Is sustainability achievable?
Essays on the economics of the energy transition

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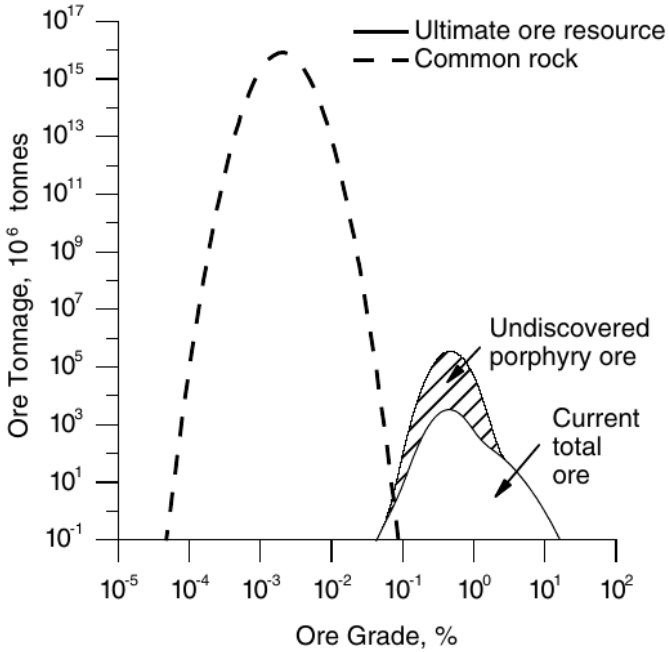
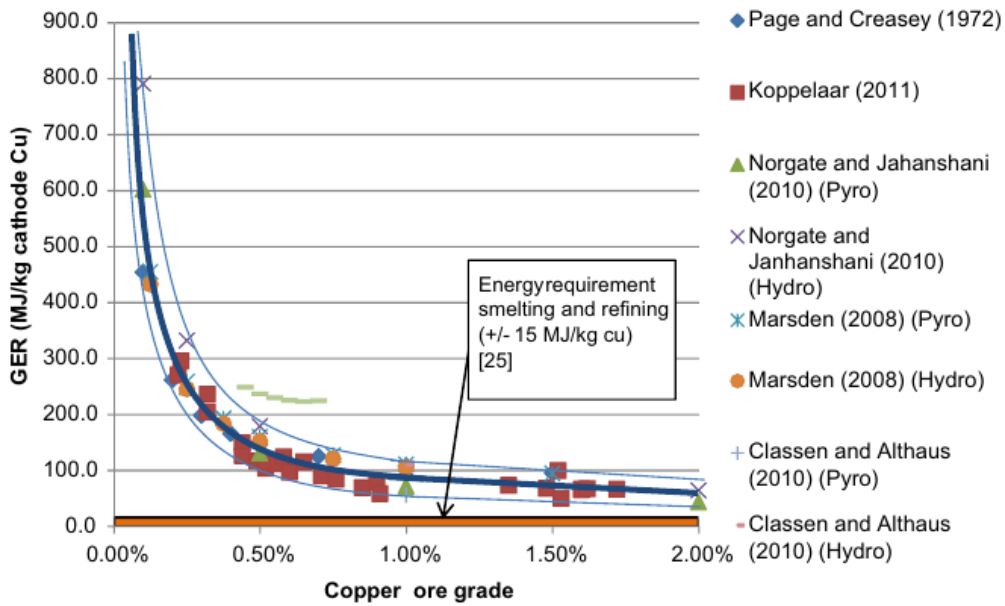
Towards a "peak copper"?

- A low ratio of resources over production...
  - Current copper extraction: 21 Mt/a
  - Reserves (economic extraction feasible): 830 Mt (40 years of prod)
  - Resources (will become economic): 6 Gt (285 years of prod)
  - $\Rightarrow$ Henckens et al. (2014): depletion in 2170; Sverdrup et al. (2014), Elshkaki et al. (2016): peak copper around 2050
- ... but much larger ultimate resources
  - Ultimate resources: 300 Gt of deposits, $4 \cdot 10^5$Gt in the crust
  - Relevant notions: tonnage-grade relationship, recovery costs



(a) All crustal copper. Source: Gerst (2008)



(b) Gross energy requirement of copper extraction, by ore grade. Source: Harmsen et al. (2013).

