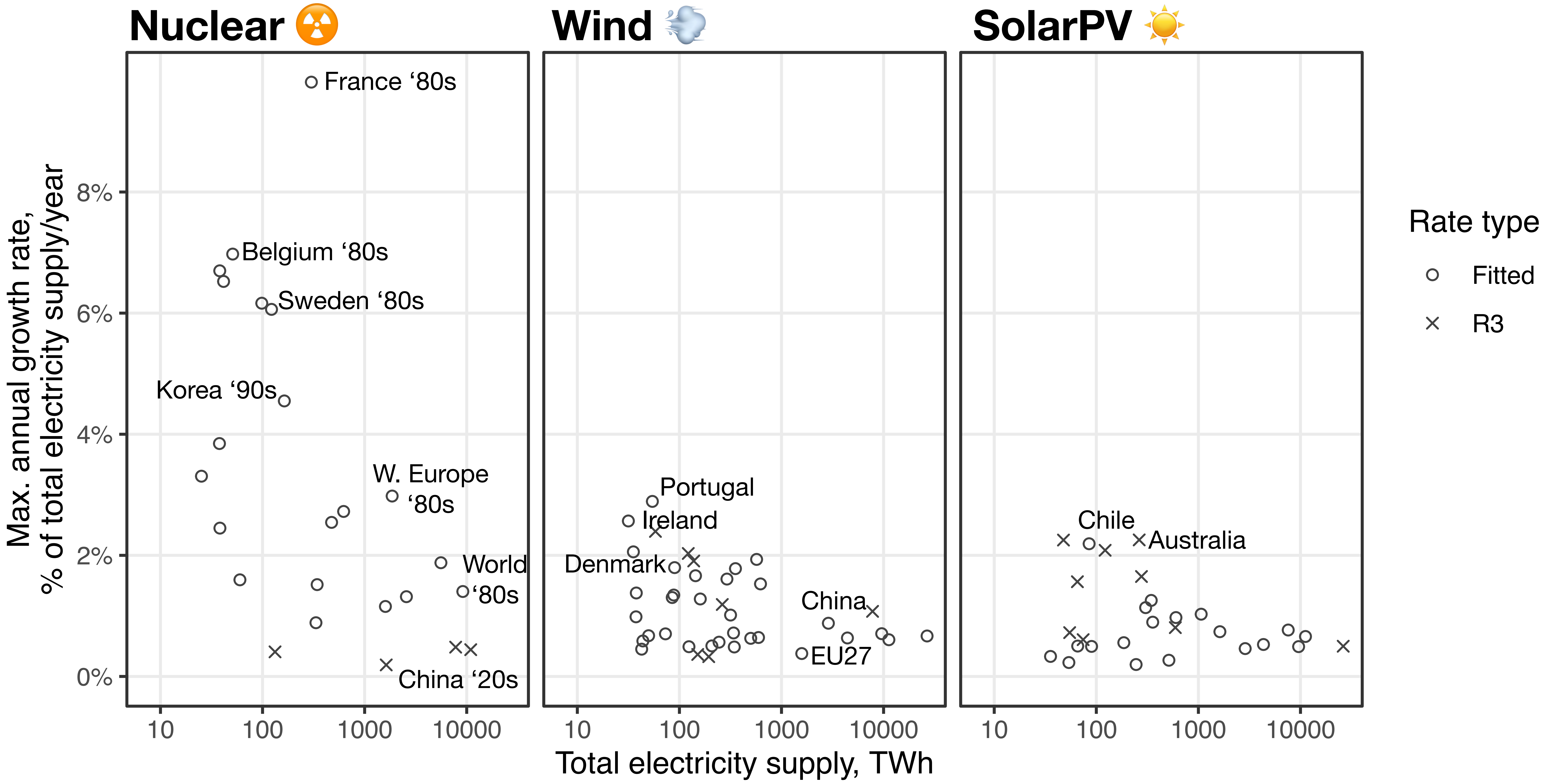
Measuring energy transitions

Vadim Vinichenko | Physical Resource Theory | 19 November 2024

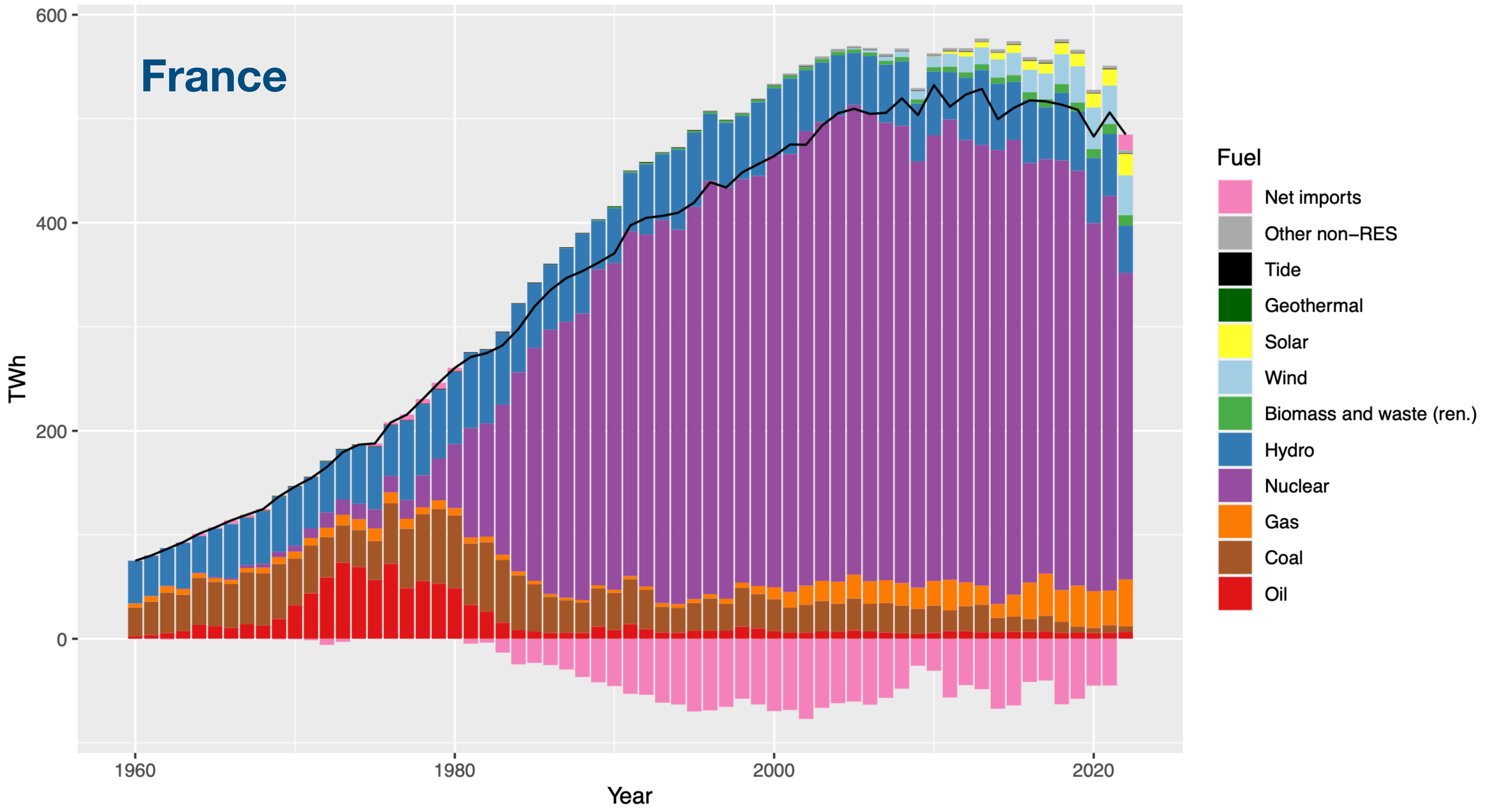
Feasibility of low-carbon electricity growth

Highest national and regional low-carbon electricity growth rates

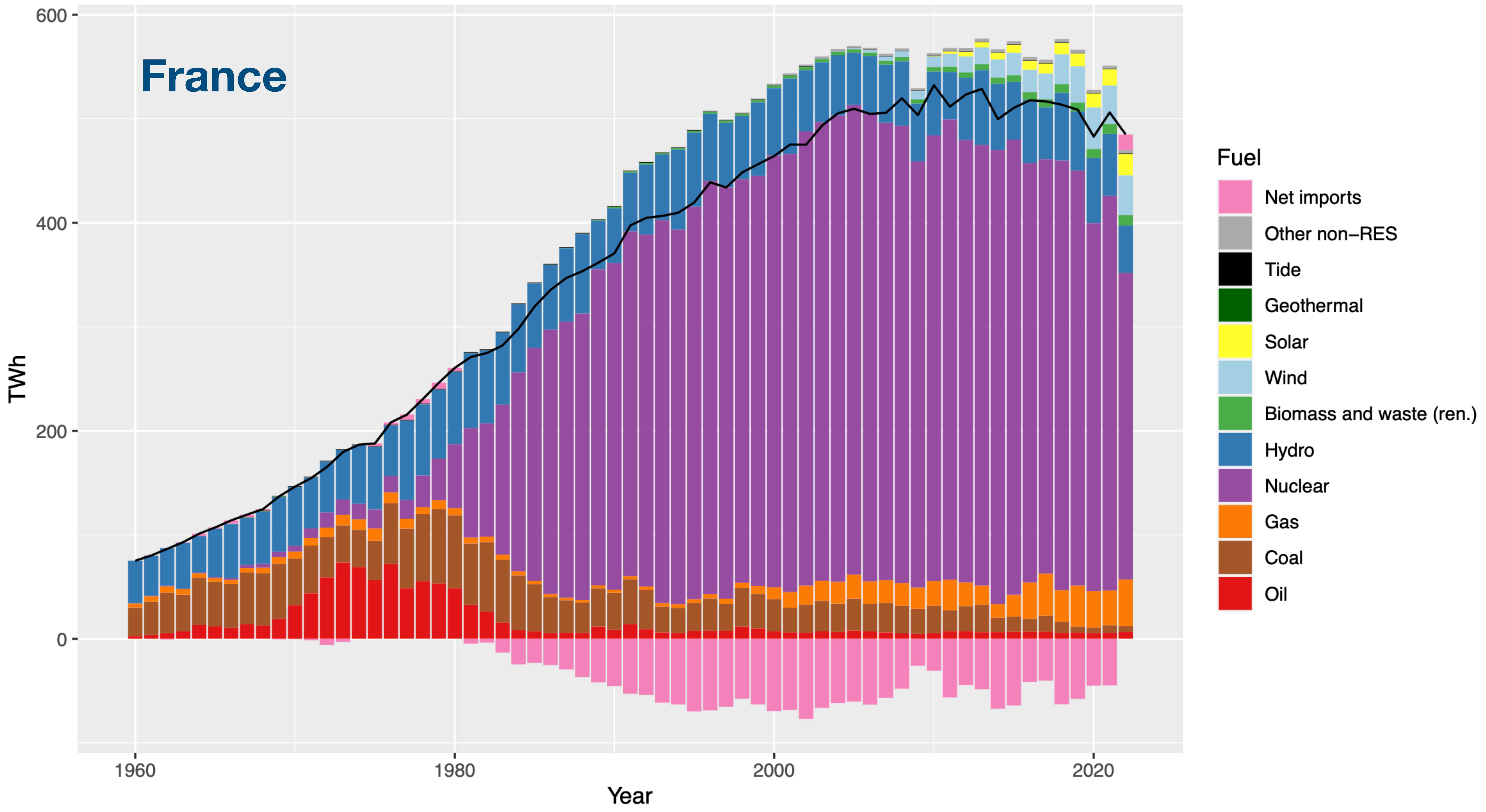


Vinichenko et al. 2023

An energy transition

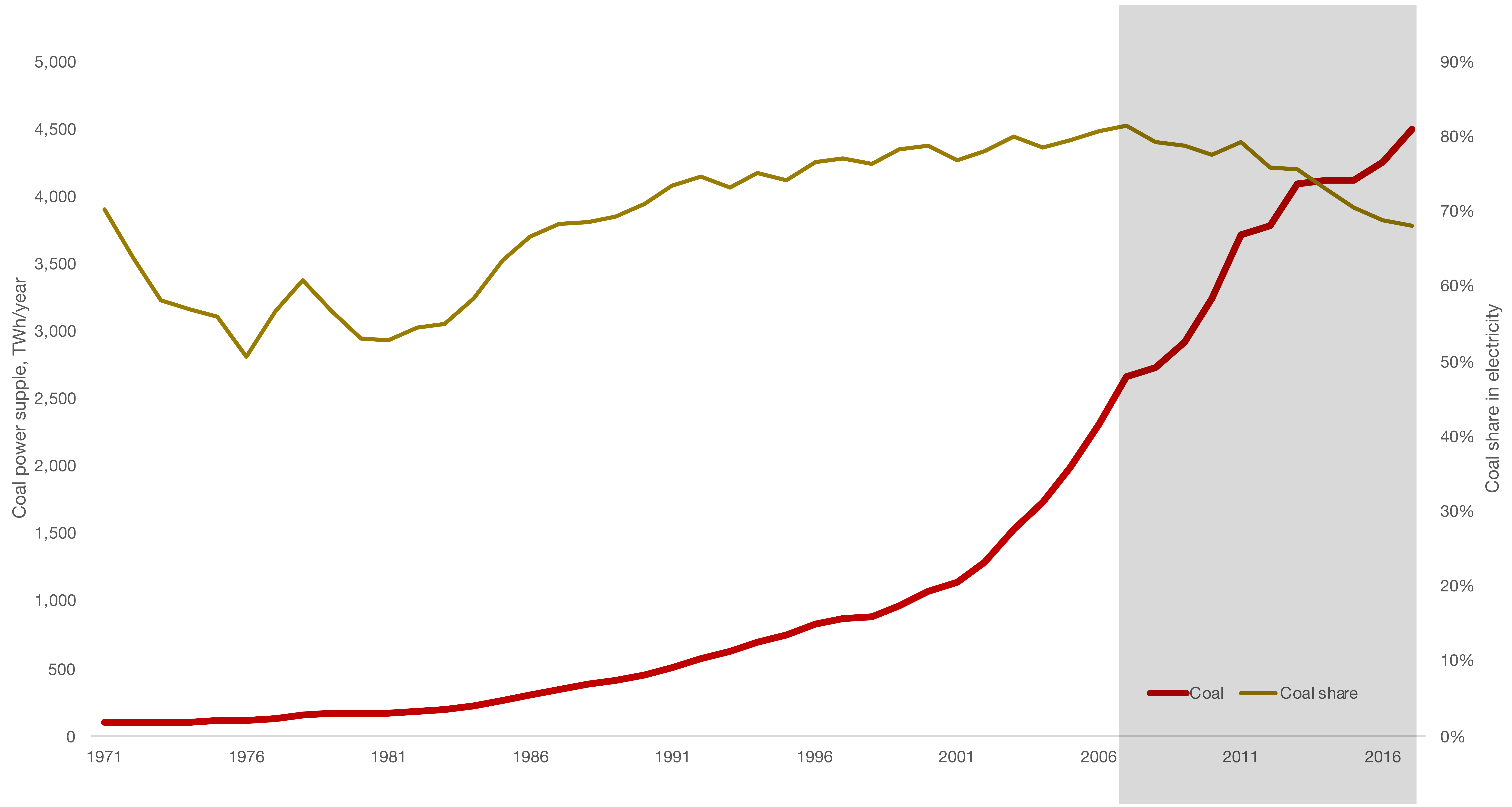


How do we measure an energy transition?

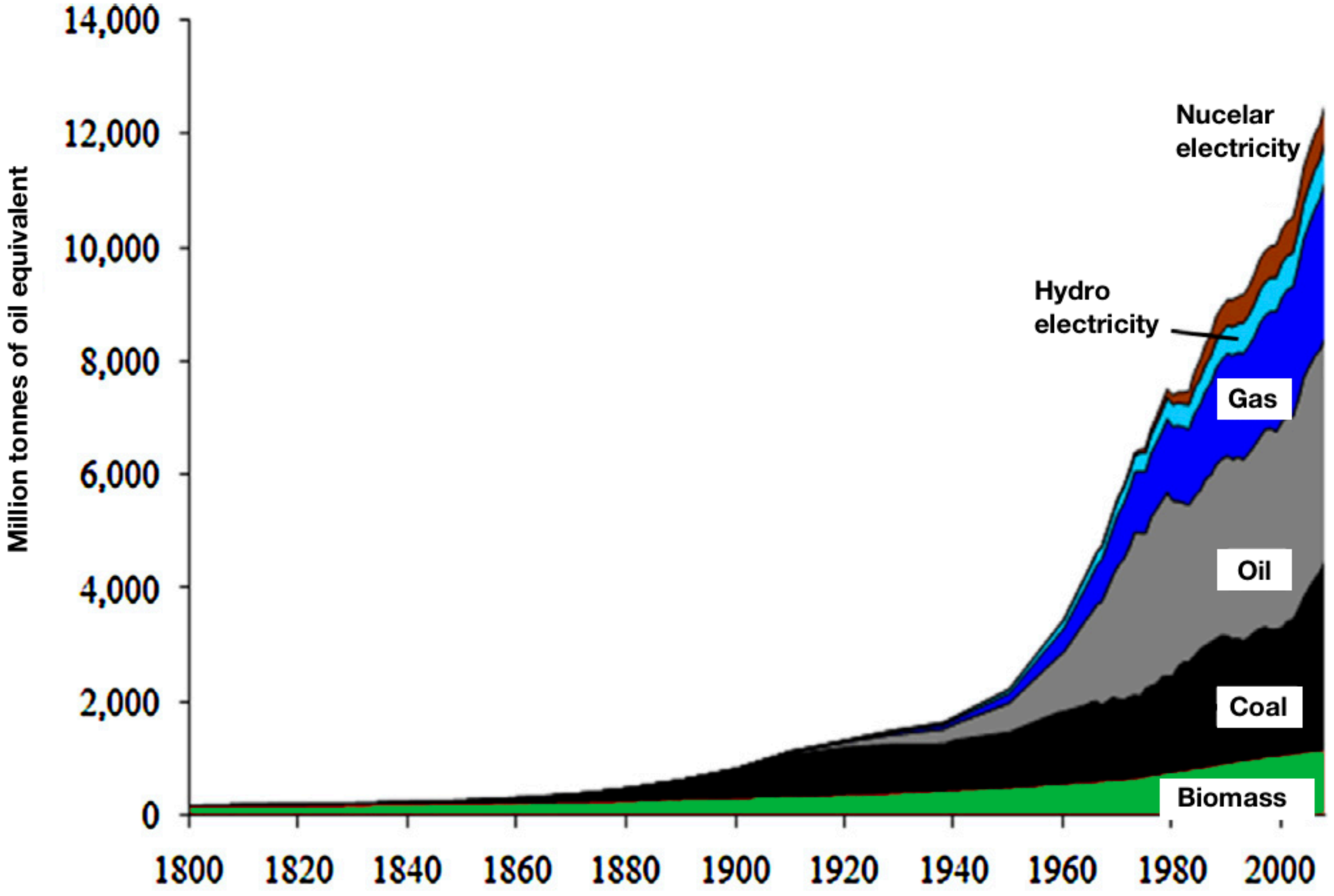


Over 10 years, country A has reduced the share of coal in its energy supply from 60% to 40%. Is it doing a good job decarbonising its energy system?

Coal-fired generation in China



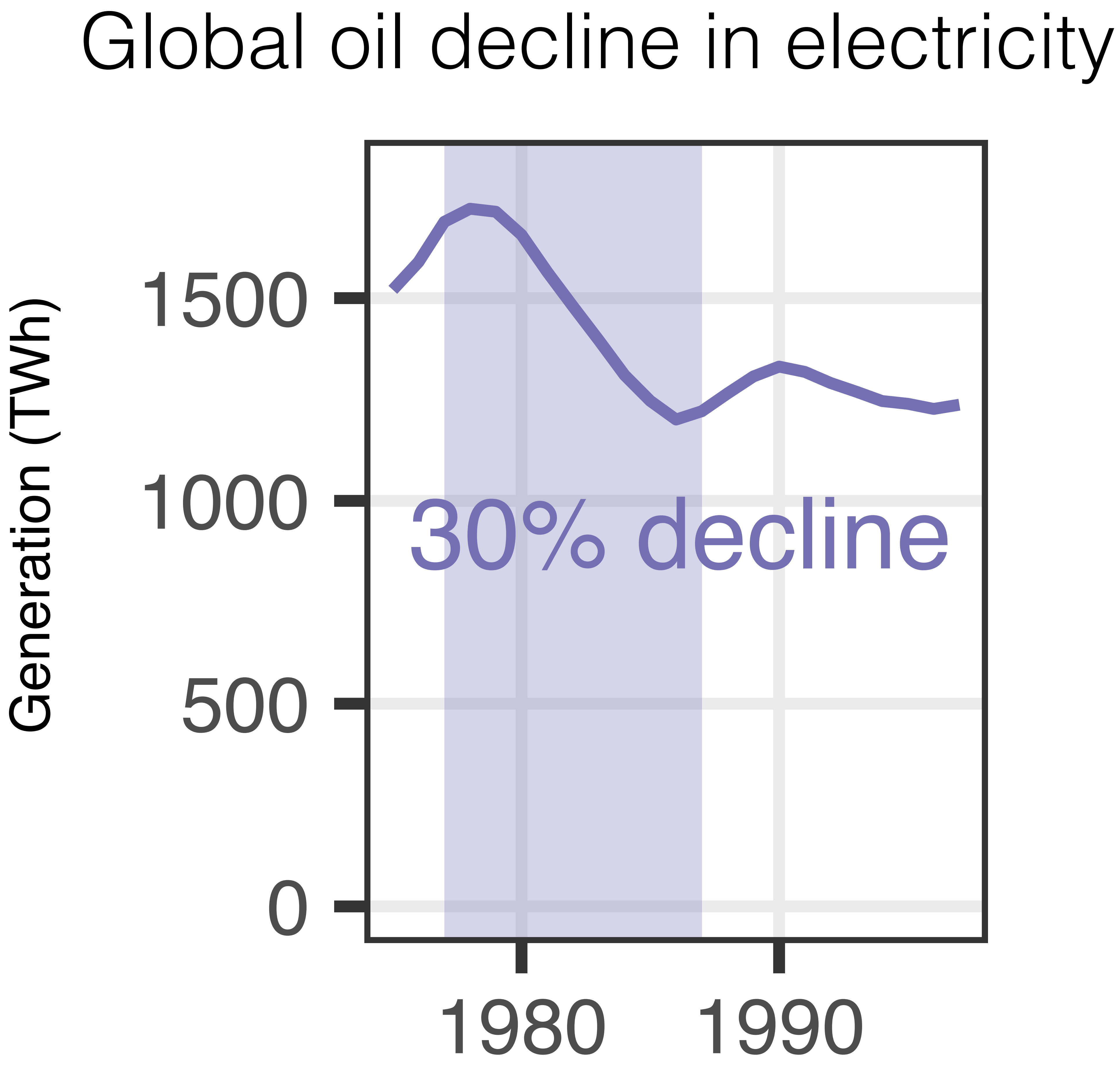
Global primary energy supply (1800–2007)



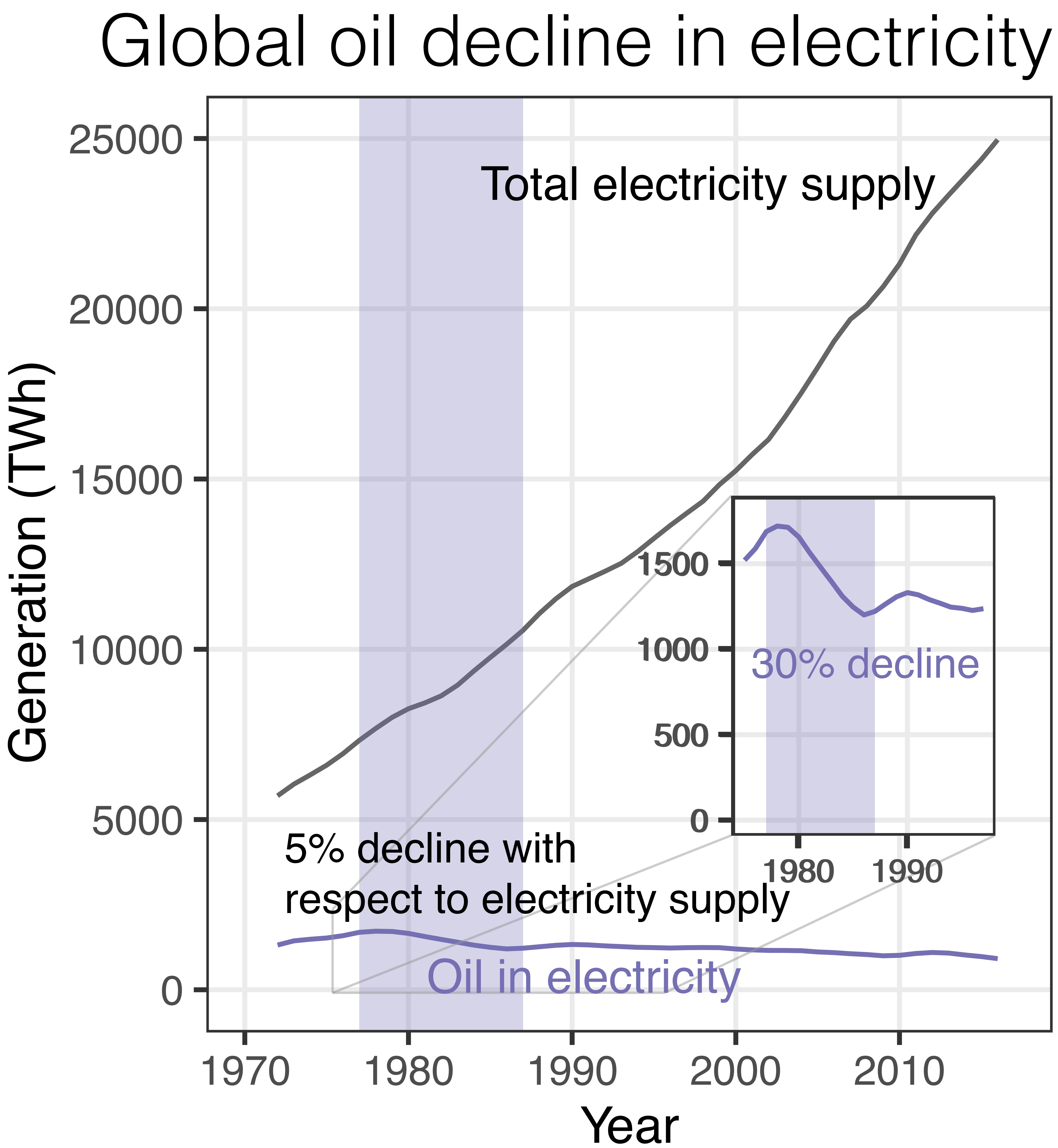
Fouquet 2016

Over 10 years, country A has reduced its use of coal by 95%. Is it doing an impressive job decarbonising its energy system?

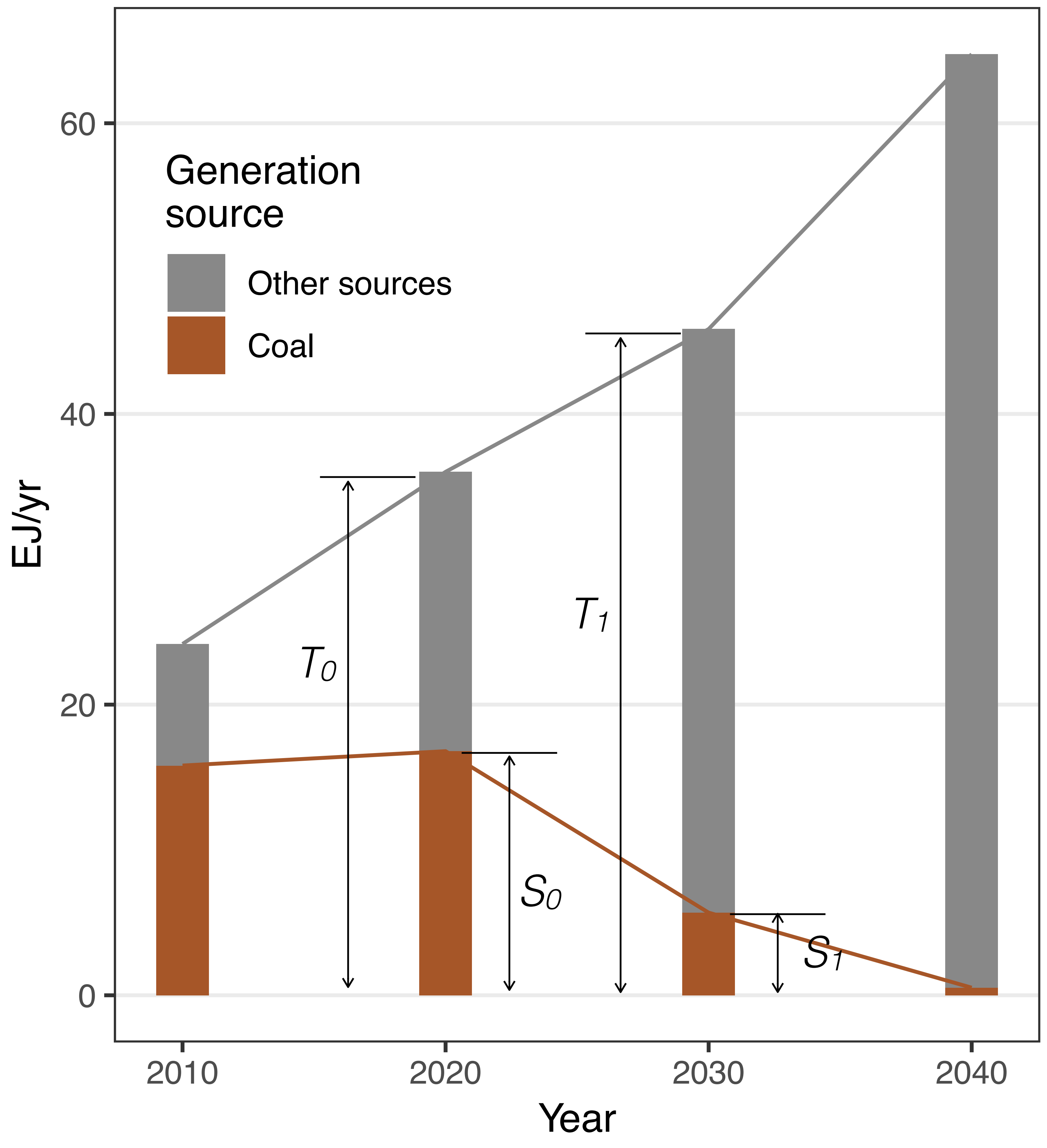
Percentage decline



Percentage decline



Metric of change in an energy system



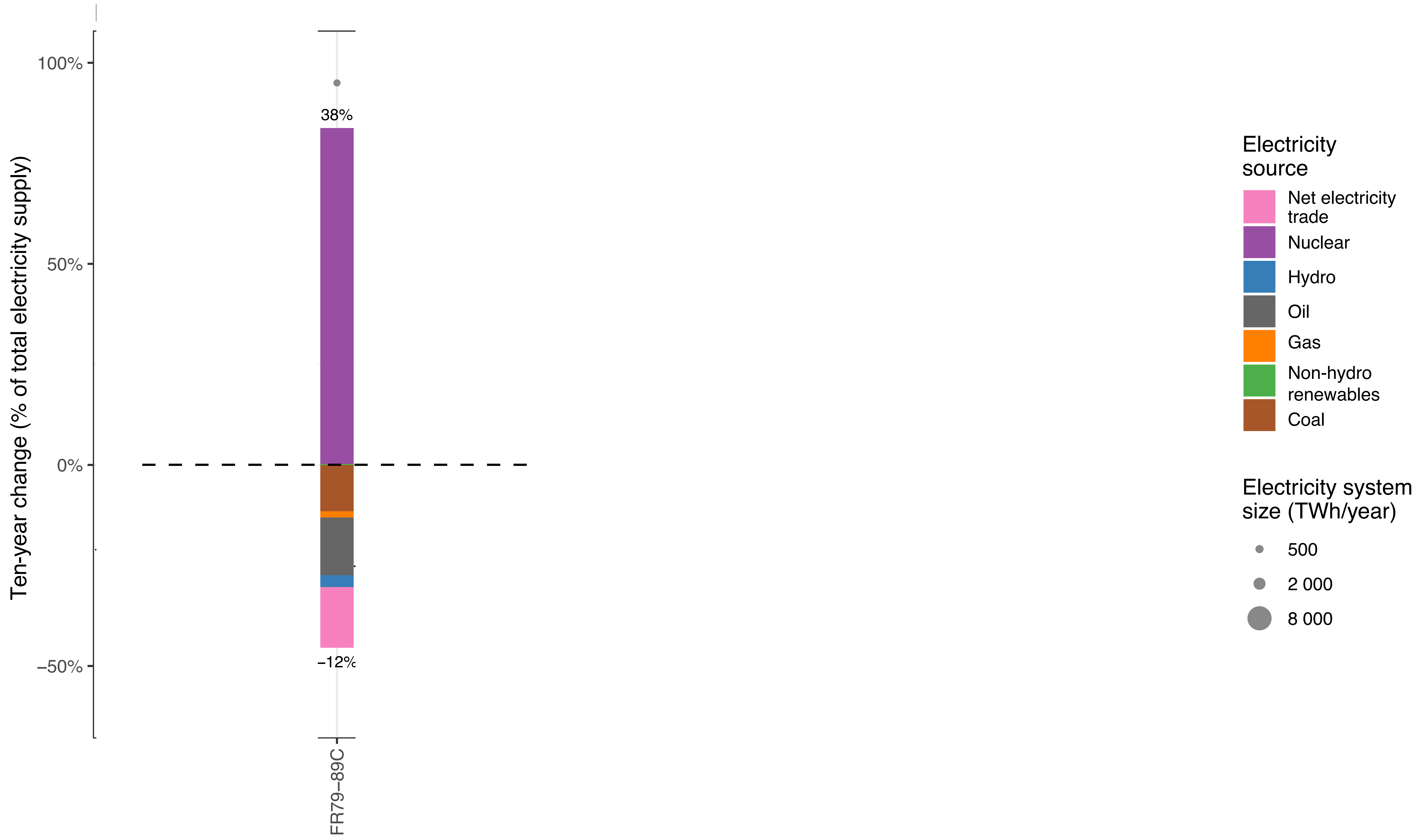
$$R = \frac{S_1 - S_0}{(T_0 + T_1)} * 2$$

$$R = \frac{5.7 - 16.8}{(36.0 + 46.0)} * 2 = -27.1\%$$

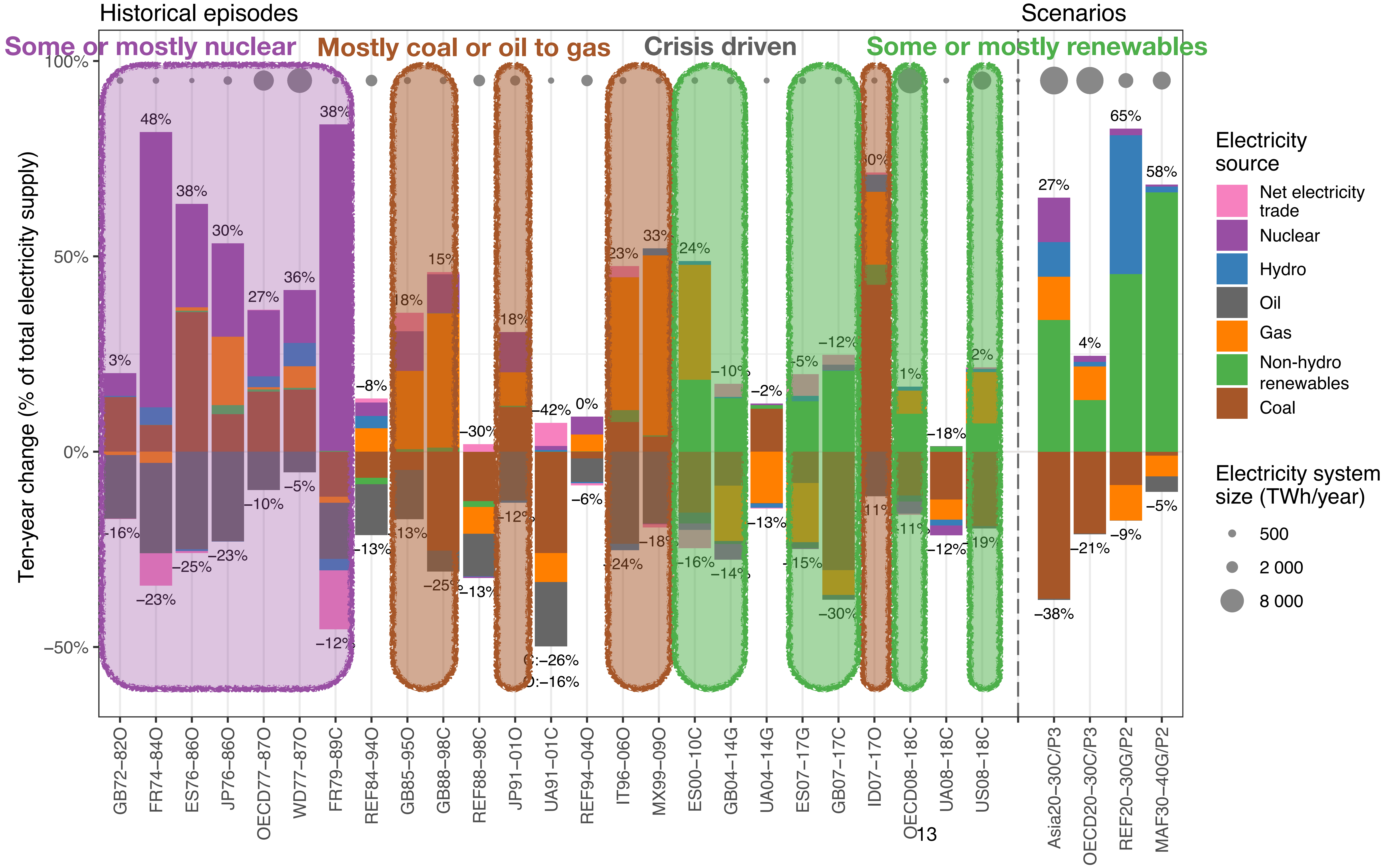
$$R_{ann} \approx -2.7\%$$

Normalised average
annual decline (or growth)

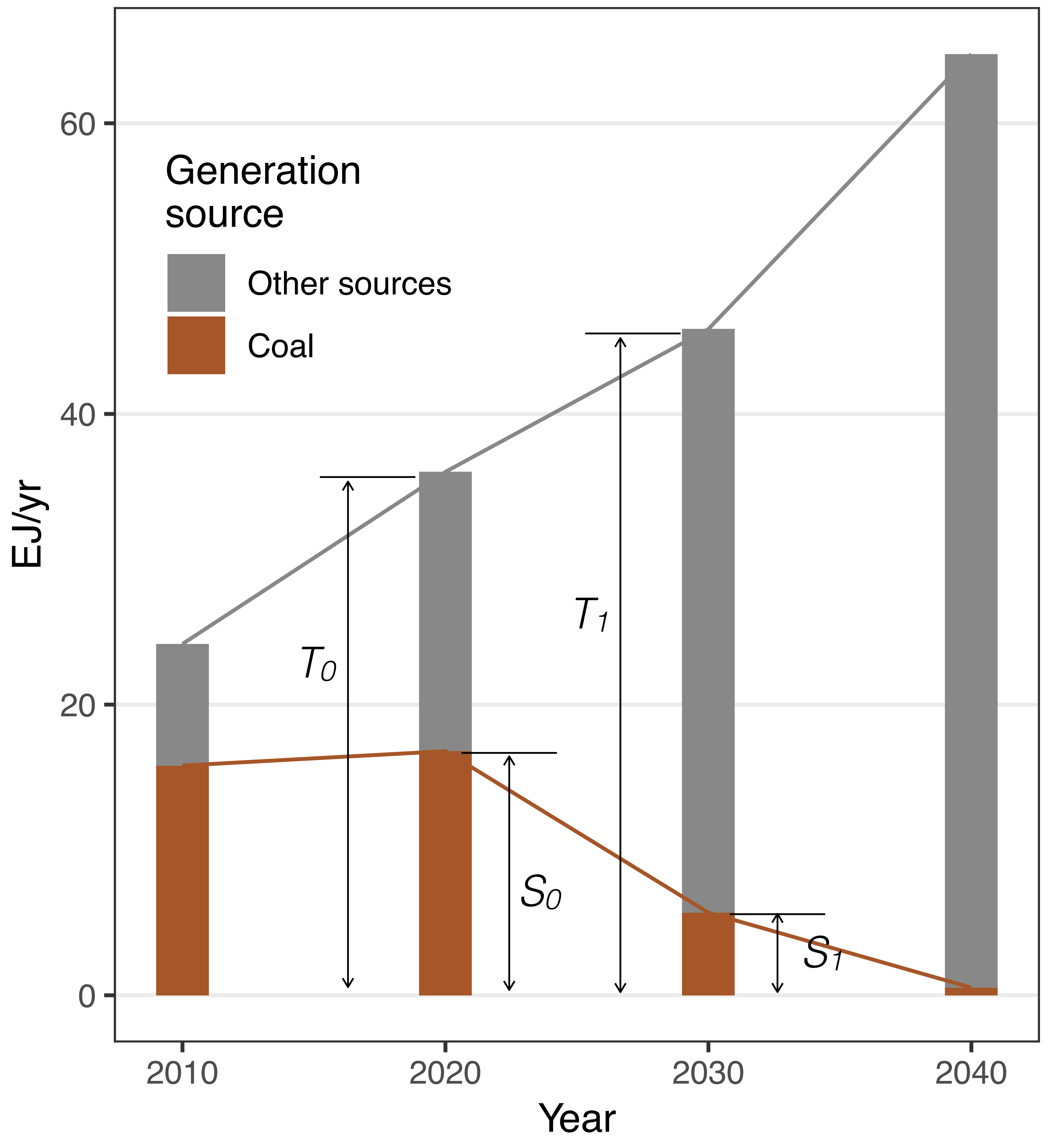
Representing change in the system: What substitutes fossil fuels?



