Outlook for Long-Term Fossil-Fuel CO_2 Emissions

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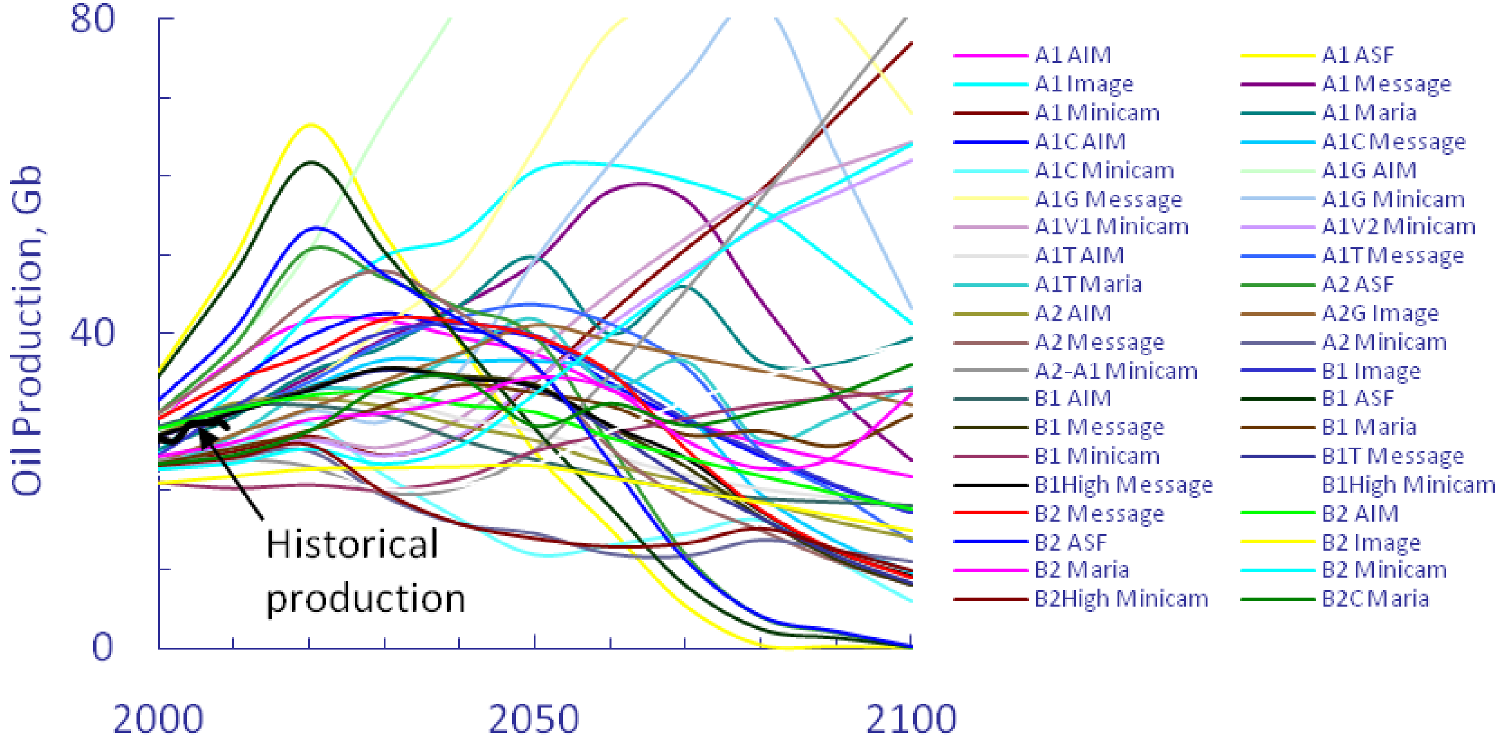
The UN Panel on Climate Change (IPCC)

For oil, gas, and coal production, the IPCC works with scenarios — "… 40 SRES [Special Report on Emissions Scenarios] scenarios together encompass the current range of uncertainties…"

Oil Production in the IPCC Scenarios



- Gb = billions of barrels, historical production from the *BP Statistical Review*
- Range for production from 2010 to 2100 is 1446Gb to 8278Gb — still growing in 13 scenarios in 2100

Goal is to Reduce these Uncertainties by Replacing Scenarios with Statistics

- US oil — Hubbert's peak
- British coal — The Coal Question
- World coal
- World oil and gas

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Estimating long-term world coal production with logit and probit transforms

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ABSTRACT

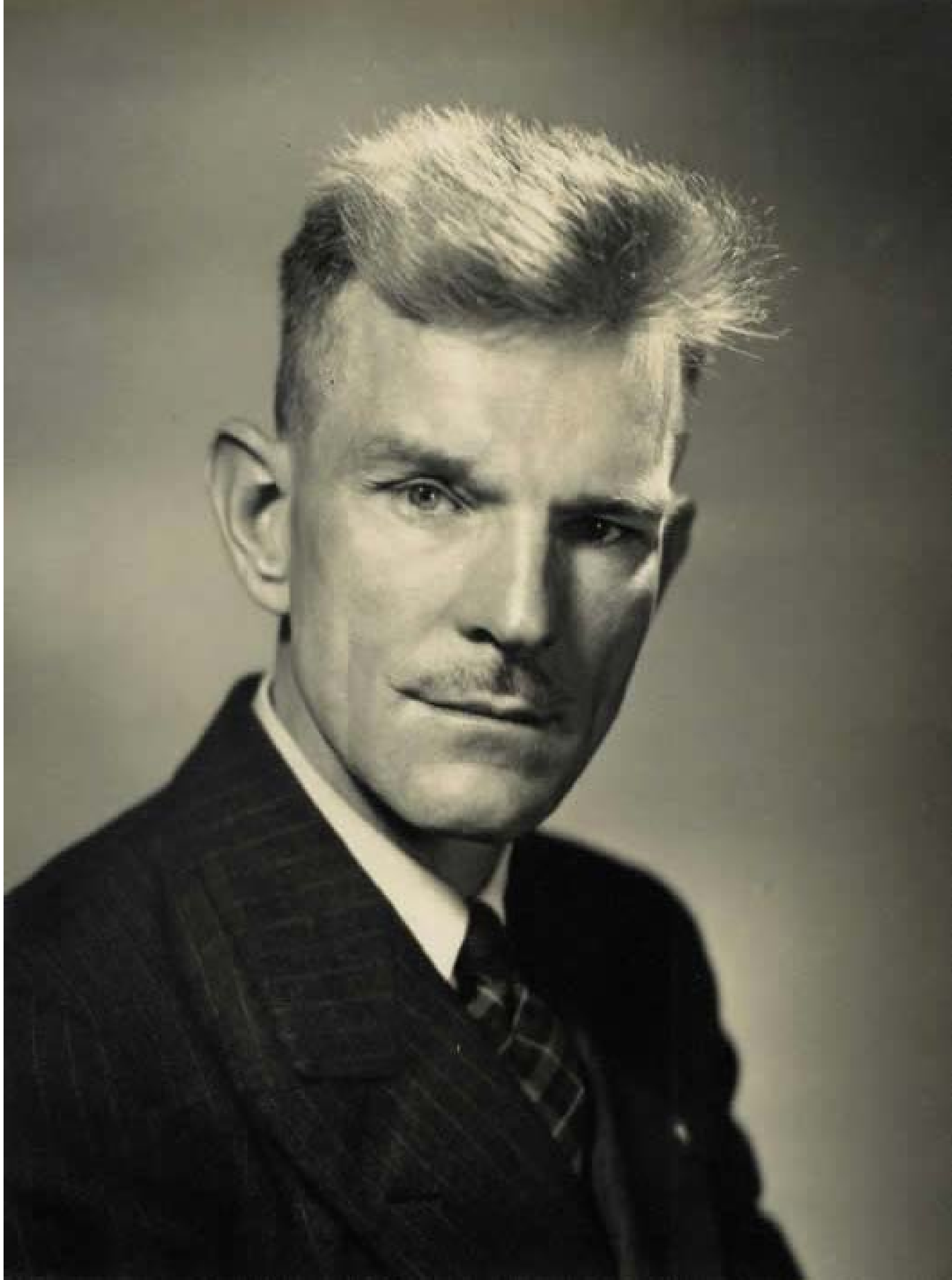
An estimate for world coal production in the long run would be helpful for developing policies for alternative energy sources and for climate change. This production has often been estimated from reserves that are calculated from measurements of coal seams. We show that where the estimates based on reserves can be tested in mature coal regions, they have been too high, and that more accurate estimates can be made by curve fits to the production history. These curve fits indicate that total world production, including past and future production, will be 680 Gt. The historical range for these fits made on an annual basis from 1995 to 2009 is 653 Gt to 749 Gt, 14% in percentage terms. The curve fits also indicate that 90% of the total production will have taken place by 2070. This gives the time scale for considering alternatives. This estimate for total production is somewhat less than the current reserves plus cumulative production, 1163 Gt, and very much less than the amount of coal that the UN Intergovernmental Panel on Climate Change, or IPCC, assumes is available for its scenarios. The maximum cumulative coal production through 2100 in an IPCC scenario is 3500 Gt.

Characterizing Uncertainty

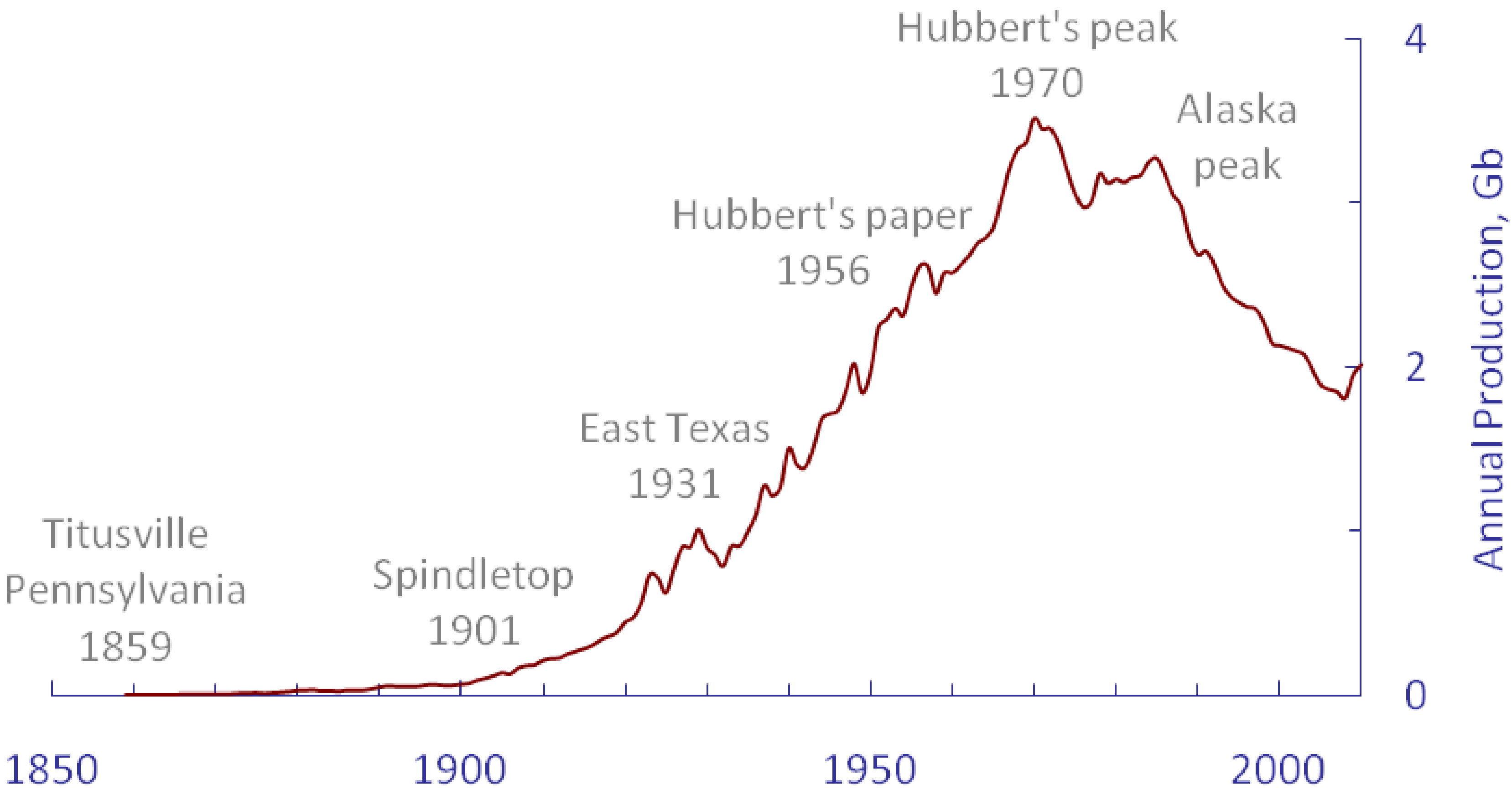
- *Residuals* are the differences between data and models
- The “best” model is used for *projections*
- *Uncertainty* refers to the inconsistency in a group of projections
- A *range* giving the upper and lower values is one measure of uncertainty — a one-sided example would be designing for the 100-year flood
- When residuals can be decorrelated, we can create bootstrap *replications*, which are effectively alternative histories with the same statistical properties as the actual history
- Replications allow us to calculate confidence intervals
- Limitations in confidence intervals (uncertainty index might be a better term) — they depend on the form of the models, some uncertainties are left out, and the models can break down
- Validation (testing the model) on historical data and with partial data is critical — difficult to validate models with more than two variables

