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

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Abstract: The Coupling Coarse Earth Model (CCEM) is a system dynamics simulation model that looks at the integration of energy, economy, climate, and associated feedback loops. CCEM combines five simpler models that address energy availability, economic adjustment to energy scarcity, energy transition, global economy and CO_2 emissions, and the impact of CO_2 emissions on warming and society. Modeling such a complex system requires several hypotheses, for which there is still no consensus. These "known unknowns" are the future availability and cost of energy, energy needs and affordability for the economy, the speed of energy substitution, expected Gross Domestic Product growth, and the economic and societal consequences of global warming. In CCEM, these are explicit parameters that enables simulation of opposite viewpoints with the same underlying logic. CCEM has been influenced both by previous systems dynamics models and other integrated assessment models (IAM); its main contribution as a simulation model is to reproduce 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", accounting for pain from warming, economic results, and energy shortages, that may trigger redirections: how society reacts when pain gets too high (a nonlinear reaction). While the complex system nature of energy/economy/climate/society is better represented and produces more realistic scenarios, taking these redirections into account makes forecasting more difficult.

Keywords: IAM, earth model, system dynamics, energy transition, global warming, ecological redirection, Anthropocene

1. Introduction

The Coupling Coarse Earth Model (CCEM) is a simulation framework that considers the Earth as a complex system, where energy production, consumption, economy, global warming and geopolitical reactions are bound together. Earth models have existed for decades and evolved into integrated assessment models (IAM) that play an important role [1], although criticized [2], to help governments and agencies to evaluate policies. The Intergovernmental Panel for Climate Change (IPCC) has used IAMs in its last iterations in evaluating the impact of mitigation and adaptation strategies [1], while at the same time most Earth models embed the findings of The Intergovernmental Panel for Climate Change [3], to assess the impact of economy-driven CO_2 emissions on the climate. A "global" Earth model also focuses on the interplay between economy and energy, which drives CO_2 emissions due to fossil fuels, and the reaction of the world to temperature increase. The different IPCC representative concentration pathways (RCP) are families of scenarios that illustrate the input loop from energy consumption to CO_2 emissions. The reverse loop, from temperature back to the economy, energy consumption, and societal behavior, is obviously difficult to capture with a model in all its richness.

In the name CCEM, the adjective "coarse" is added to emphasize the voluntary simplicity of each component models in order to make beliefs explicit. A key contribution of this paper is the fifth component sub-model, which describes the reactions of the world (here subdivided into five zones) to global warming and the retroaction on the world economy and its energy consumption. Many global Earth models have focused on the loss of productive capacities due to global warming (and its very large scope of catastrophic consequences); in this study, we attempted to extend toward a more comprehensive societal model. This fifth model is called "ecological redirection" because, following the lead of Latour [4], CCEM sees the consequences of global warming as a sequence of catastrophic events yielding "re-directions," as opposed to a hypothetical "ecological transition roadmap." This sub-model aims to explore what will happen if, which seems likely, the Paris agreement is not upheld and the temperature rises over the +2C° threshold (compared to pre-industrial level).

This paper is a follow-up to the CCEM introduction in the study by Caseau [5], with both the updated version 6 of the model and a complete description of the associate equations. Section 2 emphasizes the relation with other earth models. We focus on "known unknowns" and show how CCEM makes the assumptions (beliefs) explicit. Then we describe how "political and societal" feedback is modeled. Section 3 presents and explains each CCEM sub-model. We start with the three models that represent energy production, consumption, and transition, followed by the fourth model (representing the world economy) and how it would grow under "normal circumstances" and how both the possible lack of energy and the catastrophic impact of global warming may affect it. Last, we address the fifth model (societal and political reaction to global warming), which combines the computation of possible impact of temperature elevation, both from the viewpoint of productive capacity loss, which is common to most earth models, and from an ecological redirection perspective. Section 4 illustrates CCEM with computational results. We show the geographical results of version 6 of CCEM, with a discussion about its sensitivity to the belief parameters. Section 5 outlines limitations and future directions for our

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CCEM work and acknowledges the model's voluntary simplifications, such as ignoring future carbon sequestration technology.

2. Motivations

2.1. Earth models

Earth models that are attempting to study the coupling between energy (production), economy (and energy consumption) and climate (the impact of the economy on global warming through CO_2 emissions) have existed for many decades. These models fall into two broad categories: IAM and System Dynamics [6] Earth Models (SDEM) such as "Limit to Growth", the MIT model that is over 50 years old [7]. SDEM are "from first principles" models where the coupling equations represent the modeler's understanding of the "world system" (with a calibration effort so that the SD model fits what was observed in the past), whereas IAM tends to be "data-driven" models where the laws that link the different components of the IAM are derived from observations from the past (most often, through regressions and other statistical tools). SDEM try to capture causality (which is hard) whereas IAMs are focused on key state variables and identify dependencies from previous data analysis. CCEM is clearly inspired by the original SDEM, "Limits to Growth," which focuses more on the sources of energy versus generic resources. Although SDEM are by construction "macro" models with a high level of abstraction, they have been shown to be a good tool to understand systemic feedback loops and have been proven to reproduce the past fairly well [8]. Nevertheless, CCEM is very much influenced by "detailed process" (DP) IAMs with similar world economy growth equations [2] and with much higher level of detail on energy production and energy consumption than what is found in SDEMs.

The most famous IAM is the dynamic integrated climate-economy (DICE) model (and its regional evolution, RICE). Although CCEM and DICE are similar, DICE relies on linear programming, while CCEM uses a more rustic but more general simulation paradigm, which is better suited to explore nonlinear coupling and catastrophic amplifications.

Among the models that were proposed during the same timeframe as DICE are global change assessment model (GCAM) [9] and integrated global system model (IGSM) [10]. Although the GCAM paper in 1994 is 30 years old, its energy product model is quite similar to what is proposed with CCEM. However, its key finding remains: the overall energy portfolio is a major driver of climate change. The MIT model is itself a combination of complex model: EPPA (human activity model) and the "earth system" (ocean, land, atmosphere, urban) model. Since CCEM uses a (simplified) abstraction of IPCC as its "earth system" model, there is more proximity with the EPPA component. CCEM economy model (M4) is similar to EPPA, at a simpler scale (fewer geography zones) but with a more developed focus on energy transition. It is also similar to IMACLIR-R [11] as far as the "world zones" economy model is concerned, and its coupling with energy sources, with 5 zones versus 16 zones.

Several models have been subsequently proposed that keep the structure of DICE but attempt to provide a more "realistic" capture of global warming damages. The controversy about the results from Nordhaus [12], which described the most likely outcome as a significant (+3C°) warming with a moderate (-3%) impact on gross domestic product (GDP), is not the model itself but the damage component of the model that underestimates the consequences of global warming as described by IPCC and illustrated by Wallace-Wells [13]. For instance, Hänsel et al. [14] proposed to update the DICE model with a more up-to-date appreciation of global warming damages and reported that the "optimal path" proposed by the revised DICE model is close to the UN climate targets. Another very interesting earth model is the advanced climate change long-term (ACCL) model [15], which has a structure similar to DICE but is based on temporal simulation using differential equations that are carefully calibrated by linear regression of past data. The economy growth model of ACCL was used as an inspiration for CCEM. Our "median belief" regarding global warming impact, as explained in Section 4.1, is mostly the research by Wade and Jennings [16], which makes it consistent with a high value of SCC as in the article by Rennert et al. [17]. More recently, the use of IAMs has been criticized from a methodological perspective [18] because IAM cannot capture the high level of risk and uncertainty that global warming damages may represent [19].

2.2. Beliefs as first-class explicit components

Assembling an Earth model is a combination of causal reasoning that we hold true with assumptions, which are hypotheses that we want to evaluate or policies that we want to optimize. In the case of the Energy/Economy/Climate coupling, there are (at least) five major "known unknowns":

1) How much energy will be available in the future? At which costs? This question is well understood for fossil fuels and is related to the size of accessible reserves. For instance, the introduction of shale oil and gas has changed our perspective since 2000. This question also applies to renewable clean sources of energy. Our capacity to execute, from material resources (e.g., metals for wind turbines) to manufacturing and installing capabilities, means that the rate at which we can deploy these renewable energy plants is a "known unknown."
2) How much energy is needed and affordable for the economy at a given cost? The energy intensity (amount of Watt x hour (W.h), to produce a dollar of GDP) is decreasing, but it is unclear to see how fast or how long this trend will last. If energy becomes rare (and/or too expensive), which activities will adapt (because they create enough value to afford a more expensive energy supply) and which ones will have to stop?
3) How fast can we substitute one form of primary energy to another? A key factor to manage global warming is to accelerate the transition to clean sources of energy. This third question addresses the capacity to switch to one form to another, because all sources are not equivalent because of energy density, mobility, intermittence, etc. [20]. CCEM is similar, although simpler, to WITNESS[1], a model with a strong emphasis on energy sources and energy transition, which makes the "viscosity" of energy substitution visible.
4) Which GDP growth can be expected from investment, technology, energy and workforce? Most integrated energy/economy/climate models are based on an implicit "economy growth engine," which is then adjusted to reflect the lack of energy or the loss of productive capacities. What the economy growth trajectory would be without these impediments is a "known unknown" (mostly, the "natural rate of growth"). It is easy to calibrate that rate from what was observed in the past decades, but this is mostly an act of faith.
5) What will be the economical and societal consequences from the IPCCs predicted global warming? There are many unknowns here. First the amount of loss of productive capacities due to global warming impacts is a topic of debate, as shown by the previous section (it is the most differentiating factors of all the models derived from DICE that have been published in the past decade). Second, considering the catastrophic nature of the impact [13], there are many other indirect impacts that will add to "capacity losses".

