http://modelccem.eu

In Memoriam

Paul Caseau

A System Dynamics Model for Global Warming Impact, from Energy Transition to Ecological Redirection

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AXA IM Presentation

Outline

1. *Why* : **Yet Another Integrated Assessment Model ?**
   - **System Dynamics, Integrated Assessment Models**
   - **Known Unknowns as Parameters**
2. **CCEM Model Overview**
   - **Coupling of 5 “coarse” models**
   - **M1 to M5 Overview**
3. **Computational Scenarios**
   - **Preliminary results**
   - **Sensitivity analysis**
4. *So What* : **What are the first insights ?**
   - **A possible new narrative of global warming**
   - **Next Steps**

Motivations for Yet Another Earth/Climate/Economy Model

Energy Future

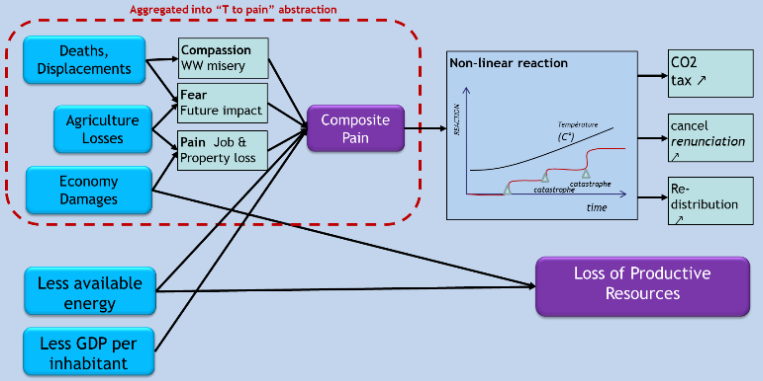
- How much fossil energy will be available, at which extraction costs in the 21st century ?
- How fast can we manufacture and deploy sustainable energies ?
- How fast can we electrify the use of energy ?
- How will the energy intensity (kWh / M$) trend evolve in the next century ? For each continent ?

Damages

- SCC (*Social Cost of Carbon*): "**Comprehensive evidence implies a higher social cost of CO2**" (Reinert & al.)
- Qualitative assessment of damages, but monetary value is hard to agree on – cf. IPCC Working Group II (Impact, Adaptation & Vulnerability)
- Double questioning of IAMs regarding damage modeling : level and non-linear tipping points (Stern, Stiglitz and Taylor, 2022)

Redirections

- Damages will trigger societal reactions as pain grows:

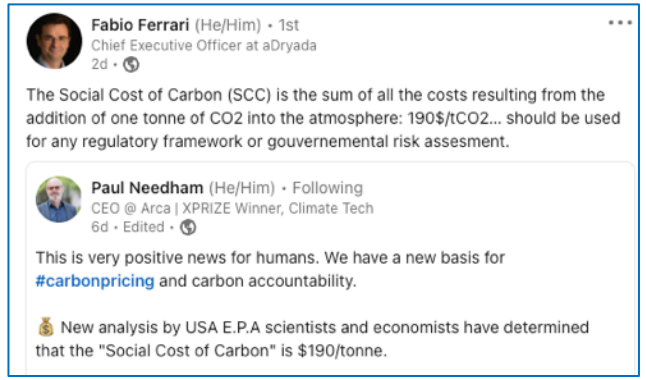


- Possible redirections
  - Cancelation (renounce a CO2 producing activity)
  - Acceleration (Energy transition & carbon taxes)
  - protectionism

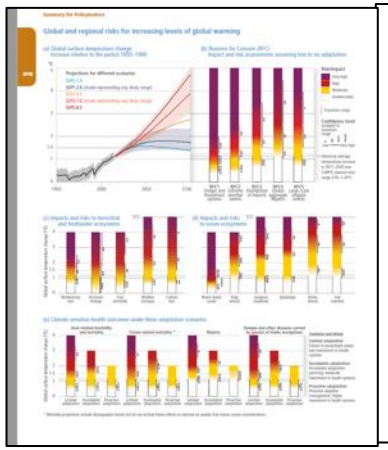
Part I - Why ?

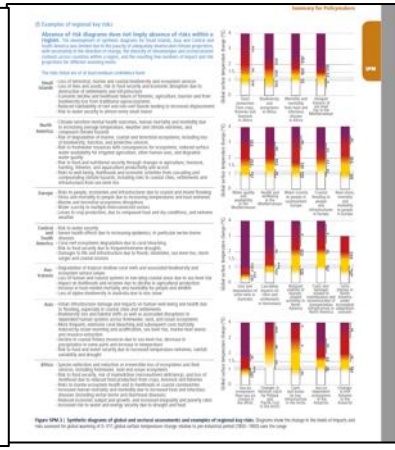
Some Key Questions about Global Warming Impact

1. Social Cost of Carbon: What should the price of a carbon tax be ?
”**Comprehensive evidence implies a higher social cost of CO2**”
   - Rennert & al, Nature 2022
   - SCC at 185$/t, mostly agriculture and mortality (GIVE model)
- CSRD will make the question of the cost of carbon strategic
   - **Each company must disclose its CO2 cost hypotheses**



2. Damages
   - IPCC Working Group II (Impact, Adaptation & Vulnerability)
   - Qualitative assessment of damages, but no monetary figures.

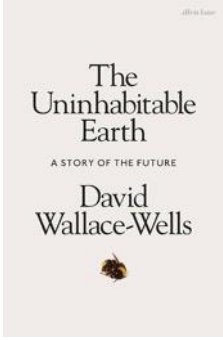




3. Questioning the relevance of Damage Models

“**The economics of immense risk, urgent action and radical change: towards new approaches to the economics of climate change**”
   - Stern, Stiglitz and Taylor, 2022
   - *Our first task in this paper is to argue that, as a methodological approach, the optimization framework embodied in IAMs is inadequate to capture deep uncertainty and extreme risk, involving potential loss of lives and livelihoods on immense scale and fundamental transformation and destruction of our natural environment*

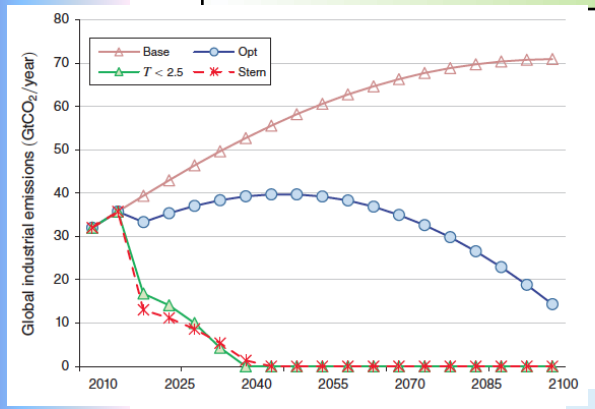
The Complexity of Assessing Damages

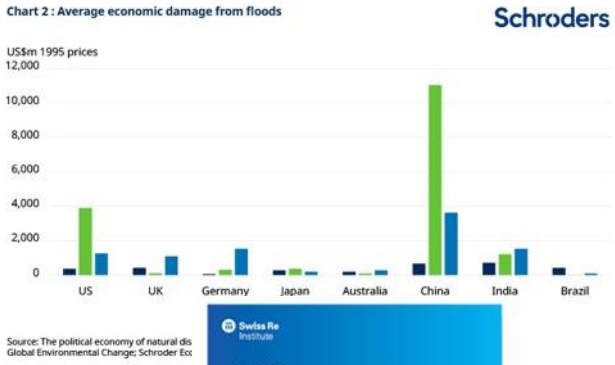


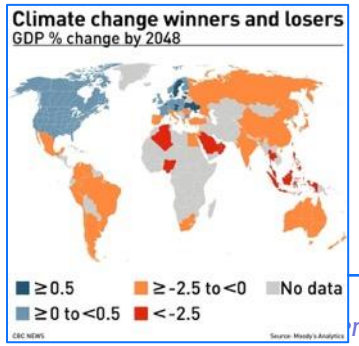
- *What is the expected GDP loss associated to a warming of +3C ?*

>= 10 years old → *>= 5 years old* → *current*

-3% for +3C → -7% to -10% for +3C → -15% to -25% for +3C

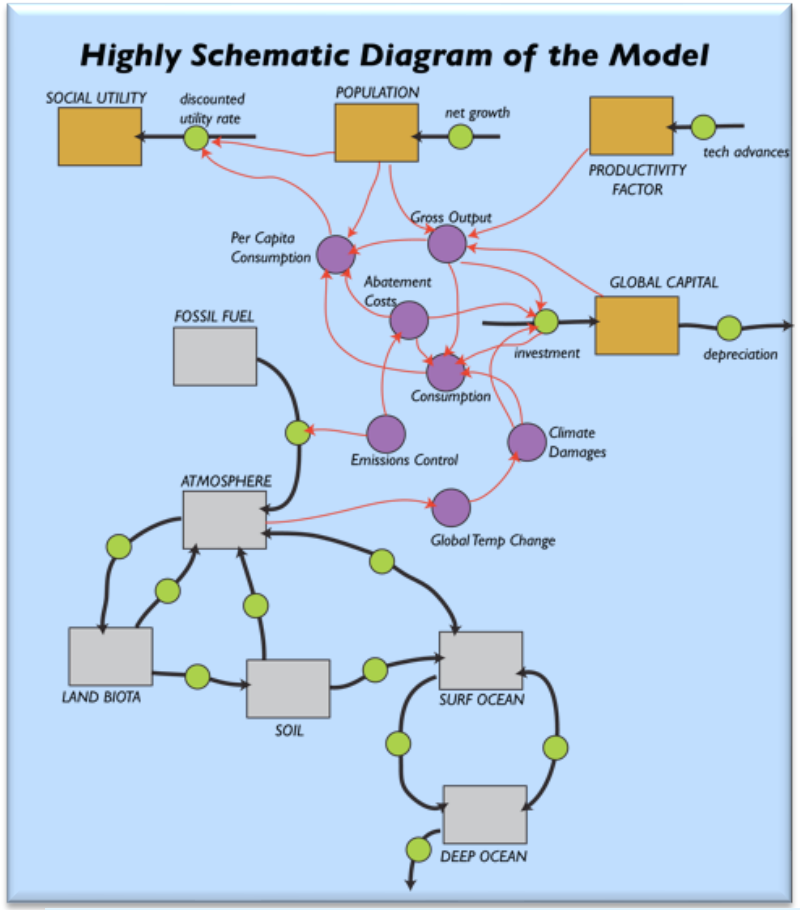






2050 (+1.7) impact is very strong (-6%)

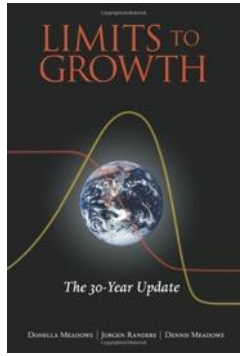
Integrated Assessment Models
System Dynamics Models



William Nordhaus (Wikipedia)

- **IAM**: (Wikipedia Definition)
  Integrated assessment modelling (IAM) or integrated modelling (IM) [a] is a term used for a type of scientific modelling that tries to link **main features of society and economy with the biosphere and atmosphere into one modelling framework**.
  - **Strengths (what it is useful for)**
    - Systemic view (more or less ☺)
    - What-if scenarios
    - Global energy / economy / climate coupling

- **System Dynamic**: (Wikipedia Definition)
  System dynamics (SD) is an approach to understanding the nonlinear behavior of complex systems over time using stocks, flows, internal feedback loops, table functions and time delays.