King Hubbert

- Geophysicist at the Shell lab in Houston, Texas
- In 1956, he wrote a paper suggesting the possibility of a peak in US oil production in 1970

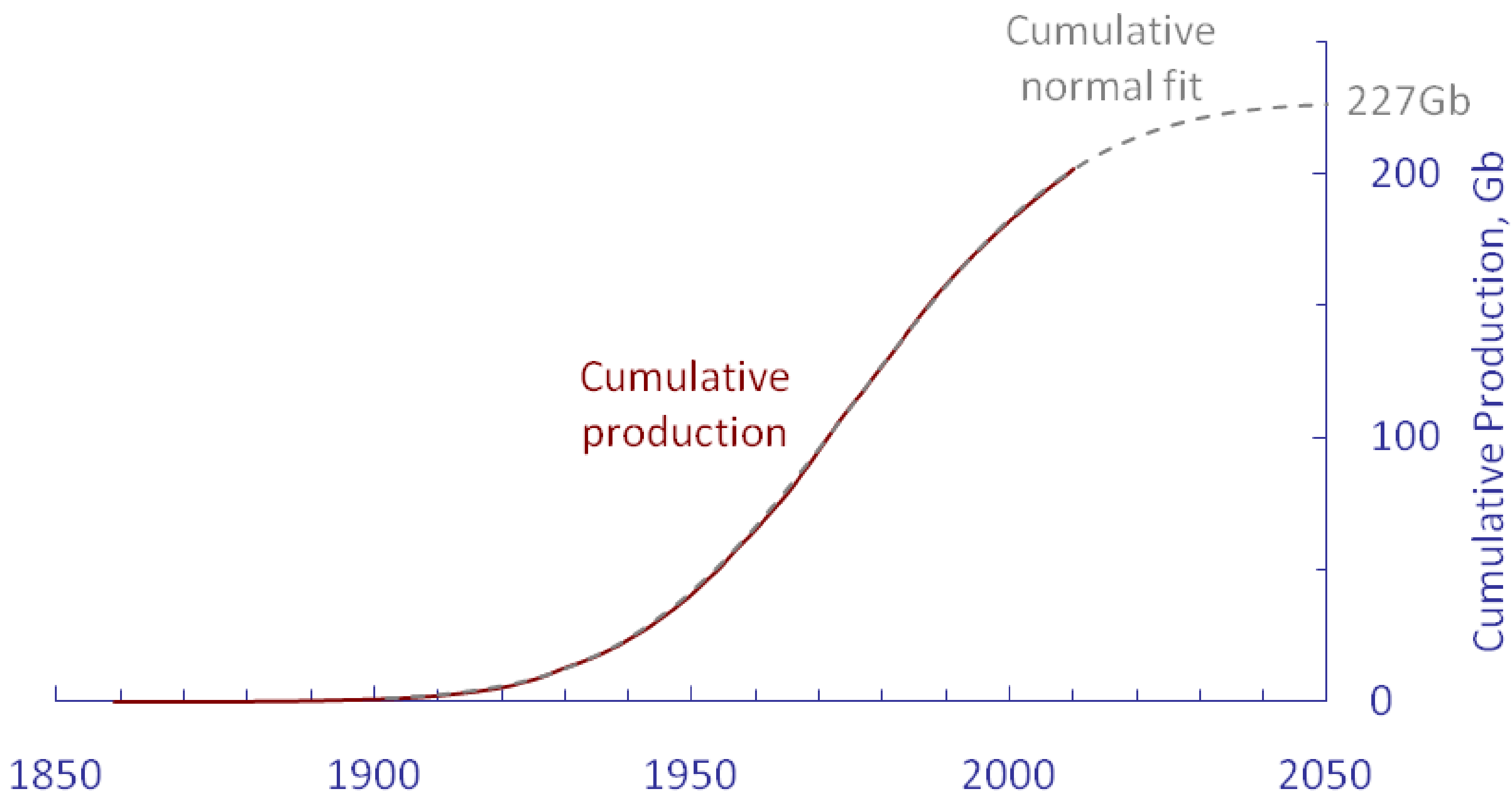


US Crude-Oil Production



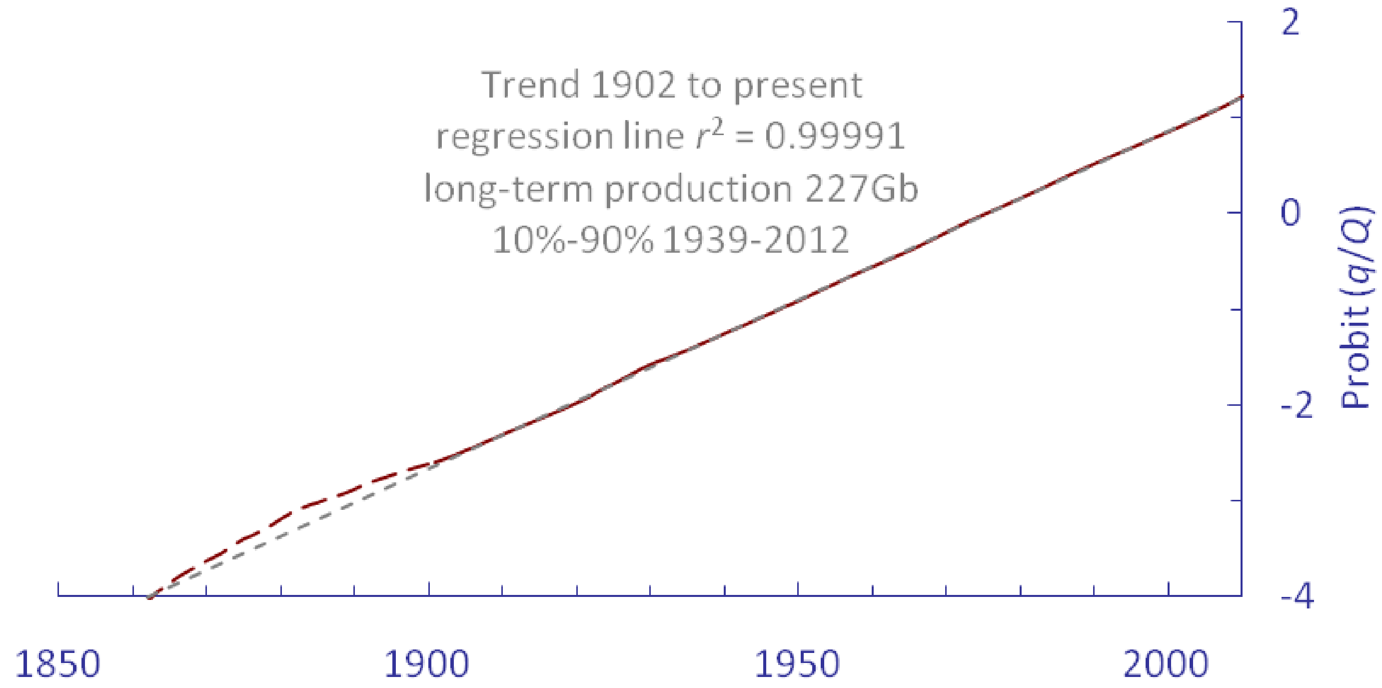
- Gb = billions of barrels
- Data from the Energy Information Administration (EIA)

Cumulative Production for US Crude Oil



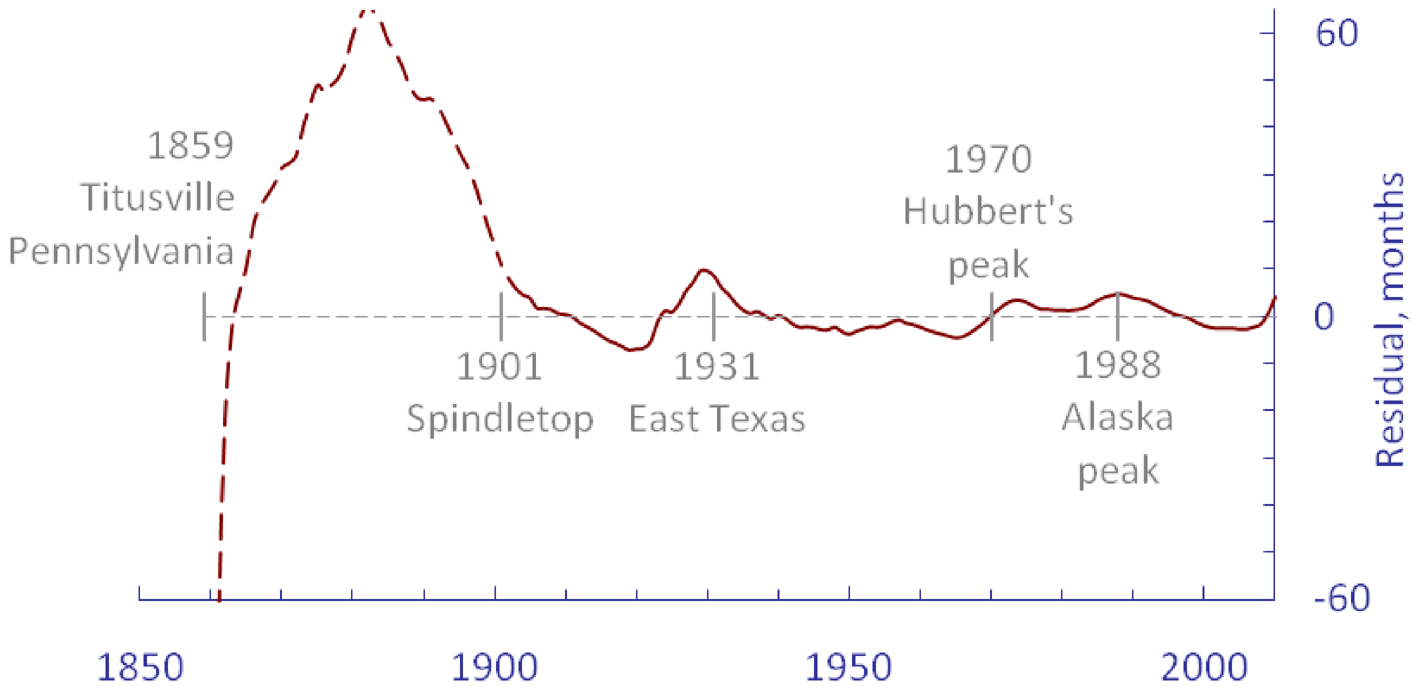
- Top of the scale for the normal gives a projection for the long-term production — total production, past and future

