CCEM: A System Dynamics Earth Model for Capturing Beliefs Related to the Coupling of Energy, Economy and Global Warming

Yves CASEAU

National Academy of Technology of France, Paris, France
(e-mail: yves.caseau@academie-technologies.fr)

Abstract: This paper presents CCEM (Coupling Coarse Earth Models), a system dynamics simulation model that represents the earth as a complex system, with a focus on the feedback loops associated with global warming. CCEM combines five simpler models, addressing energy availability, economic adjustment to energy scarcity, energy transition, global economy and CO2 emissions, and the impact of CO2 emissions on warming and society. The model aims to make implicit beliefs explicit and demonstrate that the same mental model can support various viewpoints by changing beliefs associated with "known unknowns". CCEM, compared with other Integrated Assessment Models (IAM), enriches the feedback loop from global warming to the energy/economy system by representing the impacts of global warming and the associated retroactions. The model introduces a "pain factor" as a non-linear trigger for redirection, accounting for pain from warming, economic results, and energy shortages. CCEM emphasizes that the complex system of energy, economy, climate, and society will evolve chaotically through redirections, making forecasting and planning difficult, but provides a foundation for game theoretical analysis of mitigation and adaptation strategies.

Keywords: IAM, system dynamics, ecological redirection, energy transition, known unknowns, global warming impacts, Anthropocene.

1. INTRODUCTION

This paper presents a novel System Dynamics Earth Model (SDEM), engineered as a simulation framework that considers energy, economy, climate change and global warming impact as a complex system with feedback loops. IAM (Integrated Assessment Models) have played a key role for policy makers, resulting with their integration into the International Panel on Climate Change (IPCC, 2021) to gauge the effects of global warming and its ensuing repercussions. This paper's SDEM endeavors to incorporate the dynamic interaction between the economic and energy sectors, which are pivotal in driving CO2 emissions from fossil fuels, and to simulate the global response to escalations in temperature. Furthermore, CCEM expands the complex causal relationships that the IPCC Representative Concentration Pathways (RCP) scenarios convey, mapping the circuit from energy consumption to CO2 emissions and vice versa.

CCEM is defined through the combination of five constituent models. The first model accounts for the availability and production cost of energy resources, acknowledging the uncertain nature of fossil fuel reserves. The second model simulates economic adaptations to the dual challenge of diminishing energy availability and escalating costs. The third model portrays the transition of energy sources, and the fourth represents the global economy's value generation from energy and resources while accounting for CO2 emissions. The final model delineates the warming effects of CO2 emissions, their impact on the economy and population, and potential societal responses. It is important to note that the paper's model accepts IPCC findings as a foundational input without contestation.

This paper is organized as follows. Section 2 further develops the motivations for this work and emphasizes the relation with other earth models. Section 3 focuses on "known unknows" and shows how CCEM makes the assumptions (beliefs) explicit. We propose a model for the "political and societal" feedback that could arise from global warming catastrophic impact. Section 4 presents the architecture of the CCEM model, made of the five sub-models (M1 to M5 in the rest of the paper) presented earlier. Each sub-model is capable to compute a part of the status of the "earth system" for a given year, from the status observed during the previous years. Section 5 illustrates CCEM with a few preliminary computational results, highlighting the importance of "median beliefs" as inputs. Section 5 also shows how making beliefs explicit support the modelling of very different visions regarding the upcoming global warming and its consequences.

2. CCEM IS A SYSTEM DYNAMICS EARTH MODEL

2.1 IAMs and SDEMs

Earth models study the interplay between energy production, economic activity, consumption, and climate effects via CO2 emissions. We suggest separating them into IAMs (Integrated Assessment Models), which are data-driven and based on past observations, and SDEMs (System Dynamics Earth Models), such as the 50-year-old "Limits to Growth" from MIT (Meadows, 2013). SDEMs are built « from first principles » with equations reflecting the *modeler's* world system understanding, while IAMs focus on state variables and dependencies identified from past data. CCEM, discussed in Section 3, aligns more with SDEM, drawing inspiration from "Limits to Growth" (LtG) but with a stronger emphasis on energy sources. Despite their abstract nature, SDEMs effectively illuminate systemic feedback loops and have historically replicated past trends well. However, CCEM also incorporates aspects of IAMs, including detailed economic growth and energy data.