Approximative difference between IAMs & SDEM

- IAMs are data-driven (calibrated from past data)
  - Risk of overfitting when projected in the next century
- SDEM are designed from « first principles »
  - Crude calibration / focus on orders of magnitude

Part II

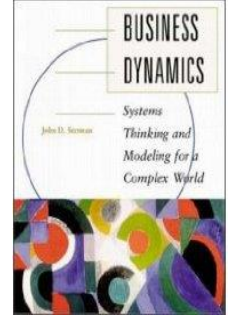
1. *Why* : Yet Another Integrated Assessment Model ?

2. **CCEM Model Overview**
   - **Coupling of 5 “coarse” models**
   - **M1 to M5 Overview**

3. **Computational Scenarios**

4. *So What* : **What are the first insights ?**

CCEM : Coupling Five Coarse Models with System Dynamics



4 instances
- Oil
- Gas
- Coal
- Clean

M1: Energy Production

delay
delay
inventory
capacity
revenue

M5: Ecological Redirection

Unknown Model
IPCC Forecasts

Societal Pressure
catastrophes
protectionism
Land Use
crises
Rate of CO2
Temperature Water rise

M2: Energy Consumption

Conso
Price
renouncement
redistribution
needs

M4: Economy

CO2 emissions
GDP/ person
Food/` person
demography
Steel
Equivalent Consumption
Wheat
GDP
Energy Invest
Growth Invest
Investments

M3 : Energy Transition

CO2 tax
delay
cost
cancel
substitution
savings
Tech Progress

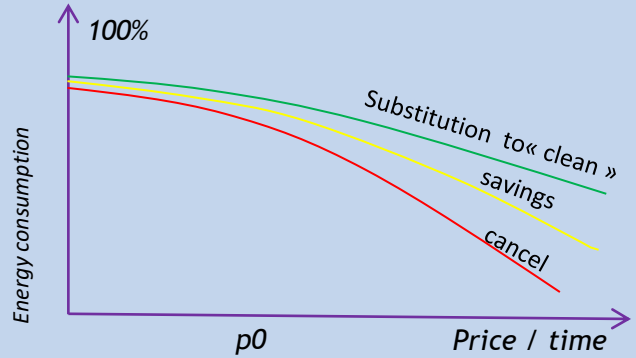
4 instances:
- US
- Europe
- China
- Rest of World

Part II - CCEM Overview

M1/M2 : Energy and M4:Economy

Energy Model

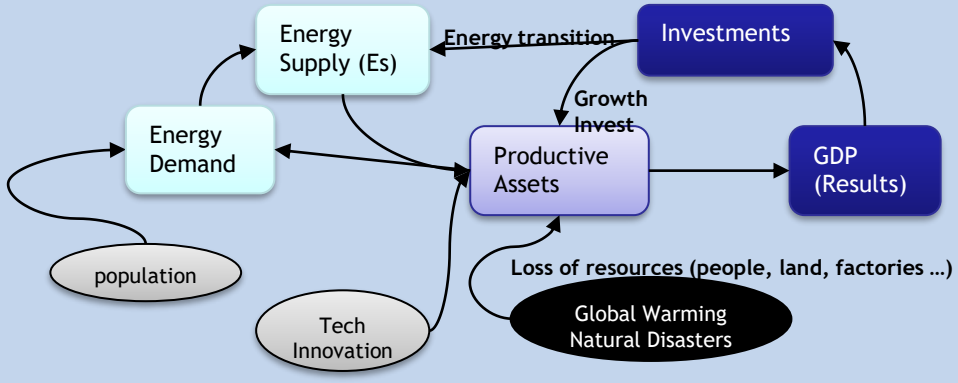
- A crude model for energy inventory (reserves) for fossil fuels & capacity evolution
- A crude mode (KNU) about the speed at which may be deployed
- A demand elasticity model that includes sobriety (chosen), efficiency, transition and cancellation (forced sobriety)



- CCEM matches demand & supply with macro price setting.

Economy

- Economy is seen as a set of productive assets that require energy and human capital to operate
- Economy growth require investments that are a fraction of results

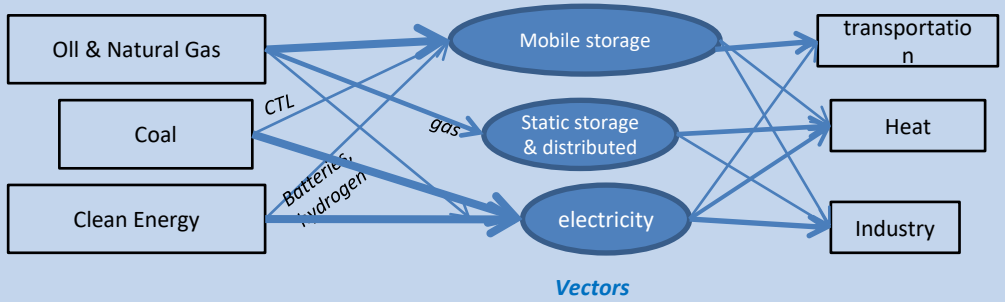


- This model is applied to 4 “Blocks” : US, CN, EU, RoW
- To represent the “material economy” we use two “proxies” : steel and wheat productions

M3 (energy transition) & M5 (Ecological Redirection)

Energy Transition

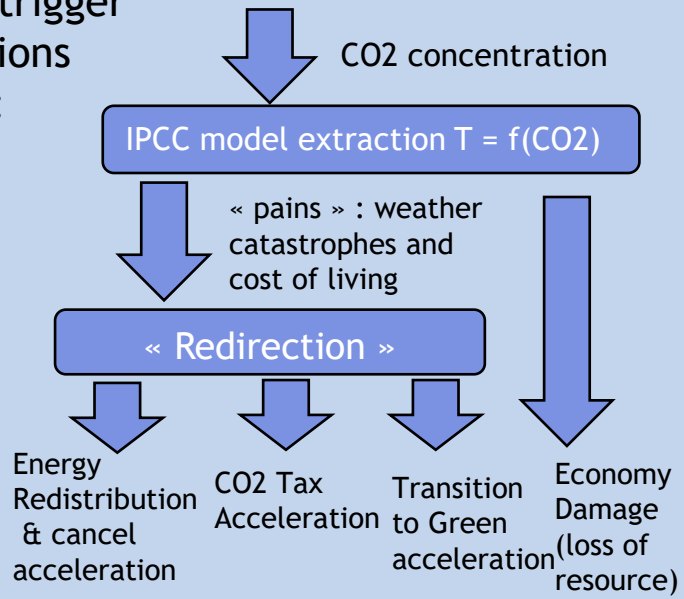
- CCEM uses a transition matrix that reflects how fast can energy consumption migrate from one primary source to another
- This reflects the use of hydrogen, but mostly the speed of electrification
- Country blocks may choose their transition speed



- CCEM bears similarities with WITNES climate model
  - Energy is critical to produce value
  - Transition map defines possible landscape

Redirections

- CO2 emission is computed from energy consumption by sources (adjusted)
- CO2 concentration is a naïve linear model
- Temperature follows IPCC RPCs
- Damages will trigger societal reactions as pain grows:



CCEM : Six KNUs (*Key kNown Unknowns*)

- These 6 KPI provide the best characterization of the CCEM "known unknowns"
  - what creates the heavier debate, for instance speed of Clean energy growth vs fossil reserve
  - These KPI can be compared with other published values from prospective institutes ☺
  - When looking at a simulated forecast, **one should always ask for these 6 hypotheses**

Clean Energy Growth Rate

KPI1: PWh added in 10 years

Default value : 13 PWh

IRENA 1.5C scenario: 25 PWh

Energy Intensity

KPI2: CAGR decrease of E/GDP

Default value : 1.2% (2010-2050)
1.4% between 1990 and 2022

IRENA 1.5C scenario: 2.7%

Energy to price elasticity

KPI3: long-term elasticity demand to price

Default value : -0.3

Values from Reed : -0.05 short-term and -0.3 long-term

Electrification of Energy

KPI4: electricity(TWh) / total energy

Default value : 48% in 2050
16% in 2020

IRENA 1.5C scenario: 80%

Return on Investment

KPI5: world average of RoI
(yearly GDP increase / investment)

Default value : 9.3% (2010-2050)

