CCEM: An Earth-Model for Capturing Beliefs about the Known Unknowns related to Global Warming

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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." Five "*known unknowns*" discussed in the text include the future availability and cost of energy, energy needs and affordability for the economy, the speed of energy substitution, expected GDP growth, and the economic and societal consequences of global warming. These "known unknowns" have no consensus answers but making them explicit in models can help clarify differences in conclusions based on varying assumptions. CCEM, compared with other *Integrated Assessment Model* (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.

1. Introduction

This paper introduces a System Dynamics Earth Model (SDEM), a simulation framework that treats the Earth as a complex system, incorporating feedback loops related to global warming. Earth models have become quite popular since 2010, although they started much earlier, because of the growing capability of computers. Earth models, in their vast majority, are not meant as forecasting models (too much is unknown) but as collaborative workbenches to evaluate and assess hypotheses. Most Earth models embed the finding of IPCC (IPCC 2021), which is itself the synthesis of multiple models designed to assess the impact of CO2 emissions on global warming and its consequences. A "global" Earth Model tries to add two ingredients: the interplay between economy and energy, which drives the emissions of CO2 due to fossil fuels, and the reaction of the world when temperatures rise. The different IPCC RCP (*Representative Concentration Pathways*) are families of scenarios that illustrate the input loop from energy consumption to CO2 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. The most famous Earth Model is DICE (Nordhaus, 2019) due to William Nordhaus and his team of colleagues at Yale University, which has led to the award of the 2018 Economy prize by Nobel committee.

The model presented in this paper is obtained from the coupling of five simpler models, as described in the following figure. The first part is to represent how much energy is available, at a given time and at a given production price. This is rather well-studied for fossil fuels, although the last decades have shown that the inventory of existing fossil energy is a "known unknown". The second component illustrates how the economy adjusts, through pricing and supply-demand equilibrium, to a world where energy become both more expensive and less available than it has been in the past decades. This model makes a simple decomposition between 4 forms of primary energy. A third component of the model illustrates the "energy transition" from one source to another. The fourth model is the bottom right quadrant of the picture, it represents the world economy, which produces value from energy (bottom left) and productive resources (that grow, or not, over time) and produces CO2 emissions. The last model describes how the CO2 emissions produce warming (based on IPCC reports), how this level of warming impacts both the economy and people from the earth, and how society may react to these negative impacts. As the rest of the paper will make abundantly clear, CCEM takes the finding of IPCC as an input and does not challenge them in any way.