More recently, the use of IAMs has been criticized from a methodological perspective (Stern et al., 2022) because IAM cannot capture the high level of risk and uncertainty that global warming damages may represent (Lenton et al., 2019). The system dynamics tradition of earth models has always made it clear that these models are not forecasting tools but designed for systemic analysis and should not be used without caution to generate SCC values using differential analysis. On the other hand, SDEM are interesting tools to address dramatic changes in the future because they can represent complex amplification loops and their "first-principle" nature makes them less sensitive to historical bias.

2.2 Going Deeper Than Previous SDEM

CCEM is a System Dynamics model (see Figure 1) which present many similarities with LtG and its many successors (Herrington, 2022), but with three specific focuses that will be presented in sections 3 and 4, and that represent the originality of the CCEM approach:

• CCEM energy production, consumption and transition (from one source of primary energy to another) is more sophisticated than most SDEM, and some IAMs. This allows for a more precise computation of energy consumption, energy savings, energy sobriety and most of all, the speed of electrification and deployments of renewable energies capacities. This makes CCEM an adequate framework for evaluating policies, such as the policies presented at COP28 and derived from IRENA scenarios (IRENA, 2023).

• CCEM has a richer-than-most model for global warming consequences (damages) and reactions (redirection). CCEM maps out the tangible and human impacts of climate change, such as natural disasters and psychological trauma, and considers the subsequent societal and political responses. These responses may include a reduction in productive capacity due to direct damage or societal costs, and the model anticipates potential political upheavals leading to "pain-induced" decisions.

• CCEM makes the "known unknowns", which we could characterize as beliefs, explicit. We recognize that, besides the model that translates CO2 into warming provided by IPCC, there are many unknowns that impact both the input (to CO2 emissions) or the "outputs" (consequences of warming). This makes CCEM a suitable framework to reproduce very different visions and trajectories, as we shall see in Section 5.2.

3. COUPLING COARSE EARTH MODELS

3.1 Making "Known Unknowns" explicit

Creating an Earth Model involves merging established causal reasoning with assumptions and policies to test hypotheses or optimize outcomes. When considering the coupling of energy, economy, and climate, we face five major uncertainties:

1. The future availability and cost of energy, notably from fossil fuels, and the speed at which renewable energy sources could be deployed. The capacity for deploying renewables is uncertain due to various factors, including material and manufacturing constraints.

2. The energy required by the economy at different costs, given the past trend of decreasing energy intensity (W.h per dollar of GDP). It's uncertain how long this trend will continue, and which sectors can adapt to or afford higher energy costs.

3. The rate at which we can transition from one type of primary energy to another, a critical element in managing global warming mitigation. This involves the complexities of different energy source characteristics and industry-specific transition capabilities.

4. The expected GDP (*gross domestic product)* growth driven by investments, technology, energy, and workforce without the constraints of energy shortage or productivity loss, which remains an uncertain "natural rate of growth."

5. The economic and societal impacts of the global warming predicted by the IPCC. The extent of productivity loss due to climate impacts is debated, and indirect effects of catastrophic climate events could deviate substantially from modeled paths, especially if temperatures exceed a 2°C increase.

3.2 CCEM Five Components Models

CCEM integrates five distinct models to simulate the complexities of global energy dynamics and their interplay with economic and environmental factors. Figure1 illustrates these five-model interaction, following the notations of John Sterman (Sterman, 2000), with some of the state variables for each model and some interactions (blue/red arrows).