Towards a circular economy?

- Endless management of metals possible iff the distribution of recovery costs in waste is similar to that in mine
- Rechberger & Gradel (2002): average recovery costs constant vs. Valero & Valero (2015): inevitable degradation of stocks
- We can reconcile both (cf. figs)
- In which case are we?
- Universal mining machine?

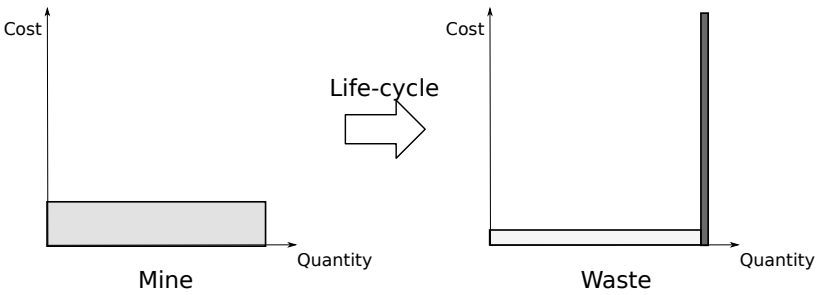
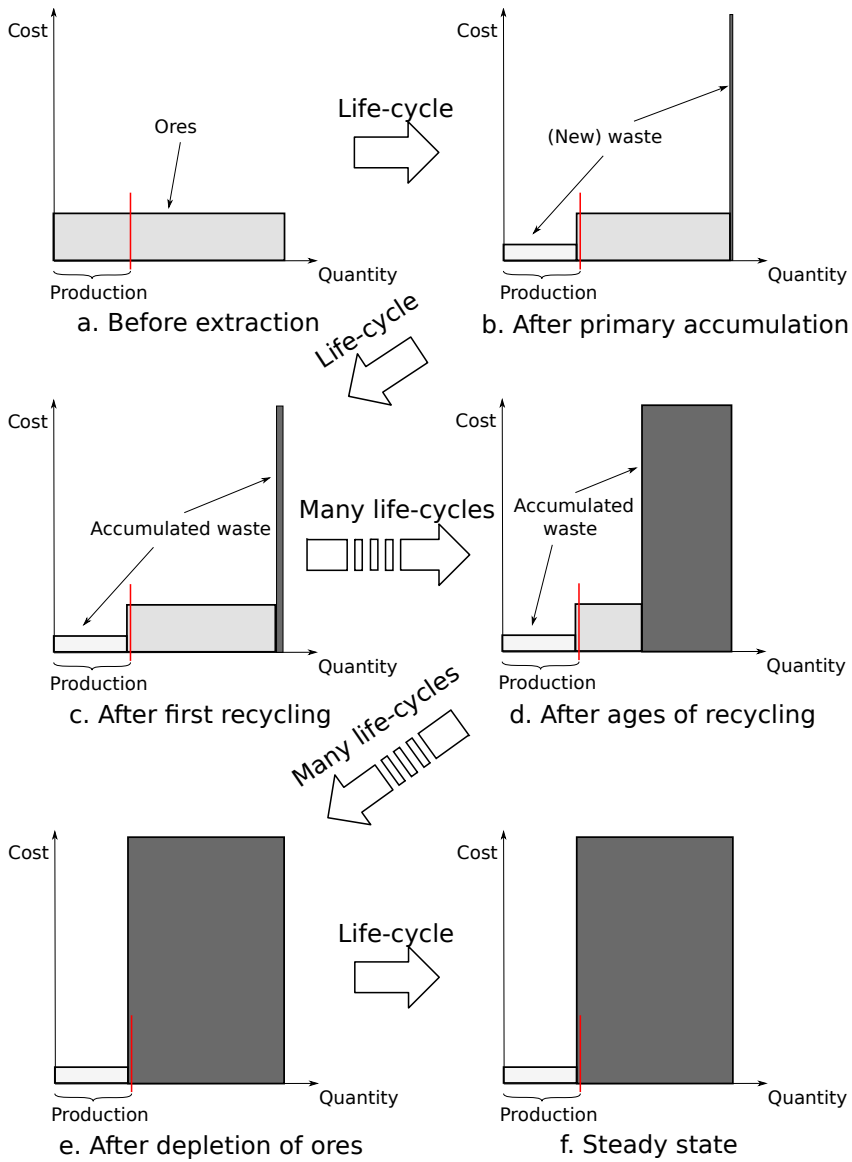


