Integrated Assessment Models (IAM), System Dynamics Earth Models, and Impact of Global Warming

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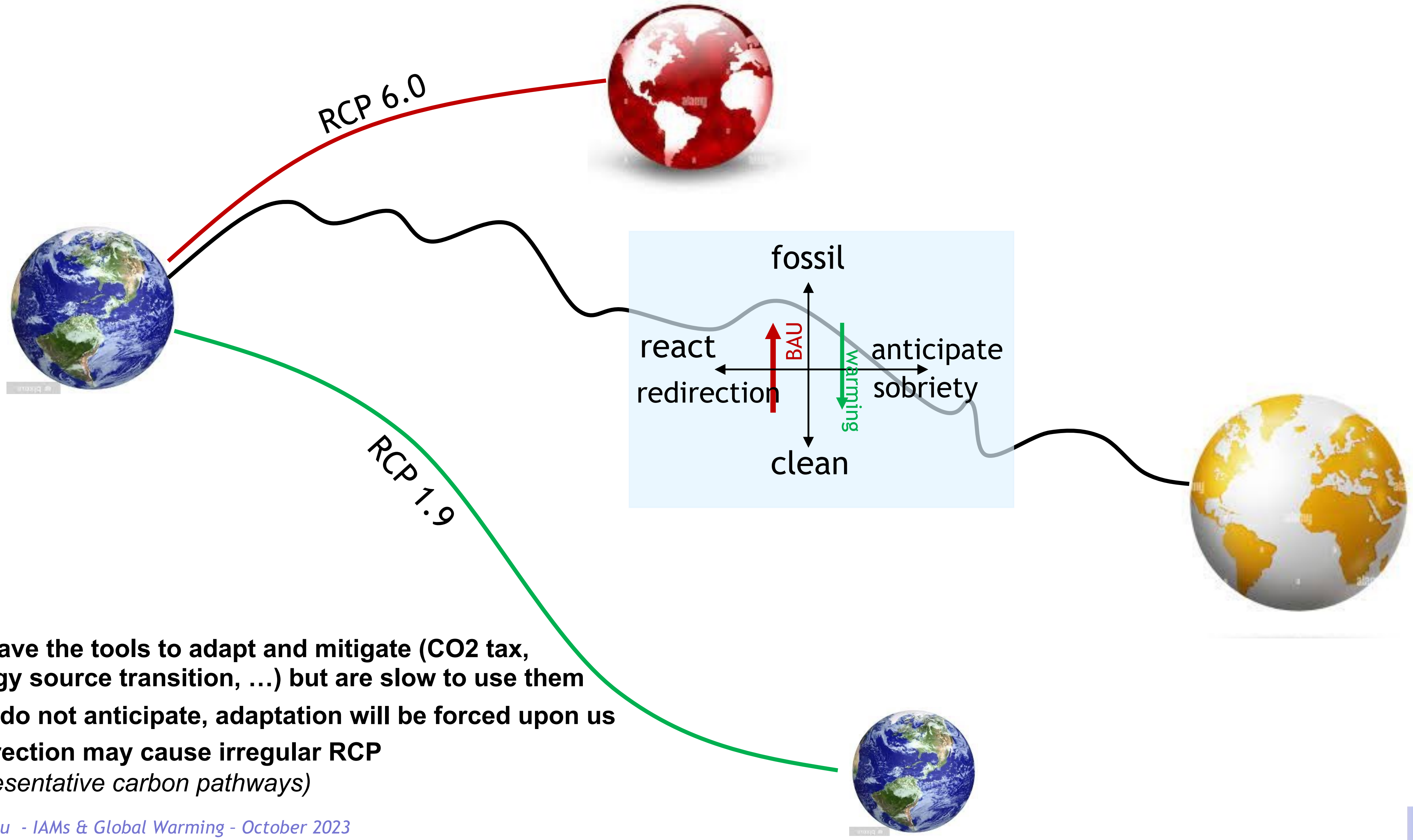
Outline

1. **Integrated Assessment Models (IAM)**
   - Modeling the Energy / Economy / Climate coupling
   - System Dynamics Tradition
   - Some short-comings

2. **CCEM presentation**
   - Coupling of 5 “coarse” models
   - Preliminary simulations

3. **Next Steps**
   - Social Cost of Carbon (Impact of Global Warming)
   - Geopolitics and Game Theory

Scope of Simulation : Earth's Reaction to Global Warming (IPCC)



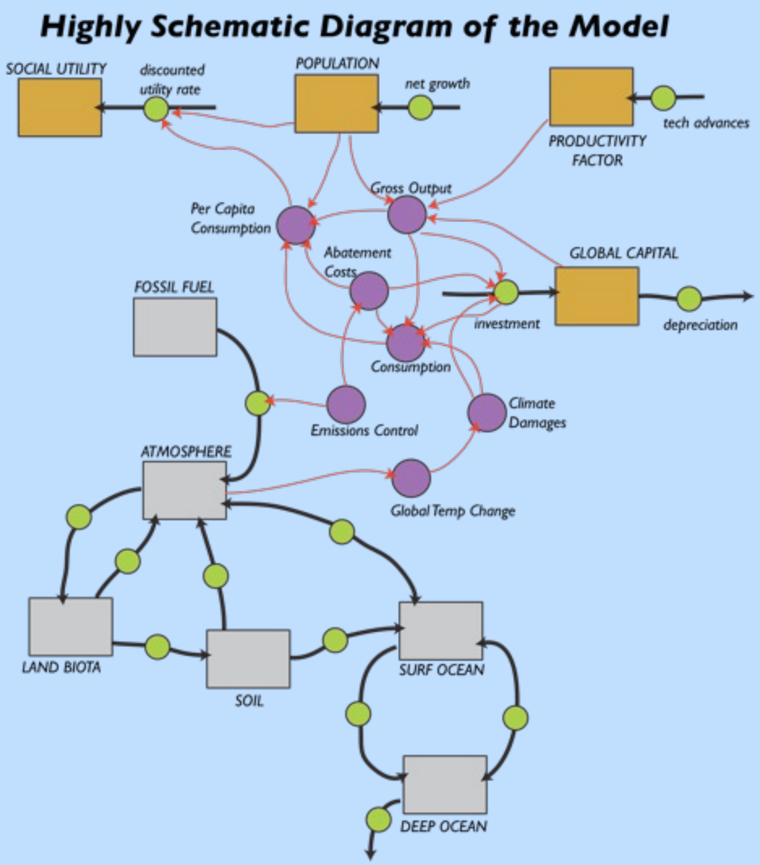
- **We have the tools to adapt and mitigate (CO2 tax, Energy source transition, …) but are slow to use them**
- **If we do not anticipate, adaptation will be forced upon us**
- **Redirection may cause irregular RCP** *(representative carbon pathways)*

Integrated Assessment 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**.

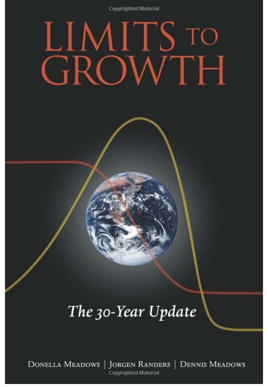
- **Strengths (what it is useful for)**
  - Systemic view (more or less ☺)
  - What-if scenarios
  - Global energy / economy / climate coupling
- **Limits**
  - Not a forecast engine
  - Feedback loop:
    - ➔ Policy is a parameter that get optimized from “outside”
  - Heavy use of time discount (when used for optimization)



IAM examples

- DICE (Nordhaus & al)
- ISGM (MIT)
- ACCL (Banque de France)
- IMACLIM (Cired)
- GIVE (Berkeley)

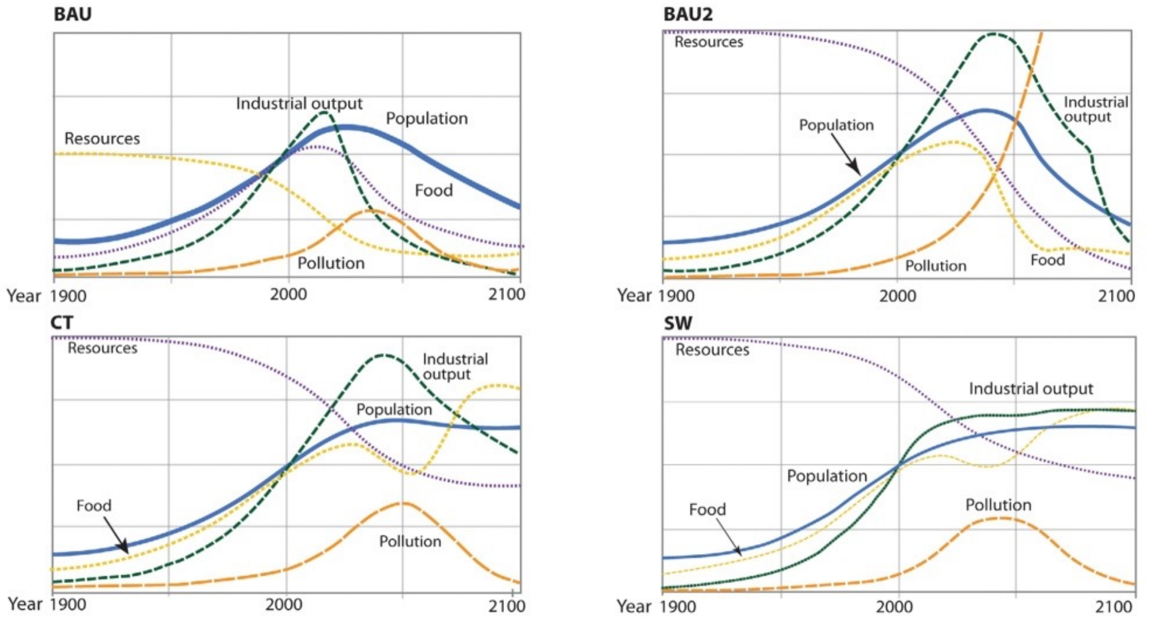
Limits to Growth – *Club of Rome*



- **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.

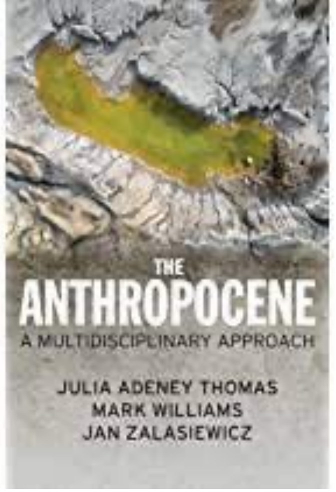
Approximative difference between IAMs & SDEM
- IAMs are data-driven (calibrated from past data)
  - Risk of overfitting when projected in the next century
- SDEM are designed from « first principles »
  - Crude calibration / focus on orders of magnitude

- **Highlights from LtG (World3)**
  - *The human economy is now using many critical resources and producing wastes at rates that are not sustainable. Sources are being depleted. Sinks are filling and, in some cases, overflowing.*
  - *There is such an enormous amount of coal that we believe its use will be limited by the atmospheric sink for carbon dioxide. Oil may be limited at both ends*
  - ***World3 is a model designed to explore the behavior modes of an interconnected, nonlinear, delayed-response, limited system.** It is not intended to spell out an exact prediction for the future or a detailed plan for action*
- **Gaya Herington, "Five Insights for avoiding Global Collapse"**
  - Post-validation of LtG model, 30 years later …
- **Earth for All: A Survival Guide for Humanity**
  - *Two novelties included in the model are the Social Tension Index and the Average Wellbeing Index.*

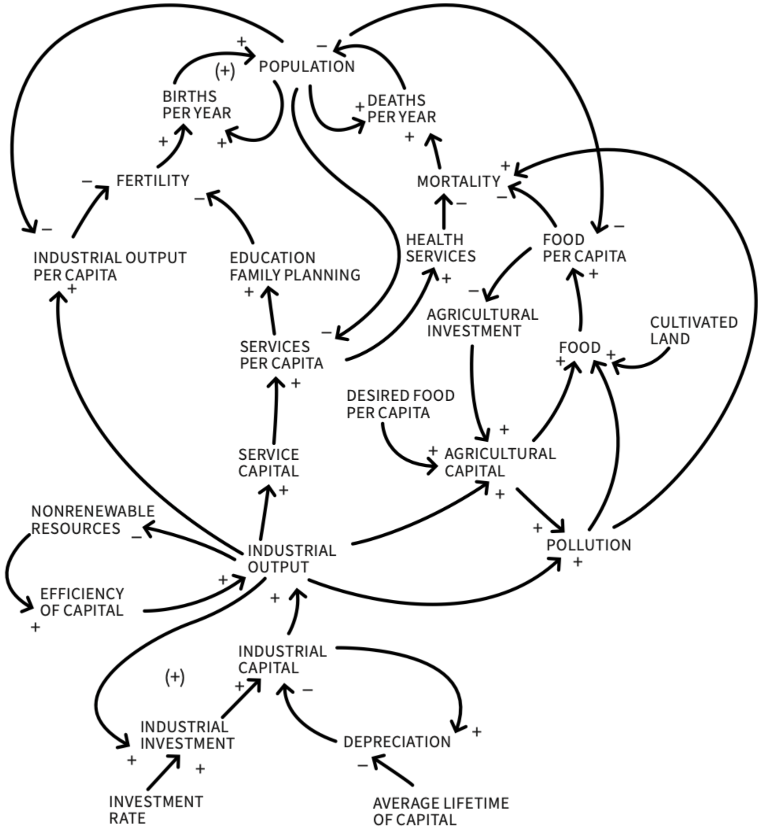


GURE 1 The BAU, BAU2, CT, and SW scenarios. Adapted from *Limits to Growth: The 30-Year Update* (p. 169, 173, 219, 245), by Meadows, D. Meadows, D. L., and Randers, J., 2004, Chelsea Green Publishing Co. Copyright 2004 by Dennis Meadows. Adapted with permission