Probit Transform for US Crude Oil



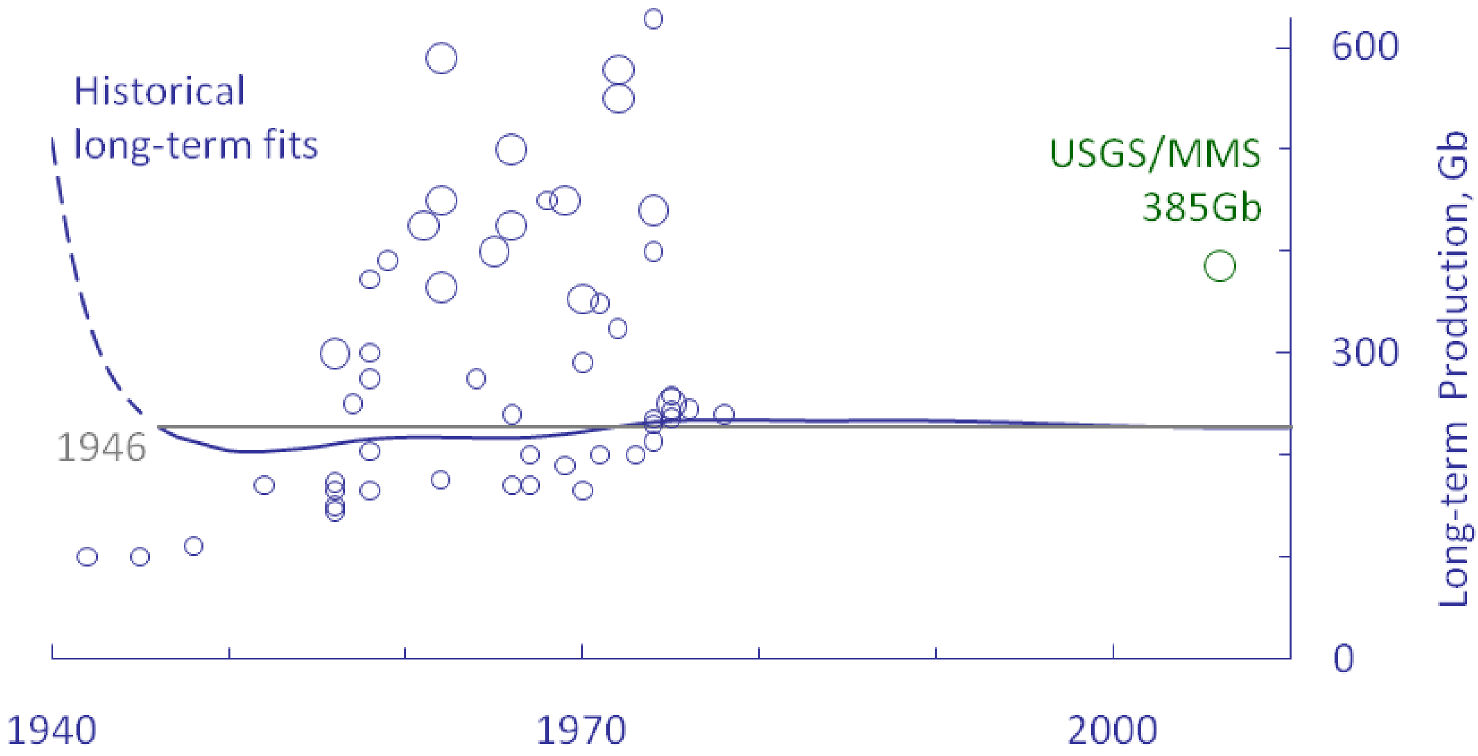
- Cumulative production is linearized by the probit transform (inverse of the standard cumulative normal)
- The plot is for probit(q/Q), where q is cumulative production, and Q is the proposed long-term production
- Maximize r^2 (correlation coefficient squared) — gives 0.99991
- A one-parameter fit, 1 second in Excel

Residuals for US Crude Oil



- Residuals are expressed in the equivalent months of production — positive residuals show we are ahead of schedule, negative residuals show we are behind schedule
- Maximum residual from 1902 on is 10 months — 4 months in 2010

Historical Fits for Long-Term Production



- Range from 203Gb to 235Gb since 1946 (14%)
- Large circles are government estimates, small circles are non-government
- Government median is 433Gb, non-government median is 230Gb
- USGS = US Geological Survey, MMS = Mineral Management Service

Kenneth Deffeyes on the USGS Assessments

"When USGS workers tried to estimate resources, they acted, well, like bureaucrats. Whenever a judgment call was made about choosing a statistical method, the USGS almost invariably tended to pick the one that gave the higher estimate."

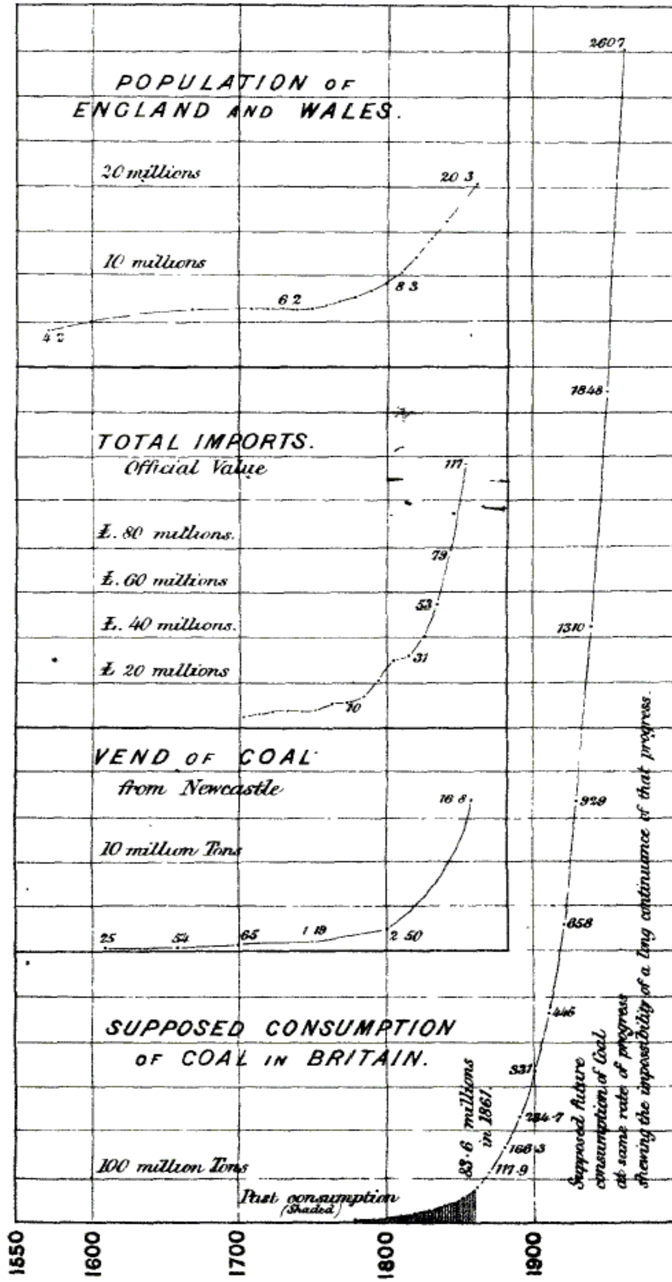
Kenneth Deffeyes
Professor of Geology, emeritus,
Princeton University