Figure: Decreasing average recovery cost.

Figure: Evolution of stocks' recovery costs.



The EROI of a technology is not intrinsic

$a_{i,j}$: quantity of input *i* required to produce one unit of output *j*.

$$A \begin{pmatrix} 0 & 0 & 1 \\ m_e & 0.2 & 0 \\ 0.1 & 0.5 & 0 \end{pmatrix} \begin{matrix} \text{energy techno.} \\ \text{materials} \\ \text{energy} \end{matrix}$$

$$A = \begin{pmatrix} 0 & 0 & 0 & p \\ 0 & 0 & 0 & 1-p \\ 0.7 & 0.1 & 0.2 & 0 \\ 0.1 & 0.1 & 0.5 & 0 \end{pmatrix} \begin{matrix} \text{PV} \\ \text{gas} \\ \text{materials} \\ \text{energy} \end{matrix}$$

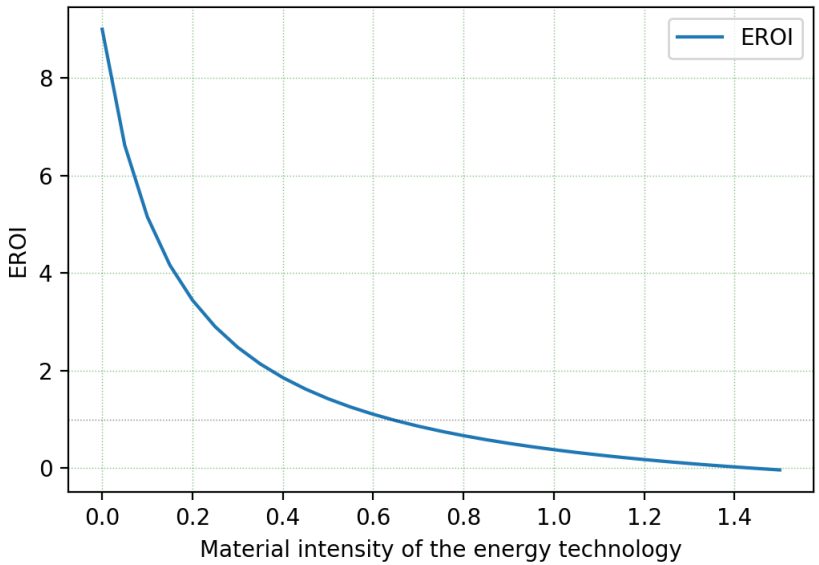


Figure: EROI in function of material intensity m_e of the energy technology.

