POTSDAM INSTITUTE FOR CLIMATE IMPACT RESEARCH

Energy System Models

NAVIGATE-ENGAGE Summer School,
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NAVIGATE
Next generation of advanced integrated assessment modelling to support climate policy making
ENGAGE
FEASIBILITY OF CLIMATE PATHWAYS
Leibniz-Gemeinschaft

Overview of the lecture

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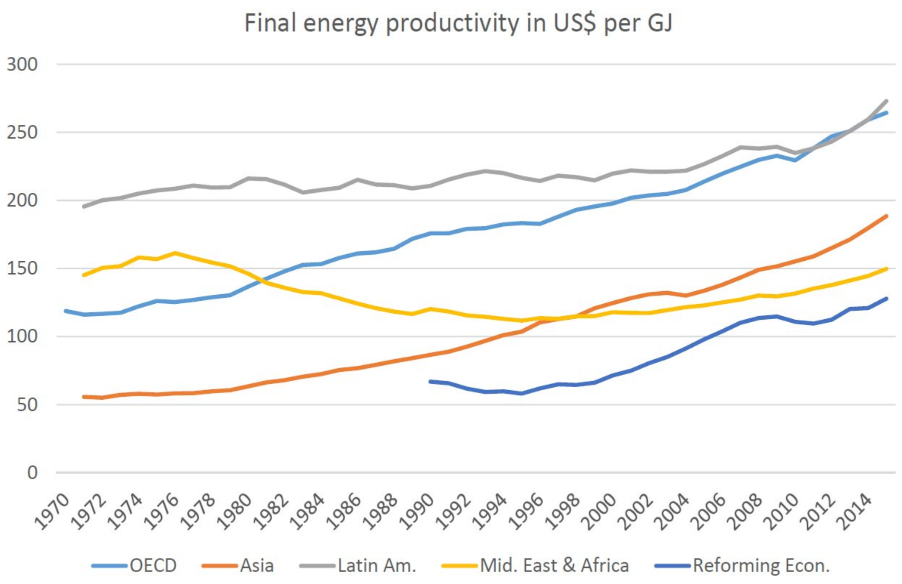
Introduction

- Energy, economy and environment
- General structure of energy system models
- Mathematical structure of a Energy System Models
  - Partial equilibrium models: Linear programming
  - Going non-linear: demands, mixes, capacity ramp-up
  - General equilibrium models: Coupling to economy model
- Applications
  - Political economy: Fossil fuel markets and climate policy
  - Endogenous technological change: the learning curve approach
  - Issue linkage: air pollution and public health

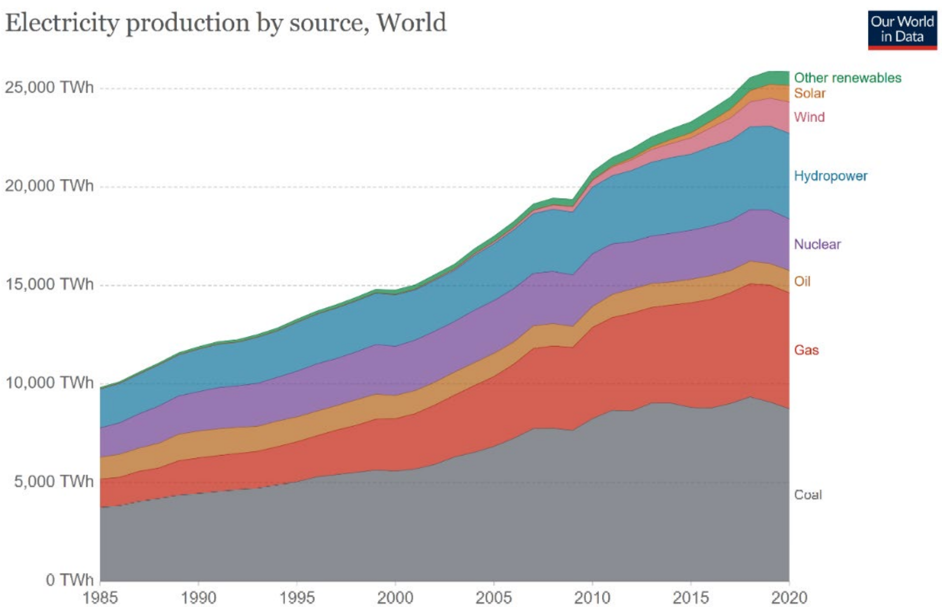
Introduction – International inequality and climate policies

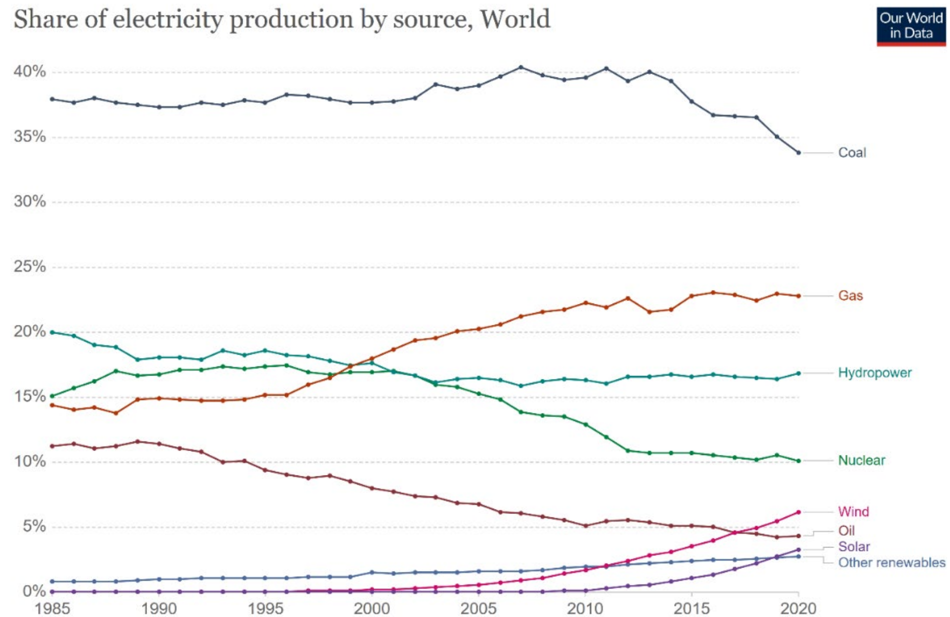


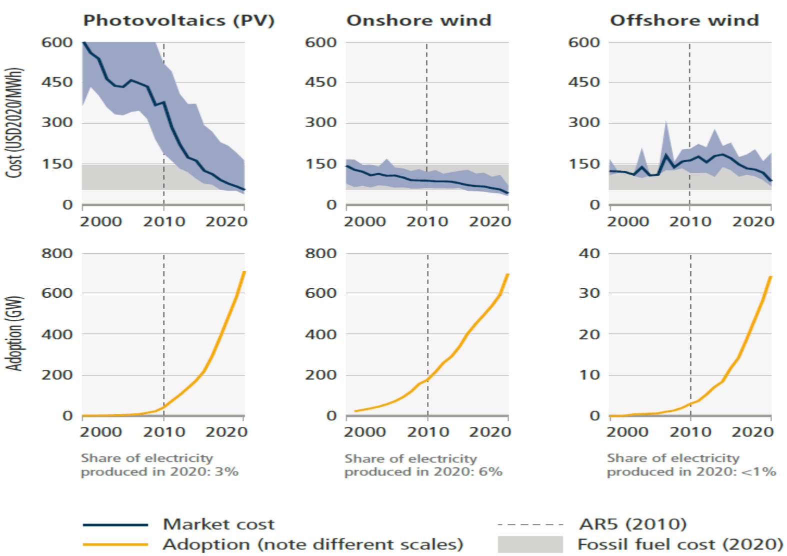
- OECD countries have high per-capita incomes
- … high CO_2 emissions per capita
- … high carbon productivity
- … high energy productivity

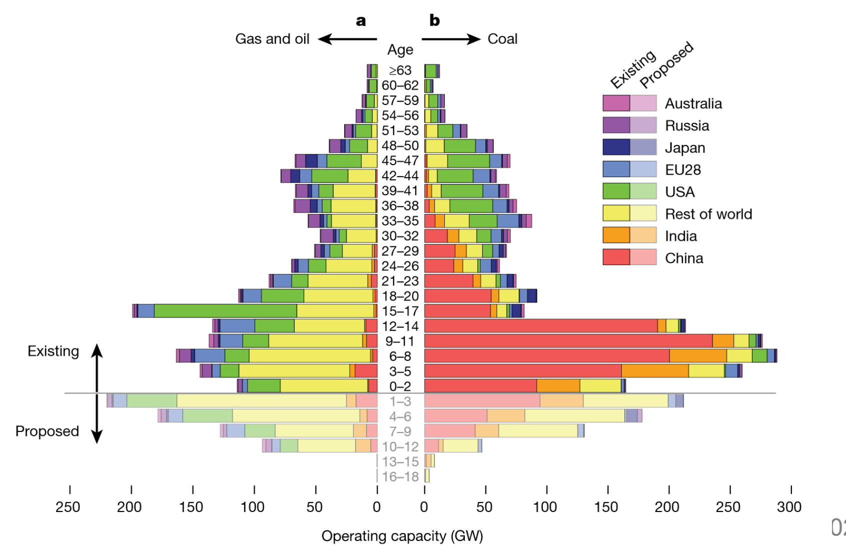
- Climate change is a global commons good problem
- Each ton of CO_2 is equal