IAM Short-comings, case for yet-another-model ☺



1. ” Make “known unknowns” explicit and parametric
   - Realistic energy transition
   - Economic reaction to lack of cheap energy
   - Economic impact of global warming
2. Societal reaction to global warming (redirection)
   - Realistic” impact of global warming (cf. Part 3)
   - Difficult since a large part is unknown
3. Blocks for geopolitics
   - Apply game theory (“*tragedy of the commons*”)
   - Different goals and different constraints

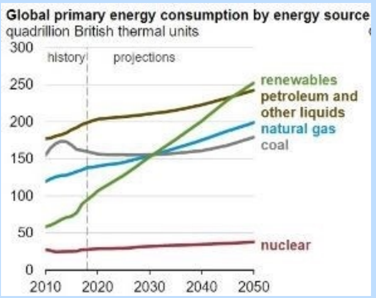


CCEM : Addressing Five "Known Unknowns"

« 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 ?

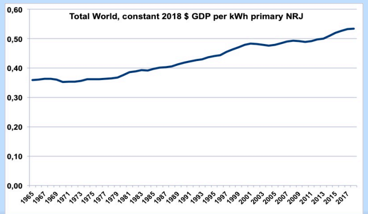
EIA



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

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

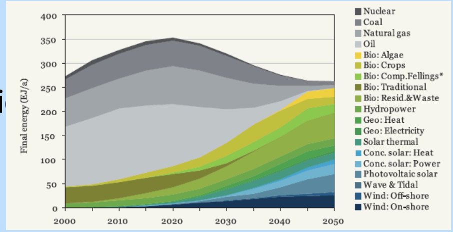
Energy
To
GDP



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

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

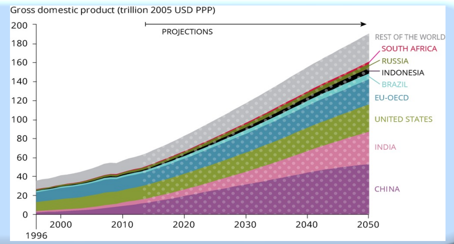
2050
Eco
transiti
Plan



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

Example:
Impact of reduced energy availability on economical output ?

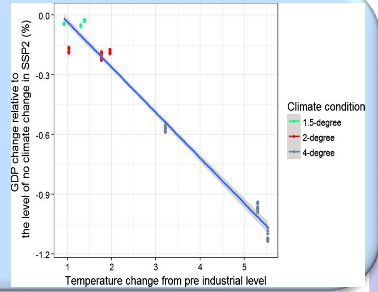
GDP
2050



« 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 2

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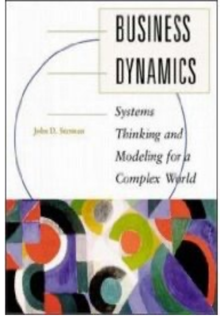
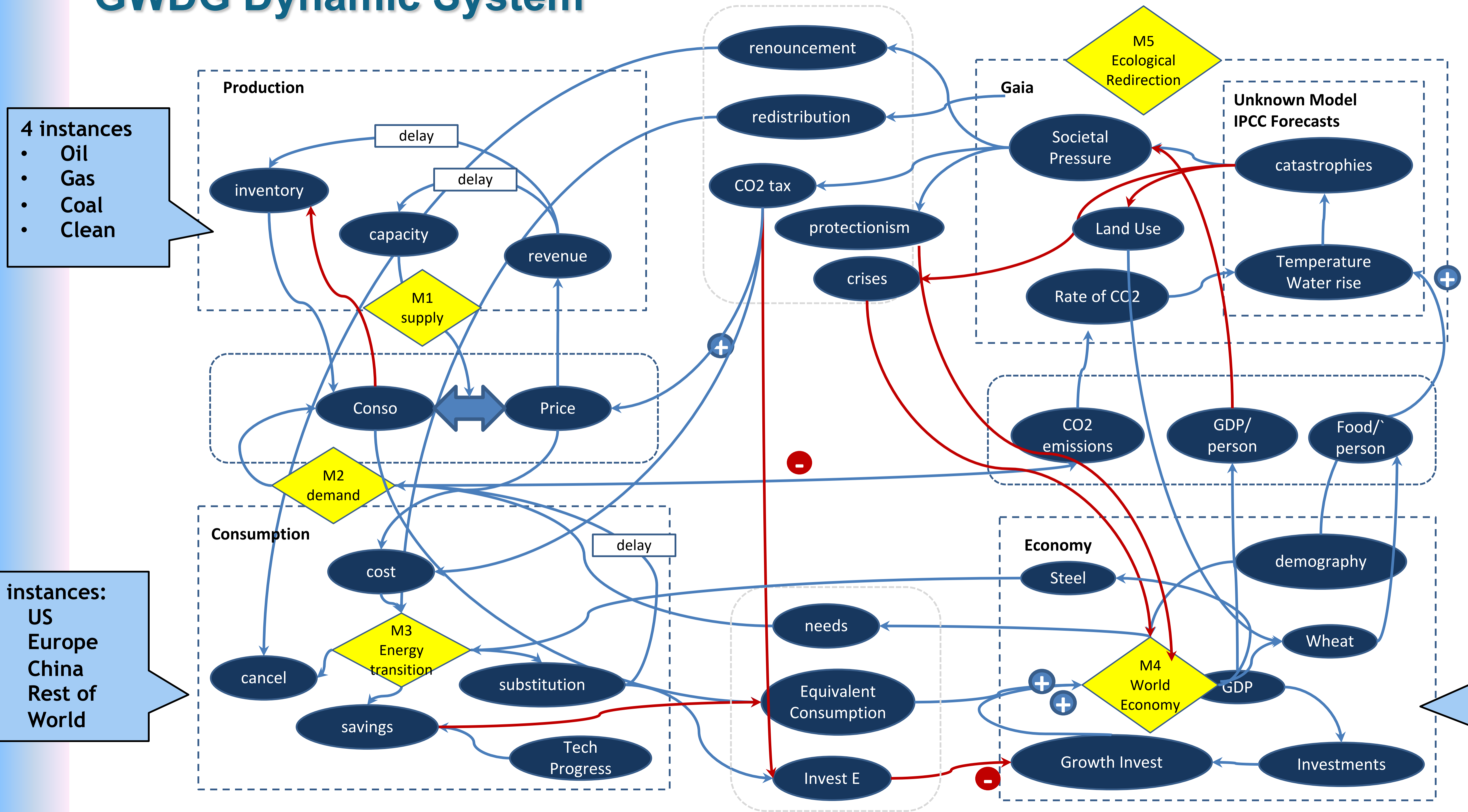
GWDG Dynamic System



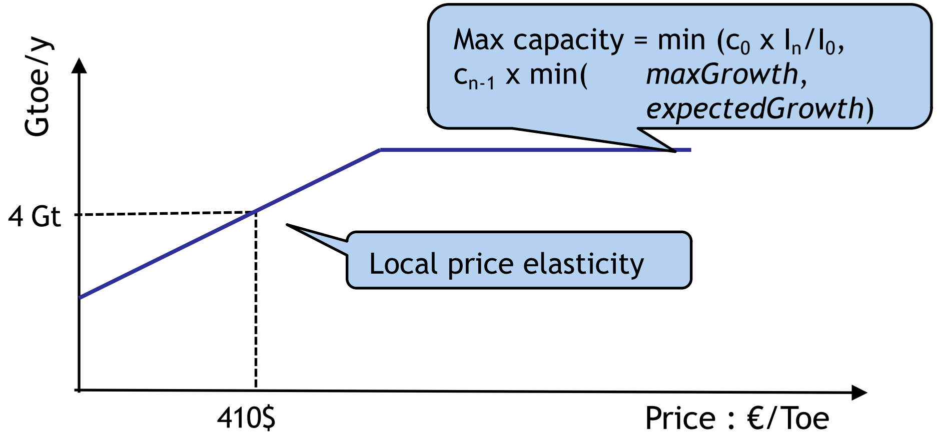


Energy Resource Model (M1)

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

Four categories

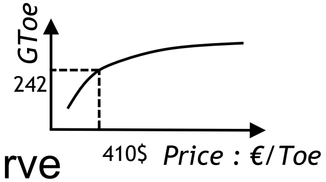
- Oil
- Natural Gas
- Coal
- Clean (hydro/solar/wind/nuclear)



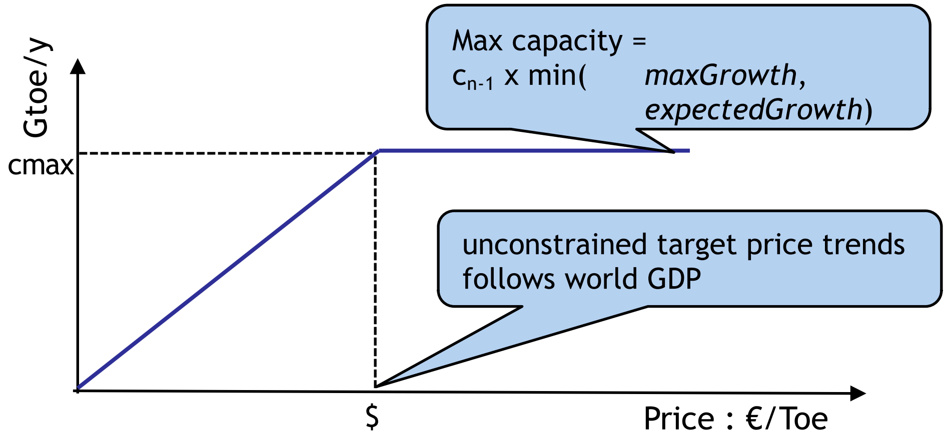
Fossil Fuel Production = f(price)

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



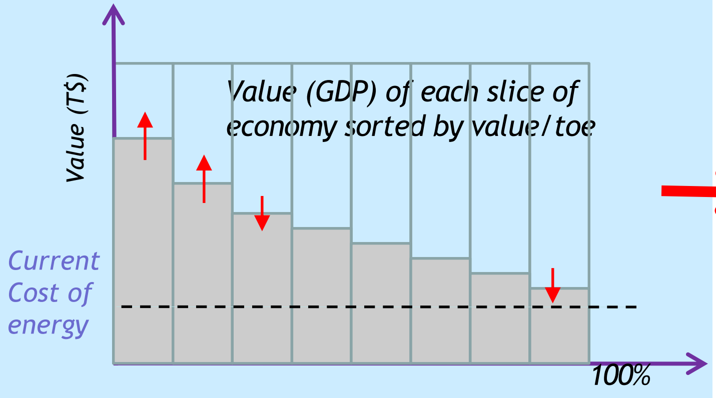
Clean Energy Production = f(price)

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/$)

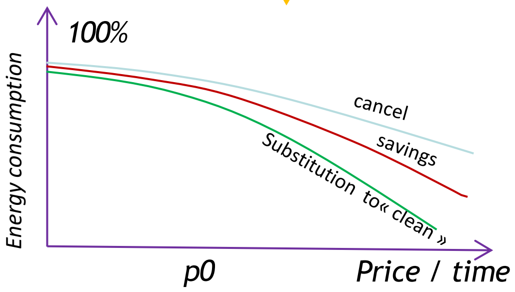
The net behavior is represented by four curves :

- 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

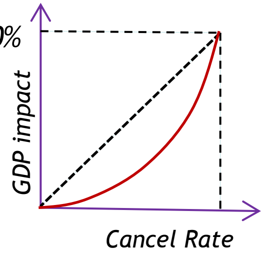
In addition, we represent the expected efficiency gains:

- “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)