Calibrated from past + guess ☺

Global Warming Impact

KPI6: GW damages, as % of GDP for +3C

Default value : -6.7% at +2.6C
approximate SCC at 270$/t

Values picked from Schroders: -8% at 3C

Part III

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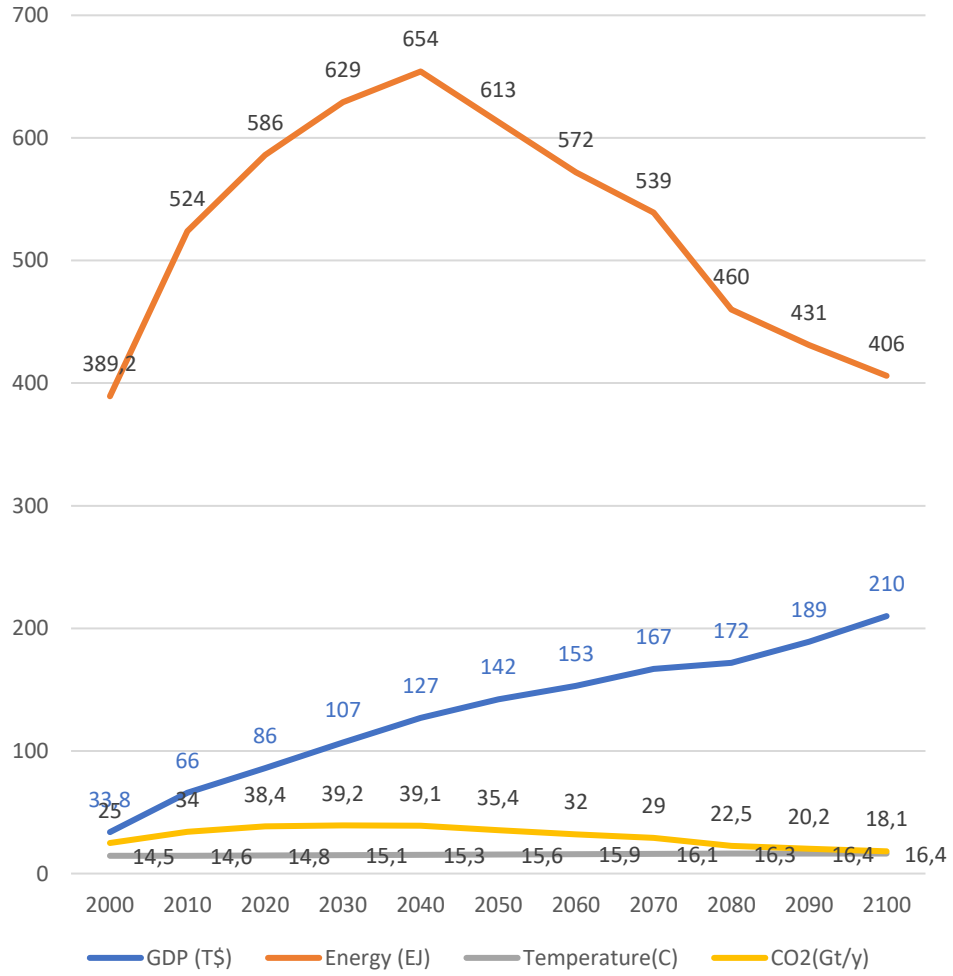
“Median KNU Belief” Scenario (WIP)

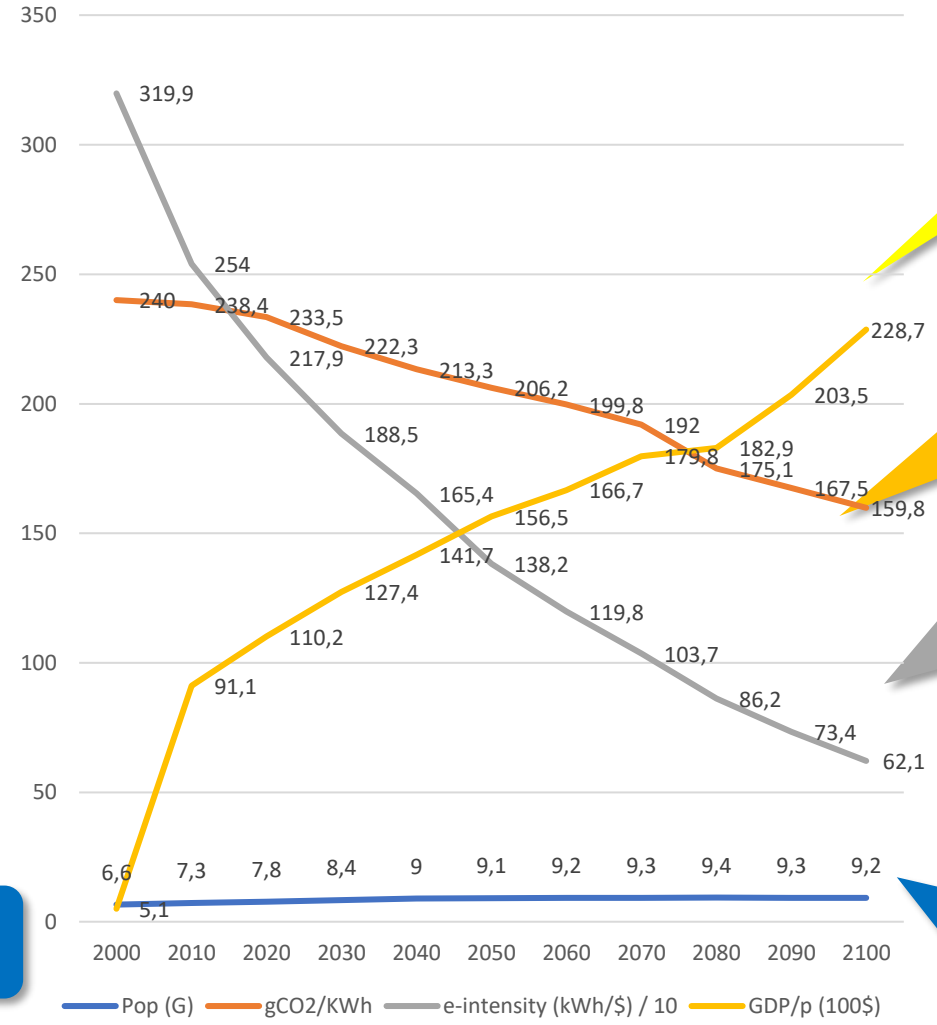
$$F = P \times \frac{G}{P} \times \frac{E}{G} \times \frac{F}{E}$$

Median Scenario



CO2 @ 582ppm

Kaya Identity



Beware of “immaterial ” dollars

Inertia of non-electric fossil energy

Growth of immaterial service economy

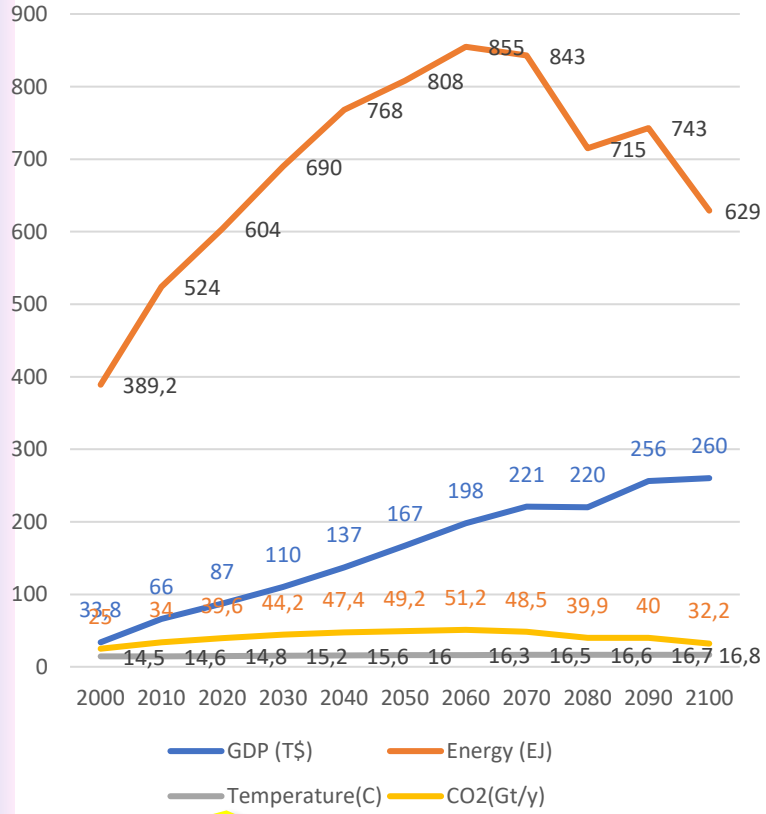
Reflects latest forecasts

Part III - Preliminary Results

Exploring Beliefs (without redirection)

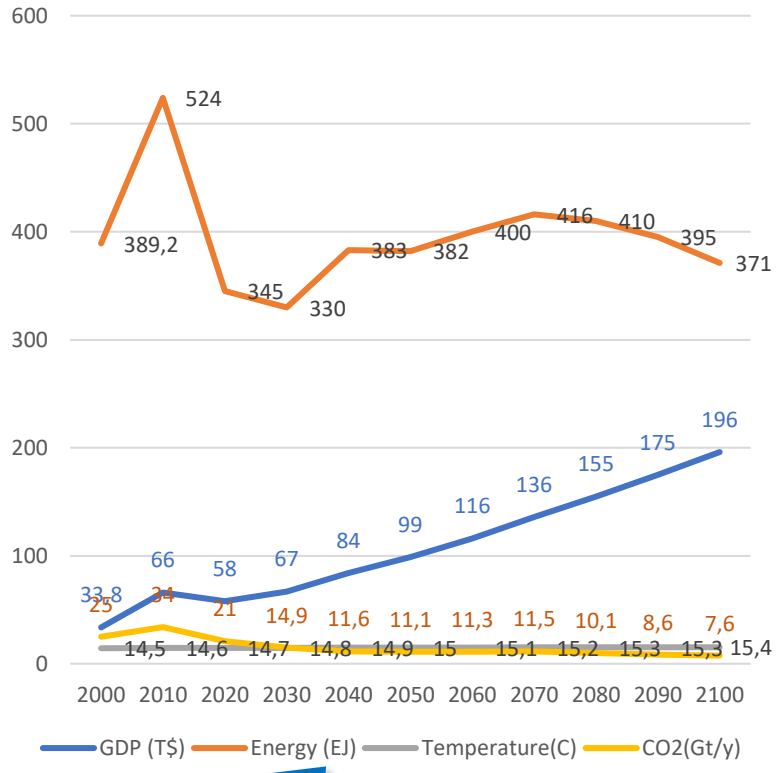
- These are the outcomes associated to three ”typical” sets of “beliefs”.