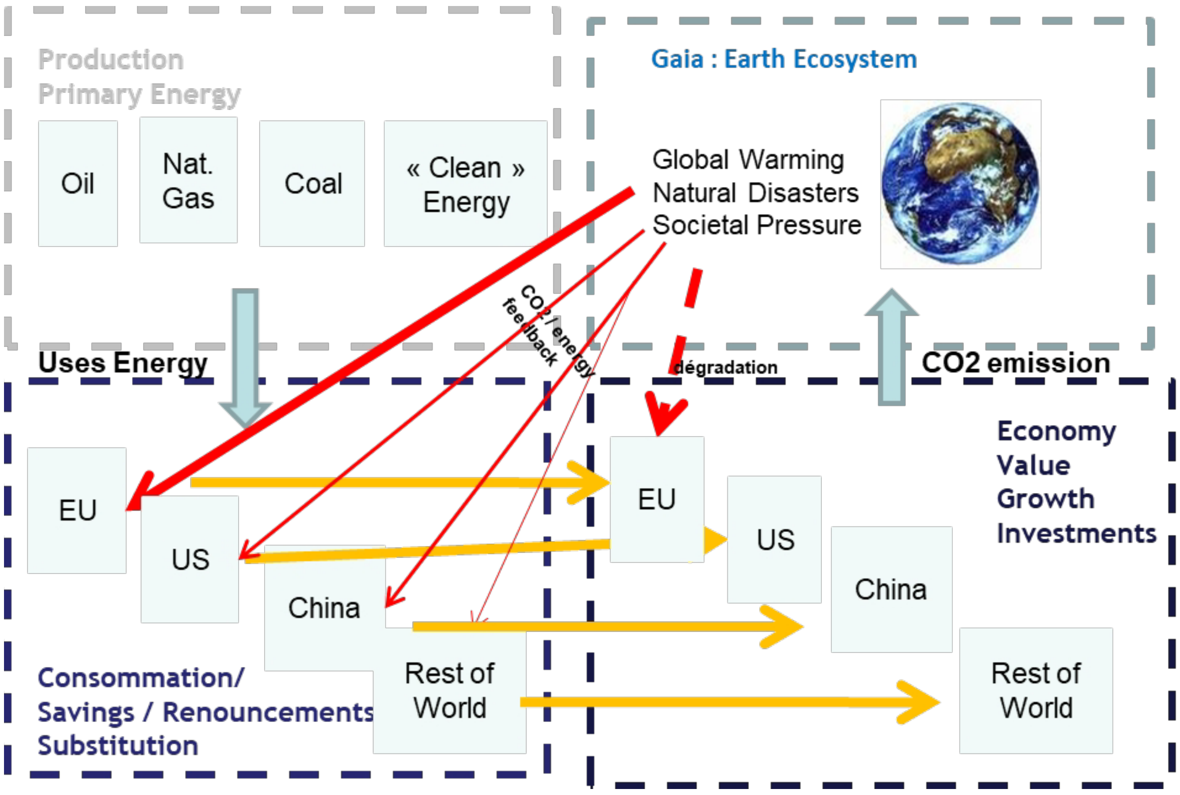

Figure 1: Coupling Earth Sub-Models

The name CCEM stands for "*Coupling Coarse Earth Models*", where the "*coarse*" adjective is added to emphasize the voluntary simplicity of each component models. The goal here is not to make educated forecasts or to better understand the mechanics of global warming policies, but to make the **implicit beliefs**, that we all have when looking at a picture as complex as Figure 1, **explicit**. One of the contributions of this paper is to show that the same mental model may be used to support the reasoning of very antagonistic viewpoints, just by changing a few of the beliefs associated with the "known unknowns". The other contribution of this paper is the fifth component sub-model, that describes the reactions of the world (here subdivided into four 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); we try here to extend towards a more comprehensive societal model. This fifth model is called "**ecological redirection**" because, following the lead of Bruno Latour (Latour, 2017), CCEM sees the consequences of global warming as a sequence of catastrophic events yielding "re-directions", as opposed to the following of a hypothetical "ecological transition roadmap". This sub-model tries to explore what will happen if, which seem likely, the Paris agreement is not upheld, and temperature rises over the +2C threshold (compared to pre-industrial level).

This paper is organized as follows. Section 2 further develops the motivations for this work and emphasizes the relation with other earth models. We focus on "*known unknows*" and show how CCEM makes the assumptions (beliefs) explicit. Then we propose a model for the "political and societal" feedback that could be the consequence of catastrophic impacts from global warming. Section 3 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. Each sub-model, therefore, may be seen as the discretization (one year at a time) of a differential equation. We start with the three models that represent energy production, consumption, and transition. We then present the fourth model, that is of the world economy, 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, which represents "Societal and Political Reaction to Global Warming". This model combines the computation of possible impact of temperature elevation, both from the point of view of loss of productive capacity, which is common to most earth models, but also from an ecological redirection perspective. Section 4 illustrates CCEM with a few preliminary computational results, highlighting the importance of "median beliefs" as inputs. Six Key Performance Indicators (KPIs) known as KNUs (*Key kNown Unknowns*) are identified to address critical uncertainties such as clean energy growth rate, energy intensity, price elasticity of energy demand, electrification of energy consumption, return on investment, and GDP loss due to global warming. Section 5 outlines limitations and future directions for our CCEM work. It acknowledges the model's simplifications, such as ignoring future carbon sequestration technology. Future versions may address energy market regionalization, impacts of conflicts and social unrest, and economic inequalities. Open questions include better capturing economic growth differences across zones, modeling protectionism's impact on GDP, and the interdependence between material and immaterial sectors. The section also discusses using human happiness proxies for policy changes and contemplates incorporating game-theoretical approaches to simulate complex geopolitical interactions.

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 CO2 emissions) have existed for many decades. These models fall into two categories: IAM (*Integrated Assessment Models*) and SDEM (*System Dynamics Earth Models*) such as "Limit to Growth", the MIT model that is 50 years old (Meadows et al., 2013). SDEM are "*from first principles*" models (Sterman, 2000) 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 statistic tools). From a system design perspective, CCEM is more of a SDEM than an IAM as we shall see in Section 3. SDEM try to capture causality (which is hard and produce the system dynamics graph) 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 a heavier focus on 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 great tool to understand systemic feedback loops, and they have also proven to reproduce the past fairly well (Herrington, 2022). Still, as the close look in section 3 will make clear when we introduce its five sub-models, CCEM is very much influenced by IAMs with similar world economy growth equations and with much higher level of detail on energy production and energy consumption than what is found in SDEMs.

IAMs (Nordhaus, 2019), have played an important role in policy assessment (hence their name) for the last decades. The most famous model is DICE, *Dynamic Integrated Climate-Economy* model (and its regional evolution RICE), but there as many similar models, such as those pointed in (Gillingham et al.,