Representing change in the system: What substitutes fossil fuels?



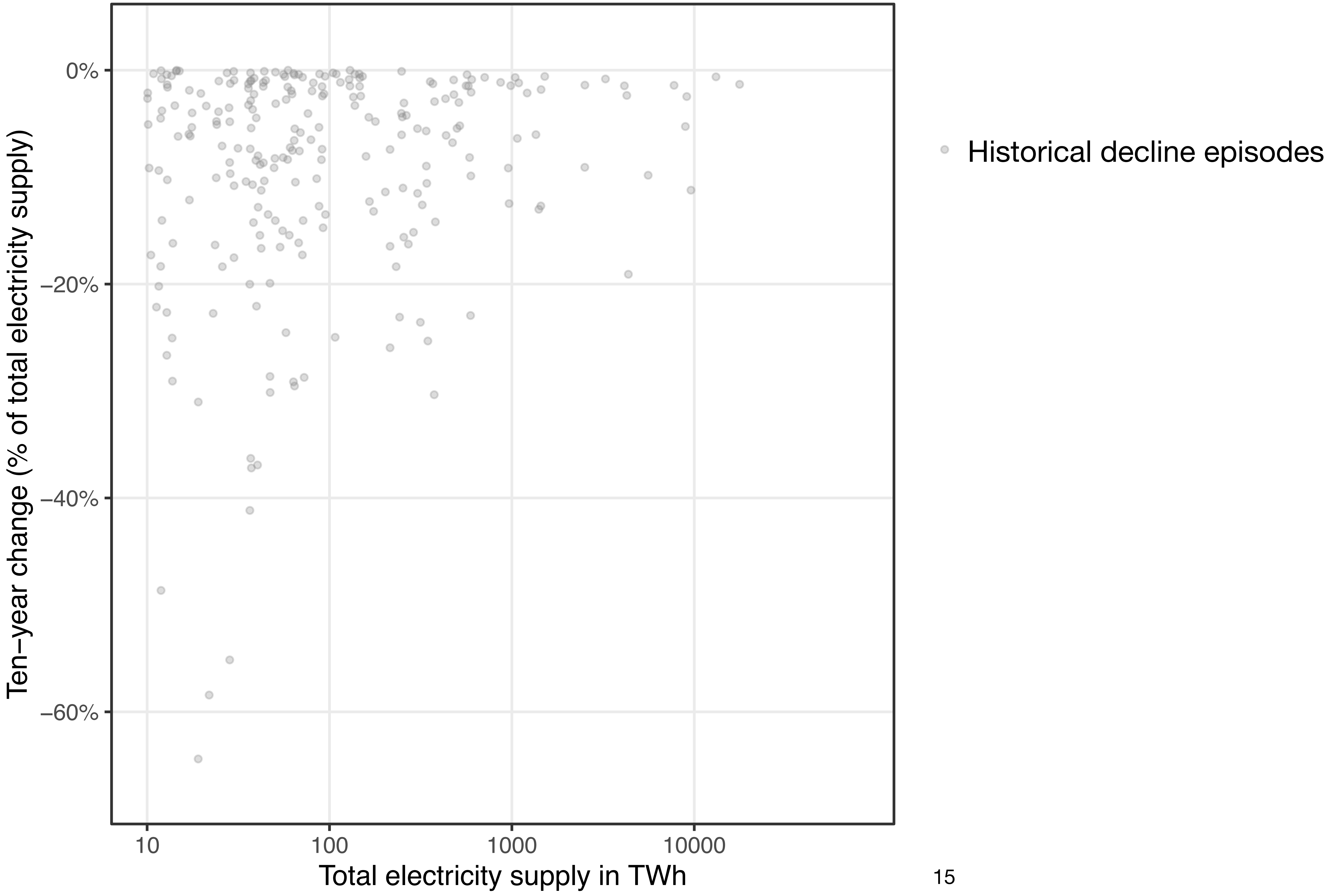
Annual average growth/decline



- Captures actual growth/decline
- Reflects systemic significance of the change (% relative to the electricity system size)
- Comparable across countries/regions
- Does not depend on the form of the growth/decline curve
- Can be measured for both historical and future* changes (*projections/targets/scenarios)
- Typically used for longer-term changes

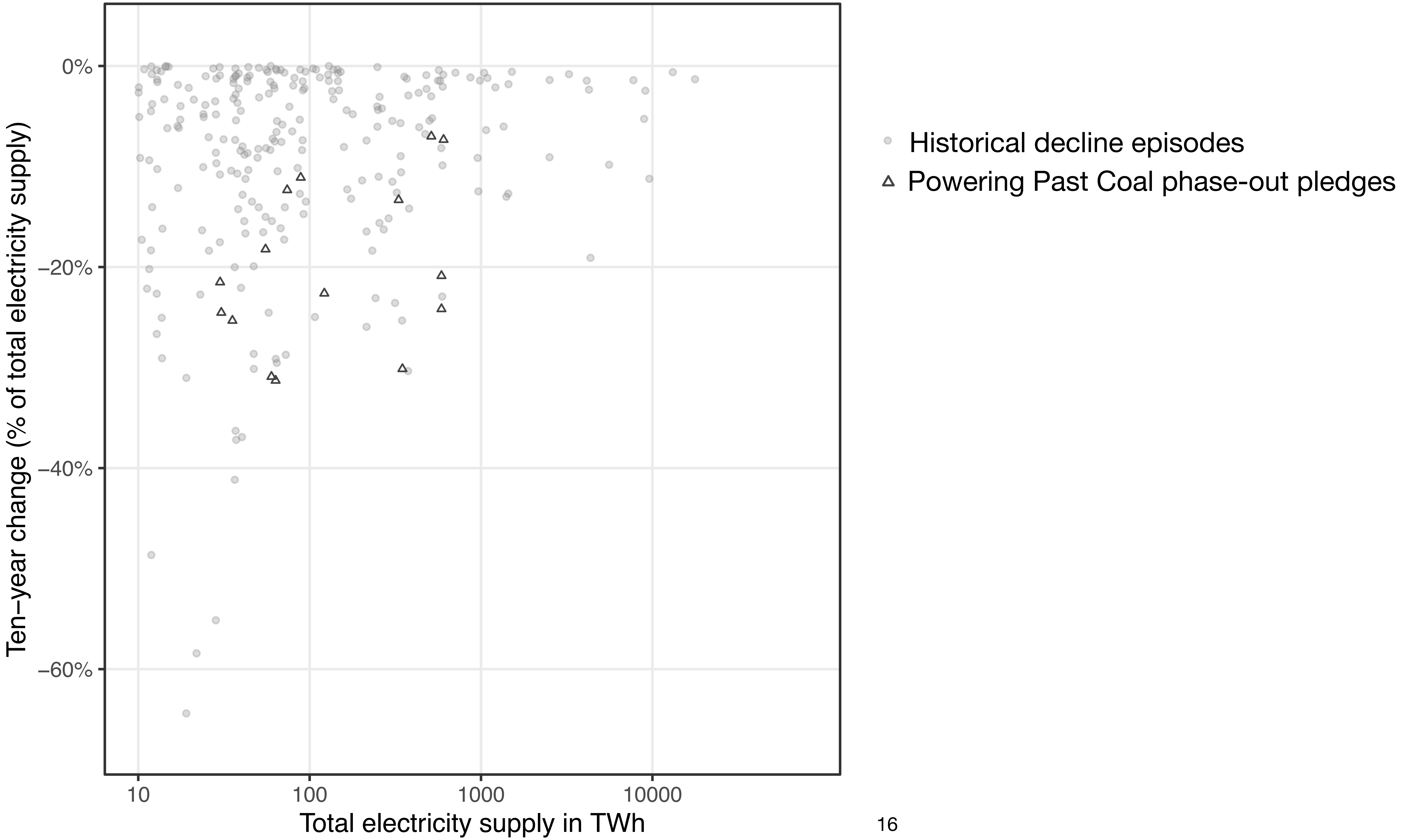
Episodes of fossil fuel decline

132 cases where fossil fuels declined > 5%



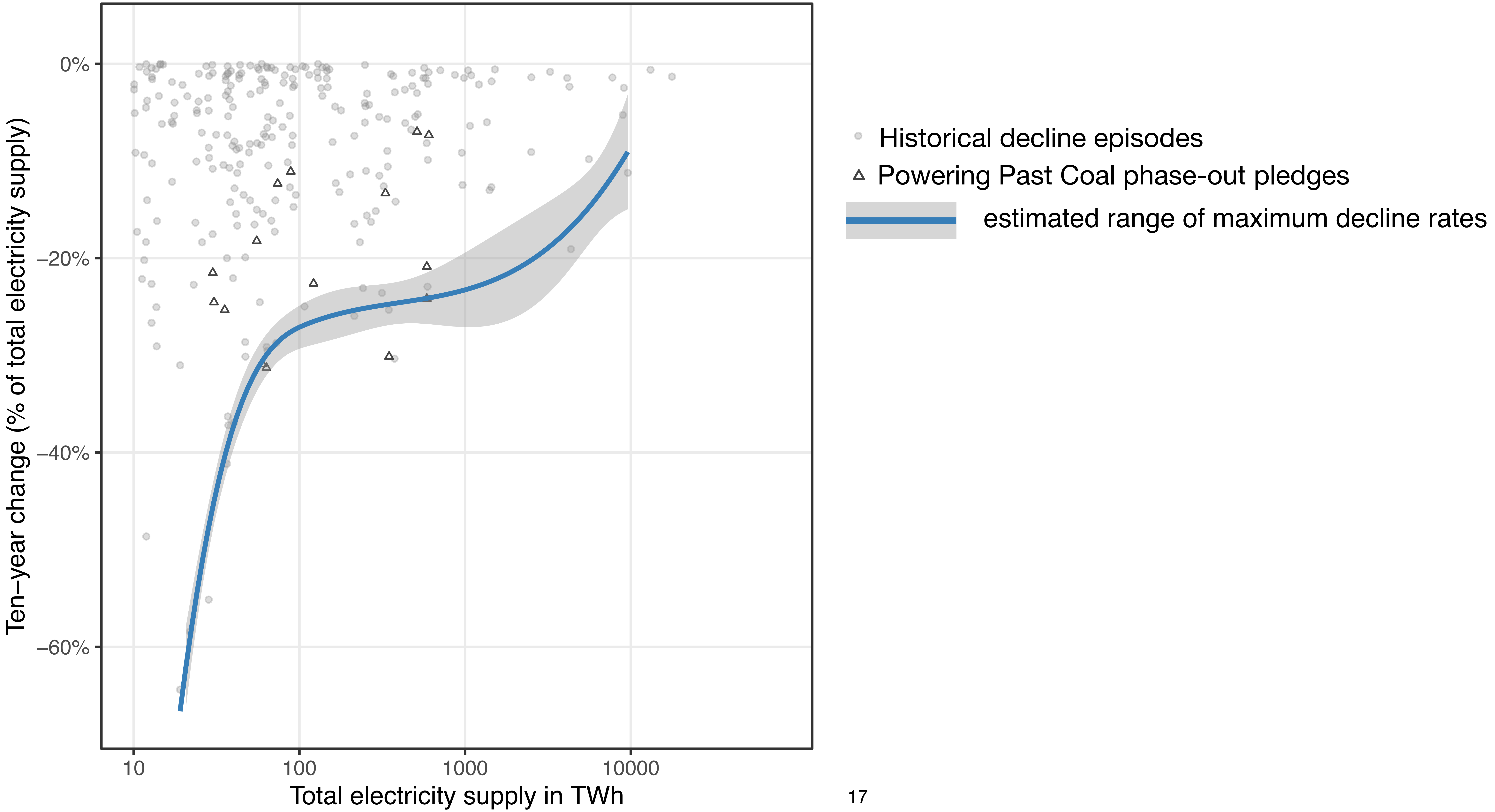
Episodes of fossil fuel decline

132 cases where fossil fuels declined > 5% + 15 pledges



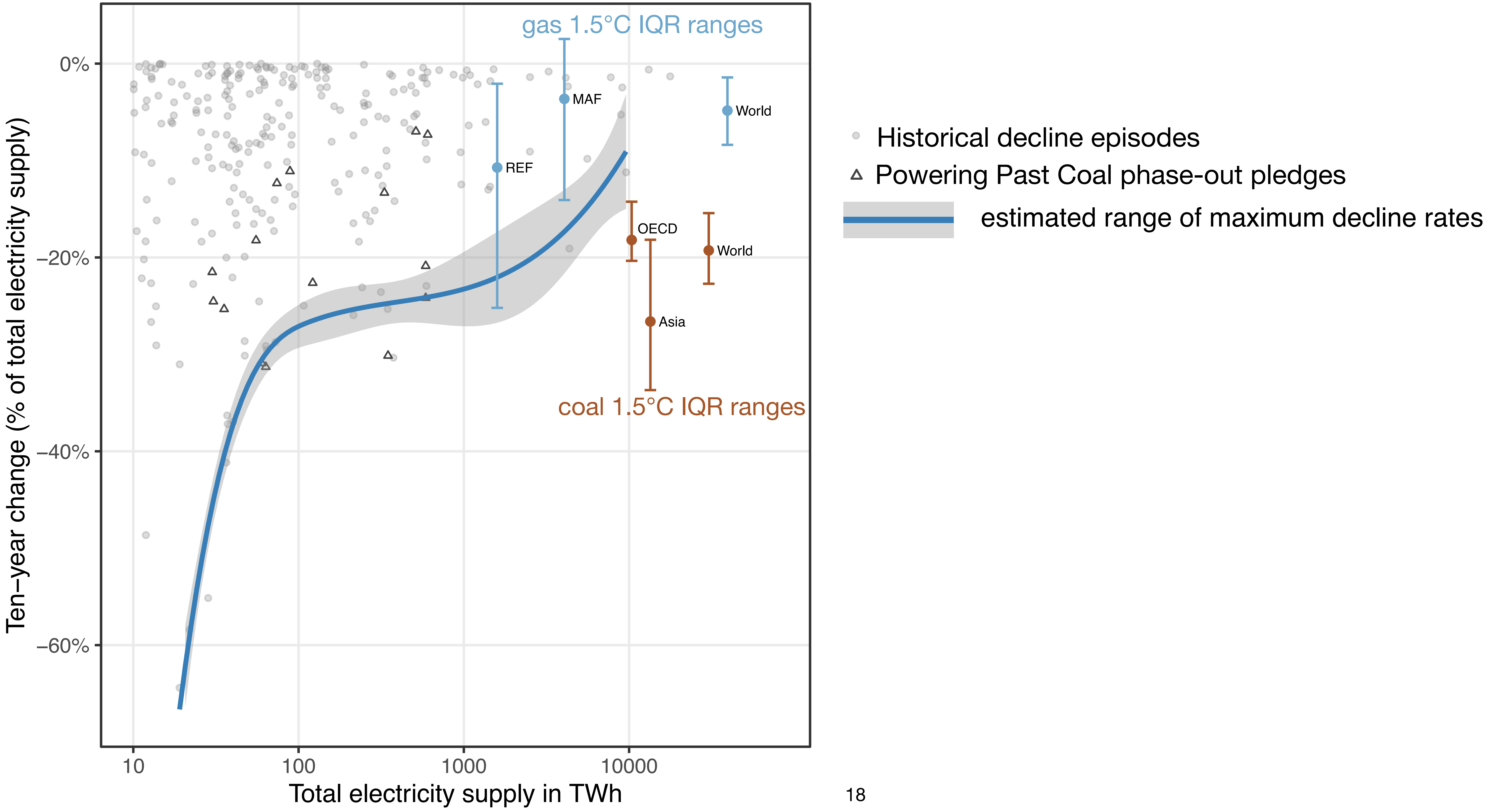
Episodes of fossil fuel decline

Smaller systems achieve faster decline rates



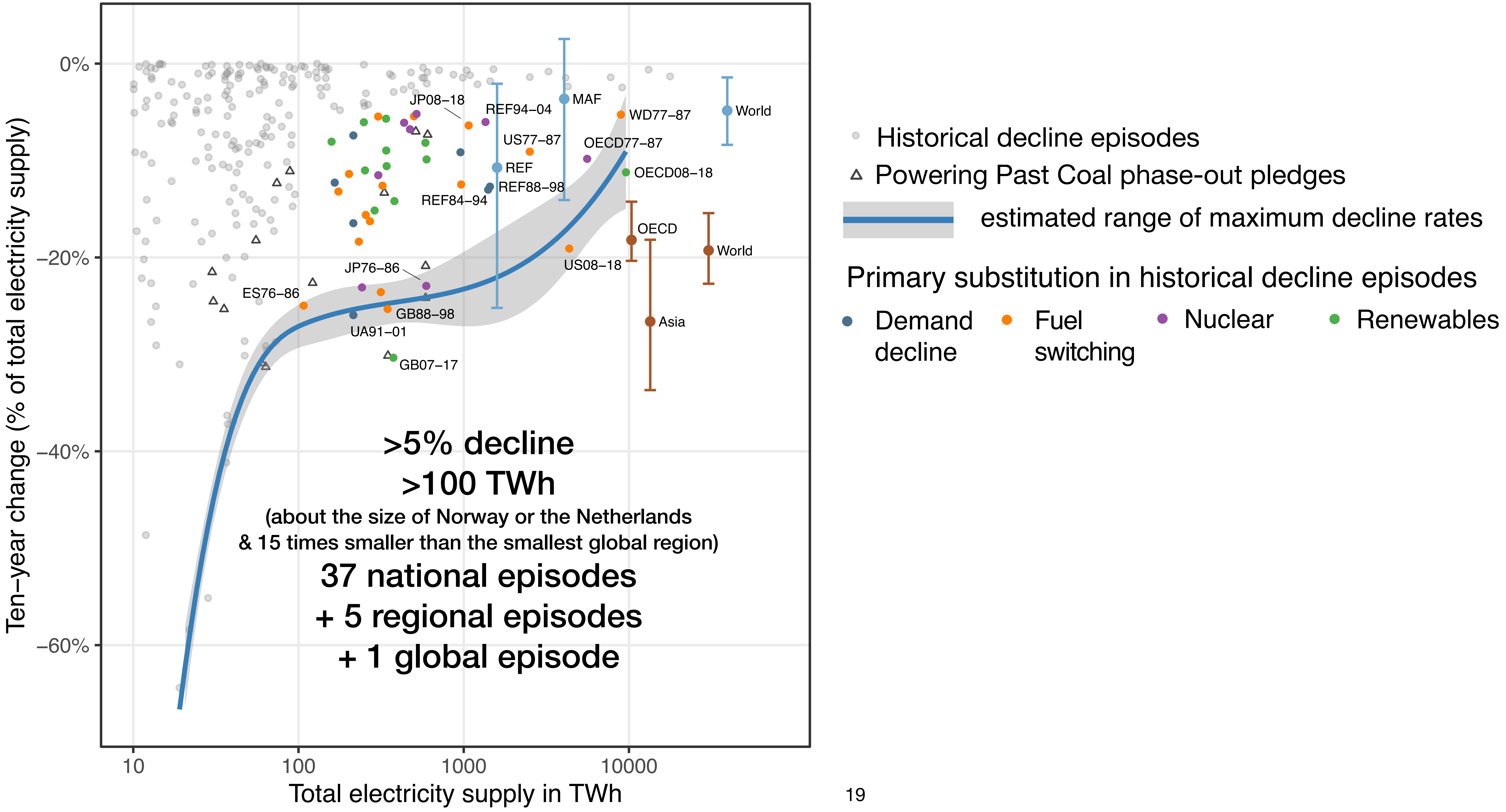
Episodes of fossil fuel decline

Smaller systems achieve faster decline rates



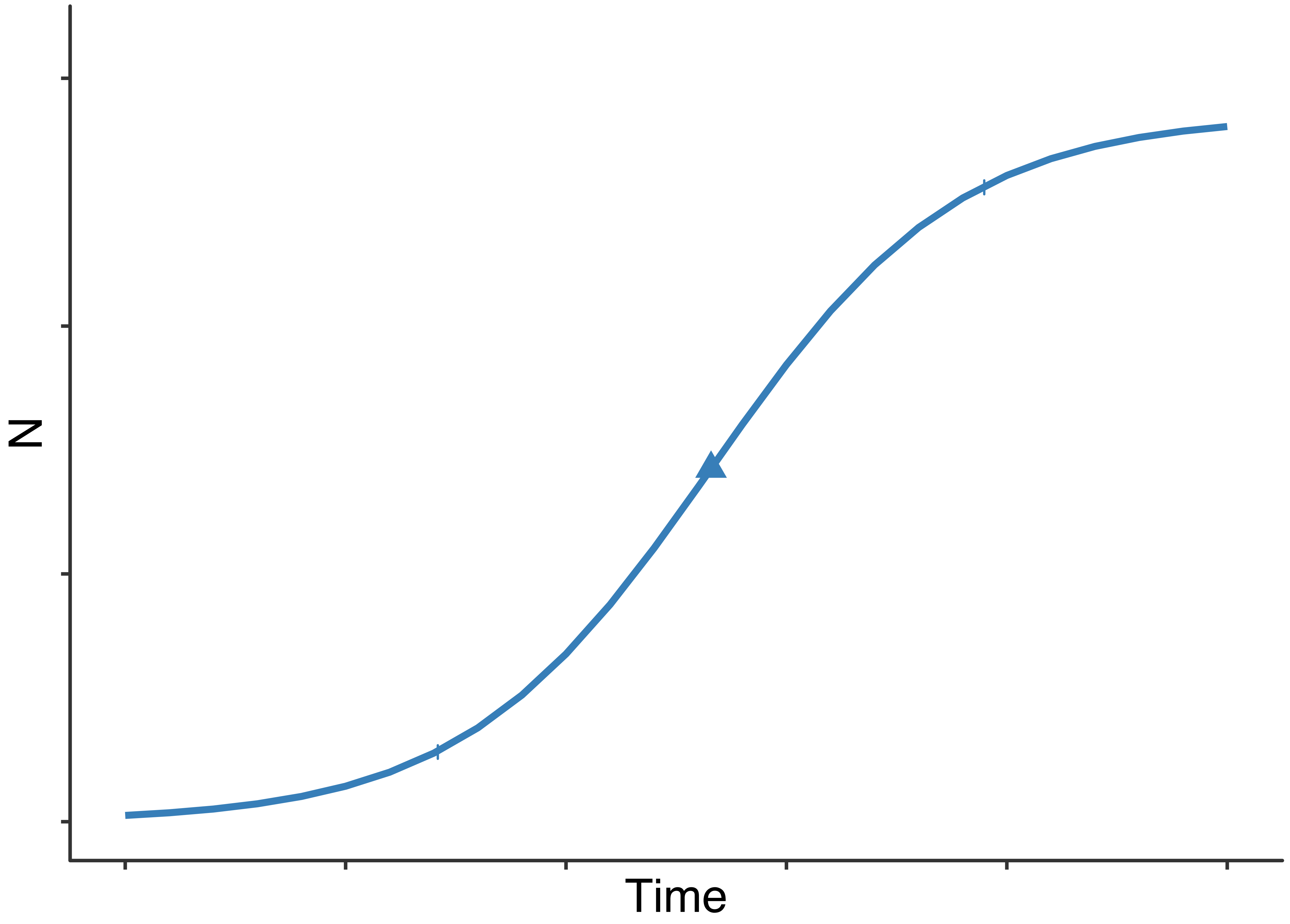
Episodes of fossil fuel decline

Significan episodes for further analysis



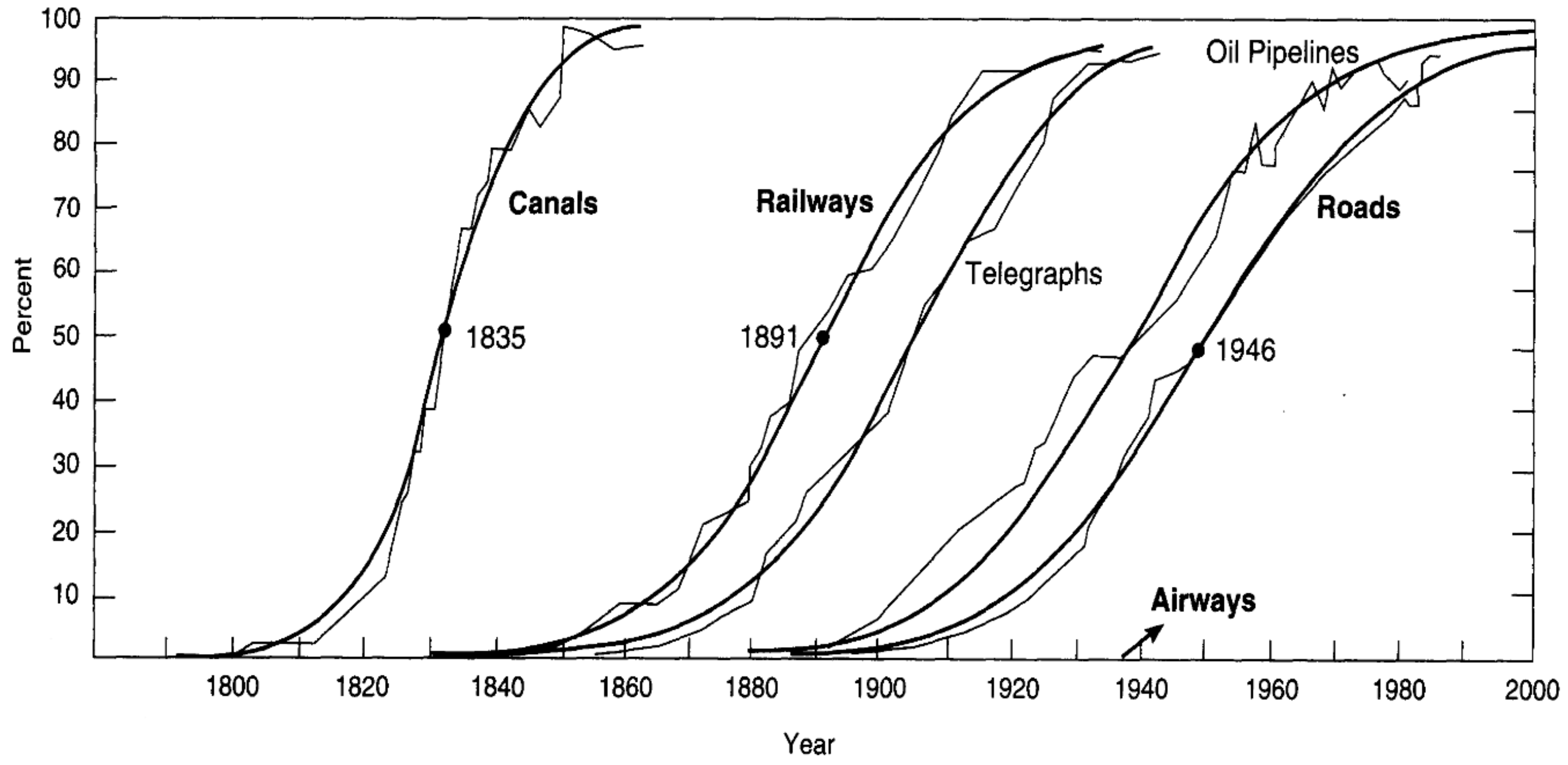
An introduction to growth models

An S-curve



Diffusion of new technologies: S-curves

Figure 4. Growth of Infrastructures in the United States as a Percentage of their Maximum Network Size.

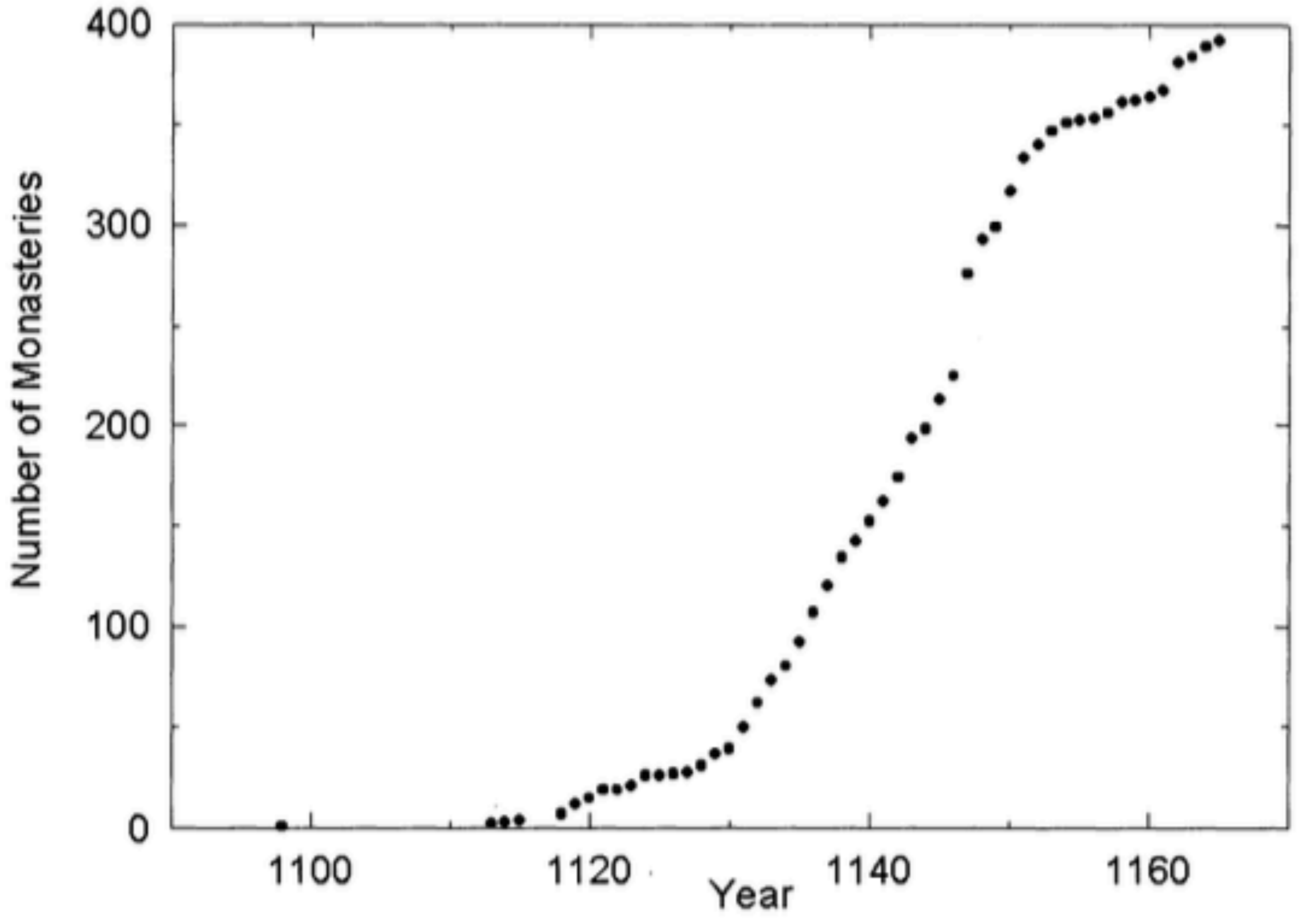


Source: Arnulf Grübler and Nebojša Nakićenović, "Long Waves, Technology Diffusion, and Substitution," *Review* 14 (2) (Spring 1991): 313–342.

Grubler 1996

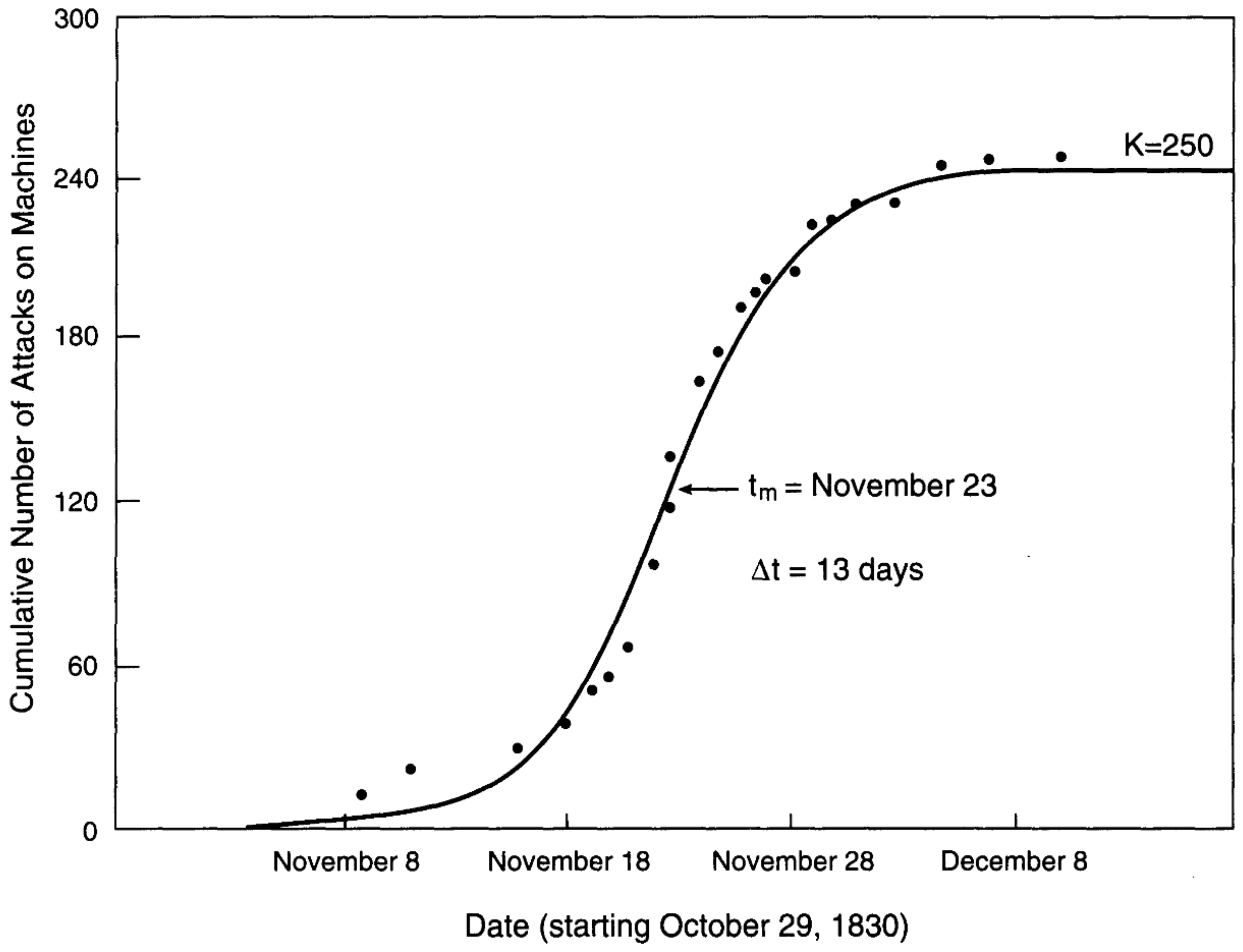
Diffusion of innovations: S-curves

Figure 1. The Initial Diffusion of Cistercian Monasteries in Europe.



Data Source: P. L. Janauschek, *Originum Cisterciensium*, Tomus I (Vienna: A. Hoeler, 1877).

Figure 2. Resistance to Technology as a Diffusion Process: Number of Threshing Machines Attacked during the Captain Swing Movement in England in 1830.



Note: Actual data and a fitted three-parameter logistic curve. See endnote 13.

Data Source: E. J. Hobsbawm and George Rudé, *Captain Swing* (New York: Pantheon Books, 1968).

