# 31C01300/31E01310
# Energy & Environmental Economics

Lecture 9: Exhaustible resource theory

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# Agenda

Last week

- Policies, distortions
- Investments

This week

- Dynamics, exhaustible resources
- Climate change economics

# Stepping stones

1. Externality
2. Policy
3. Firms adaptm i.e. make decisions on
   a. Production/consumption
   b. Investments
   c. Innovations
4. Market allocates
   i. Efficient use of existing resources
   ii. Price signals

# Allocation over time: It's like trade

Efficiency of allocation over time:

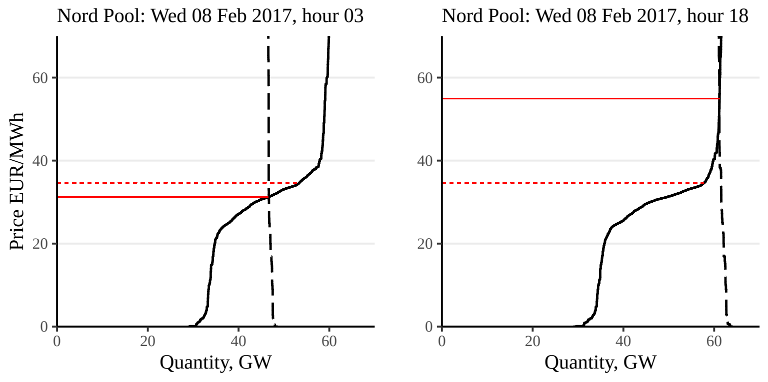



**Figure 1:** Buy cheap (left), sell dear (right) – it's like trade!

# Dynamics in the electricity market

- So far the analysis has been with static technologies
  - It matters a little for a condensing plant when it is running.
  - Consumers have been unresponsive to prices, treated as “load”.
- Intermittent renewables force market changes
  - Solar and wind will shape short-term electricity market outcomes.
- Storage technologies are a response to these changes
  - Battery storage gains a lot of attention.
  - For the market, demand response is almost the same.
  - Storage can also be in the supply side: hydropower!
- Understanding dynamics over time becoming more important!

# Dynamics in general

- Re-producible goods
  - Bicycles, software, services, ...
  - Total supply over time is unlimited
- Renewable goods (resources)
  - Timber, fish, hydro electricity, agricultural commodities
  - Resource base is finite but the overall output is in principle unlimited
- Non-renewable or exhaustible goods (resources)
  - Industrial metals: copper, nickel, aluminum
  - Fossil fuels: oil, coal, gas
  - Resource base and the output are both finite

# Carbon budget=exhaustible resource

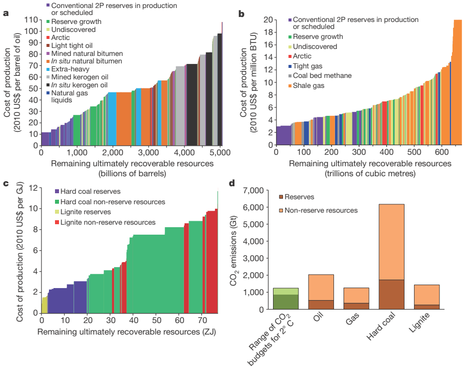



**Figure 1 | Supply cost curves for oil, gas and coal and the combustion $CO_2$ emissions for these resources.** **a–c**, Supply cost curves for oil (**a**), gas (**b**) and coal (**c**). **d**, The combustion $CO_2$ emissions for these resources. Within these resource estimates, 1,294 billion barrels of oil, 192 trillion cubic metres of gas, 728 Gt of hard coal, and 276 Gt of lignite are classified as reserves globally. These reserves would result in 2,900 Gt of $CO_2$ if combusted unabated. The range of carbon budgets between 2011 and 2050 that are approximately commensurate with limiting the temperature rise to 2 °C (870–1,240 Gt of $CO_2$) is also shown. 2P, 'proved plus probable' reserves; BTU, British thermal units (one BTU is equal to 1,055 J). One zettajoule (ZJ) is equal to one sextillion ($10^{21}$) joules. Annual global primary energy production is approximately 0.5 ZJ.

Source: Glade & Ekins (Nature, 2017). Scarcity: figure d. How should the price of scarcity develop over time such that the carbon budget is not exceeded?

Compare with the real-time CO2 budget: link.

