DRAFT

CCEM :
Coupling Coarse Earth Models

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March 2023

Latest update : March 24th, 2023

Outline

In Memoriam

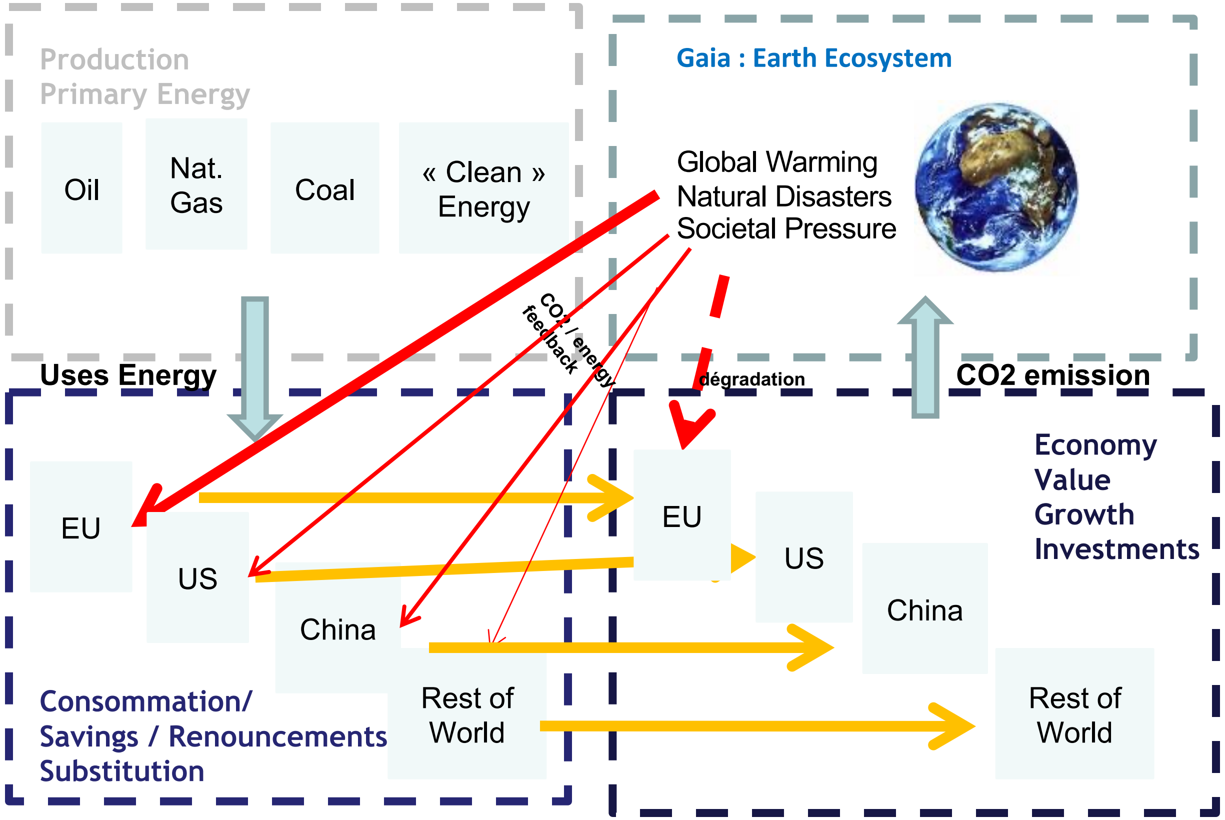
Paul Caseau

1. Why : Global Warming Dynamic Games
2. M1 (first model): Energy Resource Model
3. M2: Energy Consumption Model
4. M3: Energy Transition Model
5. M4: GDP Model
6. M5: Ecological Redirection Model
7. Coupling these five models (M1 to M5 together: CCEM)

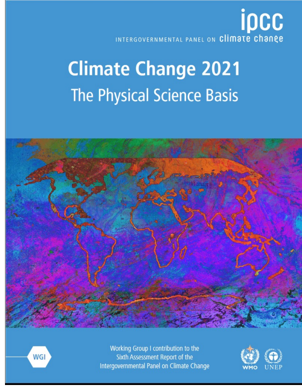
Global Warming Dynamic Games

William Nordhaus (Wikipedia)

- **Global Warming Games** : (Wikipedia Definition)
  A **global warming game**, also known as a **climate game** or a **climate change game**, is a type of serious game.
  As a serious game, it attempts to simulate and explore real life issues to educate players through an interactive experience
- Our CCEM model looks at the interaction between five "coarse" models:
  - Energy Production
  - Energy Consumption
  - Energy Transition (fossil fuel to clean)
  - Economy (value from energy)
  - Ecological Redirection : reaction of society to the outcome predicted by IPCC
- My goal is to produce a « serious game » using GTES
  - You select a block (continent)
  - You select a strategy
  - GTES plays the role of the other players
  - Multiple scenarios based on beliefs about peak oil, energy transition and reserves.



Global Warming Dynamic Games: Preliminary Roadmap



- 2008-2009: GWDG v1
- 2020 – 2021 : foundations (CLAIRE 4)
- 2022 : GWDG v2
- 2023 : CCEM
- 2024: GTES/Game

Two goals for CCEM (2023):

- clear/formal presentation (feedbacks / criticisms)
- Meta-model that is wide enough to « capture »:
  - W. Nordhaus
  - P. Diamondis (Singularity)
  - JM Jancovici (Shift Project)

Warning !
GWDG (CCEM as a tractable and meaningful computational model) feasibility is only a hypothesis at this point
Iteration of despair & insights … will converge or not ☺

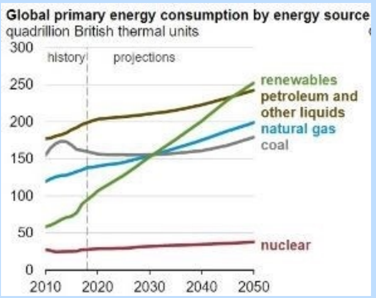
« Coarse Model »: capture beliefs into a simple computational model

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 ?

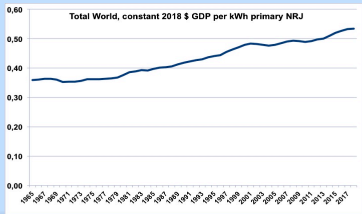
EIA



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

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

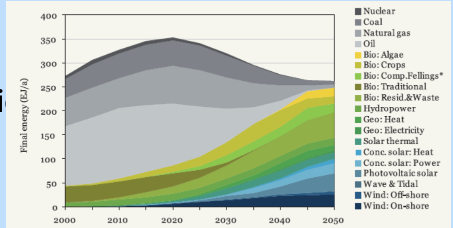
Energy
To
GDP



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

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

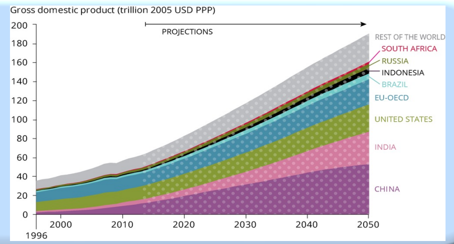
2050
Eco
transiti
Plan



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

Example:
Impact of reduced energy availability on economical output ?

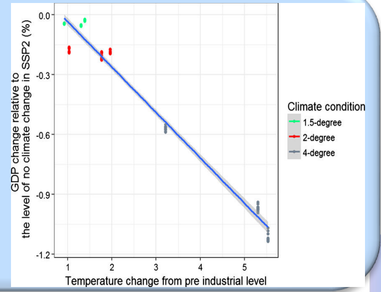
GDP
2050



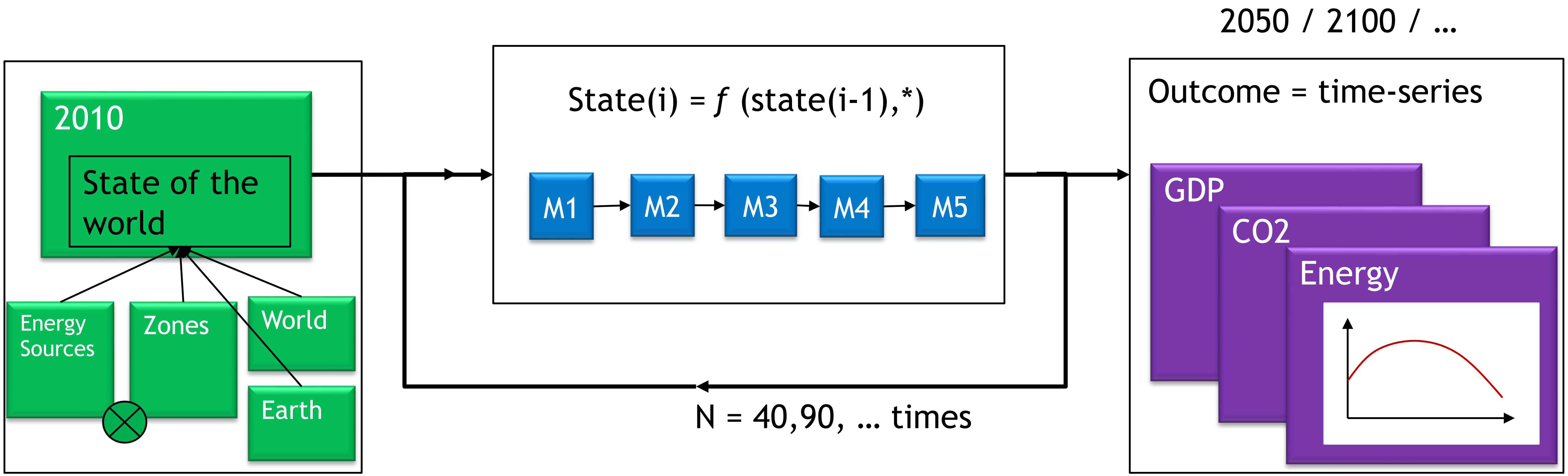
« What will be the economical and societal consequences from the IPCCs predicted global warming ?»