Grubler 1996

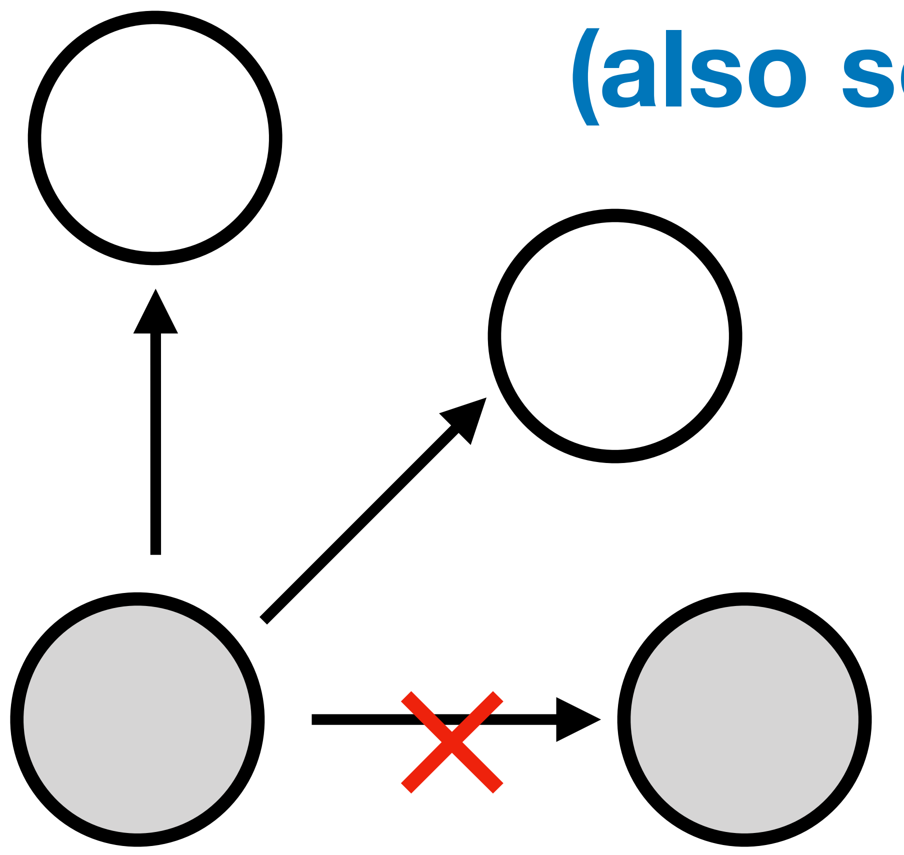
Diffusion of innovations: explanations of an S-curve

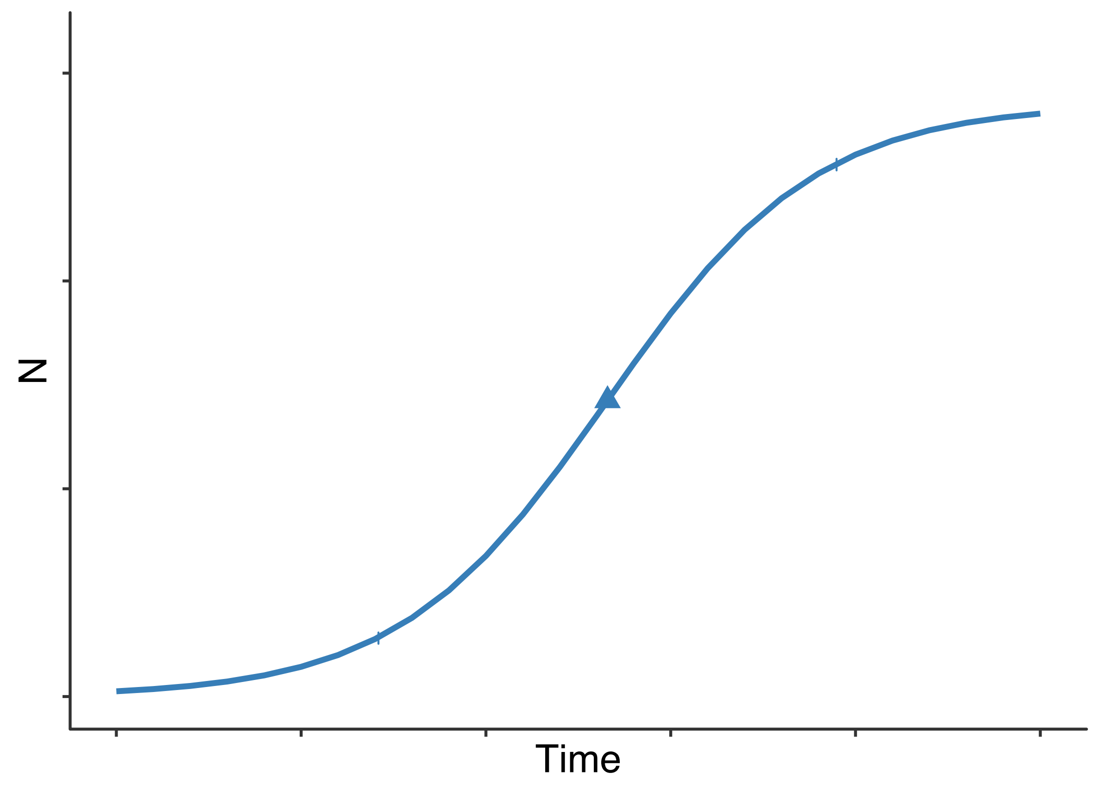
- S-curve mechanisms:
  - Sociological

Diffusion of innovations: explanations of an S-curve

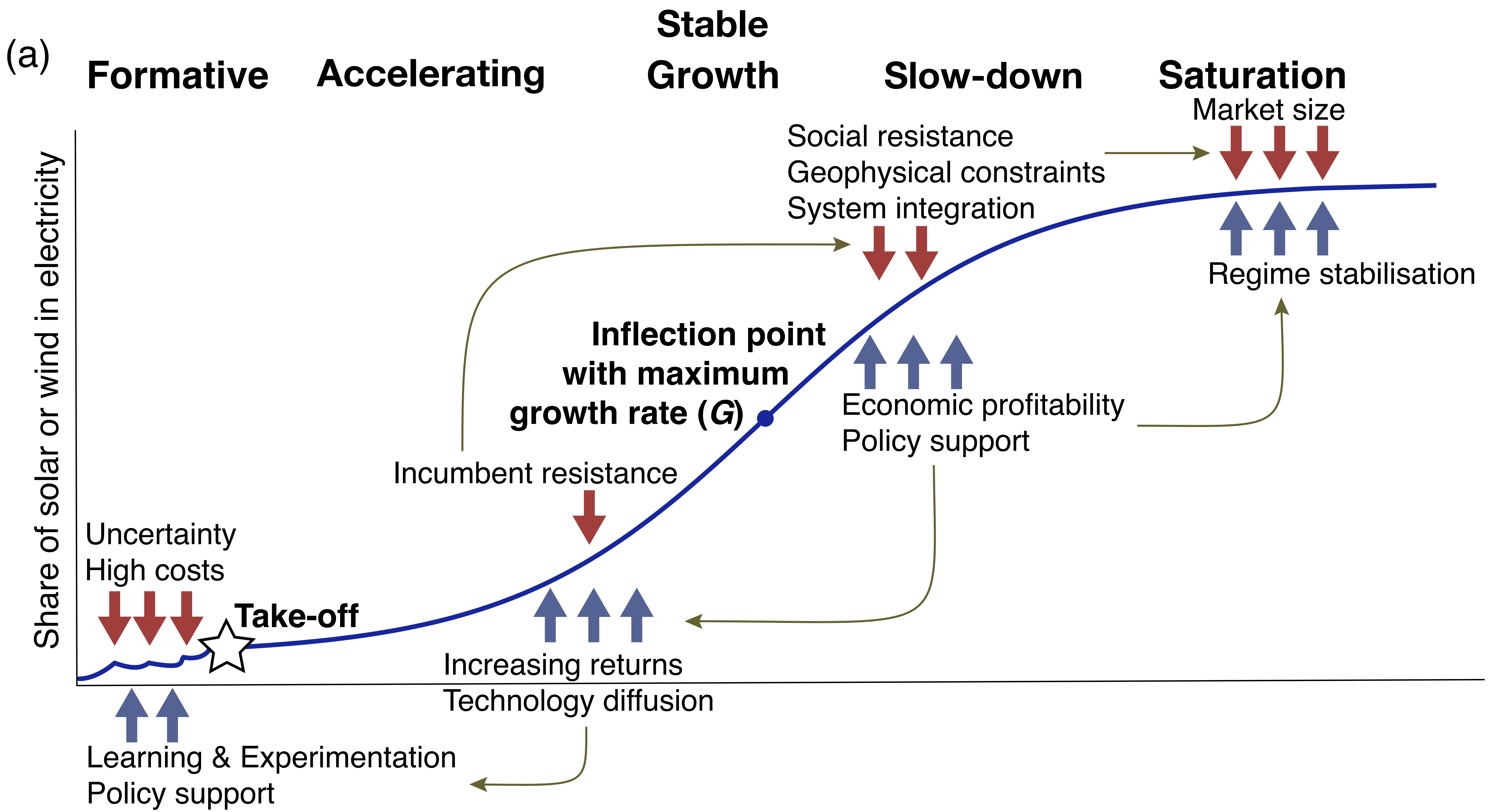
- S-curve mechanisms:
  - Sociological
  - Epidemiological →
  - Changing characteristics of the technology due to learning (e.g. costs, performance)

Contagion
(also sociology: information spread)





Mechanisms over the S-curve of technology adoption



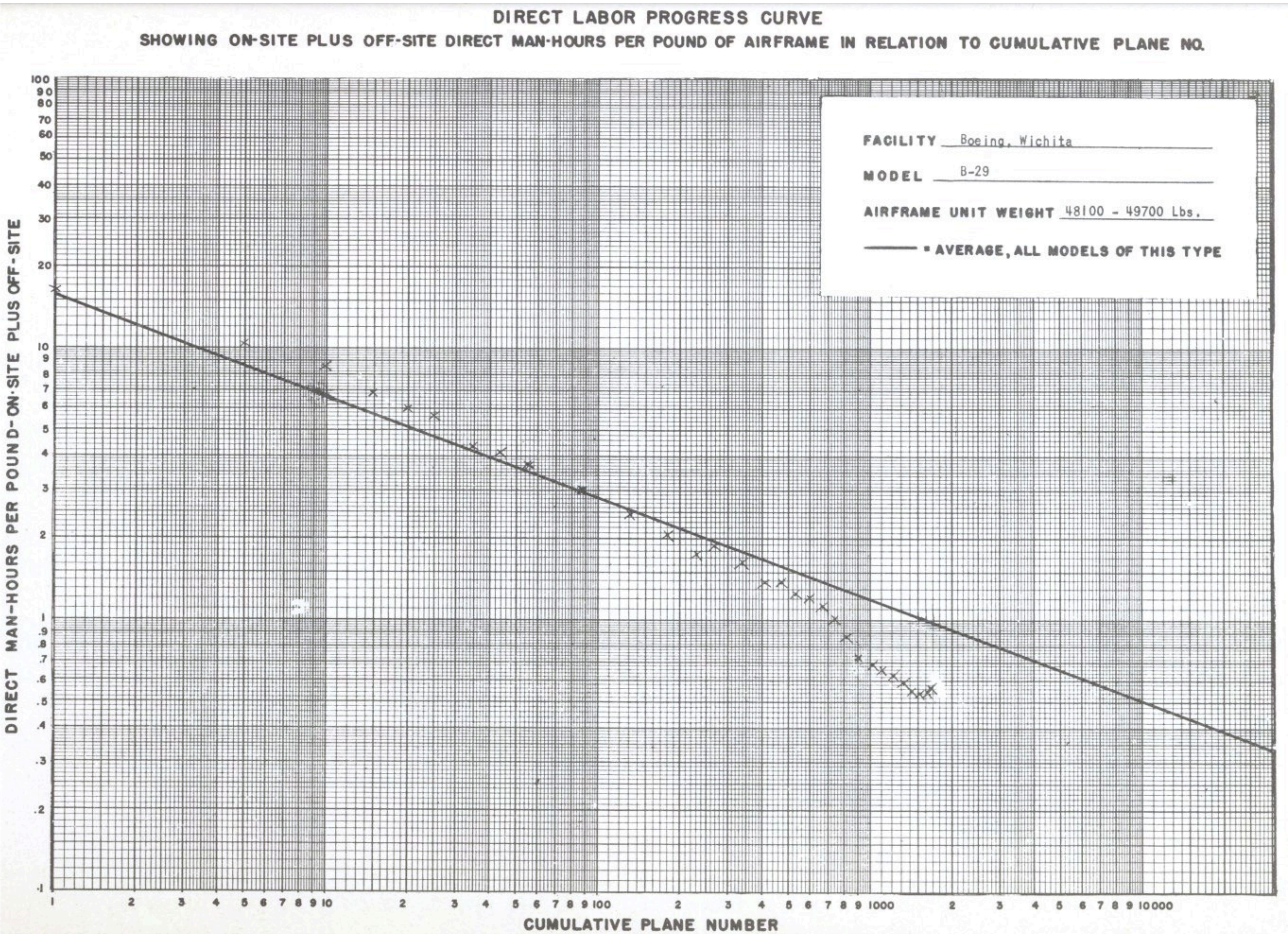
Cherp, Vinichenko, Jewell et al. *2021*

Learning: Write's law

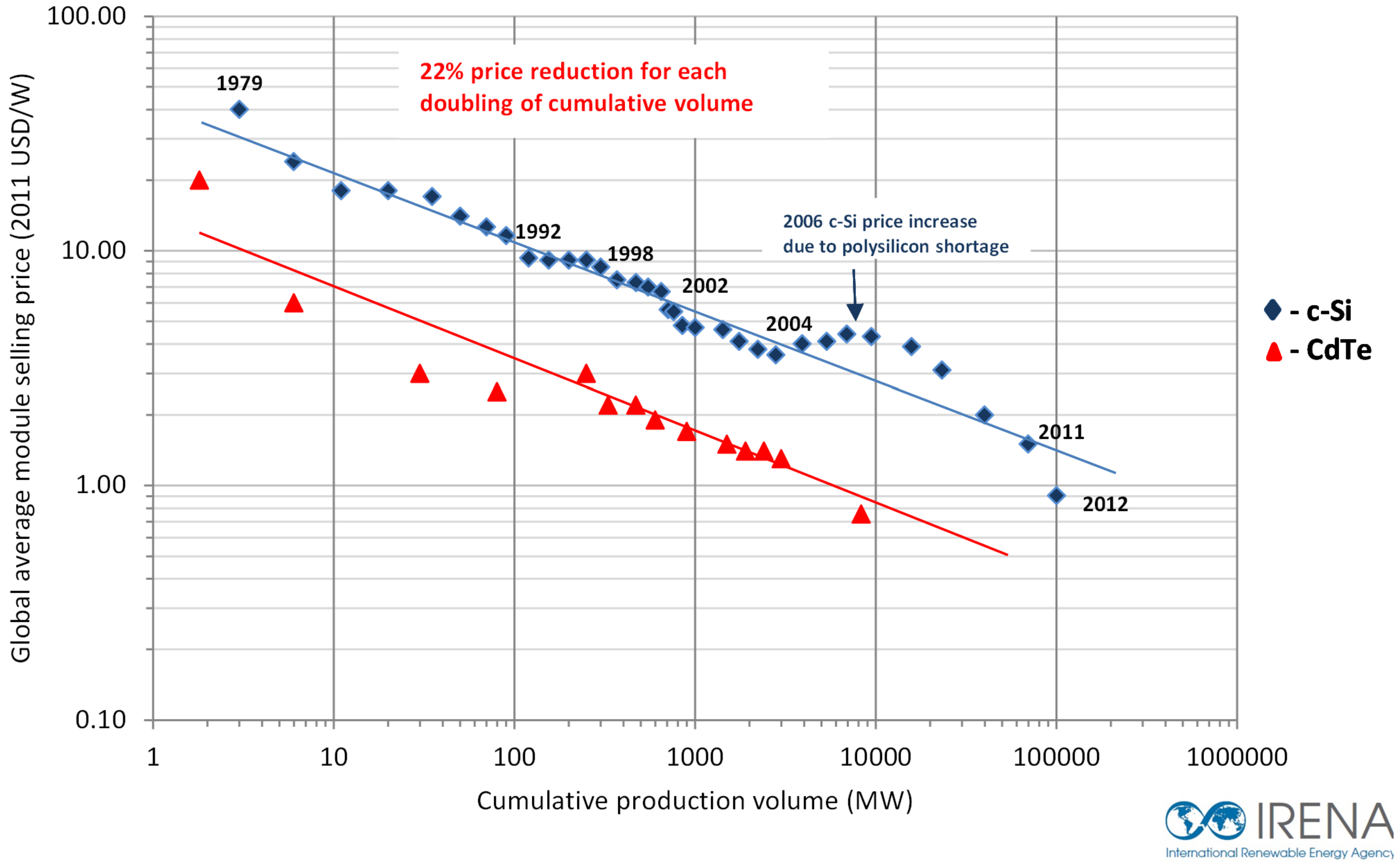
For every doubling of the output, the required labor time for a new unit declines by 20%...

...or declines 2 times when the output grows 10 times

A power law (straight line in log-log coordinates)



Learning: solar panels



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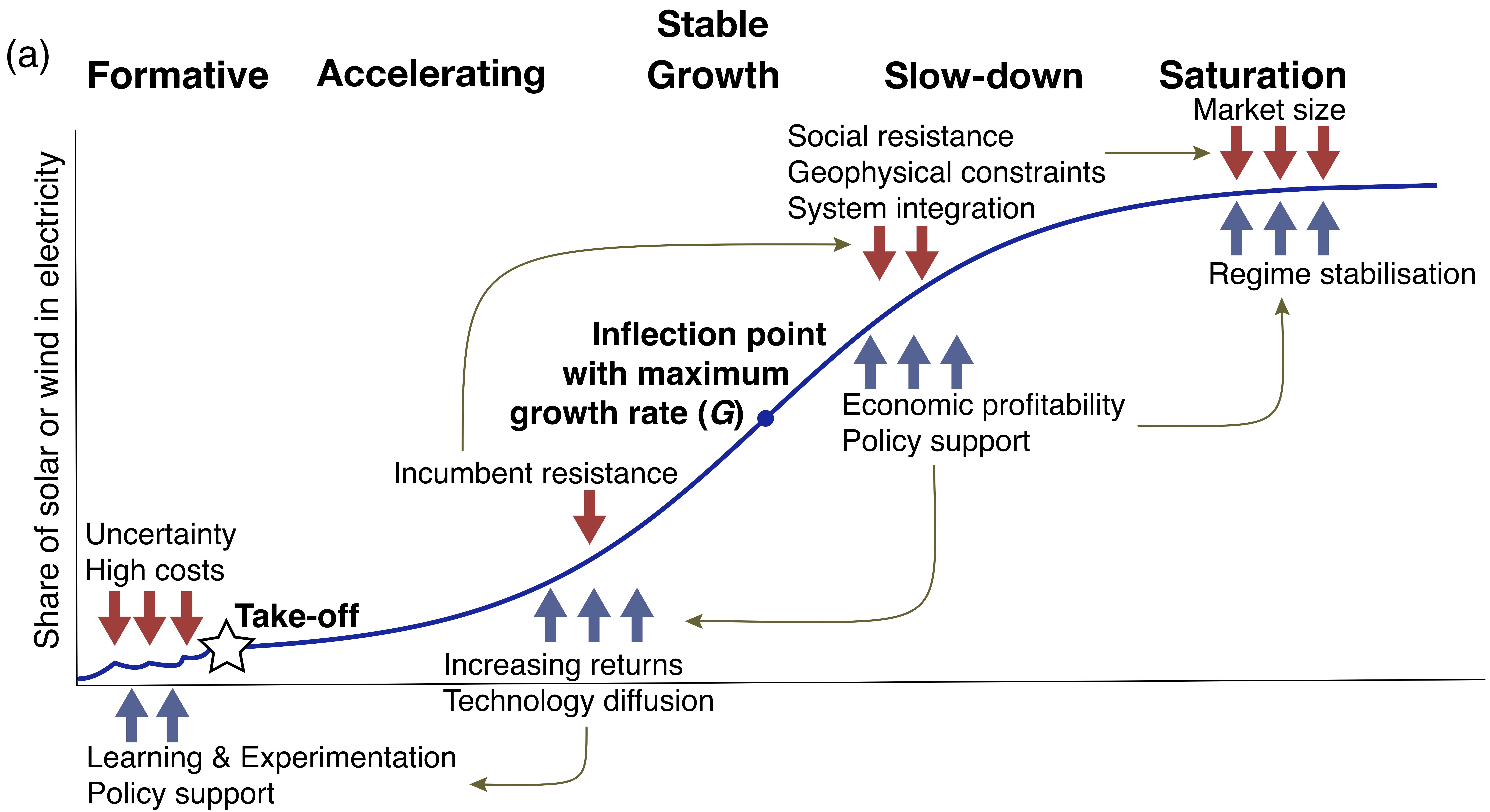
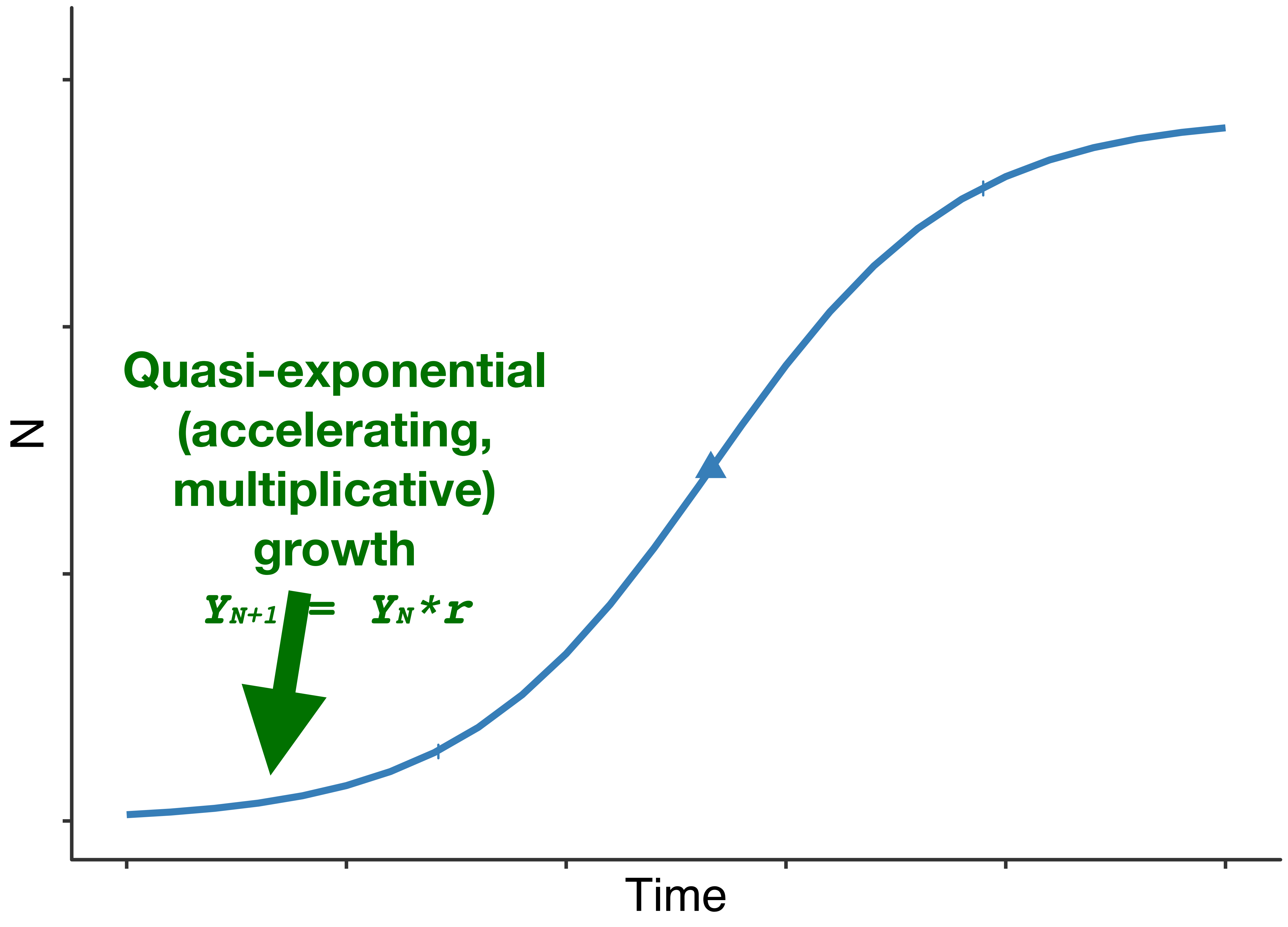


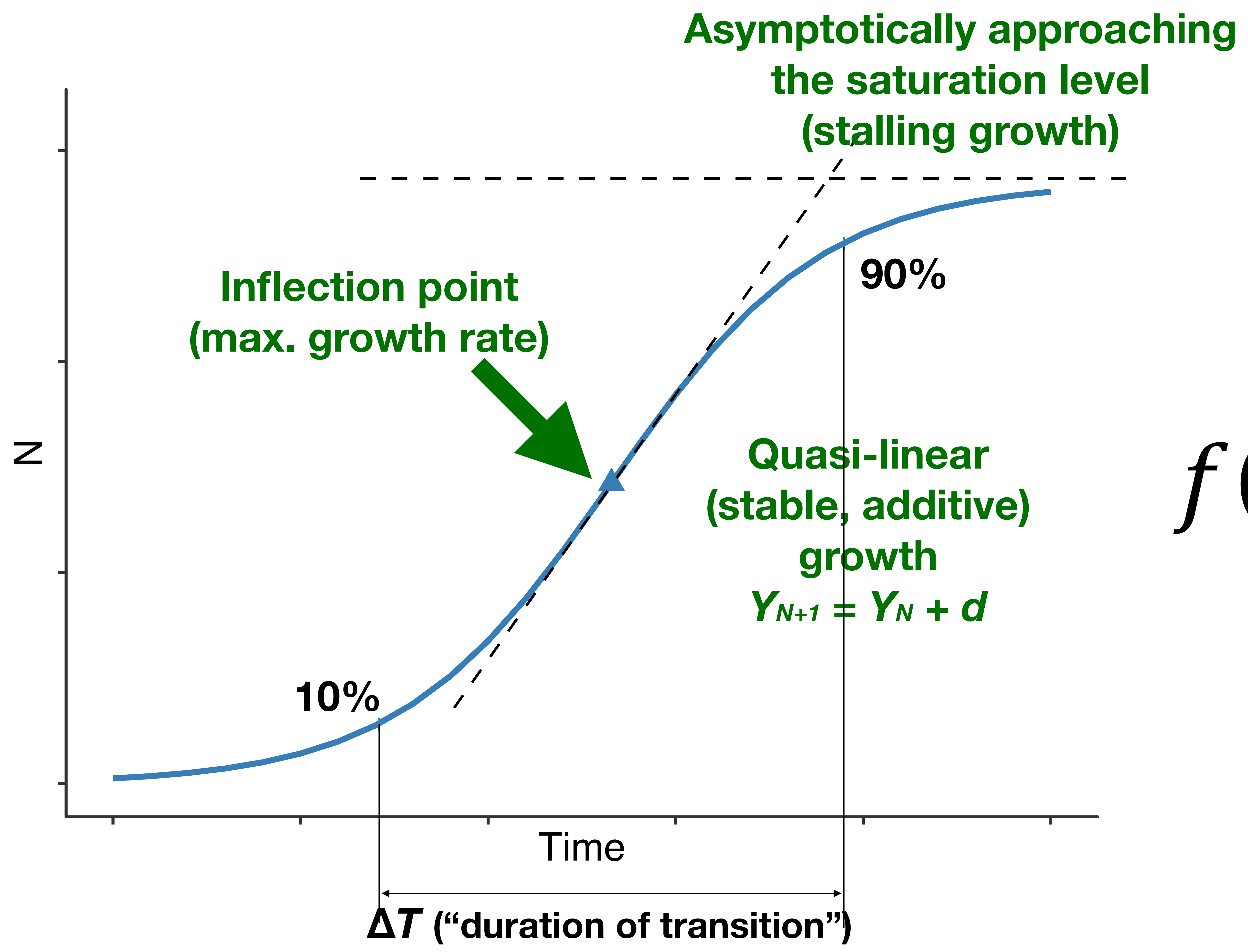
Cherp, Vinichenko, Jewell et al. *2021*

The most famous S-curve: logistic curve



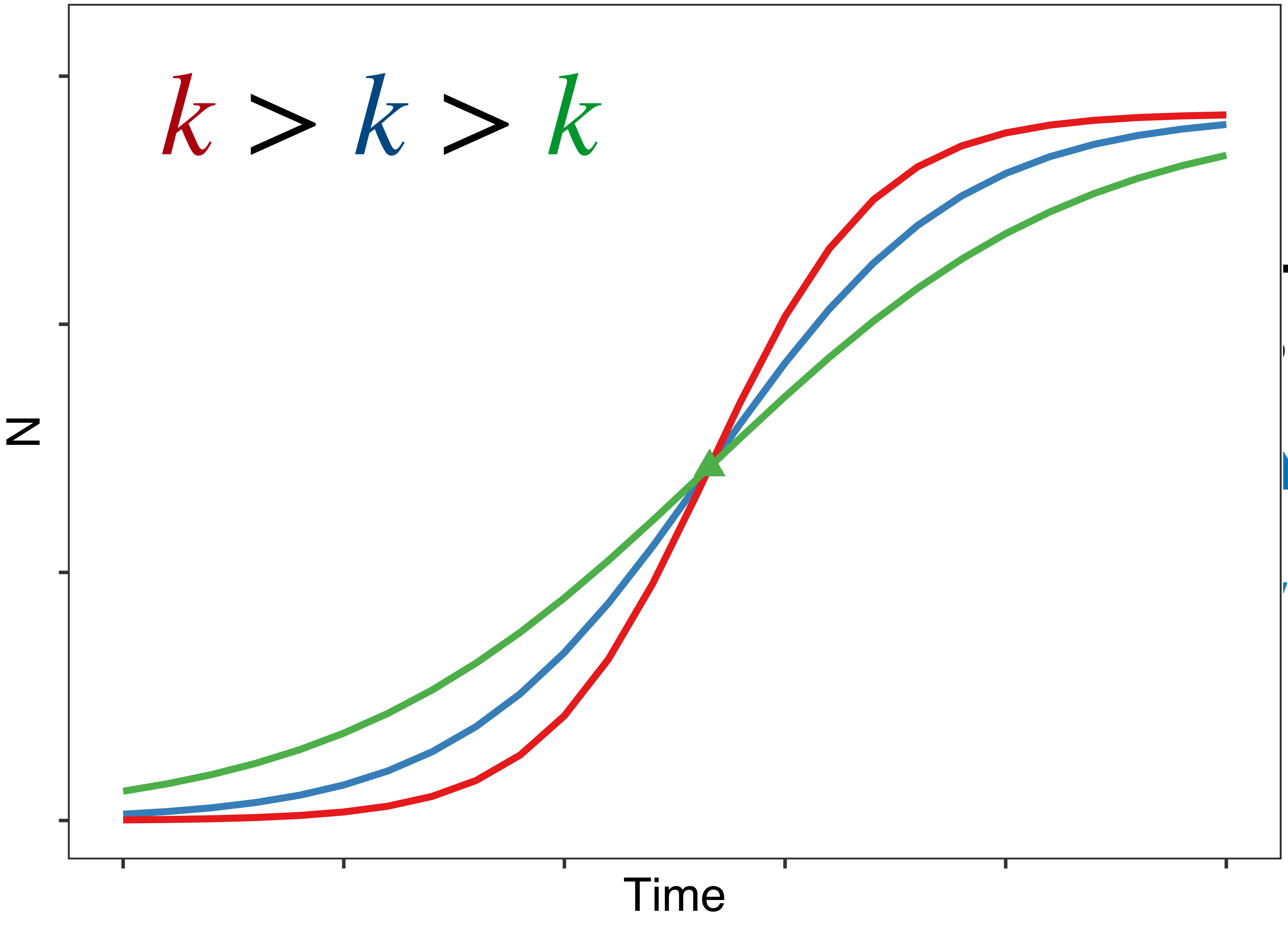
$$f(t) = \frac{L}{1+e^{-k(t-t_0)}}$$

The most famous S-curve: logistic curve



$$f(t) = \frac{L}{1+e^{-k(t-t_0)}}$$

Parameters of a growth model (logistic)



$$\frac{L}{\quad -k(t-t_0)}$$

Parameters of a growth model

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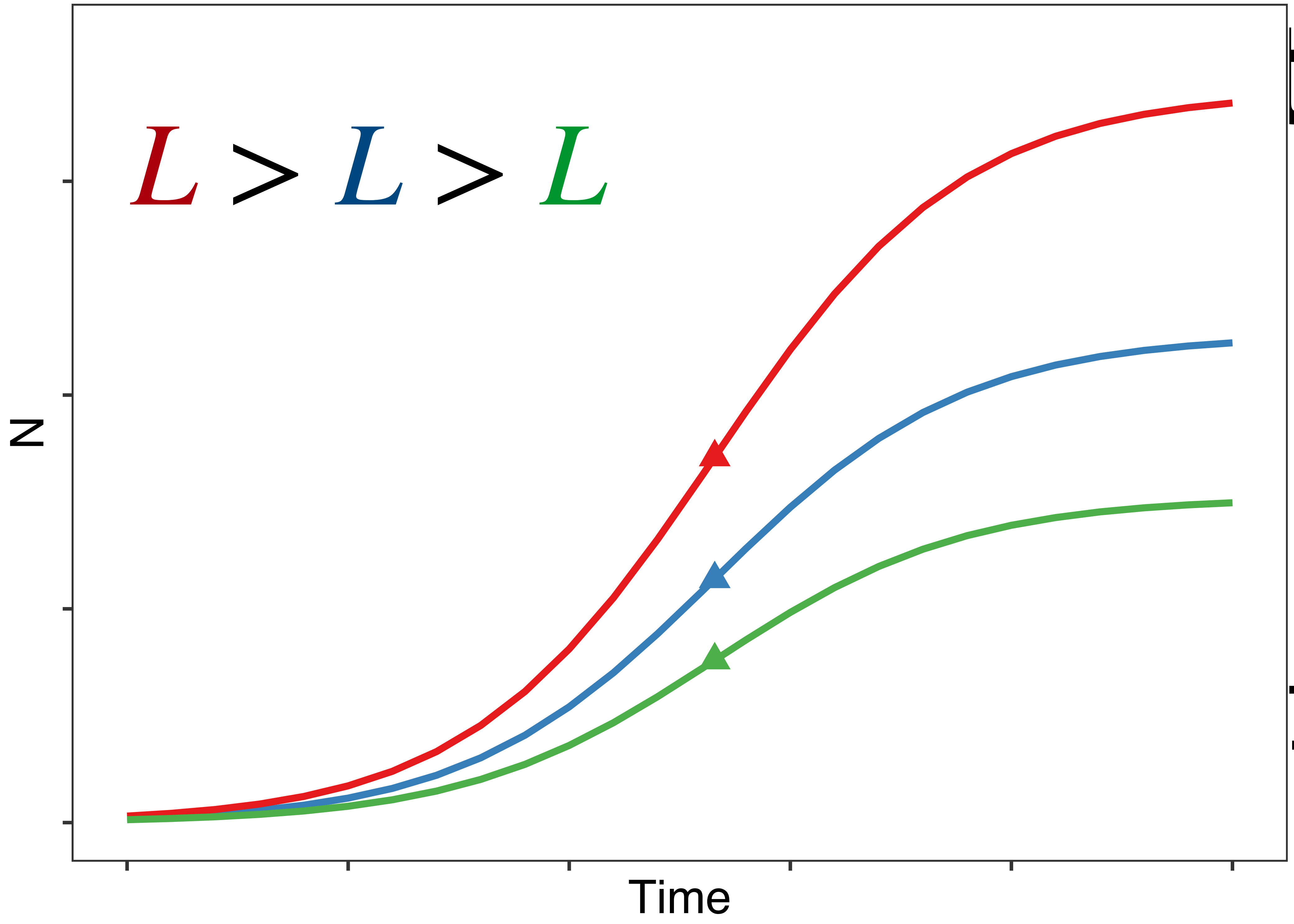
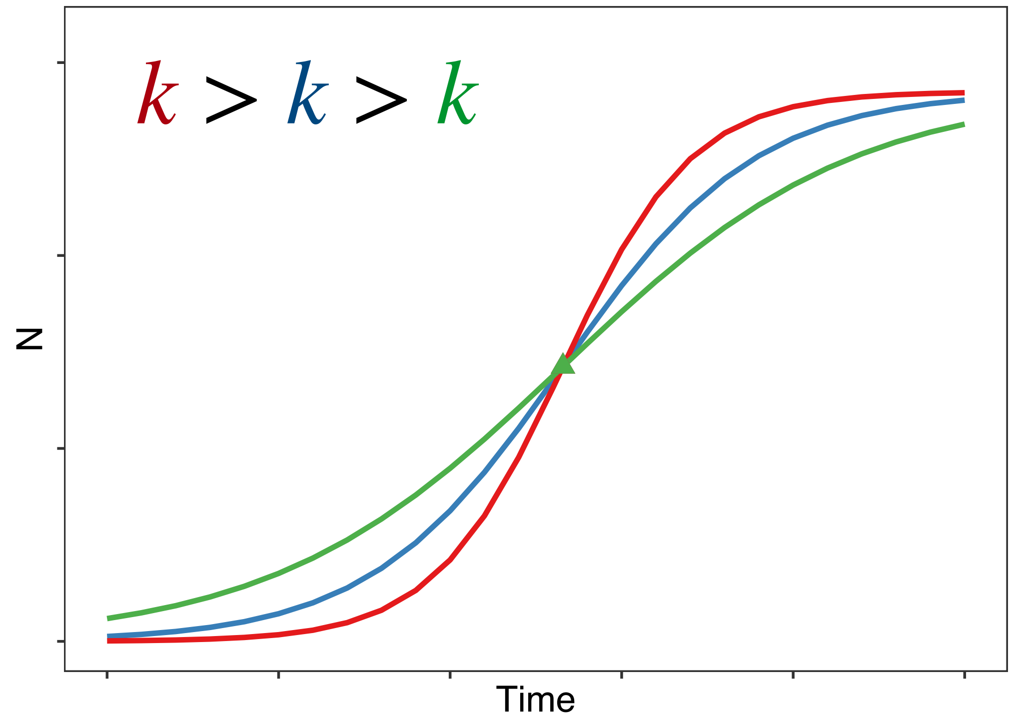


$$\frac{L}{-k(t-t_0)}$$



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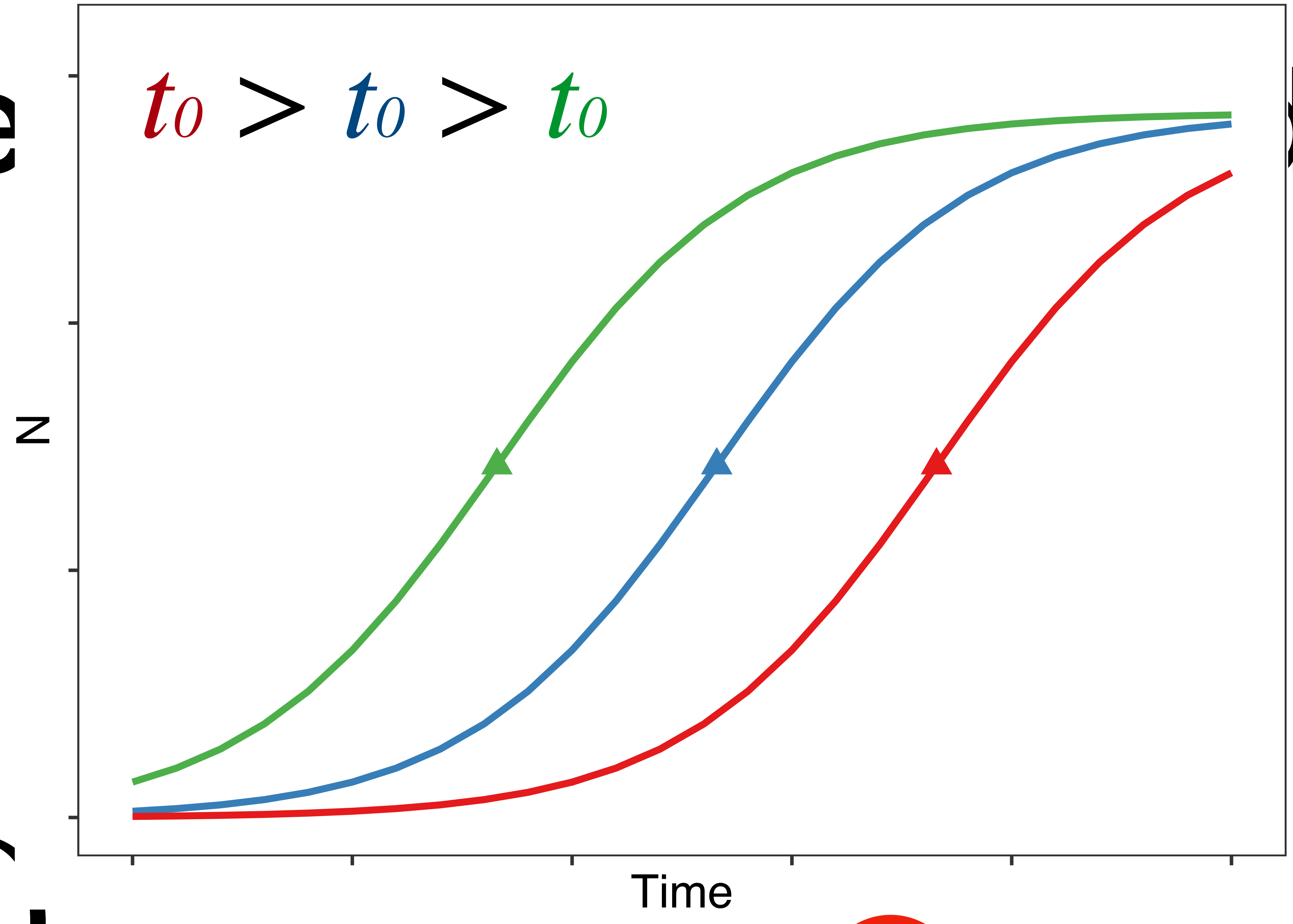
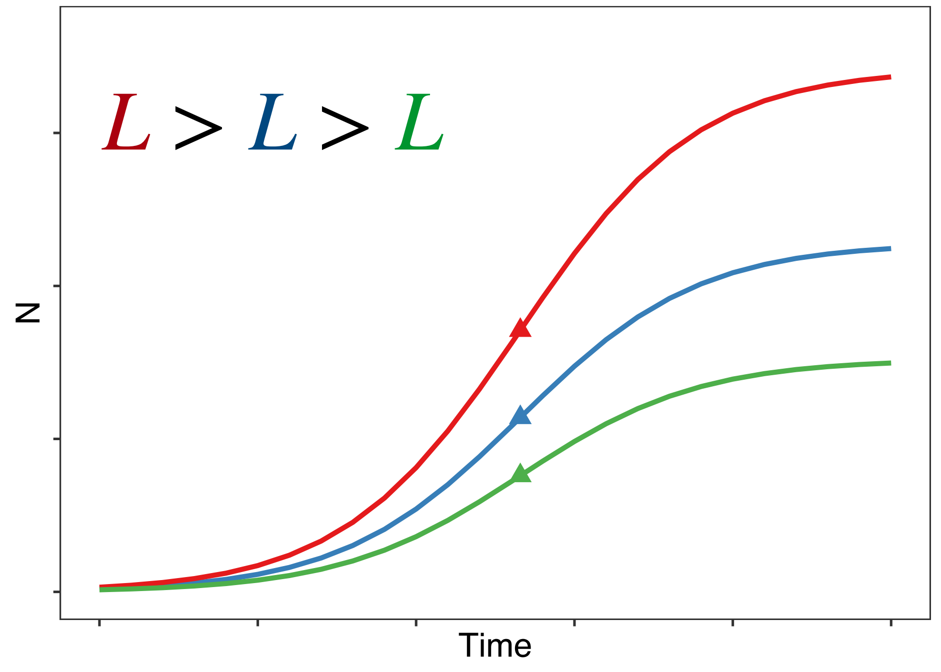
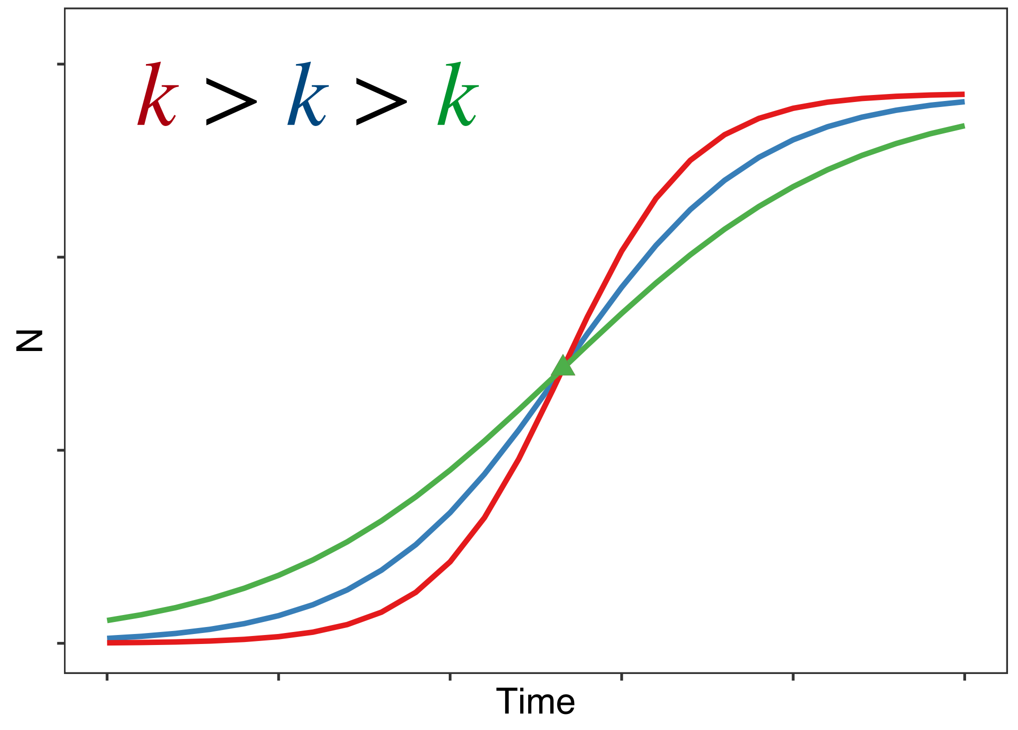
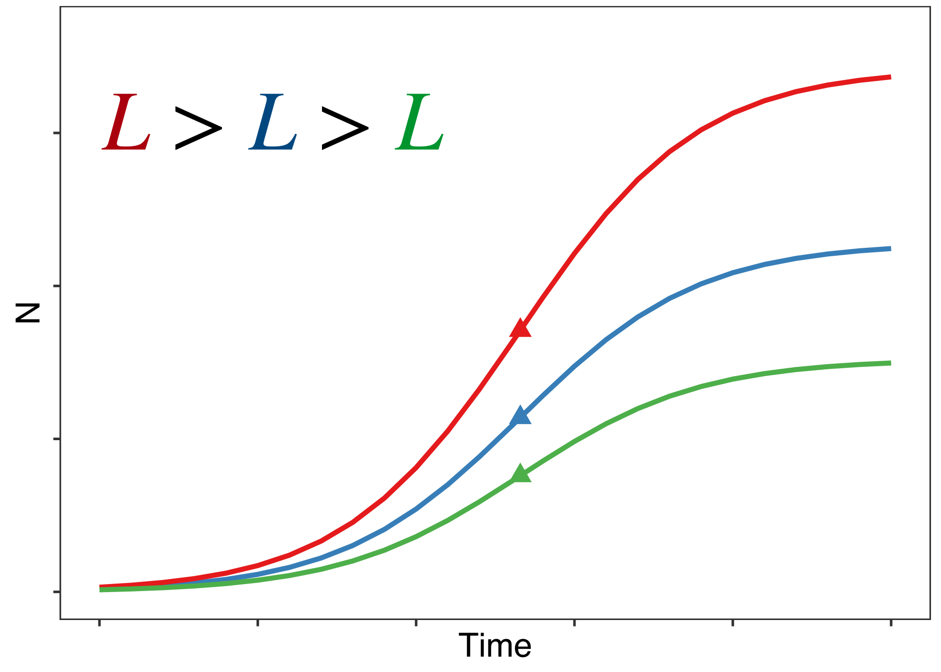


