Energy Economics, Winter Semester 2021-2
Lecture 10: Resource Management

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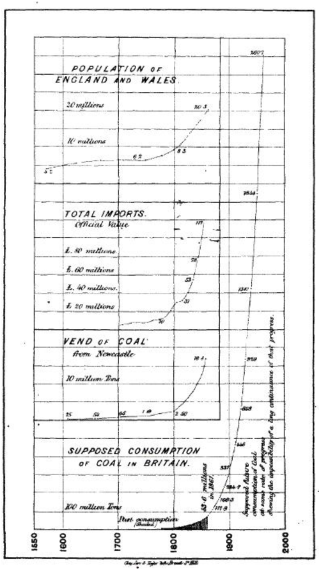
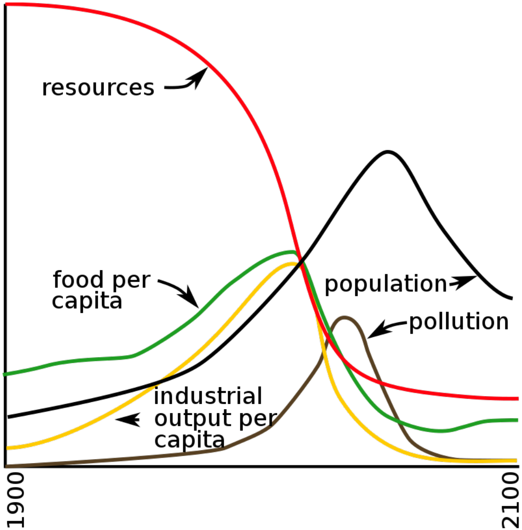
Introduction to Resources and Reserves



In 1865 William Stanley Jevons published **The Coal Question**, whose concern was the exhaustion of coal reserves in Britain given exponentially rising demand.

- "I must point out the painful fact that such a rate of growth will before long render our consumption of coal comparable with the total supply. In the increasing depth and difficulty of coal mining we shall meet that vague, but inevitable boundary that will stop our progress."
- "If we lavishly and boldly push forward in the creation and distribution of our riches, it is hard to over-estimate the pitch of beneficial influence to which we may attain in the present. But the maintenance of such a position is physically impossible. We have to make the momentous **choice between brief greatness and longer continued mediocrity**."

Source: Jevons,1865



1972 report **The Limits to Growth**, commissioned by the Club of Rome, examined consequences of exponential economic and population growth with a finite supply of resources with a computer simulation.

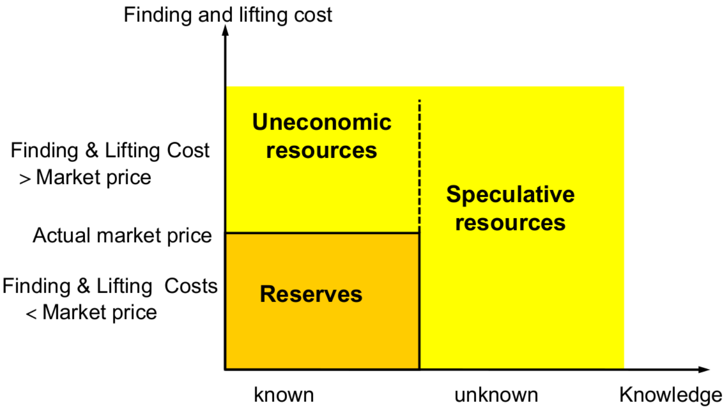
- Conclusion: "the most probable result will be a rather **sudden and uncontrollable decline** in both population and industrial capacity".
- But ignores role of technological progress.
- Growth versus limits versus progress: debate continues today.

Source: Limits to Growth

Reserves versus resources

Resources are all useful raw materials existing in the ground, including those only presumed to exist or now too costly to extract using available technology.

Reserves are those resources known to exist with high probability that can be extracted at a cost below the market price. (⇒ reserves depend on prices and costs.)