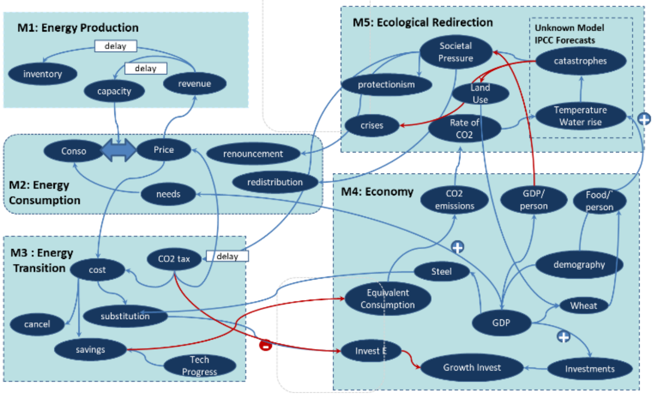

Figure 1: System Dynamics Simplified Overview

Model M1 forecasts the availability and cost of energy, distinguishing between fossil fuels and clean energy. Model M2 calculates the expected energy supply and actual consumption based on market prices across different world zones. The current version of CCEM operates over four zones: US, Europe, China and the rest of the world. Model M3 delineates the shift from one primary energy source to another, considering the pace, proportion, and investment required for this transition. Model M4 represents the global economy's value creation, factoring in growth from investments and energy supply from the other models, and includes a basic feedback loop for productivity loss due to ecological impacts. Model M5 abstracts from IPCC's global warming scenarios to assess temperature rises and their consequential negative impacts, which include productivity losses and policy shifts in energy and economic management.

3.3 CCEM Damages & Redirection Model

The term "redirection," as borrowed from Bruno Latour (Latour, 2017) and researchers on the Anthropocene (Adeney Thomas, 2020), encapsulates two critical insights within the CCEM framework. First, it recognizes the unpredictable and chaotic evolution of the interconnected energy, economy, climate, and society systems, acknowledging that planning in the face of such complexity is fraught with uncertainty. Second, it characterizes the system's evolution as a series of redirections, or context-specific decisions made in response to events such as major natural disasters. CCEM's feedback mechanisms, depicted in the associated Figure 2, include a production feedback loop and a societal feedback loop. The production loop deals with the GDP loss due to climatic catastrophes like fires and floods, which, despite being challenging to quantify, have been somewhat estimated in existing literature. The societal loop, or "redirection loop," is driven by the societal impact of global warming, which necessitates various redirection measures as a response to the experienced pain and disruptions.

In CCEM, a "pain factor" is introduced as a key driver for policy redirection in response to global warming. This factor is quantified by aggregating three types of pain: the direct or indirect pain from warming, which encompasses the fear and actual impact of natural disasters on lives and property; the pain from economic strain due to increasing inequalities and reduced growth, challenging governments to maintain social balance; and the pain from energy shortages, which forces reductions in energy use and the cessation of certain activities, especially critical ones. The "pain from warming" component is an aggregate of various climate impacts, portrayed in a specific section of the model. Pain is used subjectively as a trigger for action, emphasizing the importance of a consistent method to evaluate the diverse sources of pain, whether it be through empathy, fear, or direct experience of a catastrophe.

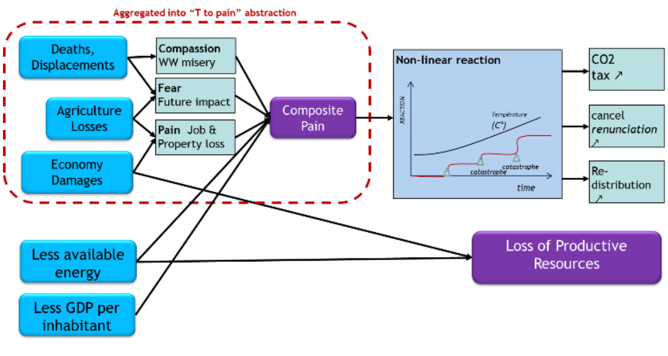

Figure 2: Pain and Redirection from Global Warming

4. FIVE COARSE MODELS

4.1 Energy production

The M1 model answers the two questions: (a) "*How much fossil energy can we access, at which costs?*" (b) "*How much clean energy could be made available in the future, at which costs?*". As mentioned earlier, CCEM distinguishes between three fossil fuels: oil, gas and coal, while regrouping all "clean" sources (wind, solar, hydro, nuclear) into one. For M1, we only consider primary sources of energies (M3 will take secondary forms and usage of energy into account).