Deffeyes' Law of Bureaucratic Resource Estimates

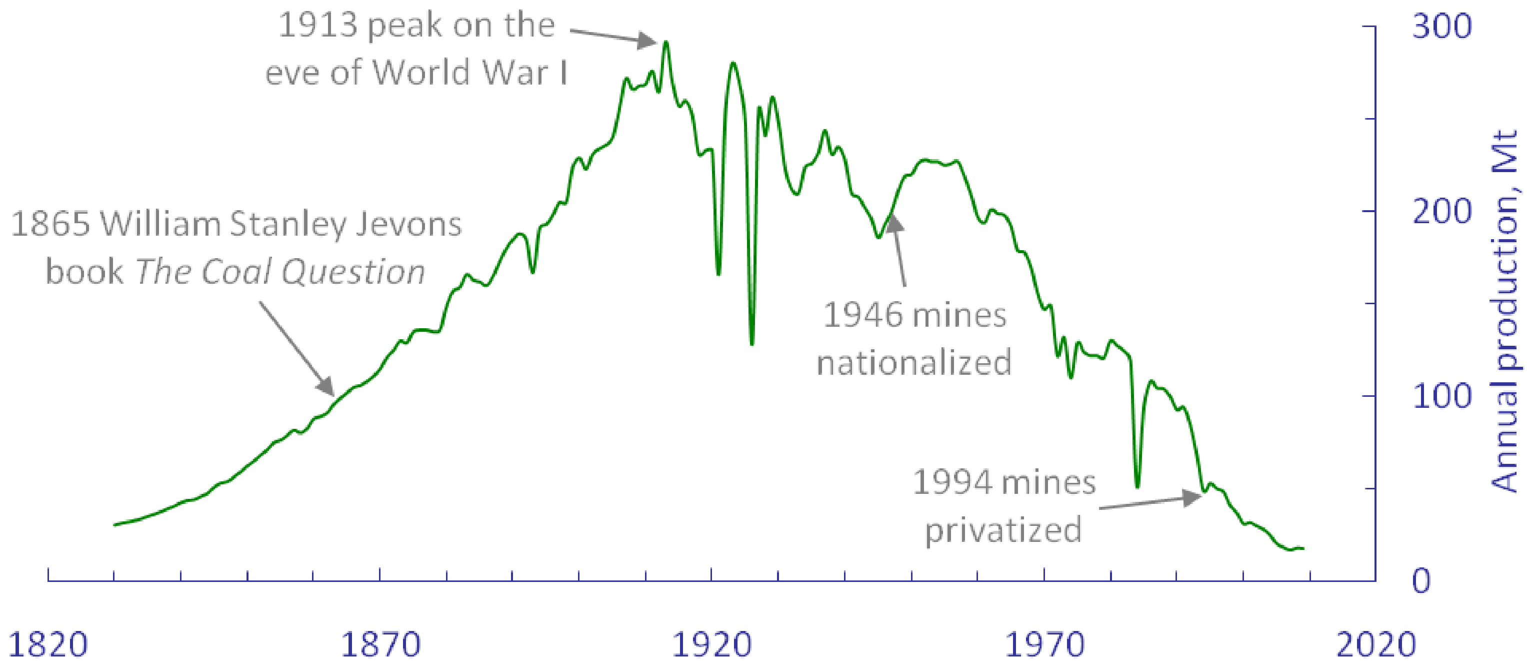

British Coal
Photo by
John Cornwell

Stanley Jevons, 1865

The Coal Question

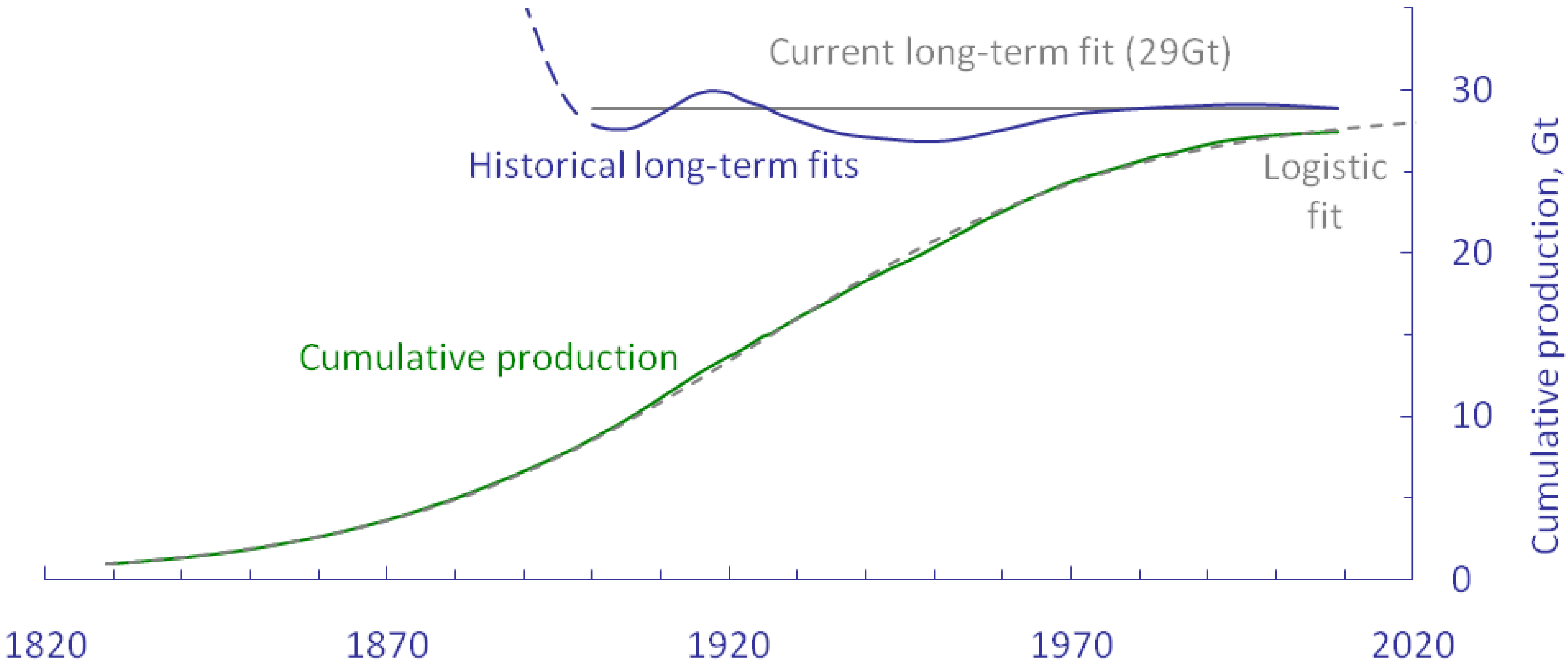


UK Coal Production



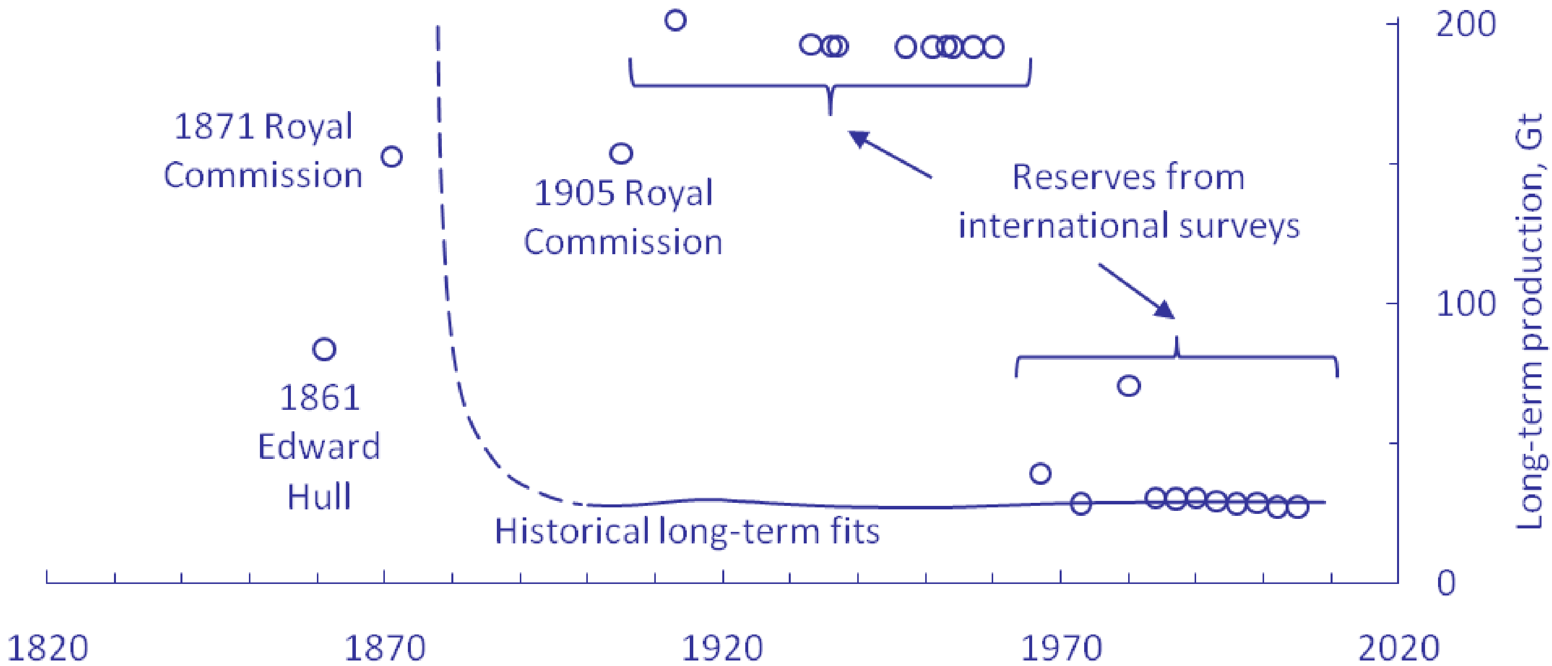
- Mt = millions of metric tons
- Production is now 16 times less than the peak — the last time the production was this low, Napoleon was alive
- In 1913, Britain exported 31% of its production — in 2010 the UK imported 59% of what it burned

Cumulative Production and Historical Fits



- Estimates for long-term production have varied in a 11% range since 1900
- Fit uses a different *s*-curve, the logistic function, that gives a better fit than the normal
- Linearized through the logit transform $r^2 = 0.9996$

Historical Long-term Fits Compared with Reserves

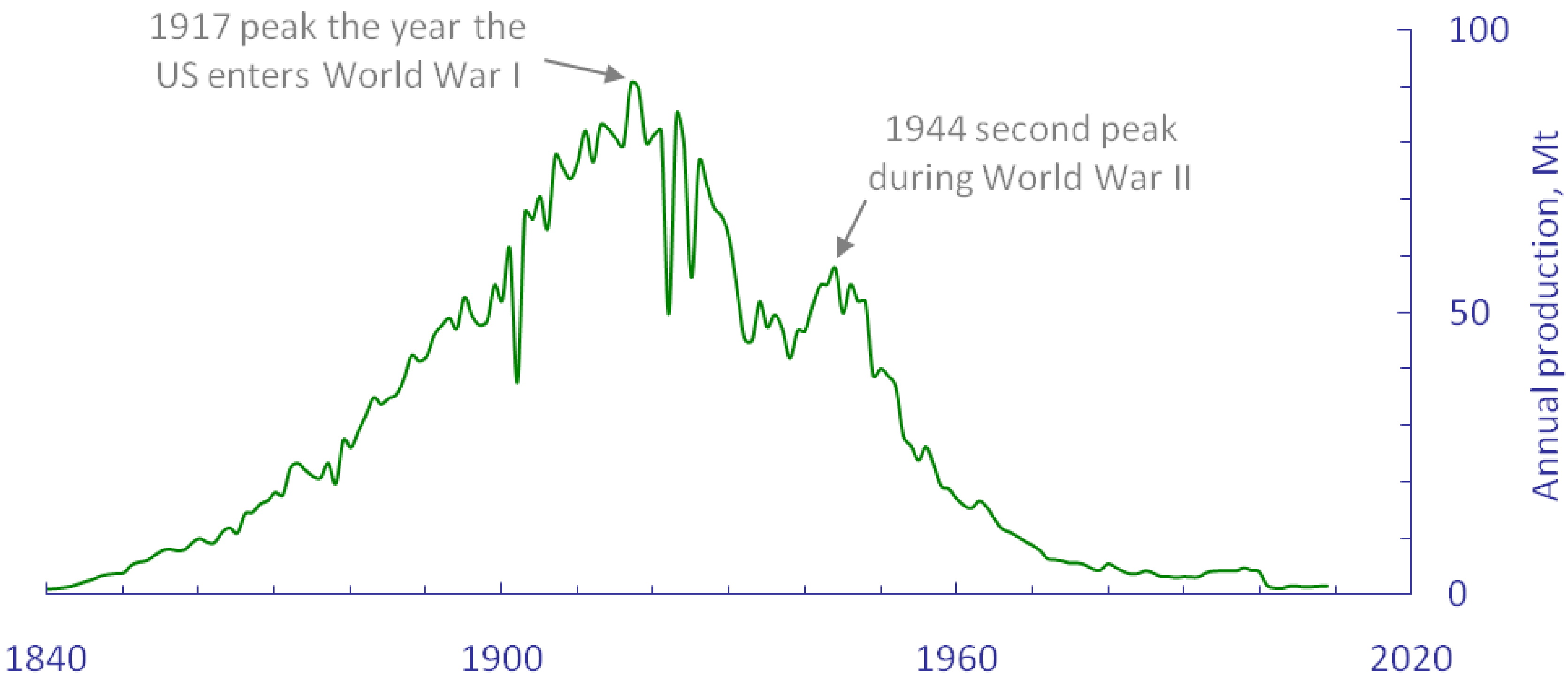


- Reserve numbers are available before long-term fits
- Produced 18% of the 1871 Royal Commission reserves + cumulative
- Criteria chosen were too optimistic — 1-ft seams, 4,000-ft depth
- Collapse in reserves in 1968 — the five collieries left with producing longwall faces (down from 803 faces in 1972) were all producing by 1968

American Coal

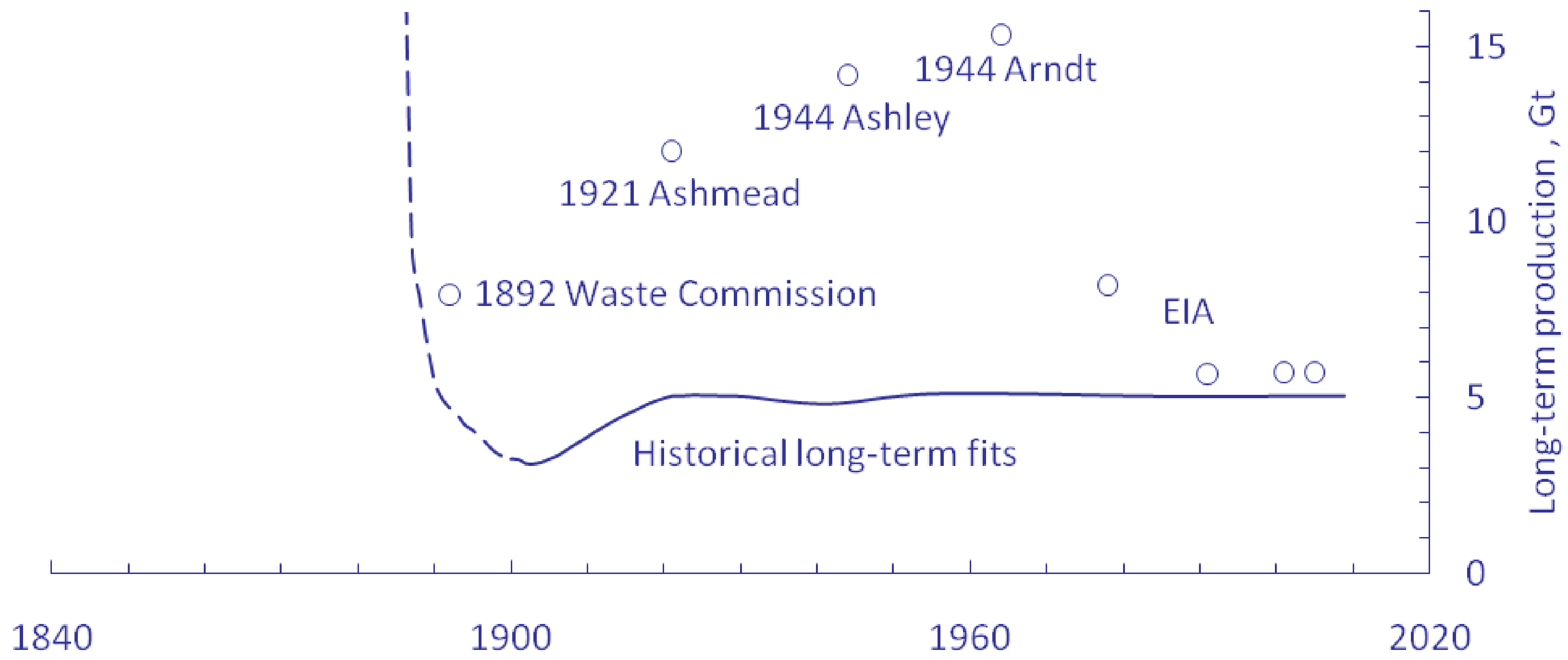
Photograph by
Christian Abraham
used with permission