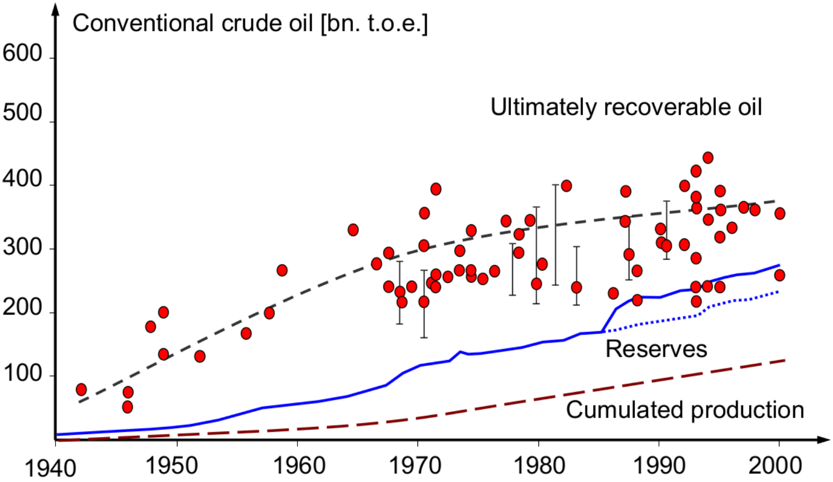


Reserves versus resources: definition

The World Petroleum Council classifies reserves according to the probability of economically viable extraction:

- **Proved (P)**: Probability of extraction $> 90\%$
- **Proved & probable (2P)**: Probability of extraction $> 50\%$
- **Proved & probable & possible (3P)**: Probability of extraction $> 10\%$

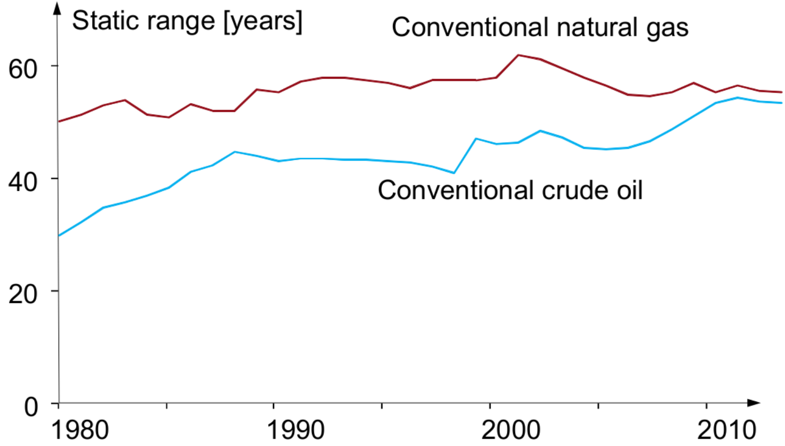
Discovery of conventional oil resources over time:



Source: BGR 2004

Static Range of Conventional Oil and Gas

Static range of conventional oil and natural gas reserves (P: Probable > 90%); higher oil prices tend to increase reserves as well as resources by stimulating exploration in the long-term.



Source: BP Statistical Review of World Energy

Fundamental question for profit maximising resource extraction

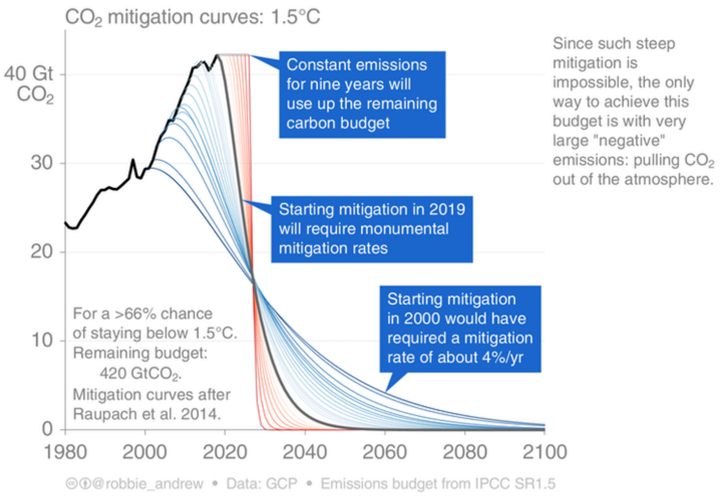
The transformation of reserves into money (i.e. extraction and sale) is an economic decision.