For fossil fuels, the key "known unknown" is the inventory of accessible resources. This inventory is represented with a monotonic increasing function of the market price at which the energy may be sold. Between the time when CCEM started, 15 years ago, and now, the inventory has increased significantly due to shale oil and shale gas. This is less relevant for coal since the known reserves cover many centuries of usage, but it is a key parameter for the next 100 years as far as oil and gas are concerned. For each fossil fuel, M1 defines its inventory (a step-wise linear function that returns the accessible capacity as a function of market price), and yearly production capacity. This production capacity is a function of the max (theoretical) capacity, which is proportional to the total accessible inventory, and the possibility to grow this capacity (for each fossil fuel, we define the maximal increment, in proportion, that can be build each year).

For clean energy, the "known unknown" is the speed at which we may grow (our solar and wind farms, the hydroelectric potential, the nuclear facilities …). There are many reasons for which this is hard to forecast: availability of material resources, evolution of technology efficiency, capacity of financing, etc. As a key belief of M1, this is represented as a yearly forecast (a monotonic increasing function that associate to each year the total capacity for clean energy).

4.2 Energy consumption

The model M2 captures the answer to the question "*How is each part of our GDP dependent on energy?*". Some economic activities are very sensitive to energy since energy is one of their major costs associated with value creation. For some others, energy plays a much smaller role. To simplify CCEM simulation, we represent our understanding of energy consumption with four curves:

• For each region *z*, *cancel(z,p)* is a function that associate to each price (of energy) the fraction of activity that is no longer profitable (hence is "cancelled"), expressed as an energy consumption share. We use the equivalent oil price to normalize these functions.

• For each zone *z*, *impact(z,p)* is another function that tells, for a given percentage of activity that is "cancelled", which share of the associated GDP is lost. If market laws are in action, we expect the less profitable activities to stop first. If energy redistribution is involved, it may be different: a management of energy shortages through restrictions and policies may produce a bigger impact (loss of the same share of GDP and activity).

• For each zone *z*, *margin(z,p)* represents the impact on profits for remaining activities (the one that are not cancelled) of zone *z* when oil-equivalent price is *p*. As price of energy goes up, it eats a faction of the profit made by the activity.

• Last, the distribution of value creation from energy evolves with time. The KPI that is used to represent this evolution is *dematerialize(e,y)* : expected decline in energy density (gdp/ energy consumption) for zone *z*. This is also called energy intensity of the economy for zone *z*.

However, there is another force at play, namely that of technological progress, that increases the energy efficiency, this reducing the amount of energy needed to produce the same value. Somehow a key prospective question for the next century is to evaluate the race between resource depletion due to overconsumption and technology innovation. This is captured with another belief associated to M2:

• For each region *z*, *savings(z,y)* is a "roadmap", a function that associate to each year *y* the percentage of energy consumption that could be saved while keeping the same output. This is a "technology potential", which requires each region to invest (the "energy investment") at a cost (G$ / saved MW) that declines over time (a coefficient that is part of the same "belief"). Note that "dematerialization" talks about the evolution of the economy, where "savings" talks about efficiency for the existing activity.

4.3 Energy transition

The Energy Transition model captures the question "*How fast can we substitute from one source of primary energy to another*?" (Püttgen, 2022). For each transition, our "belief" is a roadmap, a function that tells for each year which share of energy consumption may be transferred to another source. Since there are four kinds of primary energy in the CCEM model, and since we assume transitions to be oriented (a simplifying assumption), there are six transitions to consider: Coal to Oil (using CTL techniques), Coal to Gas (which we have seen a fair amount in the US during the last decade), Coal to Clean, Oil to Gas, Oil to Clean, and Gas to Clean.

