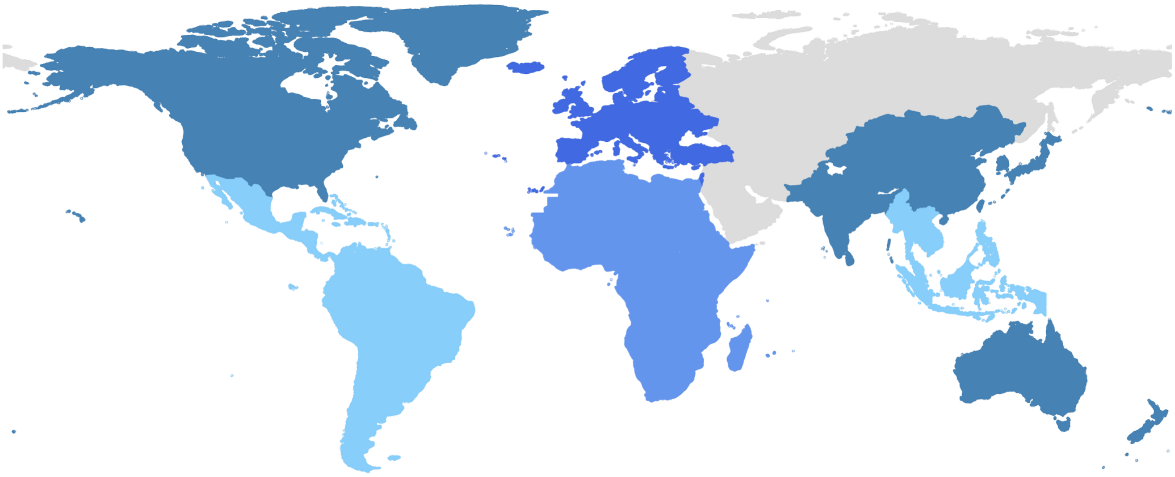
Supplementary Figure 16. Years by which projected median of countries reach 50% and pass 95% of the market saturation of hydrogen electrolysis. The values derive from projections weighted projections of all analog groups (Table 1, Supplementary Figure 1). Countries in dark grey reach the saturation levels after 2100. Countries in light grey have no projections. Geographic boundaries come from Opendatasoft[9]. Related to Figure 4.



Supplementary Figure 17. Projected median capacities of hydrogen electrolysis with confidence levels per country in 2070 and 2100. The projections use each analog from the three analog groups only once (Table 1), leading to fewer countries with projections if a country does not have historical data for all analogs. The darker the shading, the higher is the confidence level the projected capacity. The confidence level[8] represents the width of a projection in the selected year. Countries in grey have no projections. Geographic boundaries come from Opendatasoft[9]. Related to Figure 4.



Supplementary Figure 18. Years by which projected median of countries reach 50% and pass 95% of the market saturation of hydrogen electrolysis. The values derive from projections that use each analog from the three analog groups only once (Table 1, Supplementary Figure 2), leading to fewer countries with projections if a country does not have historical data for all analogs. Countries in dark grey reach the saturation levels after 2100. Countries in light grey have no projections. Geographic boundaries come from Opendatasoft[9]. Related to Figure 4.



Supplementary Figure 19. Six investigated world regions for hydrogen electrolysis as grouped by International Energy Agency[10] (Supplementary Tables 1-2). Middle East has no projection of hydrogen electrolysis due to insufficient available data on analogs. Geographic boundaries come from Opendatasoft[9]. Related to Table 1.

Supplementary Tables

Supplementary Table 1. Countries with projections of hydrogen electrolysis per analog group.

Type of adopter	Complexity	Material use
Argentina	Argentina	Argentina
Australia	Australia	Australia
Austria	Austria	Austria
Brazil	Belgium	Brazil
Bulgaria	Brazil	Bulgaria
Canada	Bulgaria	Canada
Chile	Canada	Chile
China	Chile	Colombia
Colombia	Colombia	Denmark
Denmark	Czechia	Egypt
Egypt	Denmark	France
France	Egypt	Greece
Germany	Finland	India
Greece	France	Italy
India	Greece	Japan
Indonesia	Hungary	Mexico
Italy	India	Morocco
Japan	Ireland	Netherlands
Mexico	Italy	New Zealand
Morocco	Japan	Peru
Netherlands	Mexico	Poland
New Zealand	Morocco	South Korea
Peru	Netherlands	Romania
Poland	New Zealand	South Africa
Portugal	Norway	Spain
South Korea	Peru	Switzerland
Romania	Poland	United Kingdom
South Africa	South Korea	United States of America
Spain	Romania	
Switzerland	South Africa	
United Kingdom	Spain	
United States of America	Sweden	
	Switzerland	
	United Kingdom	
	United States of America	

Supplementary Table 2. World regions with projections of hydrogen electrolysis per analog group. World regions include the projections of countries as grouped by International Energy Agency[10] (Supplementary Figure 16).