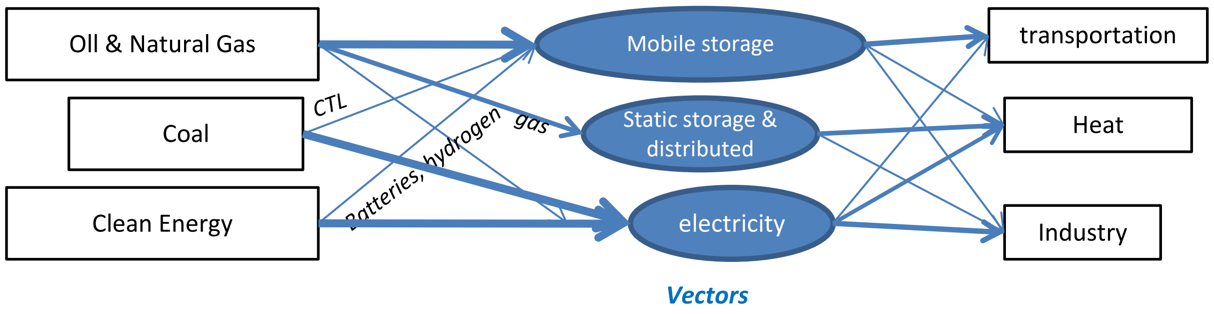
Margins for surviving activities are reduced by increasing energy prices

Energy Transition Model (M3)

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

Substitution matrix

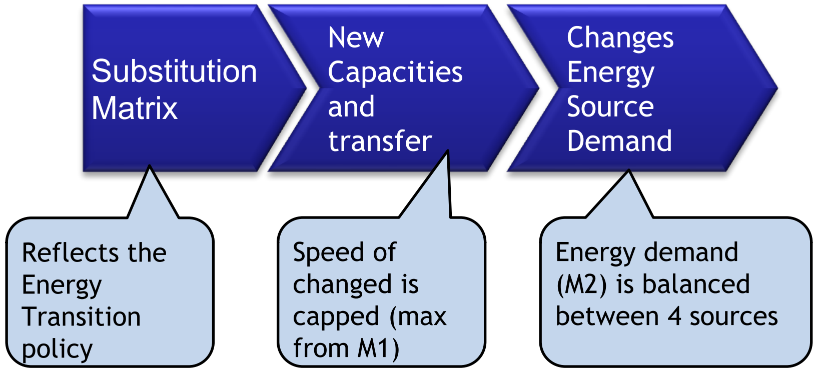
- Oil to Coal to Gas to Clean
- 6 flows (N x N-1 / 2)
- A substitution matrix as 6 coefficients (share of energy consumption that should be transitioned), depending on year (policy)
- The matrix takes into account the "source to vector" possible paths (cf. illustration) – It should also factor the constraints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



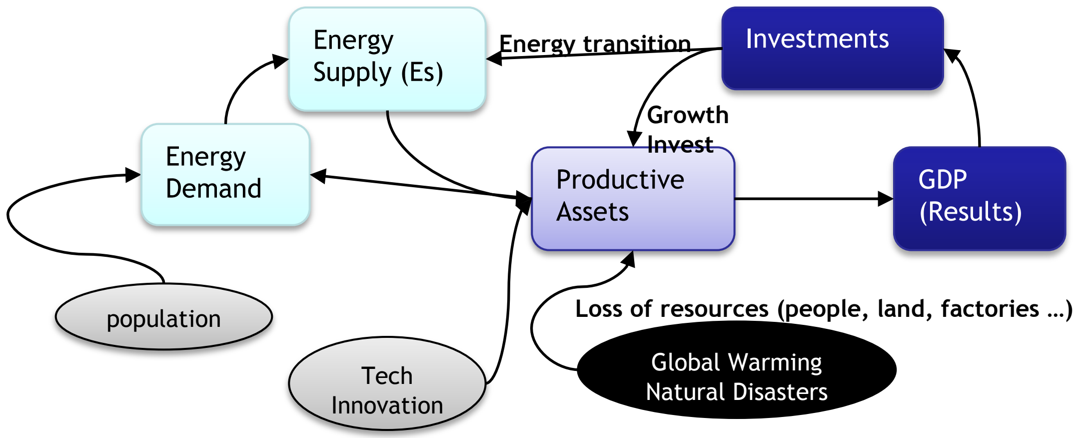
GDP Model (M4, World Economy)

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

Description

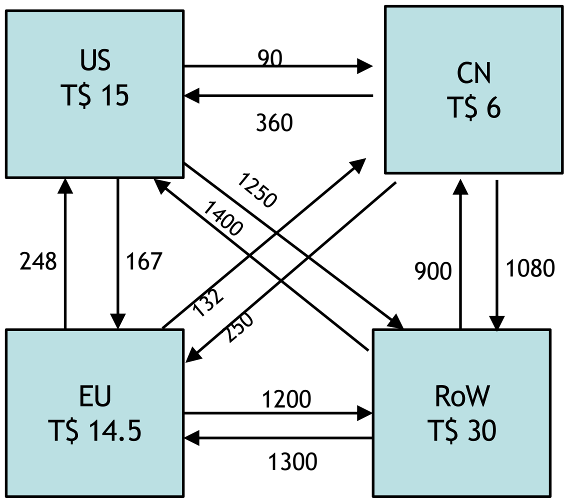
Economy is seen as a set of productive assets that require energy and human capital to operate

Economy growth require investments that are a fraction of results



We use a crude exponential growth model

- Output is linked to energy (cf. M2 + redistribution)
  - Demography is factored through energy consumption
- Assets grow as a result of investments
- 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 ”redirections of zone policies” (M5)
- The model computes the consumption without savings that drives the GDP and the consumption with savings that drives CO_2 emissions
- This model is applied to 4 “Blocks” : US, CN, EU, RoW

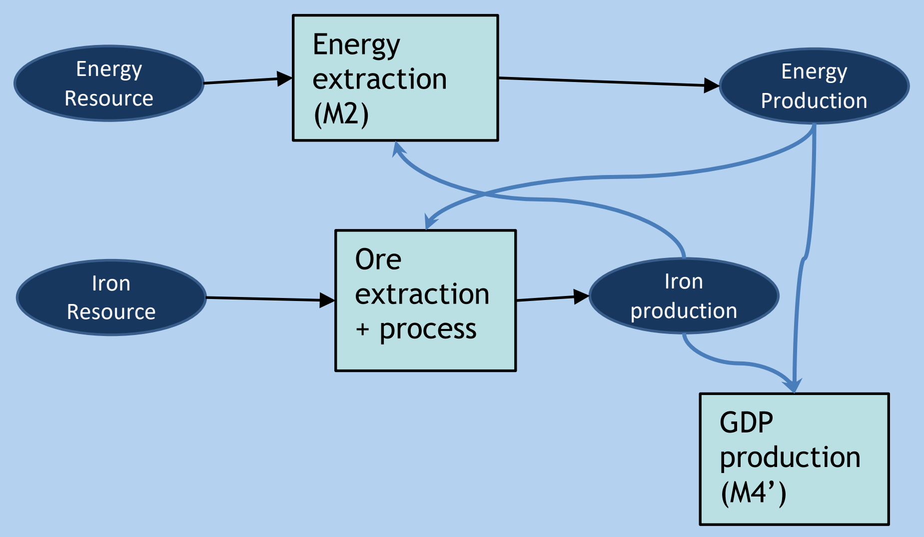


2010 world economy crude decomposition (trade in G$)

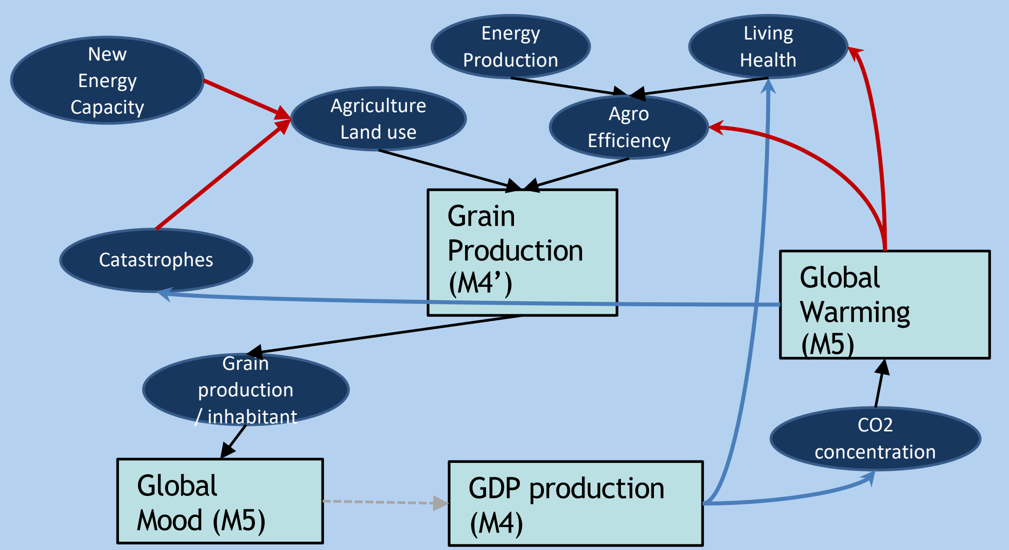
M4: Physical versus Immaterial GDP

- The model uses “current dollars” as monetary unit (for GDP and energy price)
  - “2100 dollars” is an abstract notion …
- High GDP growth in the past 30 years reflects the growing importance of “immaterial” economy
- The “$CCEM_4$” model (4th iteration) adds two outputs to evaluate the “material” side:

Steel production (proxy of material goods)



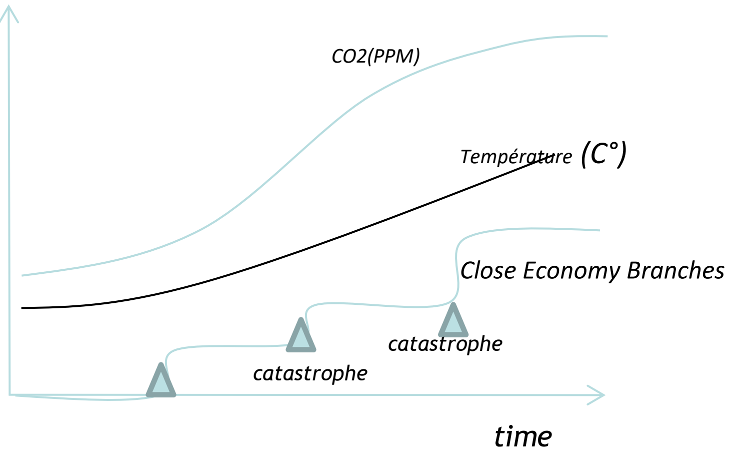
Wheat production (proxy of Agriculture)



Ecological Redirection (M5)

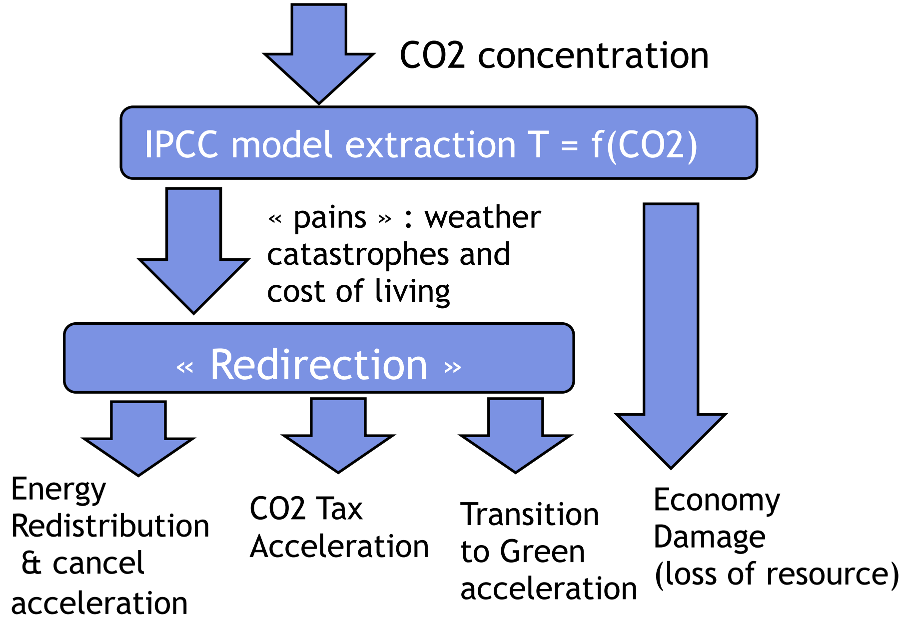
M5 answers the question « ***What kinds of redirection should we expect from the IPCCs global warming consequences*** ?»