There are many constraints that make this energy transition difficult and costly. Energy sources have different uses with different constraints (such as mobility, intermittence, etc.) which yields the use of secondary sources of energy, also called "vectors" (electricity, hydrogen, …). Substitutions require time and investment. Therefore, they are represented in M3 as a "belief", a transition roadmap for each zone that says, for each of the fix transition (A →B), which share of A's consumption may be transformed into B. The model will compute the actual level of substitution achieved for a given year and will also generate the requested "energy investments". Energy Transition is a critical belief and one where there is a huge difference between the techno-optimists who believe that electrification of energy can be pushed forward very fast, and the "realists" who see a lot of viscosity in the transfers.

4.4 World and zone economies

The world economy model (M4) represents the question "*which GDP is produced from a given amount of investment, technology, energy and workforce*?". It uses a simple exponential growth model (as is the case of most earth models) based on productive assets creating value over a unit of time using energy. The exponential growth comes from the fact that a part of the output at time N is invested into adding to the productive assets for the next years, as illustrated by Figure 3. Investments are separated into energy transition investments, which are necessary to perform the transition steps (see M3), and growth investments. This exponential growth may be slowed down if not enough energy is available, or if some resources are incapacitated by the catastrophic consequences of global warming (output from model 5). This figure also illustrates some aspects of energy demand shown in M2, namely the influence of population, technology and economic activity. The input loop of "energy demand" represents the positive influence of population growth and technology improvement on economic growth.

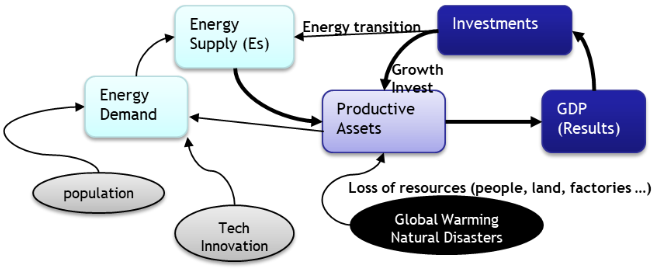

Figure 3: Economy Growth System

The key variable here is GPD, measured in current dollars for each zone. Still, monetary values (GDP, as well as energy prices) are to be considered with caution. Fortunately, their main role in CCEM is to act as a regulation agent between sub-models, and this works irrespectively of what the value represents. Because GDP, when measured in current dollars, is somehow immaterial, we have added two material outputs that are reasonably easy to forecast and may act as "proxies" of the material economy, namely steel output and wheat output.

• Taking steel production into account is a way to capture "raw materials" as a limiting factor for energy transition (Vidal, 2021). The steel output is derived from iron density (observed through the past decade and defined as a new CCEM "known unknown" parameter). The steel price evolution takes into account the "energy density" of steel production and the energy price computed by M2.

• Similarly, CCEM takes agriculture into account though wheat production. The production is derived from the total surface made available for agriculture (which may be reduced both by global warming and through assigning lands to energy production), and the productivity of agriculture, itself a combination of yield (another "known unknown" parameter, for which many studies are available) and automation through energy and machines (as energy gets more scarce, it has an impact on how much production may be delivered).

4.5 Ecological redirections

The M5 Model answers the question "*What kind of consequences should we expect from the global warming* *forecasted by the IPCC models*?". There are three successive sub-questions:

• What is the temperature elevation produced by the raise of CO2 (and other greenhouse gas)?

• What are the economic consequences of this warming? (mostly, the SCC question)

• How will the humanity react (from the population to the economy as a system)?