2018) study mentioned by Nordhaus in his prize lecture. The similarity between CCEM and DICE (see Newbold, 2010 for an introduction) will become abundantly clear during the presentation, although DICE relies on linear programming as the modelling technique while CCEM uses a more rustic but more general simulation paradigm, which is better suited to explore non-linear coupling and catastrophic amplifications. If we follow the presentation of the DICE model proposed by Stephen Newbold, we find precisely the same structure as the one that we propose in this paper: energy, economy and climate, including damages.
Among the models that were proposed during the same timeframe as DICE, are GCAM (Global Change Assessment Model, by (Edmonds, Wise and MacCracken, 1994), and IGSM (Integrated Global System Model, Sokolov et al., 2005). Although the GCAM paper is close to 30 years old, its energy product model is quite similar to what is proposed with CCEM, and it provides with interesting calibration results (that is, we can see how our vision of world energy has changed in 30 years). However, the key finding of the 1994 paper, that is that the overall energy portfolio is a major driver of climate change, remains. The MIT model it itself a combination of complex model, namely 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, the comparison is especially interesting 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 (see Section 6). It is also similar to IMACLIR-R (Sassi, 2010) as far as the world zones economy model is concerned, and its coupling with energy sources, with 4 zones versus 16. The results provided in and (Sokolov, 2005) and (Nordhaus, 2019) also make for an interesting source of comparison with CCEM since on the one hand they are easily reproducible (because of the similarity of the models) but they require strong underlying assumptions (what we call "belief" in the next section). The trajectories proposed in the ISPG paper are plausible, but they assume both access to large amounts of energy and limited feedback from the consequent global warming.

Many following models have been proposed that keep the structure of DICE but attempt to provide a more "realistic" capture of global warming damages. As noticed by Kenneth Gillingham in 2018, the controversy about the results from Nordhaus, which described the most likely outcome as a significant (+3C) warming with a moderate (-3%) impact on GDP, is not the model itself but the damage component of the model which underestimates the consequences of the global warming as described by IPCC and illustrated by (Wallace-Wells, 2019). For instance, the paper (Hänsel et al, 2020) proposes to update the DICE model with a more up-to-date appreciation of global warming damages and finds that the "optimal path" proposed by the revised DICE model is close to the UN climate targets. Another very interesting earth model is ACCL (*Advanced Climate Change Long-term*) proposed by (C. Alestra, G. Cette, V. Chouard and R. Lescat, 2020). This model 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 model is quite detailed from a geographical perspective and reflects a huge effort of data analysis. The economy growth model of ACCL was used as an inspiration for CCEM. The impact of warming through SCC (Social Cost of CO2 emissions) is, like in the previously quoted paper, assessed to be higher than in Nordhaus original work, resulting in "preferred trajectories" that impose a strong reduction of CO2 emissions. Our "median belief" regarding global warming impact, as explained in Section 4.1, is mostly based on (Wade, 2016), which makes it consistent with a high value of SCC as advocated in (Rennert, 2022). 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 very clear that these models are not forecasting tools and should not be used 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 Beliefs as First-Class Explicit Components

Assembling an Earth Model means to combine pieces of causal reasoning that we hold true (using whichever modeling technique: linear constraints, state differential equations, fragments of code, etc.) with assumptions, which are hypotheses that we want to evaluate or policies that we want to optimize. For instance, all the model mentioned in this paper are built on the causal models about climate change described in the IPCC reports. In the case of the Energy/Economy/Climate coupling, there are (at least) five "known unknowns":

- *How much energy will be available in the future? At which costs?* This question is well known for fossil fuels and is related to the number of accessible inventories. For instance, the introduction of shale oil and gas has changed our perspective between 2000 and now. On the other hand, the cost of extraction for future resources is difficult to foresee. This question also applies to renewable clean source of energy. We now have a better understanding of cost evolution (although it is a matter of debate) but our capacity to execute, from material resources such as metals for wind turbine to manufacturing capabilities, means that the rate at which we can deploy these renewable energy plants is a "known unknown".
- *How much energy is needed and affordable for the economy at a given cost?* The energy intensity (amount of W.h, that is Watt x hour, 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? The "hot question" of the need for energy subsidies – when a government helps some human activities to have access to a lower energy price – is part of this second issue.
- *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. The first question addressed our capacity to produce this clean 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. This a complex question since the answer is different for each type of industry (Gates, 2022).
- *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.
- *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 (Wallace-Wells, 2019), there are many other indirect impacts that will add to "capacity losses". If the temperature rises above +2C, fear and pain may create all kinds of bifurcations from the "modeled path".

These are "*known unknowns*", as popularized by United States Secretary of Defense Donald Rumsfeld in a famous 2002 speech, in the sense 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 variation of opinions over the past decades, as shown by the Energy resource example). We make these beliefs "first-class citizens" of the CCEM model, which means that we use a closed abstraction (most often a table or a single-parameter function) to represent the answer to the questions that we just listed. We want to make beliefs explicit in CCEM because we find that other studies with very different conclusions differ, not on their earth model principles, but on their unspoken hypothesis about some of these known unknowns. For instance, the main difference between the various DICE-related models presented in the previous section is foremost about the answer to the fifth unknown.