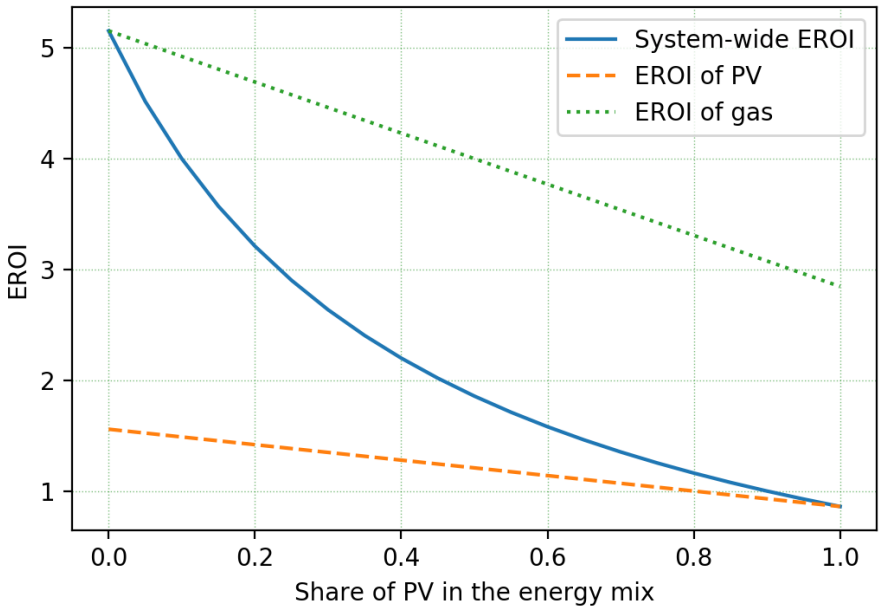


Figure: EROIs in function of the share *p* of PV in the energy mix.

Estimation of current and future EROIs using THEMIS

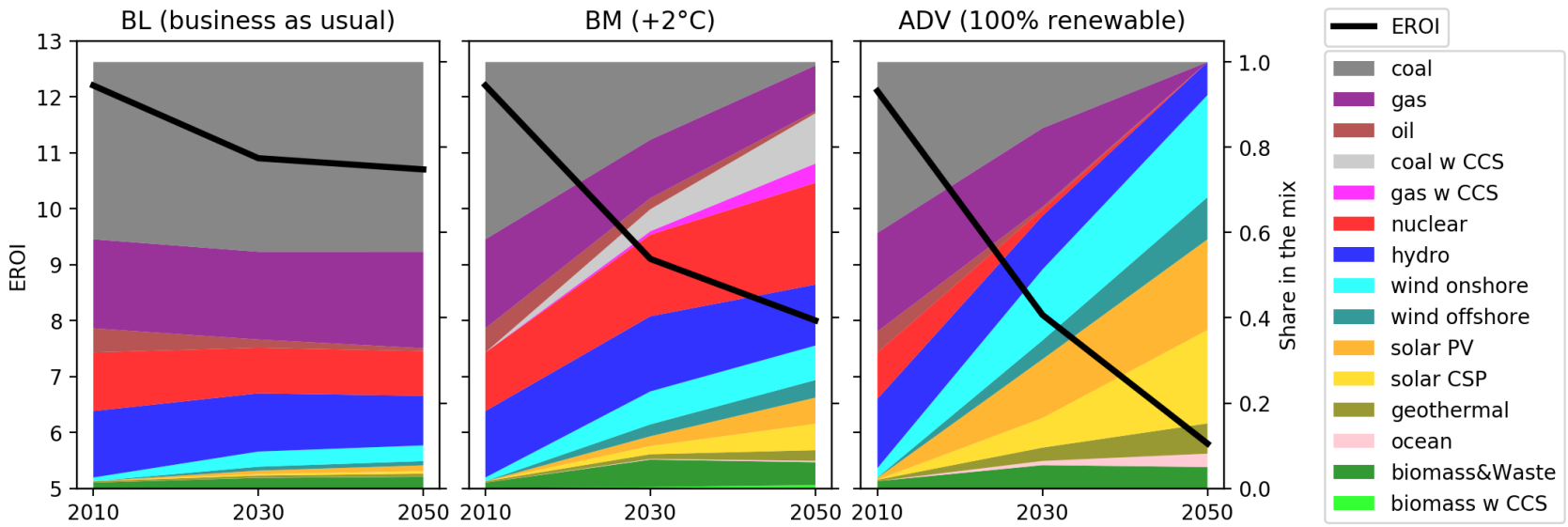


Figure: Evolution of global EROIs and mixes of electricity for different scenarios.