The first sub-question is addressed by abstracting the IPCC forecasts into a function that tells the temperature elevation as a function of the atmosphere CO2 concentration (cf. section 2.3). This is a coarse simplification and shows that CCEM does not attempt to be as precise as some other models such as IGSM (Sokolov, 2005). This function is extracted from the representative concentration pathways (RCP 4.5, RCP 6 and RCP 8.5) of the IPCC reports. More precisely, it means that we have extracted from these RPC a linear relationship between CO2 emissions and CO2 concentrations.

The second sub-question is more complex but there is a wealth of literature on the topic. CCEM lets the user represent her "belief" as a function that gives the percentage of GDP loss as a function of temperature elevation. This is a *known unknown*, as there is a wide variety of opinions on this topic, but it also fairly easy to decide if you want to use the output of Nordhaus model (Nordhaus,2019), or a more realistic output from ACCL (Alestra, 2020), or come up with your own belief after reading a transverse study such as (Wade, 2016).

The third question is the more difficult one, and the reason for building the CCEM model. Without a feedback loop, it is easy to forecast a catastrophic ending, or a "business as usual" scenario, depending on your initial belief. But the reality of our "path towards catastrophe" will probably show some bifurcations, with some drastic reactions to some of the catastrophic events that global warming is bound to produce. This is where the concept of ecological redirection is quite useful. Instead of talking about "ecological transition" which makes little sense for a complex system with so many couplings (unless your beliefs are such that you think it will continue to operate "linearly" in the next century), it is better to assume that we have no idea of the final destination ("*où atterrir?*", Bruno Latour, 2017). Redirection modeling may be seen as an oxymoron, it means to simply model the possibility of bifurcation along the path of global warming. In the current version of the model, we only consider three kinds of redirection:

• Acceleration of CO2 taxes (which includes the globalization and forced adoption by all countries).

• "Cancellation", that is renouncing as some form of energy source for some usages. The example of banning non-electric cars in Europe starting 2035 is a perfect example.

• Energy policy, which is the combination of accelerating the energy transition and modifying the "energy redistribution" policy. Redistribution here means distributing either the energy or the right to produce CO2 emissions according to a political rule, by opposition to market forces. The state subsidies of energy for citizens, that we saw as a consequence of the Russia-Ukraine war, is a perfect example.

5. CCEM COMPUTATIONAL RESULTS

5.1 Results on typical beliefs

The outcome shown in Figure 4 are just illustration of what the outcome of a simulation run looks like. The time origin is 2010. The models M1 to M4 were developed so that they may reproduce the "past" (1980-2010), and then calibrated to match 2020 results. The left part of the figure reports the indicators that are usually found in similar reports about earth models (see DICE or ACCL for instance): GDP, total primary energy production, CO2 emission and resulting temperature (yearly worldwide average). The right part of the figure reports the same data using the Kaya identity to define performance indicators: GDP / inhabitant, energy density (W.h to produce 1$ of GDP), and CO2 intensity of energy (gCO2 / kW.h). It should be stated that SDEM are not meant to produce static displays, but more to produce dynamic graphs that the user may interact with. Showing a static trace sends the wrong message that this is a tool for forecasts, whereas SEDMs are tools to experience feedback loops.

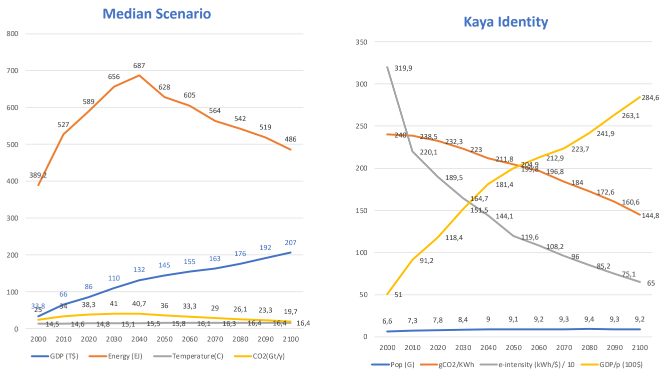

Figure 4: Simulation outputs for a "median beliefs" scenario

5.2 CCEM supports very different viewpoints

The following figure (Figure 5) illustrates 3 simulations where we have changed the beliefs to attempt to capture other trajectories that are reported by other authors (we do not claim to reproduce other more complex models here, but rather to be inspired by alternative scenarios):