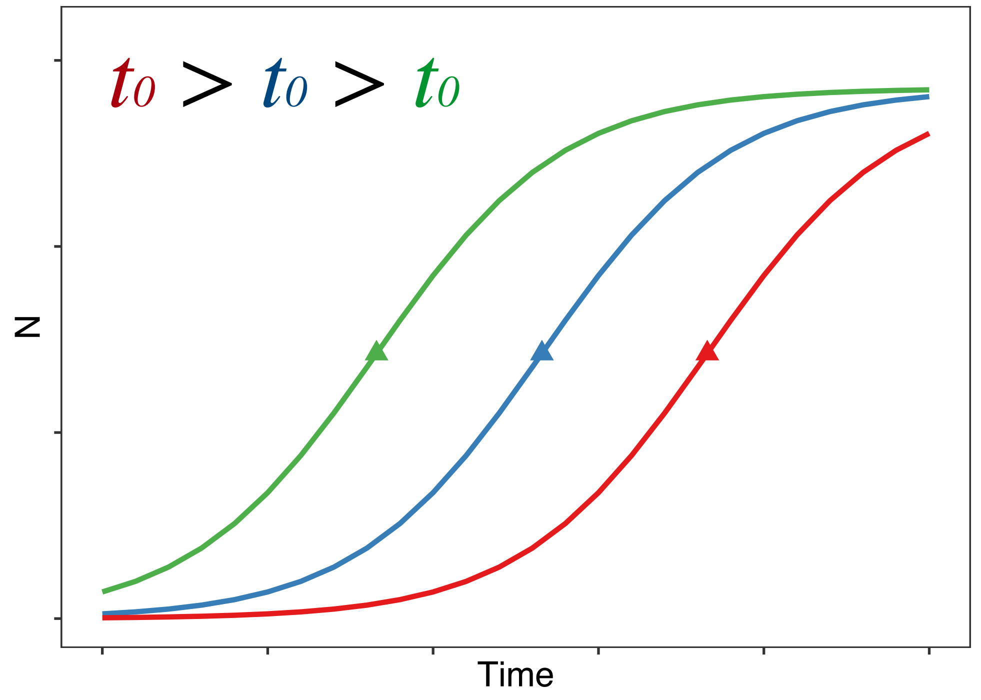


$$f(t) = \frac{}{1+e^{-k(t-t_0)}}$$



Parameters of a growth model (logistic)





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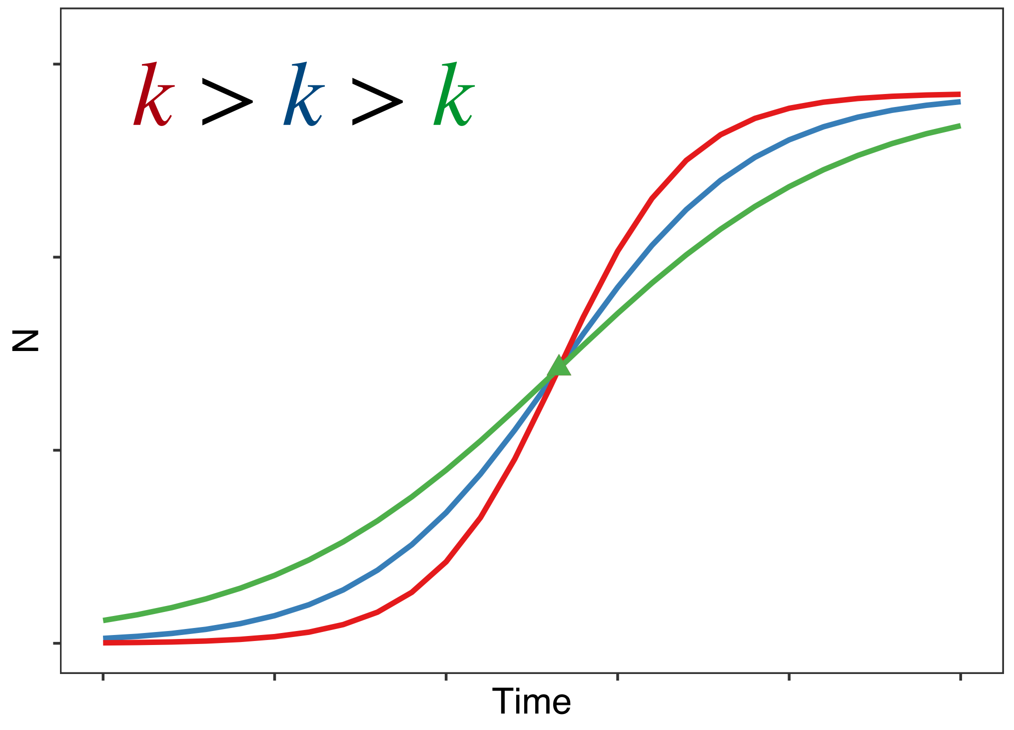


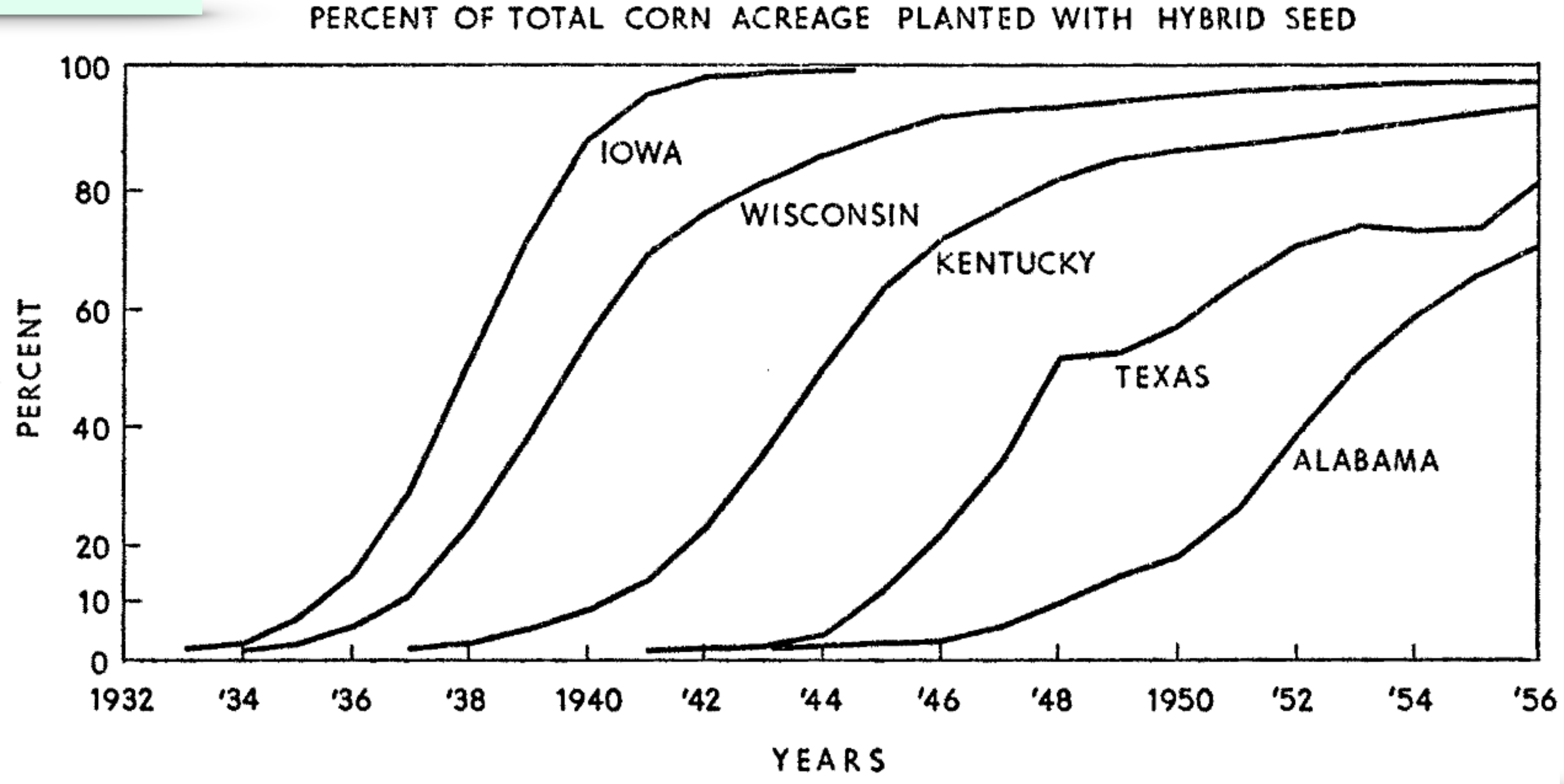
Comparing technology diffusion

ECONOMETRICA

VOLUME 25 | October, 1957 | NUMBER 4

HYBRID CORN: AN EXPLORATION IN THE ECONOMICS OF TECHNOLOGICAL CHANGE [1]

BY ZVI GRILICHES



How to measure technology growth?

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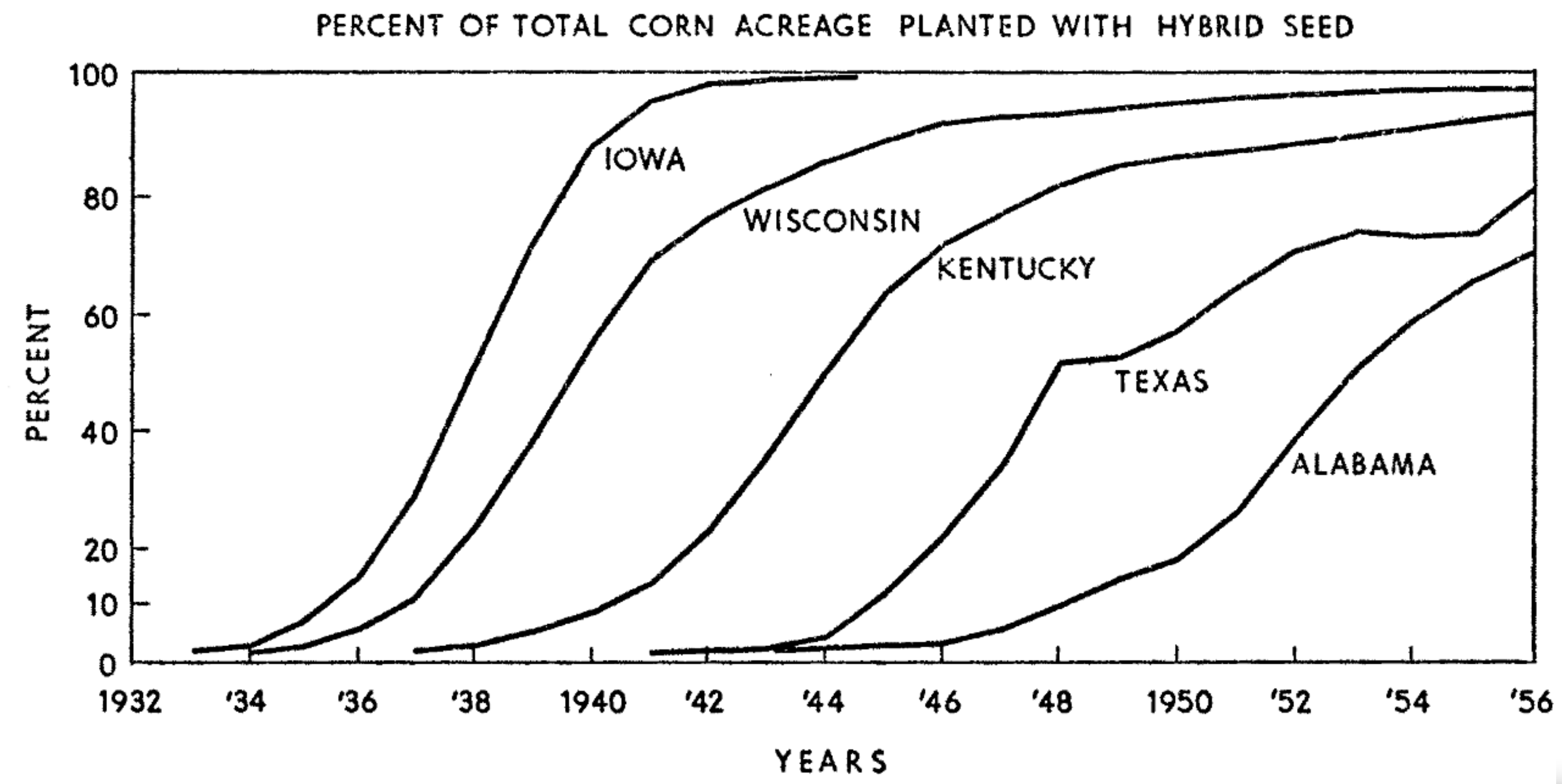
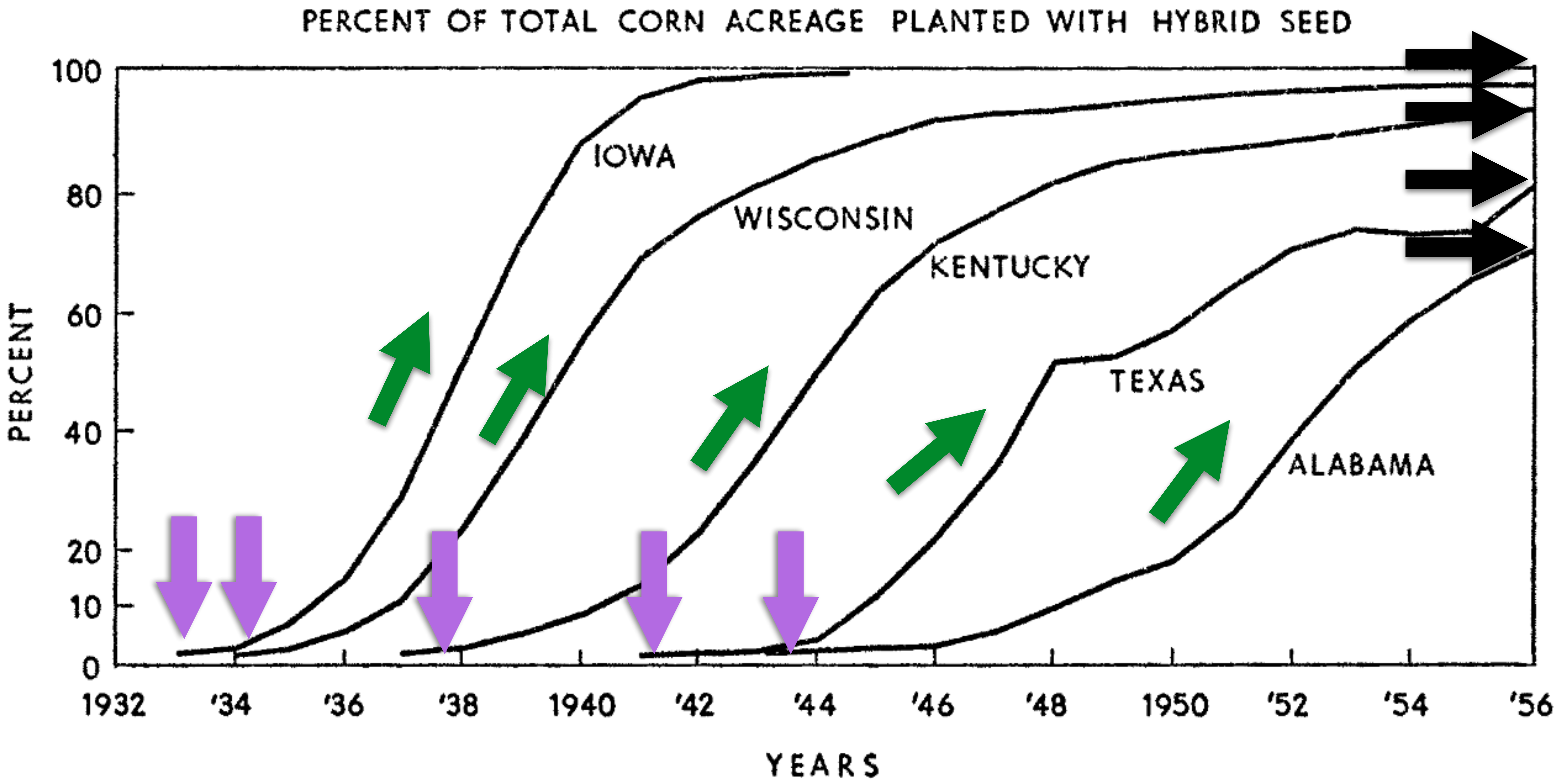


2. THE METHOD AND THE MODEL

A graphical survey of the data by states and crop reporting districts along the lines of Figure 1 led to the conclusion that nothing would be gained by trying to explain each observation separately, as if it had no antecedent.[4] It became obvious that the observations are not points of equilibrium which may or may not change over time, but points on an adjustment path, moving more or less consistently towards a new equilibrium position. Hence we should phrase our questions in terms the beginning of the movement, its rate, and its destination. This led to the decision to fit some simple trend functions to the data and concentrate on the explanation of the cross-sectional differences in the estimates of their parameters.

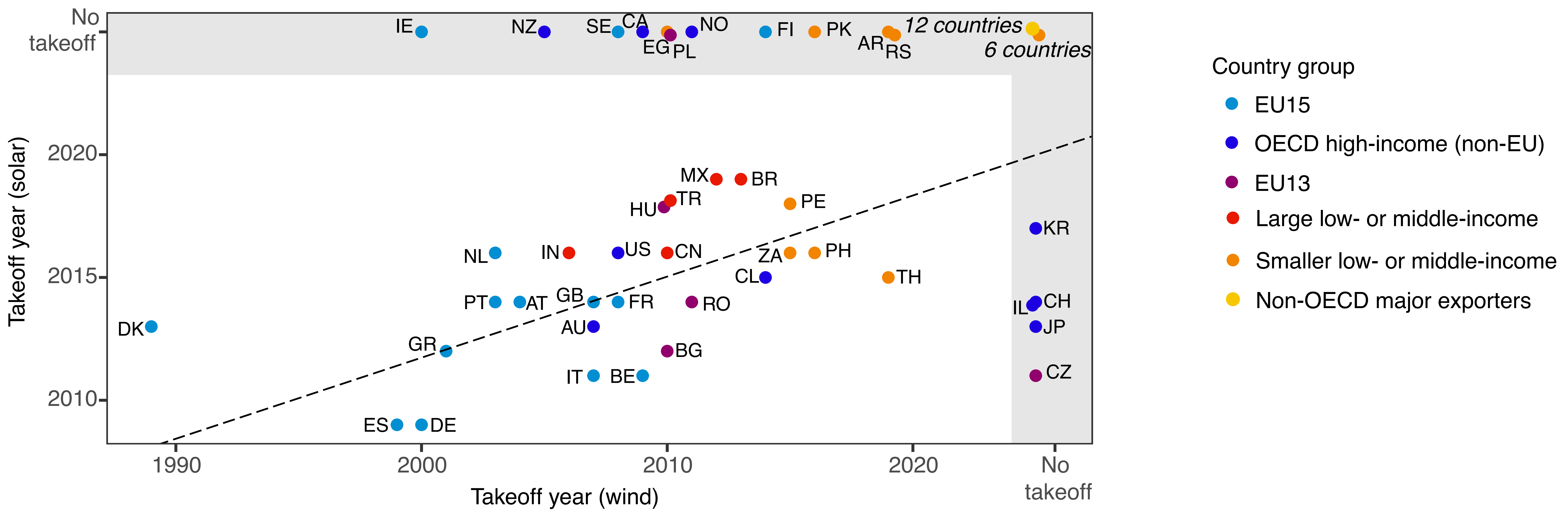
How to measure technology growth



the beginning of the movement, its rate and its destination

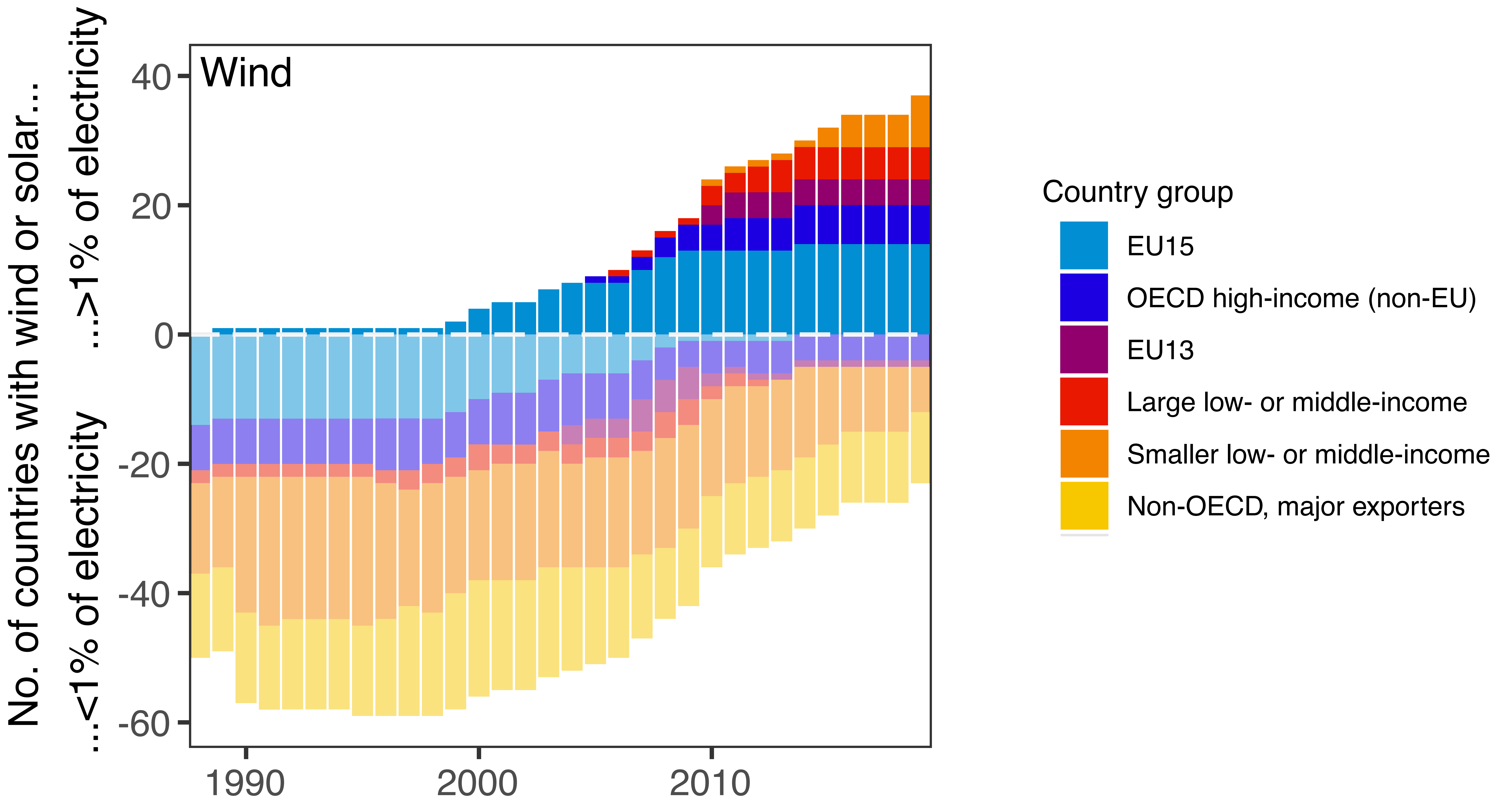
Wind and solar take-off

Generation from the source in question reaches 1% of the total electricity supply



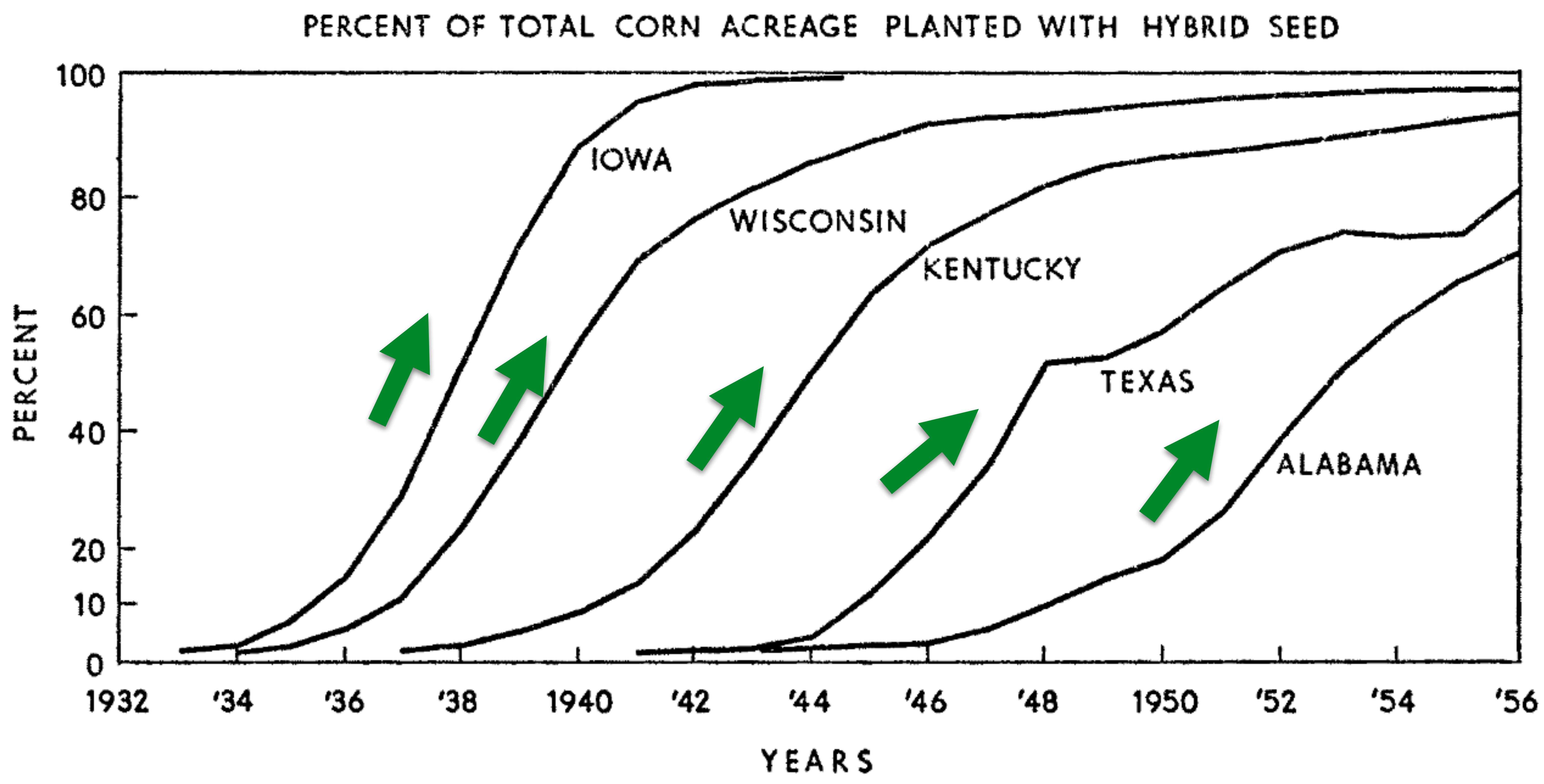
Cherp, Vinichenko, Jewell et al. *Nature Energy* 2021

Global take-off sequence, wind power



Cherp, Vinichenko, Jewell et al. *Nature Energy* 2021

How to measure 'the rate'?



the beginning of the movement, its rate, and its destination

Griliches, Z. (1957). **Hybrid Corn: An Exploration in the Economics of Technological Change** Econometrica 25(4), 501. https://dx.doi.org/10.2307/1905380

How to measure growth of technologies?

Δt = the duration of transition

The dominant approach in the literature

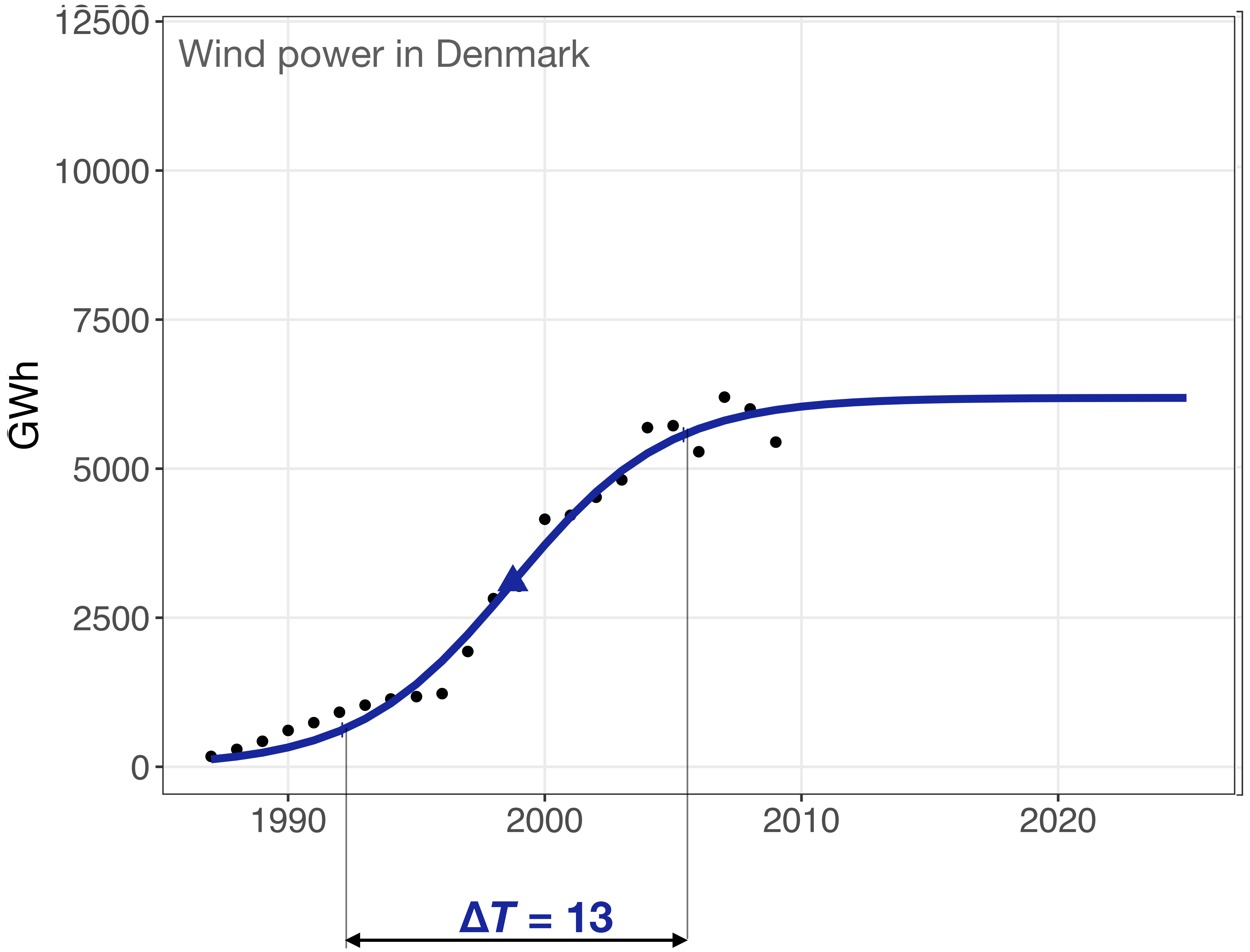
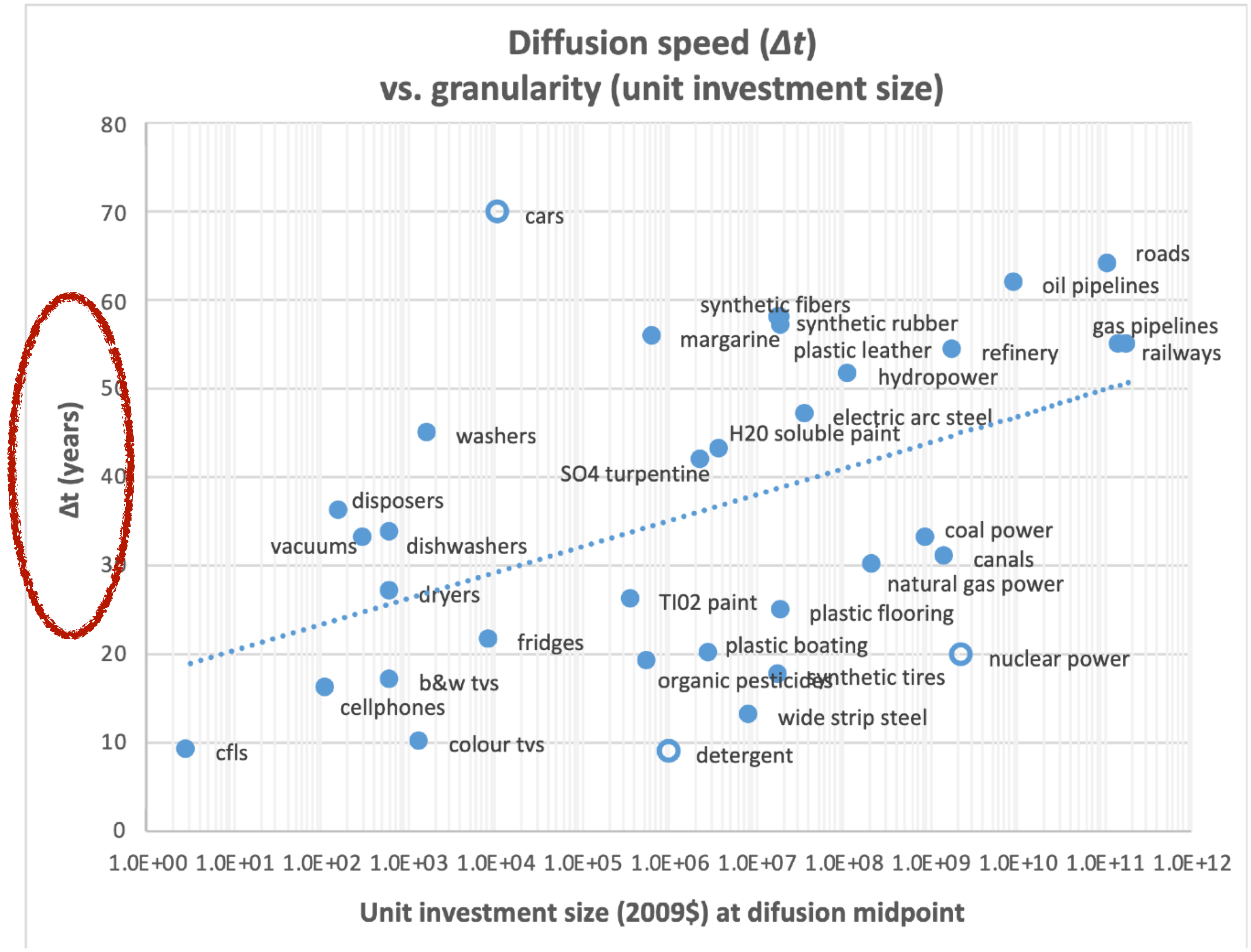


FIGURE SM-1.1. UNIT INVESTMENT SIZE VS. DIFFUSION SPEED (ΔT) FOR 35 INNOVATIONS IN THE US. THREE OUTLIERS SHOWN BY OPEN CIRCLES.