There are two alternatives:

- **wait for higher prices**: leave the reserve in the ground and wait for a higher market price (expected due to increased scarcity)
- **extract resource and invest money**: i.e. put the money in securities or assets thereby earning the market interest rate

There are opportunity costs to each decision.

Not just hydrocarbons: carbon emissions to atmosphere are exhaustible



- We have a carbon budget by 2050 to keep within Paris Agreement.
- E.g. from 2019 there was a budget of 420 $GtCO_2$ to have at least a 66% chance of staying below 1.5° C.
- How should carbon emissions be managed and priced?
- Should we emit the budget all now or start reducing emissions now to avoid a steeper path later?

Source: Robbie Andrews

Hotelling Rule

Hotelling Price Trajectory

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Swedish economist Hotelling (1931) developed a simple model to answer the fundamental question for a **finite, non-renewable resource**. Basic assumptions:

- Perfectly Competitive Markets
- Resource Owners:
  - Profit Maximizing Behavior
  - Constant marginal extraction costs c
  - Perfect information about the finite resource stock S

Basic Decision Problem of the Resource Owner:

- The market price p_t cannot be influenced by the resource owner ('price taker'), therefore they just adjusts the extraction rate R_t in each period t (e.g. years)
- Profit Π_t in each period follows: $\Pi_t = p_t R_t - cR_t$
- Question: To extract, or not to extract?

Resource Extraction: Hotelling's Rule

- If the profit in the next period, Π_{t+1}, is greater than the profit in the current period times the discount factor $\Pi_t \cdot (1+i)$, we **do not extract** now but wait

$$\Pi_{t+1} = p_{t+1}R_{t+1} - cR_{t+1} > \Pi_t \cdot (1+i)$$

- If the profit in the next period, Π_{t+1}, is less than the profit in the current period times the discount factor $\Pi_t \cdot (1+i)$, we **extract and invest** to earn the interest

$$\Pi_{t+1} = p_{t+1}R_{t+1} - cR_{t+1} < \Pi_t \cdot (1+i)$$

- If all resource owners behave in a profit-maximising manner, they adjust their extraction rates until:

$$\Pi_{t+1} = p_{t+1}R_{t+1} - cR_{t+1} = \Pi_t \cdot (1+i)$$

Iterating this idea and assuming that all of our stock S is extracted by the end of the planning period, then the resource owners maximize the Net Present Values of profits by adjusting the extraction rates each period:

$$\max_{R_0,\ldots R_T} NPV = \sum_{t=0}^{T} \frac{\Pi_t}{(1+i)^t} = \sum_{t=0}^{T} \frac{(p_t - c)R_t}{(1+i)^t}$$

subject to the available total resource stock S constraint

$$\sum_{t=0}^{T} R_t = S \tag{1}$$

We can incorporate this constraint in the objective function using a **Lagrange multiplier** λ and maximise the Lagrangian L

$$\max_{R_0,\ldots R_T,\lambda} L = \left[\sum_{t=0}^{T} \frac{(p_t - c)R_t}{(1+i)^t} - \lambda\left(\sum_{t=0}^{T} R_t - S\right)\right]$$

Resource Extraction: Hotelling's Rule

The first order optimality conditions satisfied at the optimum are for variable λ

$$\frac{\partial L}{\partial \lambda} = \sum_{t=0}^{T} R_t - S = 0$$

(just reproducing the constraint), while for each R_t we have

$$\frac{\partial L}{\partial R_t} = \frac{p_t - c}{(1+i)^t} - \lambda = 0$$

This is non-trivial and gives us **Hotelling's Rule**

$$p_t = c + \lambda(1+i)^t$$

In words: the price is always higher than the extraction cost, and increases over time.

Scarcity rent

Consider **Hotelling's Rule**

$$p_t = c + \lambda(1+i)^t$$

If the resource is infinite or inexhaustible, $S = \infty$, then the constraint will not be binding and we will have $\lambda = 0$ and a constant price equal to the marginal cost $p_t = c$.