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 CO_2 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 CO_2 & temperature rise
- A redirection model (very naïve) with three components
  - Increase into energy redistribution (feedback to M2)
  - Increase CO_2 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)

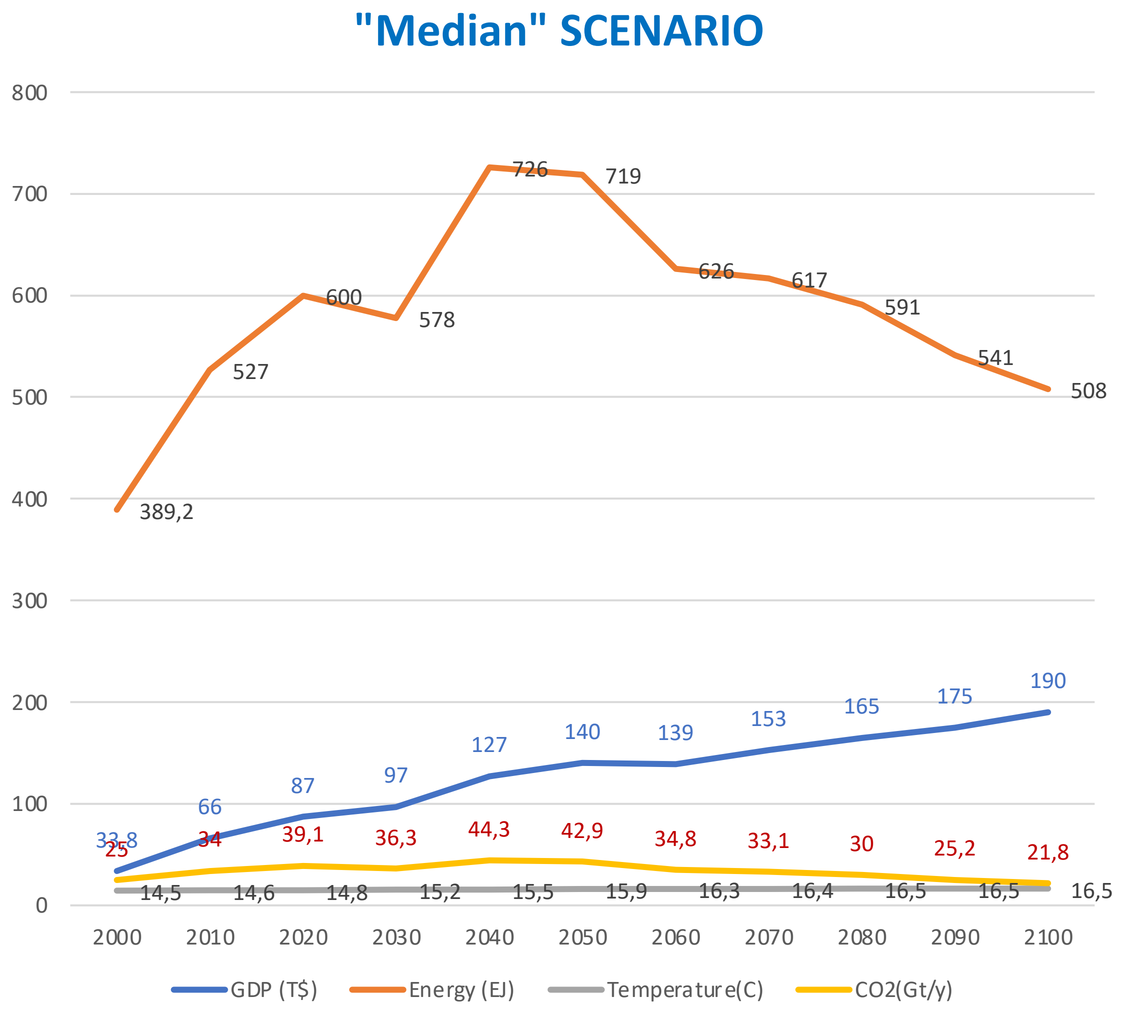


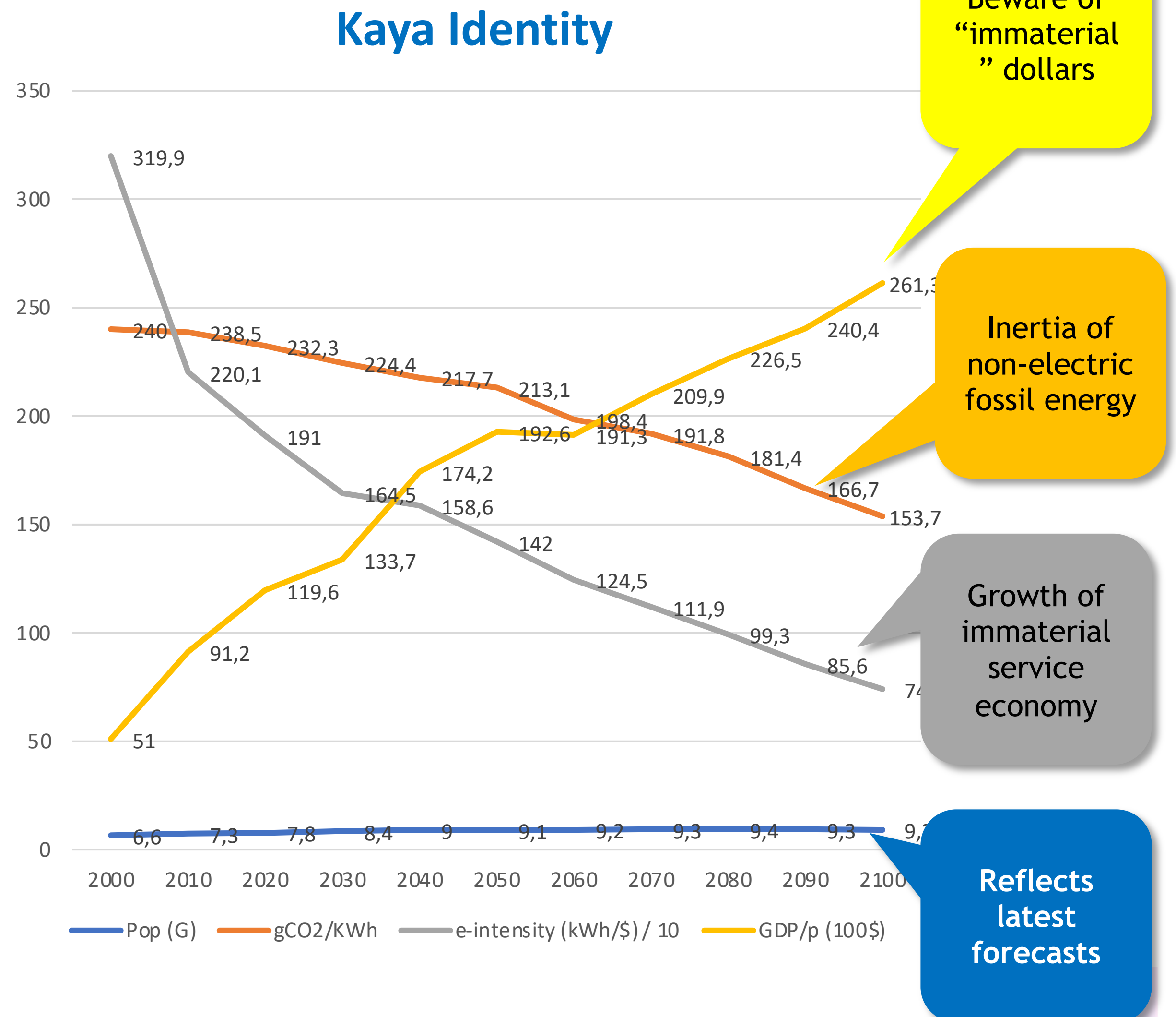
Three drivers : fear (of future production loss), pain (less revenue) and compassion (disaster happening elsewhere)

“Yves Belief” Scenario (WIP)