- EROIs of renewables should decrease, as anticipated
- System-wide EROI is currently 12; decreases slightly until 11 in Baseline
- Decrease much more pronounced in 100% renewable scenario: 6 in 2050
- Room for improvement, e.g. including the transportation system.

Implications of a decreasing EROI on prices and GDP

- Empirically: inverse relationship (N=2111, $R^2 = 0.6$)

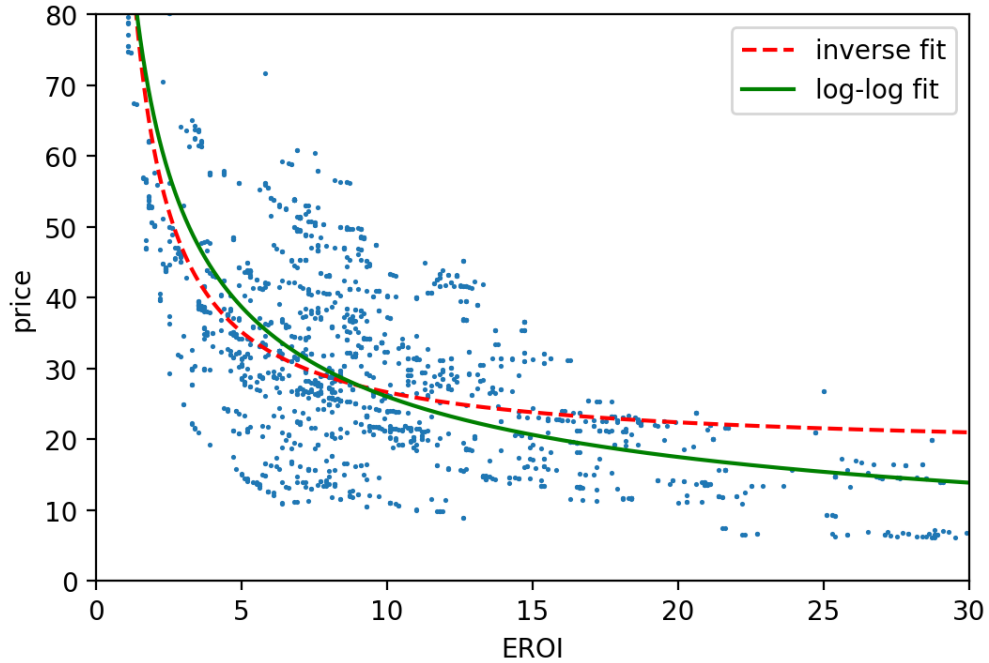


Figure: Regressions p $\sim$ EROI using all scenario estimates

- But in theory, price and EROI can both decrease together
- Still, most probable is that decreasing EROI $\Rightarrow$ increasing price
- Yet, no clear relationship with GDP, caution with "minimum viable EROI"

The infinite horizon model

- Minerals can be recycled, while fossil resources cannot
- When should we exploit these resources?
- Benevolent social planner solves

$$\max \sum_{t\geq 0} \left(\frac{1}{1+\rho}\right)^t \frac{1}{1-\varepsilon} \left(f_t^{\alpha} K_t^{1-\alpha}\right)^{1-\varepsilon}$$

$$st \begin{cases} K_t = K_{-1}\delta^{t+1} + \sum_{\tau=0}^{t} m_\tau \delta^{t-\tau} \\ F \geq \sum_{t\geq 0} f_t \\ M \geq \sum_{t\geq 0} m_t \end{cases}$$

$f_t, m_t \geq 0$, M, F, K_{-1} given.