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

Temp
to GDP
loss



CCEM : Simulation Model



- Each model M1 to M5 represents a discrete one-year difference equation
  - Inputs: some of the state variables (at year n – 1)
  - Outputs: some of state variables (M1 to M5 partitioning)
  - 10 to 30 lines of code (each)

CCEM : From Beliefs to Simulation to Outcomes

True value : revisit your beliefs from observing outcomes

What you Give as An input

Beliefs
- Energy assets
- Savings roadmap
- GDP Energy-elasticity
- Global Warming impacts
- Expected growth if resources

N iterations

Outcome
(make an excel Example)

What you Play with during simulation

Levers
- Energy Transition roadmap
- CO2 Tax
- Redistribution

GTES
Game-Theory Evolutionary Simulation

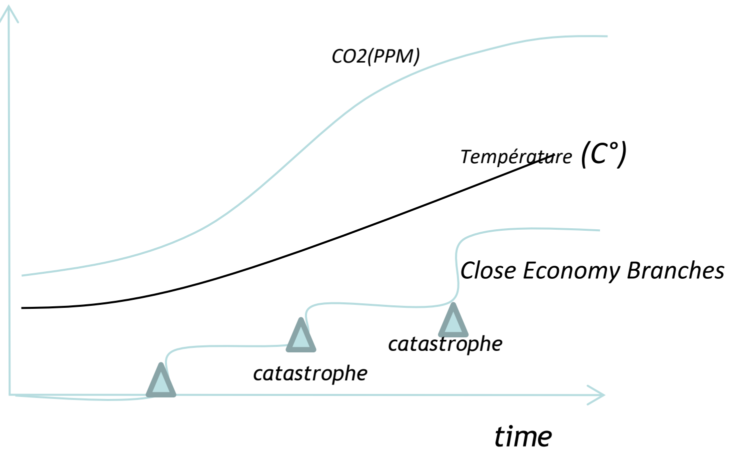
Do not use CCEM if you disagree

Foundations
- CO2 -> temperature (IPCC)
- Assets x Energy -> GDP -> investments -> delta(assets)
- Production to Demand adjust through prices

Ecological Redirection (M5)

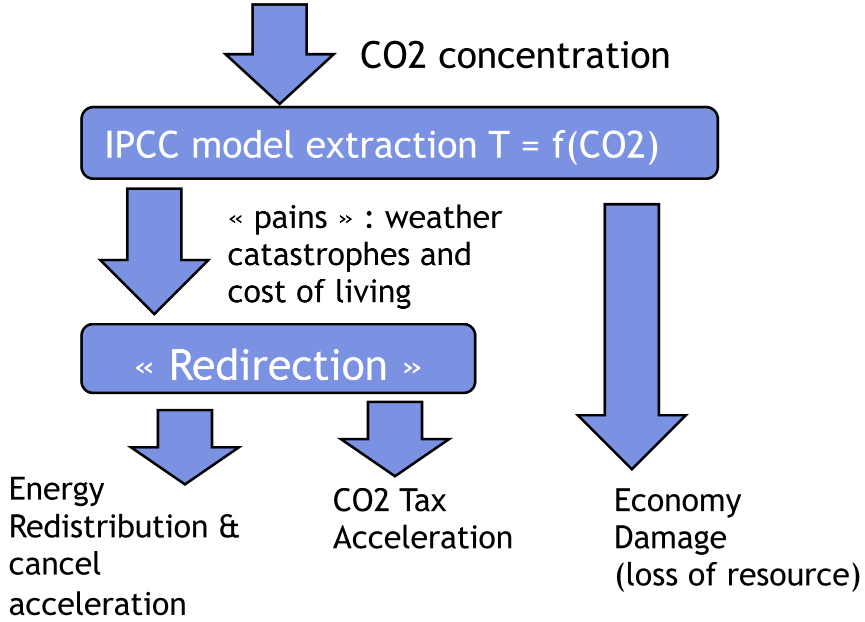
M5 answers the question « ***What kinds of redirection should we expect from the IPCCs global warming consequences*** ?»

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:

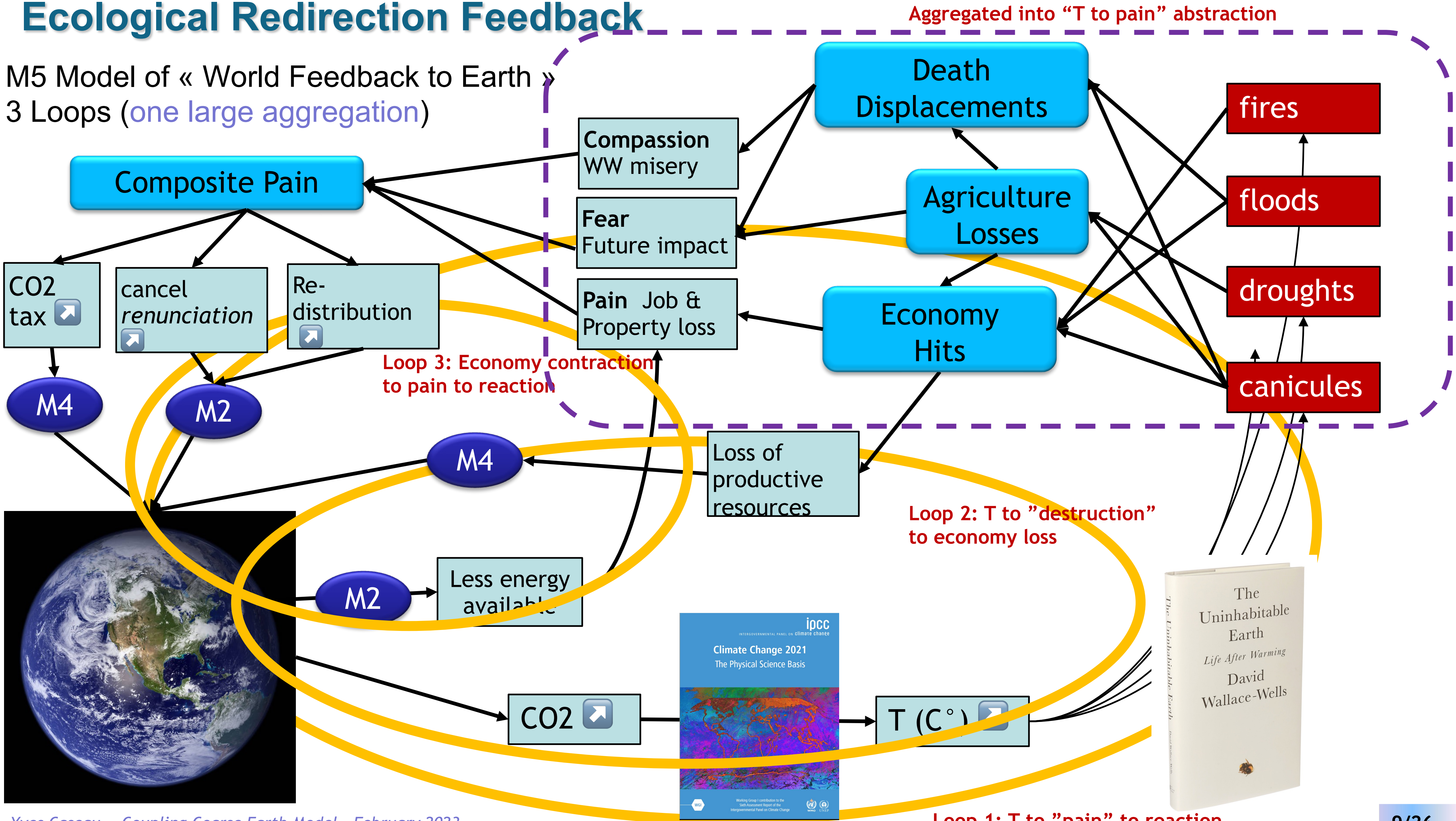
- A simple projection from IPCC to link CO2 output (from M2-M3) to expected temperature rise (using RCP 4.5, 6 and 8.5)
- A random, discrete function that define "pain thresholds" as CO2 & temperature rise
- A redirection model (very naïve) with three components
  - Increase into energy redistribution (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)