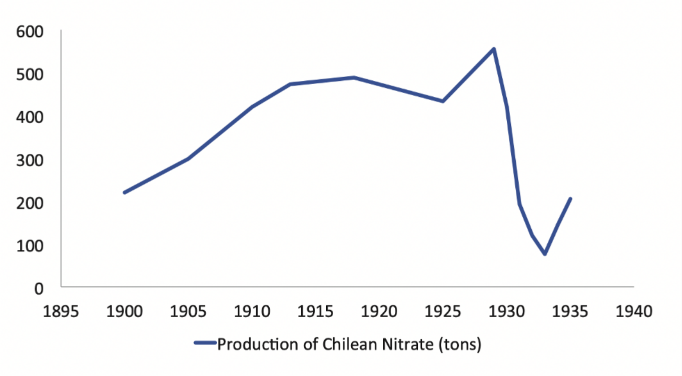
# Example: Commodity markets

A story of an important resource that was made redundant by a substitute

- Historical illustration: Chile was the monopoly producer of "natural nitrogen" in 1880-1920.
- Sir William Crookes, the president of the British Association for the Advancement of Science, in 1889 appealed to chemists to develop a synthetic solution to the nitrogen problem, as otherwise "All England and all civilized nations stand in deadly peril of not having enough to eat", potentially as early as in 1930.
- What happened?

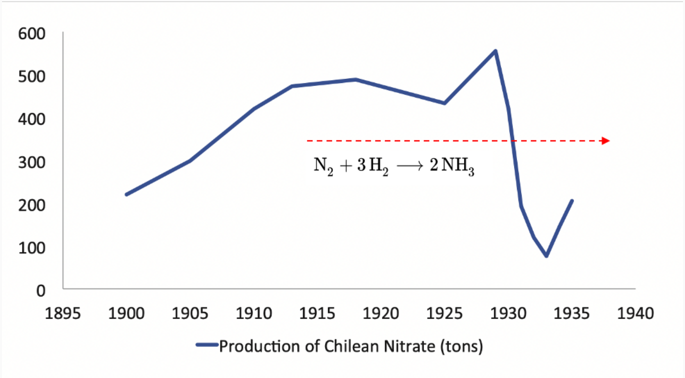
# Atacama desert

# Historical illustration




Chilean production over time

# Haber-Bosch process for synthetic production




Chilean production over time

# Theory: allocation of scarce resources over time

**Basic definitions**:

For exhaustible goods, overall consumption is finite

- Consumption today reduces what is available for future
- Two types of costs in extraction: (i) out-of-pocket marginal cost of production; (ii) opportunity cost of production (scarcity rent)
- Demand and supply meet at a different point in every period, depending the on the resource stock left

# Equilibrium (or optimality) conditions

time periods $t = 1, ..., T$

1. price $p_t$ is equal to marginal cost of production $MC$ plus the opportunity cost of production $R_t$

$$p_t = MC + R_t$$

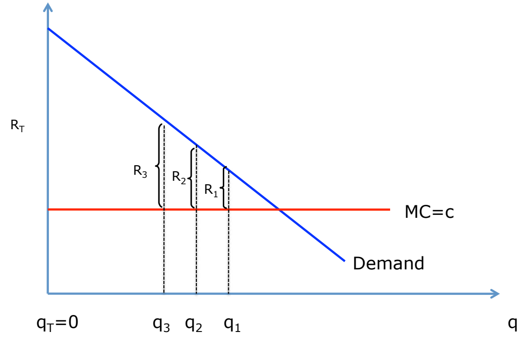
2. opportunity cost should grow at the rate of interest $r$

$$R_t = R_{t+1}/(1 + r)$$

3. production over time equals the total resource endowment $S$

$$q_1 + ...q_T = S$$

# Consumption, scarcity rent, and prices




Observe: consumption declines, scarcity rent increases, producer receives a resource rent (despite constant MC), consumption ceases when the choke price is reached

# Equilibrium condition 1-2: Hotelling rule

Suppose interest rate $r > 0$ is constant over time, and that there is a constant cost $c > 0$ per unit of resource produced. Condition 1 above is called "Hotelling rule": it is an arbitrage condition for the sellers.

**Sell a unit today:**

$$P_t - c$$

**Sell next period**, after $\Delta > 0$ units of time:

$$[P_{t+\Delta} - c]e^{-\Delta r}.$$

# Equilibrium conditions 1-2: Hotelling rule

Indifference:

$$P_t - c = [P_{t+\Delta} - c]e^{-\Delta r}$$
$$\approx [P_{t+\Delta} - c](1 - \Delta r)$$
$$\Rightarrow$$
$$\frac{P_{t+\Delta} - P_t}{\Delta} = r(P_{t+\Delta} - c)$$
$$\Rightarrow$$
$$\lim_{\Delta \to 0} = \frac{dP_t}{dt} = r(P_t - c)$$

This is a differential equation with solution

$$P_t = c + [P_0 - c]e^{rt}$$

We will discuss how to use this to analyze the resource-extraction over time. See also the lecture note on "Exhaustible resources".