These are "known unknowns" in that the issues are well understood and documented, but there is no consensus about what the answers might be. In the remainder of the paper, we call these "known unknowns" beliefs to emphasize the lack of consensus (and/or the

[1] WITNESS: A "What if?"Tool for exploring policy options and climate change by Michael Tiemann. https://ossna2024.sched.com/event/1aBNw.

variation of opinions over the past decades, as shown by the energy resource examples).

2.3. Societal reactions to global warming

The main contribution of CCEM is to enrich the feedback loop from global warming back to the energy/economy system. To address this feedback, we need to represent two things:

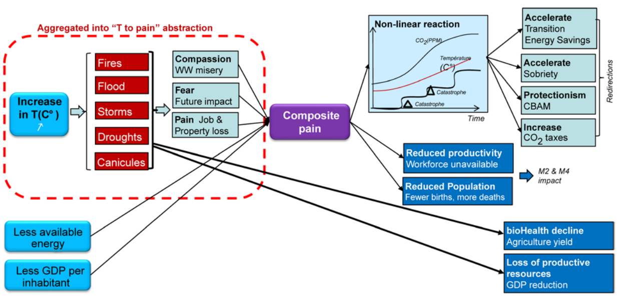
1) Which are the impacts of the global warming: floods, canicules, wildfires, water shortages, and sea level elevations, to name the most obvious ones? These impacts are both material and human, either with physical loss of life or abilities, as well as severe psychological pain.
2) Which retroaction must we consider? Most models consider a reduction in productive capabilities, caused either by the loss of capacity (direct impact) or societal costs. However, when the pain from catastrophes becomes high, we are bound to see, at least in some parts of the world, political uproars and associated "pain-induced" decisions. Obviously, the scope of the decisions that we may consider is linked to the overall energy/economy model, to produce a feedback loop.

We borrow the term "redirection" from Latour [4] and from many research scientists who work on the Anthropocene [21, 22]. There are two key insights with the concept of redirection: first, there is no roadmap nor any "transition," the complex system energy/ economy/climate/ society will evolve in a chaotic manner, demonstrating amplifications and bifurcations that makes forecasting and planning hazardous. Second, the system will evolve through redirections: decisions taken at a given moment in a given context, for instance, following a major natural disaster.

These feedback loops are implemented with CCEM model M5 (Section 3.6 and the associated Figure 1). The various natural disasters create in parallel a physical feedback loop and a societal feedback loop. The first loop tells about the GDP loss that is the consequence of fires, floods, droughts, and canicules. This feedback loop also includes the feedback on the agriculture ecosystem: when temperature rises it impacts the "bio Health" and reduces the yield of crops. Last, the "pain level" produced by global warming has also an impact on labor productivity (from reduced number of days because to heat waves, absenteeism rise or engagement decline because of lower moral, to more severe impacts because of health decline).

The second loop is the "redirection loop," where the pain caused by global warming pushes some of the redirection mechanisms. We introduce a "pain factor" that is fed by the different negative outcomes of global warming and acts as a nonlinear trigger to redirection. Pains trigger "redirections," which are reactions to the global warming impacts, such as energy redistribution, forced sobriety, CO_2 tax acceleration, protectionism (e.g., EU project of CBAM: Carbon Border Adjusment Mechanism) and intensification of investments with clean energy and improved energy efficiency. A key idea is that redirection represent both the political reactions of governments (through policies) and those of companies, influenced by their stakeholders (investors, employees, customers). It is quite likely that enterprises will be the actual leaders of de-carbonation, which is represented through redirection in the M5 sub-model.

Figure 1
From pain to redirection



3. CCEM Presentation

3.1. CCEM architecture

CCEM is a simulation model, described by state variables (a few hundreds), that vary in time. Time is discretized and the model describes how each component of the model evolve year after year. The starting point is 2010, because the work presented here started a decade ago and it makes 2020 an interesting point for calibration. Although the equations presented (blue box) are designed "from first principle," they are tested against the past three decades. Then a calibration is made using the 2020 data (hence the capacity to roughly reproduce 2020 from 2010 is not a surprise but a consequence of the methodology).

CCEM is defined as the coupling of five models:

1) Energy resource model (M1): This model predicts, for the years to come in the simulation range, how much energy will be accessible at given costs. The model separates three forms of fossil fuel and combines all "clean" (no CO_2 usage-impact) into one category (solar, wind, nuclear, biomass, etc.).
2) Energy consumption model (M2): This dual model computes the expected input of energy (for each world zone) and how much would be actually consumed as a function of the market price. The combination of M1, M2 and M3 makes for a computable general equilibrium (CGE, [23]) model.
3) Energy transition model (M3): This model describes how the energy consumption may evolve from one primary source of energy to another: which share, how fast (transition is expressed as a roadmap), and for which investment.
4) Economy model (M4): This is how we represent the GDP/value creation of the world economy, divided into five zones, through assets that grow according to investments, using energy that is "provided by the other models." We also capture, in a crude way, the feedback loop from M5 (loss of productive capacity).
5) Ecological Redirection model (M5): This model starts, as seen in Section 2.3, with an abstraction of IPCC global warming RPC and translates the temperature elevation that in turn creates negative impacts. These impacts are measured through loss of productive capacity and trigger redirections and changes in the energy/economy management policies.

Figure 2 illustrates the complete CCEM system, where each of the five models interact with each other.

3.2. Energy resource model (M1)

The M1 model answers the two questions:

1) "How much fossil energy can we access, at which costs?"
2) "How much clean energy could be made available in the future, at which costs?"

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 (e.g., oil reserves). This is not a value, but a function of the market price at which the energy may be sold. For clean energy, the "known unknown" is the speed at which we may grow (solar and wind farms, the hydroelectric potential, the nuclear facilities, etc.). There are many reasons for which this is hard to forecast: availability of material resources, evolution of technology efficiency, or capacity of financing. As a key belief of M1, this is represented as a yearly forecast

Figure 2
System dynamics (simplified) representation of CCEM

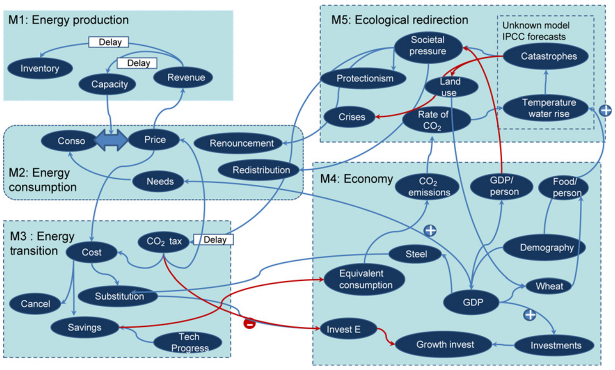
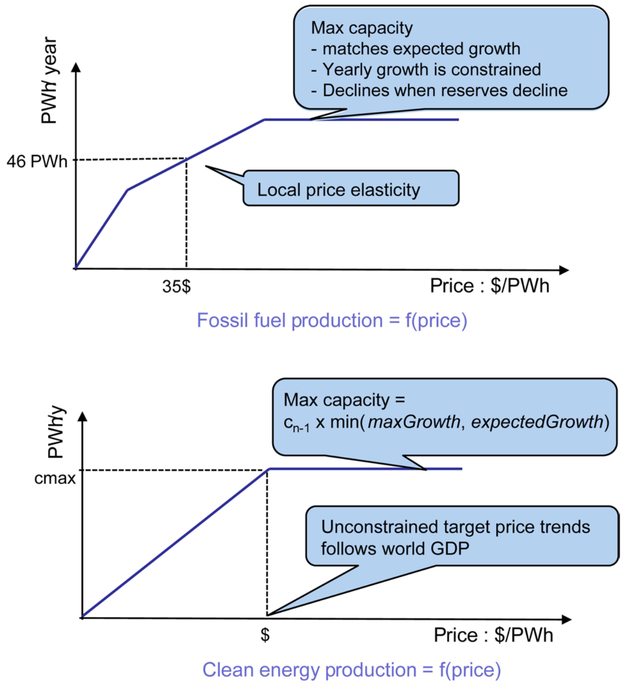


Figure 3
Adapting the fossil energy production to price



(a function that associates to each year the total capacity for clean energy). Energy is measured in PWh, since electrification is one of the key strategic questions.