• The "energy-rich" scenario is an attempt to reproduce some the results from older DICE simulation, using parametric optimization to assess the best CO2 taxes to optimize GDP output. The most interesting aspect is that we need to revisit the previous M1 belief to give full access to enough non-conventional oil and gas, in order to get at the same time a higher GDP output than the previous scenario and, as a consequence, higher CO2 emissions, yielding the +3C global warming mentioned in the introduction.

• The "stick to the Paris Agreement" scenario is an attempt to stay as close as possible to the +1.5C global warming, forcing an accelerated move towards energy saving and energy transition through aggressive CO2 taxation. The energy output is very much reduced, which is the only way to reduce the CO2 emission to the desired level. Consequently, the economy output is also significantly reduced compared to other scenarios, especially in the 2040-2050 period (things get better at the end of the century once the transition is achieved).

• The third "Exponential Technologies" scenario is an attempt to reproduce the approach from some thinkers associated to the Singularity University, such as (Diamandis, 2012). In that scenario, global warming is allowed to grow faster than the Paris Agreement before 2050, but the technology progress, that amplifies from 2040, supports a much better balance of clean energy (more abundant, at lower costs) and the energy savings & transition accelerate, resulting in the second half of the century which is better than the reference scenario.

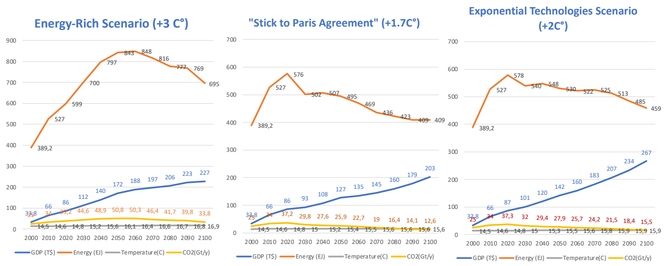

Figure 5: Simulations outputs for three kinds of beliefs

6. CONCLUSIONS

CCEM is a work in progress, based on the core model described in this paper. It has reached a level of maturity where simulations can be run successfully with a wide range of input beliefs.

The first contribution of CCEM is the explicit representation of "beliefs", within a common simulation framework. Any earth model uses parameters to describe these known unknowns, often implicitly, since energy/economy/climate modeling is complex and must use some hypotheses by construction. The design specificity of CCEM is emphasize five of these "key unknowns" and to make them explicit and modular constructs.

The second contribution of CCEM as an earth model is to enrich the feedback loop "from temperature to societal action", compared to the more traditional evaluation of GDP impact using SCC (social cost of carbon). The explicit feedback loop supports the explicit representation of ecological redirection. For instance, when a resource become too scarce, would it be energy, water or land, it is no longer clear that market laws and supply-demand should govern resource usage. Redirection happens when regulations kick in to enforce some kind of fairness to manage scarcity.

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APPENDIX

CCEM is part of a larger project (GWDG: *global warming dynamic games*, including model stressing and evolutionary game theory). The CCEM model represents 1000 lines of high-level programming language (3000 lines of Javascript) with a few hundred state variables (time series). The current version (v4: **https://github.com/ycaseau/GWDG**) of the code with a detailed description of the model equations is accessible on GitHub. For lack of space, we only present in this appendix the main equations of M1 to M4, while leaving M5 aside since redirections are not used in the results presented in section 5.