Energy-Rich Scenario (+2.9 C°)



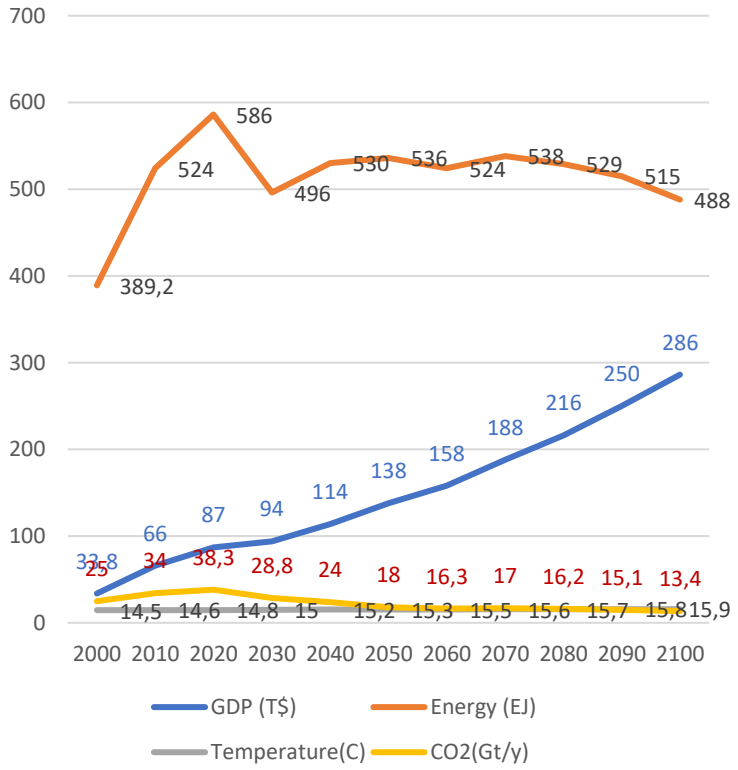
High estimates of fossil reserves
Coal production constant growth allowed
Moderate transition efforts

"Stick to Paris Agreement" (+1.5C°)



Block Coal production growth,
sets a high CO2 tax at 400+$/t
accelerate green transition
promotes sobriety through regulation

Exponential Technologies Scenario (+2C°)



More efficiency gains and accelerated
cost of technology decline
Accelerated energy transition
Moderate CO2 tax (300)

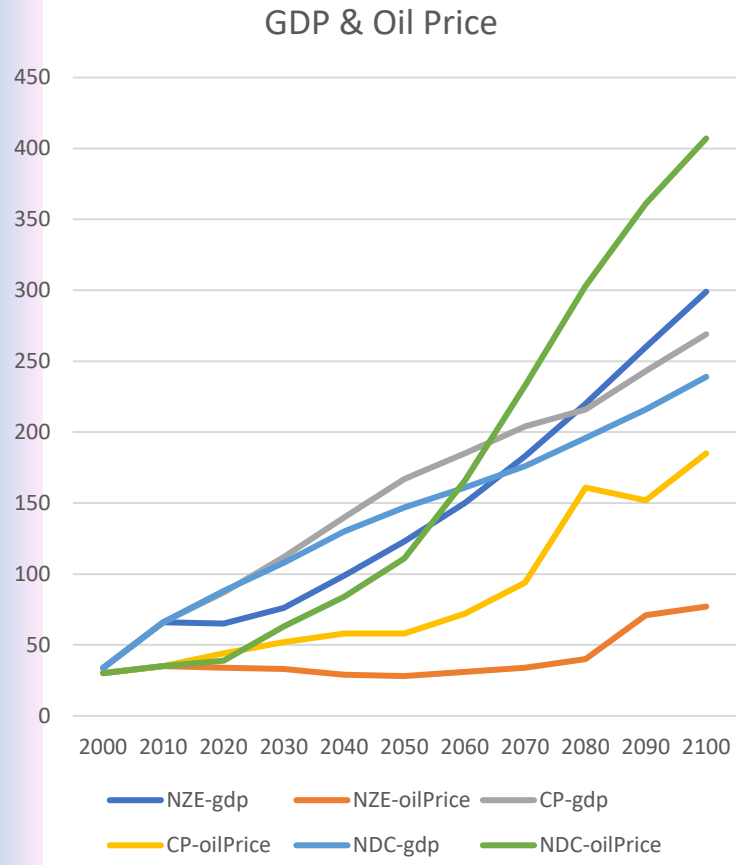
NGFS-inspired scenarios

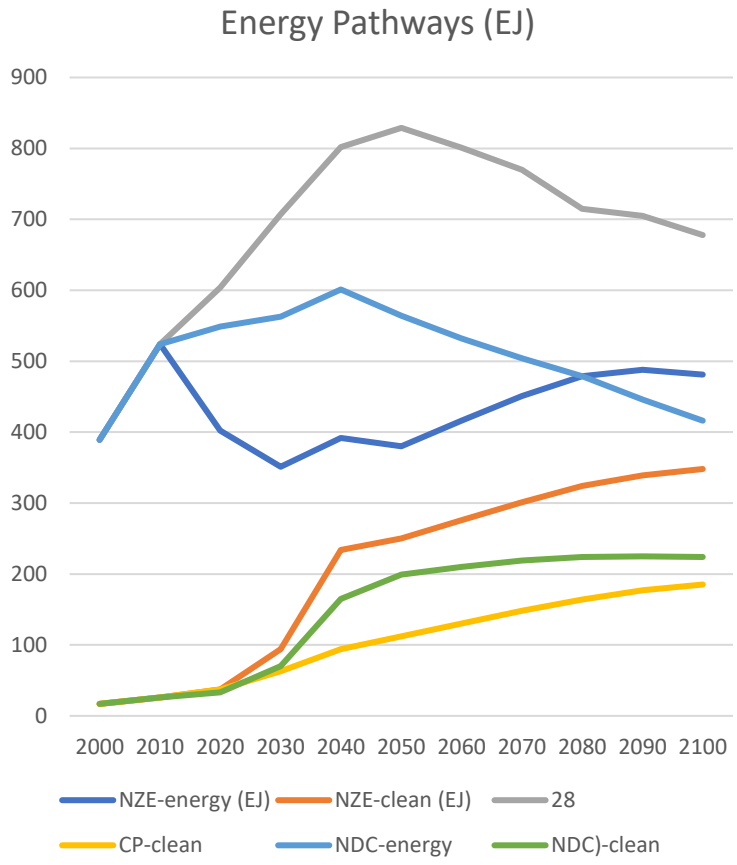
- Attempt to reproduce NZE (carbon ”neutral”), CP (business as usual) and NDC (expected policies)

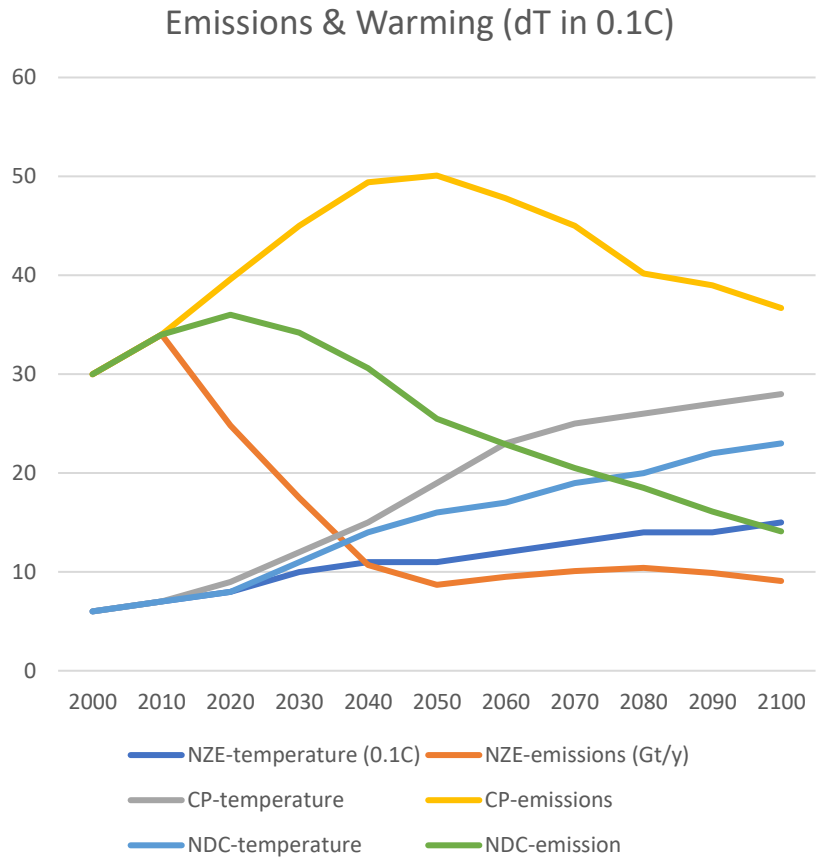
Need Energy Hypotheses aligned with IRINA or EIA (NZE) plus Aggressive dematerialization
+1.5C

Similar to previous “BAU” with improved fossile inventories
+2.8C

Implementation of carbon tax tp increase transition with ”more realistic” energy source viscosity
+2.3C (no sequestration)







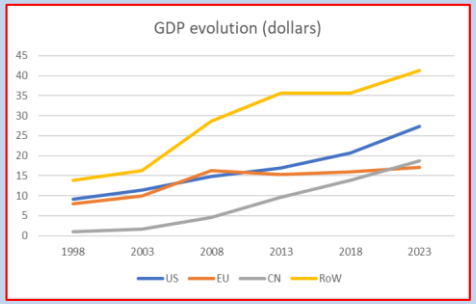
Sensitivity & Redirections Analysis

Sensitivity Analysis & Randomization

- Energy prices will rise significantly, with geography-dependent impact on economy
- Under current IPCC hypothesis about T/CO2 sensitivity, +2.5C (+/- 0.5C) is the most likely hypothesis
- Carbon taxes are efficient to accelerate transition and reduce CO2 emission, but at a cost which makes global adoption very unlikely (e.g. China)
- The most important factor is the viscosity of the energy transition (cf. examples)
- The second-most is the dematerialization trend, but it affects more GDP (including immaterial economy) than material economy (steel & wheat).

Redirection

- Acceleration of sustainable energy capacities in Europe does not improve much global CO2 (rebound)
- Europe's lead on carbon tax has no effect on global CO2, it is a self-sacrifice towards others (same reason)
- However, accelerating towards green energy is a good move for Europe to regain long-term competitiveness



- CO2 taxes have a strong effect, more important than what NIGEM predicts, especially for China (the less dematerialized the economy, the bigger the impact)

Part IV

1. *Why* : Yet Another Integrated Assessment Model ?
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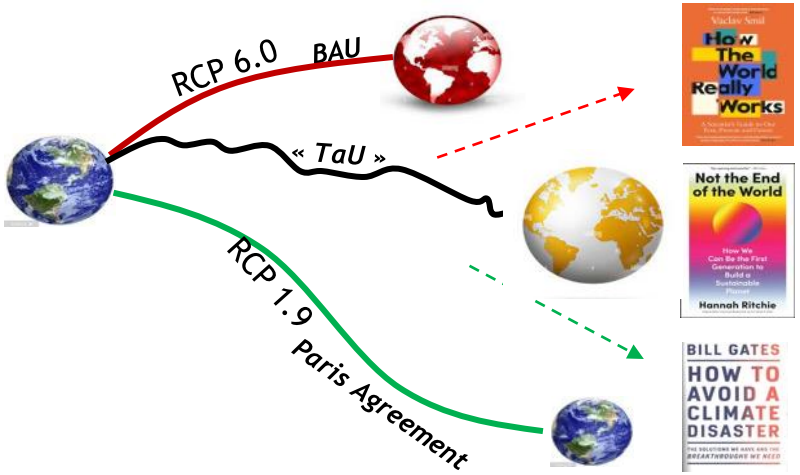
4. *So What* : **What are the first insights ?**
   - **A possible new narrative of global warming**
   - **Next Steps**