M1 uses the following state variables to describe the energy system year after year (the parameter y represents the current year):

- $O_e(y)$: output (production) in PWh for energy *e* at year *y*
- $C_e(y)$: max capacity in PWh for energy *e*
- $A_e(y)$: added capacity for energy e through transfers (M3)
- $tO_e(y)$: total output in PWh from years 1 to *y*
- $P_e(y)$: price in \$ for 1 MWh 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*

There are three key steps for fossil fuels:

1) To compute the expected capacity, its evolution is planned to match the demand forecast based on the previous 3-year history (this is a gross simplification that does not reflect the delay between market price, drilling decisions, and exploitation).
2) To adjust the current capacity if the reserves (inventory) are lower than a threshold value (80% of the initial known reserves), the adjustment is made with a piecewise quadratic function so that the capacity is proportional to the fossil reserves below half of the threshold.
3) The production ("supply" function) uses a piecewise affine function that cannot exceed the current capacity (Figure 3) and reflects price elasticity.

The case of clean energy is simpler with only two steps:

1) The capacity $C_e(y)$ is computed to match the expected demand.
2) The supply function is proportional to the proposed price up to the max capacity, with a price sensitivity that reflects a price increase that should follow the world GDP.

The logic of M1 can be described with the following numbered equations (blue box):

(1) *Supply*(e,p,Cmax) tells the production of fossil energy *e* at price *p*, knowing the max capacity Cmax (that was computed earlier). The default production is based on the initial production $O_e(1)$, adjusted for capacity.
(2) There are two separate sections for fossil and clean energies. *Supply*(e:Clean,p,Cmax,y) reflects the chart on Figure 3. The production grows linearly according to the proposed price until Cmax, with a price sensitivity adjusted so that the nominal capacity is reached to a price that follows the economic growth (G(y – 1) / G(y)) modulo a sensitivity linear factor.
(3) For fossil energies, capacity evolution is determined by *ExpectedCapacity*(*e*,*y*), but the yearly evolution is the average between existing and forecasted capacities, as a way to smooth oscillations. The expected capacity tries to follow the expected consumption (Equation (5)); in the modulo equation, the maximum yearly growth is defined by *maxGrowthRate*(*e*). This expected capacity is then reduced according to the current level of reserves (inventory minus past consumption).
(4) For clean energy, capacity is driven directly by *ExpectedCapacity*(*e*,*y*), which also attempts to follow the *expectedGrowth* modulo and the *maxYearlyGrowth* constraint that also takes additions into consideration ($A_e(y)$: when other sources of energies are transformed into clean energy; M3).
(5) The two previous formulas use *expectedGrowth*, which is a linear regression of the past 3 years consumptions. This function returns growth expressed as a ratio of previous volume.

Equations (functions & differential state)

$$\begin{aligned}
&\mathit{Supply}(\text{e:Fossil},p,C_{max}) = \min(C_{max}, \max(0,O_e(1) \times \\
&\qquad \min(1,(C_{max} / C_e(1))) \times \mathit{PriceAdjust}(e,p / P_e(1)))\\
&\quad \mathit{PriceAdjust}(\text{e:Fossil},r) = \textbf{\textit{if}}\ (r < 0.5)\ r \times (2 - \mathit{sensitivity}(e))\\
&\qquad\qquad \textbf{\textit{else}}\ 1 + (r - 1) \times \mathit{sensitivity}(e)
\end{aligned} \tag{1}$$

$$\begin{aligned}
&\mathit{Supply}(\text{e:Green},p,C_{max}),y) = \min(C_{max},\\
&\quad (C_{max} / \mathit{targetMaxRatio}(e) \times\\
&\qquad (p / (P_e(1) \times (1 + (G(y-1) / G(1) - 1) \times \mathit{sensitivity}(e)))
\end{aligned} \tag{2}$$

$$\begin{aligned}
&\mathit{Capacity}(\text{e:Fossil},y) = ½ \times (C_e(y - 1) + \mathit{ExpectedCapacity}(e,y)\\
&\quad \mathit{ExpectedCapacity}(\text{e:Fossil},y) =\\
&\qquad \mathit{InventoryToCapacity}(e, C_e(y - 1) \times\\
&\qquad\quad (1 + \min(\mathit{expectedGrowth}(e,y), \mathit{maxGrowthRate}(e))),\\
&\qquad\quad (\text{Inventory}(e,p) - tO_e(y - 1))/ \mathit{threshold}(e)))\\
&\quad \mathit{InventoryToCapacity}(\text{e:Fossil},c,C_{max},r) =\\
&\qquad \textbf{\textit{if}}\ (r > 1)\ c\ \textbf{\textit{else if}}\ (r < 0.5)\ \min(c, r \times C_e(1) \times 1.75)\\
&\qquad \textbf{\textit{else}}\ \min(c, C_e(1) \times (1 - (1-r)^2 * 0.5)
\end{aligned} \tag{3}$$

$$\begin{aligned}
&\mathit{Capacity}(\text{e:Green},y) =\\
&\qquad \mathit{ExpectedCapacity}(e,y,\text{average}(\{P_e(i) \mid i \in [y-10,y-1]\})\\
&\quad \mathit{ExpectedCapacity}(\text{e:Green},y) = C_e(y - 1) +\\
&\qquad \min(C_e(y - 1) \times \mathit{expectedGrowth}(e,y), C_e(y - 1) +\\
&\qquad\quad (\mathit{maxCapacityGrowth}(e,y) - A_e(y-1)),
\end{aligned} \tag{4}$$

$$\begin{aligned}
&\mathit{expectedGrowth}(e,y) =\\
&\qquad \max(0, [\Sigma_{z \in zone}\ \text{linearRegression}(UD_z(y-3), UD_z(y-2),\\
&\qquad\qquad UD_z(y-1))] / C_e(y - 1) - 1)
\end{aligned} \tag{5}$$

The simplicity of the functions used in M2 illustrate the adjective "coarse" in CCEM. For fossil fuels, the major focus is the management of inventory (reserves), which is a complex topic. For renewable energies (although one may argue that nuclear would require to model inventory management), the main focus is the speed of deployment. Hence, Equation (1) is more sophisticated than Equation (2) (supply for fossil and green), and we see a similar difference between (3) and (4) (*ExpectedCapacity*).

These equations use additional parametric functions associated to M1 (the bold functions represent the "known unknown" that are the "parameters" of CCEM):

- *maxCapacityGrowth*(*e*,*y*): for clean energy *e*, expected max capacity in PWh 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 the decline of reserves (strong influence on PeakOil date)
- *targetMaxRatio*(*e*): expected ratio between (max) capacity and output (constant depending on the type of energy)
- *maxGrowthRate*(*e*): percentage of capacity that can be added at most in a year for fossil energy *e*.
- *sensitivity*(*e*): price factor for energy *e*.
- $CO_2perPWH(e)$: CO_2 emissions to produce one PWh of energy *e*

3.3. Energy consumption model (M2)

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. Model M2 answers these questions with three curves:

1) 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 "cancelled"), expressed as an energy consumption share. We use the equivalent oil price to normalize these functions with the simplifying assumption of using the same function for each energy source.
2) For each region *z*, ***impact***(*z*,*p*) is another function that tells, for a given percentage *p* 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). The *impact*(*z*,*p*) factor is applied twice in M4's equations: to reduce the GDP and to reduce the investments that are generated. As the energy goes up, it eats a faction of the profit made by the activity (using the same factor for GDP output and for investment is a crude simplification, in the spirit of a "coarse" model).
3) The quantity of energy that is necessary for economic activity evolves in 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*. As the share of "immaterial" economy (e.g., services) increases over "material" economy (e.g., manufacturing), the ***dematerialize***(*e*,*y*) ratio decreases.

However, there is another force at play (that of technological progress) that increases the energy efficiency, thus reducing the amount of energy needed to produce the same value. 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$ / installed MW) that declines over time (a coefficient that is part of the same "belief"). Note that "dematerialization" refers to the evolution of the economy, where "savings" is about efficiency for the existing activity.
- *energyIntensity*(*z*,*e*,*y*) is the combination of

(1 - *dematerialize*(*z*,*e*,*y*)) and (1 – savings(*z*,*y*)).

M2 uses the following state variables to describe the energy system year after year:

- $R_z(e,y)$: raw needs for energy *e* in PWh 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
- $T_r(e_1,e_2,y)$: 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*. It is important to note that we model the consumption of primary energy sources, without limiting to energy usage. Thus, the use of fossil fuels for chemistry or other industrial usage is both captured for its economic output and its contribution to CO_2 emissions.
- $P_e(y)$: price for energy e ($/PWh) at year *y*
- $S_z(y)$: percentage of savings reached at year *y*
- $GW_z(y)$: percentage of capacity lost because of global warming, cumulative to year *y*

M2 is computed at the region level. The computation of the energy demand goes through three steps:

1) The initial "raw" demand ($R_z(e,y)$: raw needs is assessed from previous consumption and the product of a few evolution factors (7).
2) The "constrained" demand ($N_z(e,y)$) is adjusted modulo the "energy transition". The substitutions produced by M3 are applied to transfer part of the remaining needs from one source of energy to another. Since substitutions are ordered, it is required to iterate Energy sources in the proper order.
3) The demand vector is produced by factoring; for each possible price, the level of cancellation that is triggered by this price.

M2 may be described with the following state equations:

(6) $R_z(e,y)$ computes the raw need for zone *z* of energy e using the initial demand (year 1) multiplied by the product of the unconstrained GDP growth (*economyRatio*) by the dematerialization ratio, then multiplied by population growth and reduced by the global warming damage factor (1 - GW_z(y)).