## Equilibrium conditions: Terminal price

We know that the equilibrium price must satisfy Hotelling rule. But how high will the price grow? Recall that demand is a relationship between quantities and prices $Q_t = D(P_t)$ where $Q_t$ is demand (=consumption) at time $t$, and $D'(P_t) < 0$. Choke price, $\overline{P}$, is defined as the price at which the demand chokes off: $D(\overline{P}) = 0$ for all $P \geq \overline{P}$. Thus, no demand for prices higher than $\overline{P}$. We assume that this choke price is finite. Let $T$ be the time it takes for price following Hotelling rule to reach $\overline{P}$, that is,

$$P_T = c + [P_0 - c]e^{rT} = \overline{P}.$$

This is the terminal price condition. It pins down the end of the price path.

# Equilibrium conditions: Exhaustion

At which time will the price path start? How long the consumption path lasts, that is, what is the precise value for $T$? The total consumption over time equals the amount of the resource available:

$$\int_0^T Q_t dt = S_0$$

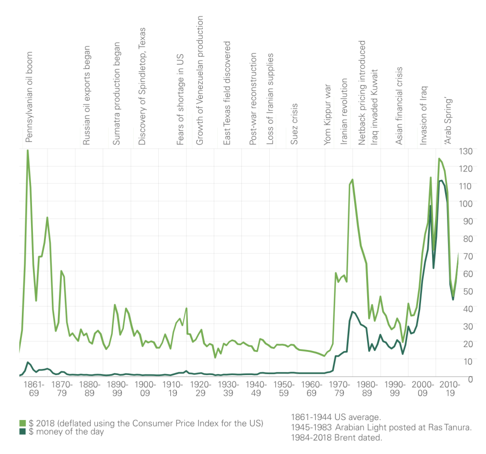
This is the exhaustion condition. Since we know the demand, we can write

$$\int_0^T D(P_t) dt = S_0$$

This may look difficult, but the equilibrium is conceptually very simple. We have three unknowns: $P_0, P_T, T$. There are three equations for finding these: Hotelling rule, terminal price, and exhaustion conditions.

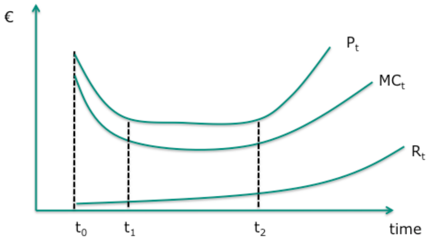
# Can we understand historical oil prices with this model?

Clearly not.




Source: BP statistical review of world energy

# How should the theory be modified?



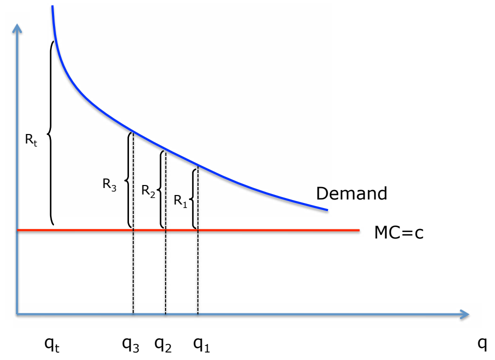

- T0->t1: technological progress reducing extraction costs dominates
- T1->t2: technological progress and scarcity rents cancel out each other
- T2->: scarcity rent dominates. See Margaret Slade, J. of environmental economics and management (1982).

# How to use the model in the analysis

Simple model that can be used to analyze what happens to the equilibrium path,

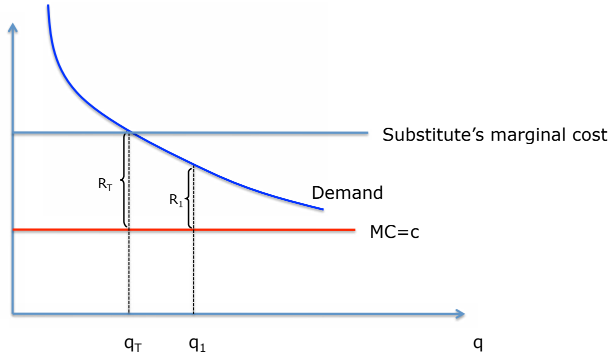
- if the interest rate becomes larger?
- if the substitute becomes cheaper?
- if there is unexpected increase in the resource stock?

# The effect of the substitute: infinitely costly substitute




Consumption never stops: Price increases to make sure that we never suddenly run out of the stock; there is no finite choke price (resource is "essential")

# The effect of the substitute: finitely costly substitute




Substitute puts a limit on prices; the time period for resource consumption is finite

# Takeaways from Hotelling

- Starting point: Firms optimize over time
- Storage smooths variations over time
- Exhaustible resources will be extracted until:
  1. They run out
  2. They become too expensive to use
  3. A more efficient substitute appears
- Ideal model, one should also consider at least
  - Extraction costs (see example above)
  - Durability (e.g. metals)
  - Market structure (monopoly prices increase slower)
  - Uncertainty (exploration reduces prices)
  - General equilibrium (prices affect interest rates)

# Agenda

This time

- Dynamics, exhaustible resources

Next time

- Climate change economics