Some basics about electricity



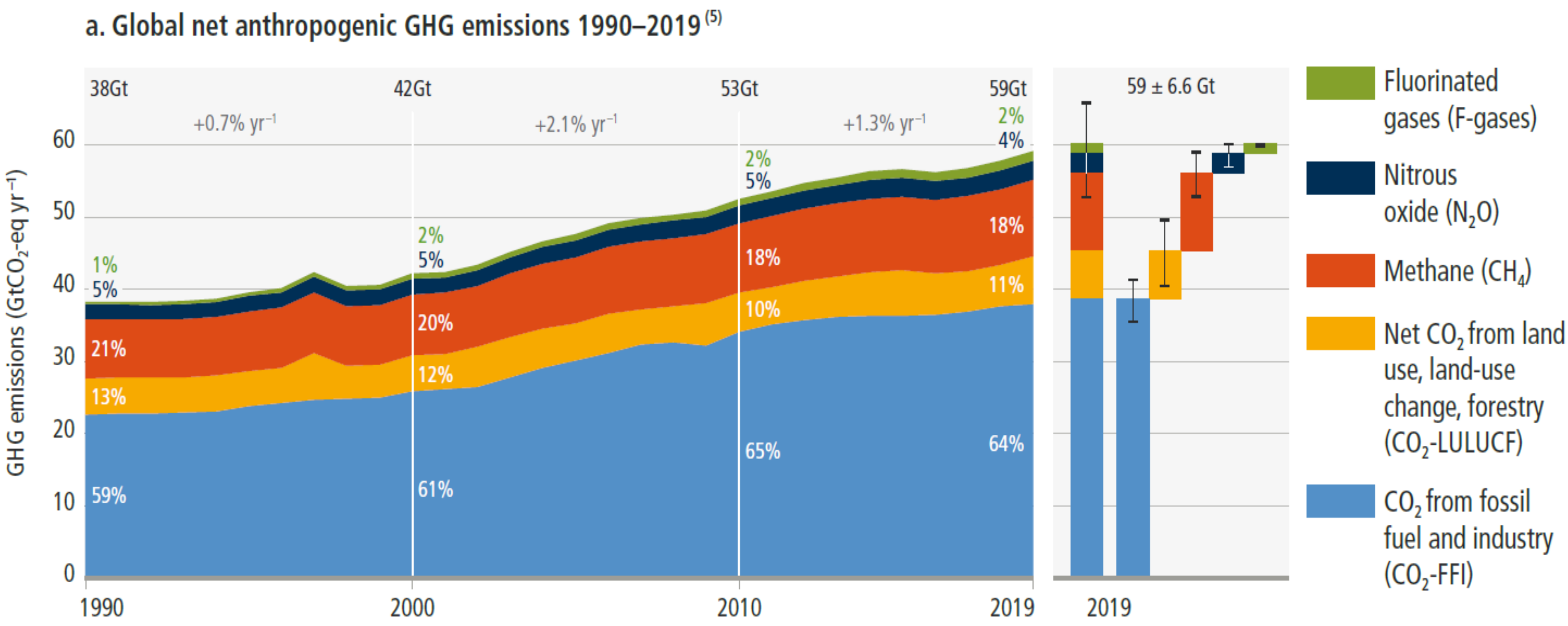






Tong et al. (2020) 10.1016/j.isci.2020.101484

Global GHG emissions



IPCC AR6 WG3 SPM Fig. SPM 1

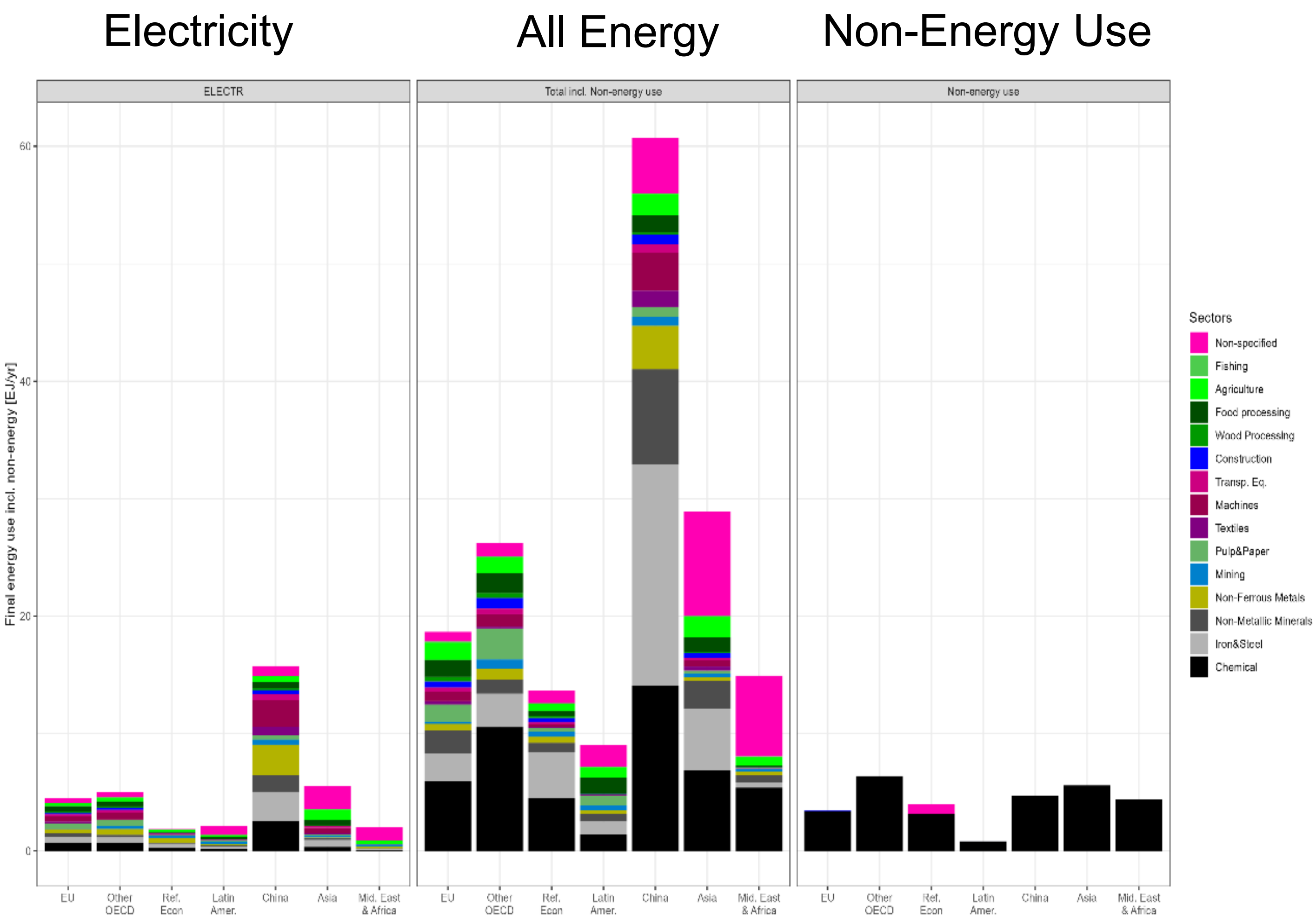
Global CO2 Emissions – Fossil Fuels

- Emissions are not measured directly
- Human activities related to emissions are measured (tax authorities, etc.) and multiplied by emission factors
- What are the annual CO2 emissions from fossil fuels?
- Activity: Annual fossil fuel combustion ➔ unit EJ/yr
- Emission factor: GtCO2/EJ
- BP energy statistics for 2021: 33.884 GtCO2

		Coal	Oil	Gas	Total
Consumption	EJ/yr	160.1	184.2	145.3	489.6
Carbon Intensity	MtCO2/EJ	95	73	55	
Emissions	GtCO2/yr	15.3	13.5	8.0	36.8

- Why the difference?

Fossil fuels are not only used for energy, but also in industry



From IEA energy balances
Data is for 2020

Making different GHGs comparable

	Unit	CO_2	CH_4	N_2O
Atmospheric lifetime	Years	~150	12	114
GWP20	Ton/Ton	1	84	265
GWP100	Ton/Ton	1	28	298
GWP500	Ton/Ton	1	7	156
Emissions 2010		31.7Gt	330Mt	10.5Mt
Emissions 2010 GWP100	$GtCO_2$-eq	31.7	9.2	3.1

- Parameters defining GWP (lifetime and radiative forcing) are uncertain
- Choice of GWP is political and depends on the time-horizon
- CH_4 reacts strongly with O2
- Some countries have higher CH_4 emissions than others
- USA from gas, China from coal