(7) *populationRatio*(*z*,*y*) represents the expected energy consumption for zone *z* associated with its projected population level (*population*(*z*)) modulo the reduction of productivity caused by the pain level (M5).

(8) *economyRatio*(*z*,*y*): heuristics that combines the expected growth of the zone GDP (from the amount of past investments) and the mutual influence of zones through global trade. The GDP is divided into local economy and trade (both import and export). The global ratio that is applied is $M_z(y-1)/M_z(1)$, growth of unconstrained economy output (M4). It is applied directly to *innerTrade*(*z*) = the faction of GDP associated to domestic activity, and with additional trade coefficients for the fraction of GDP that is respectively associated to imports and exports. For imports, we multiply by $M_z(1)/M_{z1}(1)$ because the share of activity associated to z1 export (*trade*(z_1,*z*)) is expressed as faction of *z1*'s GDP.

(9) The energy need $N_z(e,y)$ is deduced from the raw demand through substitutions using $Tr(e_1,e_2,z)$, which is the percentage of the consumption of energy of type e_1 for zone z that has been moved to energy e_2. This function is computed in M3.
(10) Last, the actual "net" demand *Demand*(e,z,y,p) is a parametric function of the sell price *p*. The energy need is reduced by the cancellation factor associated for each zone to a price *p*. The sell price is augmented by the current level of CO_2 tax in zone *z* at time *y*.
(11) By construction, demand and supply are two decreasing and increasing, respectively, monotonic functions. Thus, the sell price may be set as the unique value for which supply matches demand.
(12) Once the price is set up, we can compute both the production capacity for year *y* (M1 uses the capacity at year *y-1* for the supply function) and the actual production $O_e(y)$.

Equations (functions & differential state)

$$R_z(e,y) = U_z(e,1) \times \mathit{economyRatio}(z,y) \times \mathit{energyIntensity}(z,e,y)) \times \mathit{populationRatio}(z,y) \times (1 - GW_z(y-1)) \tag{6}$$

$$\mathit{populationRatio}(z,y) = 1 + (\mathit{population}(z,y) / \mathit{population}(z,1) - 1) \times \mathit{pop2energy}(z) \times (1 - PAIN_z(y) \times \mathrm{productivityFactor}) \tag{7}$$

$$\begin{aligned}
\mathit{economyRatio}(z,y) &= (M_z(y-1) / M_z(1)) \times \mathit{tradeRatio}(z,y) \\
\mathit{tradeRatio}(z,y) &= \mathit{innerTrade}(z) + \mathit{outerCommerceRatio}(z,y) + \mathit{importReductionRatio}(z,y) \\
\mathit{outerCommerceRatio}(z,y) &= \Sigma_{z1 \neq z} (\mathit{trade}(z,z_1) \times \mathit{protect}(z,z_1) \times \mathrm{protectionismOutFactor}) \\
\mathit{importReductionRatio}(z,y) &= \Sigma_{z1 \neq z} (\mathit{trade}(z_1,z) \times \mathit{protect}(z_1,z) \times (M_z(1) / M_{z1}(1)) \times \mathrm{protectionismInFactor})
\end{aligned} \tag{8}$$

$$N_z(e,y) = R_z(e,y) + \Sigma_{e1<e} R_z(e_1,y) \times Tr(e_1,e,y) - \Sigma_{e<e2} R_z(e_2,y) \times Tr(e,e_2,y) \tag{9}$$

$$\begin{aligned}
\mathit{Demand}(e,z,y,p) &= N_z(e,y) \times (1 - S_z(y-1) - \mathit{cancel}(z,p + \mathrm{tax}(z,e,y))) \\
\mathit{Demand}(e,y,p) &= \Sigma_z \mathrm{Demand}(e,z,y,p) \\
\mathit{tax}(z,e,y) &= CO_2\mathit{Tax}(z,CO_2(y-1))
\end{aligned} \tag{10}$$

$$P_e(y) = \; ! \, p \;\mid\; \mathit{Demand}(e,y,p) = \mathit{Supply}(e,y,p) \tag{11}$$

$$\begin{aligned}
C_e(y) &= \max(C_e(y-1), \mathit{Capacity}(e,y,P_e(y))) \\
O_e(y) &= \Sigma_z \mathit{Supply}(e,z,y,p)
\end{aligned} \tag{12}$$

These equations used additional parametric functions that represent the "known unknowns" associated with M2. The first four functions below are in bold to indicate that they represent the "belief" associated with "energy consumption":

- ***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*
- ***margin***(z,p): impact on profits for remaining activities of zone *z* (i.e., those that are not cancelled) when oil-equivalent price is *p*.
- ***dematerialize***(z,e,y): expected decline in energy density (GDP/consumption) for zone *z*.
- *population*(z,y): expected population of zone *z* at year *y*.
- *pop2energy*(z): ratio between energy consumption growth and population growth.
- *CarbonTax*(z,y): carbon tax set up in zone *z* in the year *y*.

3.4. Energy transition model (M3)

The Energy Transition model captures the question "How fast can we substitute from one source of primary energy to another?" For each transition, our "belief" is a roadmap, a function that predicts 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 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 United States during the last decade), coal to clean, oil to gas, oil to clean, and gas to clean.

Energy sources have different uses with different constraints (mobility, intermittence, etc.), which yields the use of secondary sources of energy, also called "vectors" (electricity, hydrogen, etc.). Figure 4 is a very simplified illustration that shows why some substitutions are easier than others. Substitutions require time and investment. Therefore, they are represented in M3 as a belief, a transition roadmap for each zone that asks: 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 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 (Figure 4) (due to Paul Caseau). The use of this matrix of transitions roadmap is what puts CCEM in the detailed path IAM category, in an attempt to model the complexity and viscosity of energy transition [24, 25].

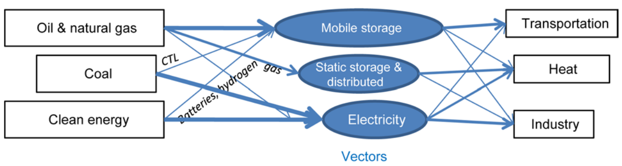
M3 uses the following state variables to further describe the energy system:

- $P_e(y)$: price in \$ for 1 PWh 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 consumption 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*

The input of M3 are the demand and supply price-vectors computed by M1 and M2, the transition matrix (*transitionRate*(z,e_1,e_2,y), which is the core "belief" of M3), and a parameter that describes the decline of energy transformation investments in time, as technology improves. The last table that we use as an input in M3 is the CO_2 tax table, for each region, that sets the CO_2 tax level as a function of the CO_2 concentration that has been reached. M3 may be described with the following numbered equations:

(13) The first step is to compute the constrained energy consumption $U_z(e,y)$ for every energy source *e* and every zone *z*. We apply the cancellation factor associated to the sell price.
(14) We compute the part of the dematerialization (M2) that is linked to voluntary efficiency savings. The saving ratio $S_z(y)$ is computed from the desired level (M5) modulo the constraint on max yearly growth.
(15) We then compute the new transfer levels $Tr(e_1,e_2,y)$, for each 6 transition from one source e_1 to e_2.
(16) The sum of CO_2 taxes is derived for each zone through the sum of multiplying the consumption of energy *e* by the CO_2 ratio (g/KWh) for each energy source.

Figure 4
Understanding energy vectors to assess possible substitutions



(17) M3 records all necessary investments $IE_z(y)$ for energy capacity growth, energy savings and energy transfers. Notice that the price of steel, which is produced in M4, is used to evaluate the costs of green energy growth.
(18) CCEM computes an approximation of the electrification factor, through a heuristic estimate of how much of energy source e usage is used through electricity as a vector (100% for Clean).
(19) Last, we compute the CO_2 emissions for zone e, using an equation similar to Equation (16). Because we track all fossil energy use, this is a simple formula that covers use of fossil fuels in industry (cement, steel, etc.).

Equations (functions & differential state)

$$U_z(e,y) = N_z(e,y) \times (1 - \mathit{cancel}(z, P_e(y))) \quad (13)$$

$$S_z(y) = \max(S_z(y), \min(S_z(y) + \mathit{maxYearlySaving}(z), SvF_z(y-1))) \quad (14)$$
$$CN_z(y) = \Sigma_e\ \mathit{cancel}(z, P_e(y))$$

$$Tr(e_1,e_2,y,) = \max(Tr(e_1,e_2,y-1), \min(\mathit{transitionRate}(z,e_1,e_2,y) + TrF_z(y), \max(Tr(e_1,e_2,y-1) + \mathit{maxGrowthRate}(e)) \quad (15)$$

$$Tax_z(y) = \Sigma_e\ (O_z(e,y) \times \mathit{CO_2perPWh(e)} \times \mathit{CarbonTax(z,y)} \quad (16)$$

$$\begin{aligned} IE_z(y) = \Sigma_e [\ & (\max(0, C_e(y) - C_e(y-1)) \times (U_z(e,y) / \Sigma_{z1} U_{z1}(e,y)) + \\ & (N_z(e,y) \times \max(0, S_z(y) - S_z(y-1))) + \\ & \Sigma_{e<e2} N_z(e_2,y) \times \\ & \max(0, (Tr(e,e_2,y) - (Tr(e,e_2,y-1)))] \times \\ & \mathit{investPrice}(e) \times \\ & (1 - \mathit{steelFactor}(e) + (\mathit{steelFactor}(e) * SP(y) / SP(1)) \times (1 - ftech)^{y} \\ & - Tax_z(y) \end{aligned} \quad (17)$$

$$\begin{aligned} Elec_z(y) = \ & \Sigma_e\ (U_z(e,y) \times eRatio_z(e) \\ & + \Sigma_{e1,e2} Tr(e_1,e_2,y) \times \\ & (1 - elec\%(e_1)) \times (1 - heat\%(e_1,e_2))) \end{aligned} \quad (18)$$

$$CO_2(y) = (\Sigma_e O_z(e,y) \times \mathit{CO_2perPWh}(e)) \quad (19)$$

Producing the energy transition matrix is a big task (even with only six transitions), and there are historical data that may be useful in the calibration. These equations used additional parametric functions that represents the "known unknown" associated with M3:

- ***transitionRate***(z,e_1,e_2,y): maximum transfer of energy needs from primary source e_1 to e_2 at year *y*, expressed as a percent
- *investPrice*(e): investment that is necessary to build a capacity of 1PWh/year 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*
- *eRatio*(*e*,*s*) : fraction of energy *e* consumption for zone *z* (year 1) that is used for electricity
- *elec%*(*e*): fraction of energy source *e* that is used to produce electricity at year 1
- *heat%*(e_1,e_2): when we transition energy consumption from source e_1 to e_2, fraction of that energy that was used without electricity (heat) that is converted to another non-electric usage (heat to heat).

3.5. Economy under energy and climate stress model (M4)

M4 answers the question "which GDP is produced from a given amount of investment, technology, energy and workforce?" It works in two steps. First, we compute what the GDP could be given enough energy and without damages, using a classical exponential growth model (as is the case of most earth models) based on productive assets creating value over a unit of time using energy, that may be characterized as inspired by the Robert Solow model [3]. 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 5. Investments are separated into energy transition investments, which are necessary to perform the transition steps (M3), and growth investments. Second, the energy and global warming consequences are considered: the "max theoretical GDP" is reduced if not enough energy is available, or if some resources are incapacitated by the catastrophic consequences of global warming (output from model 5). Figure 5 illustrates some aspects of energy demand shown in M2: the influence of population, technology, and economic activity.

The key variable here is the global GPD, divided into each zone's GDP, measured in constant (2010) dollars. Still, monetary values (GDP, as well as energy prices) are to be considered with caution; however, their main role in CCEM is to act as a regulation agent between sub-models, and this works irrespectively of what the value represents (i.e., whatever 500 \$/MWh may mean in 2060, what matters is that the economy cannot consume more oil that is available at this time).

Because GDP as a measure of economic health is often criticized, we have added two material outputs that are reasonably easy to forecast and may act as "proxies" of the material economy: steel output and wheat output.

1) Taking steel production into account is a way to capture "raw materials" as a limiting factor for energy transition [26]. As shown in Figure 6, 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 considers the "energy density" of steel production and the energy price computed by M2.
2) Similarly, Figure 6 shows how CCEM takes agriculture into account through 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 [10], 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).

M4 uses the following state variables to describe the economy system:

- $M_z(y)$: theoretical "max output" for zone z, that is the "GDP that would have occurred if all necessary energy was here, without global warming impact"
- $G_z(y)$: GDP for zone z on year y (with $G(y) = \sum_z G_z(y)$)
- $I_z(y)$: amounts of investments (energy + growth)
- $IG_z(y)$: amounts of growth investments
- $SC_z(y)$: steel consummation for zone *z* at year *y*

Figure 5
GDP growth model

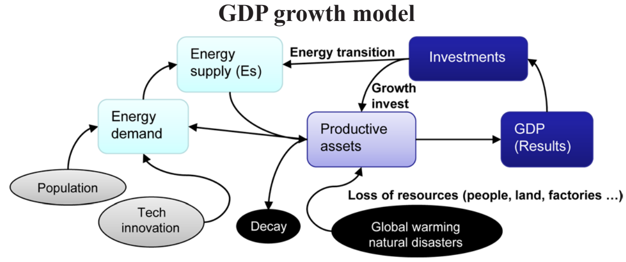
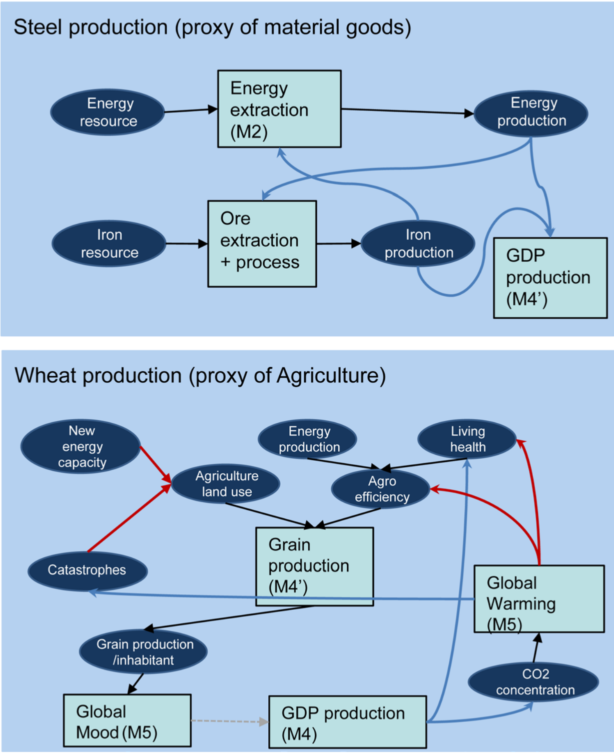


Figure 6
Introducing steel and wheat production as proxies for the "material" economy



The logic of M4 can be described with the following numbered equations:

(20) We first compute the "maximum output" expected from the previous investments. It is the sum of two factors. The first is the value produced by previous assets, adjusted for population growth and reduced by natural decay. As with WORLD3(LtG), we assume a natural decay of productive assets, but we use a much lower value of 2%/year. The second favor reflects the growth of productive assets, thanks to (growth) investments, multiplied by an *RoI* factor that is specific to each zone and varies in time (one of the "input belief").

(21) We compute $GWD_z(y)$, the loss of productive capacity from global warming impact. Because this value is read from a "belief table" that gives the impact as a fraction of GDP, we multiply by 0.7 to factor in the propagation toward investment (proportional to results; Equation (25)).

(22) The population growth is the growth factor (value for year *y* divided by the value for year *y-1*) of the population expected at year *y* in the input table "population" modulo a productivity factor that is derived from the pain lever (M5). This feedback loop may capture multiple effects of disruption onto productive hours of work: disengagement, absence because of catastrophic heat waves or other disaster, social unrest from strikes to larger conflicts. The coefficient that defines this feedback loop is a key parameter for the CCEM model.

(23) The actual GDP of zone *z* on year *y*, $G_z(y)$, is derived from the unconstrained output times the cancelation factor (1 – *impactFactor*(*z*) and the *tradeFactor* (M2).

(24) The function *impactCancel*(*z*,*y*) returns the part of the GDP that is not produced when energy is lacking. It is a combination (with weight = *alpha*(*z*,*y*) – the fraction of energy that is redistributed through subsidies) between "a redistribution model" (all activity is equally affected) and a "market model" (where activities that consume more energy per creation of value unit are more impacted by energy price hikes, using the *impact*(*e*,*p*) parametric input defined in M2).

(25) The new amount of total investment is computed using the previously introduced linear regression and is split between previously computed "energy investments" (to which CO_2 taxes are subtracted; M3), and "growth investments."

(26) Last, we compute the amount of iron that was necessary to produce this GDP, based on expected iron density at year *y*, as well as the cost of iron (per ton), using the price of energy as a driver, which is itself multiplied by the forecasted energy intensity of steel production at year *y* (either from digging ore from mines or from recycling).

Equations (functions & differential state)

$$M_z(y) = M_z(y-1) \times (1 - \mathit{decay}) \times \mathit{populationGrowth}(z,y) + IG_z(y-1) \times \mathrm{roi}(z,y) \tag{20}$$

$$GWD_z(y) = 0.7 \times \mathit{disasterLoss}(z, T(y-1)) \tag{21}$$

$$G_z(y) = M_z(y) \times (1 - GWD_z(y)) \times (1 - \mathit{impactCancel}(z,y)) \times \mathit{tradeRatio}(z,y) \tag{22}$$

$$\mathrm{populationGrowth}(z,y) = (\mathrm{population}(z,y) \times (1 - PAIN_z(y) \times \mathrm{productivityFactor}) / (\mathrm{population}(z,y-1) \times (1 - PAIN_z(y-1) \times \mathrm{productivityFactor}) \tag{23}$$

$$\mathit{impactCancel}(z,y) = \mathrm{alpha}(z,y) \times (CN_z(y) / (U_z(y) + CN_z(y))) + (1 - \mathrm{alpha}(z,y)) \times \mathrm{impact}(z,OP_e(y)) \tag{24}$$

$$\begin{aligned} I_z(y) &= G_z(y) \times \mathit{iRevenue}(z) \times (1 - \mathit{margin}(z,\mathrm{oilEquivent}(y)) \times (1 - \mathit{impactCancel}(z,p)) \\ IG_z(y) &= I_z(y) - IE_z(y) \\ \mathit{oilEquivalent}(y) &= (\Sigma_e P_e(y) \times P_{oil}(1) \times O_e(y) / P_e(1)) / (\Sigma_c O_e(y)) \end{aligned} \tag{25}$$

$$\begin{aligned} SC_z(y) &= G_z(y) / \mathit{ironDensity}(z,y) \\ SP(y) &= SP(1) \times (\mathit{oilEquivalent}(y) \times \mathit{energy4steel}(y)) / (\mathit{oilEquivalent}(1)) \times \mathit{energy4steel}(1)) \end{aligned} \tag{26}$$

These equations used additional parametric functions that represents the "known unknown" associated with M4:

- ***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*

Let us emphasize the simplicity of the investment model that does not take any "time shifting" into account, such as debt or capitalization for future use. If there is no energy and the activity reduced, the associated investment will be governed by the *iRevenue*(*z*) ratio.