- Key PKI for CCEM outcome

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



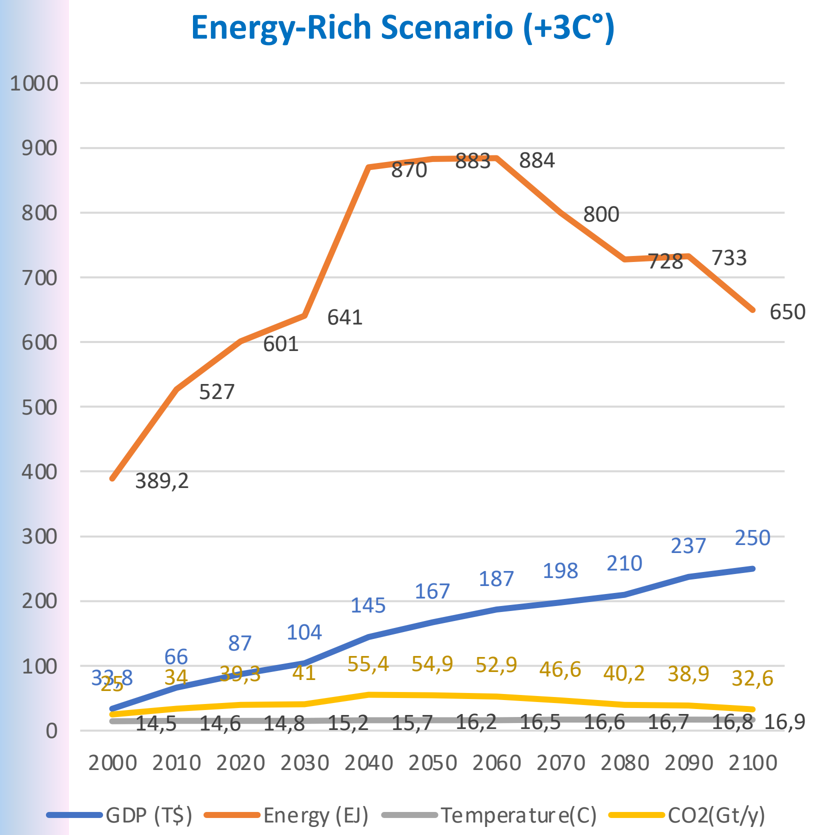


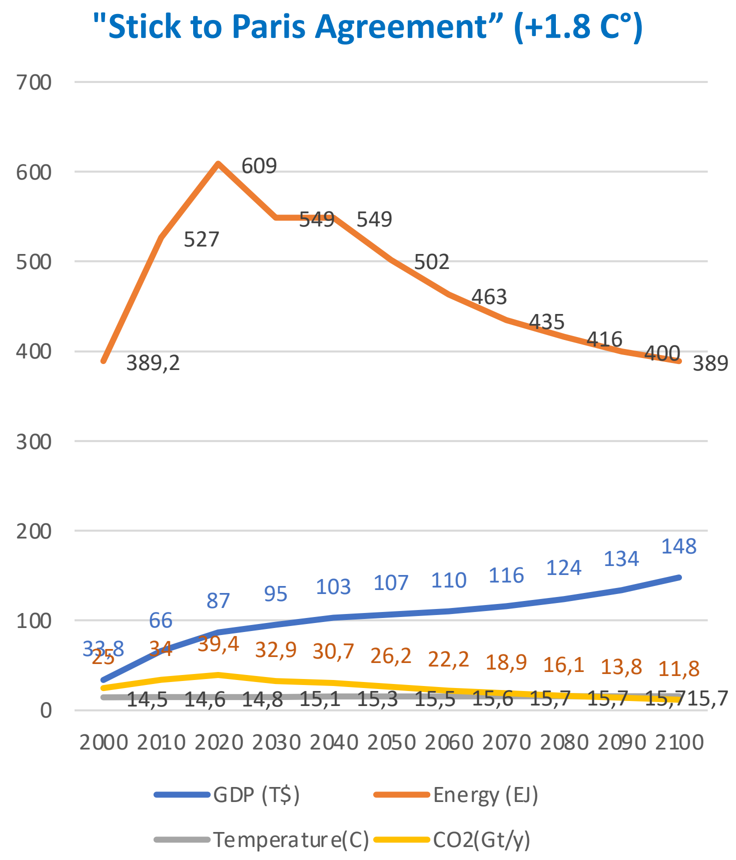
Sensitivity Analysis for Key Beliefs

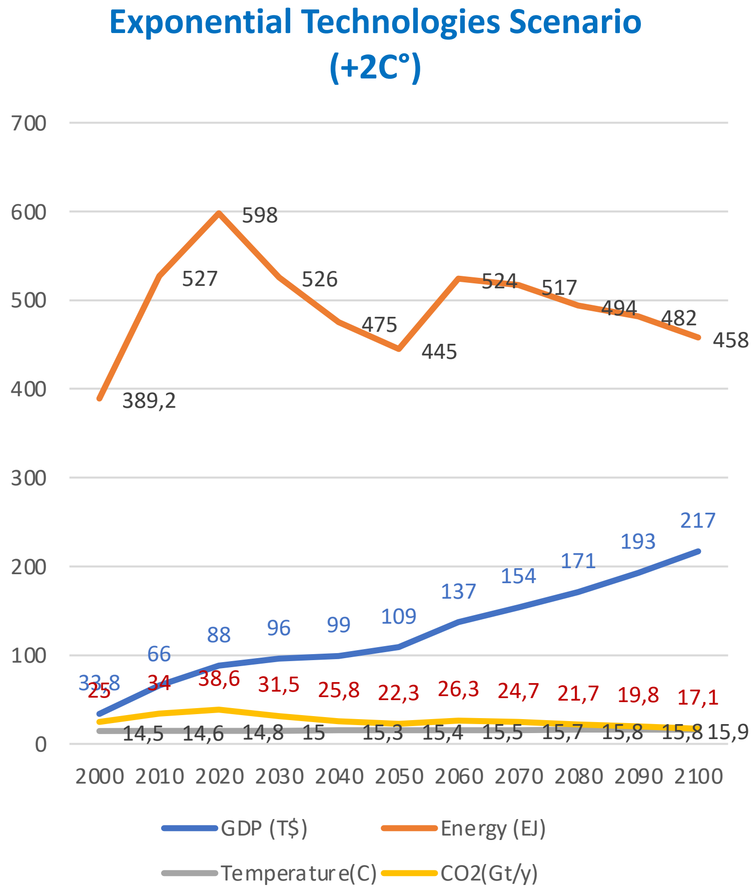
Fossil Energy	Influence of estimated reserve @ price	*Very strong influence both on final GDP and CO2 RCP*
	Open or limit the growth of Coal	*Large influence on China, important to curtain CO2*
Transition to clean energy	Rate of possible clean TW.h additions	*Heavily debated, strong influence on GDP if serious about CO2 reduction (versus Coal) – Breakthrough (fusion) impact is dominated by transition …*
	Speed of Energy transition (move to e)	*Strong inertial factor, that makes "Accord de Paris" unrealistic, but for a major loss of GDP (order of magnitude : -50%, not -3%)*
Efficiency and Sobriety (cancel)	Technology capacity to increase efficiency	*Large influence, but not major (unless a complete breakthrough happens … but large diversity of use cases)*
	Sensibility of the cancellation model	*Important but not major – still one of the difficult "known unknown" to forecast over the 21st century*
Growth & Price sensitivity	Sensibility of growth model	*Very large influence of projected GDP, less on CO2 emissions*
	Impact of price elasticity parameters	*Moderate influence since energy price is mostly a signal in CCEM to adjust supply and demand (feedback loop on steel price)*

Exploring beliefs (no redirection)

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







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

Block Coal production growth,
sets a high CO_2 tax at 400+$/t
accelerate green transition
promotes sobriety through regulation

More efficiency gains and accelerated
cost of technology decline
Accelerated energy transition
Moderate CO_2 tax (150-200)

Part 3

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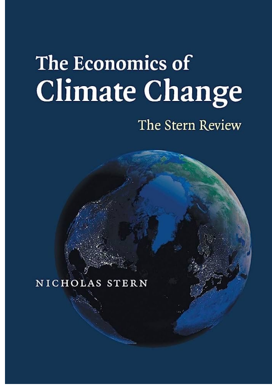
Global Warming Impact and SCC (Social Cost of Carbon)

- Social Cost of Carbon
  - Wikipedia: *The social cost of carbon (SCC) is the marginal cost of the impacts caused by emitting one extra ton of carbon emissions at any point in time.[1] The purpose of putting a price on a ton of emitted CO2 is to aid people in evaluating whether adjustments to curb climate change are justified*.
  - Range of price : 50$ to 500$/t (100-200$/t is the current preferred estimate)
  - Link with companies “benchmark price” of CO2
- ”**Comprehensive evidence implies a higher social cost of CO2**”
  - Rennert & al, Nature 2022
  - SCC at 185$/t, mostly agriculture and mortality
    - ➔ Very wide dispersion of agro-impact (FUND model, from Canada to Southeast Asia)
    - ➔ SCC is computed by Monte-Carlo (naïve) simulation
  - Simulations are based on GIVE model
    - ➔ Damages (*simple interpolation of published tables ☺*)
      - – Health (Cromar et al), Agriculture (Moore et al), Energy dropdown (Clark et al), Coastal impacts (small, cf Diaz)

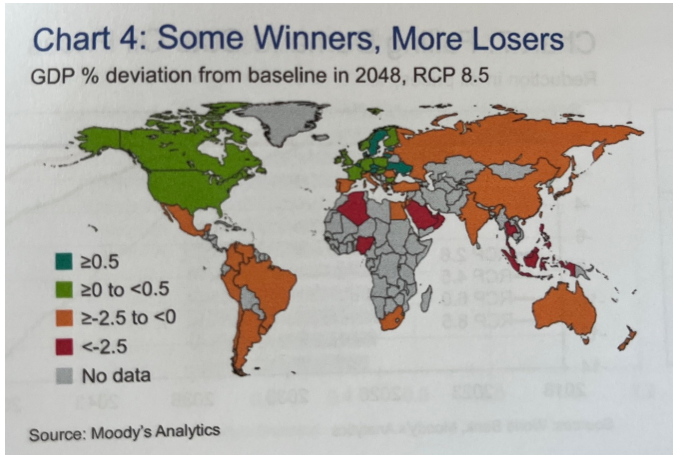
Social Cost of Carbon (SCC) and IAMs



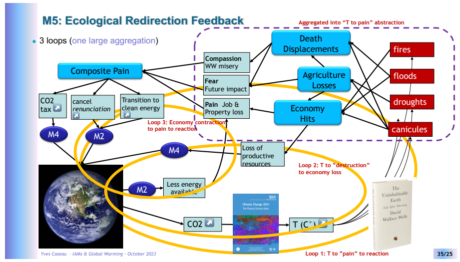
- **“Climate tipping points - too risky to bet against”**
  - Lenton & al, Nature 2019 (Main reference for Stern, Stiglitz & Taylor)
  - *Models suggest that the Greenland ice sheet could be doomed at 1.5 °C of warming, which could happen as soon as 2030. Thus, we might already have committed future generations to living with sea-level rises of around 10 m over thousands of years. …. At 1.5 °C, it could take 10,000 years to unfold3; above 2 °C it could take less than 1,000 years*


Comment
Climate tipping points — too risky to bet against

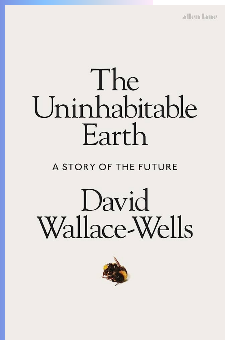
- **“The economics of immense risk, urgent action and radical change: towards new approaches to the economics of climate change”**
  - Stern, Stiglitz and Taylor, 2022
  - *“the optimization framework embodied in IAMs is inadequate to capture deep uncertainty and extreme risk”*
  - *IAM provide no guidance on how to resolve differences in key judgements around risk and uncertainty*
- **The conservative/incomplete nature of impact assessment in IAM is well-documented**
  - Swiss Re Institute
    - → -11% in 2050 at +2C, -14% at +2.6C, -18% at +3.2C
    - → Rule of thumb applied to Moody’s model : x 10 ☺
  - Moody’s “The Economic Implication of Climate Change”, 2019
    - → For US, equivalent to Nordhaus’s finding !
+1.5C : 0.7% impact on GDP, 2C: 1.3%,4C:3.6%
    - → The world map is interesting

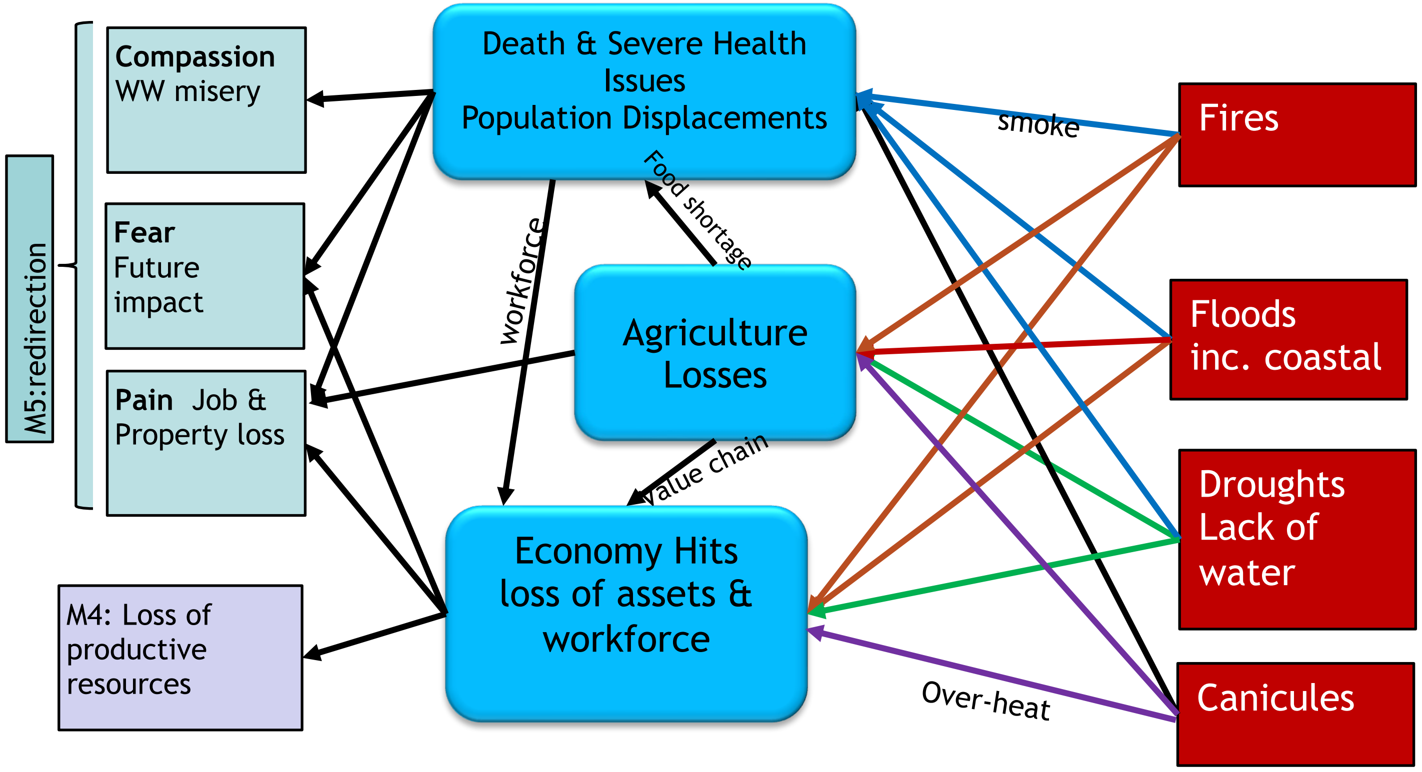


Global Warming Impact : The Unknown Unknown



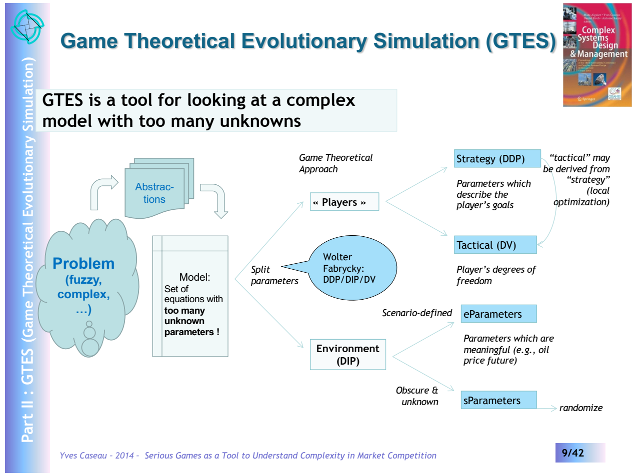
- A synthesis of hundreds of published research articles
  - *Compared to the trajectory of economic growth with no climate change, their average projection is for a 23 percent loss in per capita earning globally by the end of this century*
  - *Which means that if the planet is five degrees warmer at the end of the century, when projections suggest we may have as many as 50 percent more people to feed, we may also have 50 percent less grain to give them*
    - *We will, almost certainly, avoid eight degrees of warming; in fact, several recent papers have suggested the climate is actually less sensitive to emissions than we'd thought, and that even the upper bound of a business-as-usual path would bring us to about five degrees, with a likely destination around four.*