Main results

- A higher recyclability δ implies to:

1) Bring forward in time the extraction of minerals and investment in green capital: $\frac{\partial m_0}{\partial \delta} > 0$

2) Choose an energy mix relatively more intensive in renewables: $\frac{\partial \frac{K_t}{f_t}}{\partial \delta} > 0$

- Our result still applies considering other factors for the timing of the transition: technical progress, substitutability or complementarity between the resources, convex extraction costs, environmental damages from fossils (extensions in 2-period)

Introduction

Figure: Some Yellow Vests

Survey and data

- 3002 responses collected on-line in February/March 2019
- Representative along six socio-demographics, median duration: 19 min
- Make sure that data of good quality (e.g. we exclude inattentive or too quick respondents)
- Description of our **Tax & Dividend** reform:
  - Tax on fossil fuels: $+50€/tCO_2$
  - $+13\%$ on gas (resp. $+15\%$ on domestic fuel) redistributed
  - $+0.11€$/L on gasoline (resp. $+0.13€$/L on diesel)
  - Revenues from households redistributed lump-sum: 110€/year by adult
  - Tax incidence: borne at 80% by consumers
  - Elasticities: -0.4 for transport, -0.2 for housing
- Do you think this reform would be effective in reducing pollution and fight climate change?
  - "scientists agree that a carbon tax would be effective in reducing pollution" randomly displayed or not
- Would you lose, win or be unaffected by the reform?
- Expected loss (or gain) among 6 (or 5) intervals?
- Would you approve this reform?
  - 10% 'Yes': approval
  - 19% 'PNR' (I don't know, I don't want to answer): acceptance
  - 70% 'No': disapproval

Biased beliefs

PDF of objective vs. subjective net gains from Tax & Dividend (in € per year per consumption unit).

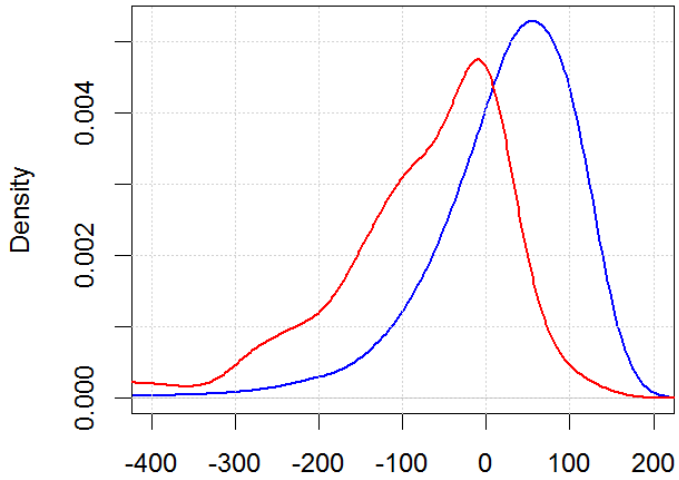


Figure: Net gain. Mean: -89/+24

- Objectively, 70% expected to win, but only 14% think they would
  - Yellow Vests and those who disapprove the reform more biased
- 66% think reform ineffective to reduce pollution and fight climate change
- 60% think the reform would not benefit poorer households

How attitudes shape beliefs

For self-interest:

1. Losers update correctly (on average): 86% align with feedback
2. Winners do not update enough: only 25% align

Possible interpretations:

- Respondents think our feedback is biased (upwards).
- Respondents give too much value to their (biased) private information.
- Respondents are uncertain and loss averse: they don't report a lower-than-expected outcome.