The following figure describes the intent of making beliefs explicit in CCEM. The CCEM simulation model is made of state variables that describe earth as a complex system, and simulation rules that we decompose into:

- The foundations, such as the IPCC "warming as a consequence of CO_2", the economic growth model, or the supply/demand adjustment loop. As pointed out in the figure, these foundations represent the backbone of the simulation model. They are the assumption that are not challenged (which is why it is important that they are shared with the previously quoted earth models).
- Beliefs as parameters to the model, that will be described in the remainder of the paper. These are only "hypotheses" that can be modified easily. The most interesting way of using the CCEM model is to use the simulation results to challenge your own beliefs (Caseau, 2012).

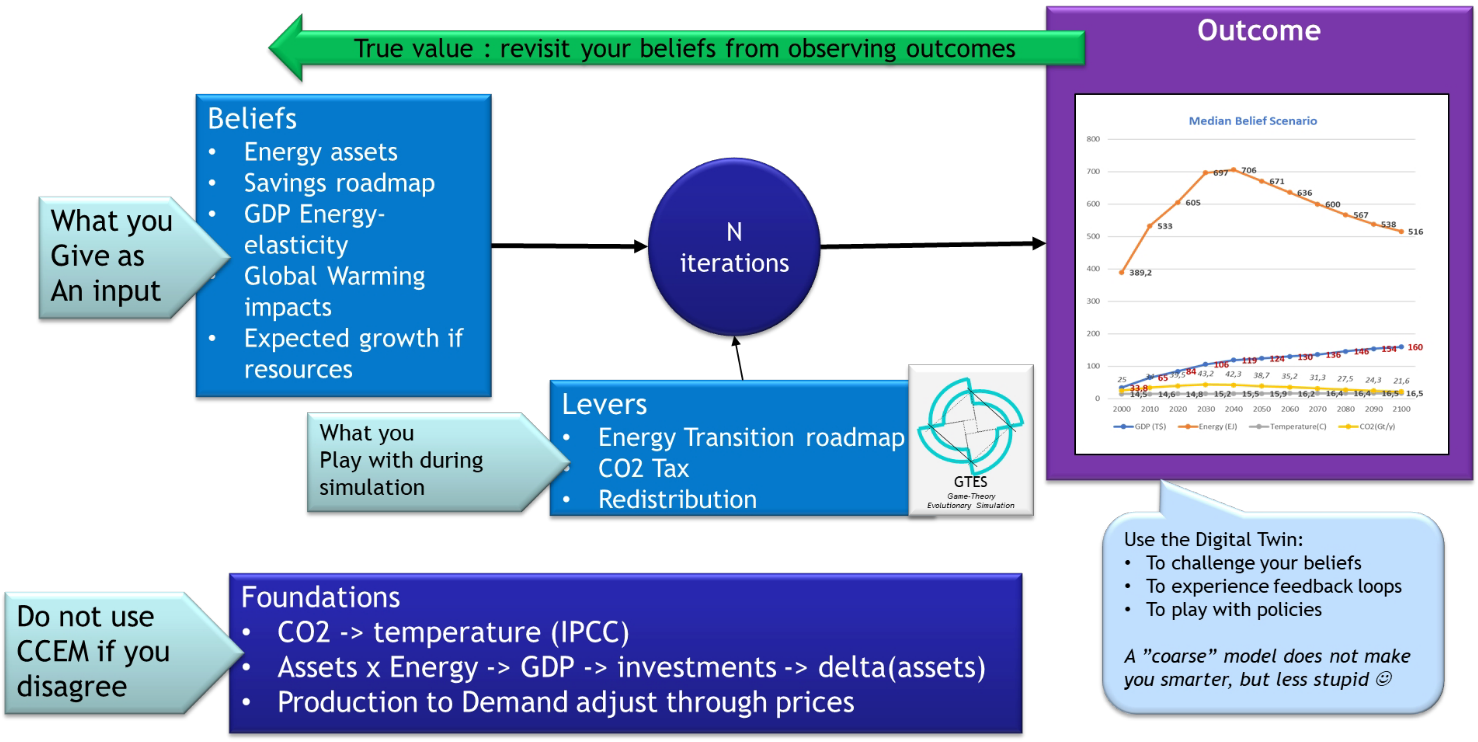

Figure 2: Beliefs, Hypotheses, Framework

A very important point must be made at the beginning of this paper: *CCEM is not designed to help you produce the answers to these "known unknown" questions*. How you produce the "belief" that is used as a CCEM parameter is up to you, which is why CCEM is simpler than many other earth models. The example of the energy transition is a good illustration: there is a huge amount of work dedicated to forecasting what is achievable as an "energy transition policy" (IRINA 2023; Püttgen 2021; Smil 2021). If you believe that raw materials such as iron is a limiting factor to switch to new energies such as wind, it should and may be reflected in the associated "belief" tables (energy assets). In a way, beliefs act as modular decoupling of other earth simulation models: each "belief model" is a crude abstraction of some other model that has been developed elsewhere.