If the resource is finite, then the surcharge over c is called the **scarcity rent** the extracter can claim over the cost:

$$\lambda_t = p_t - c = \lambda(1+i)^t$$

Note that it grows exponentially!

However, no price can in really grow forever - there will be some substitute technology.

Eventually p_t will attain the price p_{subst} at which some other energy source becomes competitive as a substitute. This alternative is the **backstop technology**.

This should happen exactly at the end of the period when we have exhausted the supply.

Therefore we assume $p_T = p_{subst}$ from which we deduce

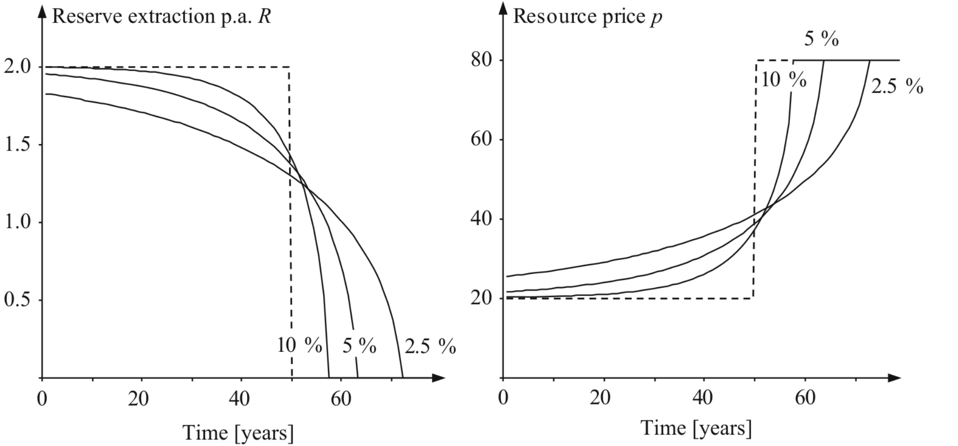
$$p_T = p_{subst} = c + \lambda(1+i)^T \quad \Rightarrow \quad \lambda = \frac{p_{subst} - c}{(1+i)^T}$$

and therefore

$$p_t = c + (p_{subst} - c)(1+i)^{t-T}$$

Role of backstop technology

Suppose we have $c = 20$, $p_{subst} = 80$ and $S = 100$, then you can see the dependence of the trajectory on the interested rate i. Low i encourages slower extraction:



Source: Zweifel, Praktiknjo & Erdmann (2017)

Hotelling Rule versus Reality

Application to EU Emissions Trading System (ETS)

The EU Emissions Trading System (ETS) puts a cap on how much carbon dioxide can be emitted between now and 2030 by large energy and industrial facilities, and issues certificates for each allowed tCO_2. There is a finite resource of certificates.

We can estimate what price must prevail in 2030 to reach 55% greenhouse gas reduction compared to 1990 levels based on the **marginal abatement cost**. Recent **estimates** put it at 130€/tCO_2. If you buy certificates you can either use them now or 'bank' them for later.

We can work back for a given discount rate $i = 0.05$ to find what the price should be now:

$$p_{2022} = \frac{p_{2030}}{(1+i)^8} \sim \frac{130}{1.05^8} = 88$$

This is exactly where the price was at the end of 2021!

Today's CO_2 certificate prices appear to be consistent with the Hotelling rule.