Type of adopter	**Complexity**	**Material use**
Africa	Africa	Africa
Asia Pacific	Asia Pacific	Asia Pacific
Central and South America	Central and South America	Central and South America
Europe	Europe	Europe
North America	North America	North America
Southeast Asia	Southeast Asia	Southeast Asia

Supplementary Table 3. Countries with projections of solar PV per analog group.

Type of adopter	Complexity	Material use
Argentina	Albania	Argentina
Australia	Argentina	Australia
Austria	Australia	Austria
Belgium	Austria	Belgium
Brazil	Belgium	Brazil
Canada	Brazil	Canada
Chile	Cambodia	Chile
Denmark	Canada	China
Finland	Chile	Denmark
France	Costa Rica	Finland
Greece	Cuba	France
Hungary	Dominican Republic	Hungary
India	France	India
Israel	Germany	Indonesia
Italy	Greece	Israel
Japan	Guinea	Italy
Kenya	Guyana	Mexico
Mexico	Israel	Morocco
Morocco	Italy	Netherlands
Netherlands	Kenya	New Zealand
New Zealand	Kuwait	Norway
Norway	Laos	Philippines
Pakistan	Lebanon	Poland
Poland	Luxembourg	Portugal
South Korea	Malaysia	South Korea
Romania	Mauritius	Romania
South Africa	Mexico	South Africa
Spain	Morocco	Spain
Sri Lanka	Namibia	Sweden
Sweden	New Zealand	Switzerland
Switzerland	Peru	Turkey
Turkey	Philippines	Thailand
Tunisia	Poland	United Kingdom
United Kingdom	Portugal	United States of America
United States of America	Rwanda	
Uruguay	Saudi Arabia	
	South Africa	
	Spain	
	Sri Lanka	
	Sweden	
	Turkey	
	Togo	
	Tunisia	
	United States of America	
	Uruguay	

Supplementary Table 4. Countries with projections of onshore wind power per analog group.

Type of adopter	Complexity	Material use
Australia	Argentina	Australia
Brazil	Australia	Belgium
Canada	Austria	Brazil
France	Bolivia	Canada
Indonesia	Brazil	Finland
Israel	Bulgaria	France
Mexico	Canada	Hungary
Pakistan	Chile	Indonesia
Philippines	China	Israel
Poland	Cuba	Mexico
South Korea	Egypt	Philippines
Romania	France	Poland
South Africa	Indonesia	South Korea
Switzerland	Israel	Romania
Turkey	Italy	South Africa
Thailand	Japan	Sweden
United States of America	Kenya	Switzerland
	Mexico	Turkey
	Morocco	Thailand
	New Zealand	United States of America
	Philippines	
	Poland	
	Portugal	
	South Korea	
	Romania	
	Russia	
	South Africa	
	Switzerland	
	Turkey	
	Thailand	
	United Kingdom	
	United States of America	
	Venezuela	

Supplementary Table 5. Out-of-sample performance of projections with different groups of analogs. The scores are means over all hindcasting years and countries for both solar PV and onshore wind power. The higher a score, the lower the performance. The weighting score is the inverse of the mean squared of the weighted interval performance indicator[8].

	Type of adopter	Complexity	Material use
Mean absolute percentage error	0.76	0.78	0.74
Calibration	1.54	1.21	1.48
Sharpness	1.36	2.44	1.16
Out-of-interval count	0.10	0.08	0.08
Weighted interval performance indicator	1.66	1.54	1.67
Weighting score	0.32	0.35	0.33

Supplementary Table 6. Out-of-sample performance of projections with growth models. The scores are means over all hindcasting years and countries for both solar PV and onshore wind power. The weighting score is the inverse of the mean squared of the weighted interval performance indicator[8].

	Bass	Bertalanffy	Gompertz	logistic	Richards-4p
Mean absolute percentage error	0.75	0.73	0.75	0.75	0.91
Calibration	1.14	1.12	1.33	2.05	1.27
Sharpness	2.39	1.74	1.46	0.38	3.85
Out-of-interval count	0.00	0.07	0.83	0.31	0.00
Weighted interval performance indicator	1.53	1.28	1.43	1.95	2.06
Weighting score	0.22	0.29	0.22	0.13	0.12

References

1. Greene, J., Gidden, M. J., Brutschin, E. & Nemet, G. F. Drivers of technology diffusion speed across countries [in review].
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