2.3 Societal and Political Reaction to Global Warming

The main contribution of CCEM as an "IAM" as defined by W. Nordhaus 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:

- Which are the impacts of the global warming: floods, canicules, wildfires, water shortages and sea level elevations, to name the most obvious ones (Wallace-Wells, 2019)? These impacts are both material and human, either with physical loss of life or abilities, but also severe psychological pain.
- 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 so see, at least in some part 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. In this paper, we shall consider three "political" reactions: to accelerate CO2 tax, to increase the set of activities which are abandoned because of their CO2 impact (reinforcing the "cancellation" loop that is shown in Section 6) or reinforcing the "energy redistribution policy".

We borrow the term "redirection" from (Bruno Latour, 2017) and many research scientists who work on the **Anthropocene** (Bonneuil, 2013) (Adeney Thomas 2020). 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.

The feedback loops that are implemented with CCEM can be summarized in the following figure. The various natural disasters create in parallel a production feedback loop and a societal feedback loop. The first loop is directly related to the fifth unknown of the previous section: what is, eventually, the GDP loss that is the consequence of fires, floods, droughts and canicules? Although this is a difficult topic to investigate, there is a fair amount of literature, as referenced in (Wallace-Wells 2019), to put forward some order of magnitudes. The second loop is the "redirection loop", where the pain caused by global warming pushes some of the redirection mechanisms.

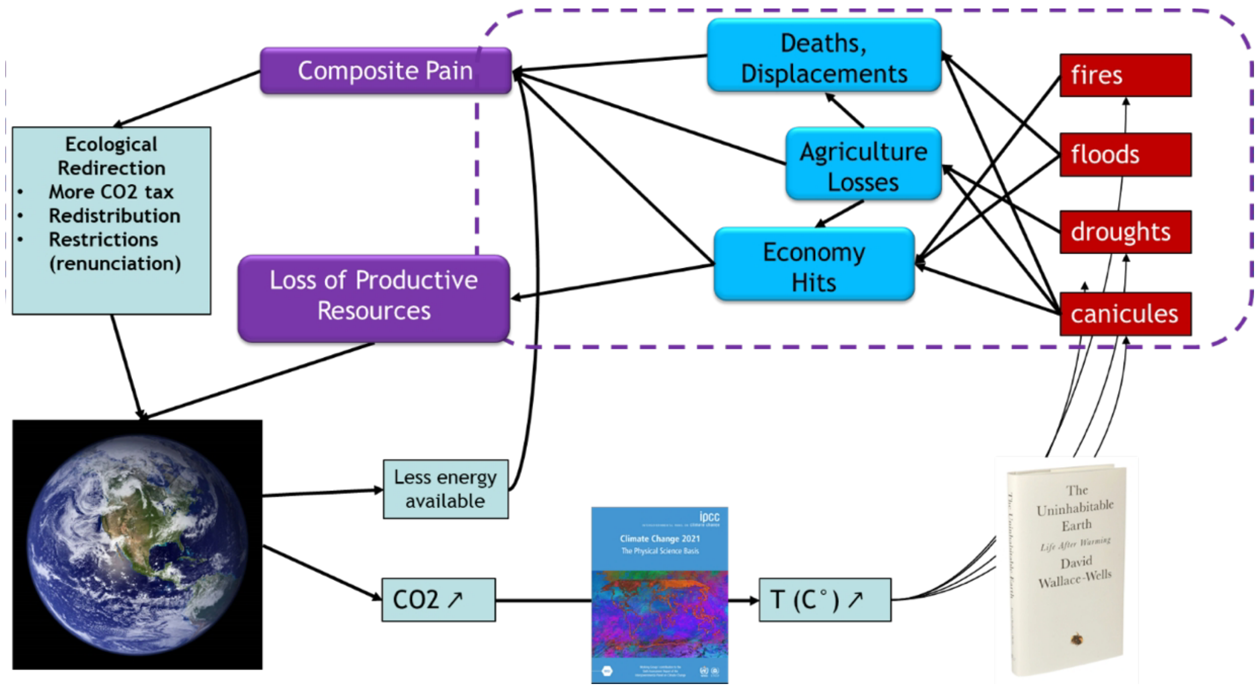

Figure 3: Looping Back Global Warming to Population

We introduce a "pain factor" that is fed by the different negative outcomes of global warming and acts as a non-linear trigger to redirection. In the current version of our M5 model, the "pain" is the sum of from three components:

- Pain from warming: this is the pain cause by being exposed to, directly or indirectly, or the fear of natural disasters and the destruction of lives and properties that they imply.
- Pain from economic results: we live in a world of growing inequality; the social balance requires growth and some form of redistribution. As growth declines (even more if it becomes negative), governments have a hard time to manage the "discomforts" of a growing part of their population.
- Pain from energy shortages: as energy price go up, people and companies have to reduce their usage, up to the cancellation of some activities. This represent a serious level of pain (depending on how "critical" the cancelled activities were.