Wilson et al. 2020

Transitions in larger and more complex systems take more time

Table 1
Hierarchy of transition processes and their timing arranged by technological complexity. Note: Examples illustrate the growth of transport technologies and infrastructures in the USA and USSR. These two countries had vastly different political, economic, and social adoption environments, yet show comparable transition speeds that increase with systems complexity. t_0 denotes the diffusion mid-point (50% market share). Δt denotes the time to grow from 1% to 50% (also from 10% to 90%) market share.

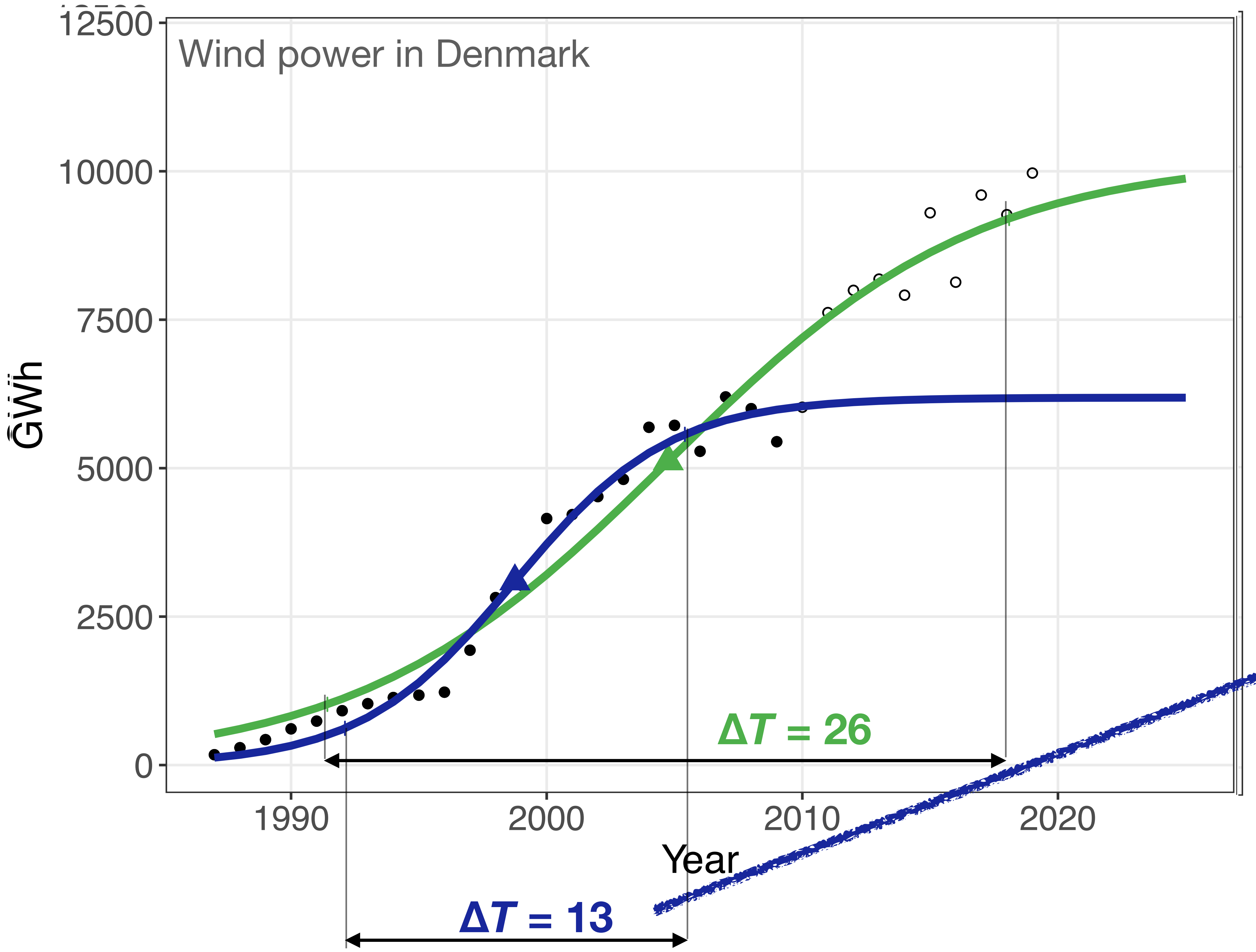
complexity & scale	transition measure	USA		USSR	
		t_0	Δt	t_0	Δt
systems of systems	Growth in total length of all transport infrastructures (km length)	1950	80	1980	80
	Growth of railway network (km length)				
individual system	1830–1930	1858	54	1890	37
	1930–1989	decline	decline	1949	44
	Railway network improvements (% of tracks)				
upgrading existing system	treated ties (USA)	1923	26		
	track electrification (USSR)			1965	27
change in single technology using existing system	Replacement of railway steam locomotives (% of t-km transported)	1950	12	1960	13

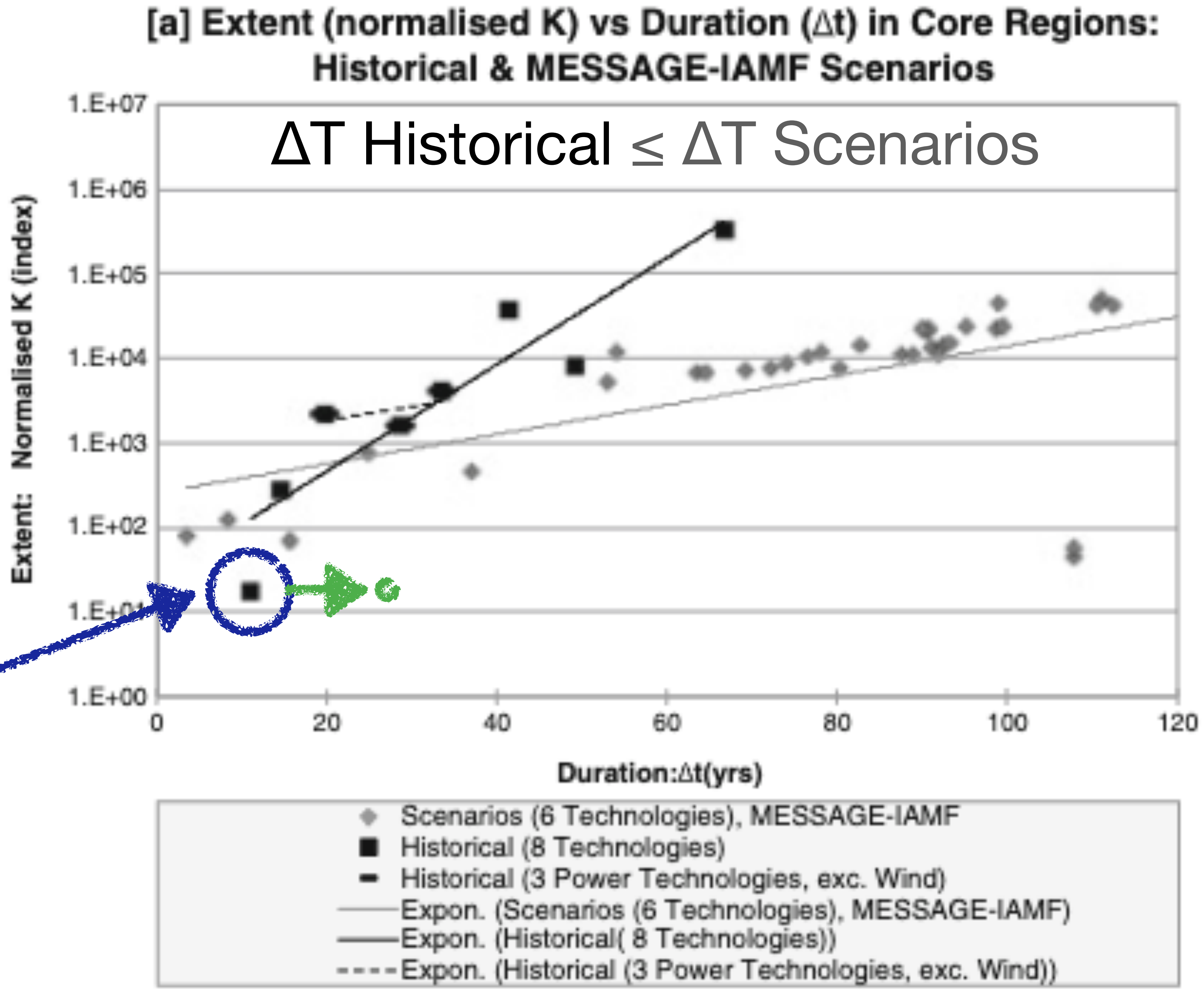
Source: adapted from Grubler et al. [18].

How to measure growth of technologies?

Δt = the duration of transition

The dominant approach in the literature

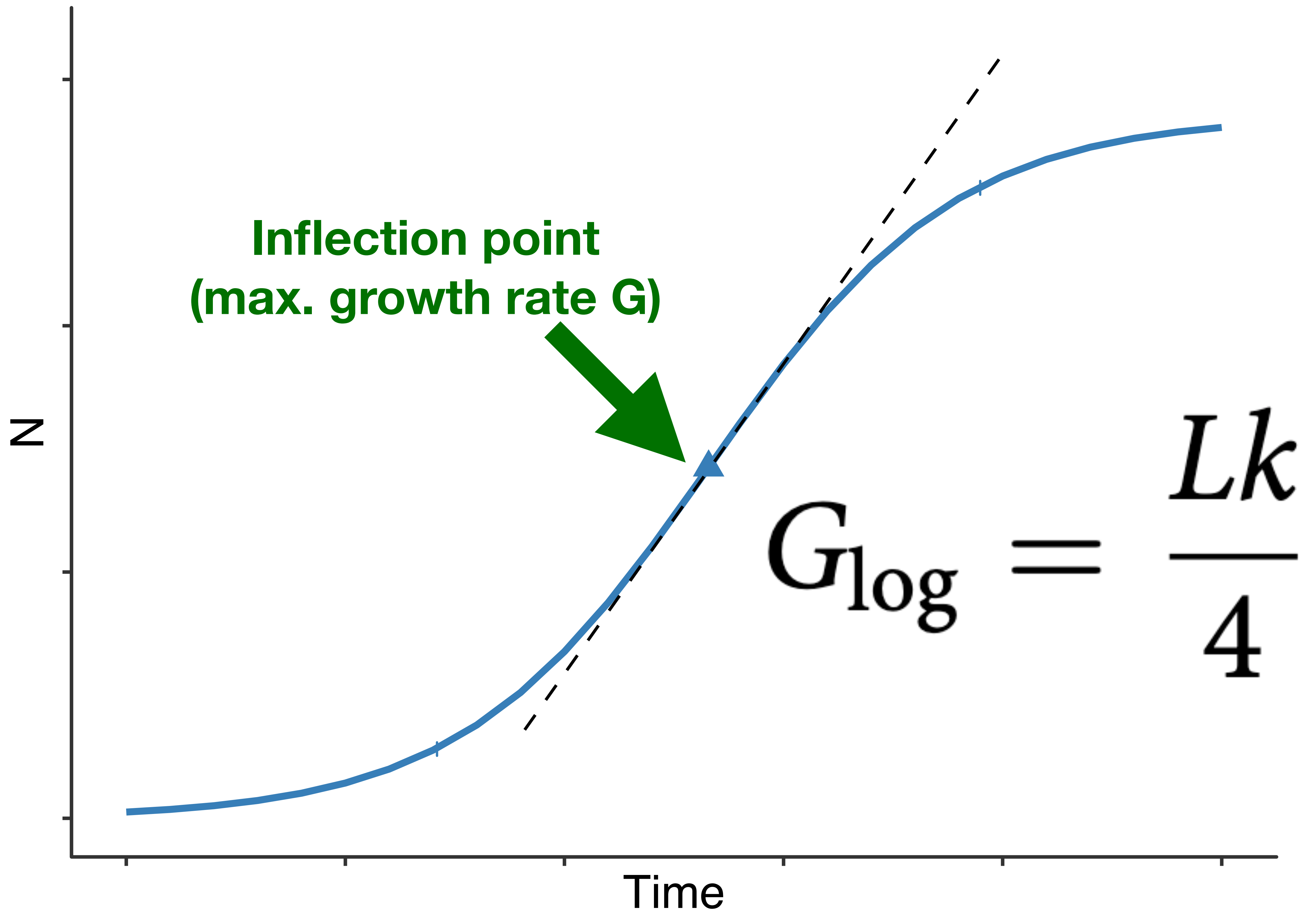




Wilson et al. 2013

How to measure growth of technologies?

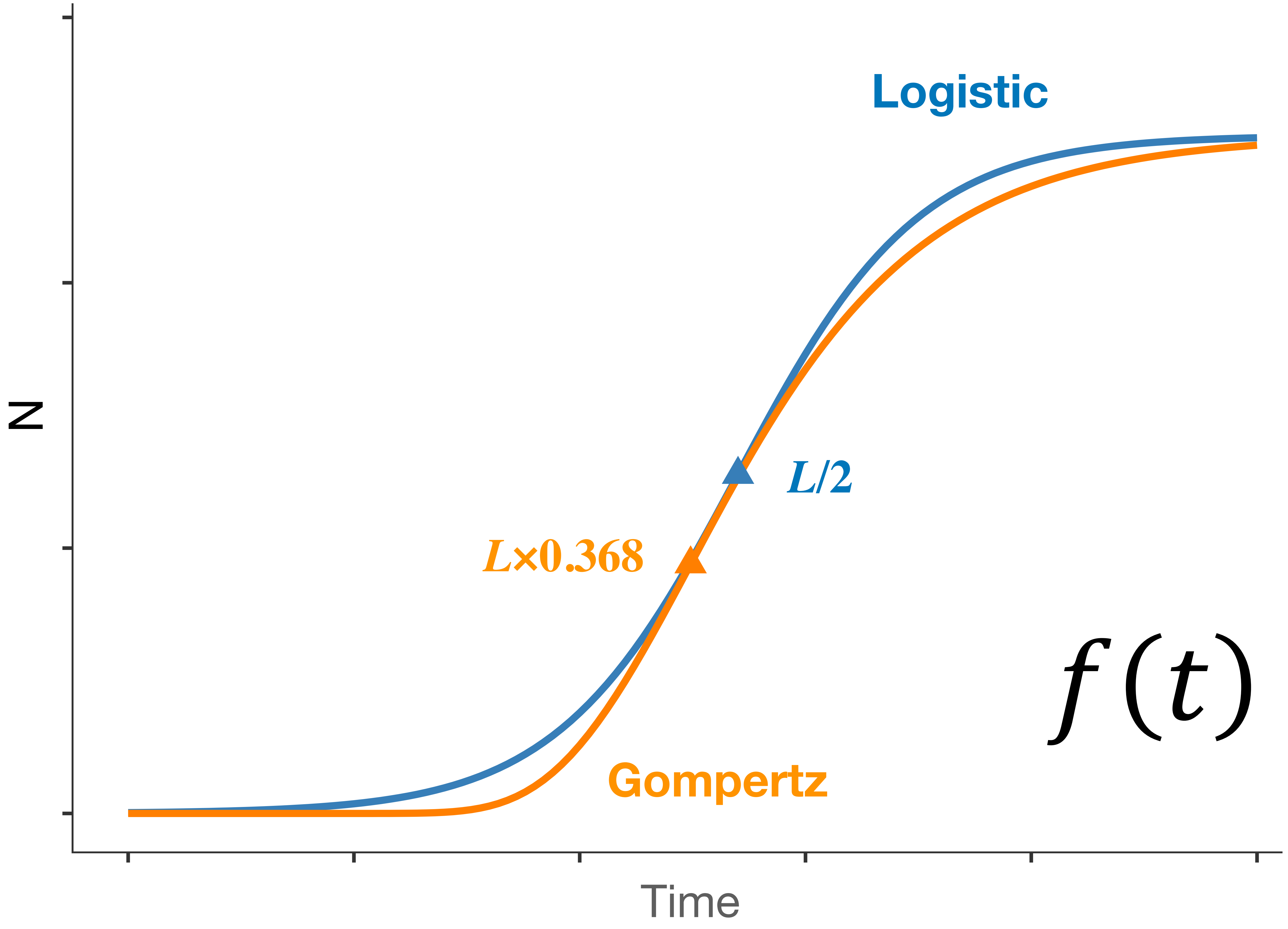
Maximum growth rate (G)



$$f(t) = \frac{L}{1+e^{-k(t-t_0)}}$$

$$G_{\log} = \frac{Lk}{4}$$

Another S-curve: Gompertz curve



$$f(t) = Le^{-e^{-k(t-t_0)}}$$

XXIV. *On the nature of the function expressive of the law of human mortality, and on a new mode of determining the value of Life Contingencies. In a Letter to* FRANCIS BAILY, *Esq. F.R.S. &c. By* BENJAMIN GOMPERTZ, *Esq. F.R.S.*

Read June 16, 1825.

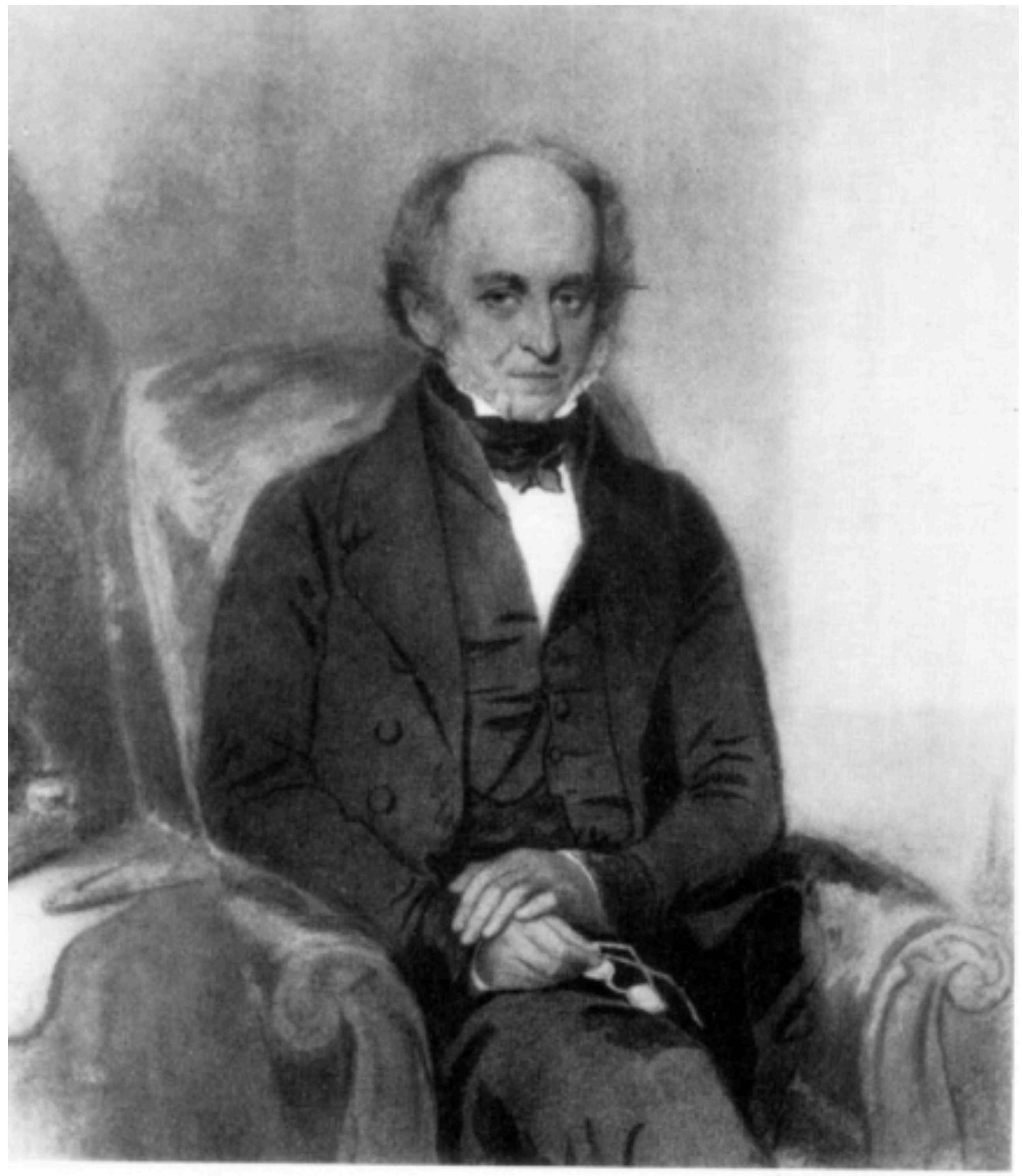
DEAR SIR,

THE frequent opportunities I have had of receiving pleasure from your writings and conversation, have induced me to prefer offering to the Royal Society through your medium, this Paper on Life Contingencies, which forms part of a continuation of my original paper on the same subject, published among the valuable papers of the Society, as by passing through your hands it may receive the advantage of your judgment.

I am, Dear Sir, yours with esteem,

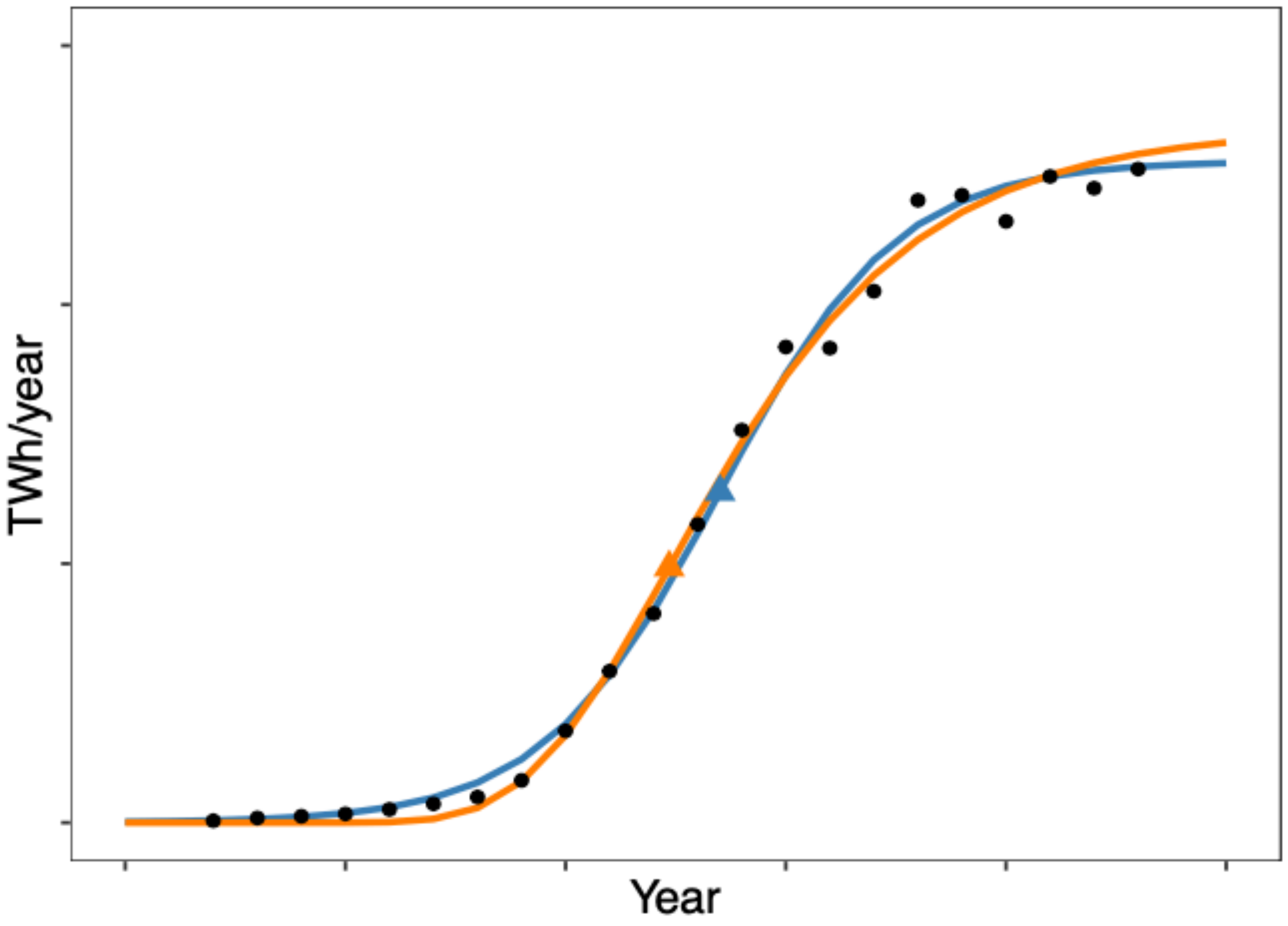
BENJAMIN GOMPERTZ.

9th June 1825.

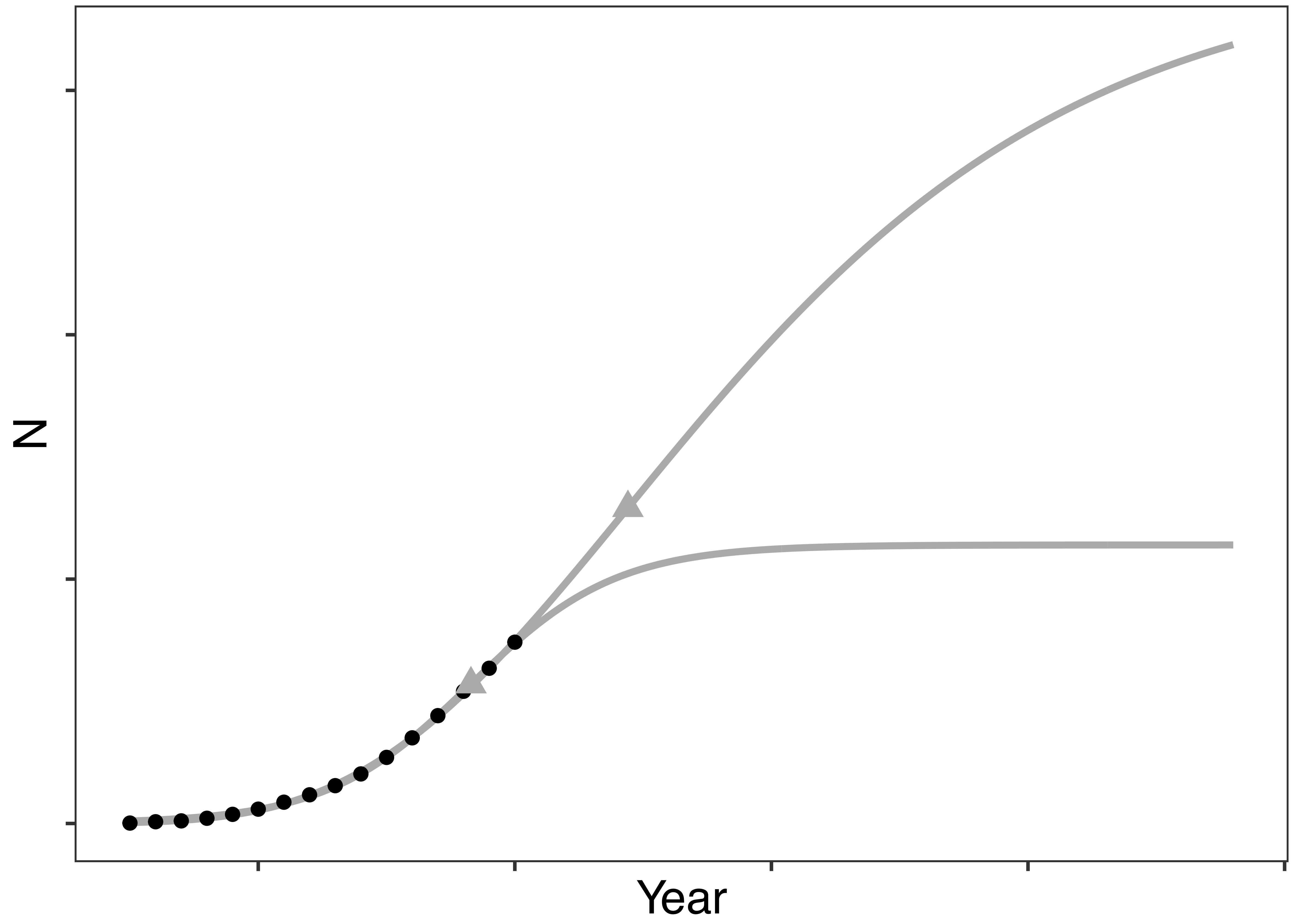


BENJAMIN GOMPERTZ, 1779–1865

Fitting growth models to empirical data



Fitting growth models to empirical data



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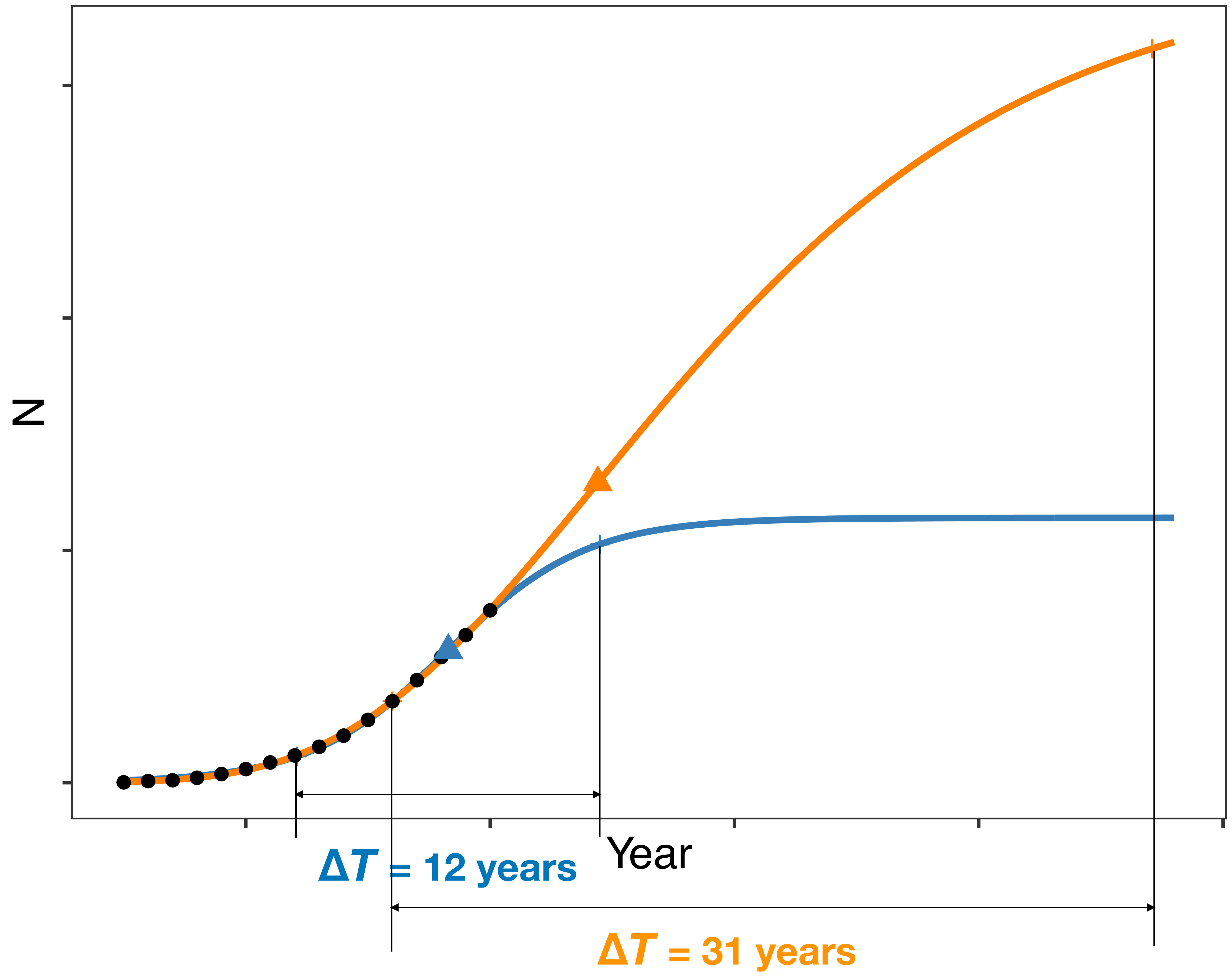
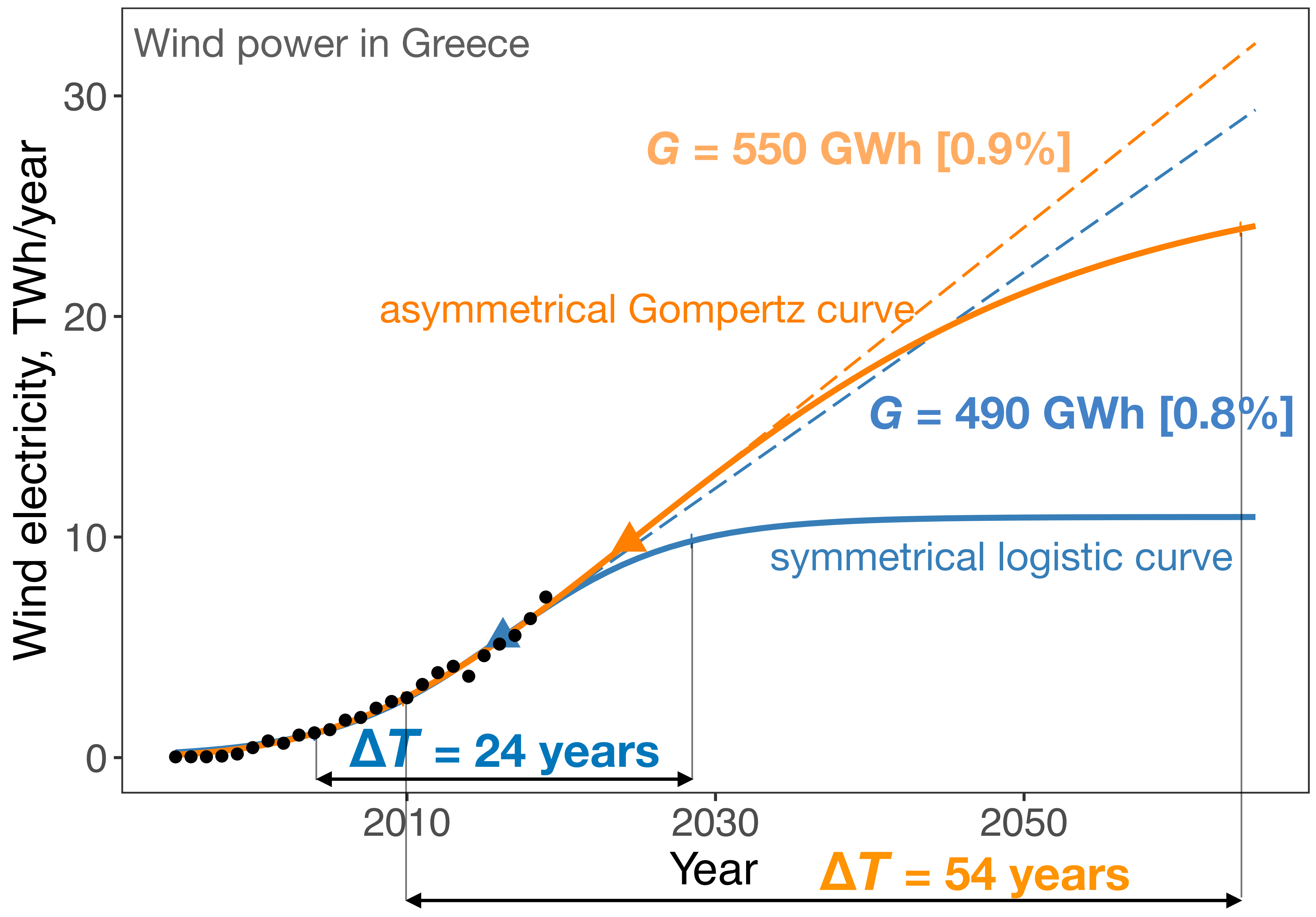


How to measure growth of technologies?