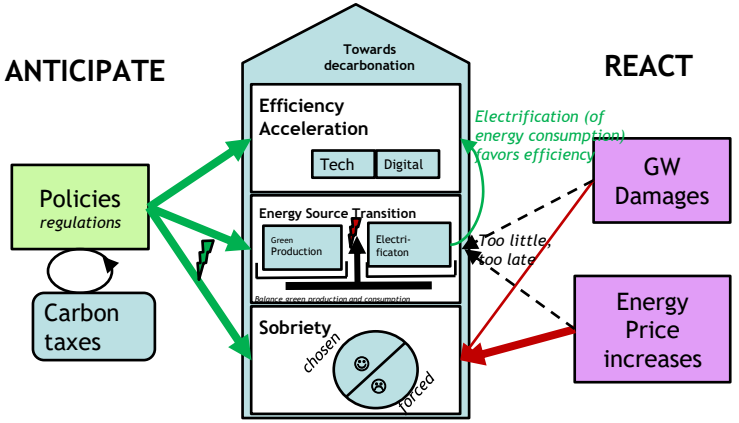
A “new narrative”:

Avoiding stress as a motivator, Avoiding a promise that we may not keep

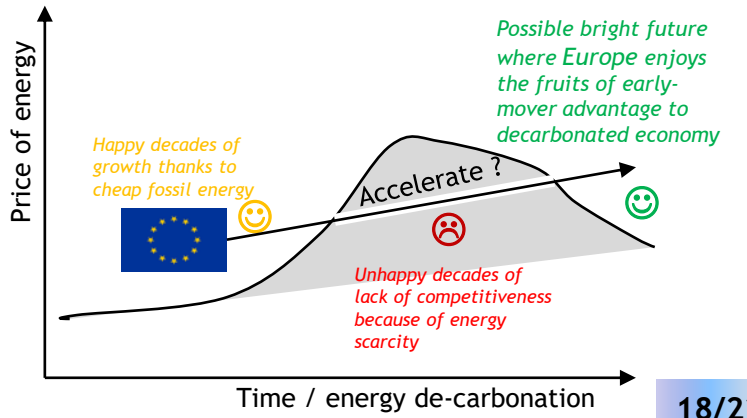


- « **Transformation as Usual** » :
  The world strategy could be « adaptation until mitigation is cost-optimal »

- **Anticipate versus React** : Energy sobriety will be forced upon us either way
  Anticipation has a cost, but it broadens the cone of possible mitigation



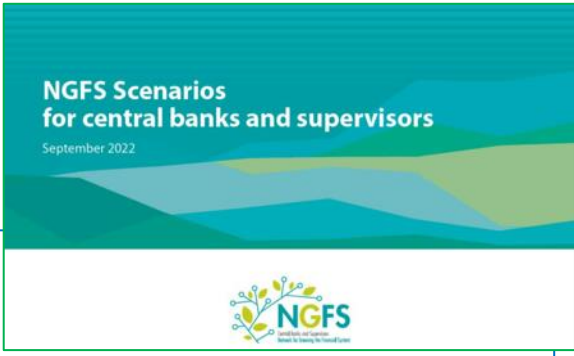
- **Europe playbook** :
  Accelerate anticipation to get out faster from « the pricey fossil fuel tunnel »
  Not to avoid the end of the world, but to avoid the end of Europe (as a major economy player)



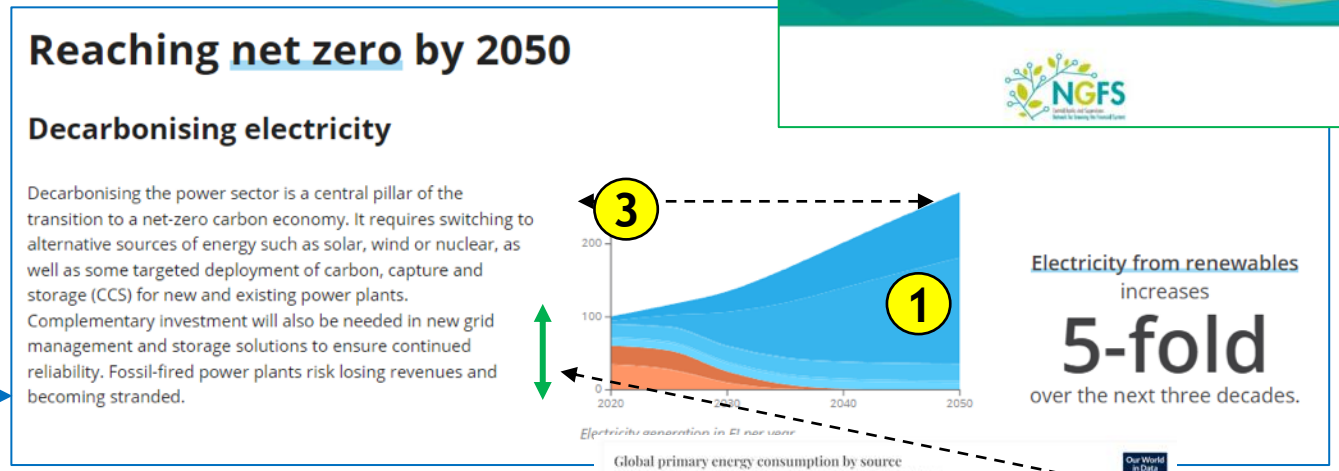
Possible Insights for Michelin

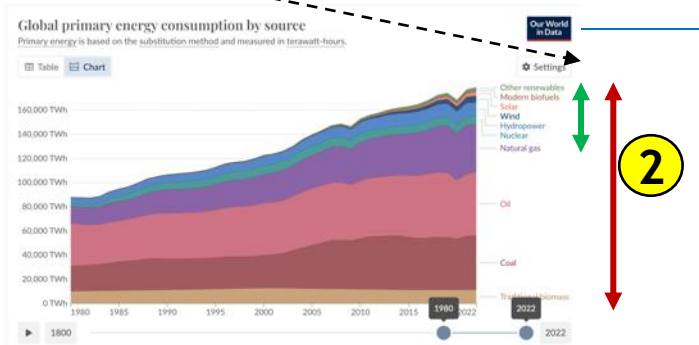
- **Energy prices will rise significantly**
  - Energy source transition is a must
  - Price increase both from scarcity and taxes
  - No longer a free market, large zone discrepancies (already started, intensified with conflicts)
- **Temperature will rise, impacts to be expected**
  - « *Paris Agreement is deader that a doornail* » - James Hansen
  - Impact will vary very strongly according to geography
  - Being conservative is smart :
    - ➔ CO2 pathways are probably exaggerated / pessimistic …
    - ➔ But CO2 to temperature rise could be under evaluated (reinforcing loops, especially at 2100 and 2200 horizon)
    - ➔ Global warming impacts estimates are very complex (hence IPCC qualitative assessments)
- **Prepare for surprises and redirection** (political reactions pushed by societal fears)
  - Ex: Ban on heavy cars for some geography
  - Ex: Water restriction for factories during draughts
  - Ex: CBAM : Carbon Border Adjustment Mechanism

NGFS Scenarios for central banks and supervisors

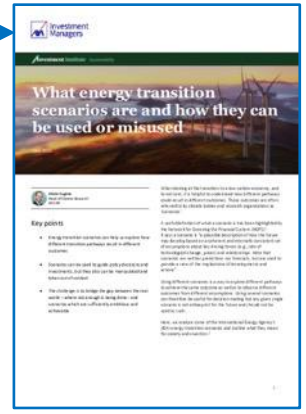


- Produced by the best IAM teams in Europe…
- **… With a purpose / message !**
- **Net Zero** (and its cousins)
  - Similar to IEA NZE …
  - Search for the three « amazing beliefs » in this illustration ☺




Global primary energy consumption by source
Primary energy is based on the substitution method and measured in terawatt-hours.
Our World in Data
Table
Chart
Other renewables
Modern biofuels
Solar
Wind
Hydropower
Nuclear
Natural gas
Oil
Coal
160,000 TWh
140,000 TWh
120,000 TWh
100,000 TWh
80,000 TWh
60,000 TWh
40,000 TWh
20,000 TWh
0 TWh
1980
1985
1990
1995
2000
2005
2010
2015
2022
1800
2
1. Rate of green electricity growth
2. Electrification (otherwise green electricity has small impact)
3. Total amount of energy available for economy (*you better believe in dematerialization economy !*)

  - As noticed in AXA IM Note « ***What energy transition scenarios are and how they can be used or misused*** »



- **Hot House World**
  - BAU scenarios (pessimistic bordering on unrealistic)
  - Damage model is strongly opiniated

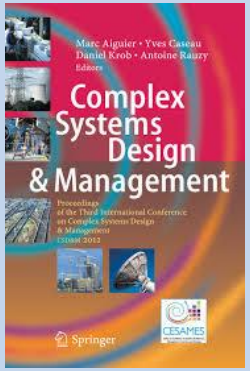
Next Step: Global Warming, Geopolitics and Game-Theory

Evolutionary Game-Theory

- Do not assume that blocks have similar goals …
- What is the benefit of an "EU green policy" facing D. Trump and Xi Jinping ?
- Is there an anticipation benefit ? ("suffer earlier, suffer less") ?
- What are the levers for player to influence each others (trade barriers, CBAM, …) ?
- Could world population indignation yield a significant systemic change ?