The "pain from warming" is itself an aggregated representation of the various impacts, as show with the "red dotted zone" in Figure 4". Pain here is a subjective factor (used as a trigger), what matters is to find a way to assess in a homogeneous way the pain from the different factors. The following figure makes explicit the difference from seeing (empathy) a catastrophe, from fearing (the occurrence of) a catastrophe and from enduring a catastrophe.

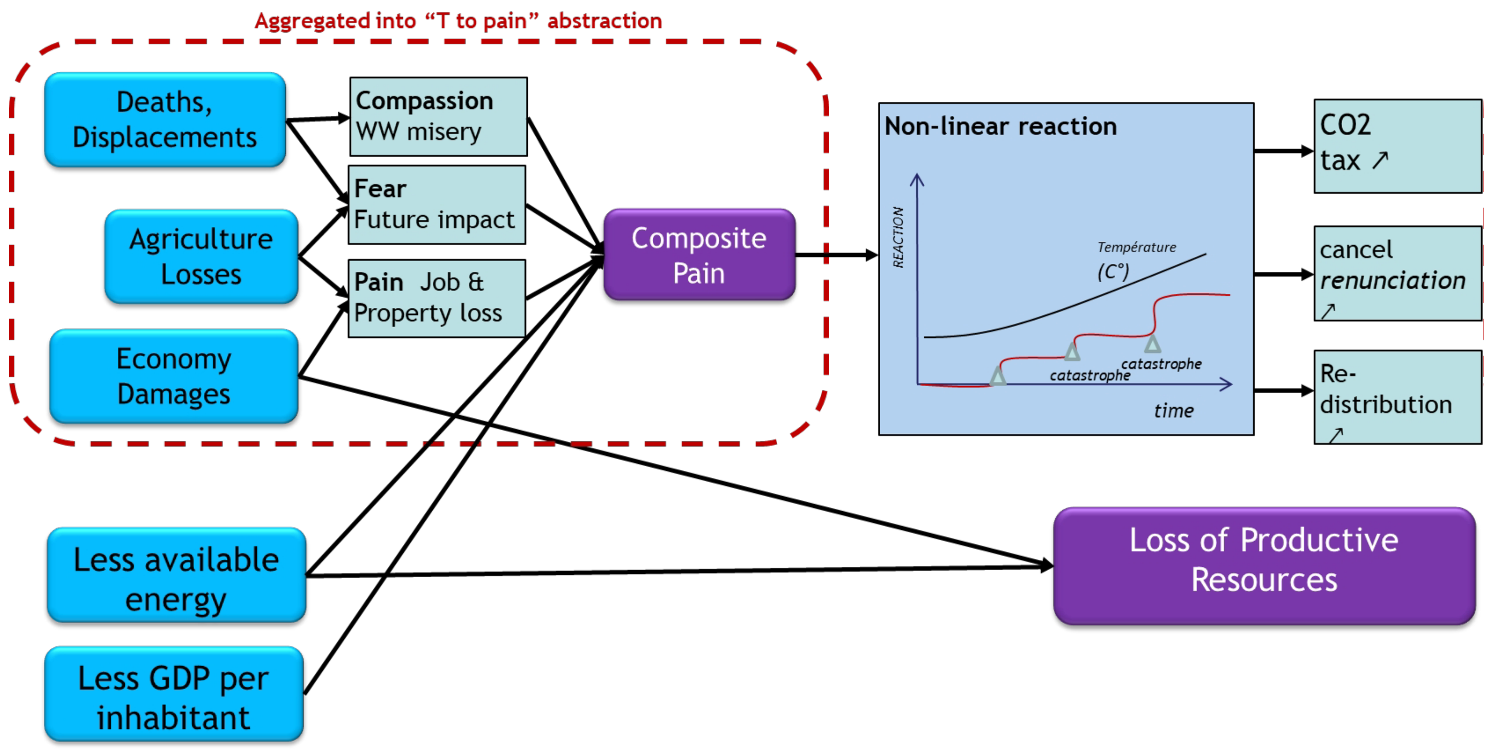

Figure 4: From Pain to Redirection

3. CCEM Presentation

3.1 CCEM Architecture

CCEM is a simulation model, where earth is considered a complex system, its various energy/ economy/ climate components being 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 overall structure of a simulation run may be described by the following figure. The starting point is 2010, first because the work presented here started a decade ago but also because it makes 2020 an interesting point for calibration. Each component is defined by a "discretized differential equation" that gives the value of the state variables associated to energy production, energy consumption, energy transition, economic output, temperature elevation and its consequence at year y as functions of the state variables' value the year before.