Pennsylvania Anthracite Production



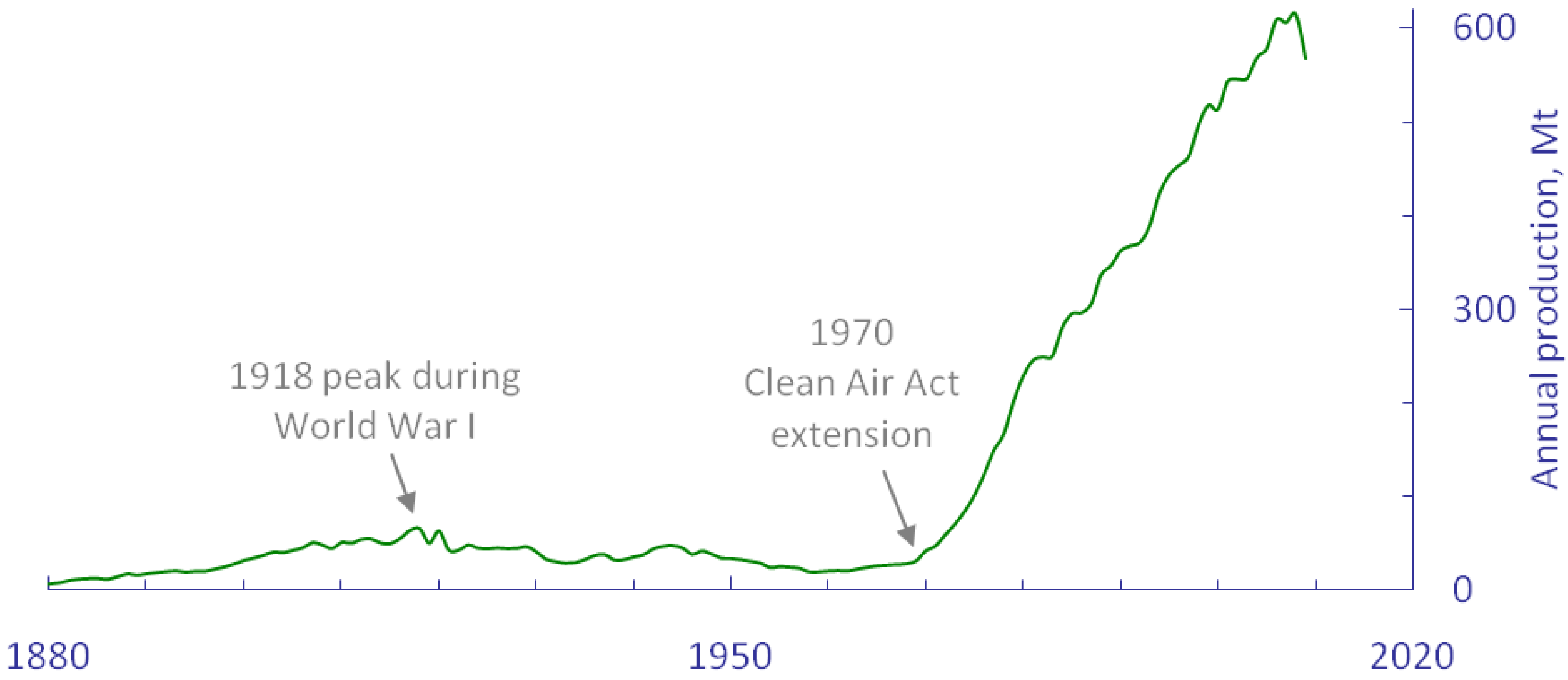
- Burns without smoke — used for home heating
- Production is now 59 times less than the peak

Historical Long-Term Fits for Pennsylvania Anthracite



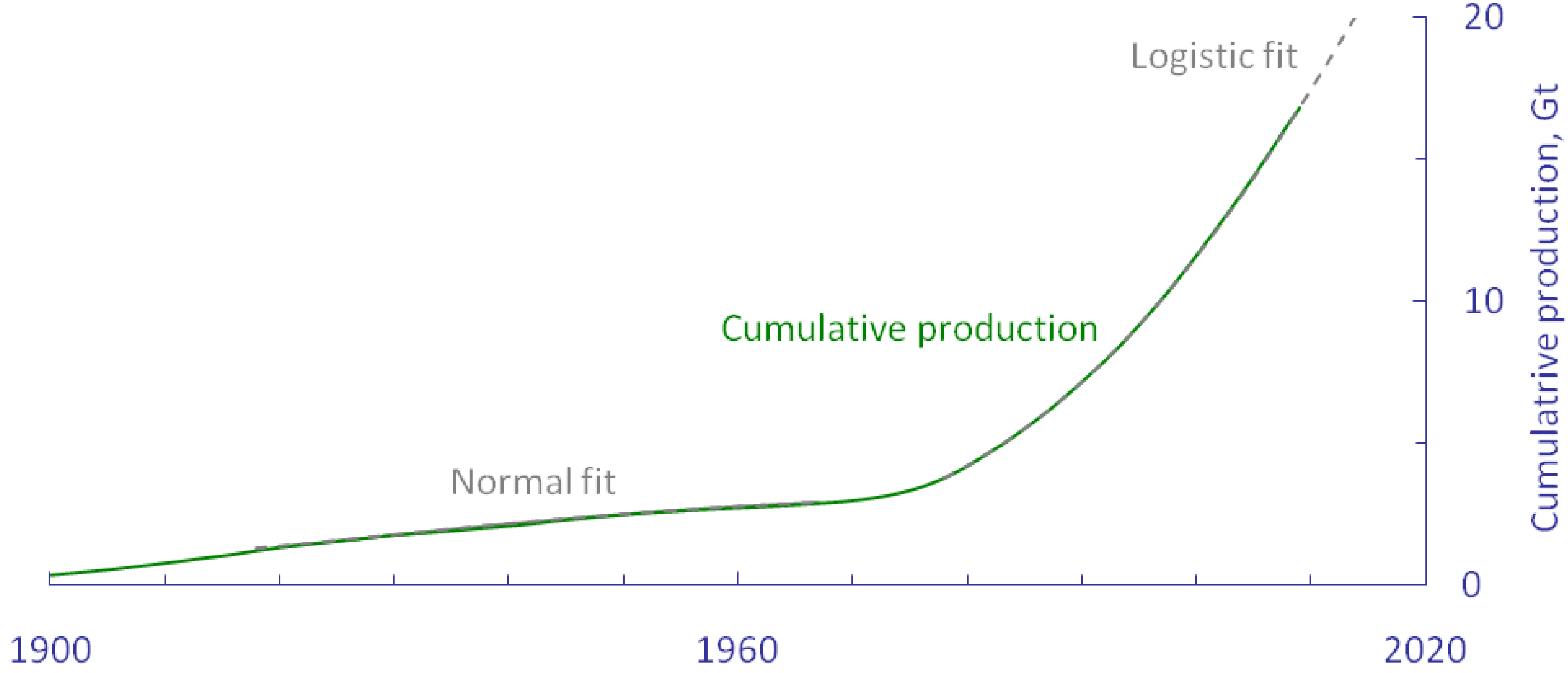
- Estimates for long-term production have varied in a 40% range since 1900
- Produced 42% of 1921 reserves + cumulative

Western US Coal Production



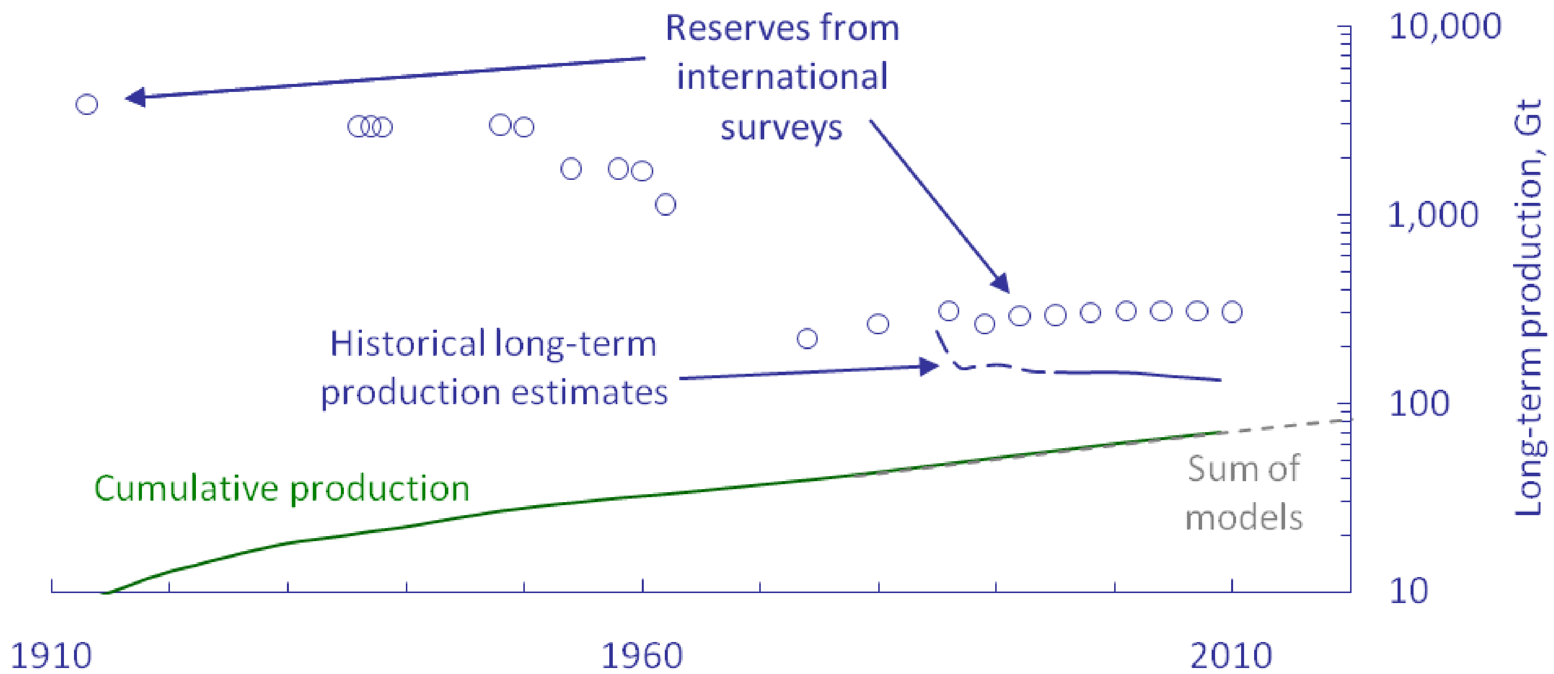
- Early production cycle peaked in 1918 — extremely limited by lack of railroad capacity to customers
- New start after the 1970 Clean-Air Act Extension, which encouraged the use of low-sulfur coal, and the 1980 Staggers Rail Act, which deregulated the railroads