Maximum growth rate (G)



Cherp, Vinichenko, Jewell et al. *Nature Energy* 2021

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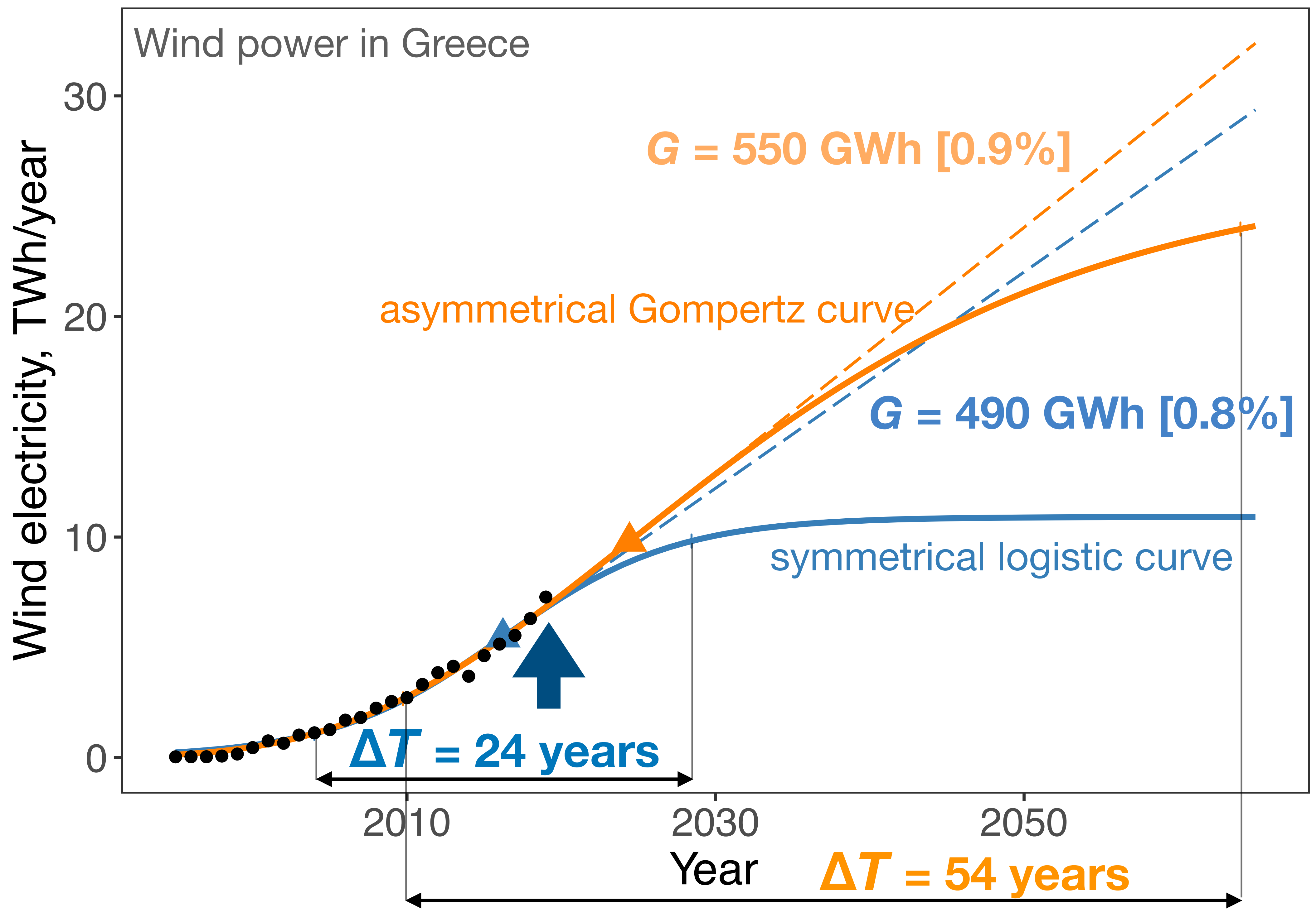
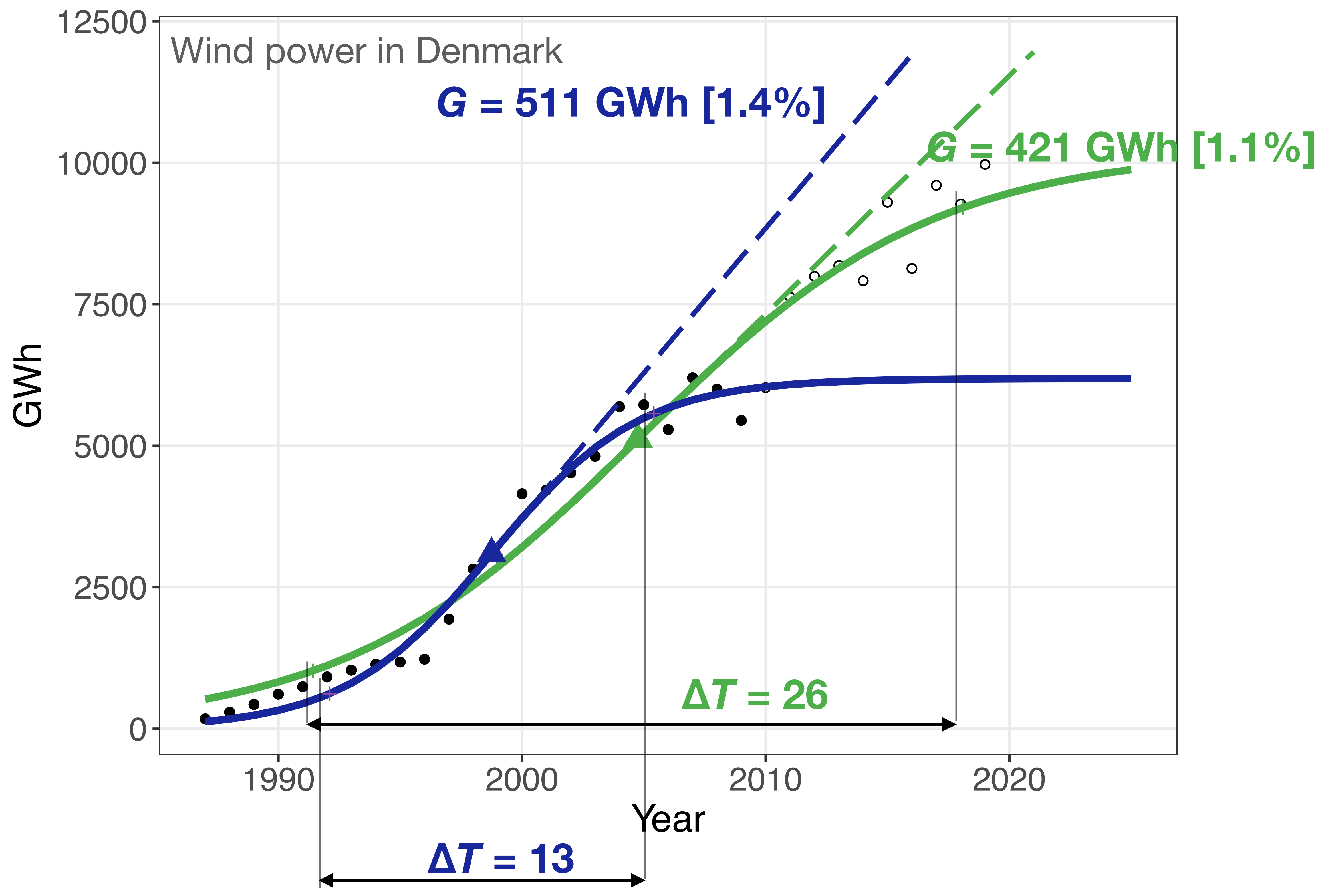
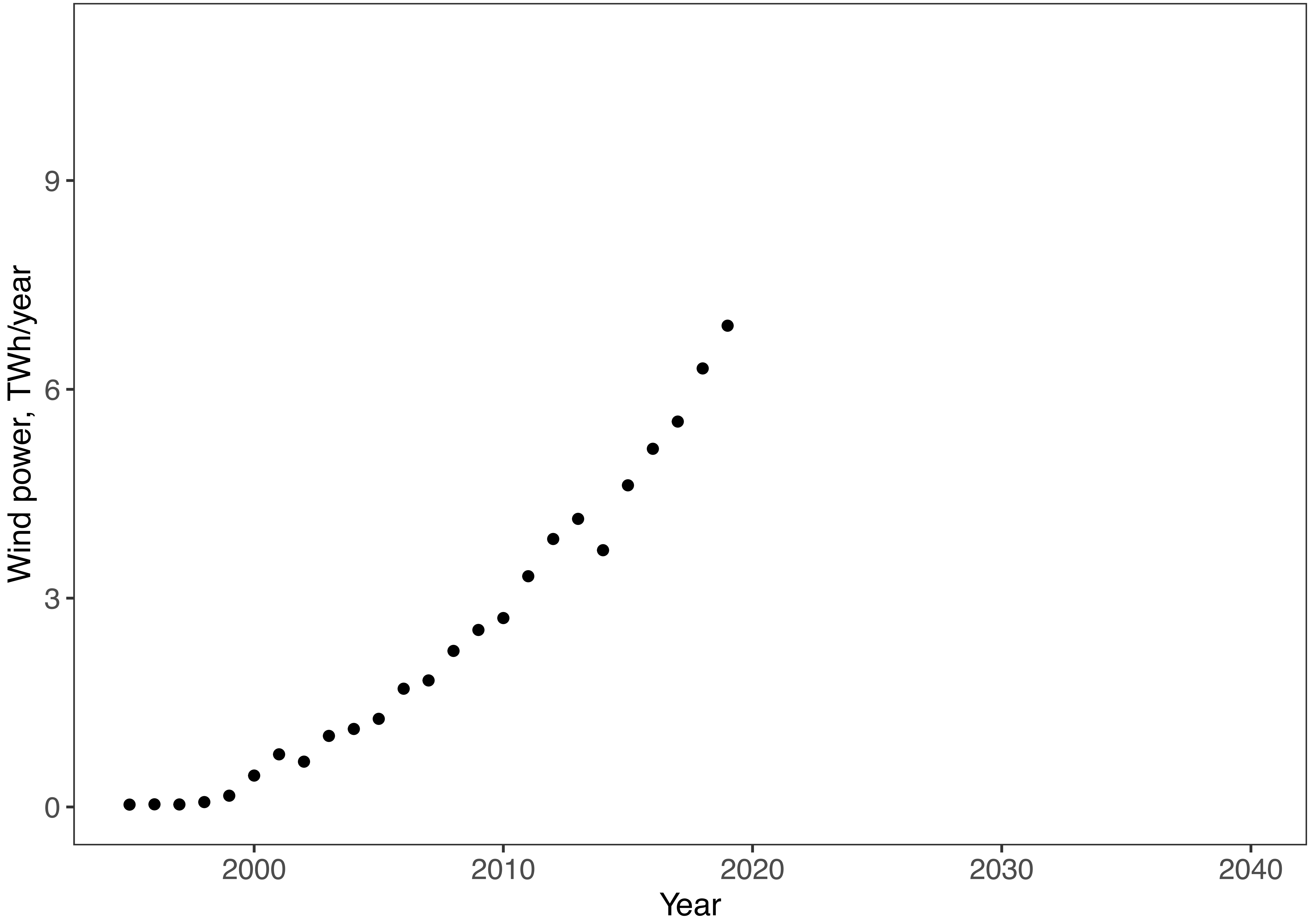
Maximum growth rate (G)



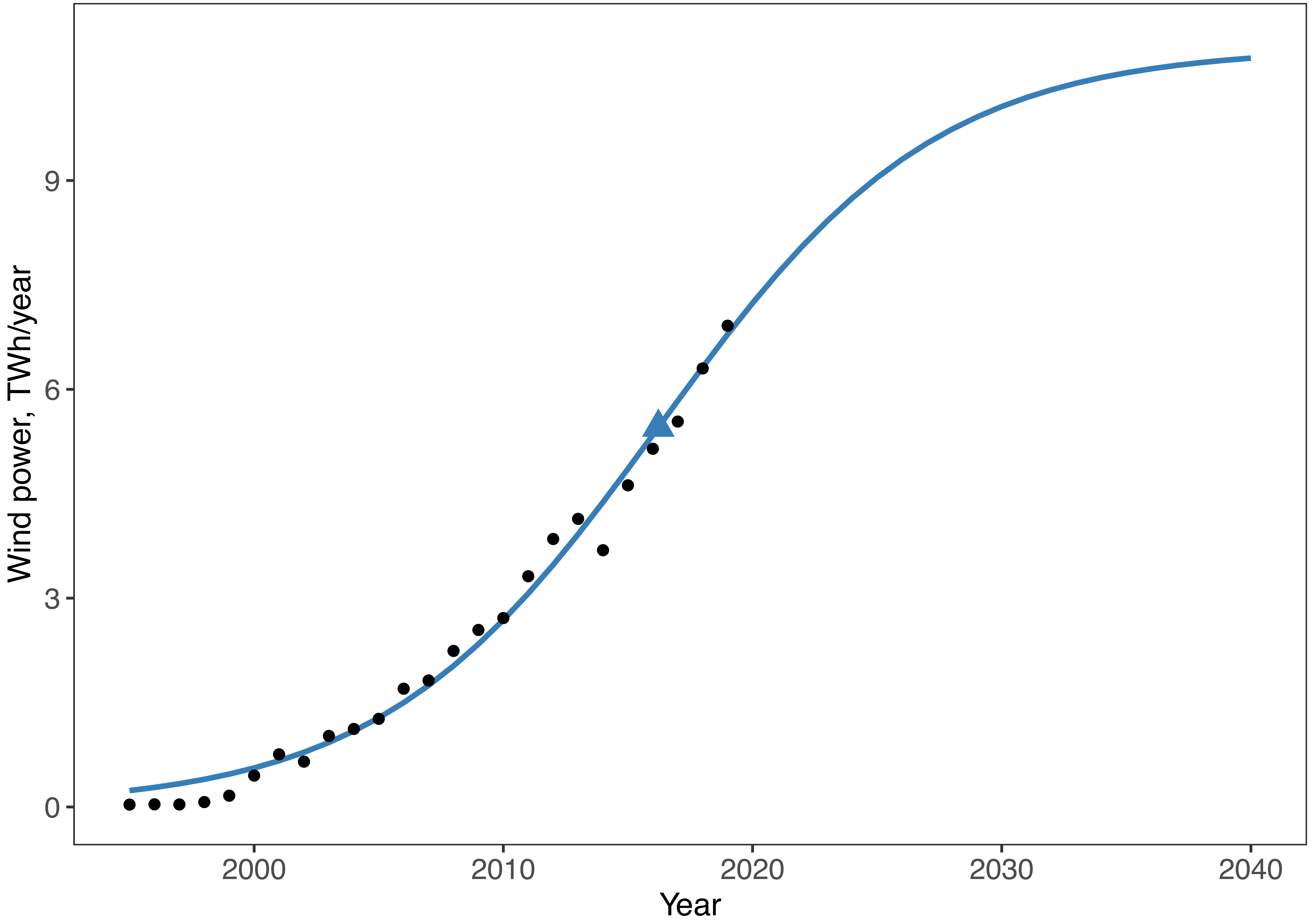


Cherp, Vinichenko, Jewell et al. *Nature Energy* 2021

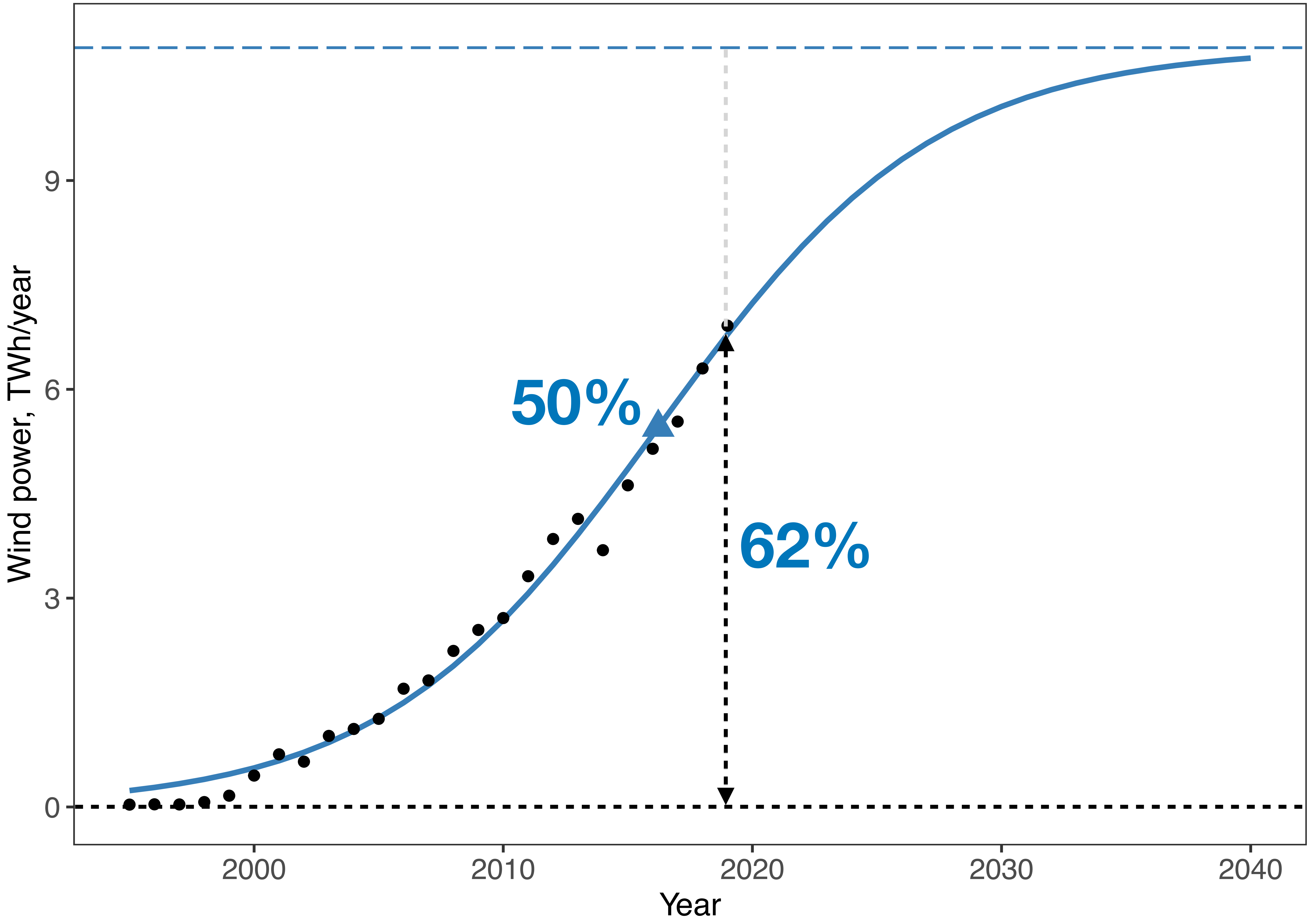
Maturity and growth phases



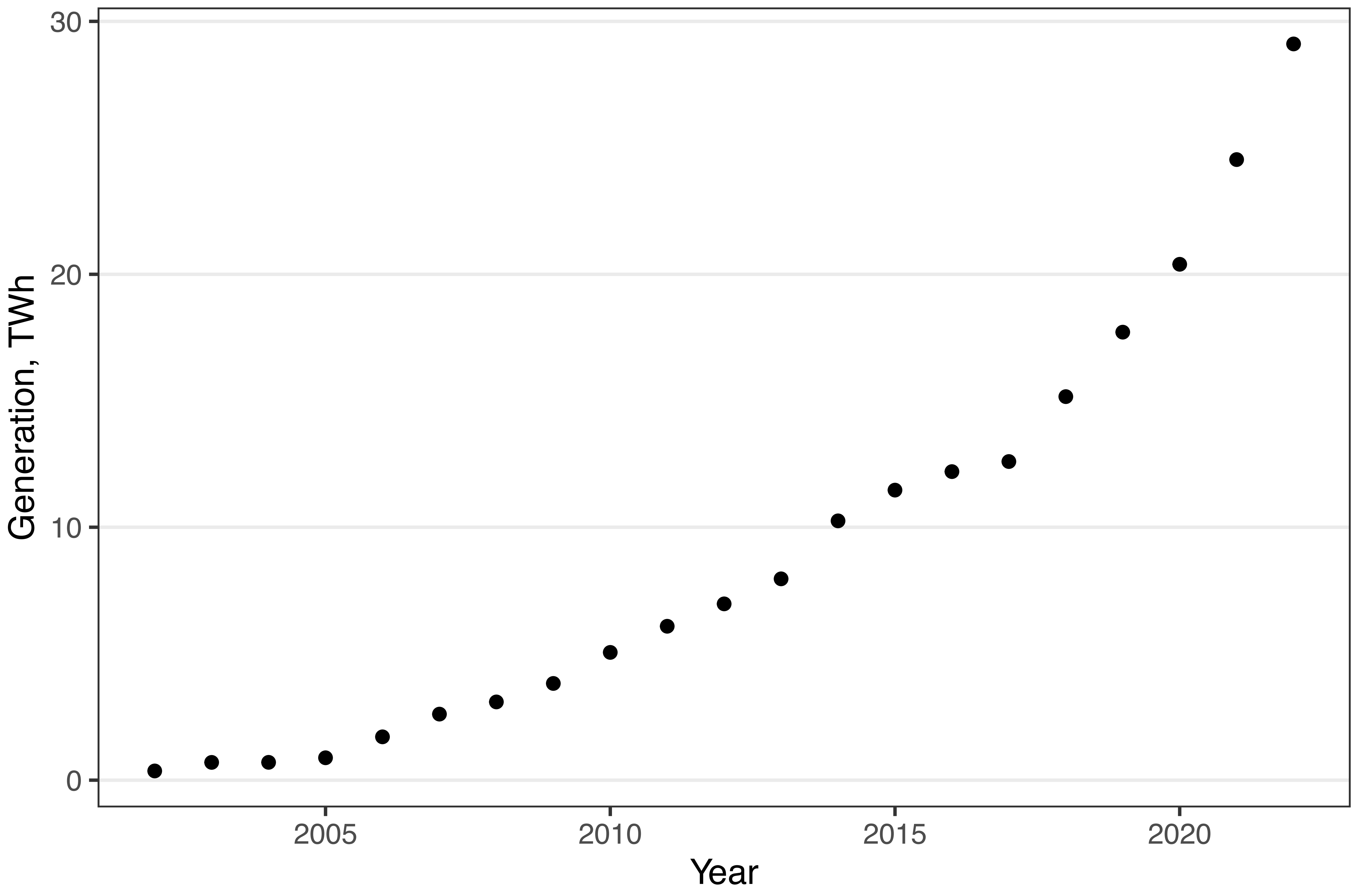
Maturity and growth phases



Maturity and growth phases



Diagnosing the phases of growth: wind in Australia



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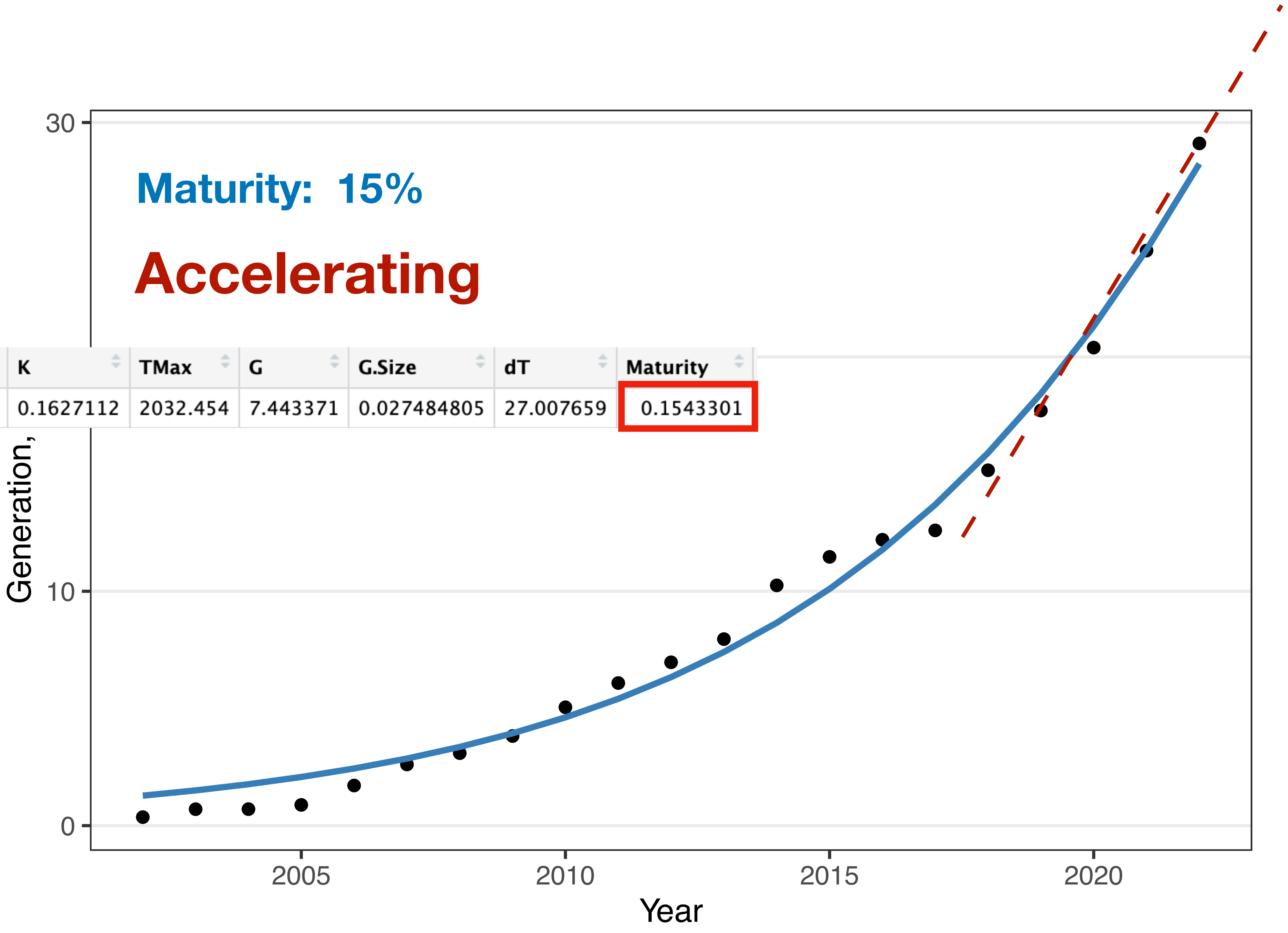
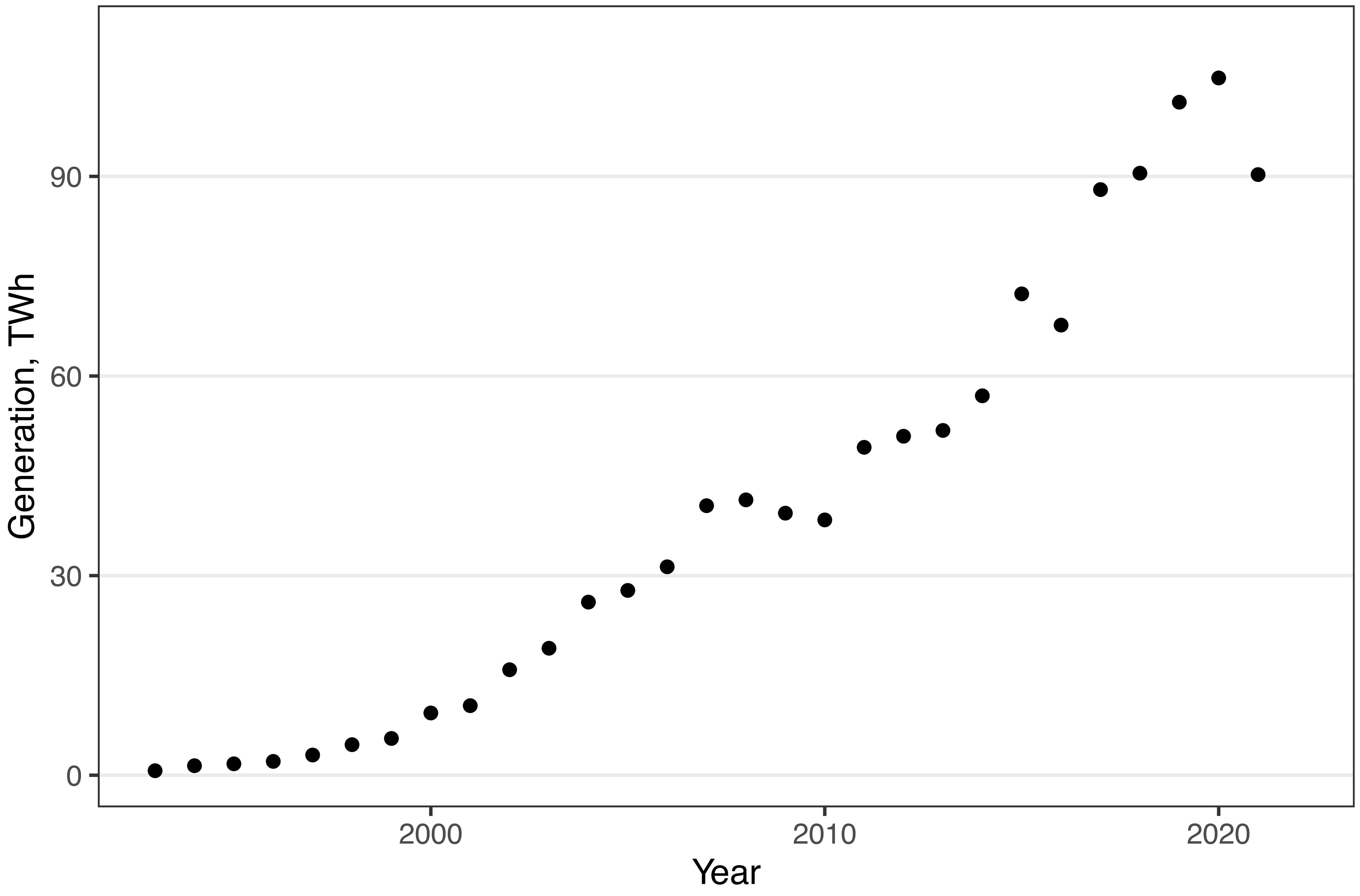


Recent growth rate
3.8 TWh/year
1.4% of TES

Country	Fuel	TO.Year	L	K	TMax	G	G.Size	dT	Maturity
AU	Wind.On	2007	182.98359	0.1627112	2032.454	7.443371	0.027484805	27.007659	0.1543301

Diagnosing the phases of growth: onshore wind in Germany



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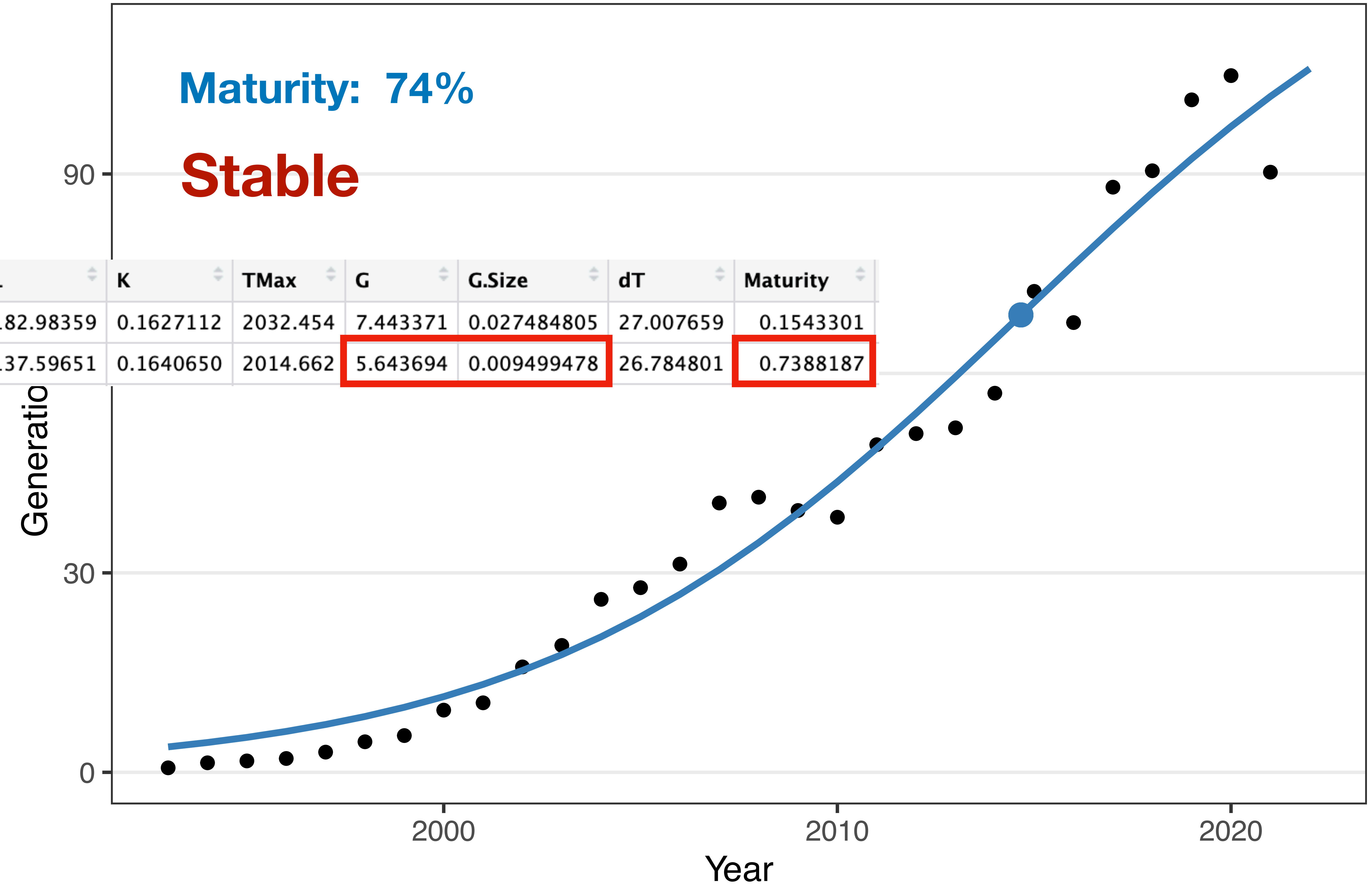

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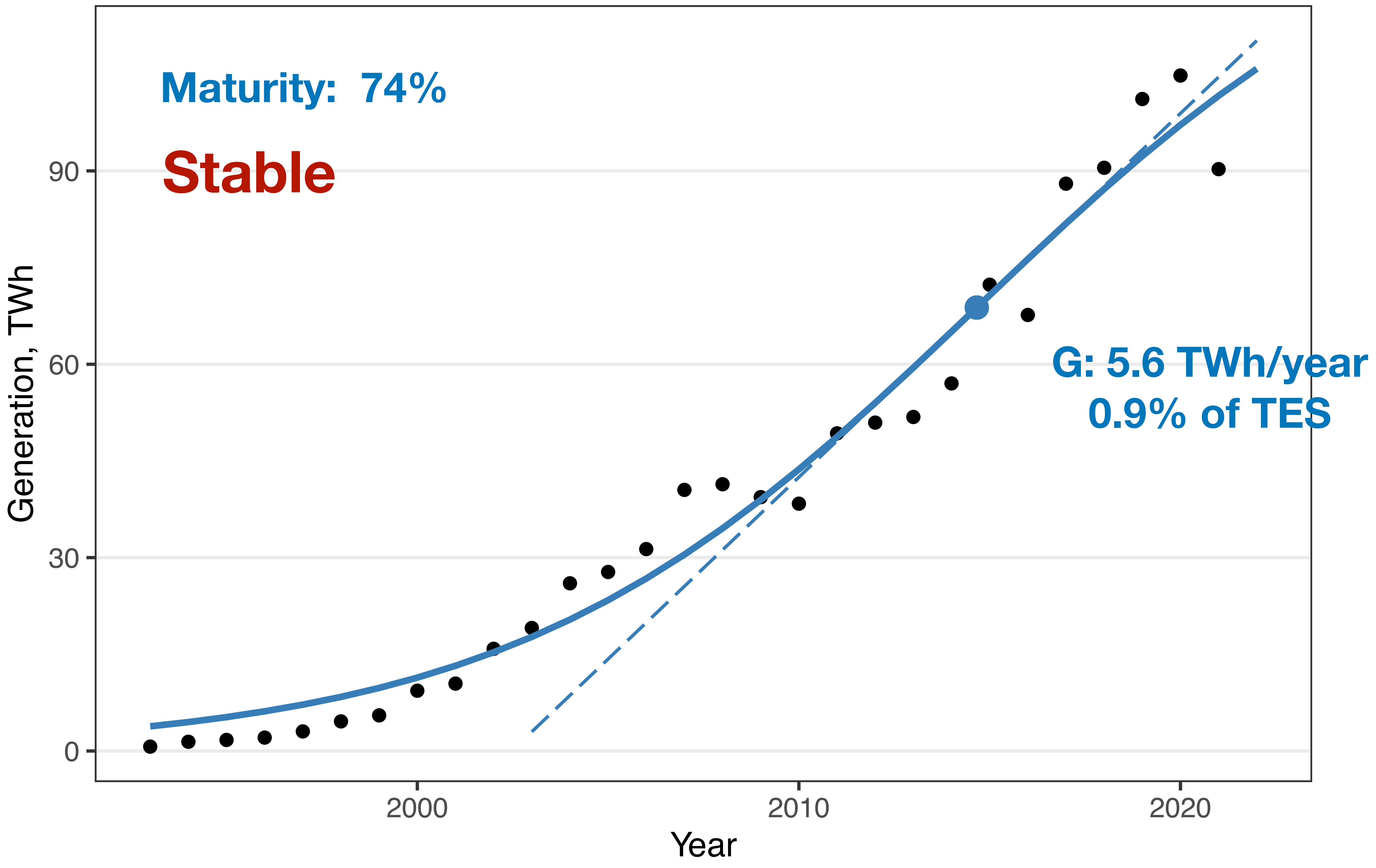
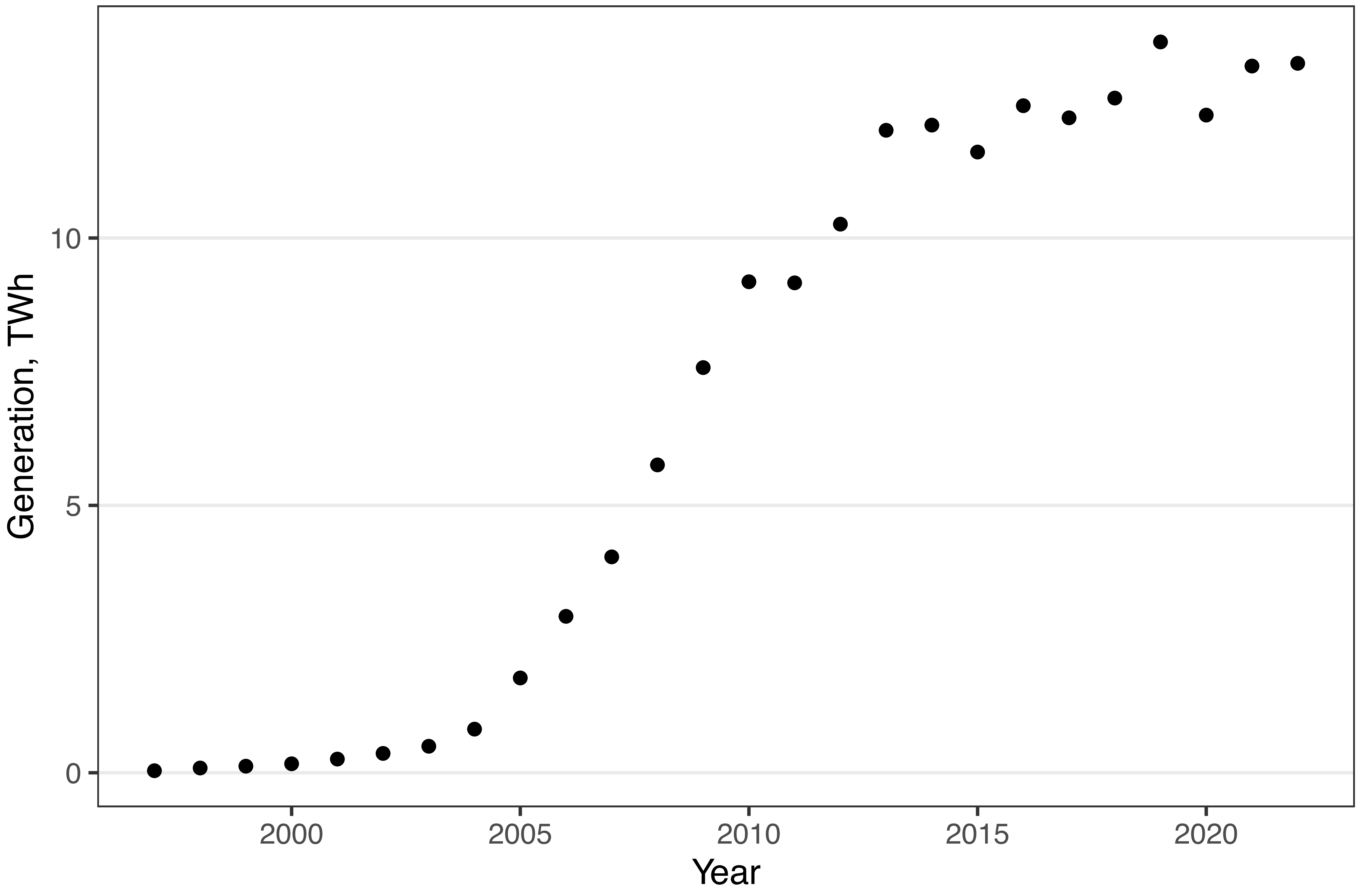
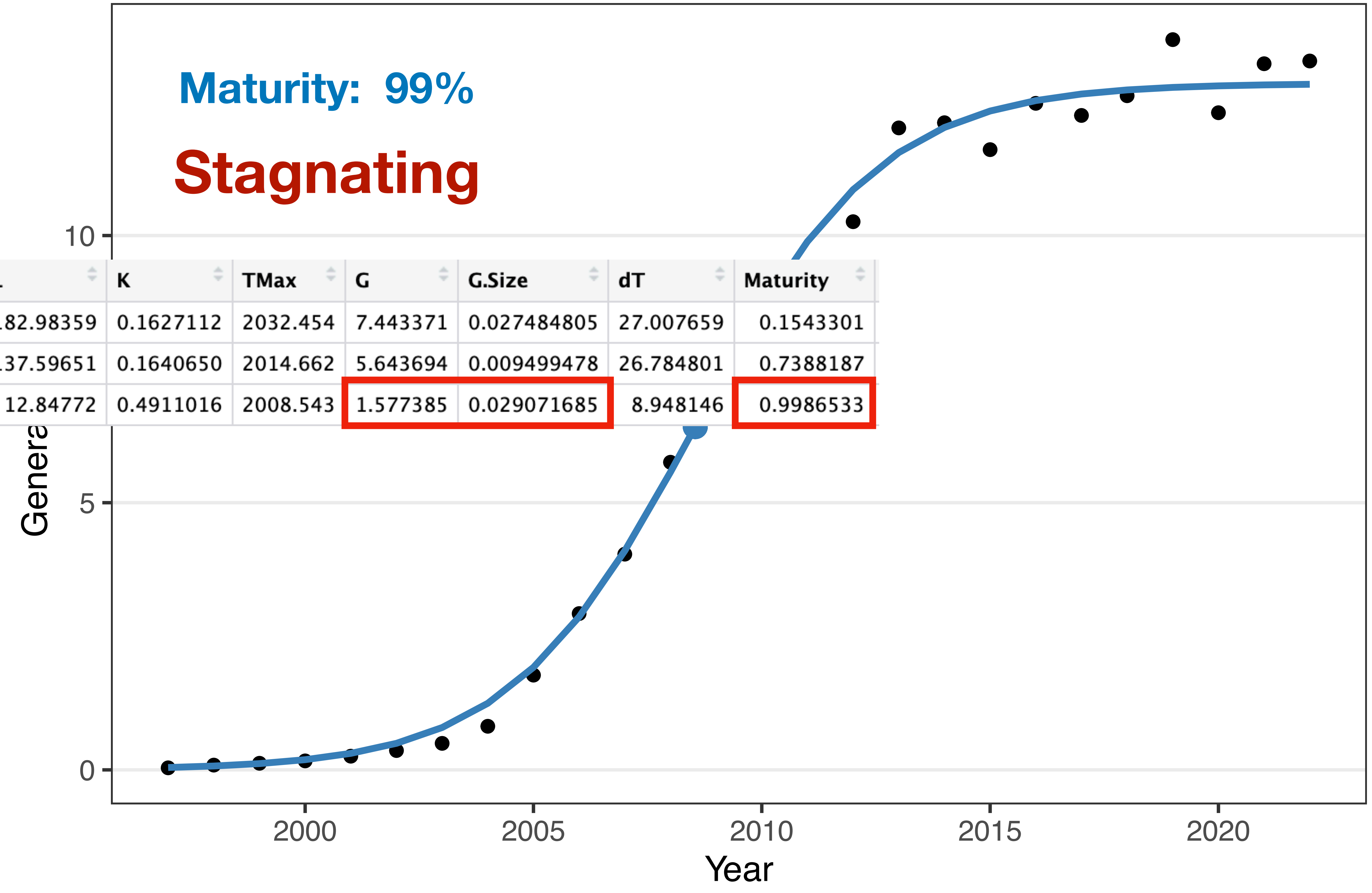