3.6. Ecological redirection model (M5)

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 rise of CO_2 (and other greenhouse gas)?
- What are the economic consequences of this warming?
- How will 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 CO_2 concentration. This function is extracted from the representative concentration pathways (RCP 4.5, RCP 6, and RCP 8.5) of the IPCC reports. Although this is indeed a "coarse" abstraction because we represent the temperature elevation as a function of CO_2 concentration, we may capture some amplification loops that are present in the RCP scenarios, such as the fact that the loss of glacier and snow-covered area is amplifying solar forcing (reducing radiation) or that additional methane may be released as a consequence of temperature elevation.

The second sub-question is complex, but there is a wealth of literature on the topic of damages. 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, but it also fairly easy to decide if you want to use the output of Nordhaus model [12], or a more realistic output from ACCL, or come up with your own belief after reading a transverse study such as the study by Lincoln [27].

The third question is the most difficult one and one of the key reasons 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. However, the reality of our "path toward catastrophe" might show some bifurcations, with some drastic reactions to some of the catastrophic events that global warming is bound to produce. Redirection modeling may be seen as an oxymoron, which 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 CO_2 taxes (which includes globalization and forced adoption by all countries, or the zone-differentiated form of CBAM).
- "Cancellation," which renounces to some form of energy source for some usages (may be defined as "forced sobriety"), for example, banning non-electric cars in Europe starting 2035.
- Energy policy, which is the combination of accelerating the energy transition and modifying the "energy redistribution policy that is built into M3 thought the alpha function." Redistribution here means distributing either the energy or the right to produce CO_2 emissions according to a political rule, by opposition to market forces. A perfect example is the French subsidies of energy for citizens because of the Russia–Ukraine war.

In the case of M5, the state variables are the following:

- AS(y): agricultural surface on year y
- ES(y): area 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)

Each step of M5 simulation may be described as follows:

(27) We compute the CO_2 level from the emissions, using an absorption ration (roughly 50% is absorbed by the ocean and the earth surface, while the other half is added in the atmosphere).

(28) We then derive the temperature elevation from the "belief" table (IPCC(c)).

(29) We compute the wheat production according to the model presented in Figure 6. The first step is to compute ES(y), the estimated cultivable land attributed to energy production (solar farms or biofuels). The second step is to reduce the total "arable land" according to the losses caused by global warming. The last step is to compute the wheat output according to four factors: the total surface used for agriculture AS(y), the expected gain in yield (productivity through better practices and technology), the reduced efficiency because of energy scarcity (expressed as a function of price, similar to the cancel function of M2), and a *bioHealth* factor that represents the expected impact of warming on wheat agriculture.

(30) For each of the five world regions (US, EU, China, India, and rest of the world [RoW]), we compute the associated pain level using a weighted sum (*painProfile*(z) is a weight vector) of three factors: global warming, energy scarcity, and combined loss of GDP/person and food/person.

(31) Once the pain level is known, we compute the "ecological redirection," represented by a tuple of factors ($TaxF_z(y)$, $CnF_z(y)$, $TrF_z(y)$, $SvF_z(y)$, $PrF_z(y)$). Each factor is a percentage that is used in the previous equations from M1 to M4 and that represents, respectively, the acceleration of carbon taxation, an increased in forced sobriety, an acceleration of energy transition, an acceleration of energy saving investments, and an increase in protectionism.

(32) Once the "protectionism factor" $PrF_z(y)$ is set for zone z, the actual trade barriers are set for each other zone z_2 according to the difference both in CO_2 emissions (per unit of energy consumed) and in the CO_2 taxes. The heuristic of Equation (32) sets a trade protection of up to $TaxF_z$(y) for those zone z_2 with higher emissions and lower carbon taxes.

Equations (functions & differential state)

$$CO_2ppm(y) = CO_2ppm(y-1) + CO_2(y) \times eCO_2Ratio \tag{27}$$

$$T(y) = T(1) + (IPCC(CO_2(y)) - IPCC(CO_2(1))) \tag{28}$$

$$\begin{aligned} ES(y) &= ES(y-1) + \Delta C_{clean}(y) \times landEImpact(y) \\ AS(y) &= (AS(y1) - ES(y)) \times (1 - landLossWarming(T(y))) \\ WO(y) &= WO(1) * \uparrow AS(y) \times \\ &\quad \uparrow aggroEfficiency(oilEquivalent(y)) \times \\ &\quad cropYield(y) \times bioHealth(y,T(y)) \end{aligned} \tag{29}$$

$$\begin{aligned} PAIN_z(y) = painProfile(z) \times (&\\ & painFromClimate(T(y)), \\ & Cn_z(y) \times (1 - Alpha(z)), \\ & satisfaction(z, WO(y) - WO(y-1), \\ & \quad (G_z(y) - G_z(y-1)) / Pop_z(y))) \end{aligned} \tag{30}$$

$$\begin{aligned} TaxF_z(y) &= pain2Tax(z, PAIN_z(y)) \\ CnF_z(y) &= pain2cancel(z, PAIN_z(y)) \\ TrF_z(y) &= pain2transition(z, PAIN_z(y)) \\ SvF_z(y) &= pain2savings(z, PAIN_z(y)) \\ PrF_z(y) &= pain2protectionism(z, PAIN_z(y)) \end{aligned} \tag{31}$$

$$\begin{aligned} protect(z_1,z_2) &= \max(0, 1.0 - PrF_{z1}(y) * \\ &\quad \max(0, (CpE(z_1,y) - CpE(z_2,y)) / 1E\text{-}3 + CpE(z_1,y)) \times \\ &\quad \max(0, (CpE(z_1,y) - CpE(z_2,y)) / 1E\text{-}3 + CpE(z_1,y)) \\ CpE(z,y) &= CO_2(z,y) / \Sigma_e U_z(e,y)) \\ TxR(z,y) &= CO_2tax(z, PAIN_z(y)) \end{aligned} \tag{32}$$

These equations used additional parametric functions that represents the "known unknown" associated with M5:

- ***bioHealth***(T,y): percentage of yield evolution, which declines when temperature rises but grows with worldwide diffusion of tech and best practices.
- ***agroEfficiency***(p): decline of productivity as energy price increases.
- ***cropYield***(y): increase of productivity in year y due to propagation of best practices and improvement in agriculture science.

- ***painProfile***(*z*): vector of three 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.
- *CO_2Ratio*: additional concentration in the atmosphere from additional CO_2 emission (ratio).
- *IPCC(c)*: temperature elevation caused by concentration *c*, extracted from IPCC RCPs. This is not a constant function as the consensus from IPCC evolves, for instance, from AR5 to AR6 (*Assessment Report*).
- *satisfaction*(*z*,*dW*,*dG*): heuristics that defines satisfaction from *WheatOutput* change and GDP change.

Interestingly, the function *painFromClimate*(*t*) is not linear nor continuous and may be used to trigger bifurcation or to represent crises. On the other hand, the consequences of "pain" (Equation (31)) are simple linear functions because we do not have enough experience or data to justify a more complex model. The use of a discontinuous step function enables CCEM to represent "punctuated equilibriums," which is a characteristic of "ecological redirection" [16], a mix of "regular" trajectories cut by a few crises.

4. Preliminary Computational Results

4.1. Six "Key kNown Unknowns" (KNU) to characterize beliefs

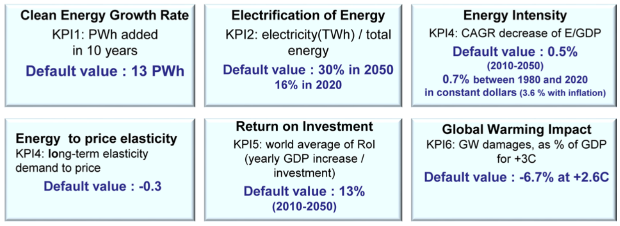
"Median beliefs" are necessary as an input to CCEM, and this is not an easy task (precisely because there is no consensus on the KNU questions). The "median" scenario is not critical since the goal of the model is to look at the impact of beliefs on outcome (i.e., the goal of CCEM is to play with different beliefs, not to claim that the "median belief" is right); still, it is necessary to understand where this median scenario comes from.