Coal West of the Mississippi



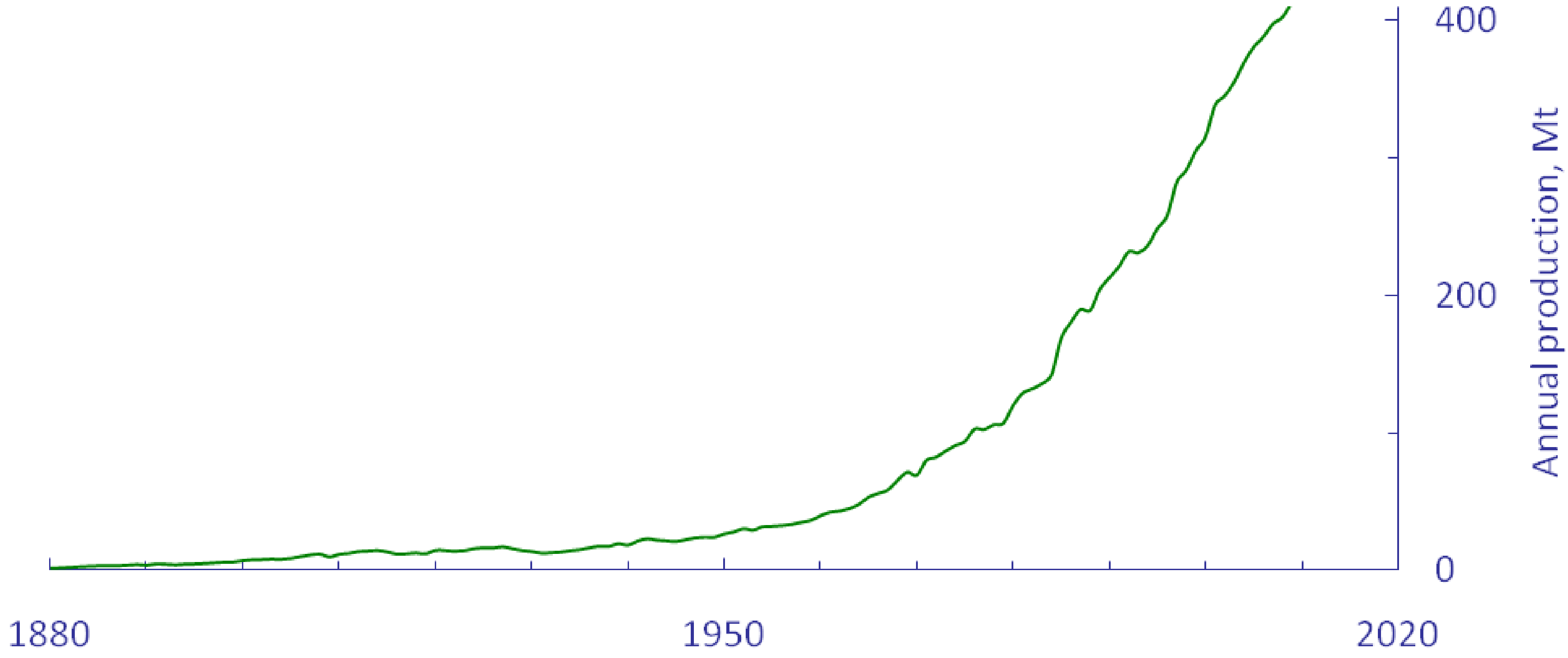
- Long-term production fit is 45Gt (28% of reserves + cumulative)

Long-term Fits Compared with Reserves for US Coal



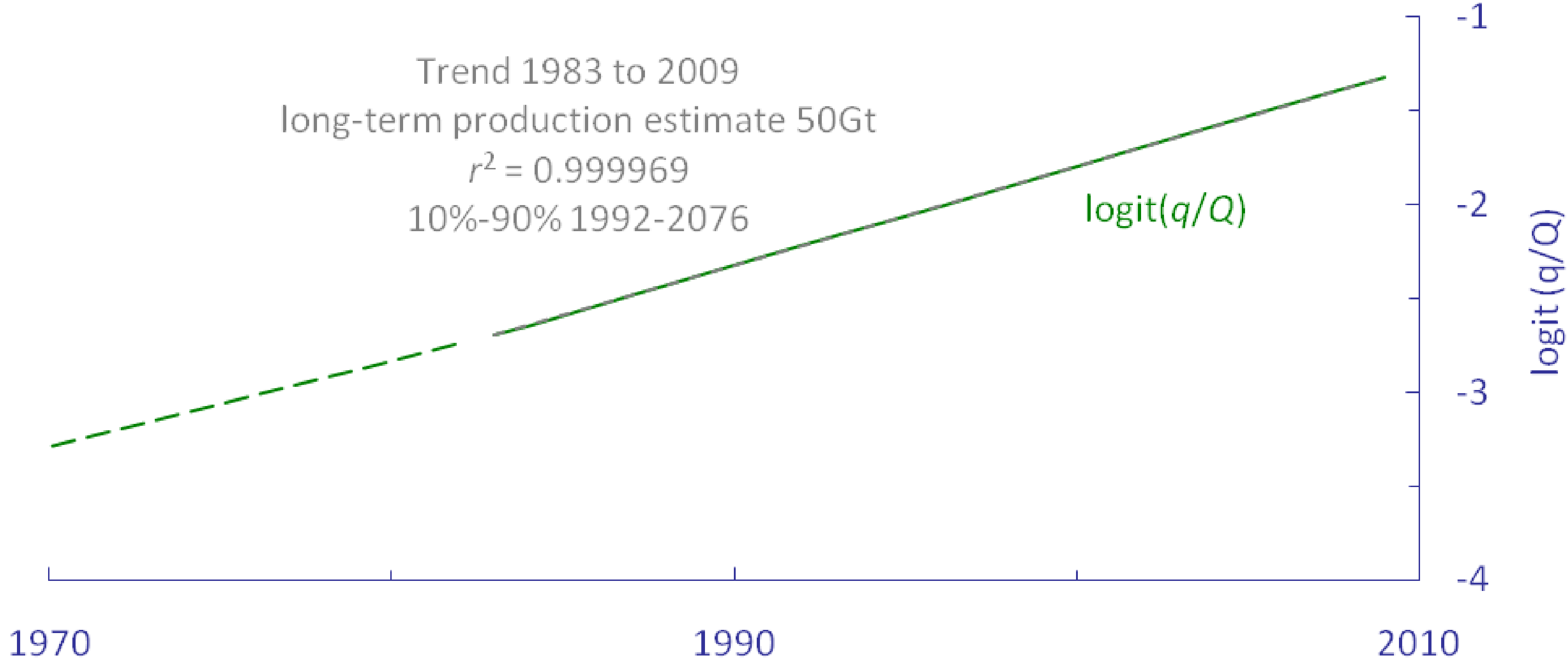
- Marius Campbell of the USGS did the first reserves in 1913
- Paul Averitt was responsible for the reserves from 1948-1975. He responded to criticism from mining engineers by tightening reserves criteria — seams at least 28 inches thick, up to 1,000 feet deep, within 3/4 mile from a measurement, 50% recovery
- Now 13 times lower than in 1913

Australian Coal



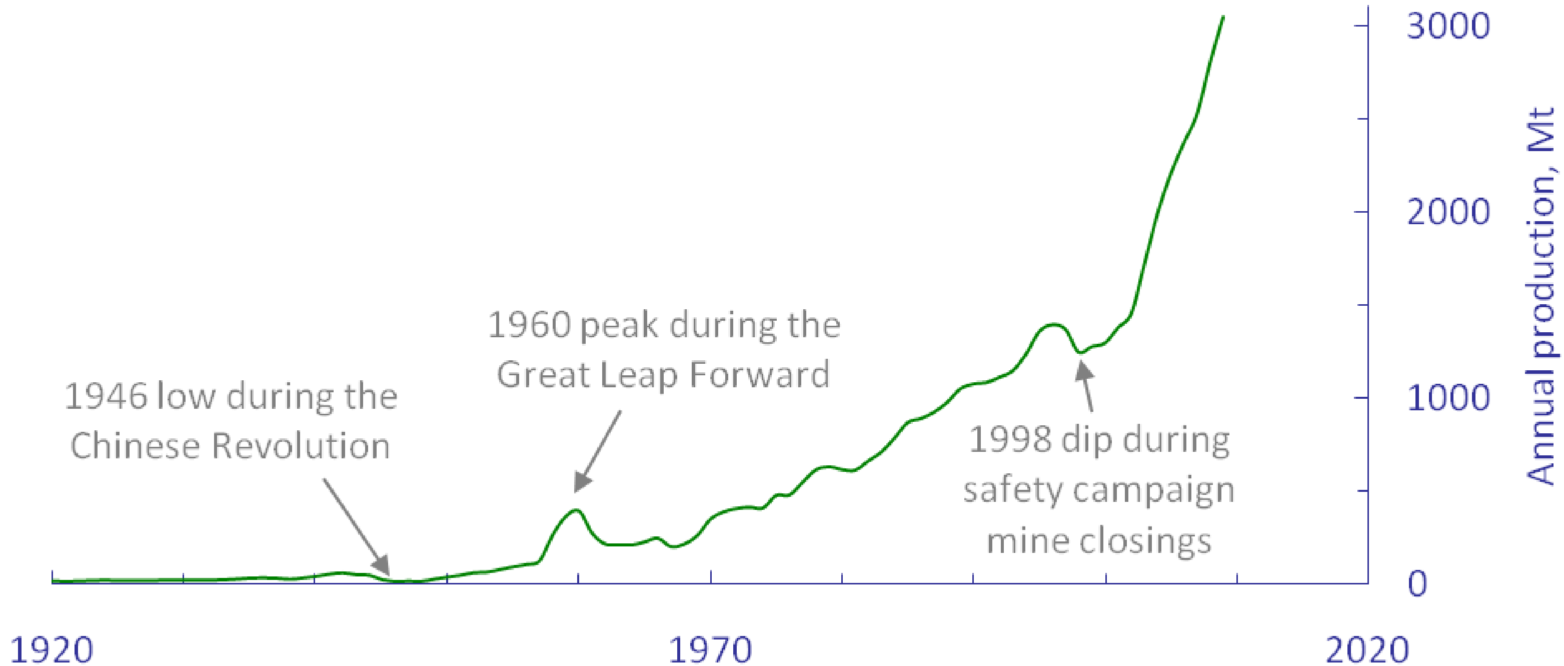
- Plot includes New Zealand — 5Mt in 2009
- World’s largest exporter — passed the US in 1984

Logit Transform for Australia



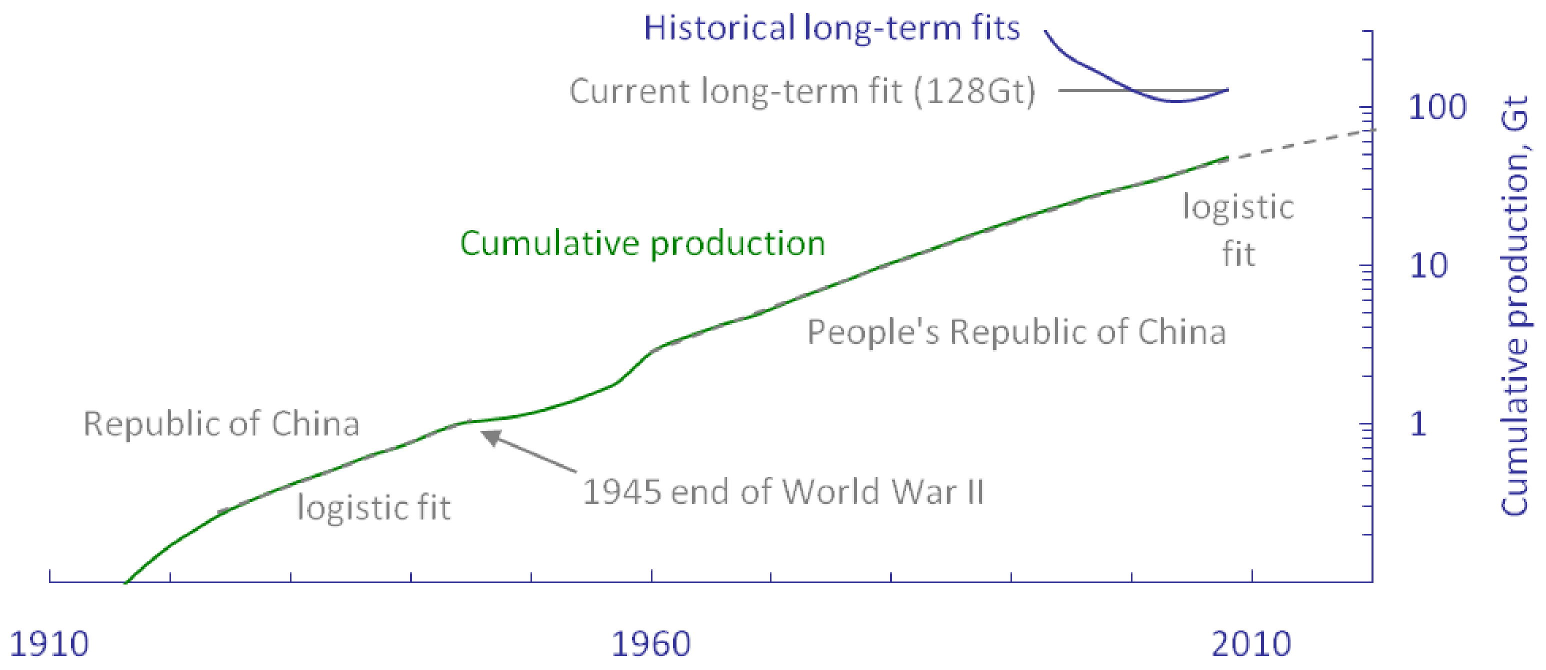
- Projection for long-term production is 50Gt (57% of reserves + cumulative)