Diagnosing the phases of growth: wind in Portugal



Diagnosing the phases of growth: wind in Portugal



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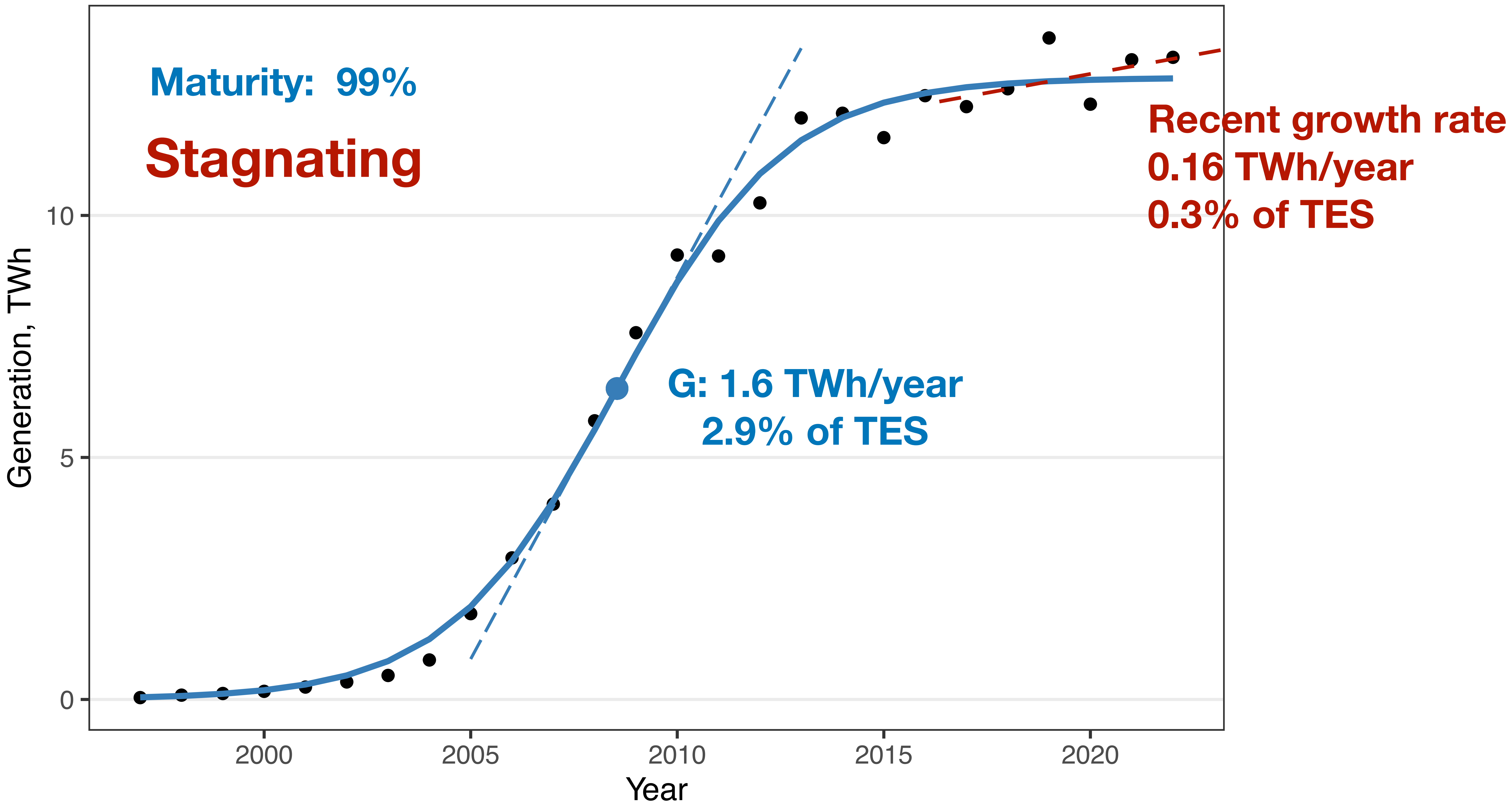
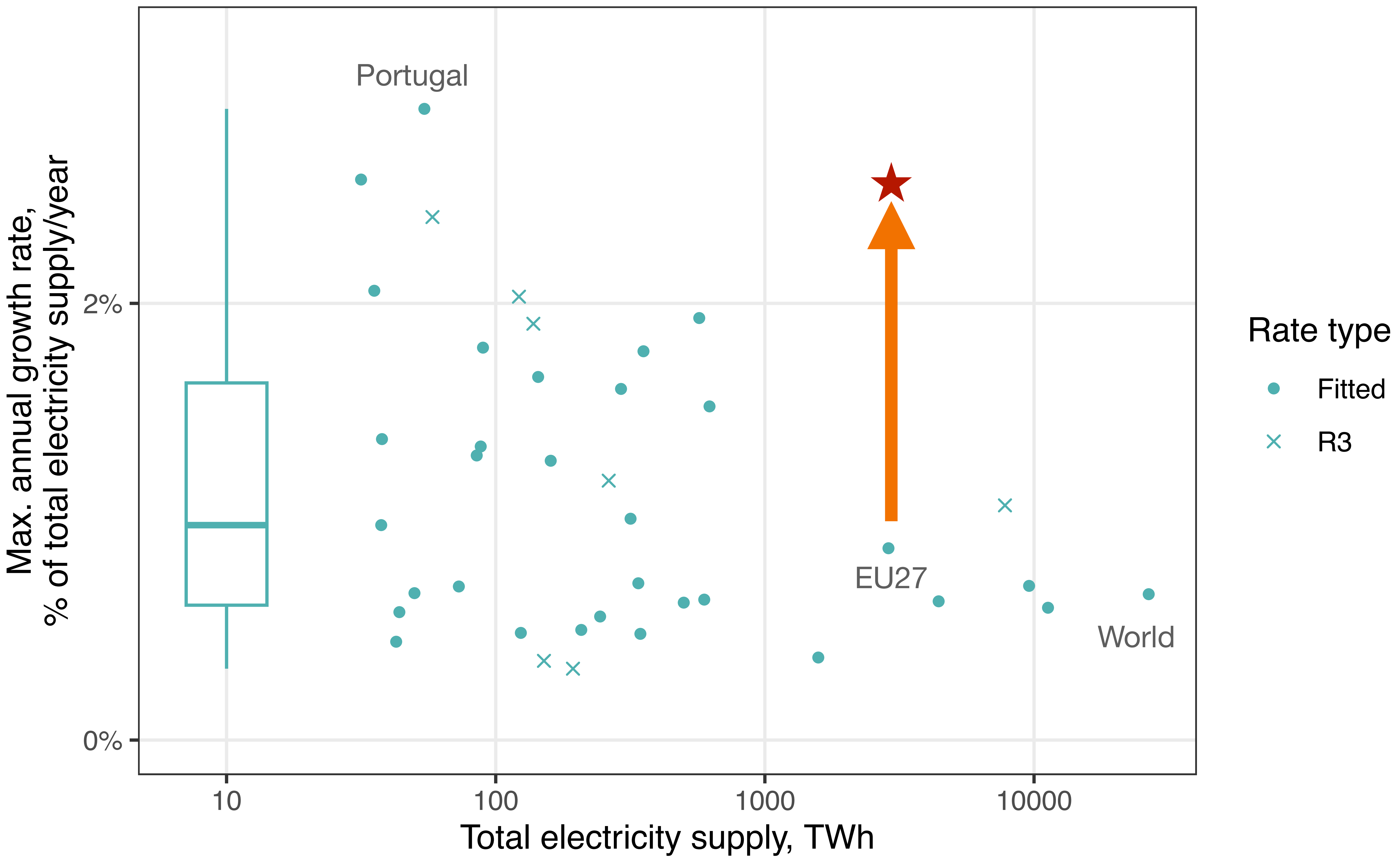
PT	Wind.On	2003	12.84772	0.4911016	2008.543	1.577385	0.029071685	8.948146	0.9986533

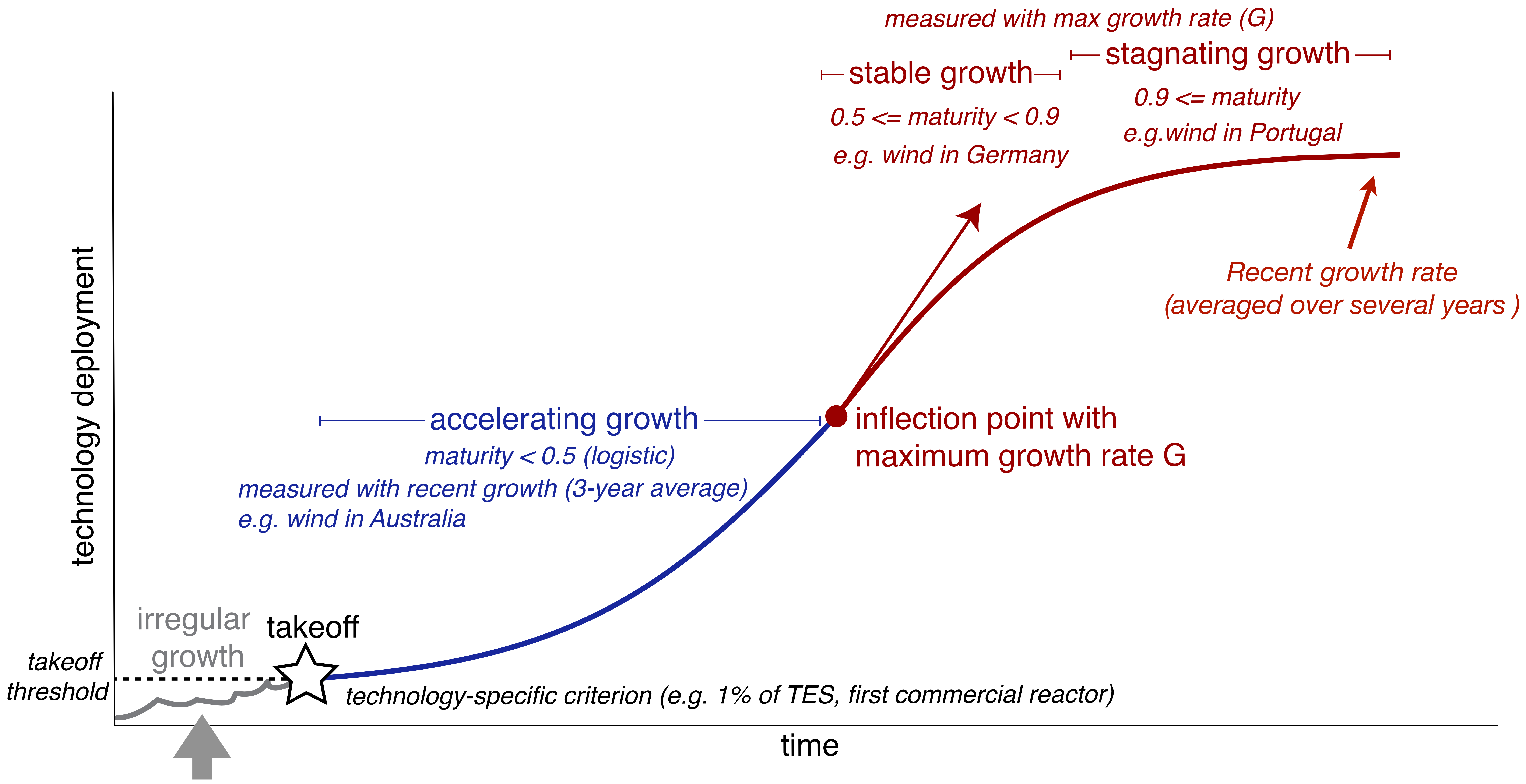
Diagnosing the phases of growth: wind in Portugal



Historical wind power growth rates

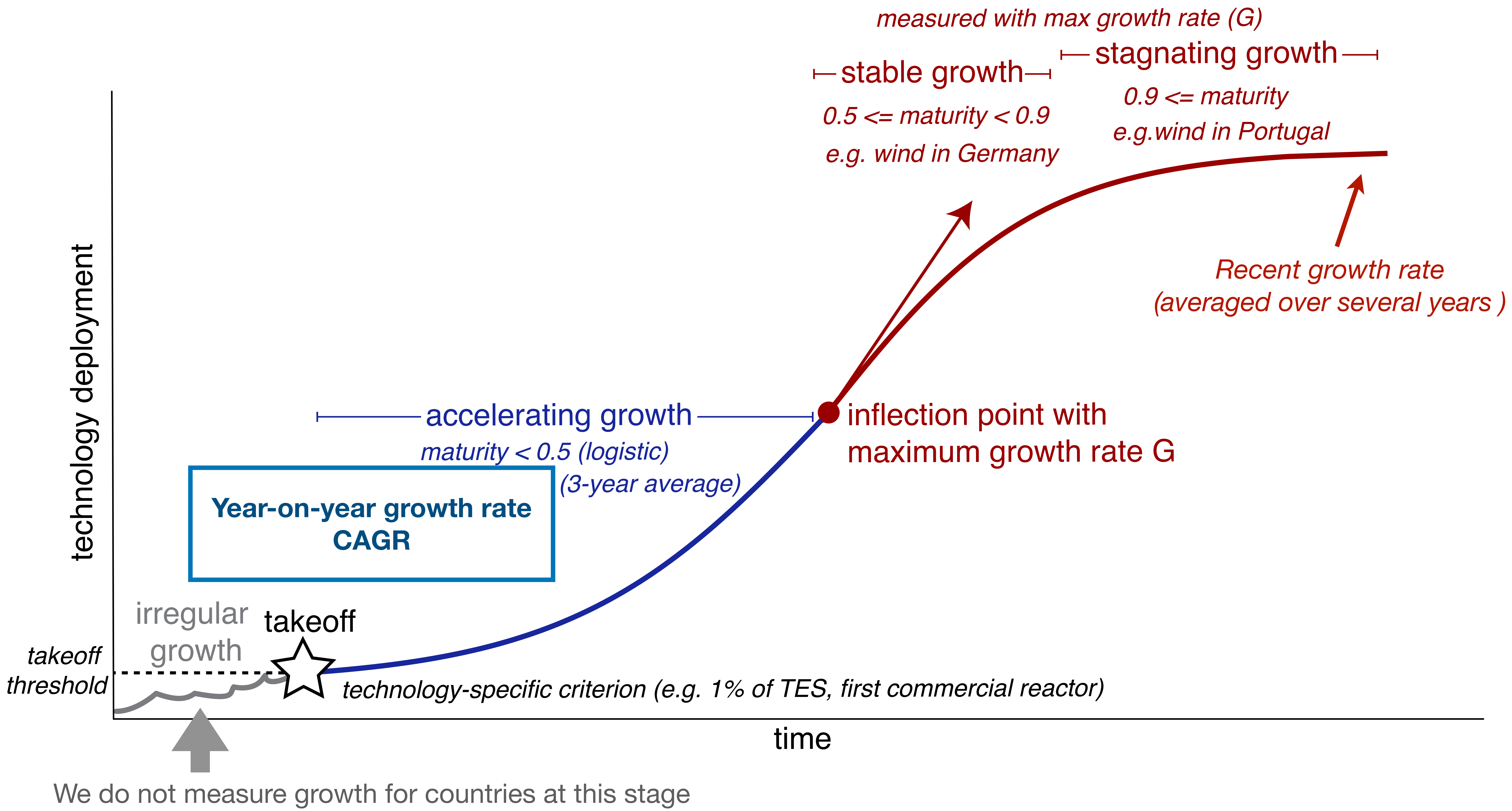


Measuring growth based on growth models: summary

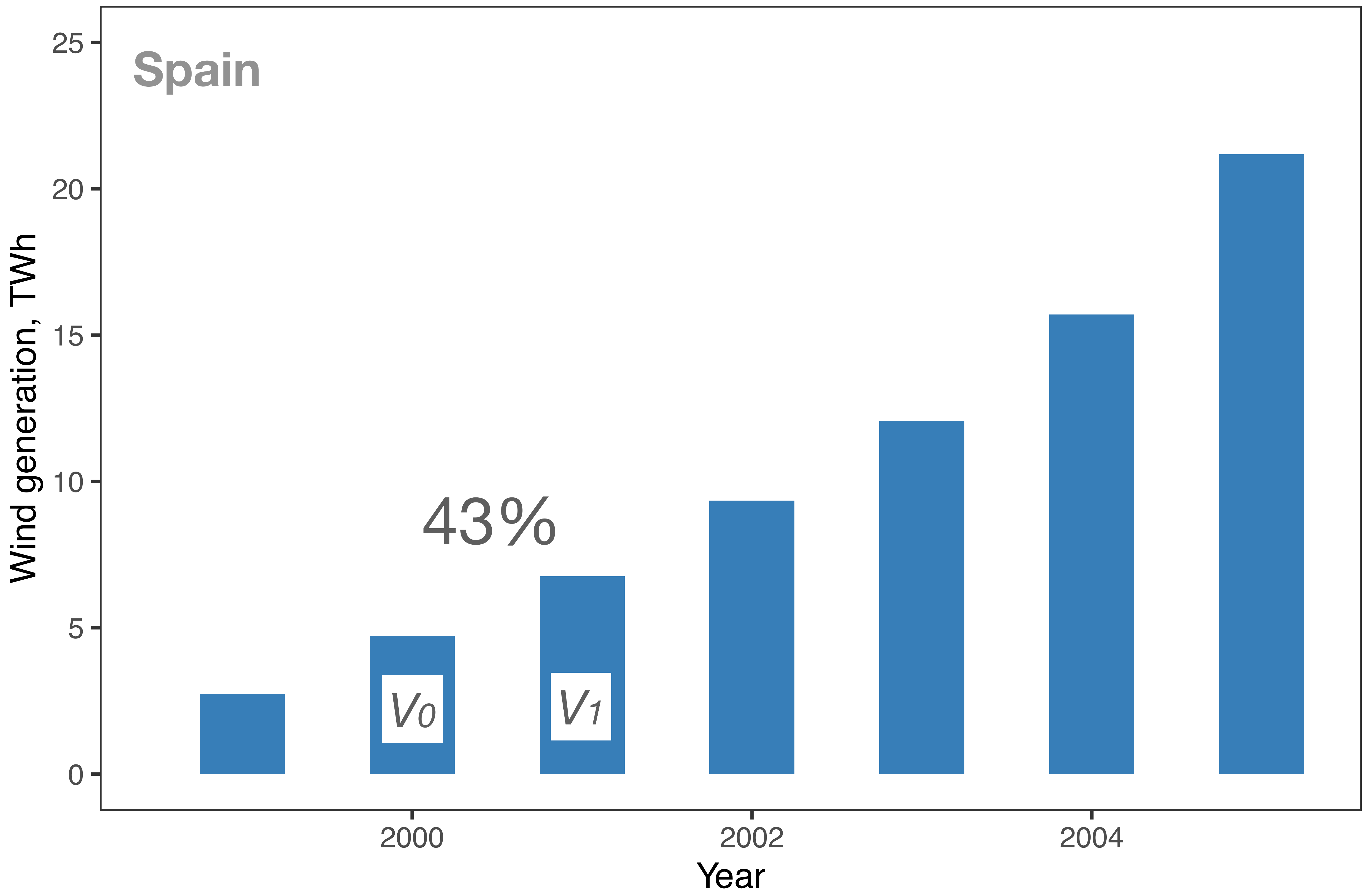


We do not measure growth for countries at this stage

Measuring growth based on growth models: summary



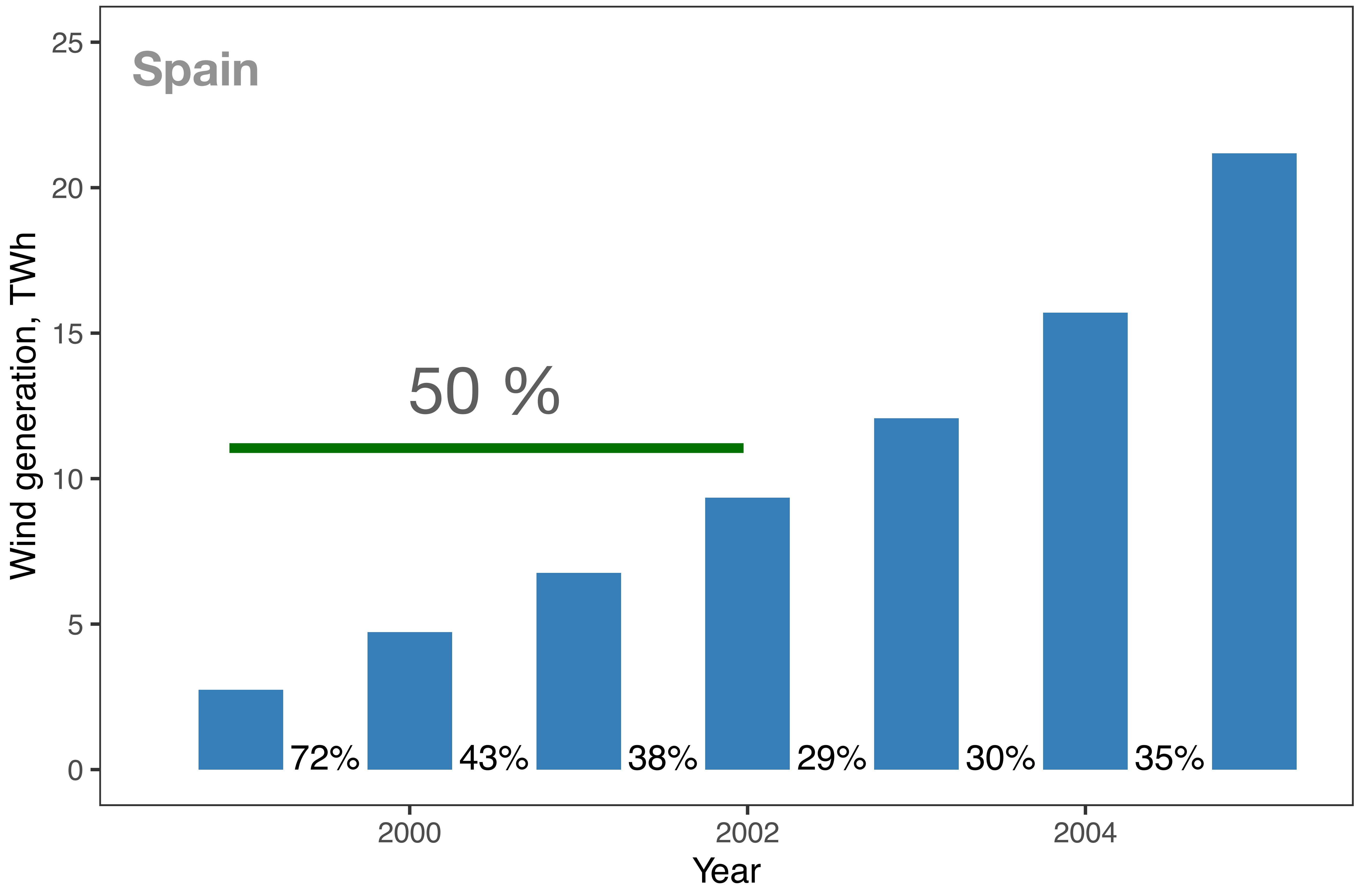
Measuring growth at the early stage: year-on-year growth rate



$$R = \frac{V_1}{V_0} - 1$$

$$R = \frac{6.759}{4.727} - 1 \approx 0.43$$

Measuring growth at the early stage: CAGR

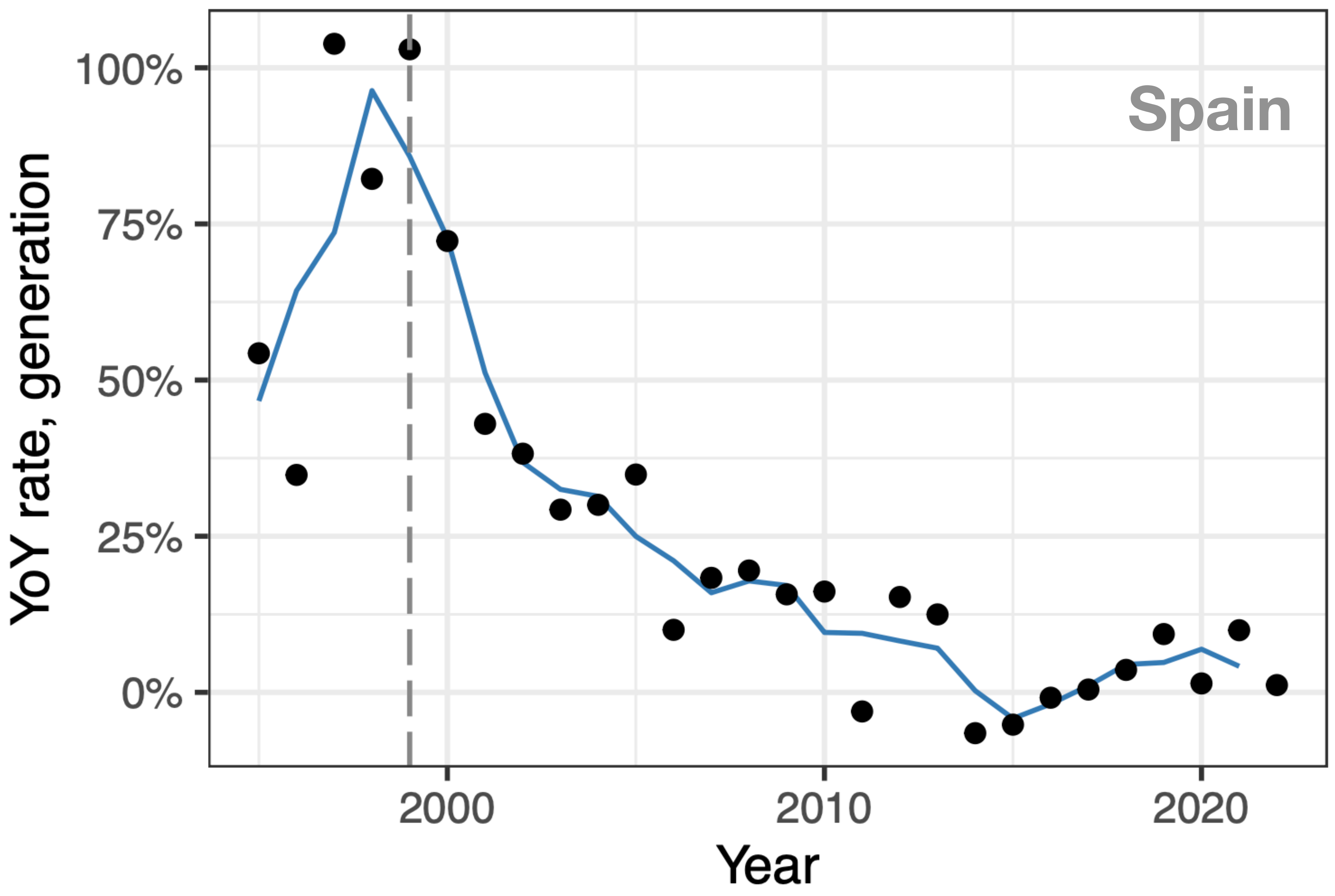


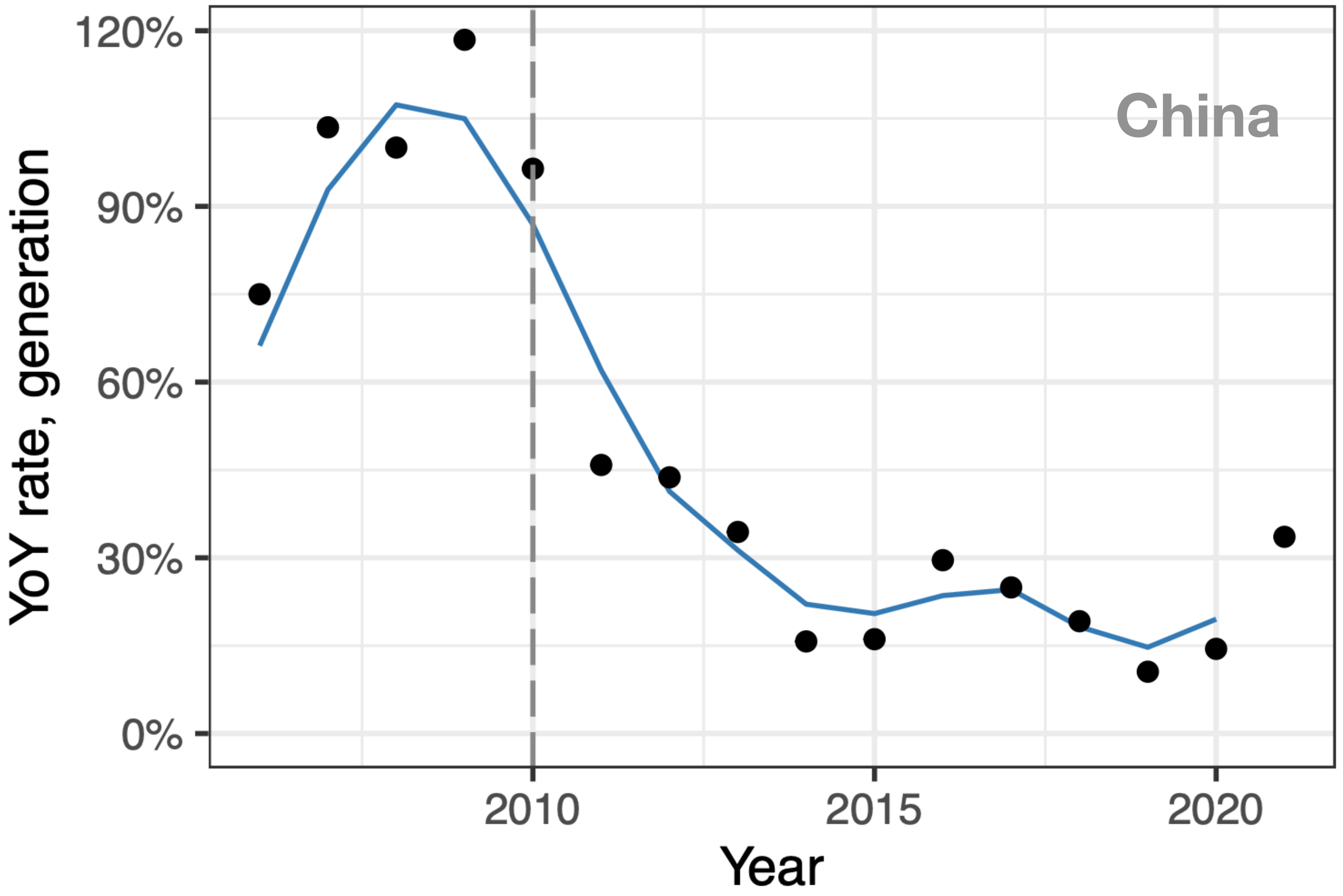
Averaged YoY growth rate
CAGR (compound average growth rate)

$$R = \left(\frac{V_1}{V_0}\right)^{1/t} - 1$$

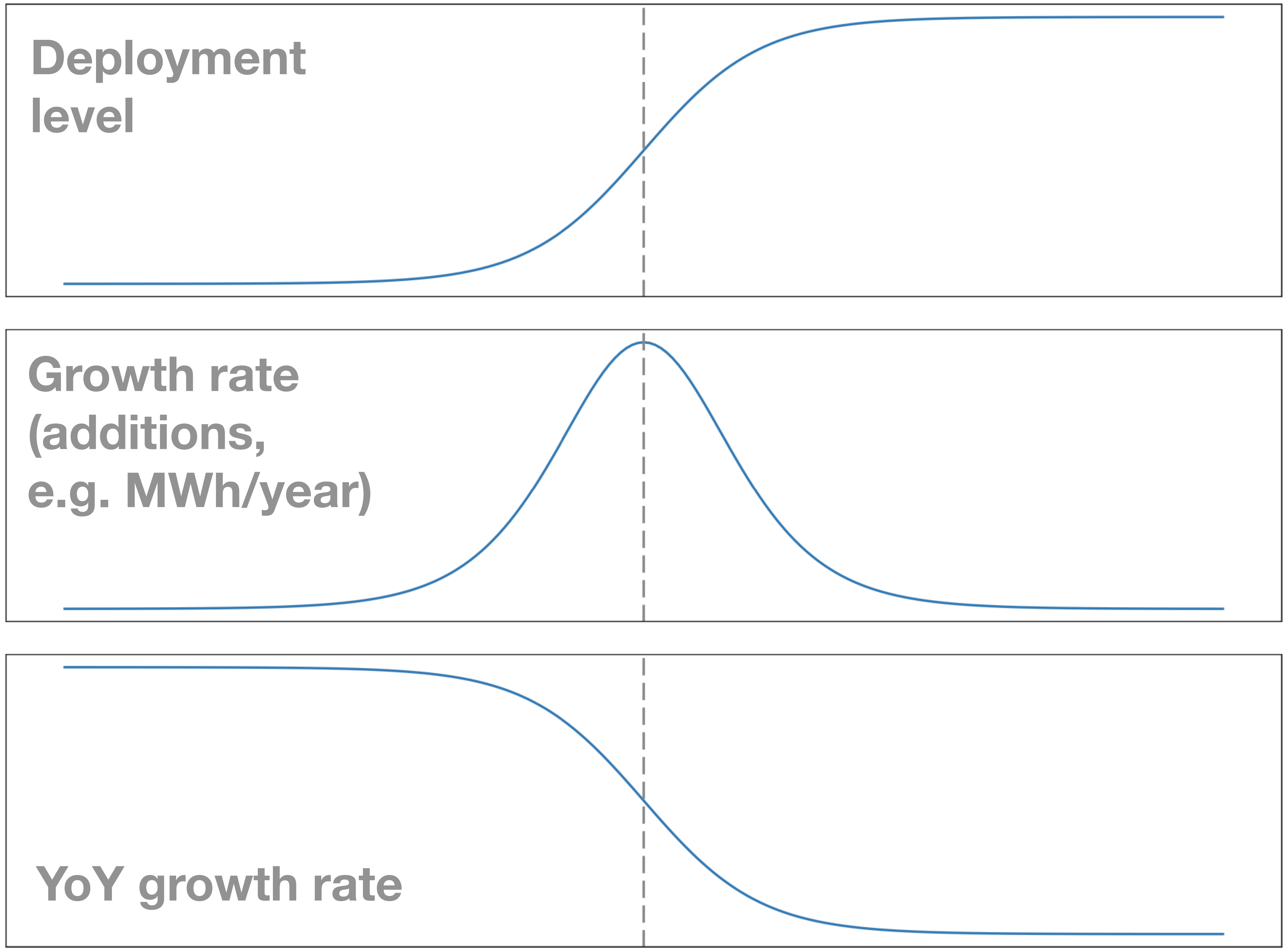
$$R = \left(\frac{9.342}{2.744}\right)^{1/3} - 1 \approx 0.50$$