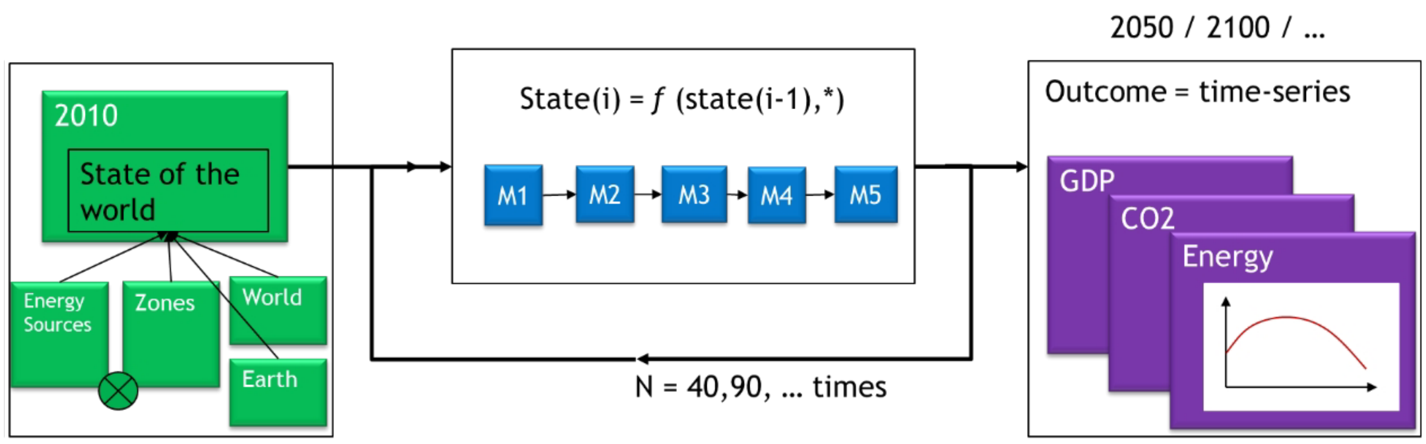

Figure 5: CCEM Simulation

Once again, the "coarse" adjective of CCEM captures the following design intent:

- Keep the model simple for readability, so that you can decide quickly whether you agree with this approach or not. However, sophisticated the earth model might be, it remains a very crude abstraction, so readability is more important than completeness. Remember that there are many "*unknown unknowns*" with this large question.
- Support fast simulation runs, since the goal is to perform millions of runs when exploring as a complex game with multiple players, using GTES simulation as told in Section 5.3.
- Make the beliefs visible, easy to understand and to modify, so that CCEM may be used to explore one's own mental models, as explained in Figure 2.

CCEM is defined as the coupling of five models:

- Energy resource model (M1): this model predicts, for the years to come in the simulation range, how much energy will be accessible at a given costs. The model separates 3 forms of fossil fuel and combine all "clean" (no CO2 usage-impact) into one category.
- Energy consumption model (M2): this dual model computes the expected input of energy, for each of the world zone shown in the introduction, and how much would be actually consumed as a function of the market price.
- 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.
- Economy model (M4): this is how we represent the GDP/value creation of the world economy, decomposed into four 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)
- 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 but also trigger redirections, changes in the energy/economy management policies.

The following figure illustrates the complete CCEM system, following John Sterman notations (Sterman, 2000), that is how each of the five model interacts with each other.