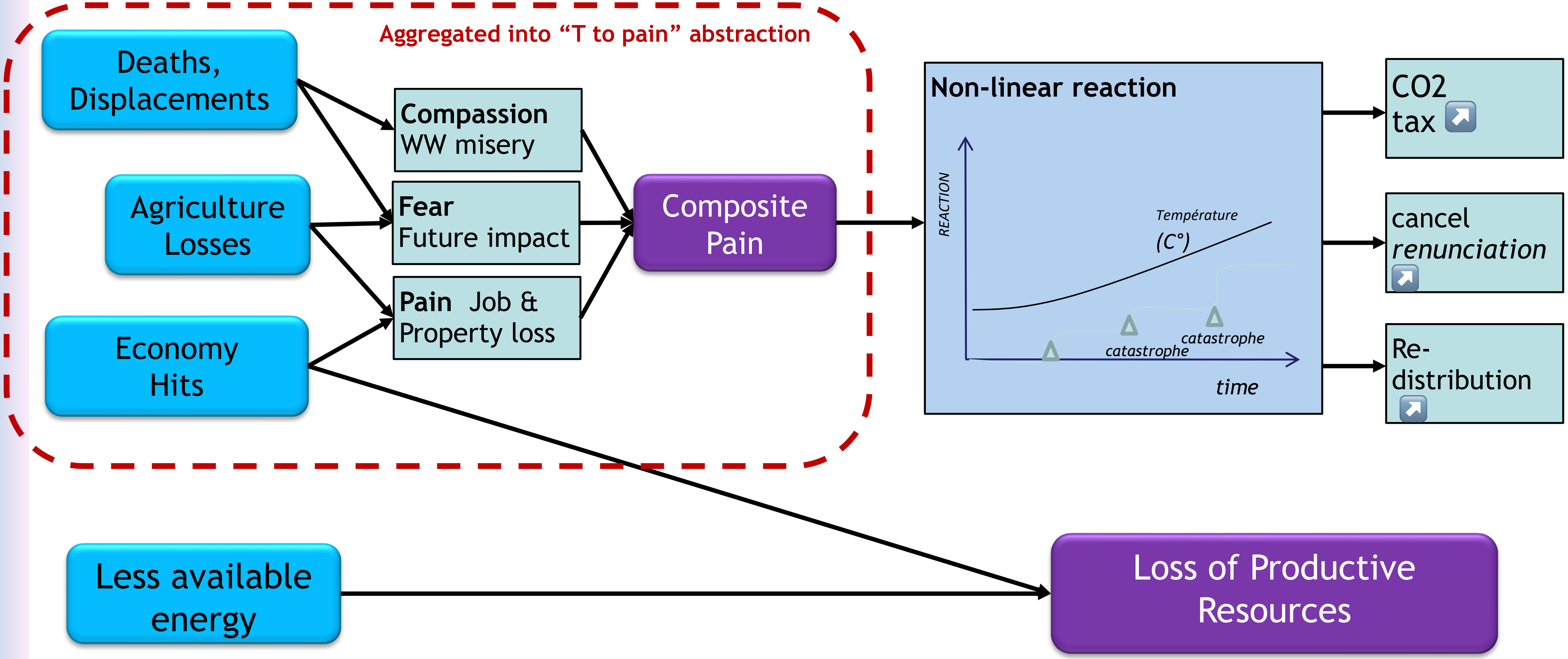


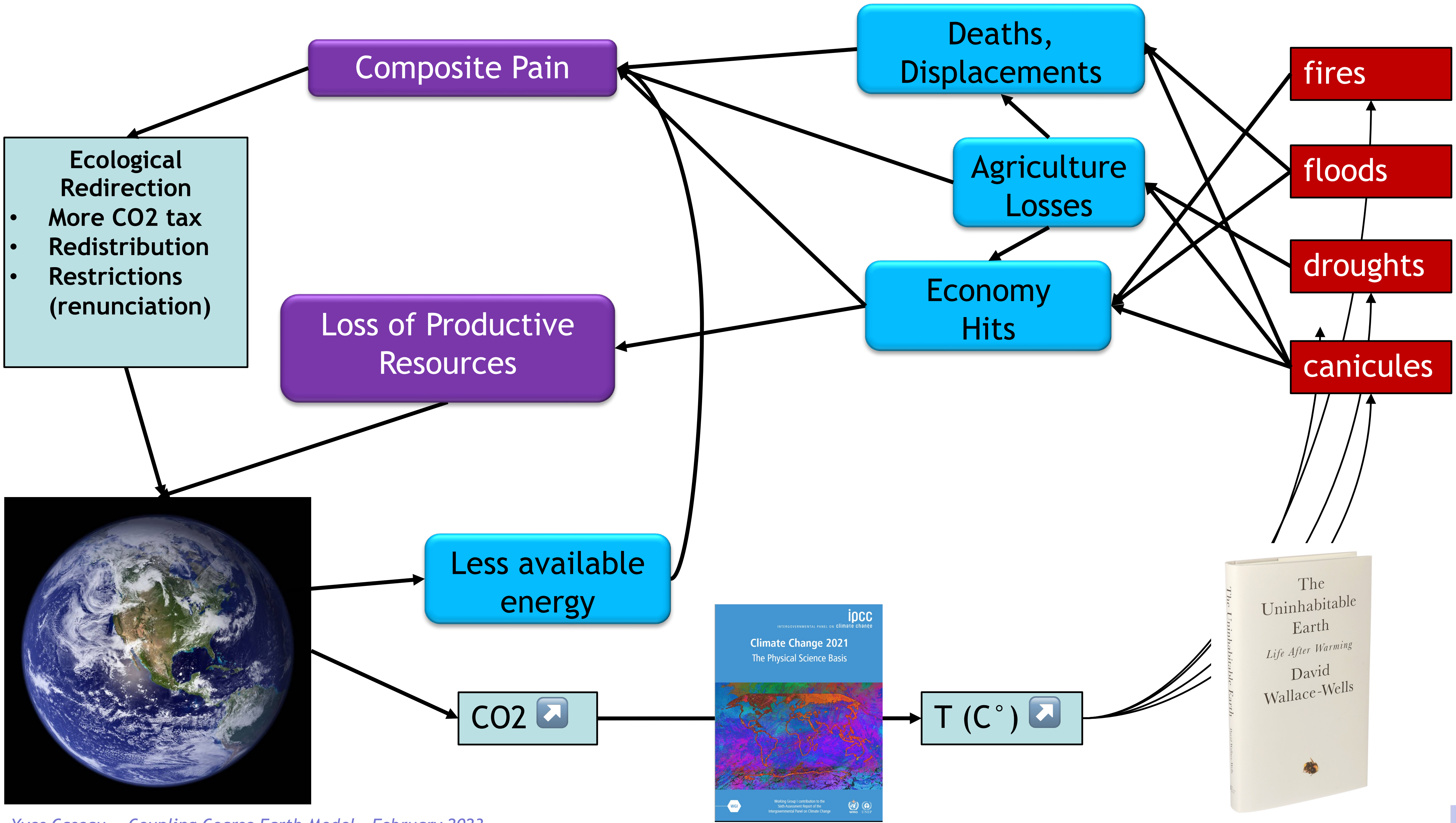
Three drivers : fear (of future production loss), pain (less revenue) and compassion (disaster happening elsewhere)

Ecological Redirection Feedback

- M5 Model of « World Feedback to Earth »
  3 Loops (one large aggregation)



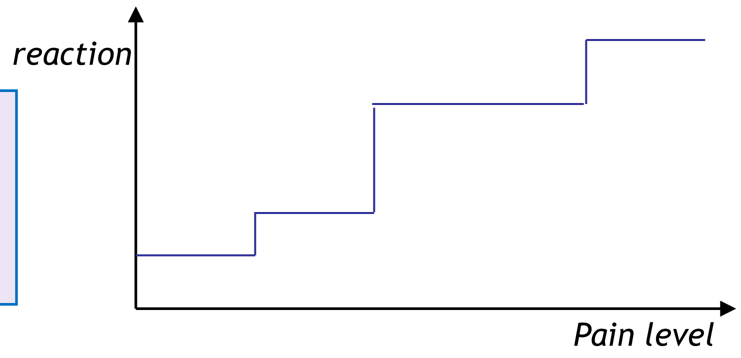

Aggregated into "T to pain" abstraction
Deaths, Displacements
Agriculture Losses
Economy Hits
Compassion WW misery
Fear Future impact
Pain Job & Property loss
Composite Pain
Non-linear reaction
REACTION
Température (C°)
catastrophe
catastrophe
time
CO2 tax
cancel renunciation
Re-distribution
Less available energy
Loss of Productive Resources