Year-on-year growth rate

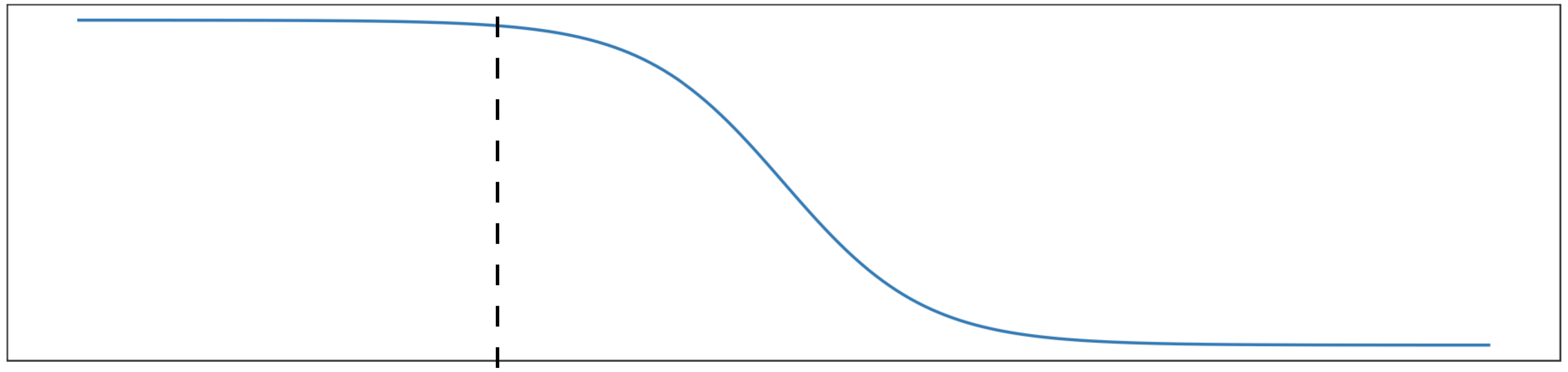


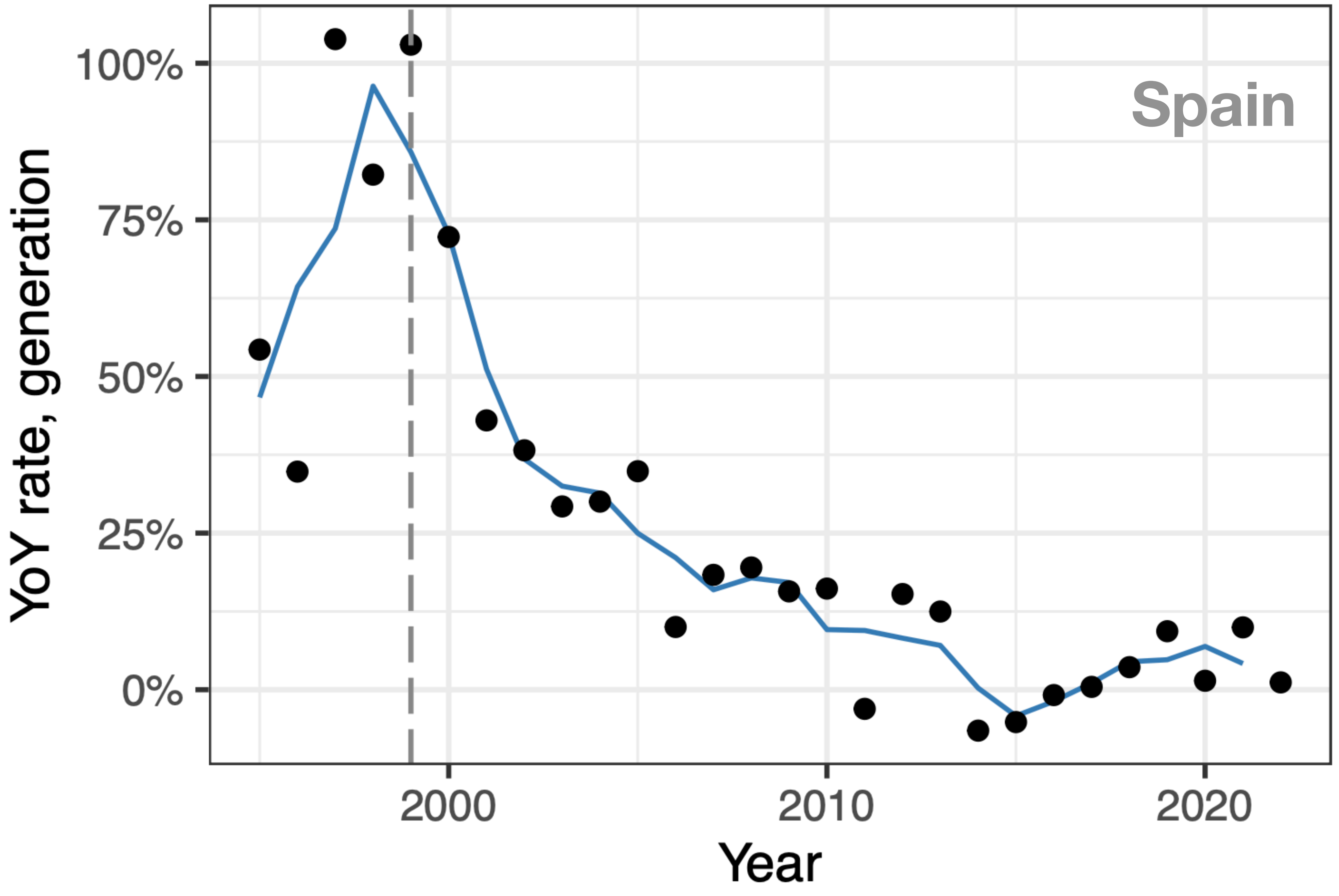


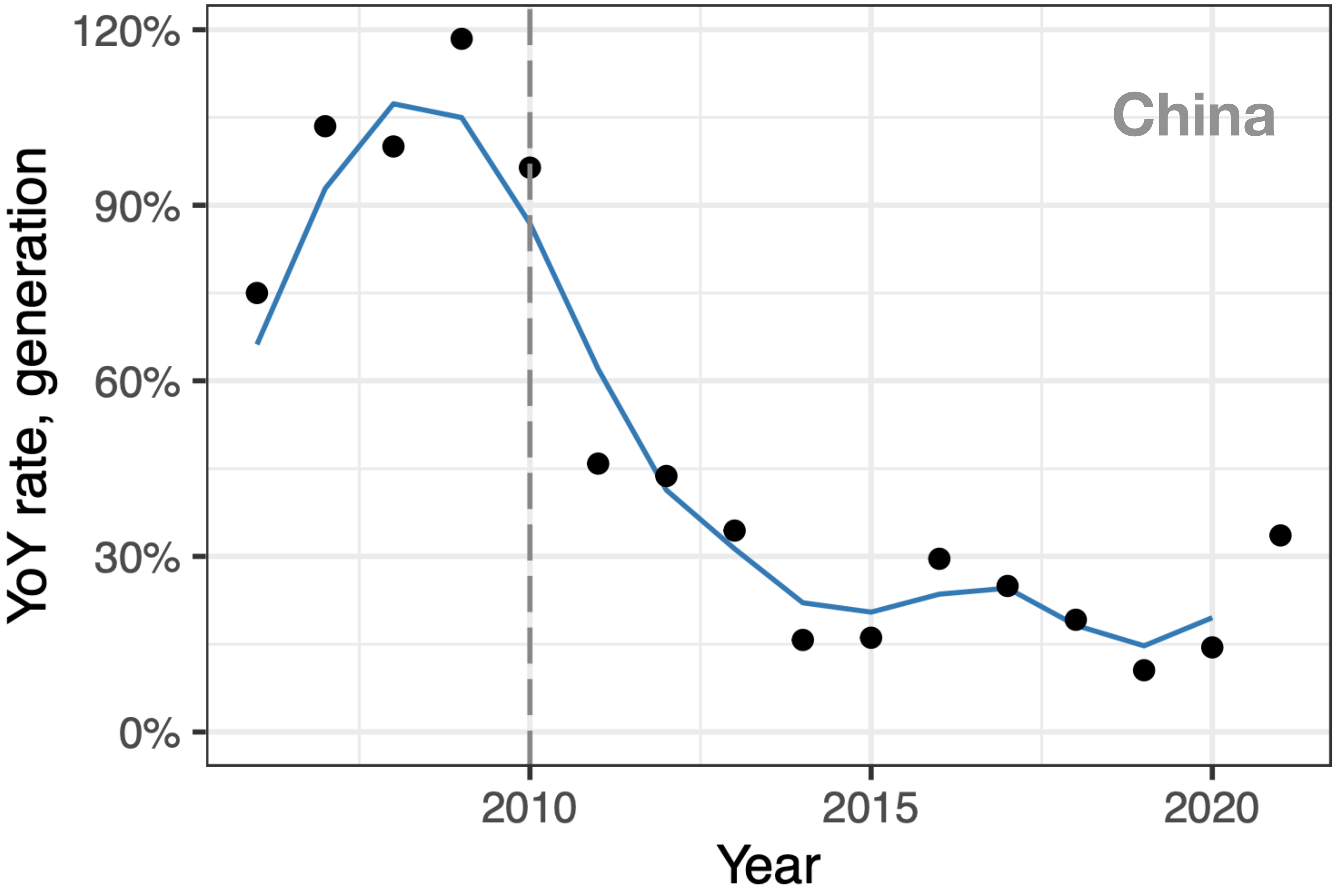
Logistic model: additions and year-on-year growth rates



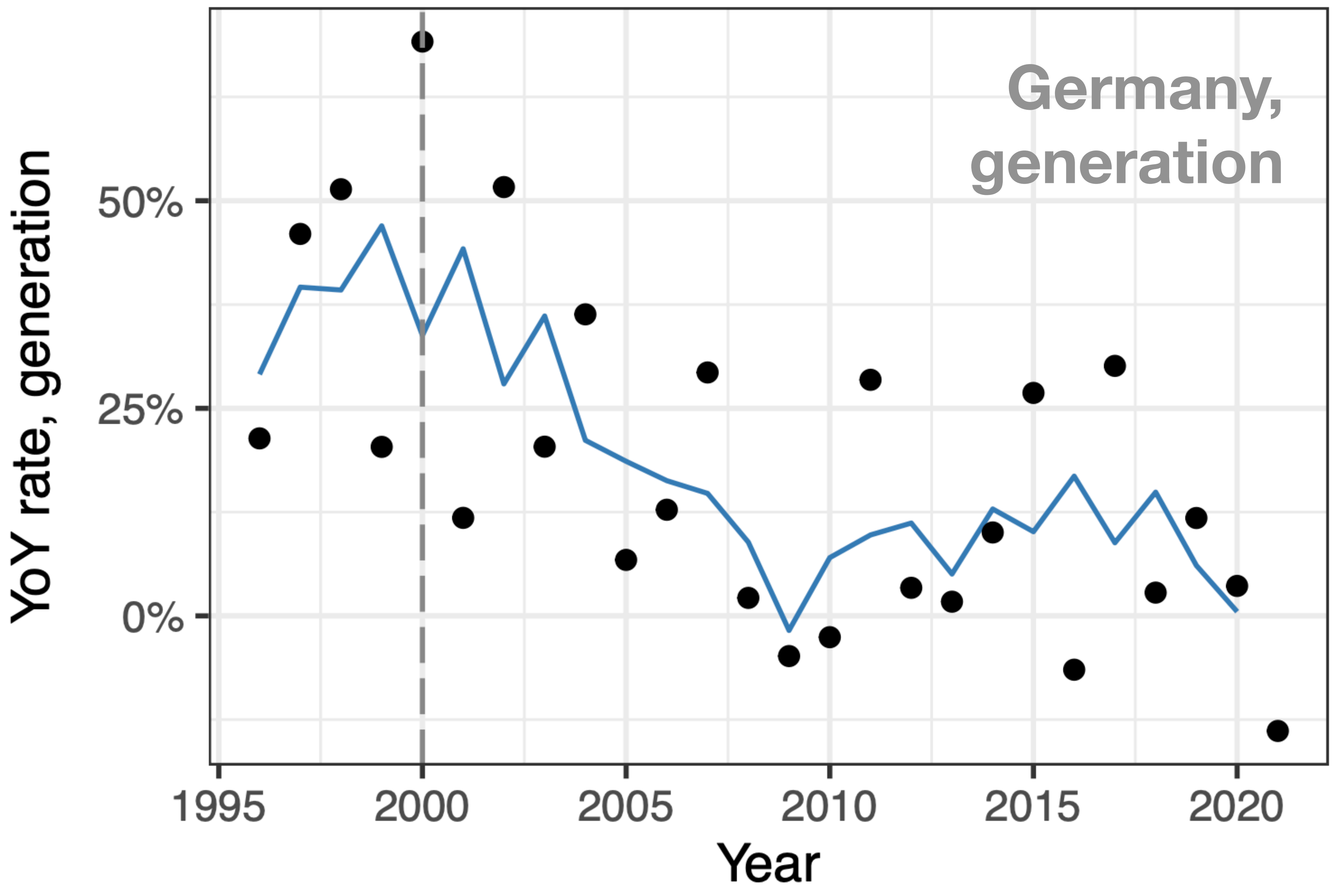
Year-on-year growth rate

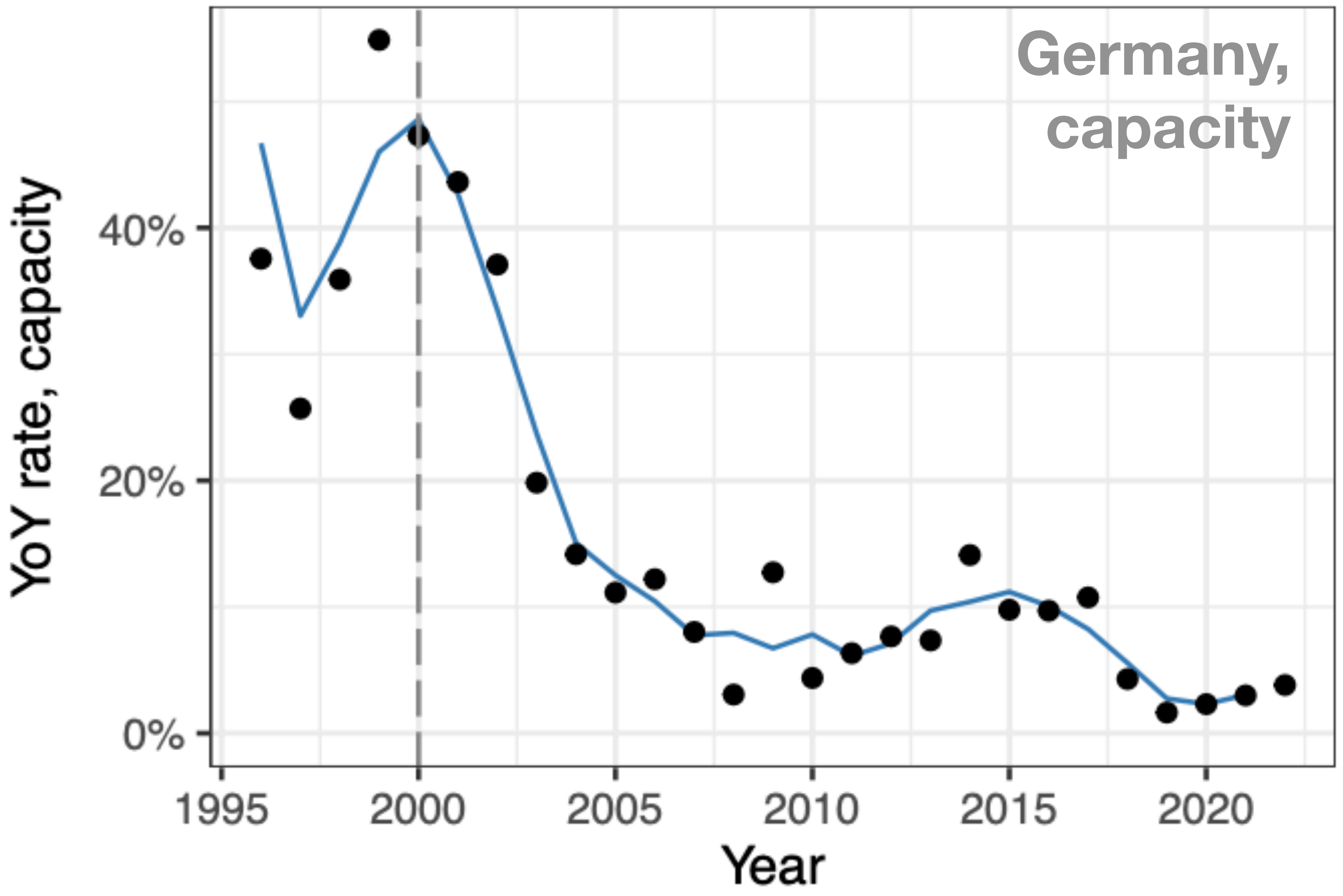




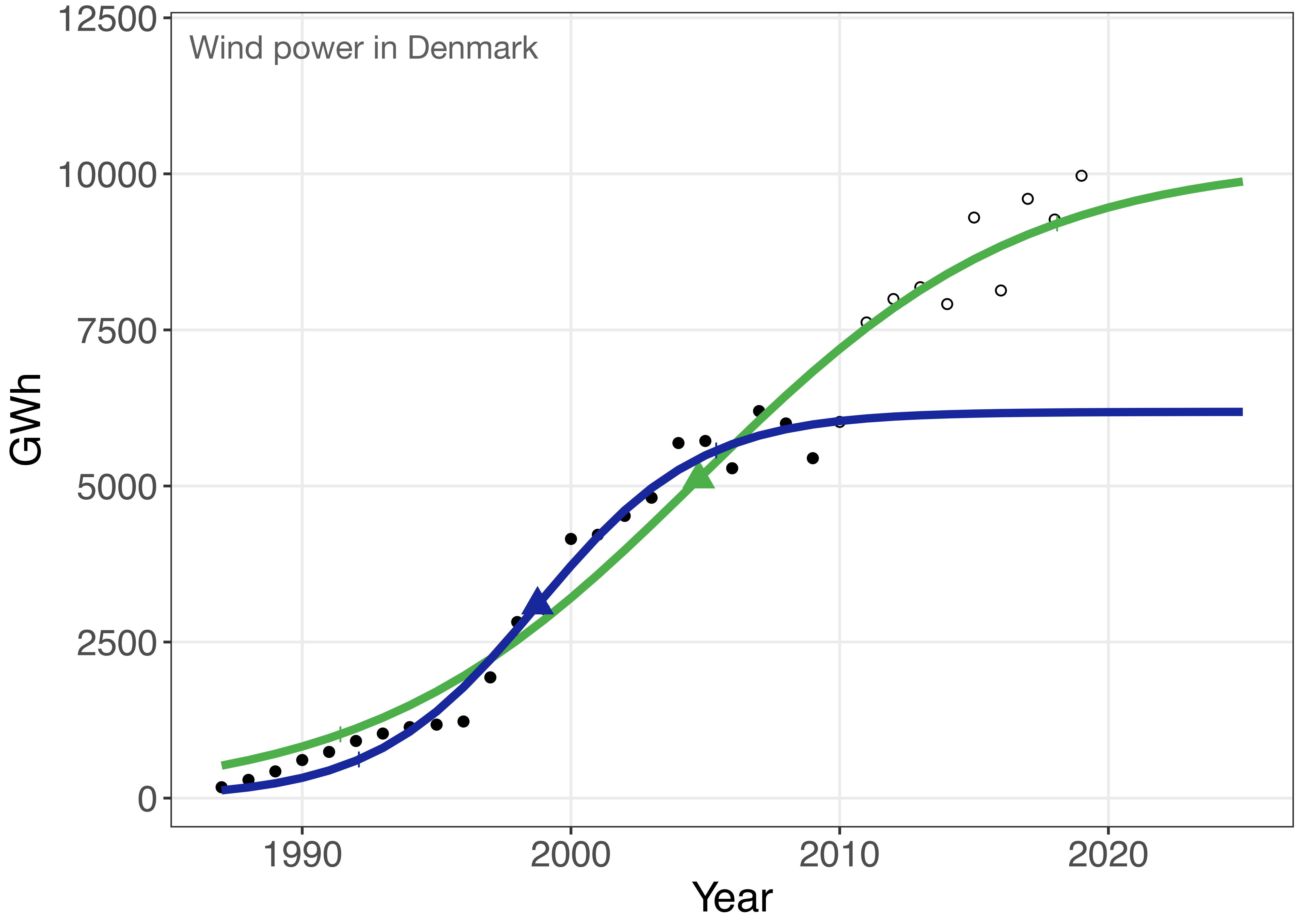


Capacity curves are often less noisy
(both for YoY rates and maximum additions)





Does fitting a curve predict the future?



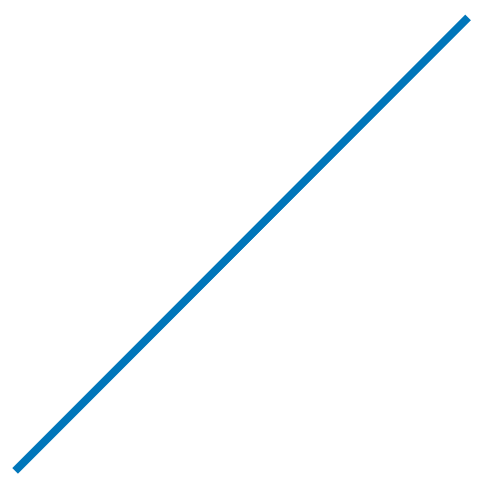
The case of global wind growth: is it still exponential?

…if wind power continues its current trend of exponential growth (21% per year) for another decade…

Summary of metrics

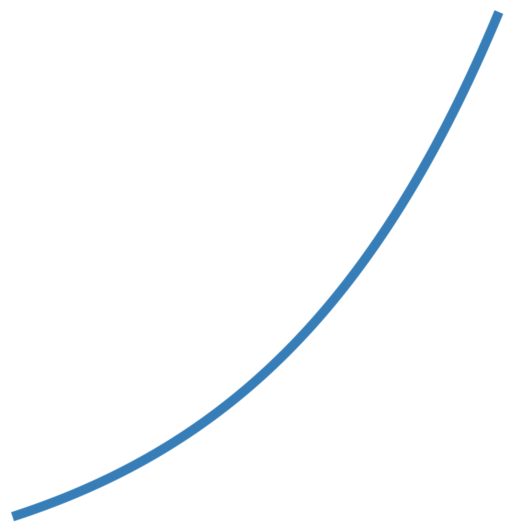
“Additive” metrics

- Average annual growth/decline rate
  - Recent growth rate
- Maximum growth rate G (measured by growth model fitting), captures quasi-linear growth at its fastest
- Can be normalised (should be for cross-country comparisons!)



“Multiplicative” metrics

- Year-on-year growth rate (captures quasi-exponential acceleration)
  - CAGR: “averaged” YoY growth rate



Summary of metrics

	Formative	Acceleration	Stable growth	Stagnation
YoY rate/CAGR				
Max. growth rate				
Recent growth rate		Phase-agnostic, also works with decline (relevance depends on the task/problem at hand)		
Average annual growth rate		Phase-agnostic, also works with decline (relevance depends on the task/problem at hand)		

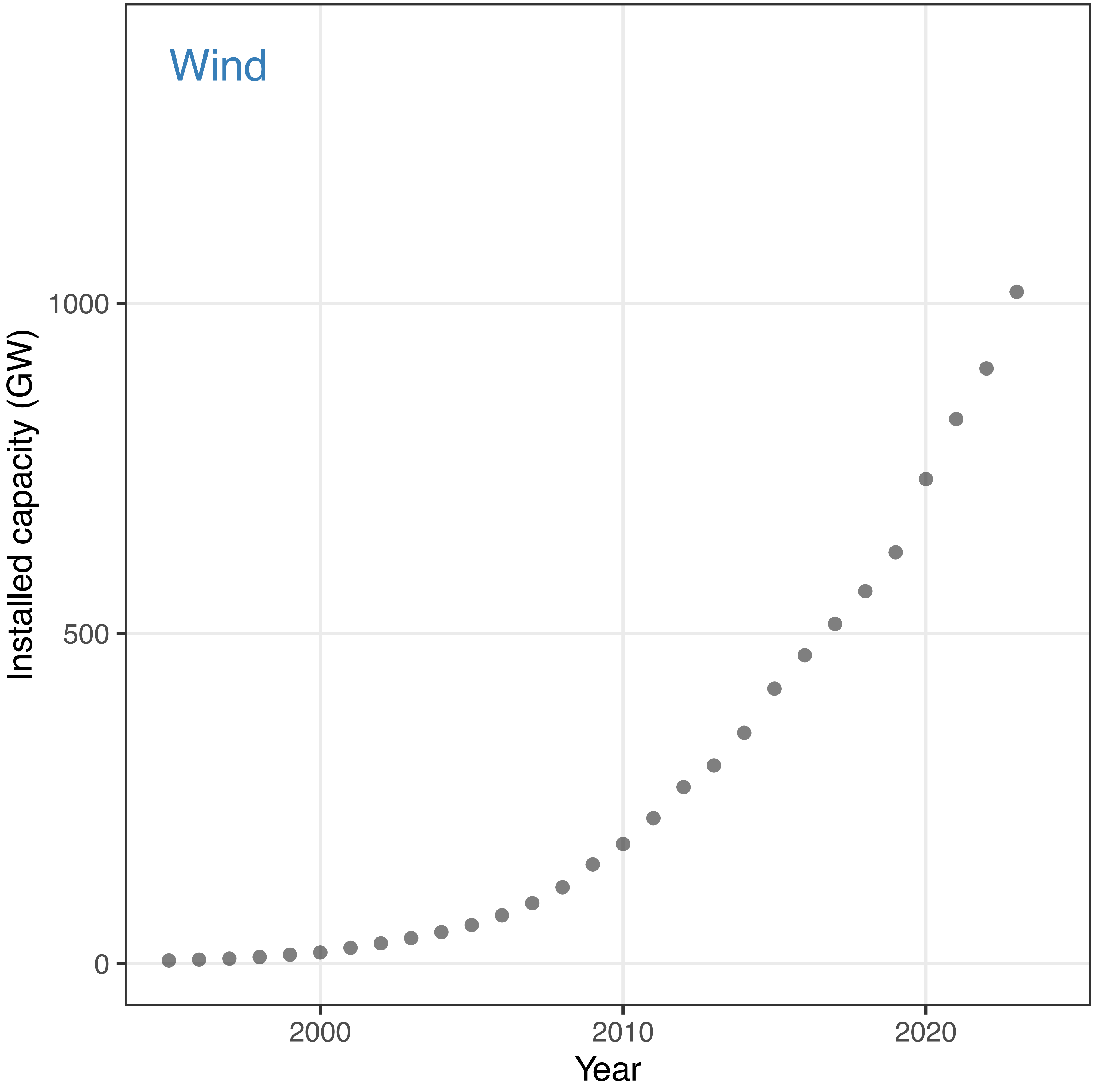
Can be measured

Can be measured on curtailed series

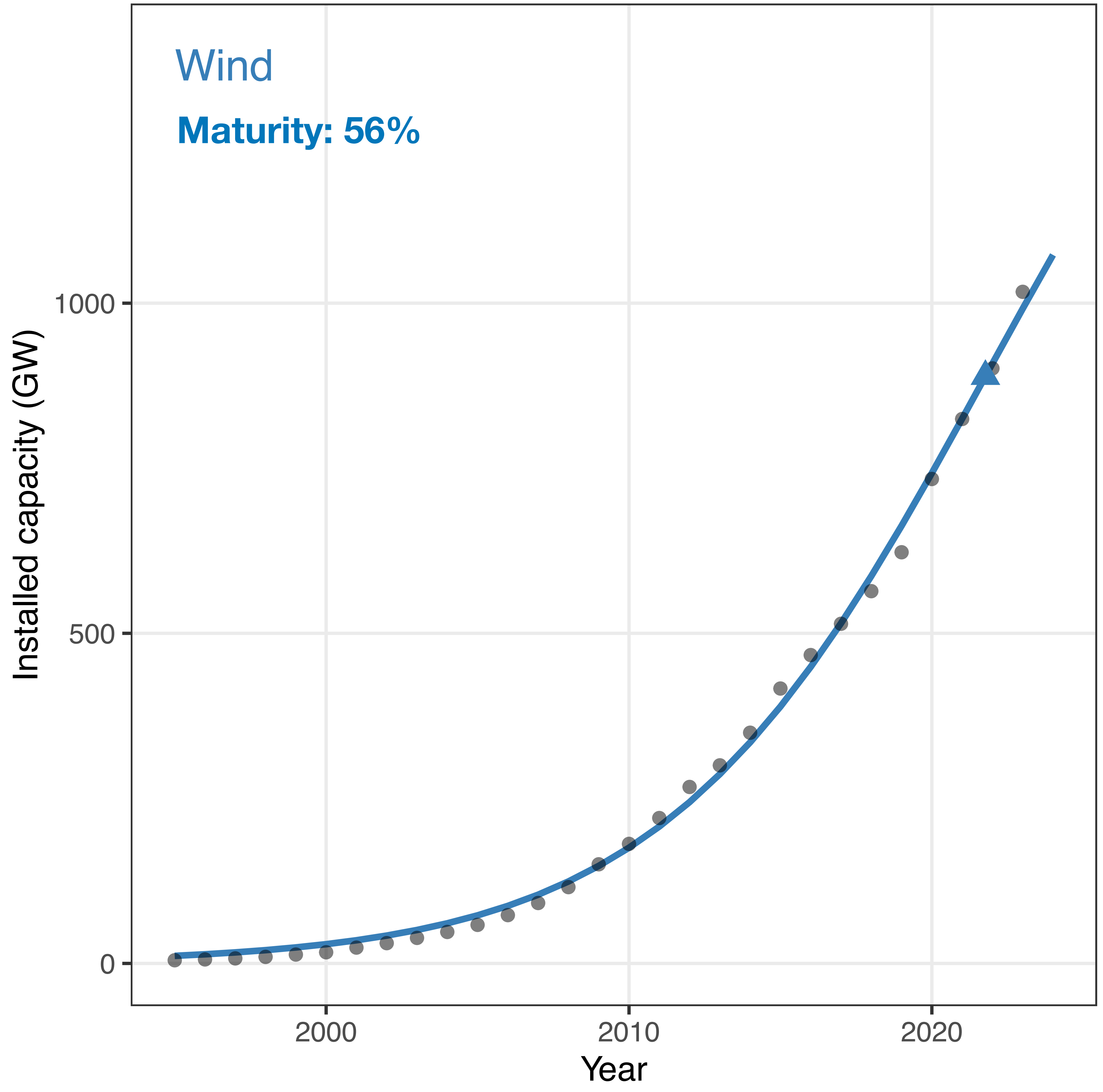
Cannot be meaningfully measured

The case of global wind growth: is it still exponential?

…if wind power continues its current trend of exponential growth (21% per year) for another decade…



The case of global wind growth: is it still exponential?



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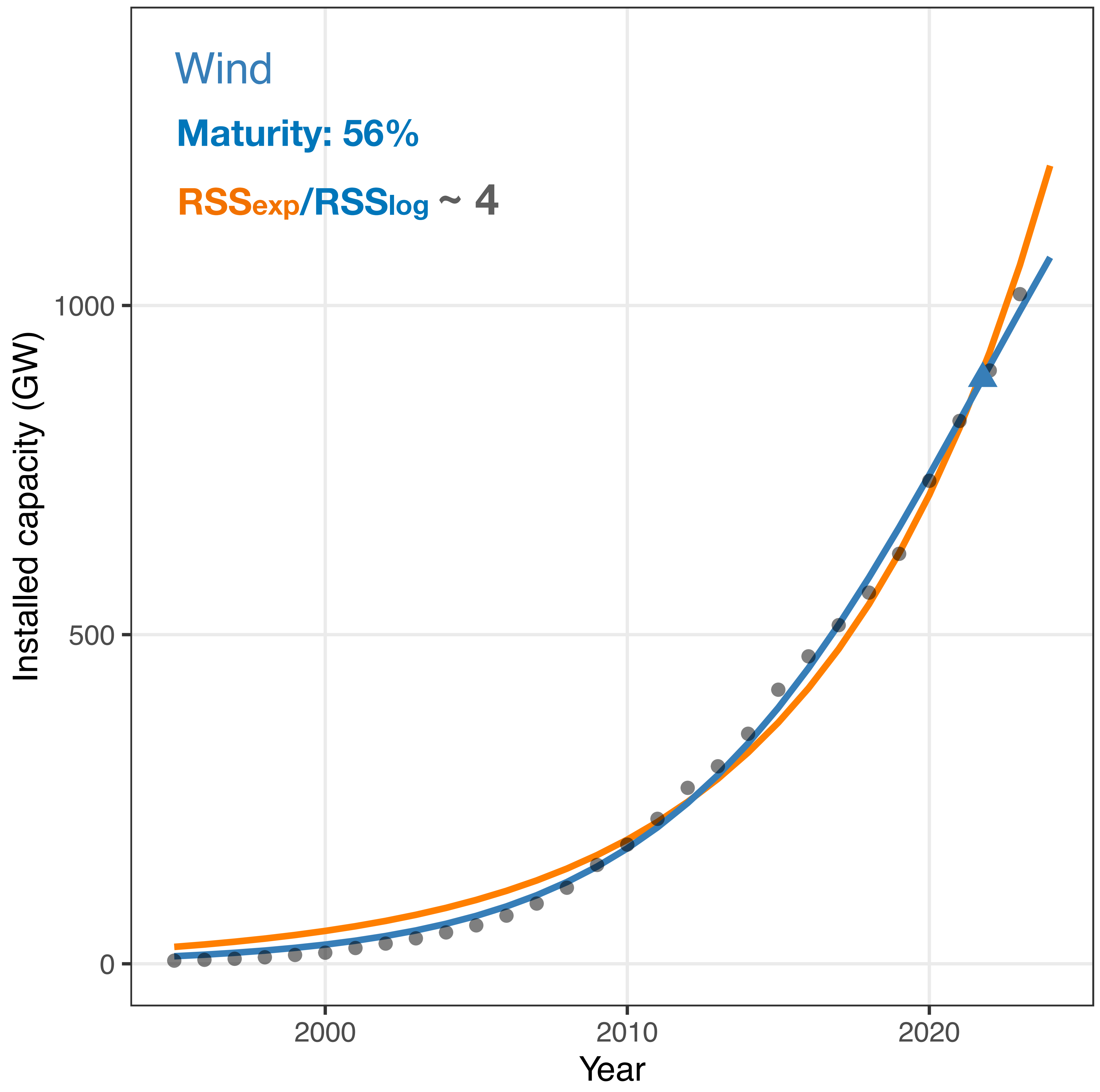
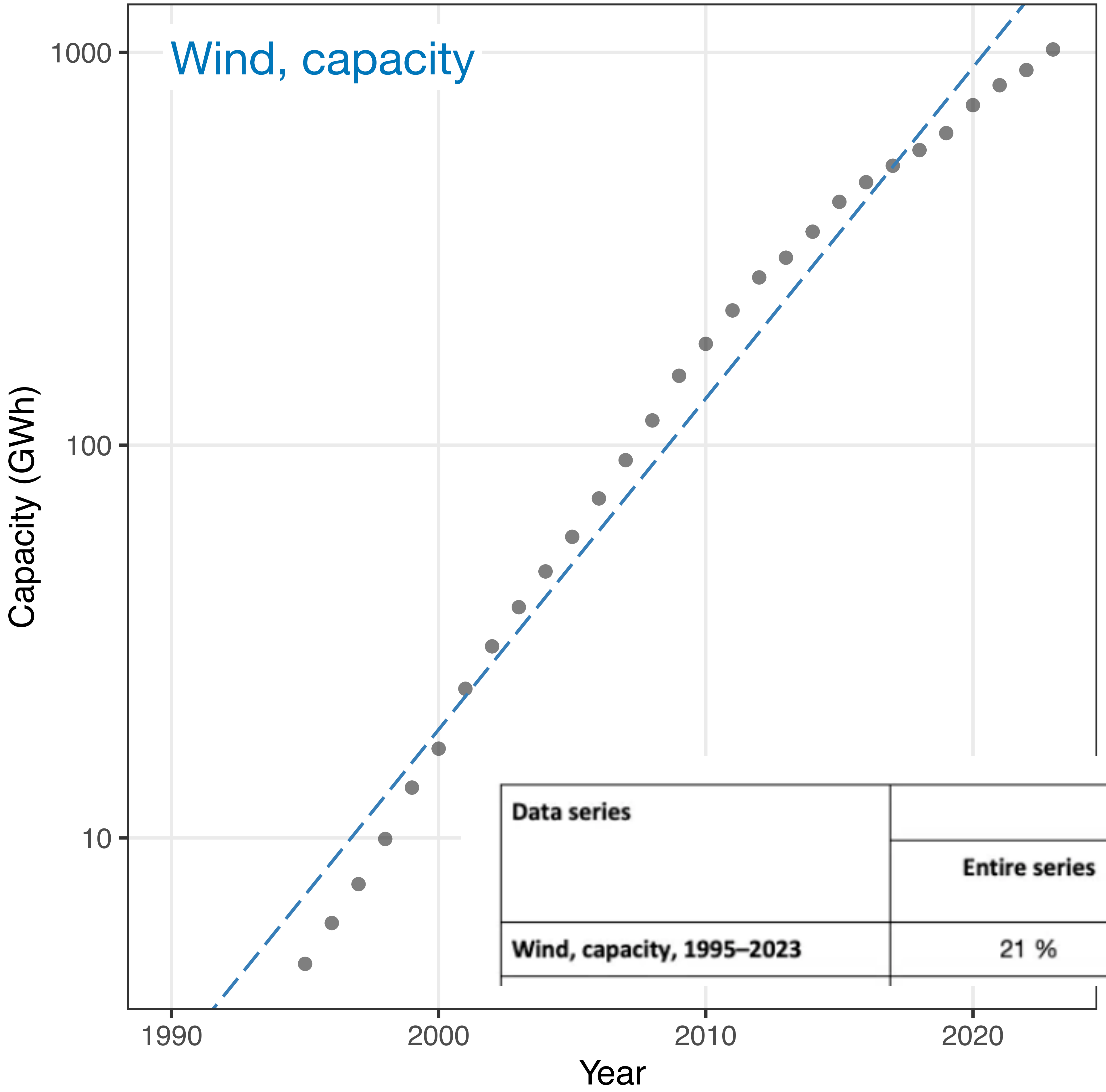
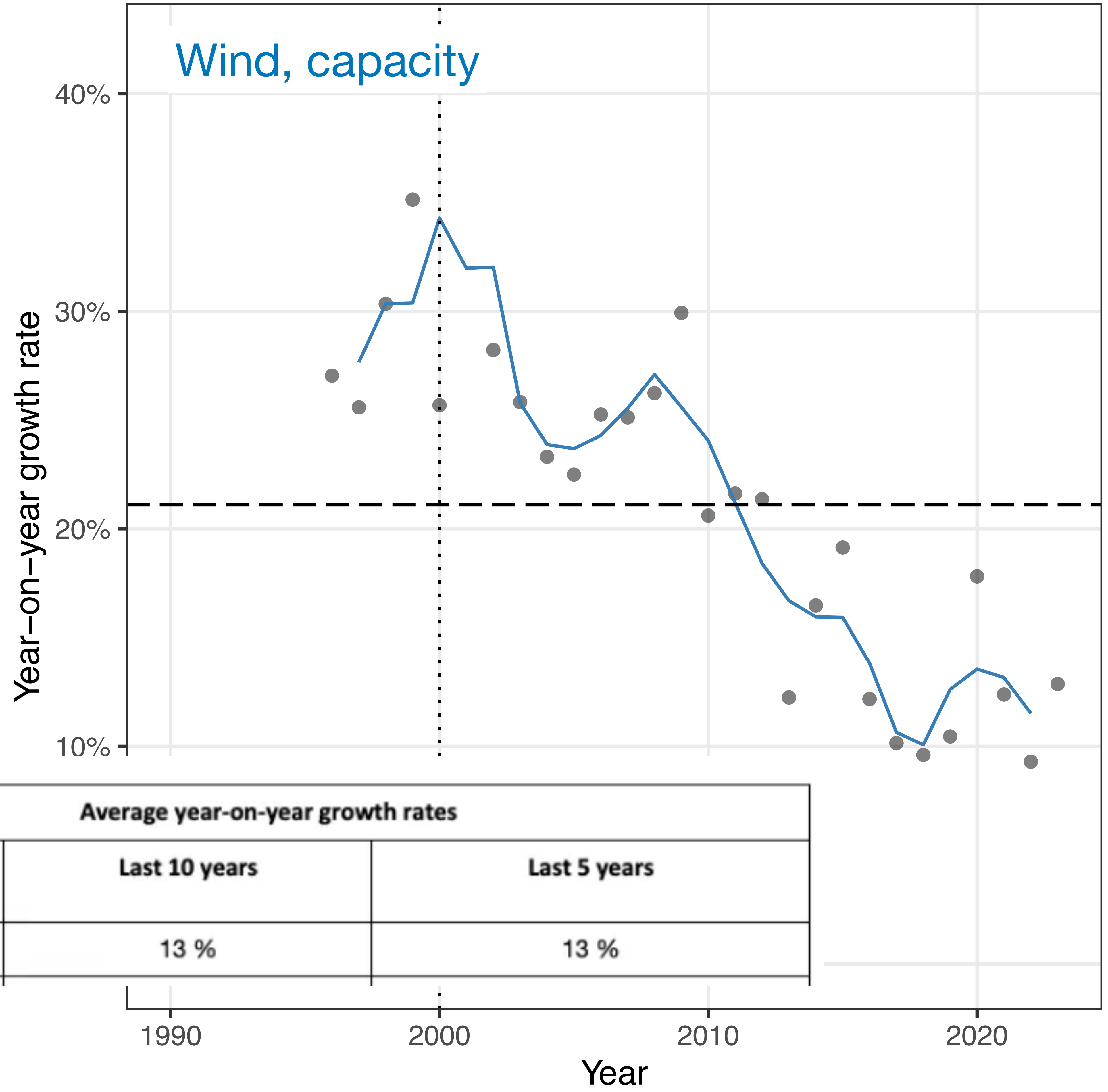


The case of global wind growth: is it still exponential?





Data series	Average year-on-year growth rates		
	Entire series	Last 10 years	Last 5 years
Wind, capacity, 1995–2023	21 %	13 %	13 %

Exercise: measuring transitions

Aim

The aim of this exercise is to give you practical experience of calculating various technology growth metrics and selecting a metric appropriate to the current growth stage in the context of feasibility analysis. After completing this exercise you will be able to:

- understand several metrics of technology growth, their advantages and disadvantages;
- calculate various types of growth metrics;
- choose a metric appropriate to the growth stage;
- use growth metrics for evaluating the feasibility of targets or plans.

Exercise: measuring transitions

Exercise description

In this exercise, you will be estimating the feasibility of Poland's renewable energy targets (offshore wind and solar PV) using different metrics of technology growth. You are given historical data on installed capacity of solar PV for 16 countries and offshore wind for 6 countries. The exercise follows the general scheme of feasibility evaluation in a simplified form….

Your specific tasks are:

- identify the growth stage of the target case (Poland's targets) for each of the two renewable energy sources;
- select relevant reference cases comparable to the target case;
- calculate the appropriate metric of growth implied by Poland's targets (target case);
- calculate the appropriate growth metric for countries in your dataset (reference cases);
- evaluate the feasibility of the target case by comparing it to the reference cases in terms of the growth metric.

Exercise: measuring transitions

Code and data on Canvas

- Choose the language (R or Python 3)
- Read `README.txt`, `file_format.txt`, comments in the main code file (`fitting.R` or `fitting_log.py`)
- Necessary packages/modules are listed in the main code file

```r
#Working directory should be set to that of the source

##Necessary packages
library(minpack.lm)
library(dplyr)
library(stringr)
```

Data and code for the exercise

- National deployment of solar power (capacity and generation, 16 countries) solar_data.csv
- National deployment of offshore wind power (capacity and generation, 6 countries) offshore_data.csv

Columns in both datasets:

  - "Country" – country, 2-letter ISO code;
  - "Year" – Year;
  - "Fuel" – energy source;
  - "Value" – installed capacity in MW;
  - "Gen" – electricity generation in GWh;
  - "Total" – total electricity supply in GWh.

- Code for growth model fitting with description (Python or R)

Fitting_Python.zip Fitting_R.zip

```python
import numpy as np
import pandas as pd
from math import log
from scipy.optimize import least_squares
import re
```

Due: Monday 25 Nov at 23:59

Due: Monday 25 Nov at 23:59

Consultation: Thursday 28 Nov at 13:00

Consultation Thursday 21 Nov:

will answer your technical questions
(after Marta's presentation)