GTES

- A Method developed 15 years ago for Telco markets equilibrium
  - 3G and 4G licenses
  - Free introduction
- Combines
  - Monte-Carlo simulation for uncertain KNU (from curves to cones)
  - Local optimization for tactical adaptation (BR)
  - Search for Nash Equilibriums

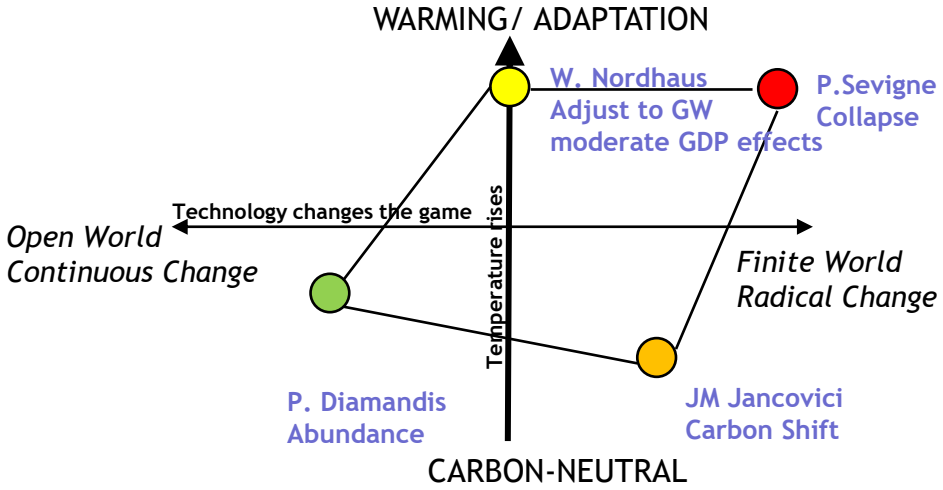


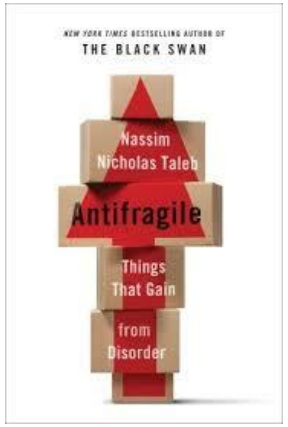
Strategy = goals for each zone
GDP, Pain level, World temperature

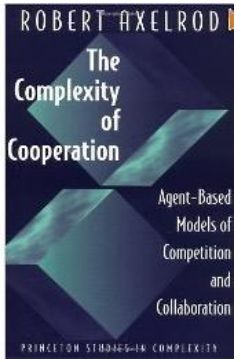
Conclusion

- A tool to explore beliefs (mental models) and their combined effects
  - Tune your own mental models from simulation feedback loops
  - Way of use : beliefs → simulation → one outcome *that seems possible* (then repeat)
  - **Antifragile** System Dynamics Modeling: Grows from criticism and conversations

- **Five Key question (Key Known Unknown)**
  - What is a plausible energy trajectory ?
  - What is a plausible elasticity scenario, so that demand lowers to possible supply ?
  - What is the best course for Europe, with other players with a different agenda ?
  - *What is the expected outcome of +2.5C warming ?*
  - *What is the best way to adapt (to protect ourselves) ?*







Appendix

https://github.com/ycaseau/GWDG

M1 to M5 Model Overview

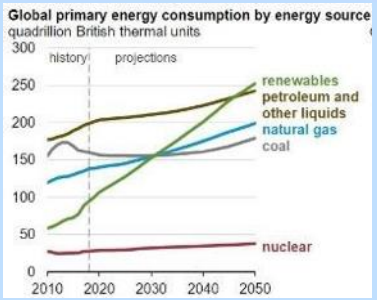
- Coupling of 5 “coarse” models
- M1 to M5 Overview
- Computational Results

CCEM : Addressing Five “Known Unknowns”

« ***How much energy will be available in the future ? At which costs?*** »

Example:
At which speed can we add clean energy in the next 30 years ?

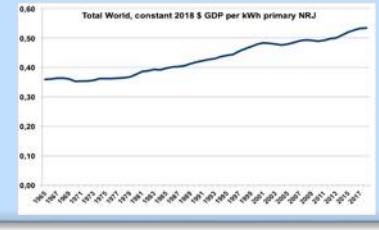
EIA



« ***How much energy is needed and acceptable for the economy at a given cost ?***»

Example:
- How much energy subvention must/can governments afford ?

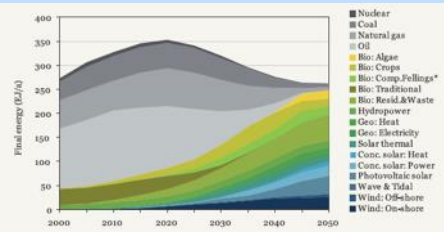
Energy To GDP



« ***How fast can we substitute one form of primary energy to another ?*** »

Example:
What is the possible speed of transition fossil>green for industry ?

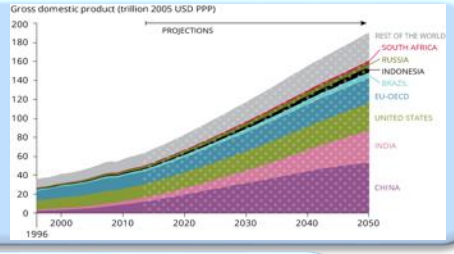
2050 Eco transiti Plan



« ***which GDP growth can be expected from investment, technology, energy and workforce ? »***

Example:
Impact of reduced energy availability on economical output ?

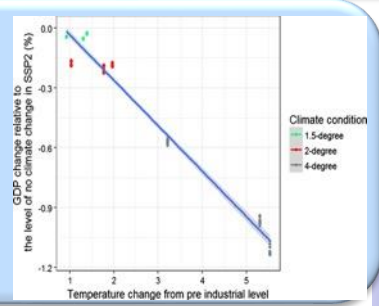
GDP 2050



« ***What will be the economical and societal consequences from the IPCCs predicted global warming ?***»

Example:
- which damage to productive resources ?
- Which redirection caused by fear ?

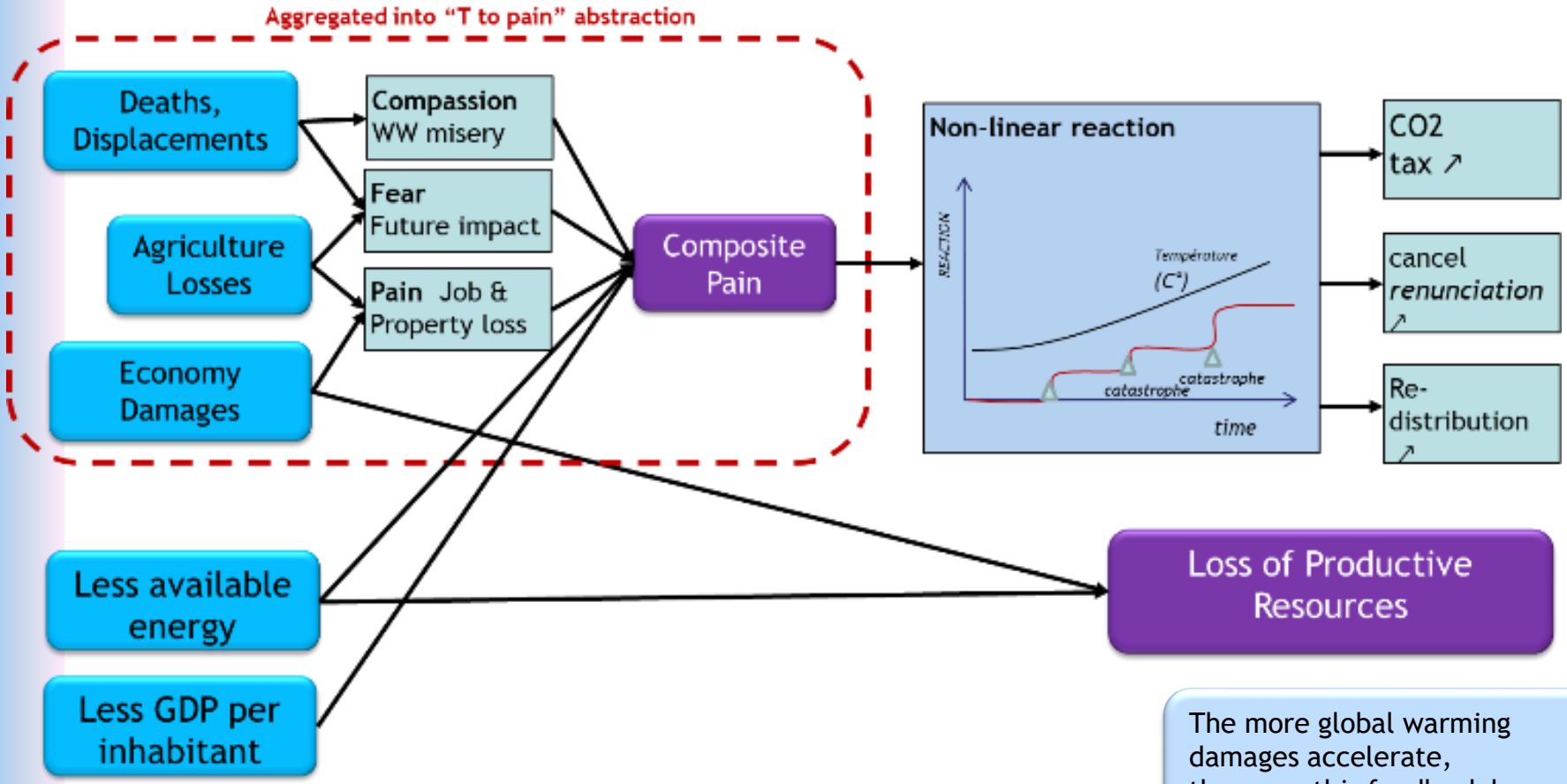
Temp to GDP loss



Part I - Why ?

Ecological redirection

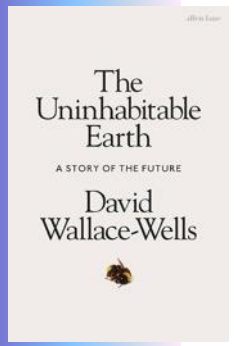
Redirection (Bruno Latour) – think of the future world evolution as a set of bifurcations (choices/reactions), not a planned transition

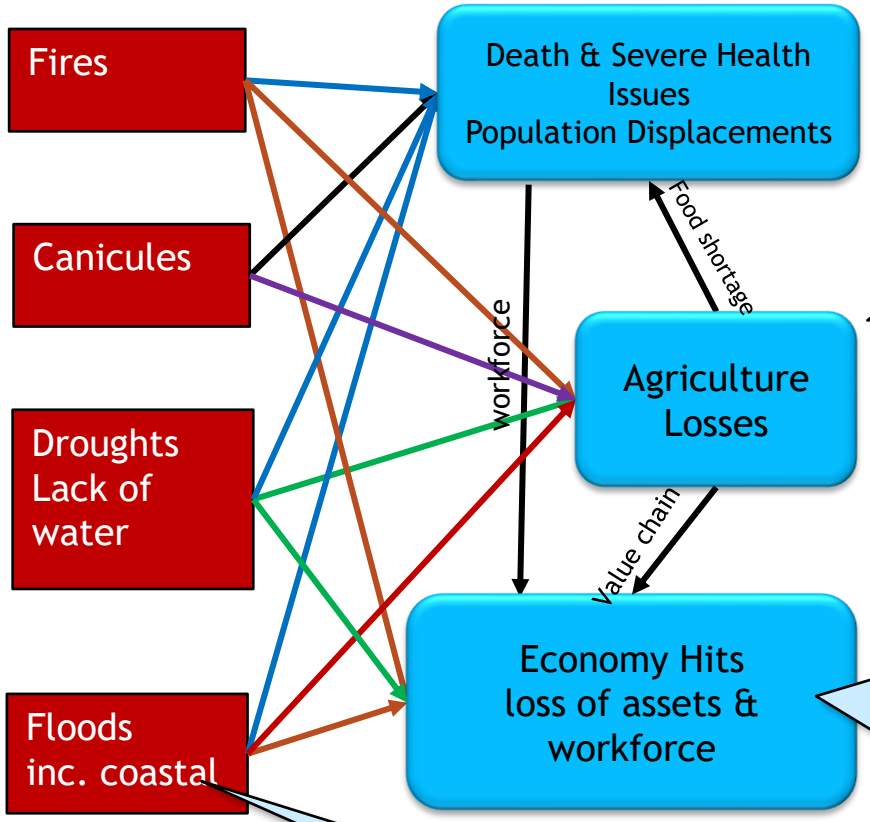


- M5 : The second category of feedback loops (*warming to world actions*)
- IAMs without theses loops are bound to be misleading