Composite Pain
Deaths, Displacements
Ecological Redirection
• More CO2 tax
• Redistribution
• Restrictions (renunciation)
Agriculture Losses
Economy Hits
Loss of Productive Resources
fires
floods
droughts
canicules
Less available energy
CO2
ipcc
INTERGOVERNMENTAL PANEL ON climate change
Climate Change 2021
The Physical Science Basis
T (C°)
The Uninhabitable Earth
Life After Warming
David Wallace-Wells

Ecological Redirection (M5)

M5 Inputs: CO_2 yearly output in the atmosphere

M5 Outputs: Four feedback signals to other models: energy redistribution, CO_2 tax, cancel, damages to economy



Fours steps

- Computes CO_2 concentration in the atmosphere, based on the ability of the Earth to absorb part of it.
  This should be updated to reflect that this ability will probably decline, by works as an approximation
  (CO_2 in atmosphere = CO_2 Output - 16Gt absorbed by forests, soil, ocean, …)
- Use IPCC models to extract the expected temperature rise
  (note : the IPCC hypothesis about CO_2 emissions in time are irrelevant here because they are computed by M1 to M4).
- A "pain level" is derived from
  - Weather : floods, agriculture losses, fires, heat waves, …
  - Economic welfare: based on growth/recessions and cost of energy.
    Note: for the time being, redistribution is only modeled as "energy cost redistribution" –
    Another model M6 would be necessary to represent "economic redistribution / social justice / social unrest"
- Pain drives "random, discrete" reactions (cf. illustration : step-wise pain-to-reaction functions)
  - Energy redistribution factor
  - CO_2 tax acceleration
  - Cancel Acceleration (collective decision to ban some usages)
  - Loss of productive capacities and Loss of productive workforce are also captured through cancellation

Open Question: add a "capital destruction" feedback ? natural disaster repair reduce investments.
Currently, this is captured in the M5->M4 productivity ratio

MSc Strategy and Design for the Anthropocene

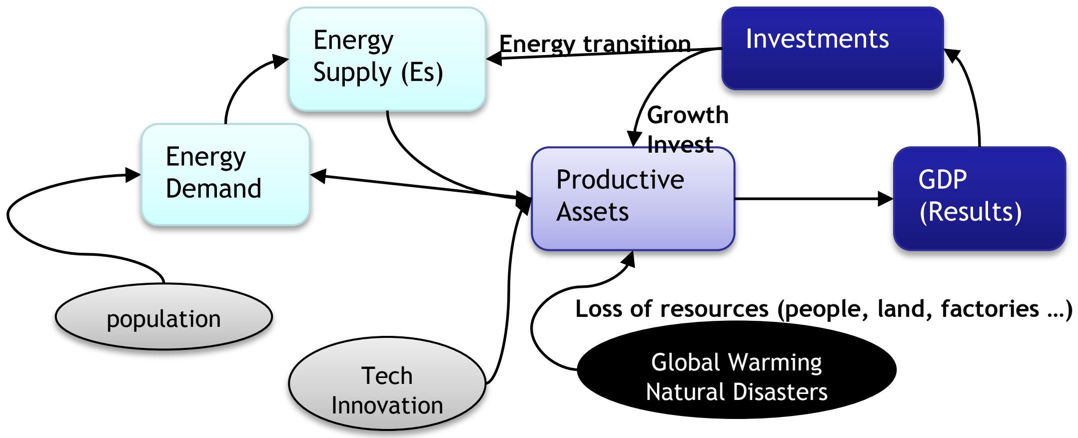
GDP Model (M4, World Economy)

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

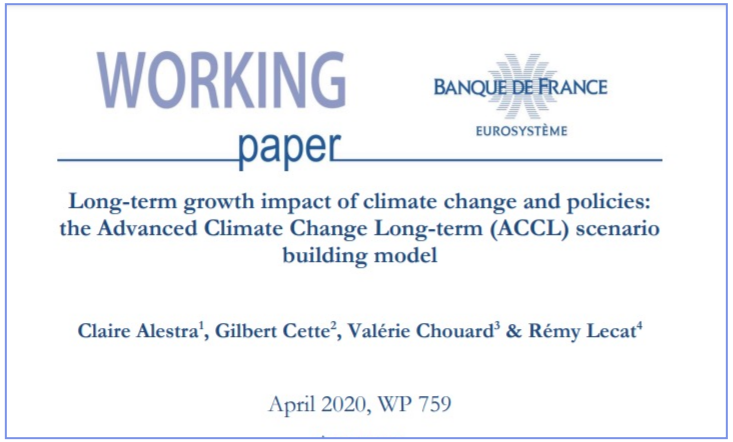
Economy growth require investments that are a share of results



We use a crude exponential growth model

- Output is linked to energy (cf M2 + redistribution)
  - Demography is factored through energy consumption
- Assets grow as a result of investment
- Energy transition investments are subtracted from total investments to compute growth investments
- GW Crises are modeled two ways : a reduction of productive assets and as an acceleration of « cancellation »
- The model computes the consumption without savings that drives the GDP and the consumption with savings that drives CO2 emissions

Open question (cf. O. Vidal) : model the "metal intensity" of value creation, either as a feedback loop for M4 or a constraint for transition (M3)



WORKING paper

BANQUE DE FRANCE
EUROSYSTÈME

Long-term growth impact of climate change and policies: the Advanced Climate Change Long-term (ACCL) scenario building model

Claire Alestra[1], Gilbert Cette[2], Valérie Chouard[3] & Rémy Lecat[4]

April 2020, WP 759

GDP Model (M4)

M4 Inputs: energy consumptions with price levels, for each source and each block.
Energy redistribution ratio (k : proportionality factor)
Energy transition investments

M4 Outputs: GDP (worldwide) and investments level

- Economic result (R = GDP) depends on energy consumption

$$R_n = R_{n-1} \times (1 + Ic_{n-1} \times r) \times (Es_n / Ed_n)^k \times (F_n / F_{n-1})$$

1. The GDP depends on the current level of productive assets, grown from previous year growth investments (r = ROI)
2. The output is adjusted to the actual energy available (Es: supply vs Ed: demand, Negawatts included)
   The exponent k represents the results of energy redistribution
   → without redistribution, k is derived from M2 (energy-to-value distribution), with complete redistribution, k = 1 (simplifying assumption !)
3. The productive assets are adjusted through "global warming disasters" loss (F_n)

"redistribution" only applies to energy in version 3

Feedback from model 5 (loss of productive force)

- Investments are computed from the GDP result and its variation using a linear regression:

$$I_n = x\% \times I_{n-1} \times (R_n / R_{n-1}) + y\% \times (R_n - R_{n-1})$$

- Energy transition investments Ie_n are produced by M3 model
  Growth investments are produced with the difference:

$$Ic_n = I_n - Ie_n$$

  A negative value is interpreted as a loss of productive capacity

- Carbon taxes are computed from energy consumption, but the model assumes that the value is recirculated into the economy (energy investments) without loss

Another option would be to reinject CO2 to alleviate pains due to loss of economic activity

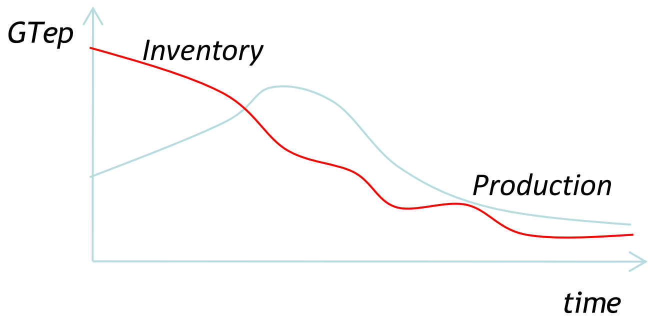
Energy Resource Model (M1)

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

Four categories

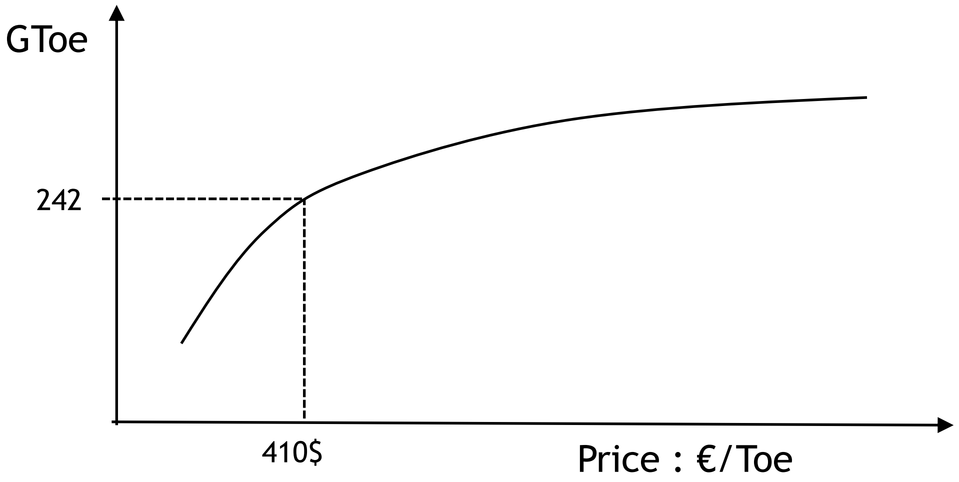
- Oil
- Natural Gas
- Coal
- Others ("clean": hydro/solar/wind/nuclear)