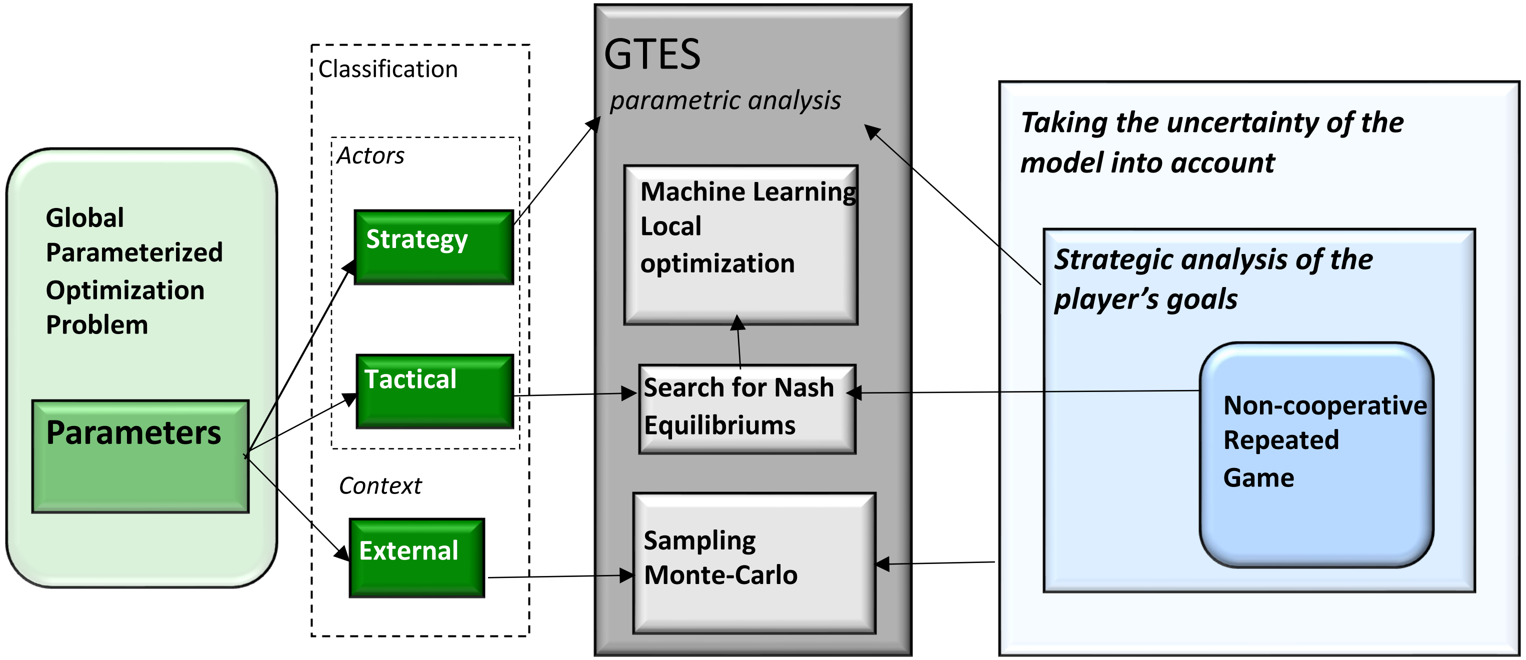
Simplified categories of impacts
- Destruction of properties
- Health – loss of productive workforce
- Lack of water
- Loss of agricultural surface
- Loss of efficiency

Global Warming, Geopolitics and Game-Theory



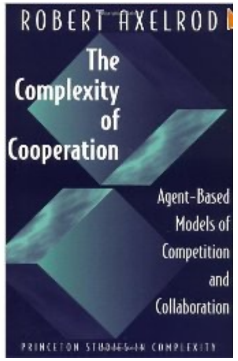
GTES (game-theoretical evolutionary simulation) is a proven framework:

- For complex systems with "known unknowns"
- To look for possible Nash equilibriums …
- … to explore the interplay of beliefs

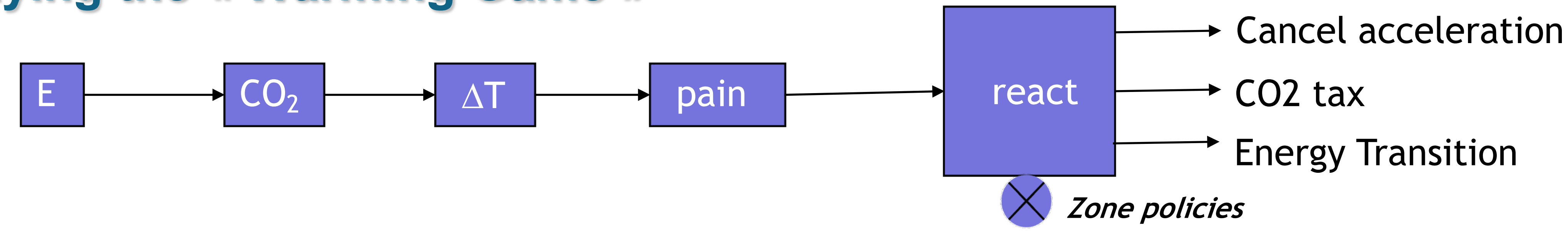


An approach inspired by Robert Axelrod pioneering work on Agent-based models of cooperation & competition

- E.g.; experimental/evolutionary validation of TIT-for-TAT strategy in a repeated prisoner dilemma game
- Developed for Telco market competition simulation (3G, 4G, Free) and other complex SD models



Playing the « Warming Game »



- **Policies** (<u>tactical</u> parameters for GTES = BR in game theory)
  - Linear function from pain to two percentages [min%,max%]
- **Strategy** = goals for each zone
  - GDP, Pain level, World temperature (vector of weight that defines the goals of zones)

- GTES will look for a Nash Equilibrium between the four players that maximizes the weighted goals

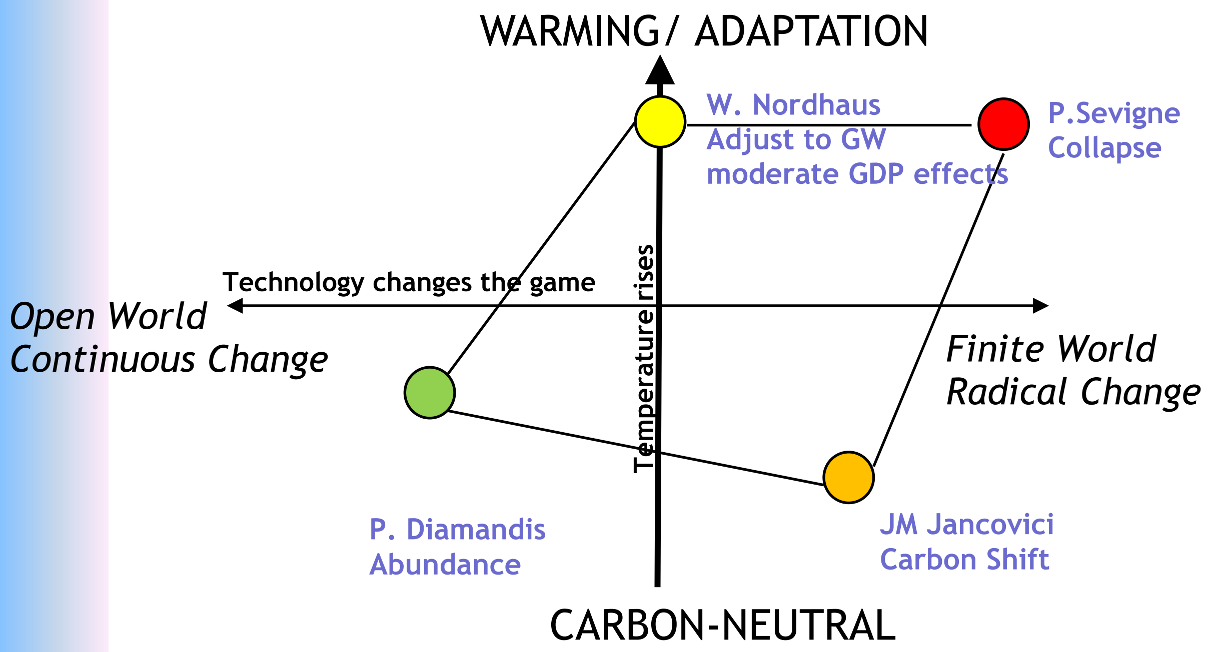
Example of Questions :

- *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, …) ?*

- Leverage GTES framework to randomize beliefs (from curves to « trapeze » areas)

Conclusion

- A tool to explore beliefs (mental models) and their combined effects
- A fine-line between over-complexity (hence overfitting) and *naiveté* (irrelevant)
- If, and only if, CCEM shows relevance, move to game-theoretical analysis
- On-going work (**https://github.com/ycaseau/GWDG**)