Linear Programming – The standard form (of the primal)

$$Min\ C = \sum_{i,j} c_{i,j} x_{i,j}$$

Subject to

Final energy demand $D_j \leq \sum_j a_{i,j} x_{i,j} \quad \forall j$

Primary energy resource $R_i \geq \sum_i x_{i,j} \quad \forall i$

Non-negativity $x_{i,j} \geq 0 \quad \forall i, j$

$c_{i,j}$ cost coefficients

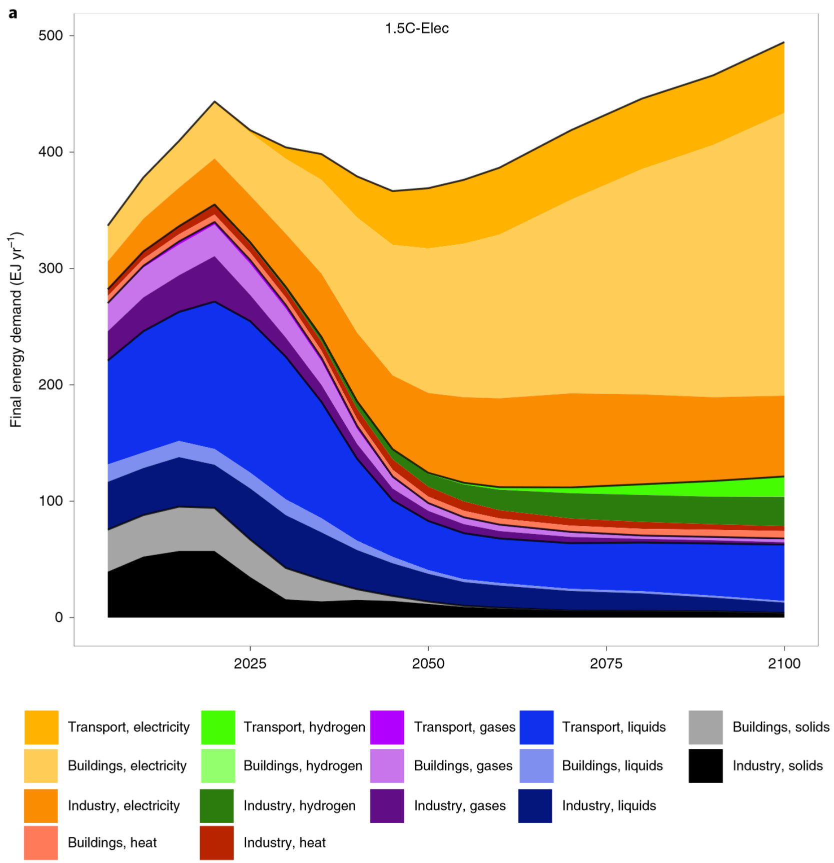
$x_{i,j}$ activity variables (primal variables)

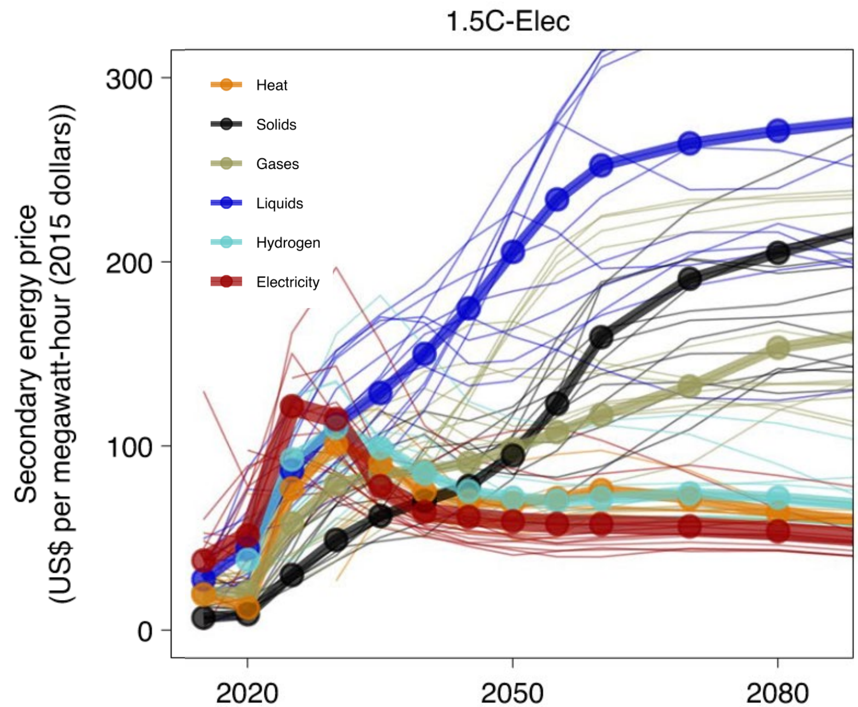
$a_{i,j}$ conversion factors

Linear Programming – Optimal solution

- Solution algorithm: Simplex algorithm finds set of $x_{i,j}$ that minimizes C
- Some inequalities are binding, but not necessarily all
- Each constraint has a dual variable ➔ shadow price
- The following complementarities hold for the inequalities
  - $\delta_j \left(D_j - \sum_j a_{i,j} x_{i,j}\right) = 0 \quad \forall j$ Final energy price
  - $\rho_i \left(R_i - \sum_i x_{i,j}\right) = 0 \quad \forall i$ Primary energy price
  - $\omega_{i,j} x_{i,j} = 0 \quad \forall i,j$ Subsidy to push $x_{i,j}$ into the market

A simple example





Luderer et al. (2021) https://www.nature.com/articles/s41560-021-00937-z

Note: this is for illustrative purposes. It is based on the REMIND-Model that represents price-responsive demands and energy substitution. This will come latter

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Linear programming – Interpretation of results

- There is an optimal solution only if the problem is feasible
  ➔ constraints define a non-empty set
- The solution is unique!
- Symmetry between
  - Centralized planner problem ➔ benevolent dictator ➔ shadow prices
  - Decentralized market solution ➔ “invisible hand” of the market ➔ market prices
- Pre-condition is the competitive market equilibrium
  - Atomistic actors that cannot influence the price
  - Full information on all technologies (no info-asymmetry)
  - No market entry and exit barriers;
  - marginal quantity changes, no ramp-up costs, unit commitments
  - No transaction costs
  - Optimal solutions can still induce external effects like air pollution, but if there is no feedback
  - [Since the model is static – so far – we need not say anything about dynamic imperfections and expectation formation]

Linear Programming – A powerful modeling tool

$$Min\ C = \sum_{i,j} c_{i,j} x_{i,j}$$

Subject to

Final energy demand	$D_j \leq \sum_j a_{i,j} x_{i,j}$	$\forall j$
Primary energy resource	$R_i \geq \sum_i x_{i,j}$	$\forall i$
Non-negativity	$x_{i,j} \geq 0$	$\forall i, j$

$c_{i,j}$ cost coefficients

$x_{i,j}$ activity variables (primal variables)

$a_{i,j}$ conversion factors

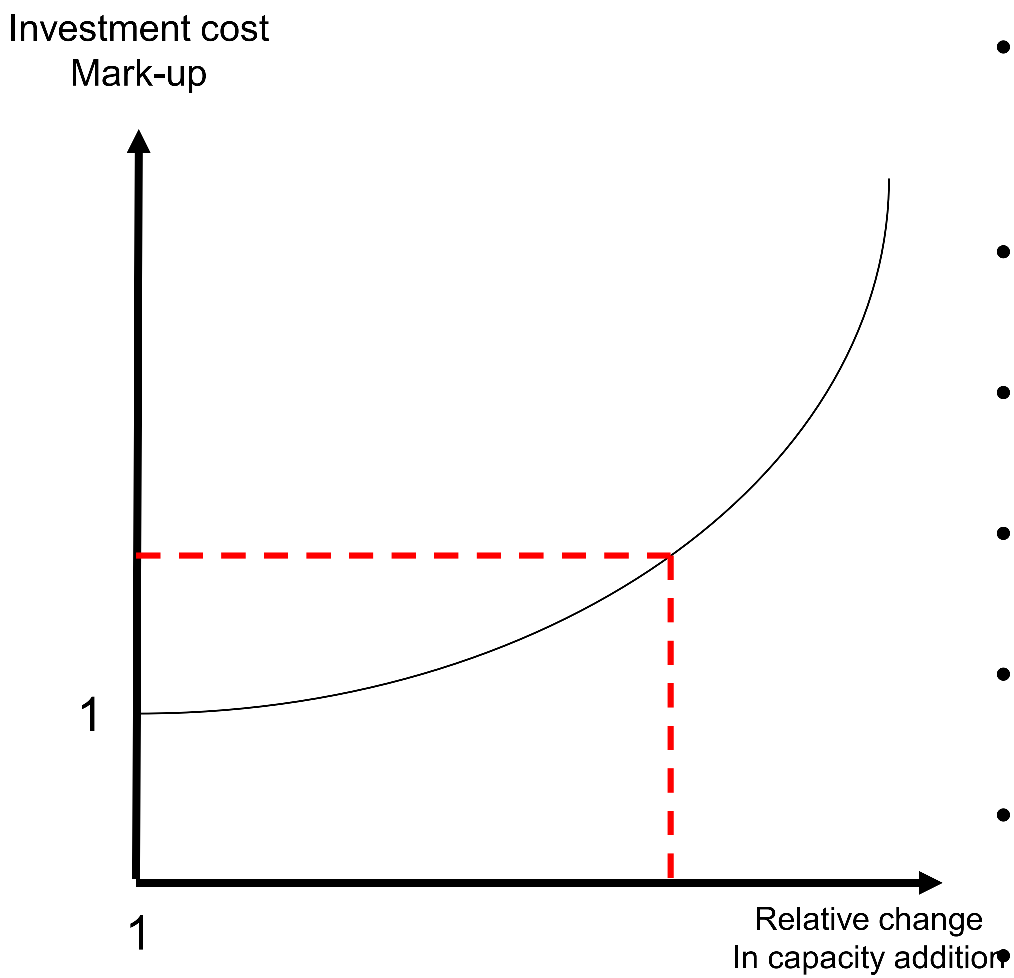
Discussion

- Emissions included via emission factors
- Dynamics can be added:
  - Exhaustible resources
  - Capacities
  - Constraints on changes
  - Changes of tech. and cost parameters (as long as no non-linearity is introduced)
- Locations, transport, net-works
- Not only energy: food, water, materials, …
- Behavioural factors can be included
- We can analyze a broad set of policies