How Hotelling Rule Fails for Most Markets in Real Life

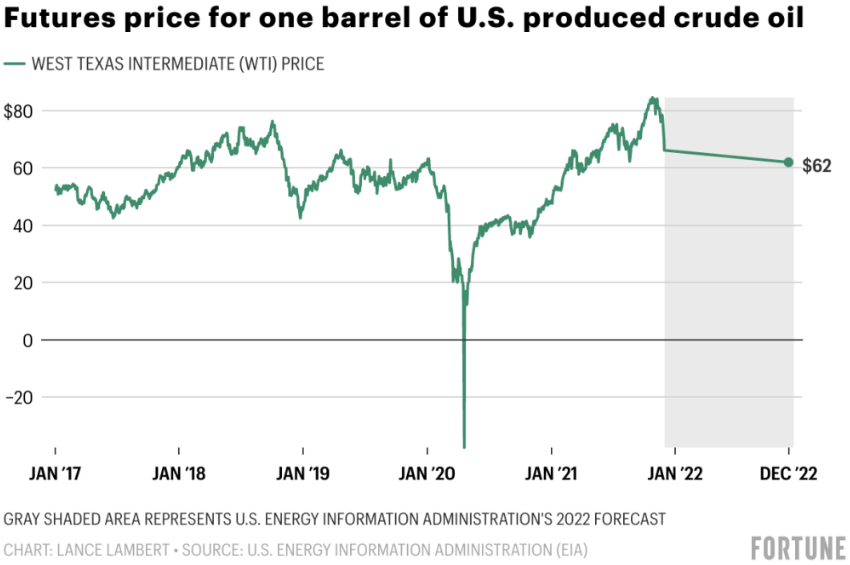
For most extractable resources, the real world does not conform with Hotelling because of the strong simplifying assumptions behind the model.

- New discoveries of reserves and resources increase the stock S over time
- Recycling can reuse already-extracted resources
- Extraction costs c change, either increasing for ever-harder-to-extract sites (e.g. ever deeper coal mines, lower pressure gas/oil), or decreasing due to learning in extraction technology (e.g. fracking for oil and gas)
- Suppliers have a monopoly and can influence price (cf. 1970s oil crises or 2021 gas crisis)
- Demand pattern changes (e.g. shift to EVs) or shocks (e.g. Covid) affect price

Oil Price Development Dominated by Demand and Geopolitics

Crude Oil Price History Chart

Oil Price Development Dominated by Demand and Geopolitics



Peak Oil/Coal

Oil Supply Pessimism

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1919	"...the peak of U.S. production will soon be past – possibly within three years"
1936	"...it is unsafe to rest in the assurance that plenty of petroleum will be found in the future merely because it has been in the past"
1981	"If petroleum is not there to begin with, all of the human ingenuity that can be mustered into the service of exploration cannot put it there..."
1990	"...non-OPEC production in the longer term will at best remain stagnant and is more likely to fall gradually due to resource constraints."
1998	"Global production of conventional oil will begin to decline sooner than most people think probably within 10 years."