Chinese Coal



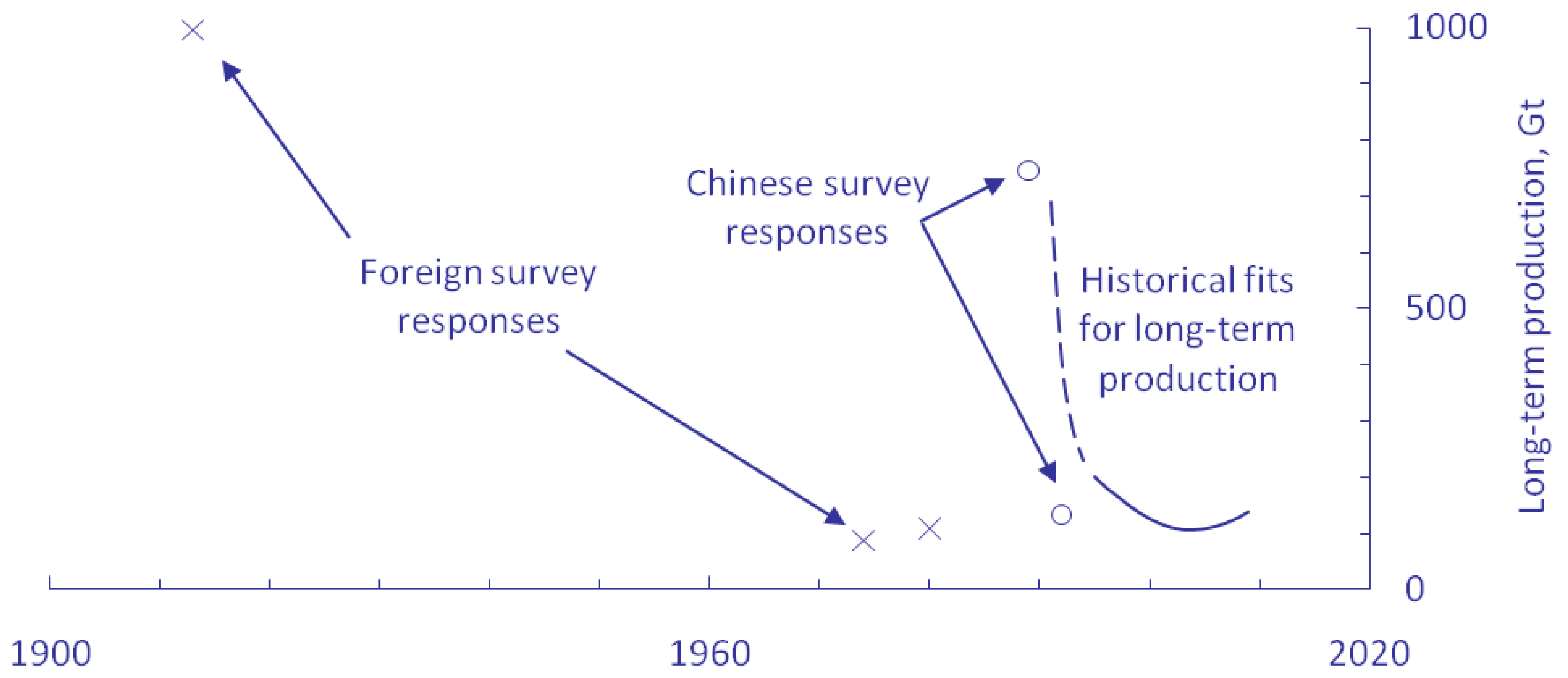
- World's largest producer — passed the US in 1985
- 44% of world's production in 2009 — four times Saudi oil
- Problems with the reliability of the production data

Cumulative Production with Curve Fits



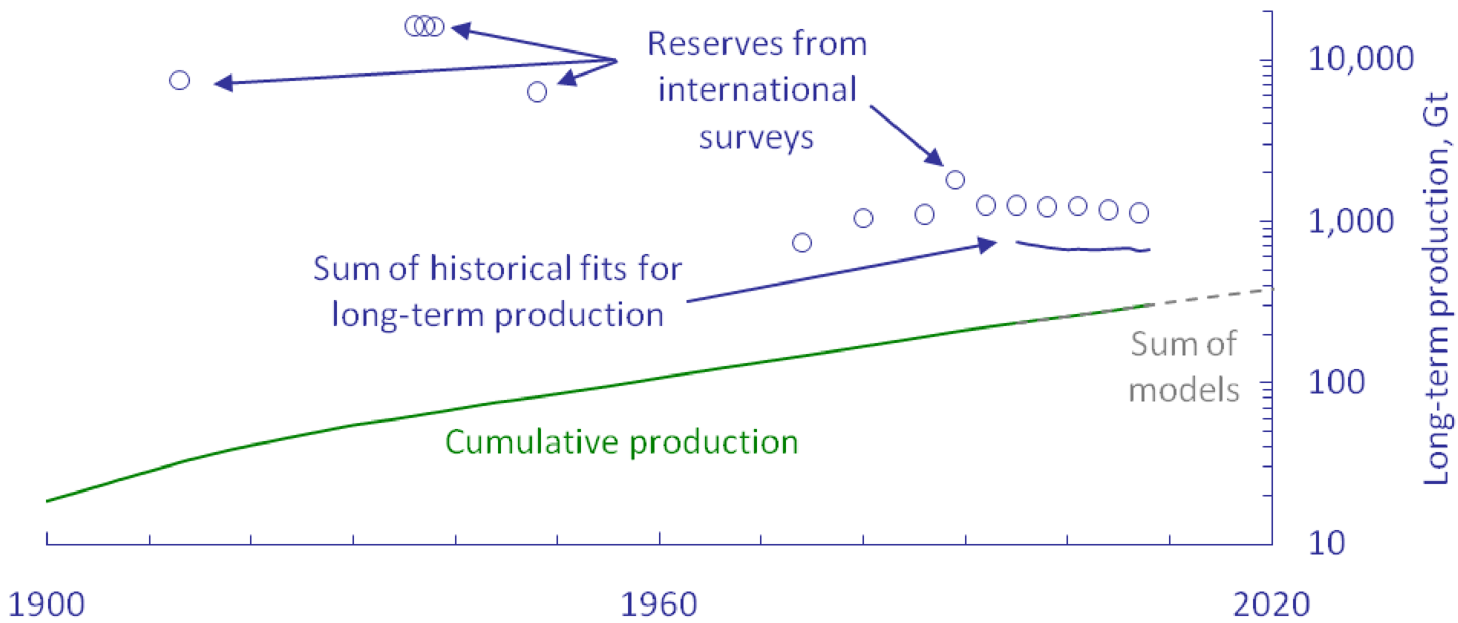
- For the current fit, r^2 is 0.99951
- Long-term production fit is 139Gt (90% of reserves + cumulative)

Historical Fits for Long-Term Production Compared with Reserves



- Reserves submitted to World Energy Council in 1989 and 1992 differ by 6:1

World Coal Production



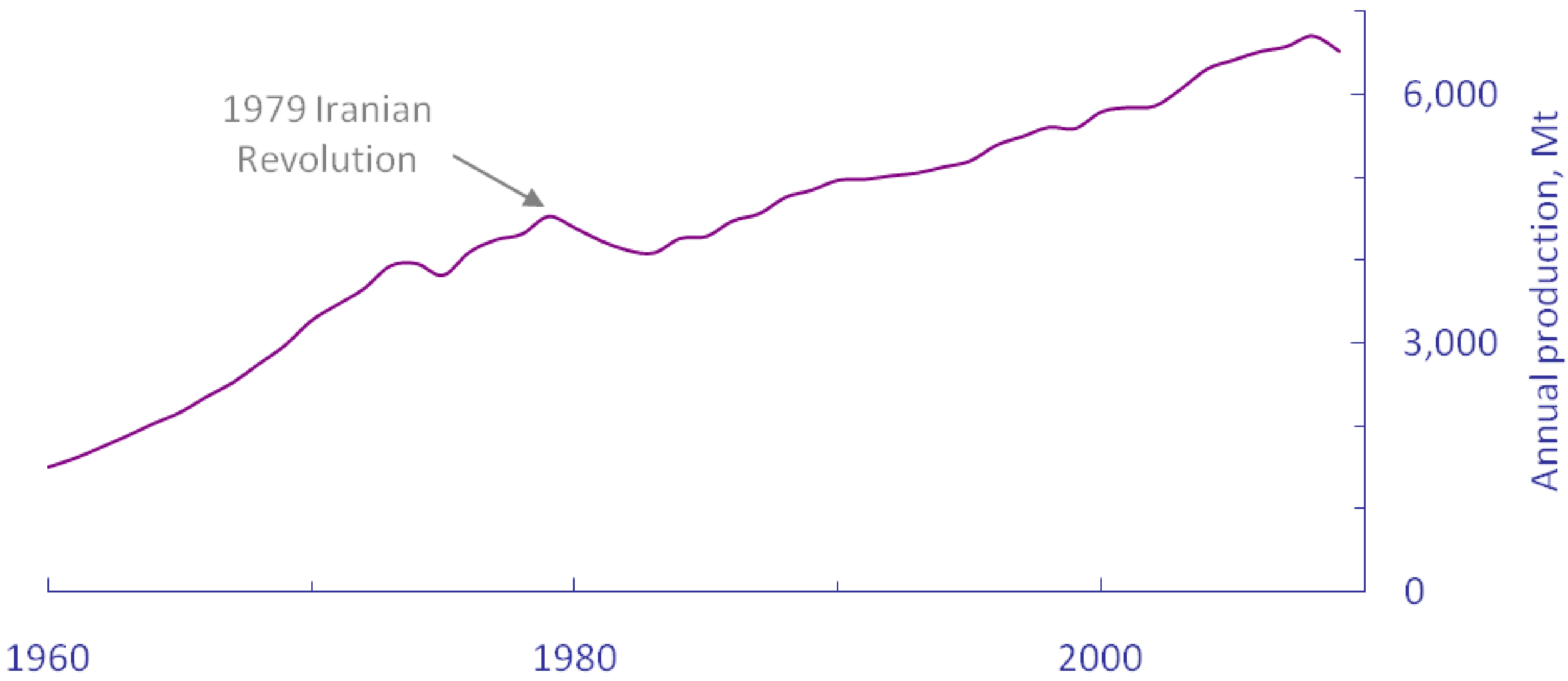
- Other regions not shown, but are available on line in an Excel workbook and in the paper
- 14% range from 1995 on
- Current long-term fit is 680Gt, 60% of reserves + cumulative
- IPCC range for production through 2100 is 355 to 3500Gt

Where Does the IPCC Get Its Coal Numbers?