- Information and data demanding method
- Sensitive behaviour due to linear structure
- Many constraints are added, with little empirical basis

- Very difficult to calibrate
  - Optimal solution usually deviates from statistics
  - Replication of data requires inclusion of more processes and policies and constraints

Going non-linear – Adjustment costs



- Capacity ramp-up can be very, very rapid, if investment costs are constant
- Hard growth constraints lead to numerical issues
- Adjustment costs are soft-constraints
- Investment costs increase, if capacity additions accelerate
- Build the capacity to build capacities
- Can be interpreted as a dynamic supply function
- Expectations & early investments

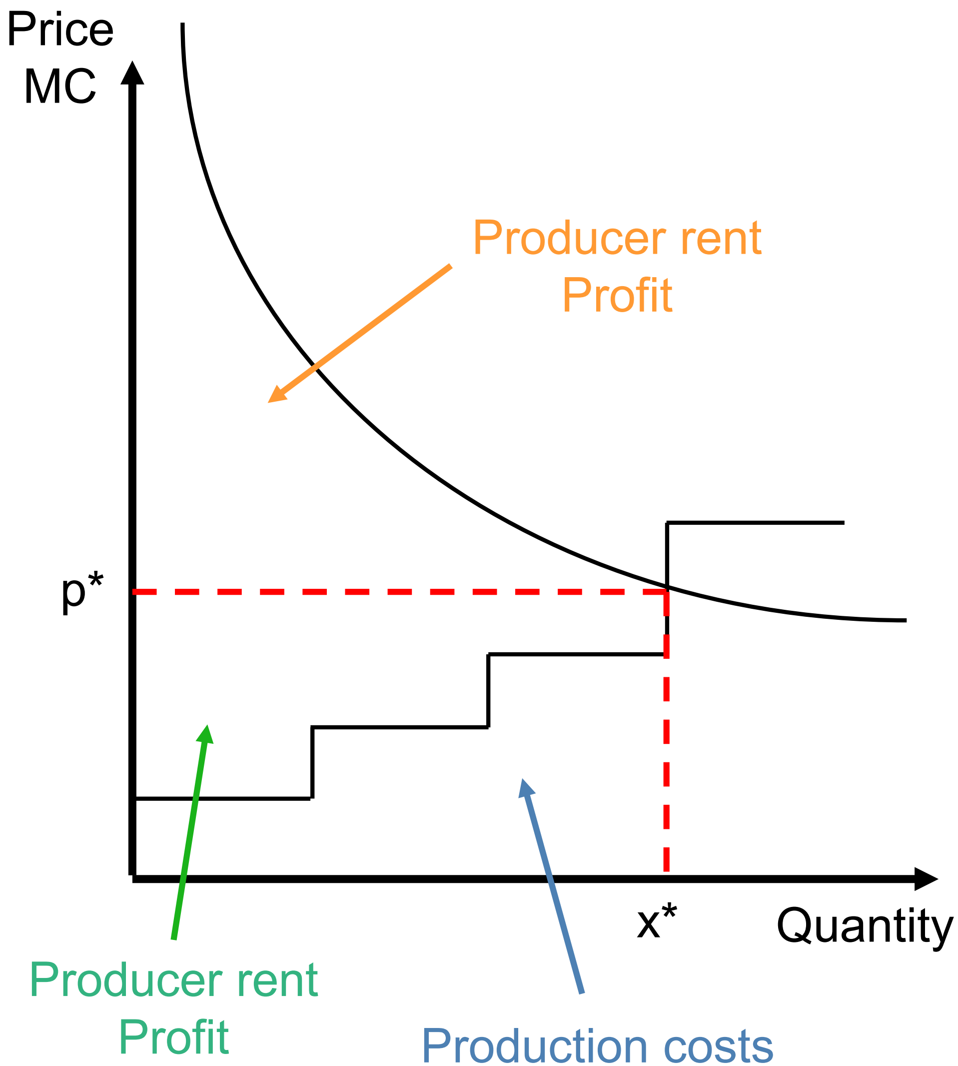
Going non-linear – Discrete Choice Models

- Addresses radical shifts in technology mix typical for LP (flip-flop, bang-bang, penny-switching, …)
- Approach: discrete choice models (e.g. multinominal logit)
- Choice probability i chooses n: $P_{n,i} = \frac{\exp(\beta c_{n,i})}{\sum_{j=1}^{J} \exp(\beta c_{n,j})}$

  characteristics of individual i and alternative n (e.g. price)
- Data for calibration: shares (e.g. modal split in transport)
- $P_{n,i}$ is constant, if $c_{n,i}$ even under growing scale

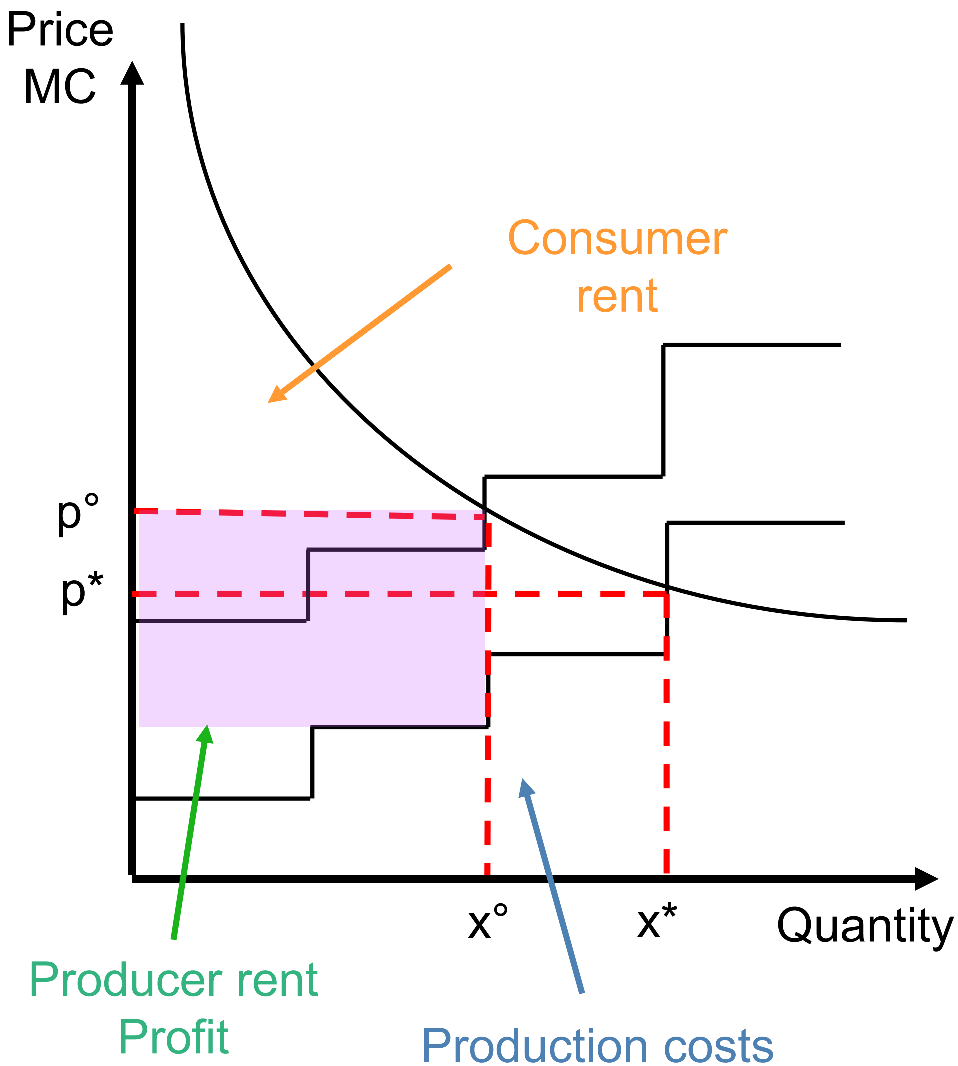
- Changes in prices shift the mix gradually, while total demand is fulfilled