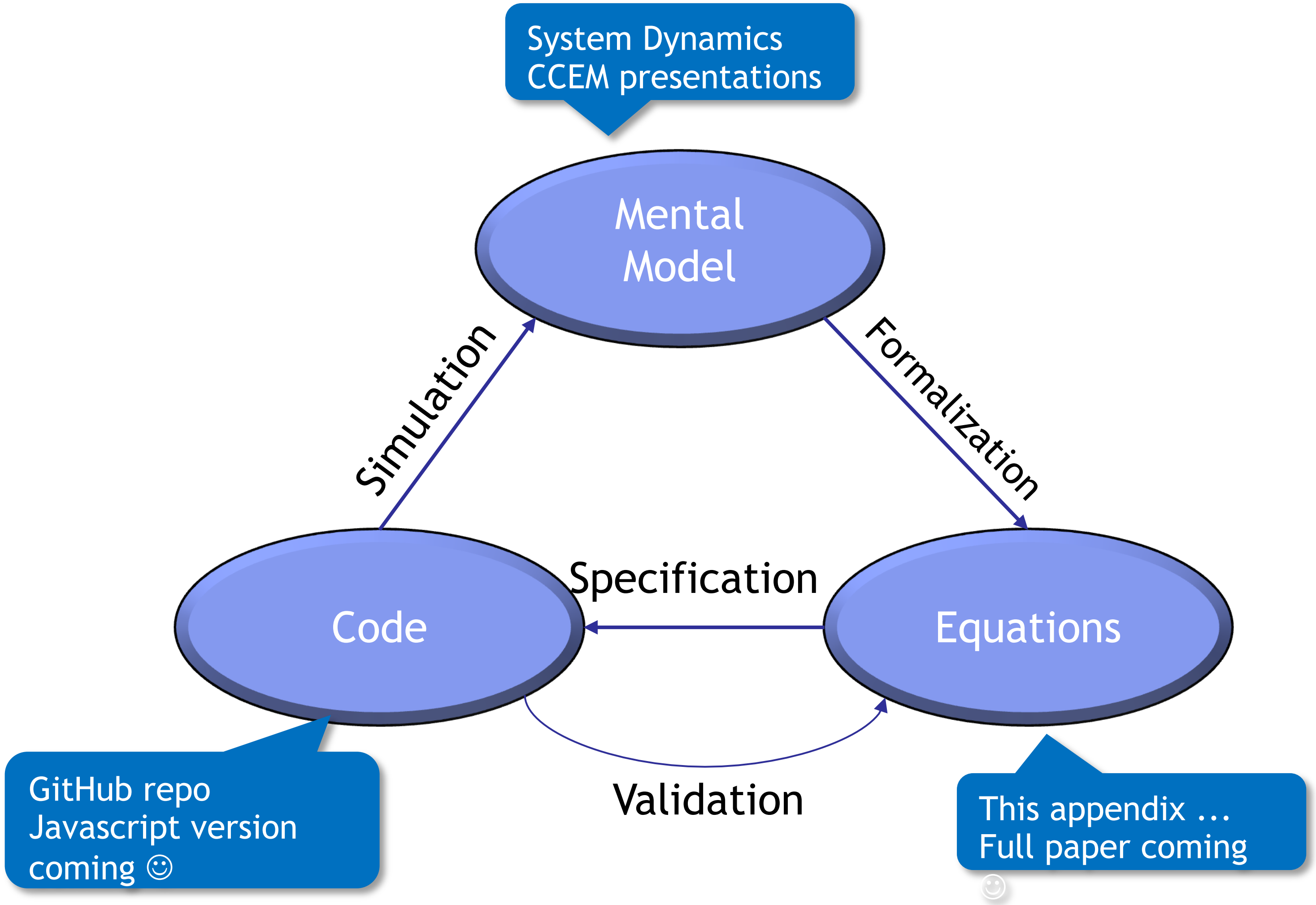


Major Open Questions

Any help is welcome ☺

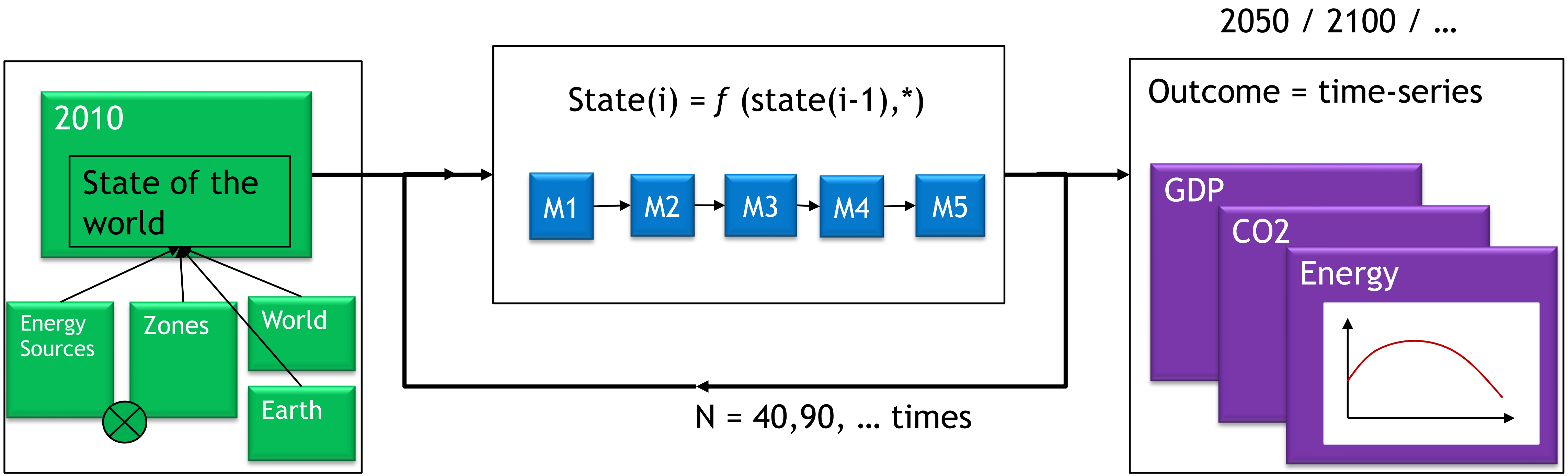
1. Zone differential growth model ….
   - *How to explain the flat decade (2010-2020) for Europe vs US / China ?*
2. Impact of global trade, for instance impact of China isolation
   - *Balance of trade is small versus GDP, but many indirections …*
3. Dependency from material to immaterial economy
   - *Cf. "Nordhaus'paradox" (Agriculture is 3% of GDP, so impact of agriculture losses should be limited …)*
4. Move from World Energy Market to regional strategic commodities with different prices ?
   - *What we see today ! Possible cause of 1 ?*
5. Global warming damages to economy

Appendix



System Dynamics
CCEM presentations
Mental Model
Simulation
Formalization
Specification
Code
Equations
Validation
GitHub repo
Javascript version
coming ☺
This appendix …
Full paper coming
☺

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)

M1: Energy Production

Belief: Known Unknowns

Data-Driven Parameters

Data Model

Two kinds of sources of primary energy (e):
- FossilFuels :Oil, Goal, Gas
- One combined “Clean” (nuclear & renewable)

Energy sources are described through the max capacity (that varies), the yearly output (depending on supply-demand) and, for fossil fuels, the known reserves

The main component of M1 is the Supply equation that describes output as a function of price

Parameters

- *maxCapacityGrowth*(e,y) : for clean energy y, expected max caoacity in Gtoe that may be added during year y (yearly production)
- *Inventory*(e,p) : expected reserves (at year 1) for fossil fuel e with a market price p
- *threshold*(e) : part of current reserve when suppliers of e reduce their output to match reserves (strong influence on PeakOil date)

- *targetMaxRatio*(e) : expected ratio between (max) capacity and output
- *maxGrowthRate*(e): percentage of capacity that can be added at most in a year for fossil e
- *sensitivity*(e) : price sensitivity factor for energy e
- *co2perTon(e)* : CO2 emissions to produce one toe of energy e

State Variables:

- $O_e(y)$: output (production) in Gtoe for energy e at year y
- $C_e(y)$: max capacity in Gtoe for energy e
- $A_e(y)$: added capacity for energy e through transfers (M3)
- $tO_e(y)$: total output in Gtoe from years 1 to y
- $P_e(y)$: price in $ for 1 toe for energy e at year y
- $UD_z(y)$: demand (unconstrained consumption) for zone z of energy e
- $G_z(y)$: gdp for zone z on year y

Equations (functions & differential state)

$$\mathit{Supply}(e{:}Fossil,p,C_{max}) = \min(C_{max}, \max(0,O_e(1) * (C_{max} / C_e(1)) * (P_e(1) + (p - P_e(1)) * sensitivity(e)) / P_e(1))$$

$$\mathit{Supply}(e{:}Green,p,C_{max}) = \min(C_{max}, (C_{max} * \mathit{targetMaxRatio}(e) * (p / (P_e(1) * (1 + (G(y-1) / G(1)) * sensitivity(e)))$$

$$\mathit{Capacity}(e{:}Fossil,y,p) = \min(\min(\mathit{expectedOutput}(e,y), C_e(y - 1) * (1 + \mathit{maxGrowthRate}(e)) + A_e(y-)), C_e(y - 1) * (Inventory(e,p) - tO_e(y - 1))/ \mathit{threshold}(e)))$$

$$\mathit{Capacity}(e{:}Green,y,p) = \min(\mathit{expectedOutput}(e,y), C_e(y - 1) + \mathit{maxCapacityGrowthRate}(e,y) + A_e(y-1)),$$

$$\mathit{expectedOutput}(e,y) = [\Sigma_{z \text{ in zone}} \text{linearRegression}(UD_z(y-3), UD_z(y-2)\ UD_z(y-1))] * \mathit{targetMaxRatio}(e)$$

M2: Energy Consumption

Belief

Data-driven

Data Model

- Four Energy sources, Four zones : EU,US, CN, RoW
- M2 is based on analyzing the gdp production through "homogeneous slices" to state 4 beliefs: Energy density, cancel, GDP & margin impact
- M2 factors efficiency gains through technology through the "saving" parameter for each zone
- M3 described the "energy transition" that transfers some of the needs from one energy source to another

Parameters

- *cancel*(z,p) : share (percentage) of economy for zone z if the oil price equivalent reaches p
- *impact*(z,p) : associated impact on gdp (output of the remaining activities) when price is p
- *population*(z,y) : expected population of zone z at year y
- *dematerialize*(e,y) : expected decline in energy density (gdp/conso) for zone z
- *savings*(e,y) : share (percent) of energy that can be saved (efficiency) with iso-output

- *economyRatio*(z,y) : heuritiscs that combines the expected growth of the zone gdp (from the amount of past investments) and the mutual influence of zones through global trade
- pop2energy(z): ratio between energy consumption grow

State Variables:

- $R_z(e,y)$: raw needs for energy e in Gtoe at year y (before efficiency or transition is applied)
- $N_z(e,y)$: needs for energy e in zone z during year y once energy transition transfers are applied
- $Tr(e_1,e_2,y)$: fraction of energy e_1 demand that has been transferred to energy source e_2 at year y
- $U_z(e,y)$: usage (constrained consumption) for zone z of energy e
- $P_e(y)$: Price for energy e (\$/toe) at year y
- $S_z(y)$: percentage of savings reached at year y

Equations (functions & differential state)

$R_z(e,y) = U_z(e,1) * \textit{economyRatio}(z,y) * (1 - \textit{dematerialize}(e,y)) * \text{populationRatio}(z,y)$

$\text{populationRatio}(z,y) = 1 + (\textit{population}(z,y) / \textit{population}(z,1) - 1) * \textit{pop2energy}(z)$

$N_z(e,y) = R_z(e,y) + \Sigma_{e1<e} R_z(e1,y) * Tr(e1,e,y) - \Sigma_{e<e2} R_z(e2,y) * Tr(e,e2,y)$

$\textit{Demand}(e,z,y,p) = N_z(e,y) * (1 - S_z(y - 1) - \textit{cancel}(z,p))$
$\text{Demand}(e,y,p) = \Sigma_z \text{Demand}(e,z,y,p)$

$P_e(y) = \, ! \, p \mid \textit{Demand}(e,y,p) = \textit{Supply}(e,y,p)$

$C_e(y) = \max(C_e(y-1) , \textit{Capacity}(e,y, P_e(y)))$
$O_e(y) = \Sigma_z \textit{Supply}(e,z,y,p)$

M3: Energy Transition

Belief

Data-driven

Data Model

Energy sources are ordered
- Oil < Coal < Gas < Clean
- Yielding 6 transitions (e1 -> e2)

The energy transition is a time-dependant matrix that represent the possible transfer of one primary source another (thanks to industrial investments or the use of vectors such as electricity)

Parameters

- *transitionRate*(z,e_1,e_2, y) : maximum transfer of energy needs from primary source e1 to e2 at year y, expressed as a percent

- *techEfficiency*(z) : yearly growth of tech efficiency (cost reduction in investment to build a production capacity)
- investPrice(e) : investment that is necessary to build a capacity of 1Gtoe/y at year 1
- ftech(z) : expected yearly decline of investPrice in zone z (technology progress)
- steelFactor(e) : part of steel cost in total cost of investment for e

State Variables:

- $P_e(y)$: price in $ for 1 toe for energy e at year y
- $U_z(e,y)$: usage (constrained consumption) for zone z of energy e
- $S_z(y)$: percentage of savings reached at year y
- $CN_z(y)$: percentage of consommation canceled in zone z at year y, because the price is too high
- $IE_z(y)$: investments for new energy capacity for energy source z at year y
- SP(y): steel price for year y

Equations (functions & differential state)

$$U_z(e,y) = N_z(e,y) * (1 - savings(z,y-1) - cancel(z, P_e(y)))$$

$$S_z(y) = \max(S_z(y-1), savings(z, P_e(y)))$$
$$CN_z(y) = \max(cancels(z, P_e(y))$$

$$Tr(e1,e2,y,) = \max(Tr(e1,e2,y-1), \min(transitionRate(z,e1,e2,y), \max(Tr(e1,e2,y-1) + \mathit{maxGrowthRate}(e))$$

$$IE_z(y) = [\ (\Sigma_e \max(0, C_e(y) - C_e(y-1)) * (U_z(e,y) / \Sigma_{z1} U_{z1}(e,y)) + \Sigma_e (N_z(e,y) * \max(0, S(y) - STr(e1,e2,y))) + \Sigma_{e1<e2} N_z(e2,y) * \max(0, (Tr(e1,e2,y) - (Tr(e1,e2,y-1)))] * investPrice(s) * (1 - sf(e) + (sf(e) * SP(y) / SP(1)) * (1 - ftech)^{y} *$$

M4: World Economy

Belief

Policy

Data Model

Computes two trajectories
- expected gdp (maxout) without energy constraints
- gdp = constrained growth because of cancellation

GDP is produced from assets that grows according to investments but require energy

Investments are a share of GDP that is reduced two ways
- when energy price goes up, margins reduce
- activities that are cancelled require social management which impairs the ability to invest

Parameters

- *impact*(z,p) : impact of cancel on gdp n zone z when oil-equivalent price is p
- *margin*(z,p) : impact on profits for remaining activities of zone z when oil-equivalent price is p
- *roi*(z,y) : expected return on investment (R/I) = additional gdp expected R for investment I in future year y for zone z
- disasterLoss(z,T) : loss of gdp (%) when temperature raises to T
- ironDensity(z,y): density of iron in z economy (gdp / Gt of steel)

- Alpha(z,t) : fraction of energy that is "redistributed" with subsidy (versus free market)

- *IRatio*(z) : part of gdp that zone z attributes to investments
- iRevenue(z): share of revenue that is invested
- Energy4steel(y) : energy needed to produce one ton of steel in year y

State Variables:

- $M_z(y)$: theoretiocal "maxoutput" for zone z = gdp that would have occurred if all necessary energy was here
- $G_z(y)$: gdp for zone z on year y ($G(y) = \Sigma_z\, G_z(y)$)
- $I_z(y)$: amounts of investments
- $IG_z(y)$: amounts of investments
- $SC_z(y)$: steel consummation for zone z at year y
- SP(y): steel price for year y

Equations (functions & differential state)

$$M_z(y) = M_z(y-1) * (\mathit{population}(z,y) / \mathit{population}(z,y-1)) + IG_z(y-1) * roi(z,y)$$

$$G_z(y) = M_z(y) * (1 - \mathit{impactCancel}(z,p)) * (1 - \mathit{disasterLoss}(T(y-1))$$

$$\mathit{impactCancel}(z,p) = alpha(z,y) * (CN_z(y) / U_z(y) + S_z(y) + CN_z(y) + (1 - alpha(z,y)) * impact(z,OP_e(y))$$

$$I_z(y) = G_z(y) * \mathit{iRevenue}(z) * (1 - \mathit{margin}(z,oilEquivent(y)) * (1 - \mathit{impactCancel}(z,p))$$

$$IG_z(y) = I_z(y) - IE_z(y)$$

$$\mathit{oilEquivalent}(y) = (\Sigma_e P_e(y) * P_{oil}(1) * O_e(y) / P_e(1)) / = (\Sigma_c O_e(y))$$

$$SC_z(y) = G_z(y) / \mathit{ironDensity}(z,y)$$

$$SP(y) = SP(1) * (\mathit{oilEquivalent}(y) * \mathit{energy4steel}(y)) / (\mathit{oilEquivalent}(1)) * \mathit{energy4steel}(1))$$