Motivated reasoning:
Those who originally disapprove (and Yellow Vests) update less correctly

For environmental effectiveness: small but significant effect of priming

For progressivity: our explanation do not convince anyone

How beliefs determine attitudes

- TODO

Knowledge of climate change

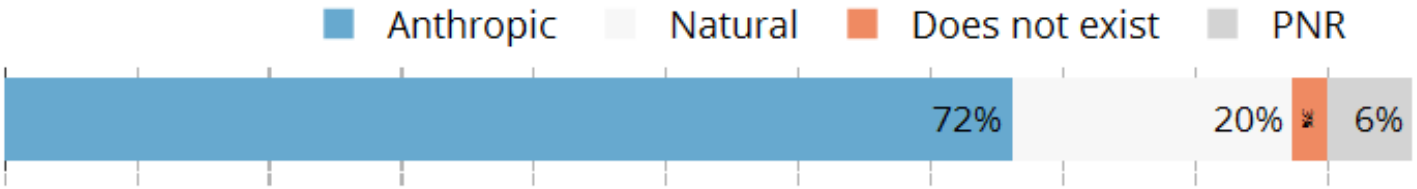


Figure: Perceived cause of climate change.

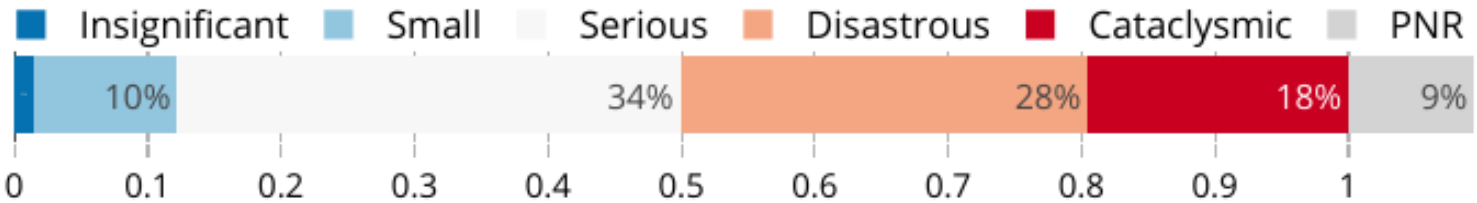


Figure: Perceived gravity of climate change.

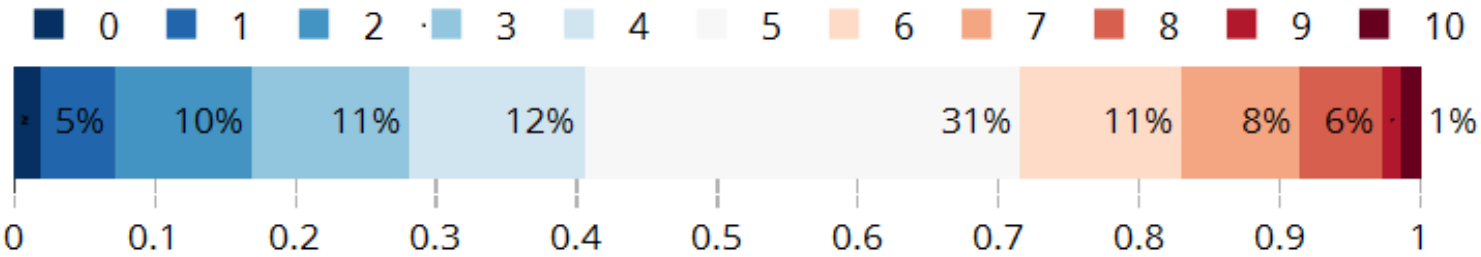
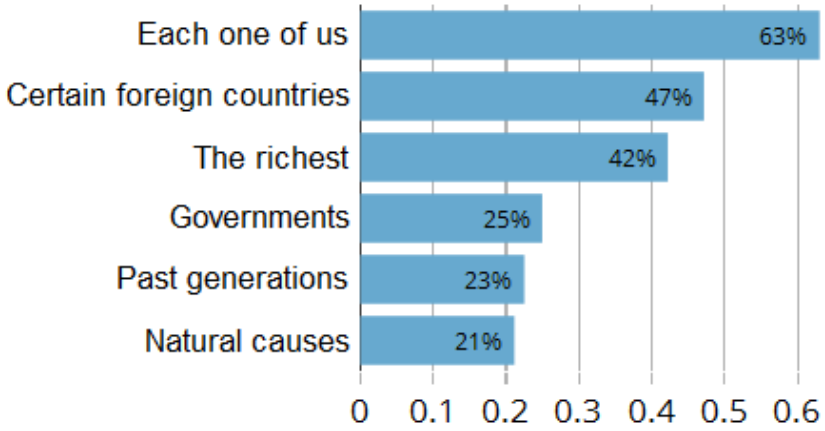


Figure: Perceived GHG emission p.c. required in 2050 to limit global warming to +2°C (in tCO_2eq/yr), given that it is now 10.