Source: Daniel Butler, U.S. EIA/DOE AEO 2001 Conference

Hubbert Peak Oil Hypothesis

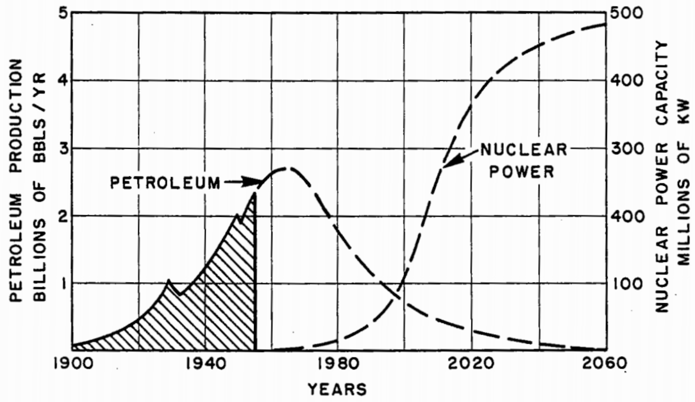


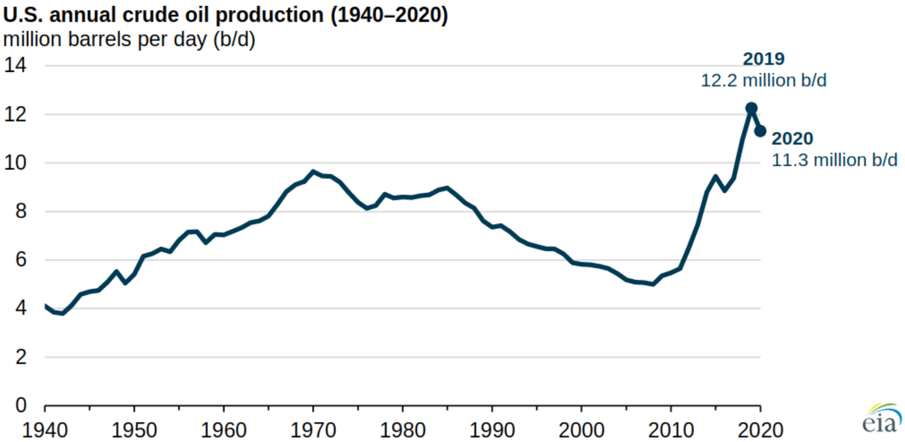
Figure 29 – Concurrent decline of petroleum production and rise of production of nuclear power in the United States. Growth rate of 10 percent per year for nuclear power is assumed; actual rate may be twice this amount.

- Possible scenario projected from 1956 by US geologist M. King Hubbert
- Based on a **logistic diffusion** model, extraction follows a logistic distribution curve (NOT a normal distribution)
- Oil production in the US did indeed peak in the 1970s, but returned to peak height in last decade thanks to shale oil extraction with fracking
- Nuclear stalled

Source: Hubbert, 1956

US crude oil 1940-2020

Actual US production peaked in 1970s, but with unconventional sources, such as shale oil and new techniques of horizontal drilling and hydraulic fracturing (fracking), attained new heights in the late 2010s. Need to model basins and resources with separate peaks!



Source: EIA, 2021

A peak for US shale oil?

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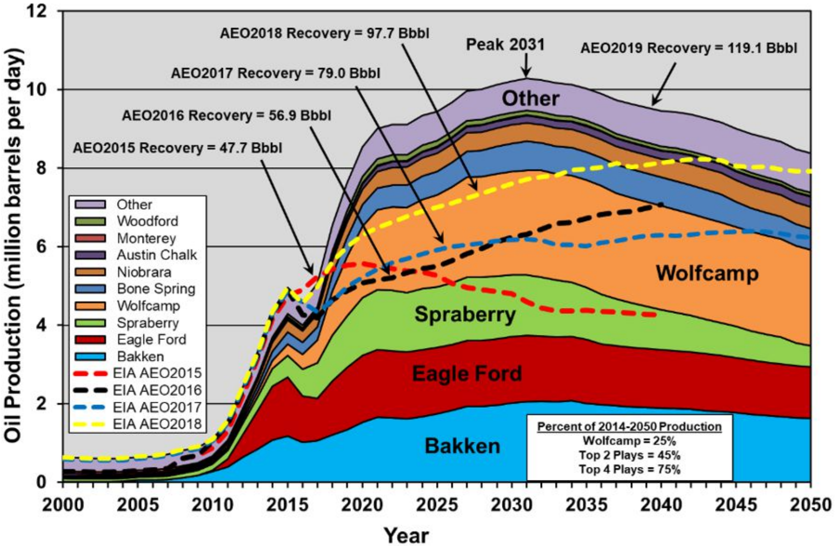
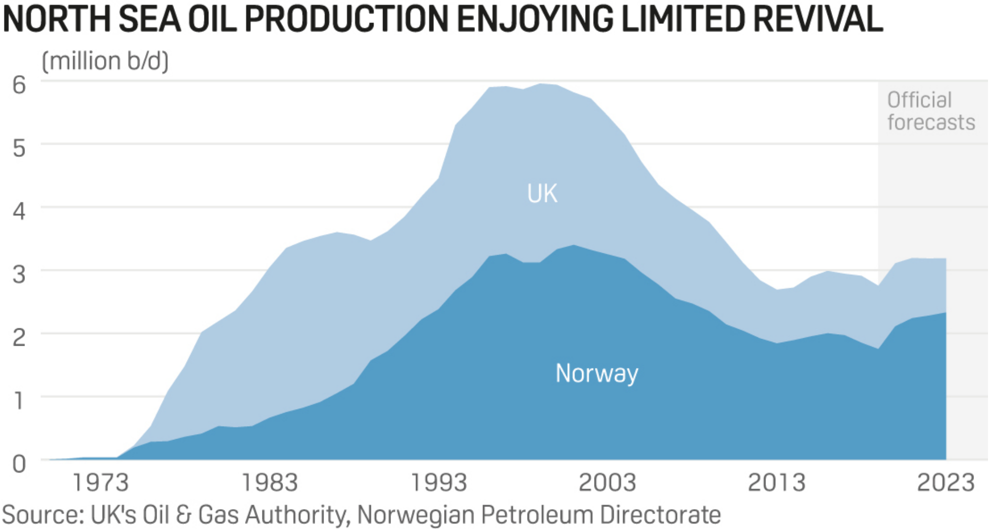
Current predictions are that shale oil production could peak in the 2030s.