World Energy Council survey	Proved recoverable reserves, Gt	Additional recoverable reserves, Gt
1992	1039	702
1995	1032	680
1998	984	3368
2001	984	409
2004	909	449
2007	847	180

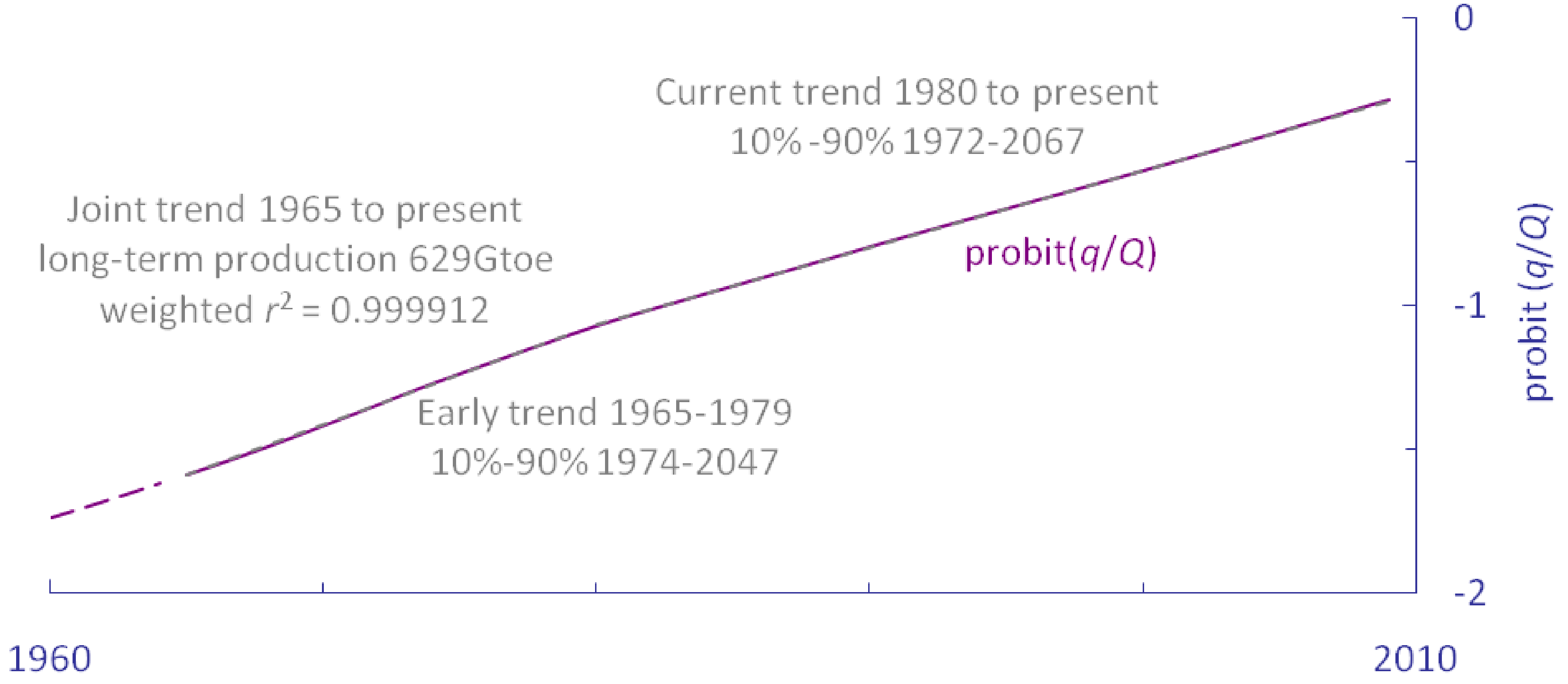
- The scenario report SRES (2000) references the 1995 and 1998 surveys
- The IPCC chose to use additional recoverable reserves and they also chose 1998 (3368Gt) instead of 1995 (680Gt) (Deffeyes' Law)
- Additional recoverable reserves are now 19 times smaller than in 1998
- The 4th Assessment Report notes the reserves for the 2004 survey, and "an estimated additional possible resource of 100,000EJ [5,000Gt] …" — with no reference

World Oil and Gas Production



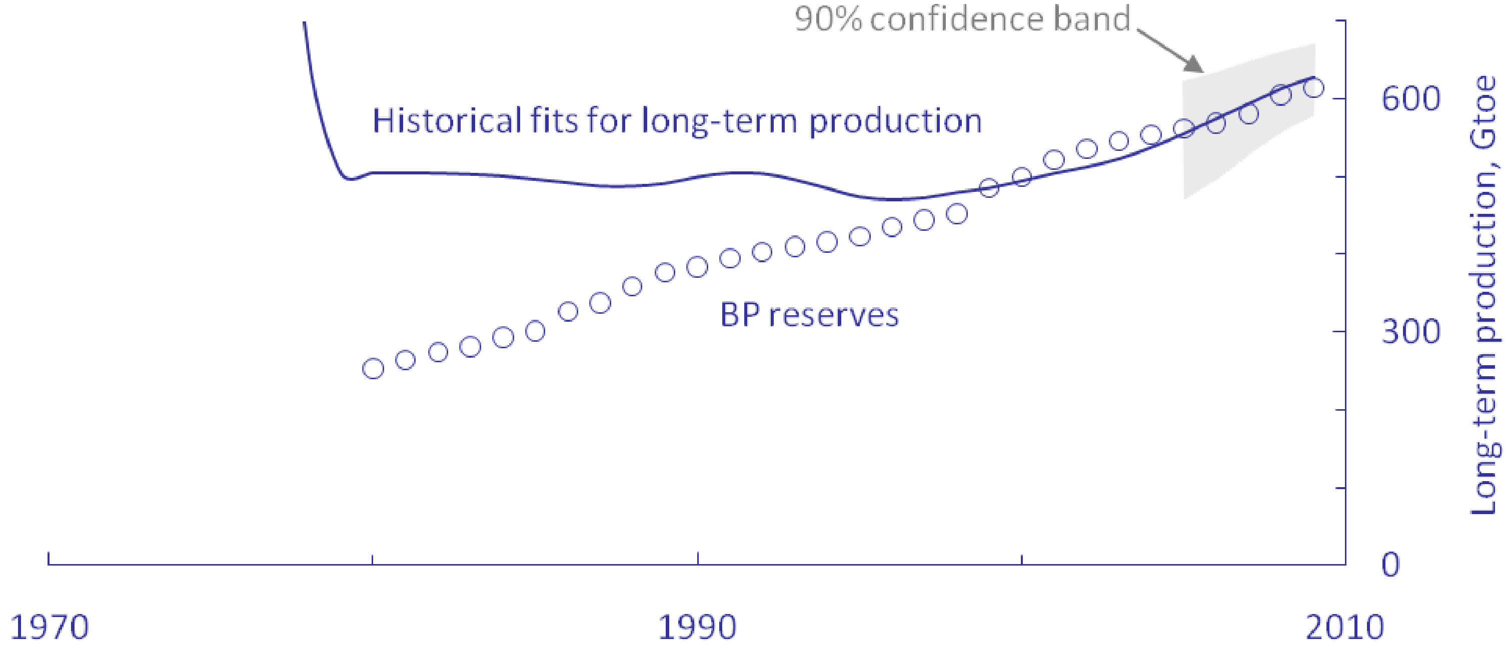
- 7.33 barrels of oil = 1 metric ton, toe = metric tons of oil equivalent
- Natural gas added as the energy equivalent

Probit Transform for World Oil and Gas



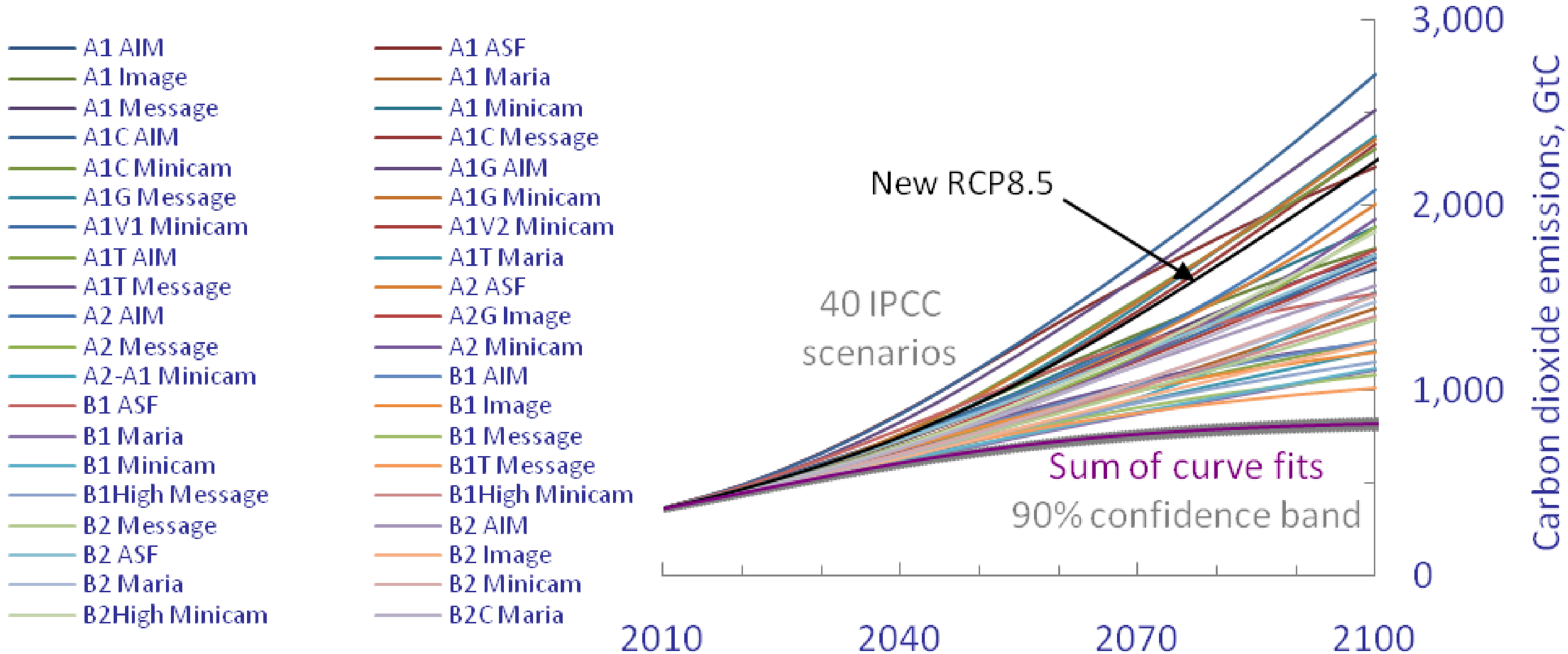
- Slowdown in the production pace causes a change in slope

Historical Long-term Fits for World Oil and Gas



- 629Gtoe is close to BP's reserves + cumulative production, 614Gtoe
- Residuals can be decorrelated by an AR2 process — passes the Ljung-Box-Pierce chi-square test ($p = 0.42$, where $p < 0.05$ indicates significant correlation)
- 90% confidence band from 1000 bootstrap replications
- Current confidence interval is 580 to 670Gtoe (14%)

Carbon-Dioxide Emissions



- Carbon coefficients for oil, gas, and coal from the BP Statistical Review
- Projection is less than any of the 40 IPCC scenarios (Deffeyes' Law?)
- For next assessment report, representative concentration pathways (RCPs) are planned — the one that does not include climate policy (RCP8.5)is shown, with long-term emissions of 6TtC (7x larger than curve fits)

Summary

- US crude-oil production has been following a cumulative normal curve since 1902 — the 1995 USGS/2006 MMS assessment is not consistent with production history
- The projection for long-term world oil and gas production is consistent with the BP reserves
- Long-term production estimates for coal from geological reserves are available early, but they are too high (6× for the UK, 2× for Pennsylvania anthracite)
- Projection for long-term world coal production is 60% of the reserves plus cumulative production — projection range has been within a 14% band since 1995

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- David Rutledge is the Tomiyasu Professor of Electrical Engineering at Caltech, and a former Chair of the Division of Engineering and Applied Science there. He is the author of the textbook *Electronics of Radio, published by Cambridge University Press. He is a Fellow of the IEEE, a winner of the IEEE Microwave Prize, and a winner of the Teaching Award of the Associated Students at Caltech. He served as the editor for the Transactions on Microwave Theory and Techniques, and is a founder of the Wavestream Corporation, the leading manufacturer of high-power millimeter-wave transmitters for satellite uplinks. In recent years, his research interest has been in developing methods for estimating fossil-fuel supplies in the long run, and in understanding the implications.*
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- The site http://rutledge.caltech.edu/ has links to the current version of these slides, an Excel workbook with calculations for the graphs, and a video from a public lecture. A book is in preparation.
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- Email contact: Dave.Rutledge@caltech.edu