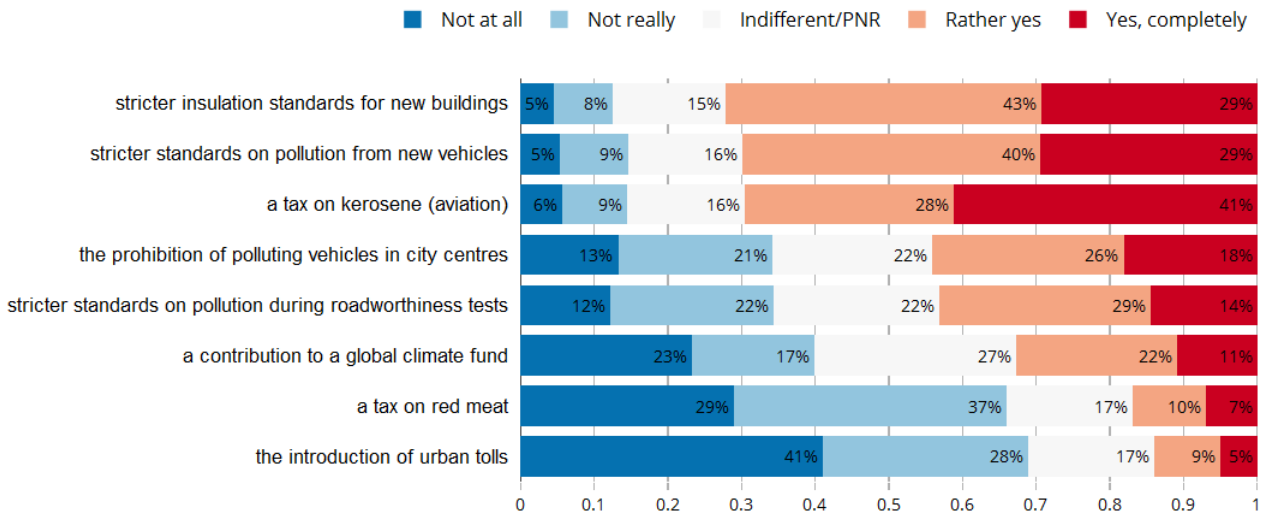
Attitudes over Climate Change

Figure: Entities perceived responsible for climate change.



- 65% are "willing to adopt an ecological lifestyle (i.e. eat little red meat and make sure to use almost no gasoline, diesel nor kerosene)", assuming that "all states in the world agree to firmly fight climate change, notably through a transition to renewable energy, by making the richest contribute, and imagining that France would expand the supply of non-polluting transport very widely" (17% "No")
- 82% would be willing to change their lifestyle under at least one of the three conditions proposed: sufficient financial resources, an alignment of policies to this goal, or an adjustment of others' behavior (about 45% each)

Attitudes over other climate policies



Determinants of attitudes

- TODO

Climate resulting from each state

Table: Climate resulting from each pair of moves. High mitigation agreement (H) is only possible if both players choose H over low (L) mitigation.

Moves by players 1 \ 2	H_2	L_2
H_2	H	L
L_2	L	L

Climatic outcomes depending on players' preferences

Table: Climate resulting from each pair of moves. Low mitigation (L) without geoengineering (G) dominates high mitigation (H) (Table 1), while G dominates all.

Moves by players 1 \ 2	H_2	L_2	G_2
H_2	H	L	G
G_2	L	L	G
L_2	G	G	G