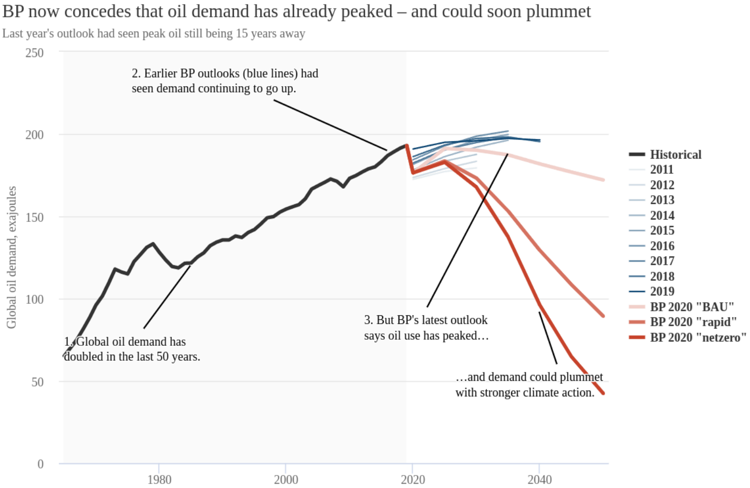


North Sea oil production (dominated by UK and Norway) appears to have peaked already.



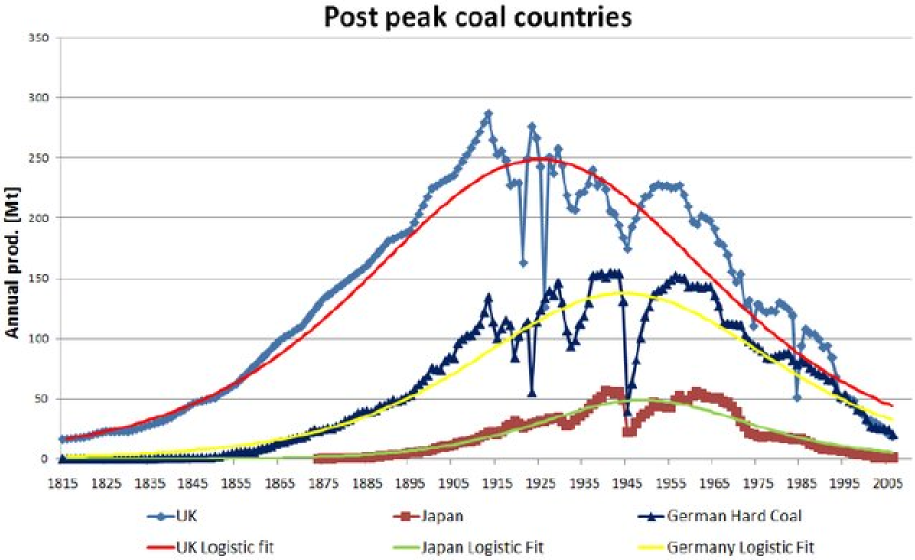
Worldwide crude oil demand

BP suggested in 2020 that worldwide demand may have already peaked. It could sink if electric vehicles eat into demand, but feedstocks for chemical industry will still drive demand.



Source: Carbon Brief

Coal has already peaked in several countries



Source: Höök et al

Hubbert curve math

Logic behind Hubbert curve: total resource is finite, initially production grows exponentially as costs fall with discovery and learning, reach a peak, then decline as marginal costs rise.