Going non-linear – Price-responsive demands



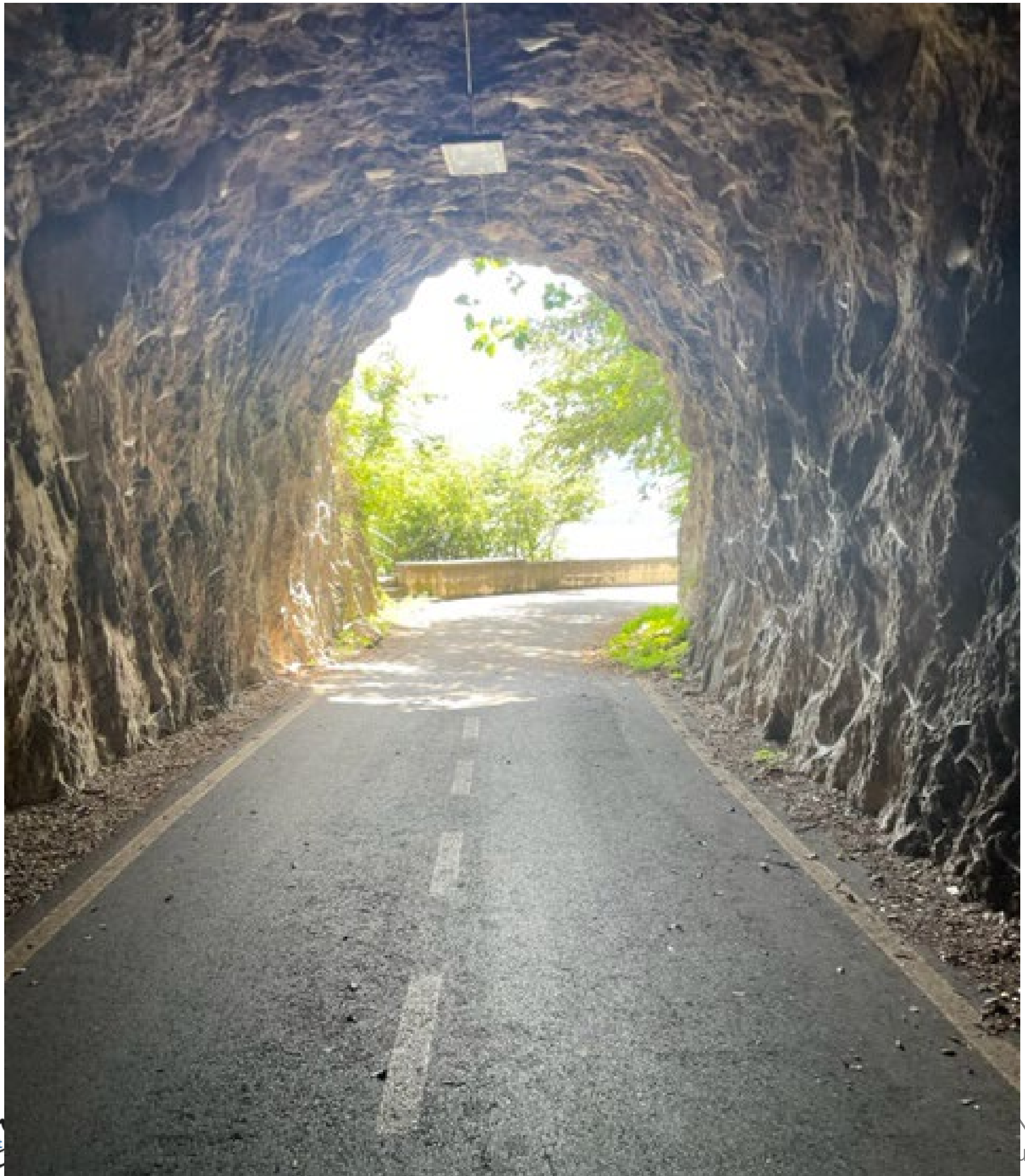
- Demand function is calibrated to replicate the demand level
- Revenue = cost + profit

Going non-linear – Price-responsive demands



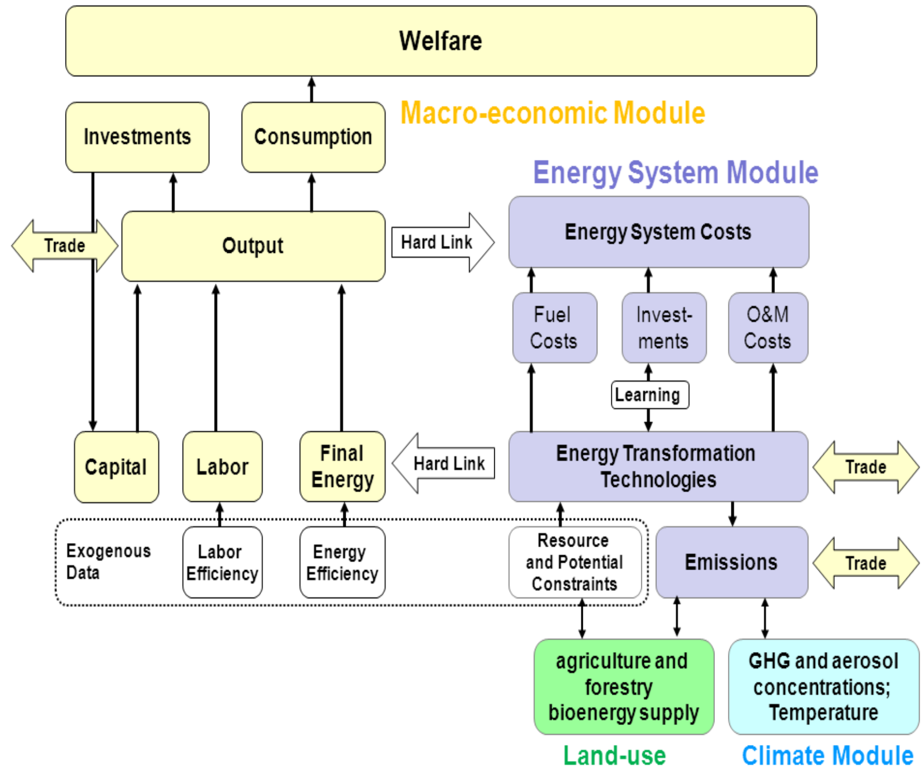
- Demand function is calibrated to replicate the demand level
- Revenue = cost + profit
- A carbon tax
  - Reduces quantity
  - Increases price
- Distributional implications
  - Decreases **production cost**
  - Decreases **producer rent**
  - Decreases **consumer rent**
  - Generates a **tax revenue**
    ➔ **can be redistributed**

There is light at the end of tunnel



From partial to general equilibrium

- Where does the finance come from?
- $GDP = C + I + ESC$
- $W = \int_{t0}^{t1} e^{-\rho t} U\left({}^{C}/_{Pop}\right) C$
- What is energy used for?
- $GDP = f_{CES}(K, L, FE)$

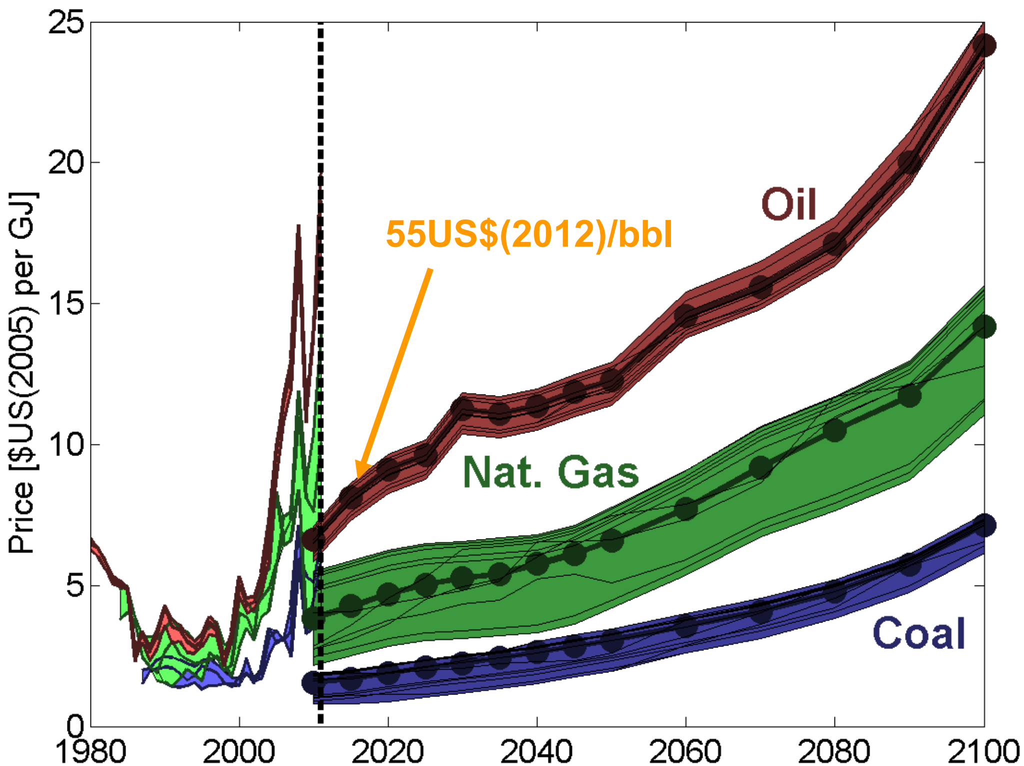


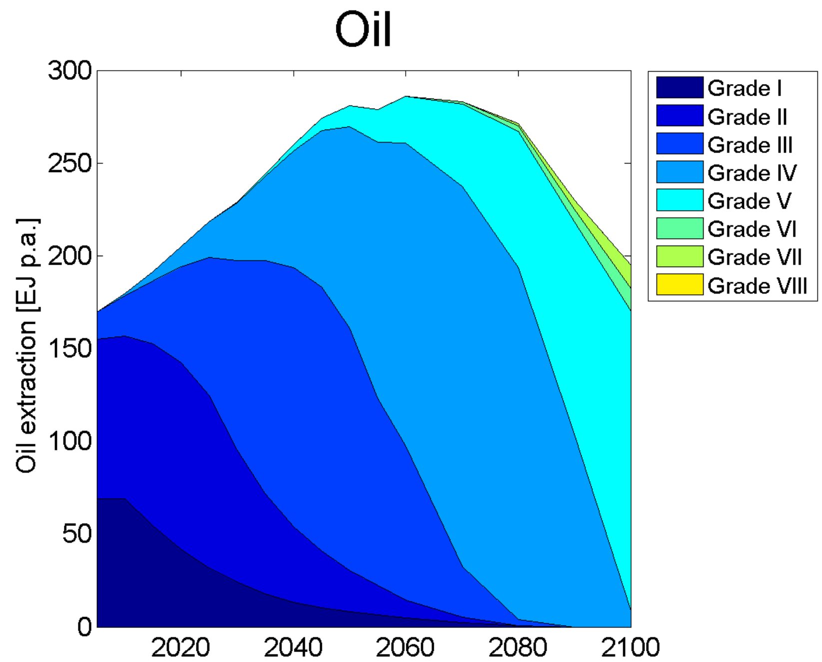
Climate Change Mitigation and Fossil Fuels