Caracteristic chart: « Peak Oil »



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" (yearly output)
- A constraint about the speed at which this capacity may evolve



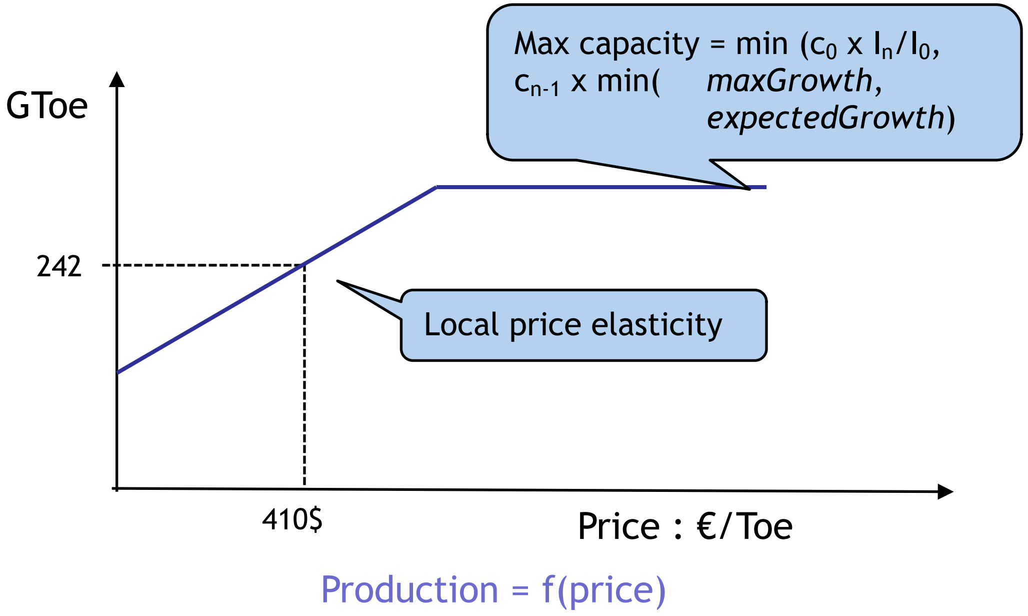
Inventory chart (oil example)

Energy Resource Model (M1)

M1 Inputs: 4 inventories / capacities / “capacity evolution” constraints
M1 Outputs: a curve that describes (for each simulated year) the output for a given market price

This is the simplest (parametric) model : for each possible sell price,

- Compute the new inventory:
  - Available resources based on 3Y averaged price,
  - minus last year consumption
- Determine new capacity goal, based on net demand of previous year (modulo a dampening factor to avoid oscillation) and operations capacity constraint (capacity growth factor is capped)
- Output is a fraction (0 to 1) of max capacity, with price sensitivity that is extracted from past history



There are two key aspects which are missing (first attempts to add into M1 failed)

- Strategy of the resource owner to speculate on current price versus expected value (versus the naïve linear output model)
- Time delay between decision to extract a new resource and actual operation is long (over 10 years) - versus the current capacity model that looks 3 years back

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) a histogram of value production:

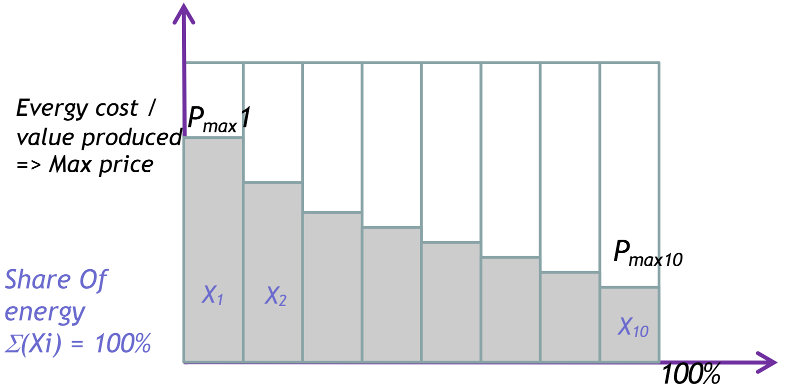
- Decomposition of value product (Y axis)
- Over segments of energy usage (X axis)
- This (virtual) decomposition is the base for telling how each actor will react to price increases

The net behavior is represented by four curves :

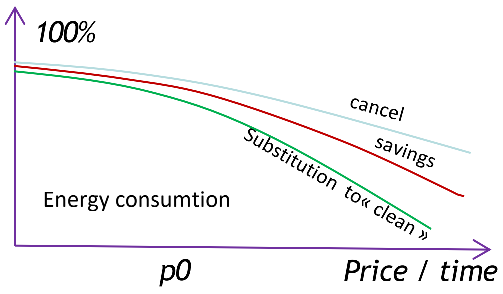
- Cancelation (% of activity that stops because price is too high) = f(p)
- Economic loss due to cancelation
- “Savings“ (energy efficiency) – reduction of consumption at iso-activity
  - *Savings are a “policy” (decision ahead of time that gets implemented) -> similar to transition (M3) and defined as a function of time (f(t))*
- Substitution towards another form of energy (using the matrix provided by M3)

The last two options triggers associated investments

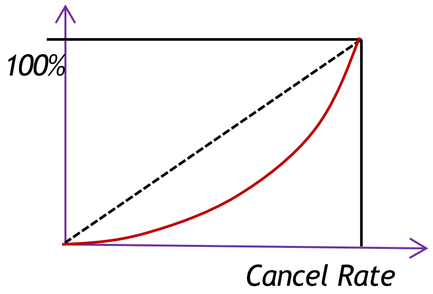
Energy redistribution policy is a factor that lowers the pain of cancellation but reduces the economic efficiency



Share of the PNB that can be produced at a given price



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)

Energy Consumption Model (M2)

M2 Inputs: For each block, population and consumption history per energy source,
M2 Outputs: Net demand for each energy source, for each geography block

Current instantiation of CCEM uses 4 blocks : US, China, Europe and RestOfWorld

This is also parametric model (based on price) :

- Iterate over energy resources (assumes a DAG order for substitution)
  - Computes the net energy need
    - Based on economy evolution (proportional [iso techno – improvement factored as “savings”])
    - Based on population $(1 + \alpha(P/P0))$ – α: share of energy consumption that is linked to pop growth
  - Distributes over energy sources using substitution that has been realized in the past years
  - Computes the resulting parametric (demand = f(price)) curves
    - Factoring cancellation according to the price
    - Savings “achieved so far” are also factored in

M1 and M2 “coupling” means to find the price that adjust supply and demand

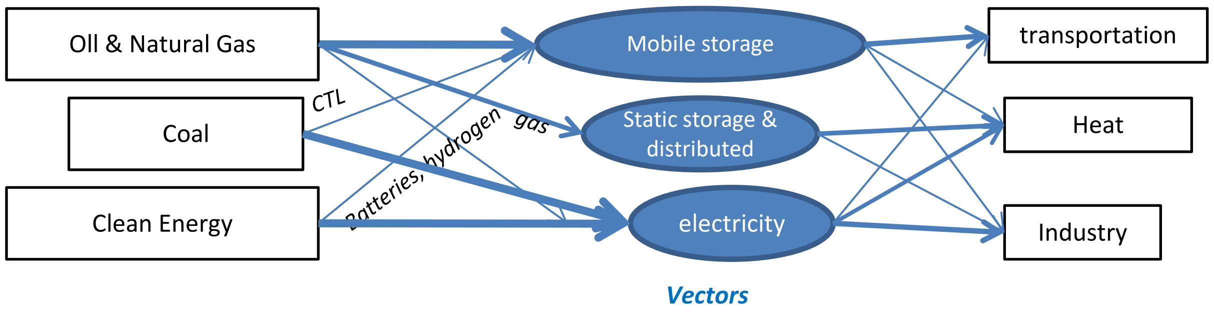
Note: A big oversimplification in the current model is to use the same cancel/saving curves for each source of energy (using a dumb ratio to account for different energy prices today)

Energy Transition Model (M3)

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

Substitution matrix

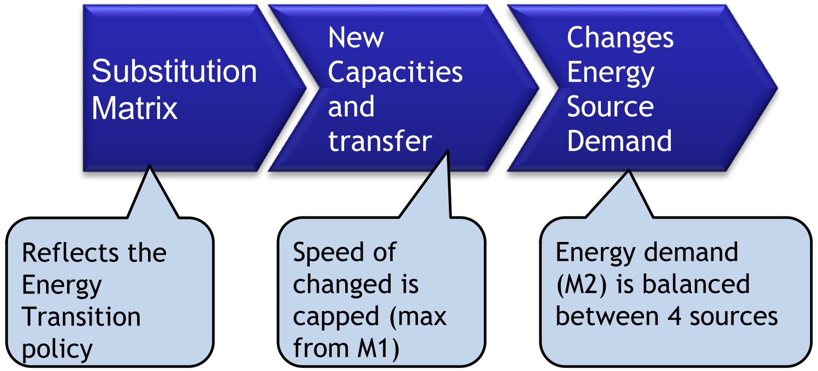
- Oil to Coal to Gas to Clean
- 6 flows (N x N-1 / 2)
- A substitution matrix as 6 coefficients (share of energy consumption that should be transitioned), depending on year (policy)
- The matrix takes into account the "source to vector" possible paths (cf. illustration) – It should also factor the constraints from natural resources such as steel.