For time t, production $P(t)$, total extraction $Q(t)$ and ultimately recoverable resource Q_∞:

$$\frac{dQ}{dt} = P = \omega Q \left(1 - \frac{Q}{Q_\infty}\right)$$

First equation: total extraction $Q(t)$ is the integral of yearly production.

Second equation: when Q is small, we get $\frac{dQ}{dt} \sim \omega Q$, which gives $Q(t) \sim c \cdot e^{\omega t}$ for some constant c. When Q is large $Q \sim Q_\infty$ we get $\frac{dQ}{dt} = P \sim 0$, i.e. production declines to zero.

Full solution to differential equation is the **logistic distribution curve**

$$P(t) = Q_\infty \omega \frac{1}{\left(e^{-(\omega/2)(\tau - t)} + e^{(\omega/2)(\tau - t)}\right)^2}$$

where τ is the time where the production peaks. Hubbert fitted the two parameters Q_∞ and ω to observed production of different resources. NB: decays slower than Gaussian.

Source: Claerbout & Muir, 2020

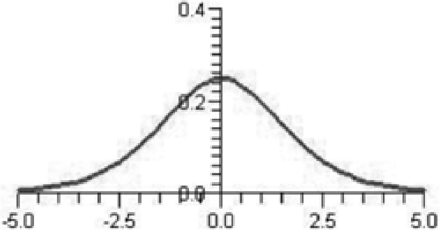
Hubbert curve math

The integral of $P(t)$ gives the total extraction $Q(t)$, which is the **logistic curve**

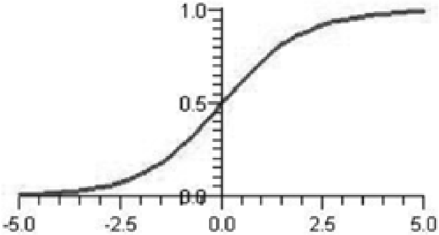
$$Q(t) = \frac{Q_\infty}{1 + e^{\omega(\tau - t)}}$$

In the past $t \to -\infty$ extraction tends to zero $Q(t) \to 0$. In the future $t \to \infty$ total extraction approaches the limit $Q(t) \to Q_\infty$.

Left is production $P(t)$, right is cumulated extraction $Q(t)$, for $\tau = 0$:



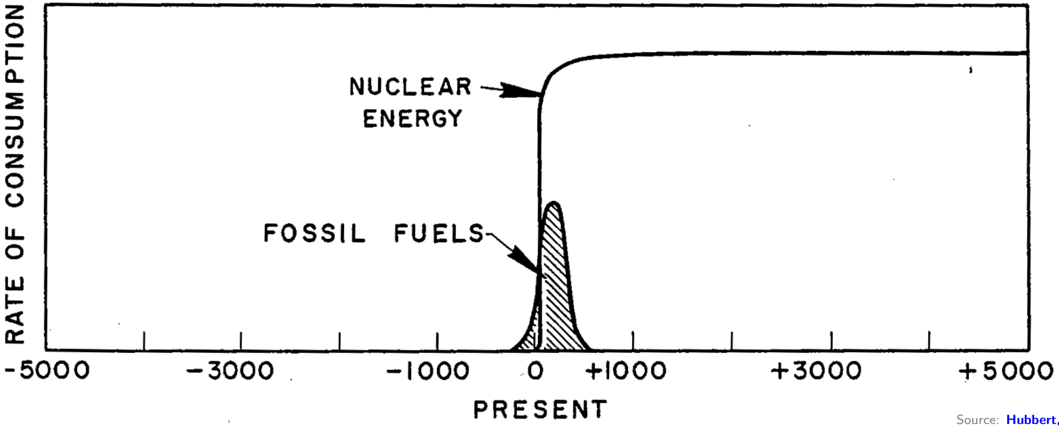
PDF of the Standard Logistic Distribution



CDF of the Standard Logistic Distribution

The view from 5000 years

In his 1956 paper Hubbert imagined the perspective from 5000 years hence, with fossil fuel use a mere blip in our history:



Source: Hubbert, 1956