M1: Energy Production

The two main equations of M1 are the update of accessible inventory (as a parametric function of price) and the evolution of production capacity. These equations are different for fossil and clean energies (*expectedOutput* and *maxGrowthRate* are "known unknown" exogenous CCEM parameters, section 3.1)

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

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

Here is a short description of the main state variables:

- $O_e(y)$: output for energy e at year y
- $C_e(y)$: max capacity for energy e
- $A_e(y)$: added (M3 transfers) capacity for energy e
- $tO_e(y)$: total output in Gtoe from years 1 to y
- $P_e(y)$: price in $ for 1 toe for energy e at year y

M2: Energy Consumption

The two main equations of M2 are the computation of the raw (unconstrained) demand based on population and economy growth, and the computation of the constrained demand that factors savings (efficiency) and cancelations. These are parametric equations that depends on the price. For each year, the equilibrium price $P_e(y)$ that matches demand and supply is computed for each energy source.

$$R_z(e,y) = U_z(e,1) * economyRatio(z,y) * (1 - dematerialize(e,y)) * populationRatio(z,y) * (1 - GW_z(y-1))$$

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

$$Demand(e,z,y,p) = N_z(e,y) * (1 - S_z(y-1) - cancel(z,p))$$

Here is a short description of M2 main state variables:

- $R_z(e,y)$: raw needs for energy e for zone z at year y
- $N_z(e,y)$: needs for energy once transfers are applied
- $Tr(e_1,e_2,y)$: fraction of energy transfer from e_1 demand to e_2
- $U_z(e,y)$: usage for zone z of energy e
- $P_e(y)$: Price for energy e ($/toe) at year y
- $S_z(y)$: percentage of efficiency savings reached at year y
- $GW_z(y)$: percentage of capacity lost because of global warming

M3: Energy Transition

The three main equations of M3 are the computation of the primary energy source transfers, of the carbon tax and the associated energy investment. Note that *transitionRate(z,e1,e2, y)* is one of the "known unknown" presented in the body of the paper, that is a exogenous parameter to CCEM (such as *cancel, impact or dematerialize* that we saw in M2).

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

$$Tax_z(y) = \boldsymbol{\Sigma}_e (O_z(e,y) * co2perTon(e) * CarbonTax(z,y))$$

$$IE_z(y) = \boldsymbol{\Sigma}_e [(\max(0, C_e(y) - C_e(y-1)) * (U_z(e,y) / \boldsymbol{\Sigma}_{z1} U_{z1}(e,y)) + (N_z(e,y) * \max(0, S_z(y) - S_z(y-1))) + \boldsymbol{\Sigma}_{e<e2} N_z(e_2,y) * \max(0, (Tr(e,e_2,y) - (Tr(e,e_2,y-1)))] * investPrice(e) * (1 - sf(e) + (sf(e) * SP(y) / SP(1)) * (1 - ftech)^{y} - Tax_z(y)$$

Here is a short description of some state variables:

- $CN_z(y)$: percentage of consumption canceled in zone z at year y,
- $IE_z(y)$: investments for new energy capacity for energy source z
- SP(y): steel price for year y
- Sf(e) : part of steel cost in total cost of investment for e

M4: Economic Growth

M4 computes a theoretical (unconstrained) GDP based on demand and productive capacity growth through investments, then an actual GDP that considers the lack of energy and the impacts of global warming. The third main equation represents the investments, based on profits but without the necessary amounts spent on energy transition. Here we see another « known unknown" meta-parameter, *roi(z,y)*, which represents the expected return on investment.

$$M_z(y) = M_z(y-1) * (population(z,y) / population(z,y-1)) * (1 - GW_z(y)) / (1 - GW_z(y-1)) + IG_z(y-1) * roi(z,y)$$

$$G_z(y) = M_z(y) * (1 - impactCancel(z,p))$$

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

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

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

Here is a short description of the main state variables:

- $M_z(y)$: theoretical "maxoutput" gdp
- $G_z(y)$: gdp for zone z on year y ($G(y) = \boldsymbol{\Sigma}_z G_z(y)$)
- $I_z(y)$: amounts of total investments
- $IG_z(y)$: amounts of growth investments
- alpha(z,t) : fraction of energy that is "redistributed" with subsidy (versus free market)
- iRevenue(z): share of revenue that is invested