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*



Energy Transition Model (M3)

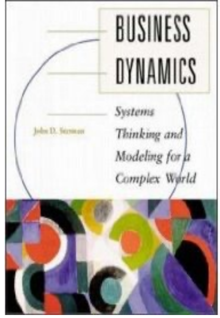
M3 Inputs: Initial transition matrix, actual output for each energy source, actual market price (source dependent)

M3 Outputs: transfer of energy consumption (yearly, starting on the date the decision is made), energy investments

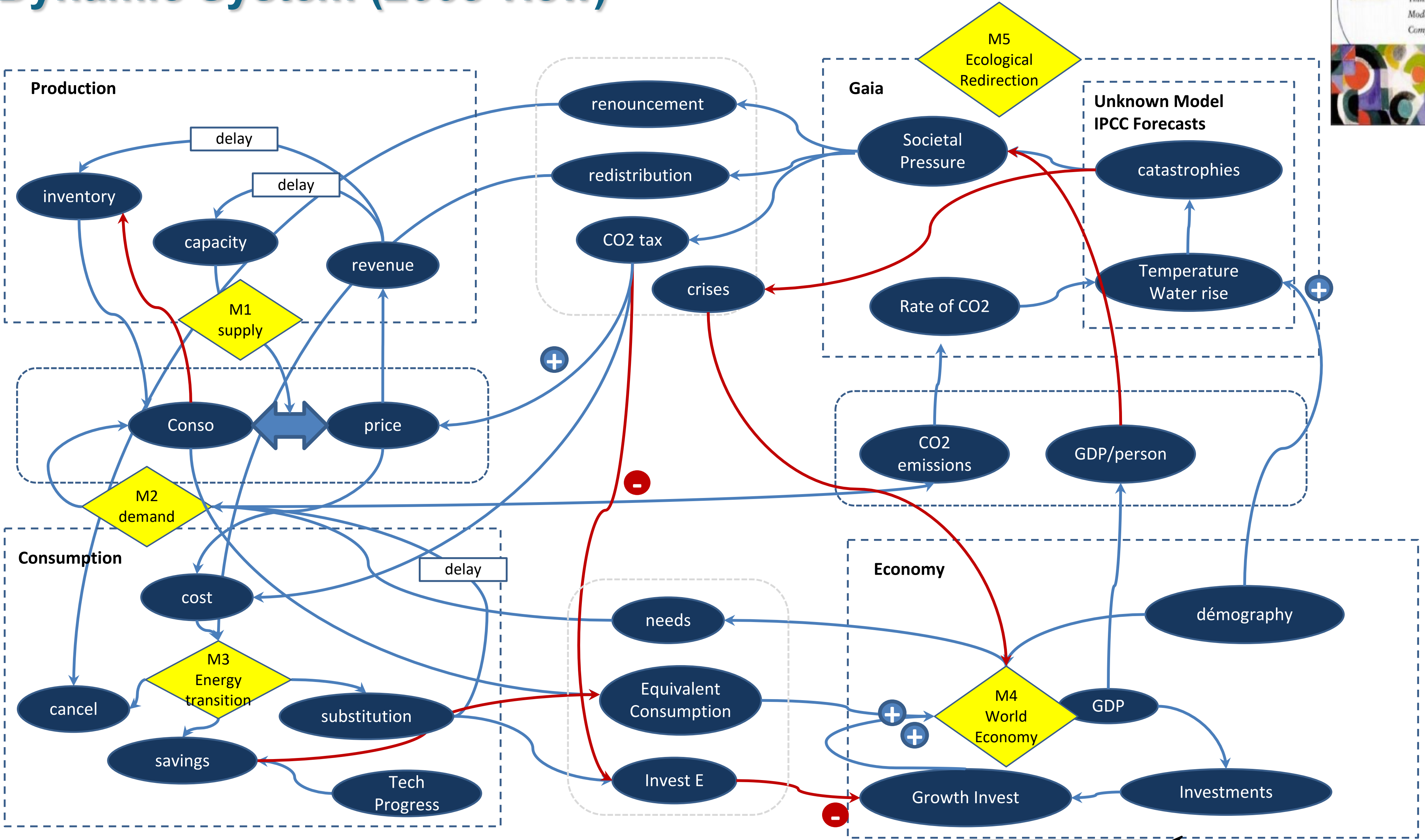
This model has two purposes:

- For M2, to compute how much energy is consumed for a given price, using the current level of substitution (called the "substitution matrix")
- As a complement to M2, once the price is set and the energy consumption is known for a year
  - For each source and each block,
  - Once cancellation and savings have been applied,
  - Computes the new level of substitution using the transition matrix (reflect the zone policy)
  - The substitution matrix is adjusted (monotonous, always grow, and capped by maxGrowth parameter from M2)
  - Level of investment is adjusted based simple "energy investment costs" (cost to produce 1MWh)
  - M3 uses a parameter "technology efficiency" that reduces over the years the cost to transition
- This model M3 also computes the CO_2 yearly emissions for each energy source

GWDG Dynamic System (2008 view)