Distributional Impacts and Political Economy

Nico Bauer
NAVIGATE-ENGAGE Summer School, Como, July 4, 2023

Climate policies and fossil fuel markets

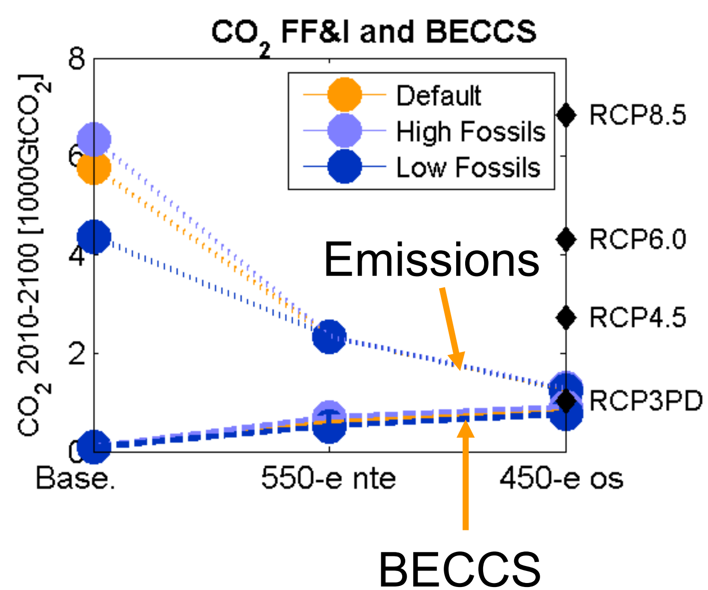




Historic data from BP (2012)

Note: BP reports gas and coal prices only for importing countries

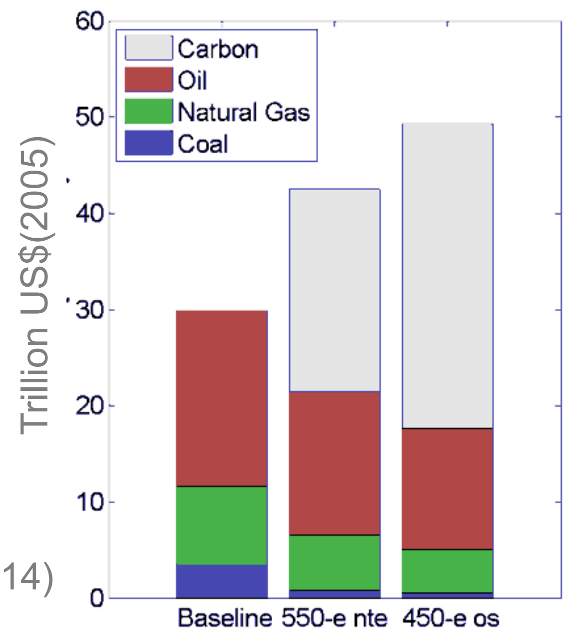
Climate policies and fossil fuel markets



Climate policies and fossil fuel markets

Discount Rate: 5%/yr

	Net Present Value tril. US$(2005)		
GDP	**1539**		
GDP Change		**-16**	**-30**



Bauer et al. (2014)

- Climate policies reduce GDP
- Fossil fuel owners loose
  - Oil: price effect
  - Coal: quantity effect
- Carbon pricing revenue can compensate losses

C-price US$/t$CO_2$	**Coal** 93tCO_2/TJ	**Oil** 73tCO_2/TJ	**Gas** 55tCO_2/TJ
	US$/GJ	US$/GJ	US$/GJ
150	16	23	13
50	**6.8**	**15.7**	**7.8**
20	3.9	13.5	6.1
0	2	12	5

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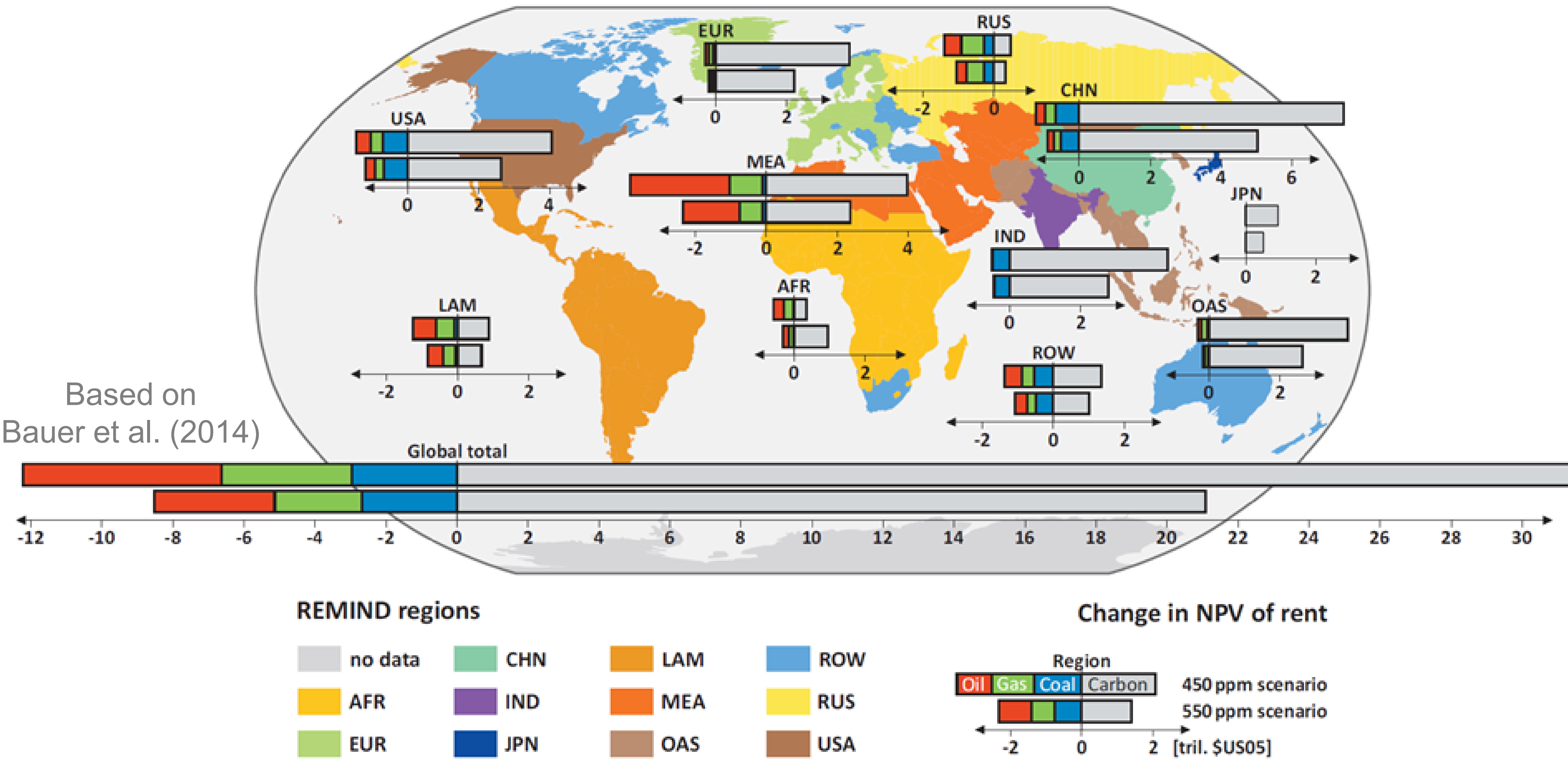
Coal price is currently in huge turmoil (US$/ton)