First, we have identified six key KPI that best describe the *known unknowns* and that address the most critical choices. For instance, the amount of fossil energy reserves, or the expected population growth in the 21st century, are critical but there is a better consensus, even though with a large deviation. The following are the six KPI (which we call KNUs), for which there is a large uncertainty but also enough literature to perform calibration:

1) The "Clean Energy Growth Rate" is the speed at which new green capability may be added.
2) The electrification of energy consumption is of one the heavily debated unknown, as told when we described M3.
3) The "Energy intensity" is the ratio of total energy used by unit of GDP.
4) The negative energy demand to price elasticity is a KPI that describes the cancellation behavior of M2.
5) The return on investment (average for each zone) is a key parameter that determines the shape of the world economy growth in a world with abundant energy (business as usual, [BAU]).
6) The damage loss of GDP as a function of warming

Figure 7 shows the value that we have obtained through a "web search" calibration process, with the assistance from a few experts from the NATF. This means that the values in this table are obtained as the mean of what we found in the papers quoted in the bibliography, as well as major web sources of data such as "Our World in Data" or "Statista."

Figure 7
A comparative chart from the study on the Bengali handwritten word dataset



These values do not claim to be more trustworthy than those used by other research scientists (precisely because they represent "known unknowns"), they are shared to understand how the upcoming charts have been generated.

4.2. Simulation outputs with "median beliefs"

The charts shown in Figure 8 illustrate the outcome of a simulation run displaying GDP, total yearly primary energy production in PWh, CO_2 emission (forcing, Gt/year), 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 CO_2 intensity of energy (gCO_2/kW.h). We do not include more detailed outcome such as the "loss of GDP because of energy shortage" or the global warming damages (loss of GDP as a percentage because of productive capacity loss), but they are already significant for a scenario such as Figure 8.

Some comments may be useful to understand the result expressed through the Kaya identity:

1) GDP figures are expressed in constant 2010 dollars (see Figure 9 for a current dollar vision with an average 2% inflation hypothesis). The impact of the lack of enough available energy is quite visible globally and is amplified by the zone differences (United States and China are still growing while EU and RoW are declining slowly).
2) The evolution of the CO_2 intensity of energy is the perfect illustration of the viscosity expressed by Vaclav Smil: the trend toward the decarbonization of energy is constant, but it takes time.
3) The figures used for demographic forecasting are based on recent studies that consider the decline in male fertility (a probable but not yet demonstrated consequence of pollution) and the impact of higher education of the female population.

Figure 8
Outcomes from one CCEM scenario

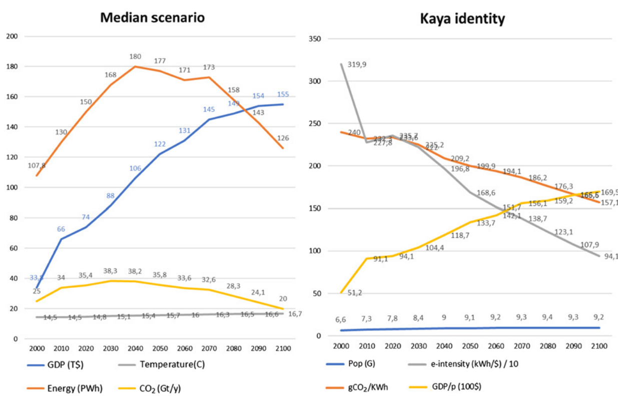


Figure 9 shows the results for each zone. The top part is the GDP per zone expressed in current dollars with the 2% inflation hypothesis. The bottom part shows energy consumption and the contribution to CO_2 emissions for each zone. The United States is benefiting from a high level of economy dematerialization, but its reliance on oil and gas hits its economy in the second part of the century, versus China whose strategy of mixed coal/clean (an aggressive but slow substitution of coal to clean energy for electricity and restrained dependance on oil and gas) is more robust against the oil and gas price increases once the "peak Oil&Gas" is reached. EU and the fifth RoW zone are severely hit by the energy situation. The "with inflation view" masks the actual recession when GDP is adjusted for inflation (what has already happened in 2010–2020).

4.3. Sensitivity analysis

We will first illustrate the "sensitivity to key beliefs" analysis with two specific examples. Figure 10 represents the impact of the fossil energy as a "known unknown." The graph at the left is the extent of fossil fuel reserves as they were evaluated in 2010. The median scenario shown previously is based on a 2020 view that integrates shale oil and gas reserves. The graph at the right is the hypothesis that the reserves can be extended by a similar amount (what was added from 2010 to 2020).

Economic growth is directly linked to the availability of cheap energy (if reserves are larger, energy is both more abundant and cheaper). As a result, the amount of fossil energy reserves is indeed

Figure 9
Results per zone

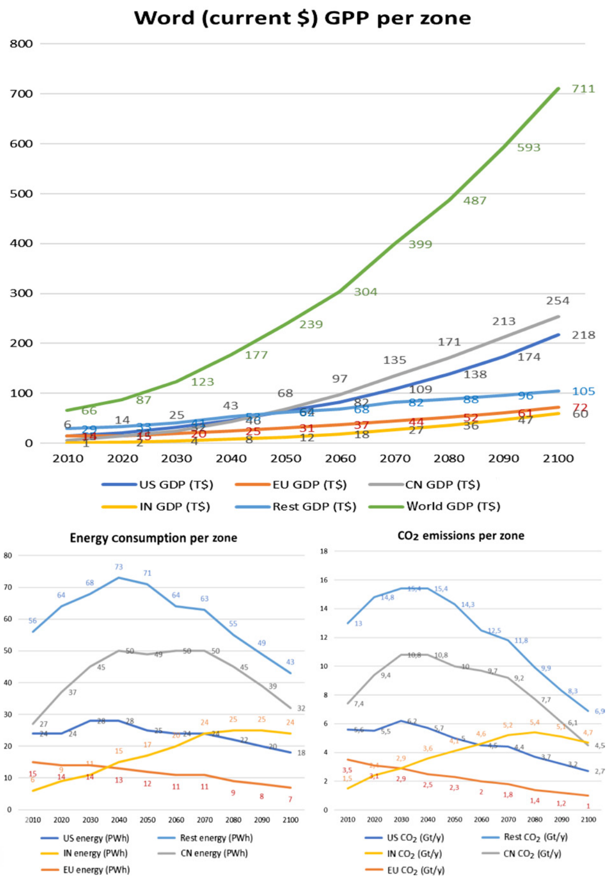
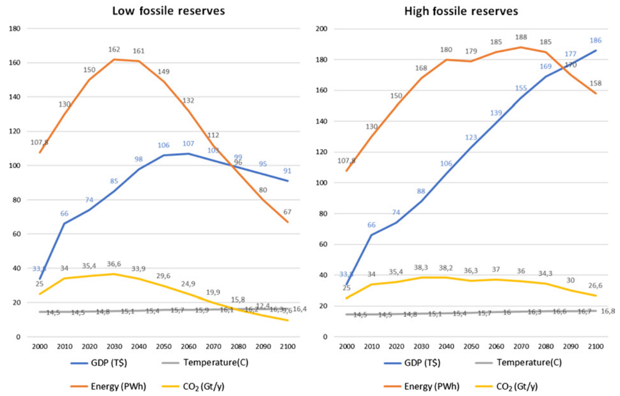


Figure 10
Sensitivity to fossil reserves



one of the key factors of climate warming, even if the "progress" of dematerialization and efficiency means that consumption peaks around 2050 and then decreases. It is interesting to report that the impact on economic growth is stronger in Europe and the United States than in China, which has made the strategic choice of abundant coal and is less dependent on the availability of oil and gas.

Figure 11 explores the sensitivity to the capacity to deploy, and to use, clean energies. The left graph shows a scenario that assumes that (1) clean energy production will grow at the speed observed in the lack decade (as opposed to the median scenario that expects a tripling of this speed, Figure 7 and the 13 PWh added in the 2020–2030 decade) and that (2) a rate of electrification that is the continuation of the historical trend. The right scenario assumes an acceleration of renewable energy production that is closer to IRENA projection, together with an acceleration of electrification. Here the "viscosity" of the model is still at play: in 2100, the electrification ratio is 43% in the left scenario, 50% in the median scenario of Figure 10 and 55% in the right scenario. CCEM is not able to produce the 80% that is associated with "net-zero" scenarios (which requires a huge leap of faith in sobriety).

This "viscosity" explains why the rate of electrification is a key parameter in global warming prevention and why simulations indicate that keeping the price of electricity low is better to reduce CO_2 emissions that a higher price set to encourage forced sobriety.