4 instances
- Oil
- Gas
- Coal
- Clean

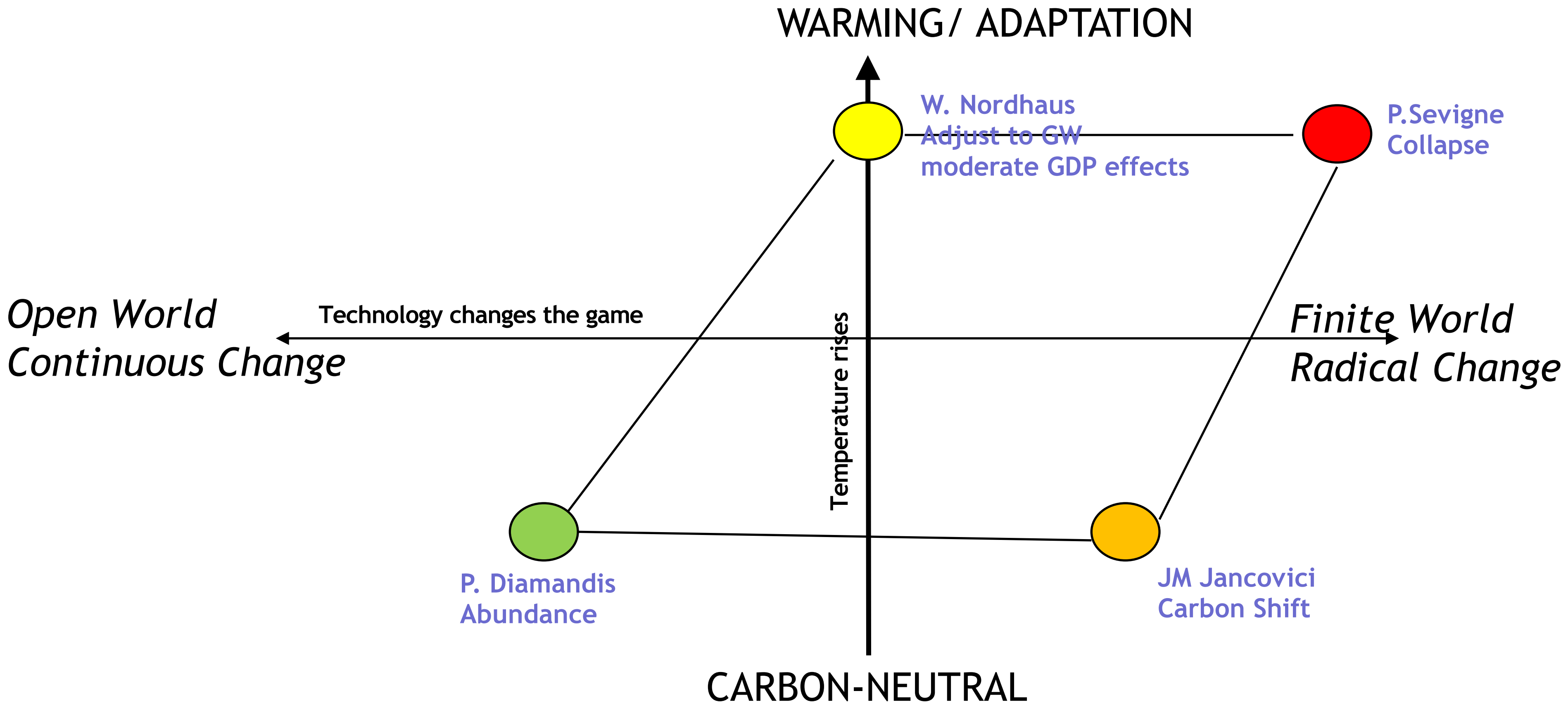


4 instances:
- US
- Europe
- China
- Rest of World

GWDG v3
One Economy

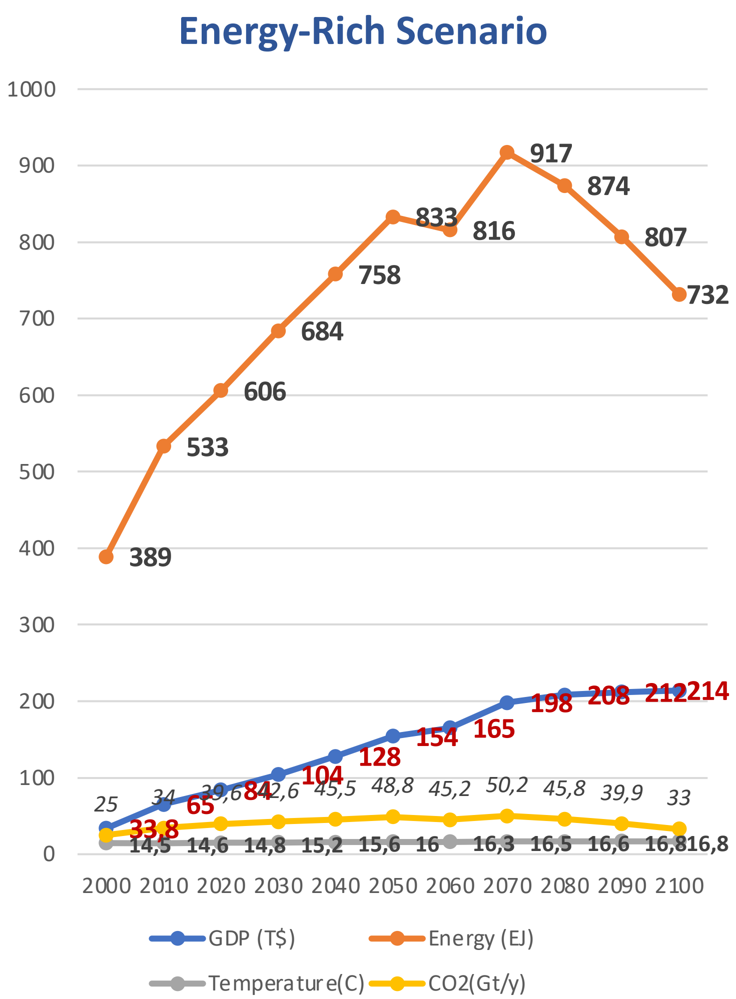
Conclusion

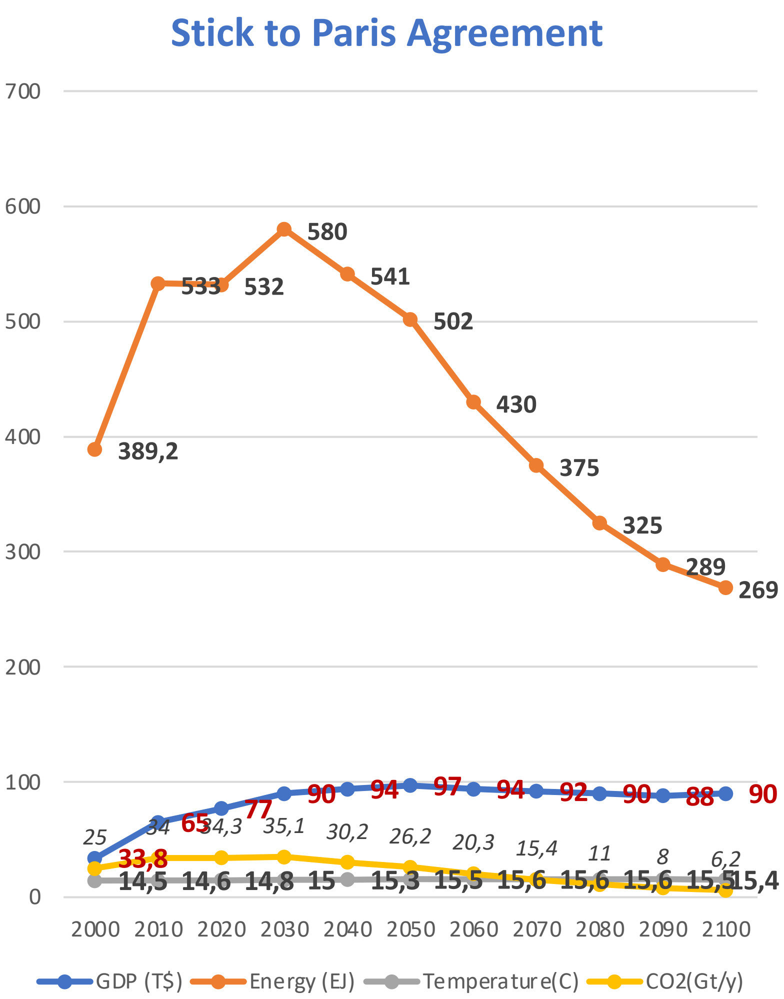
- On-going work (*this slide deck should be kept synchronized with the code*)
- First implementation (with CLAIRE) – to be translated to JavaScript for easier share
- A tool to explore beliefs (mental models) and their combined effects

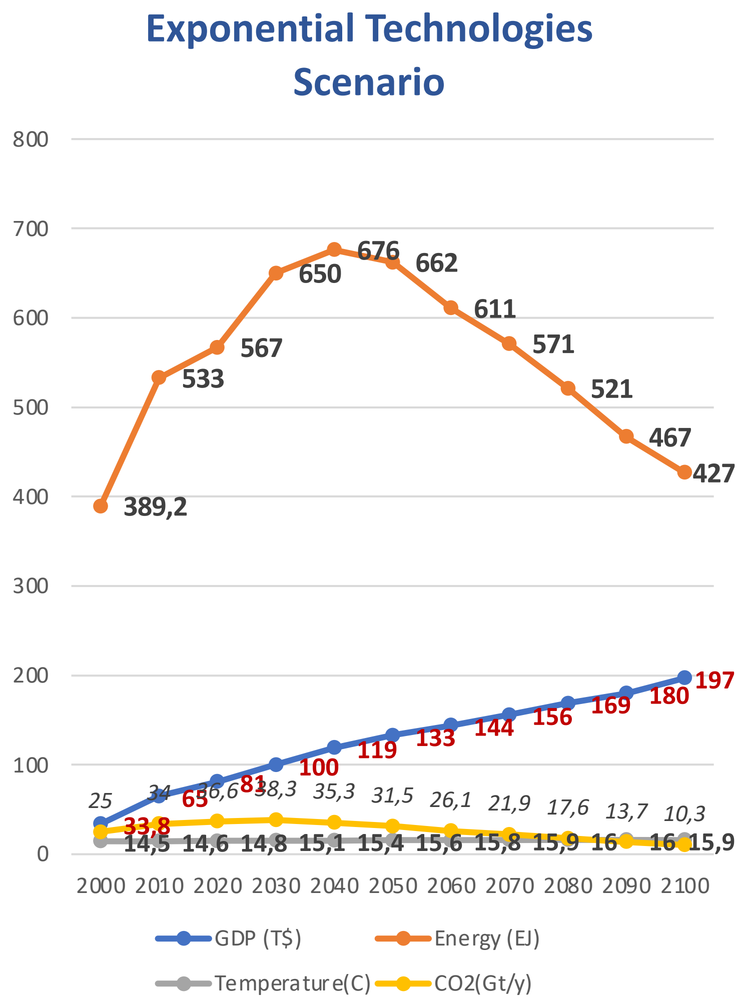


Preliminary results

- These are the outcome associated to the previous “three sets of beliefs”