The more global warming damages accelerate, the more this feedback loops matter

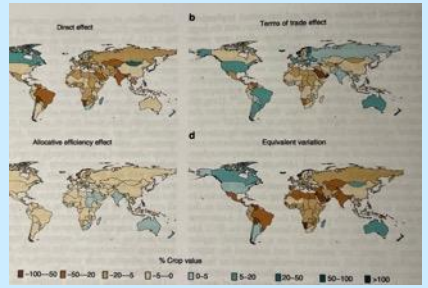
Global Warming Damages





Cromar et al.,
Systematic Reviews, Annals ATS, July 2022

New science of climate change impacts on agriculture implies higher social cost of carbon. Frances C. Moore, Uris Baldos, Thomas Hertel, Delavane Diaz, Nature Communications, 8:107



- The economics of climate change: inaction is not an option - April 2021 - Swiss Re Institute
- **The impact of climate change on the global economy - Wade and all, Schroders, 2016**
- The economic implication of climate change – June 2019 - Moody's Analytics
- The Social Cost Carbon Explorer - GIVE Model - RFF-Berkeley Green House Gas Impact Value Estimator

Simplified categories of impacts

- Destruction of properties
- Health – loss of productive workforce
- Lack of water
- Loss of agricutural surface
- Loss of efficiency

•Diaz, D.B. Estimating global damages from sea level rise with the Coastal Impact and Adaptation Model (CIAM). Climatic Change 137, 143–156 (2016).
•Anticipating Climate Change Across the United States! 2023, Adrien Bilal, Esteban Rossi Hansberg

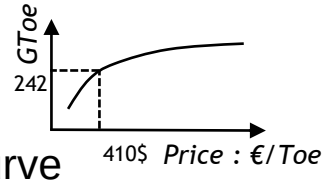
Energy Resource Model (M1)

M1 captures the answer to the questions « ***How much fossil resources do we have ? At which costs?*** »

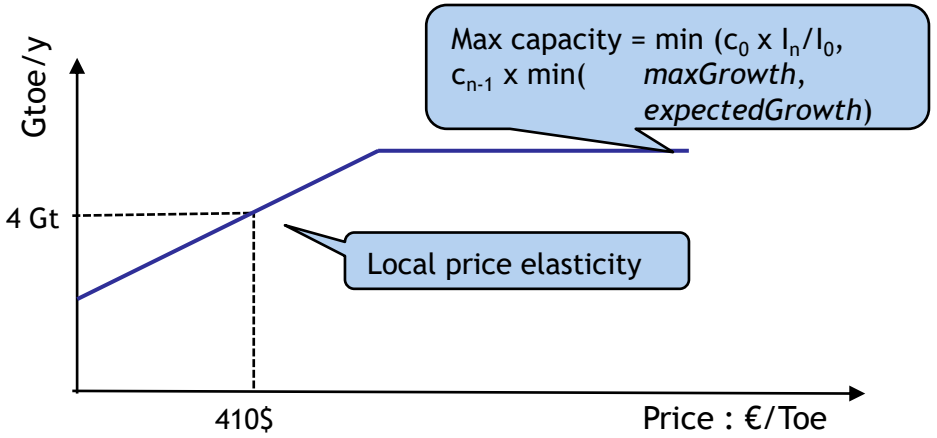
Four categories

- Oil
- Natural Gas
- Coal
- Clean (hydro/solar/wind/nuclear)

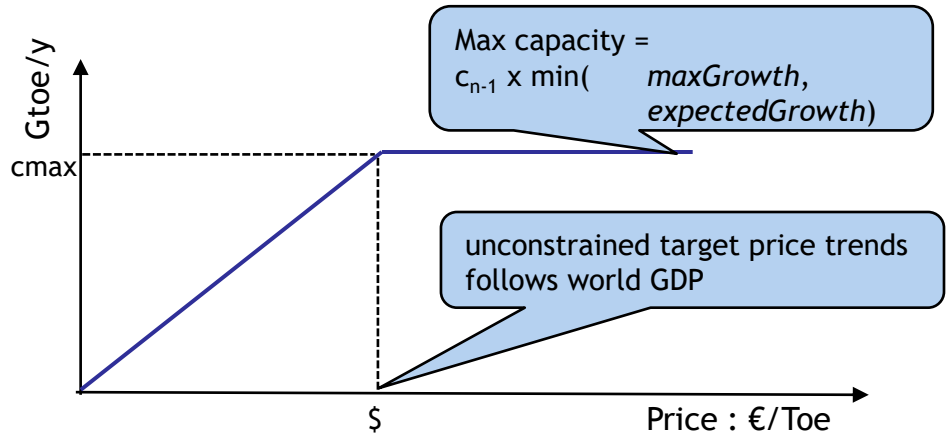
Each resource is defined through:



- For fossil energies, its *inventory chart* (available Toe according to sell price)
- For clean energies, a *growth potential* curve (max capacity in the future year, according to manufacturing and resource constraints)
- A “max capacity” (max yearly output)
- A constraint about the speed at which this capacity may evolve + a heuristic formula that adjusts the capacity each year



Fossil Fuel Production = f(price)



Clean Energy Production = f(price)

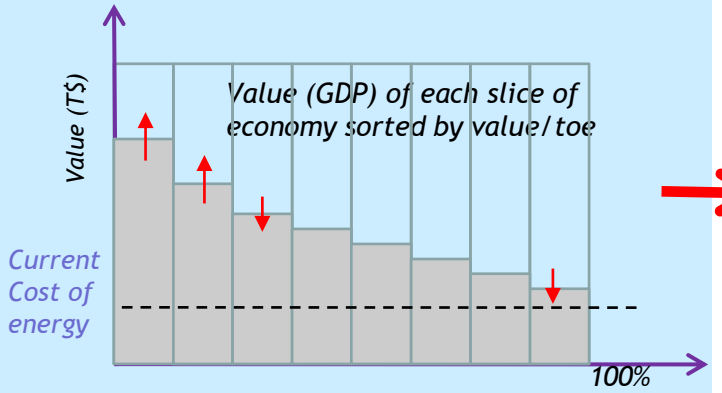
Energy Consumption Model (M2)

M2 captures the answer to the question

« ***How much energy is needed for the economy at a given cost ?***»

The heart of this model is (for each source & each zone) a histogram of value production:

- Decomposition of value product (Y axis)
- Over "segments" of energy usage (X axis), sorted by energy intensity
- This (virtual) decomposition is the base for telling how each world zone will react to price increases



Evolution of distribution represents the dematerialization of the zone economy (kW/$)

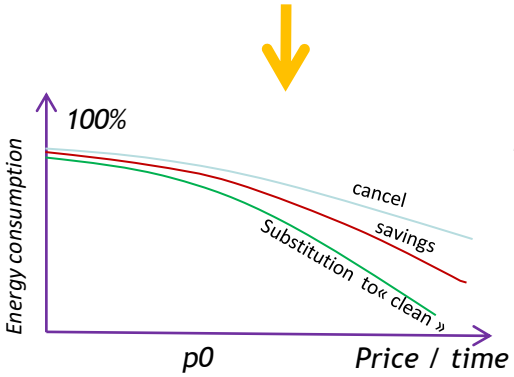
The net behavior is represented by four curves :

- Economy dematerialization trend (kW/$)
- Cancelation (% of activity that stops because price is too high)
- Economic loss due to cancelation (GDP impact of cancel)
- Margin reduction

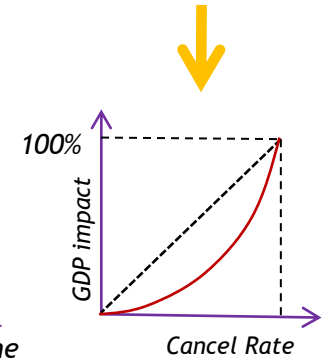
In addition, we represent the expected efficiency gains:

- "Savings" (energy efficiency) – reduction of consumption at iso-activity
  - *Savings are a "policy" (decision ahead of time that gets implemented)*
- Substitution towards another form of energy (using the matrix provided by M3)
- The last two options triggers associated investments

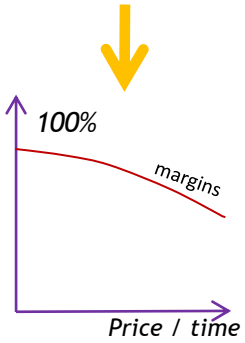
Energy redistribution policy is a factor that lowers the pain of cancellation but reduces the economic efficiency



Energy consumption for a given price decreases according to cancelation (upper histogram), energy savings and substitution (M3: one energy source to another)



The loss of economic value due to Energy-based cancellation follows a convex law (lower value creation activities stop first)



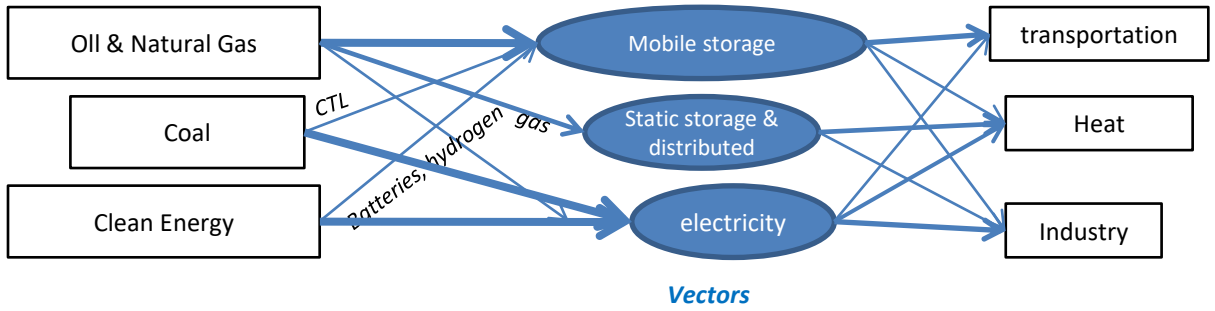
Margins for surviving activities are reduced by increasing energy prices