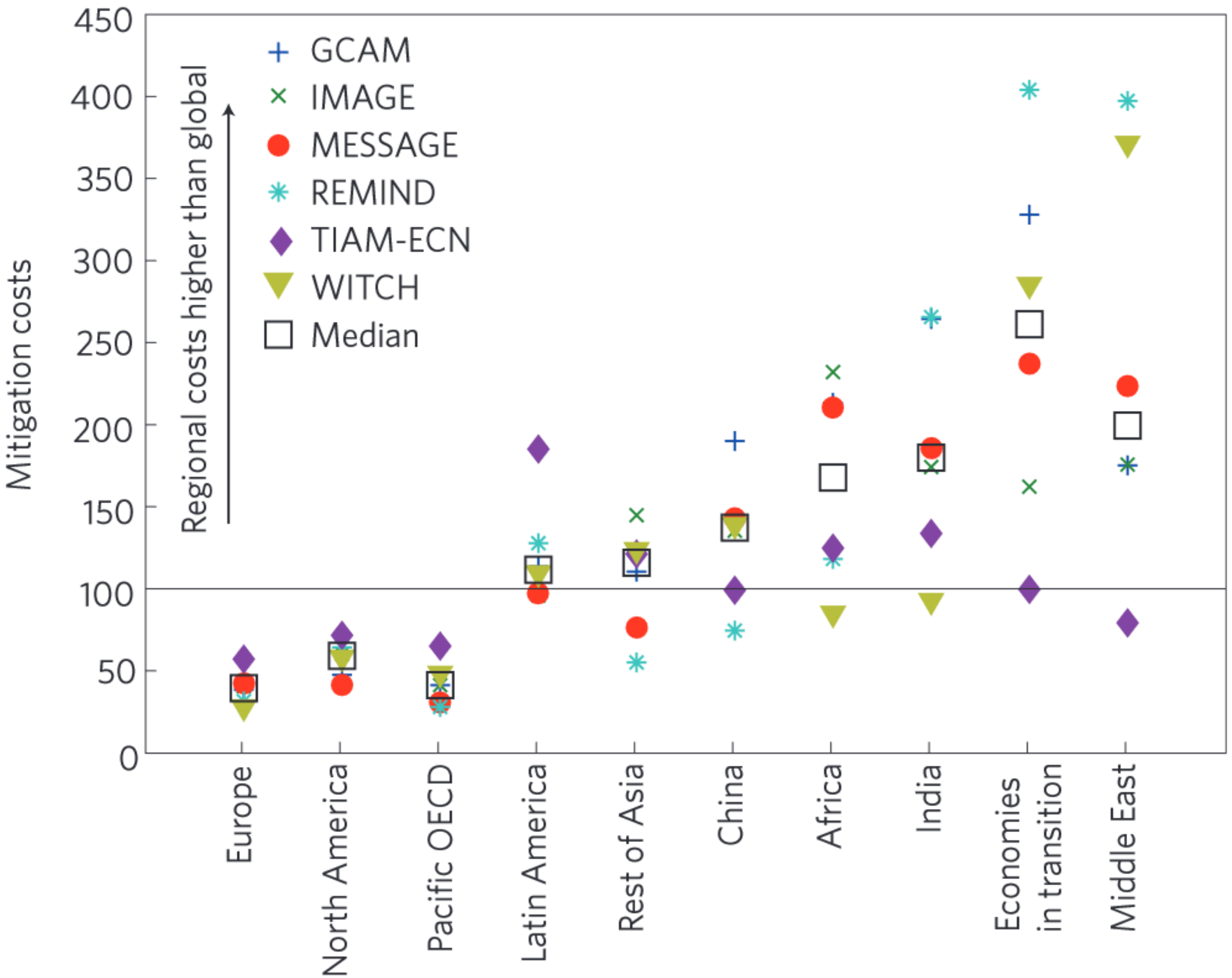
source: tradingeconomics.com

Climate policies and fossil fuel markets

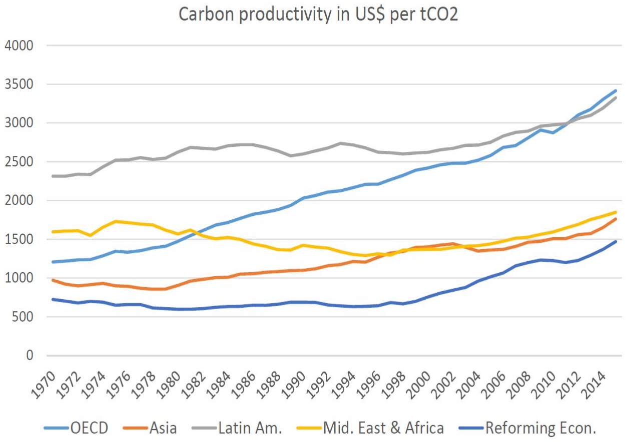


Based on Bauer et al. (2014)

Short note on regional mitigation costs



Remember from the intro slides



Tavoni et al. (2015)
http://www.worldscientific.com/doi/abs/10.1142/S2010007813400095

Endogenizing Technological Change

Rushing down the Learning Curve

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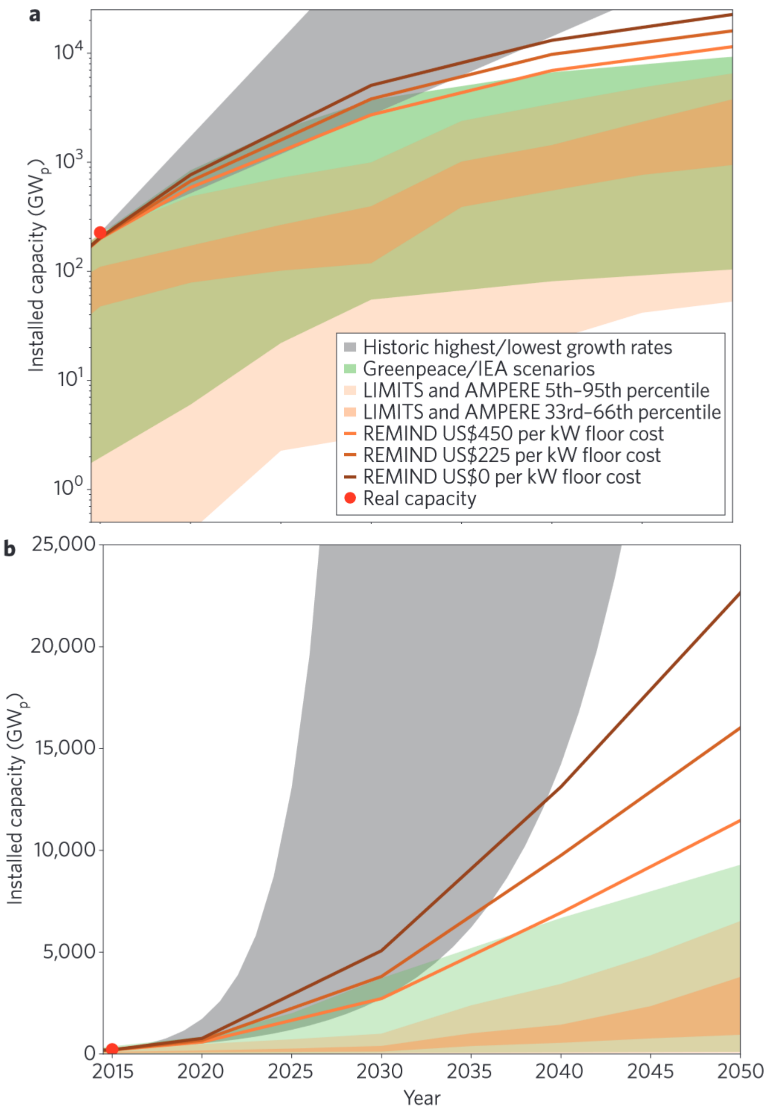
Endogenous Technology Change – The Learning Curve Approach



Creutzig et al (2018)
https://www.nature.com/articles/nenergy2017140

Learning curves can be implemented and solved by:

- Non-linear optimization
- Mixed-Integer Programming

Time horizon for investment decisions

Infinite

Recursive dynamics models

Learning is a spillover
➔ subsidy needed

Intertemporal perfect foresight;

Internalization of cost-reduction benefit

Myopic

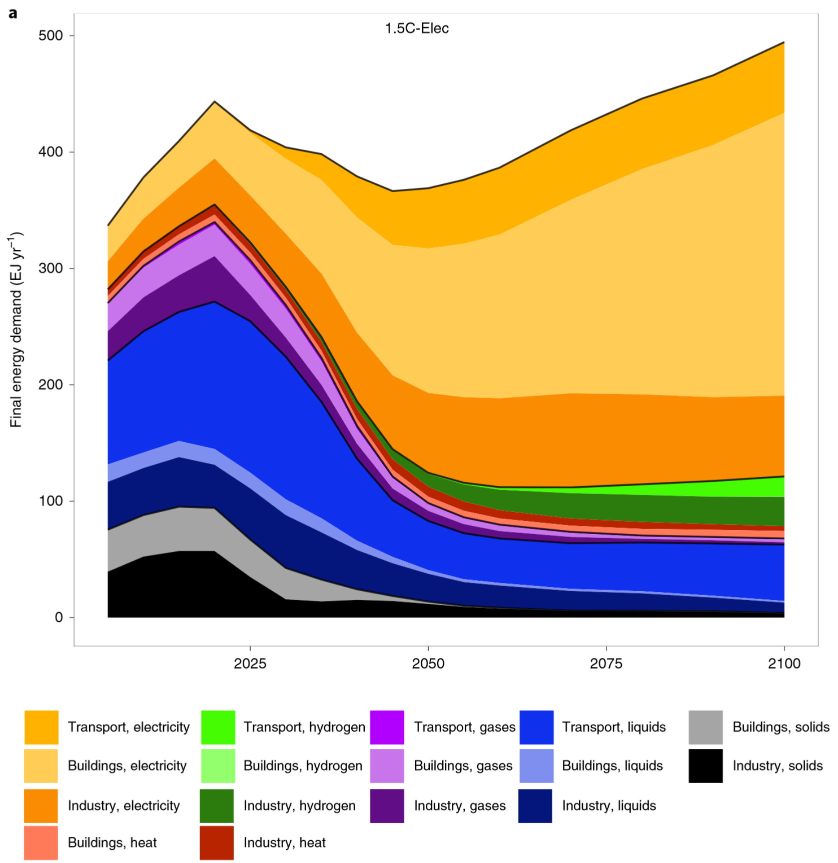
Why invest anyways?