M5: Ecological Redirection

Belief | Policy

Data Model

We compute multiple impacts of CO_2 emissions:

- Average temperature elevation
- Total Area used for agriculture
- Wheat Output (a proxy of agriculture output)
- Reduction of gdp due to global warming
- Pain due to global warming

From the zone level of pain, we compute ecological redirection according to each zone policies, impacting CO_2 tax, sobriety (cancel) and energy transition acceleration

Parameters

- *bioHealth*(T,y): percentage of yield evolution, which declines when temperature raises but grows with worldwide diffusion of tech and best practices
- *agroEfficiency*(p) : decline of productivity as energy price increases
- *painProfile*(z) : vector of 3 coefficients that define the global pain level
- painFromClimate(T): step function that sets a pain level as temperature rises
- pain2Cancel(z,p) : policy that sets cancel acceleration (sobriety) as a function of pain
- pain2Transition (z,p) : policy linear function that links pain level p to Energy Transition acceleration
- *co2Neutral* : level of emissions that is approximately balanced by nature
- *co2Energy*: percentage of CO_2 emission due to fossile energy
- *co2Ratio*: additional concentration in the atmosphere from additional CO_2 emission (ratio)
- IPCC(c): temperature elevation caused by concentration c, extracted from IPCC RCPs
- *satisfaction*(z,dW,dG) : heuristics that defines satisfaction from WheatOutput change and GDP change

State Variables:

- AS(y): Agricultural surface on year y
- ES(y) : Areal that was transferred from Agriculture to Clean Energy Production
- WO(y): Wheat Output
- CO_2(y): emission for year y in Gt
- CO_2ppm(y): CO_2 concentration reached on year y
- T(y): average globe temperature on year y
- $PAIN_e(y)$: pain factor for zone z at year y
- $TaxF_z(y)$: intensification factor of CO_2 tax for z
- $CnF_z(y)$: acceleration of cancel (factor) for zone z
- TrF(y): acceleration of energy transition (factor)

Equations (functions & differential state)

$$CO2(y) = (\Sigma_e O_e(y) * co2perTon(e)) / co2Energy$$
$$CO2ppm(y) = CO2ppm(y-1) + (CO2(y) - co2Neutral) * eCO2Ratio$$

$$T(y) = T(1) + (IPCC(CO2(y)) - IPCC(CO2(1)))$$

$$ES(y) = ES(y-1) + \Delta C_{clean}(y) * landEImpact(y)$$
$$AS(y) = (AS(y1) - ES(y)) * (1 - landLossWarming(T(y)))$$
$$WO(y) = WO(1) * \uparrow AS(y) * \uparrow aggroEfficiency(oilEquivalent(y)) * bioHealth(y,T(y))$$

$\uparrow F(y) = F(y)/F(1)$

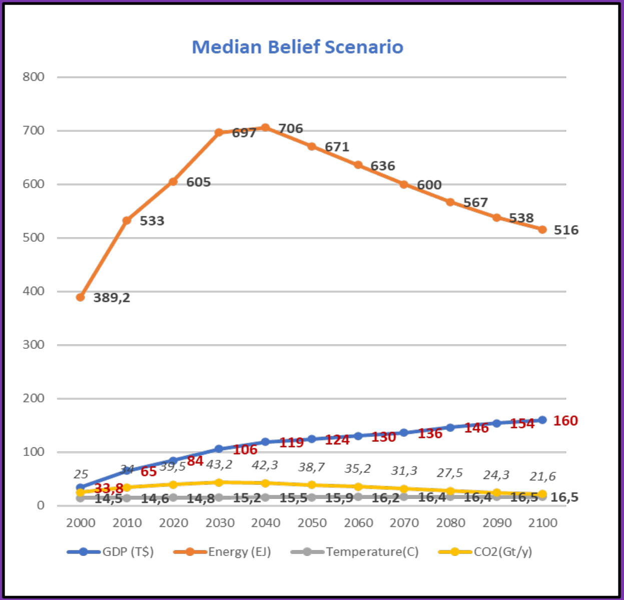
$$PAIN_z(y) = painProfile(z) \,.\, (painFromClimate(T(y)),\ (Cn_z(y) \times (1 - Alpha(z)),\ satisfaction(z, WO(y) - WO(y-1), (G_z(y) - G_z(y-1)) / Pop_z(y)))$$

$$TaxF_z(y) = pain2Tax(z, PAIN_z(y))$$
$$CnF_z(y) = pain2cancel(z, PAIN_z(y))$$
$$TrF_z(y) = pain2transition(z, PAIN_z(y))$$

CCEM : From Beliefs to Simulation to Outcomes

True value : revisit your beliefs from observing outcomes

Outcome



What you
Give as
An input

Beliefs

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

N
iterations

What you
Play with during
simulation

Levers

- Energy Transition roadmap
- CO2 Tax
- Redistribution

GTES
Game-Theory
Evolutionary Simulation

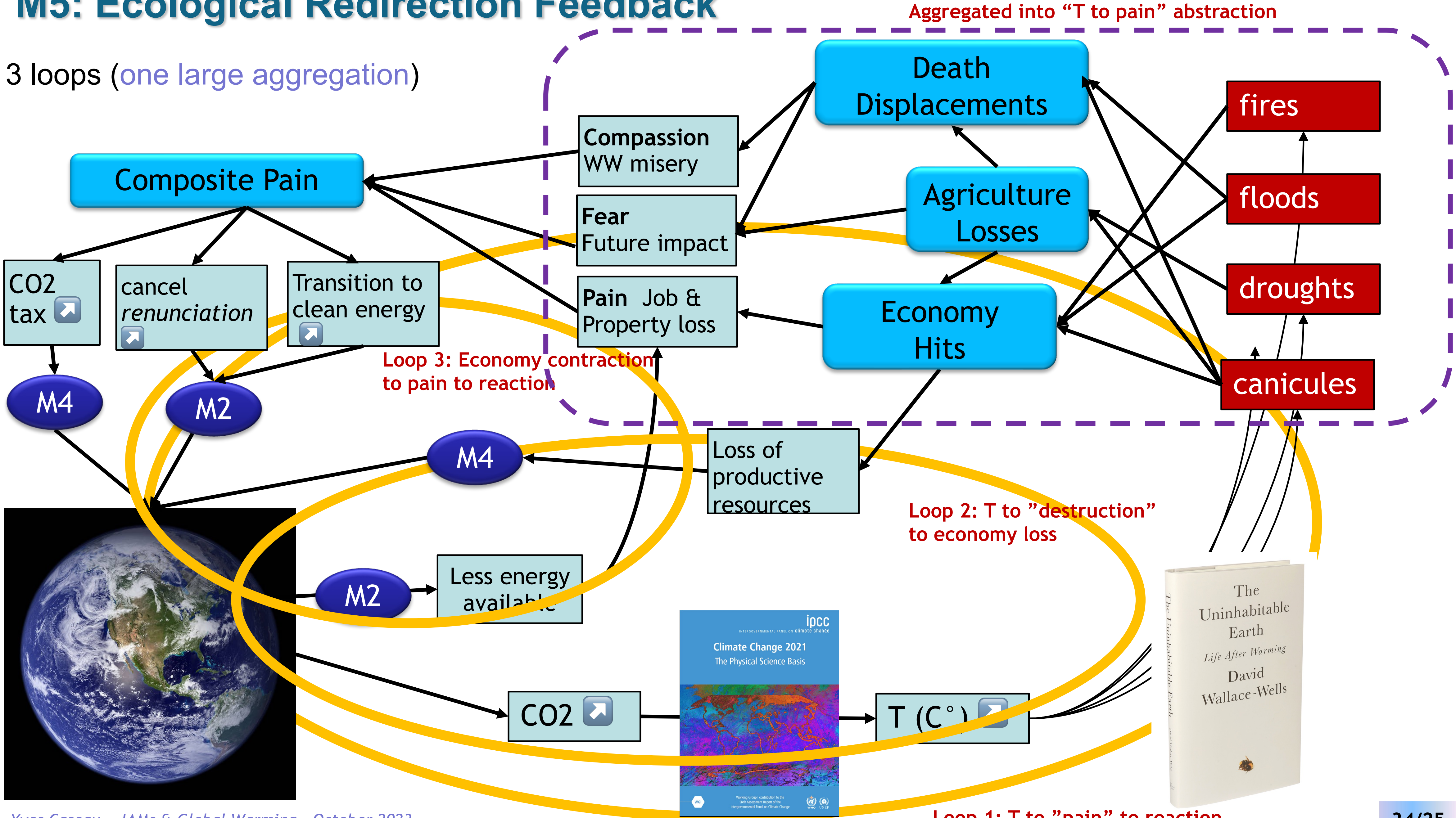
Do not use
CCEM if you
disagree

Foundations

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

M5: Ecological Redirection Feedback

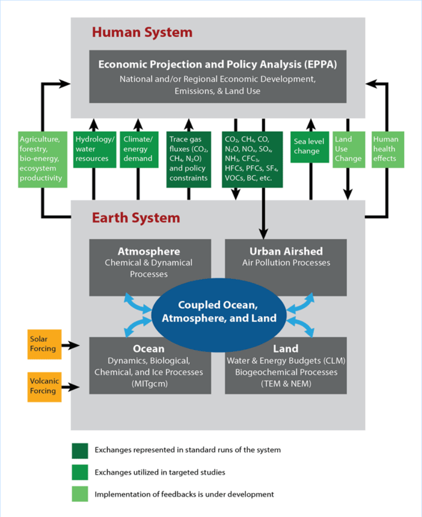
- 3 loops (one large aggregation)



Similar Earth Models

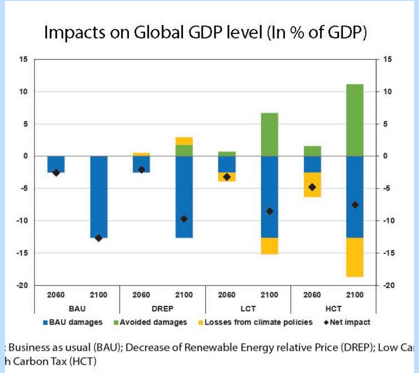
MIT Integrated Global System Modeling (IGSM) Framework

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.



ACCL (Banque de France)

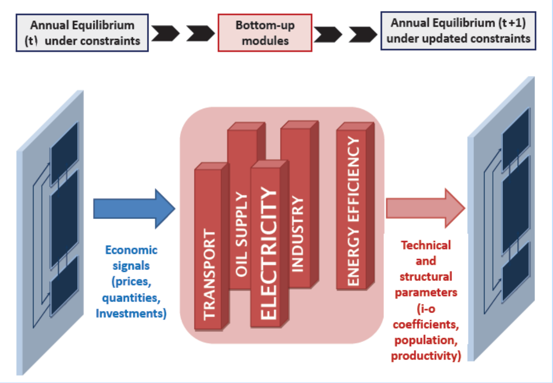
A tool to build climate change scenarios to forecast Gross Domestic Product (GDP), modelling both GDP damage due to climate change and the GDP impact of mitigating measures. It adopts a supply-side, long-term view, with 2060 and 2100 horizons. It is a global projection tool (30 countries / regions), 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,



IMACLIM (Cired)

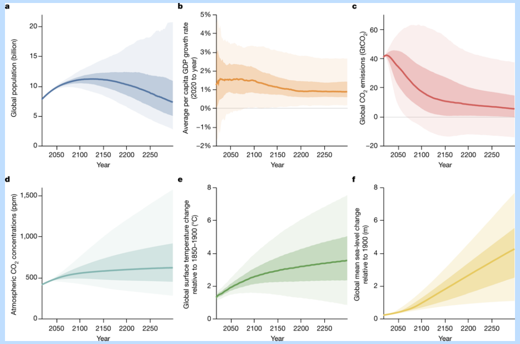
IMACLIM-R is a hybrid recursive general equilibrium model of the world economy that is split into 12 regions and 12 sectors. The base year of the model is 2001 and it is solved in a yearly time step. IMACLIM-R is built on the GTAP-6 database that provides, for the year 2001, a balanced Social Accounting Matrix (SAM) of the world economy. Like any conventional general equilibrium model, IMACLIM-R provides a consistent macroeconomic framework to assess the energy-economy relationship

It represents the interactions between sectors and countries over time through the clearing of commodities markets



GIVE (Greenhouse gas Impact Value Estimator)

The Social Cost of Carbon Explorer is a data tool that allows users to generate updated estimates of the social cost of carbon (SCC), which is the dollar estimate of the economic damages from emitting one additional ton of carbon dioxide into the atmosphere. The SCC Explorer is powered by the open-source RFF-Berkeley Greenhouse Gas Impact Value Estimator (GIVE) model which iis based on Four modules: Socioeconomic, Climate, Damages, Discounting (for SCC)



Serious Games : Key Take-aways from 2012