Energy Transition Model (M3)

M3 captures the answer to « ***How fast can we substitute one form of primary energy to another ?*** »

Substitution matrix

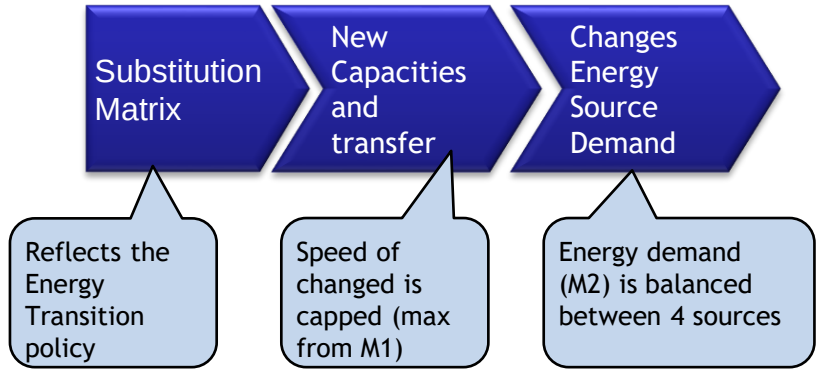
- Oil to Coal to Gas to Clean
- 6 flows (N x N-1 / 2)
- A substitution matrix as 6 coefficients (share of energy consumption that should be transitioned), depending on year (policy)
- The matrix takes into account the “source to vector” possible paths (cf. illustration)



The substitution matrix describes which substitution is feasible & desirable from an energy policy viewpoint (on the demand side)

- Irreversible
- When acted (a given year), generate the associated Investment (same for savings)

Note: *Models M1 / M2 focus on primary energy sources, M3 takes the energy vectors (electricity, hydrogen, …) into account to define which transitions are feasible*



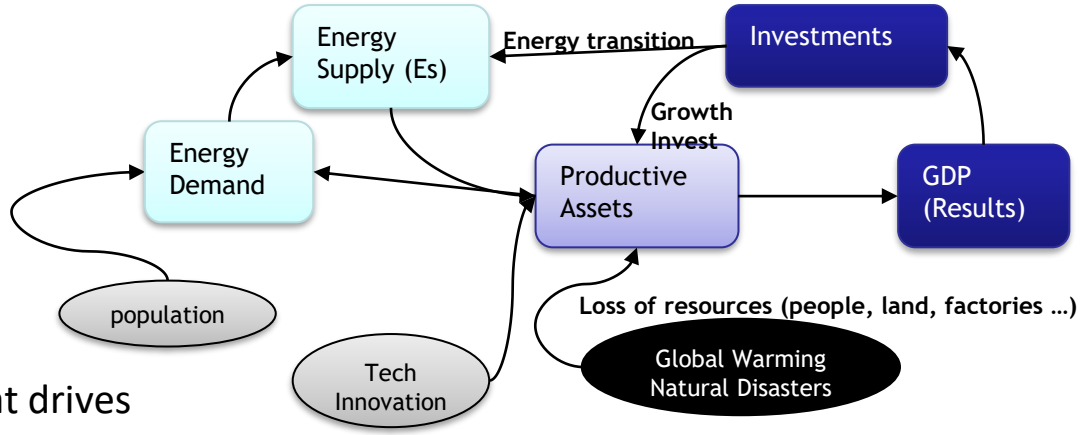
GDP Model (M4, World Economy)

M4 represents the question:
« ***which GDP is produced from investment, technology, energy and workforce ? »***

Description

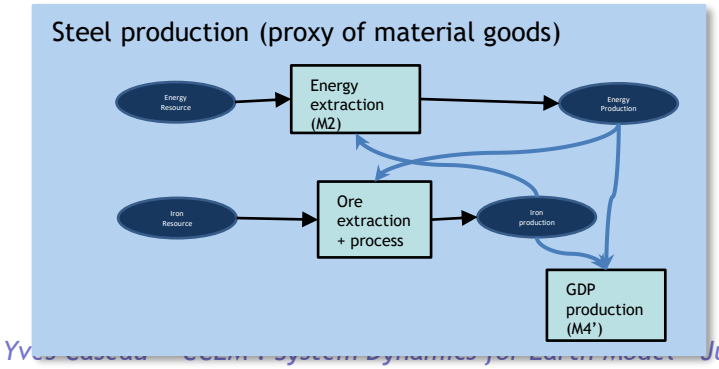
Economy is seen as a set of productive assets that require energy and human capital to operate

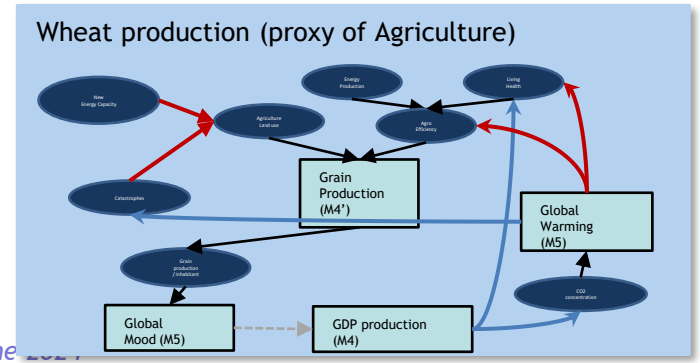
Economy growth require investments that are a fraction of results

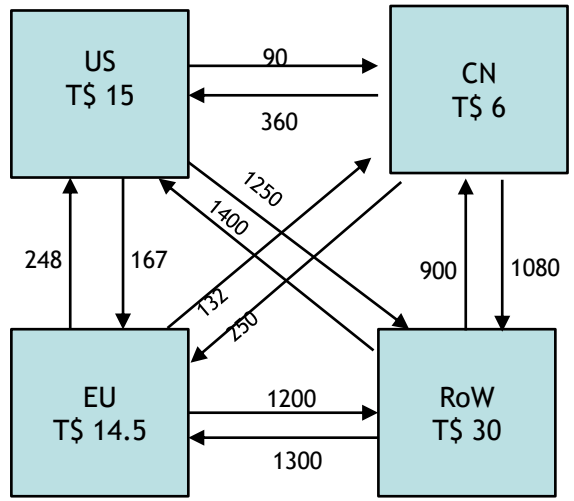


We use a crude exponential growth model

- The model computes the consumption without savings that drives the GDP and the consumption with savings that drives CO2 emissions
- This model is applied to 4 “Blocks” : US, CN, EU, RoW
- To represent the “material economy” we use two “proxies” : steel and wheat productions





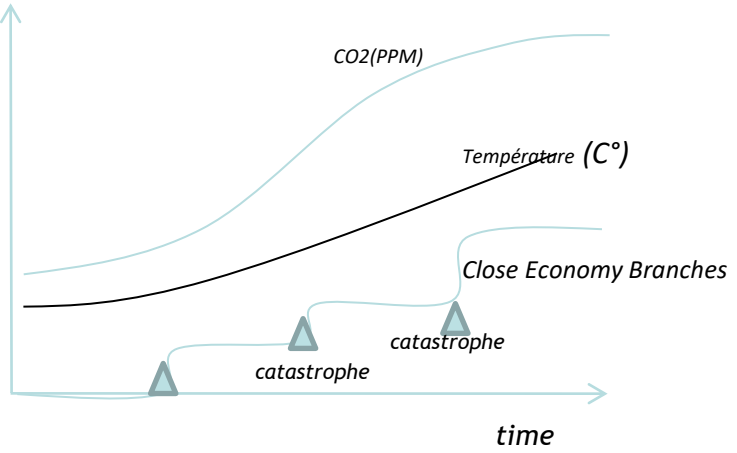


2010 world economy crude decomposition (trade in G$)

Ecological Redirection (M5)

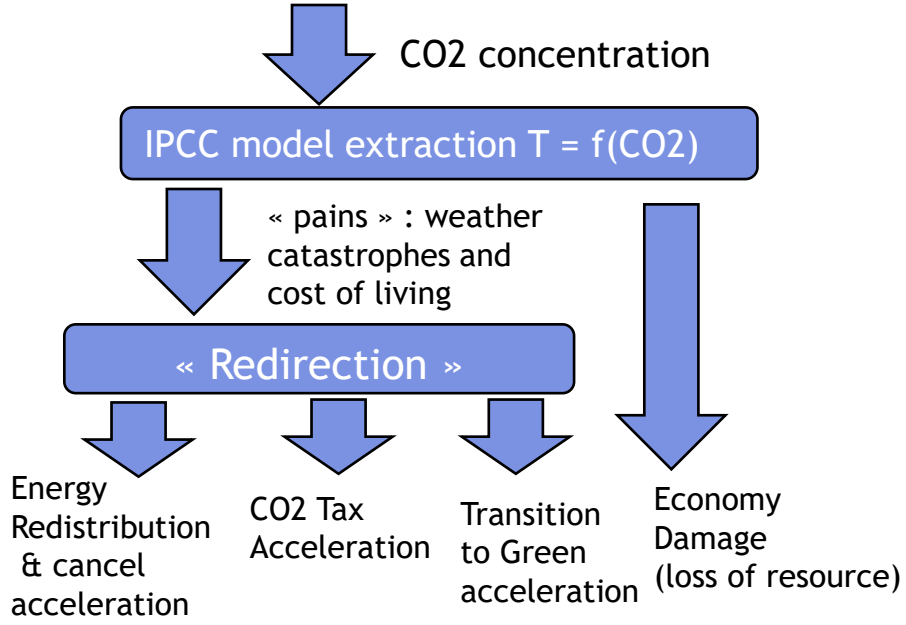
M5 answers the question « ***What kinds of redirection should we expect from the IPCCs global warming consequences*** ?»

Bruno Latour's **redirection** concept tells that this is a non-linear coupling.
There is no "point A to point B" trajectory, but reactions along the way, based on the catastrophic events that will unfold



M5 is made of three components:

- A simple projection from IPCC to link CO2 output (from M2-M3) to expected temperature rise (using RCP 4.5, 6 and 8.5)
- A random, discrete function that define "pain thresholds" as CO2 & temperature rise
- A redirection model (very naïve) with three components
  - Increase into energy redistribution (feedback to M2)
  - Increase CO2 tax (versus planned trajectory)
  - Economic crisis (feedback to M4)
    - ➔ Production capability damaged by warming (e.g. agriculture)
    - ➔ Workforce disruption (from strikes to massive death tolls of natural catastrophes and wars)



Three drivers : fear (of future production loss), pain (less revenue) and compassion (disaster happening elsewhere)