Adaptative

Foresight

Expectation formation

Endogenous Technology Change – The Learning Curve Approach



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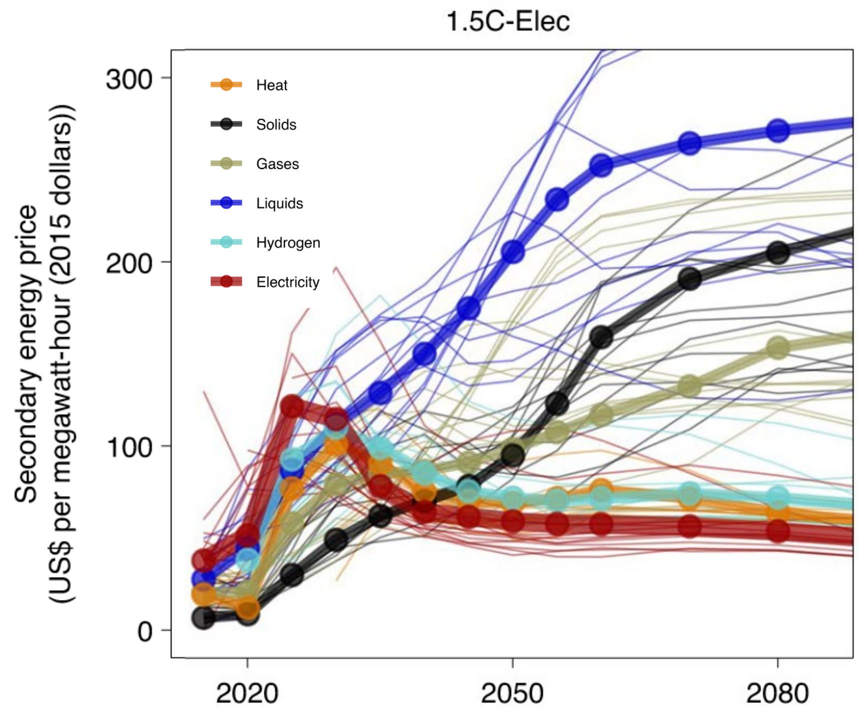
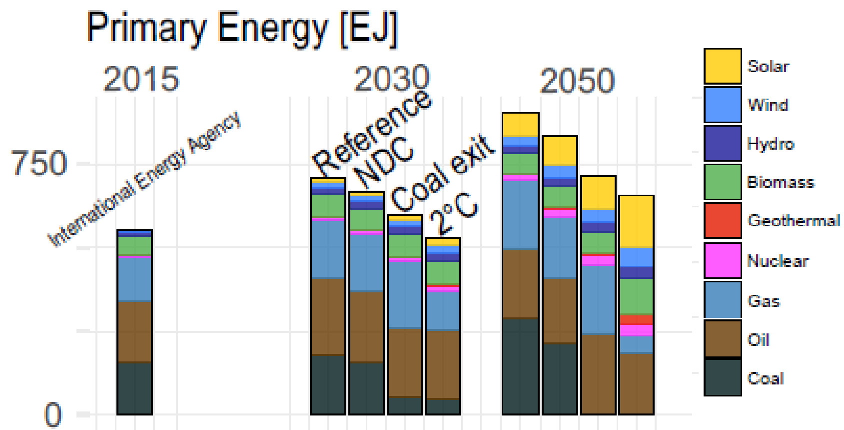


Note: this is for illustrative purposes. It is based on the REMIND-Model that represents price-responsive demands and energy substitution. This will come latter

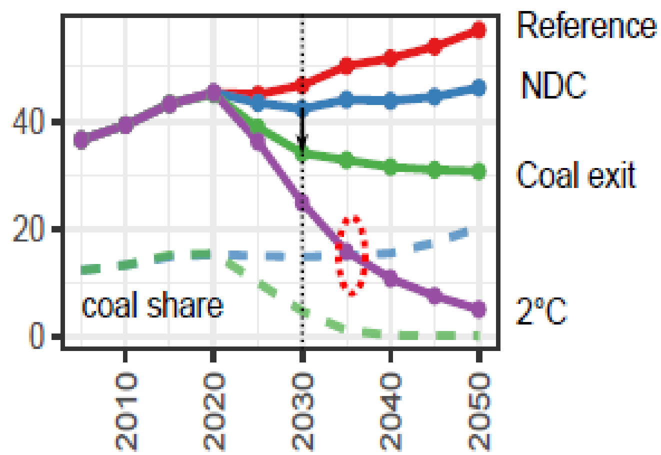
Air pollution and health impacts driven by IAM results

Health and environmental effects of coal phase out

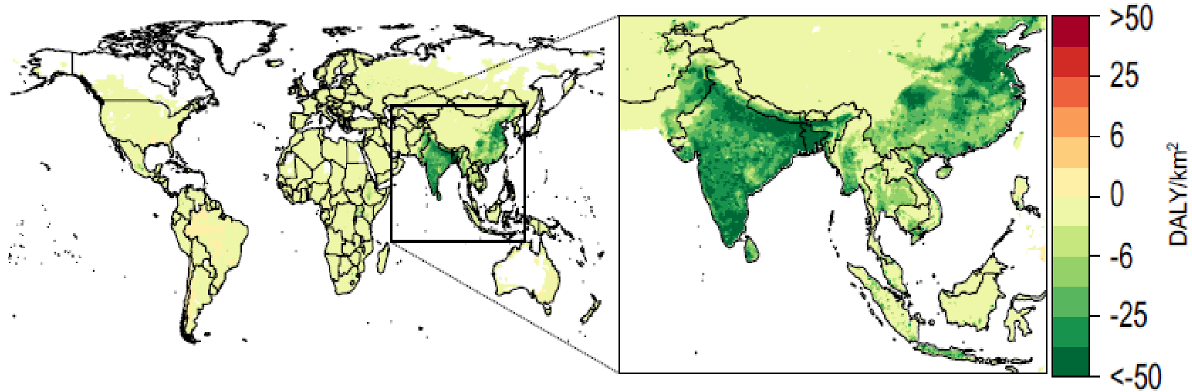


Reference: no policy case
NDC: policy evaluation of NDCs
Coal exit: Policy evaluation of coal phase-out from 2°C scenario
2°C: policy optimization

Global CO_2 emissions in $GtCO_2$



Health effects from „Coal Exit“ due to reduced air pollution



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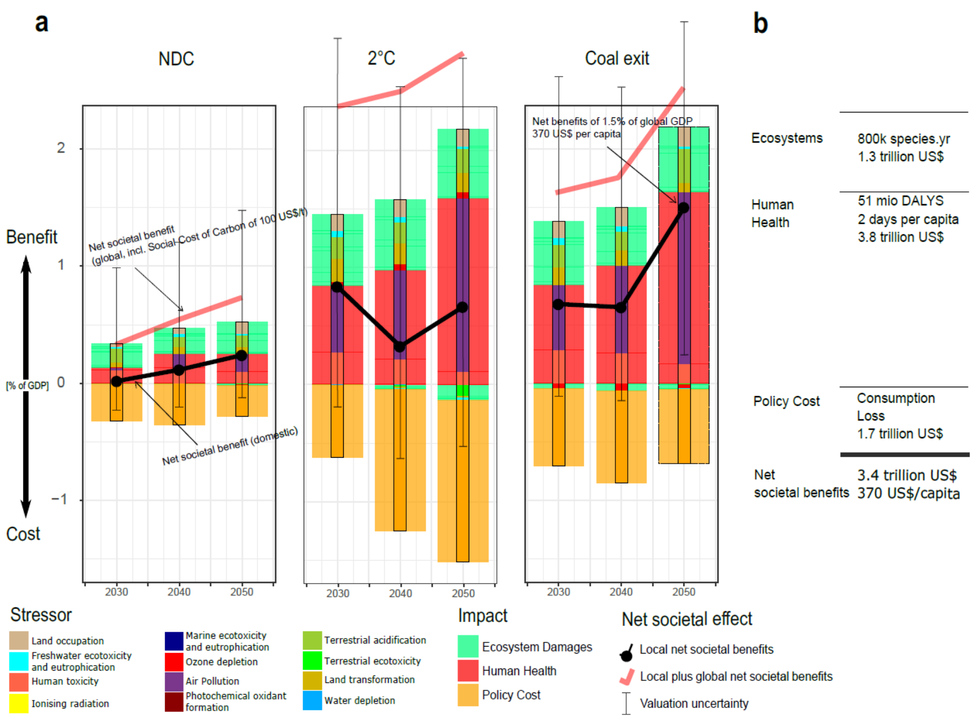
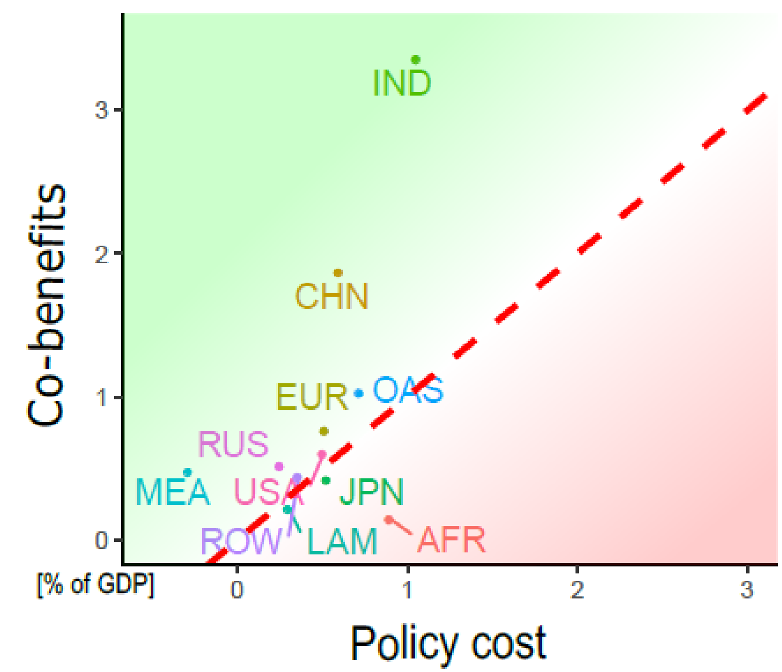
Rauner et al. (2020)

Health and environmental effects: global and regional effects

Global perspective
[based on current values]



Regional perspective
[based on net present value in 2050]



Rauner et al. (2020)
https://www.nature.com/articles/s41558-020-0728-x


Madonna del Ghisallo
Patrona dei Ciclisti