Figure 12 represents the sensitivity to carbon tax. The left simulation is performed with a uniform carbon tax of \$50/t that is

Figure 11
Sensitivity to deployment and electrification of clean energies

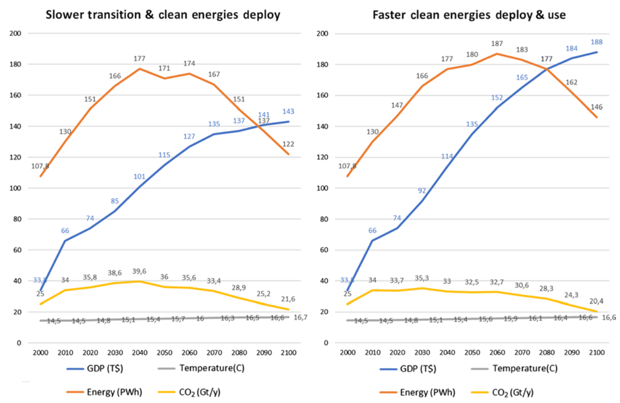
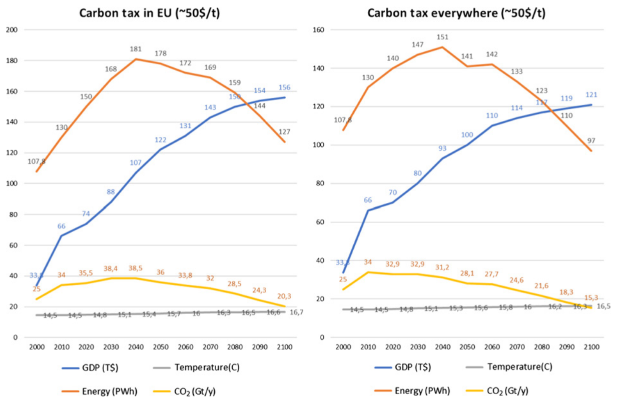


Figure 12
Sensitivity to carbon tax



applied only in Europe (but on all energy consumption). The right simulation applies the same level of tax everywhere in the world. In the first scenario, there is a clear impact of CO_2 tax in Europe, which automatically reduced fossil fuel consumption and CO_2 emissions. However, this fossil fuel "surplus" is picked by other players, resulting on a null impact on global warming. In the second scenario (right), the impact is very visible, both on CO_2 emissions and on GDP. The impact on temperature is lessened by the inertial of the atmosphere. This second result is one where CCEM differs significantly from other models that do not see such a big economic impact of CO_2 taxes because CCEM supposes a strong link between available energy and economic outcome. With the current price of coal, applying a $50 tax on a ton of CO_2 means to triple the (2010) price of coal, which would very strongly impact China's economy, thus making this scenario very unlikely.

5. Perspectives and Future Work

5.1. Obvious CCEM limitations

By construction, CCEM is a "coarse model" with many limitations. We mention here the most obvious ones. For some of them, it is a design choice, and they will remain a limiting factor. We already encountered two such cases: the fact that carbon sequestration technology is not considered and the simplistic link between CO_2 output and CO_2 ppm concentration, without explicitly taking other greenhouse gas as factors. For some other limitations, a new version of the model will evolve to capture at least part of the fair criticism that can be made in the current state:

1) Hybrid energy market: CCEM assumes a world energy market, where energy circulates freely. As the price increases and as the tensions materialized by the "pain" in this model grows, it is likely to see more protectionism and a price for energy that is regionalized.
2) Wars, conflicts, and social uprising are somehow out of scope, as soon as their scale is large enough to disrupt the world economy significantly. A moderate amount of this feedback loop may be represented using the "pain to productivity" factor described in Section 3.5.
3) Redistribution as inequalities rise need to be better represented. We need technology to address the 21st century challenges, and the use of technology will increase inequalities between zones, between countries, and between citizens in each country. This aspect is left aside in the current version of the model (the only social dimension is the level of pain that is caused both by energy price increase and the reduction of GDP growth).
4) M5 uses a crude ("coarse") projection of IPCC RPCs to derive a function that links global warming to the CO_2 concentration, itself derived from direct CO_2 emissions (e.g., without LULUCF). It does not mean that other GHG or that other factors are ignored, but that they are not represented in CCEM other that what is implied in the average IPPC scenario.
5) Biofuels such as wood are simply aggregated in the clean category, which is a gross simplification (and the object of debates) but seems an acceptable approximation considering the global share in the energy sources.

This paper describes the sixth version of CCEM, which will evolve to better address some of the following questions:

1) How to model biomass distinctly from renewable energies? This would allow us to address the question of the true CO_2 lifecycle emissions associated with biomass.
2) How to expand the GHG emissions model, to gases other than CO_2, and to better address the cumulative paths through transient climate response to cumulative carbon emissions.
3) How to represent the effect of technology lifecycle and volume discounting? Currently, the cost of technology decreases exponentially, and it would make sense to link this decrease with the volume-based experience with this technology.
4) How should the impact of global warming on health and life expectancy (from sickness to accidental deaths) be represented, in addition to the previously mentioned "pain to productivity" loop?

5.2. Observations drawn from CCEM simulations

George Box stated that "all models are wrong, but some are useful." In the case of a "coarse model" like CCEM, "being wrong" is by design, and its value comes from the questions that yield from running multiple "what-if" simulations. For instance, noticing that one-sided carbon taxation in an energy-constrained world has no actual effect on the global warming since the decrease in consumption of one "player" leads to another being able to consume more, is a useful systemic observation drawn from the simulation in Section 4. Displaying static outputs of some scenarios as we did in the previous section does not do justice to the usefulness of SDEM, which should be used in a dynamic context, precisely to observe the relationship between the different decisions (playing what-if). A reference model for CCEM in the future is the interface of the En-ROADS [28] model from MIT that allows to explore the model as a serious game.

Here are three observations that can be drawn, as a summary of doing multiple simulations with different scenarios, especially a thorough sensitivity analysis of the many "known unknown" in Section 4.1:

1) The extreme scenarios, Net-Zero or BAU, are equally unlikely. On the one hand, the known oil and gas reserves make it almost impossible to reach the high temperatures associated with BAU. We are more in a slow transformation as usual, as pointed out by Ritchie [28]. Similarly producing Net-Zero scenarios (where global warming is kept below 2°C, thanks to a rapid move to clean energies – IRENA [29, 30]) is possible with CCEM [5]. However, this requires hypotheses about clean energy transitions, which are quite unrealistic [25].
2) Two key unknowns are the upcoming peak "Oil+Gas" and the moment where clean energy will surpass fossil fuel; but it is very likely that a gap of many decades will exist between the two. This means that the main feature of the simulations shown in Section 4 (i.e., an energy shortage coupled with the associated price hike) is very likely.
3) This gap means that the middle of the 21st century will be characterized by the lack of cheap energy, the resulting slowdown

of economic growth and damages associated with a 2–3°C global warming. This situation will vary considerably for each zone, both in terms of growth and impact of severe weather.

5.3. Future directions

Simulations from Section 4 do not include redirections yet. The calibration of the "pain to redirection" process is under evaluation to ensure that it produces reactions that are aligned with the zones' strategies. CCEM v6 is the first evolution with a "redirection catalog" that addresses a large part of the global warming policies. It took a number of CCEM version iterations to produce a "pain model" that is broad enough to capture, as explained in Section 3.6, the variation of GDP per person, the production of wheat per person (used as proxy for agriculture's health), energy scarcity and pain the disasters caused by global warming (Section 2.3, we use a composite "painFromWarming" parametric function that represents the cumulative effects of direct impact, fear and compassion). Following our experience with other global models [25], we try to guide the computation of the best redirection (seen as a "tactical" reaction to the signals captured with the "pain" indicator) through the maximization of a "strategic satisfaction" that is specific to each geographical zone. The satisfaction is the objective function, defined through:

1) the expected economic growth
2) the level of population satisfaction (the opposite of "pain")
3) the actual level of global warming
4) a time discounting factor, which represents how the zone is focused on long-term versus short-term

The next major step for our work is the integration of the CCEM simulation with the Game Theory and Evolutionary Systems (GTES) framework to tackle complex models with numerous unknowns and multiple interacting players. Developed two decades ago, GTES combines Monte Carlo sampling, Nash Equilibrium search, and local search techniques to analyze models by learning through examples [25]. GTES identifies three categories of unknown parameters: environmental factors sampled through Monte Carlo simulations, strategic goals guiding actors' decisions, and tactical parameters optimized through evolutionary algorithms to align with strategic objectives.

6. Conclusion

CCEM is an SDEM based on four distinctive principles:

1) **Ecological redirection** represents a nonlinear set of reactions from geopolitical blocks as global warming occurs. This supports the production of trajectories that are more realistic than homogeneous BAU (keep warming without feedbacks) or Net-Zero scenarios (where the difficulties and the consequences on developing economies are underestimated).
2) **Explicit beliefs** (Known Unknowns) make it possible to reproduce very different viewpoints with the same model [5].
3) **Geopolitical** modeling, from separated but interconnected blocks to the use of constant dollars models (without inflation), makes the difference between block strategies and goals very visible.
4) **Emerging cooperation**, taking the conflicting interests into account, may be simulated in CCEM, through the differentiation of strategic goals and policies. CCEM may be used to model the emergence of cooperation in times of global warming catastrophes. The next step with CCEM research will be to look for game-theoretic equilibriums, versus top-down planned governance (e.g., "COP agreements" from the UN Climate Change Conferences), which has proven to be difficult to sustain.

Ethical Statement

This study does not contain any studies with human or animal subjects performed by the author.

Conflicts of Interest

The author declares that he has no conflicts of interest to this work.

Data Availability Statement

The data and the code that support the findings of this study are openly available in GitHub at http://github.com/ycaseau/GWDG/.

Author Contribution Statement

Yves Caseau: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – Original draft, Writing – review & editing, Visualization, Supervision, Project administration.

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