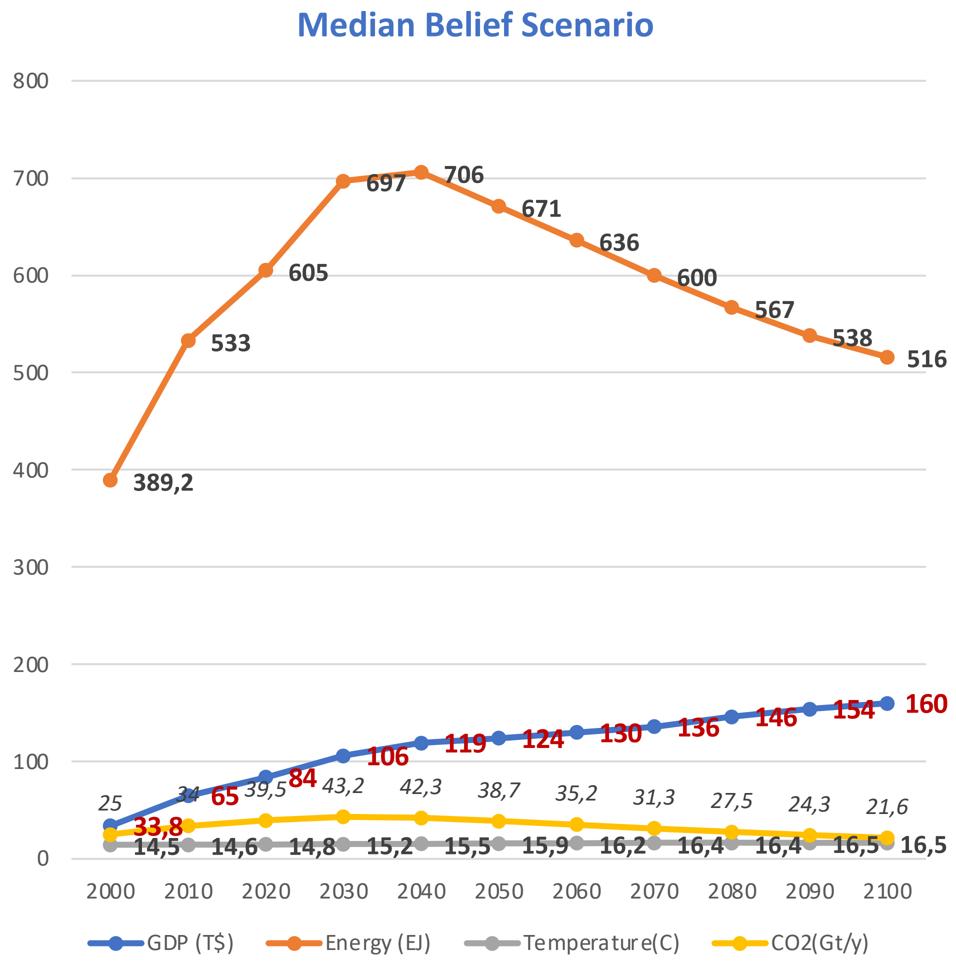


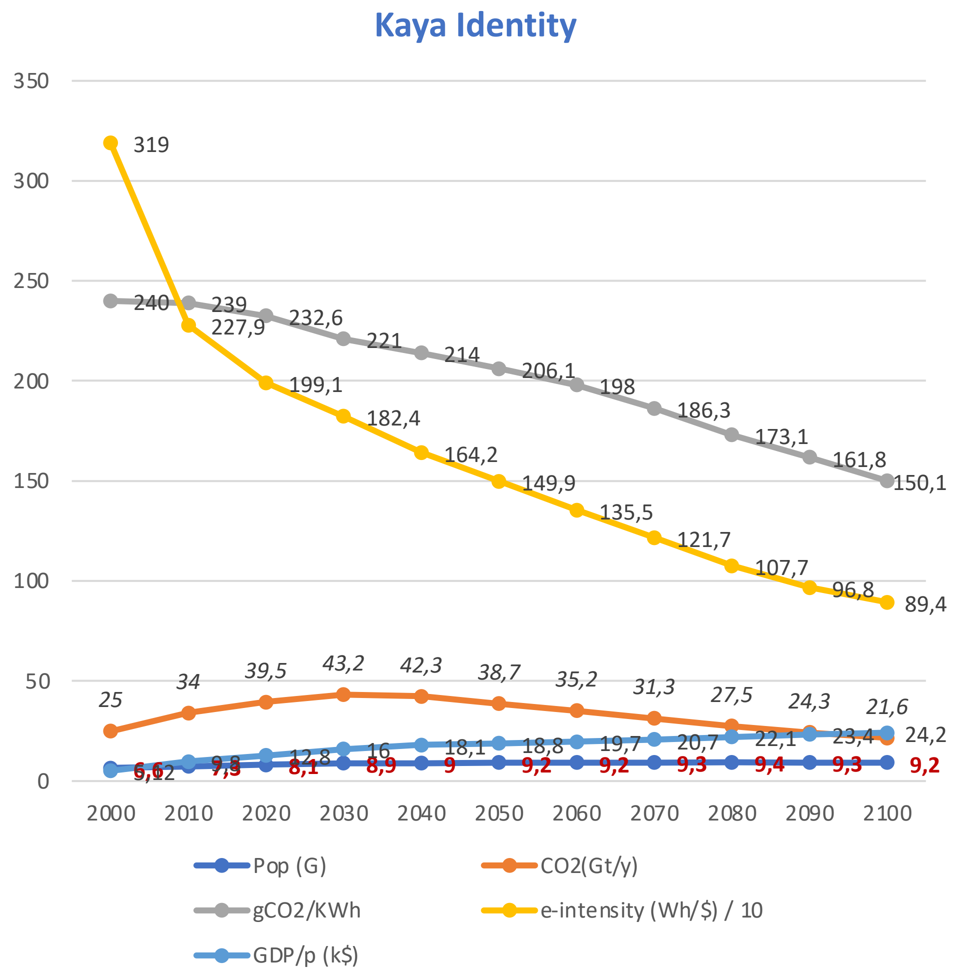


Median Belief Scenario (WIP)

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

- Key PKI for CCEM outcome + Kaya coefficients

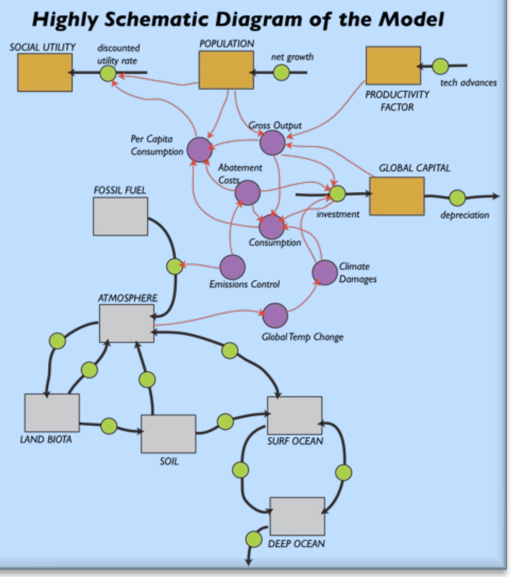




Similar Earth Models

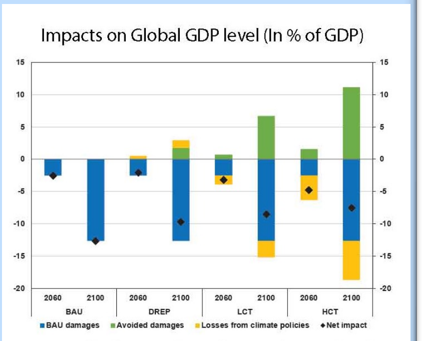
Nordhaus: DICE Model

The economic model we will explore here is based on a model created by William Nordhaus of Yale University, who is considered by many to be the leading authority on the economics of climate change. His model is called DICE, for Dynamic, Integrated Climate and Economics model. It consists of many different parts … we can carry out some experiments with this model to explore the consequences of different policy options regarding the reduction of carbon emissions.



ACCL (Banque de France)

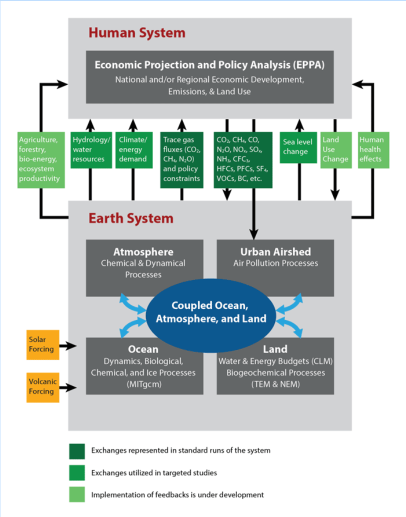
A tool to build climate change scenarios to forecast Gross Domestic Product (GDP), modelling both GDP damage due to climate change and the GDP impact of mitigating measures. It adopts a supply-side, long-term view, with 2060 and 2100 horizons. It is a global projection tool (30 countries / regions), with assumptions and results both at the world and the country / regional level. Five different types of energy inputs are taken into account according to their CO2 emission factors., Total Factor Productivity (TFP), which is a major source of uncertainty on future growth and hence on CO2 emissions, is endogenously determined,



: Business as usual (BAU); Decrease of Renewable Energy relative Price (DREP); Low Ca
h Carbon Tax (HCT)

MIT Integrated Global System Modeling (IGSM) Framework

The IGSM framework consists primarily of two interacting components—the Economic Projection and Policy Analysis (EPPA) model and the MIT Earth System model (MESM). The EPPA model simulates the evolution of economic, demographic, trade and technological processes involved in activities that affect the environment at multiple scales, from regional to global.



SOS Trades

SoSTrades is a web-based, multi-user, interactive publication-quality graph simulation platform. It allows users to drop new modules without additional coding, and provides embedded advanced numerical capabilities for simulation and multi-disciplinary optimization. It also has built-in collaborative capabilities to allow different experts to work together.