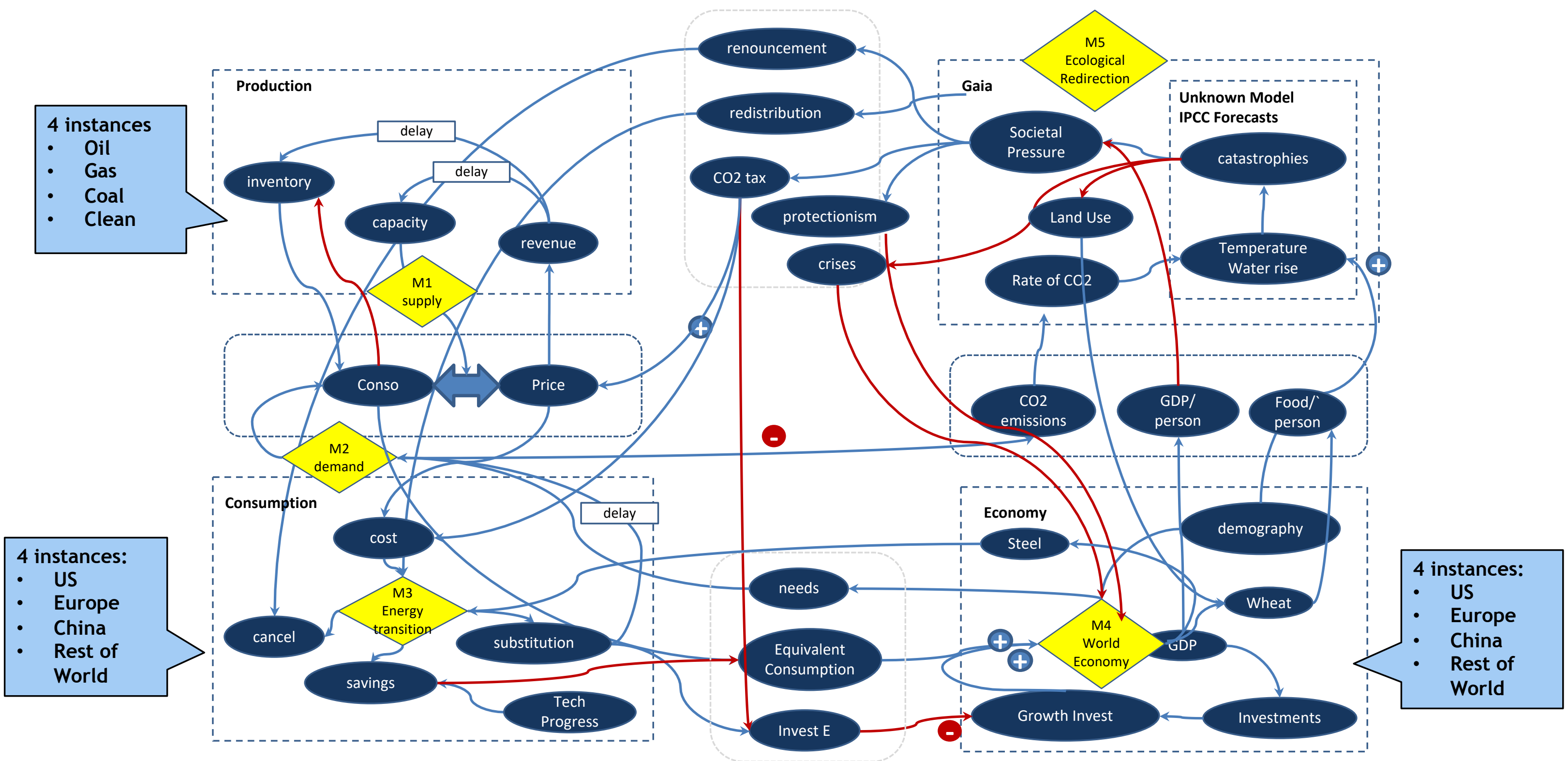

Figure 6: System Dynamics representation of CCEM

3.2 Energy Resource Model (M1)

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 is not a value, it 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 (affine 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 possible 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). Energy is measured in Gtoe (giga tons of oil equivalent) for CCEM v4; we shall use TWh and PWh in future versions, 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 Gtoe for energy e at year y
- $C_e(y)$: max capacity in Gtoe for energy e
- $A_e(y)$: added capacity for energy e through transfers (M3)
- $tO_e(y)$: total output in Gtoe from years 1 to y
- $P_e(y)$: price in \$ for 1 toe for energy e at year y
- $UD_z(y)$: demand (unconstrained consumption) for zone z of energy e
- $G_z(y)$: gdp for zone z on year y

For the sake of simplicity, the price range is discretized between 0 and P_{max} by P_{inc} increments. There are three key steps for fossil fuels:

- Compute the max inventory capacity: mostly a function of the inventory "belief", based on the average market price during the past 3 years (obviously, this is a gross simplification that does not reflect the delay between market price, drilling decisions and exploitation).
- Adjust the current capacity (bounded by the max inventory)
- The production uses a piecewise affine function that cannot exceed the current capacity (cf. Figure 8) and reflects price elasticity (calibrated at the decade level).

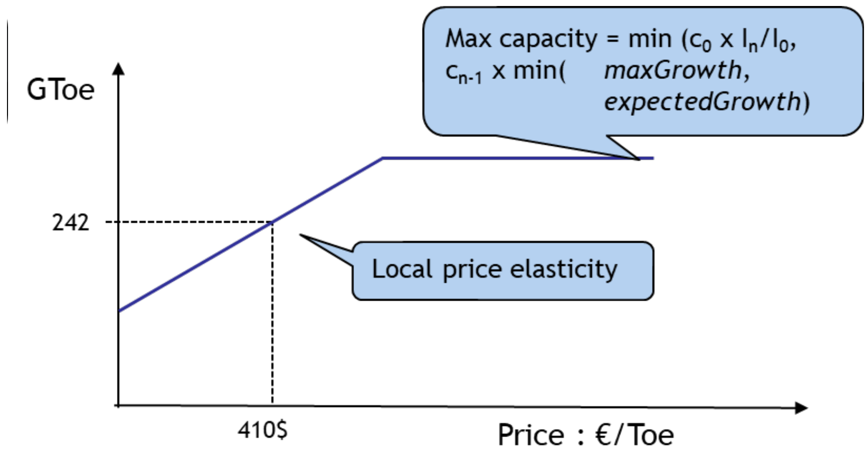

Figure 7: Adapting the fossil energy production to price

The logic of M1 can be described with the following equations. There are two separate sections for `Fossil` and `Clean` energies. For fossil fuels, we compute the maximum theoretical capacity from the inventory (with the three years average price). This theoretical capacity is an upper bound for the actual "max capacity" that mimics the growth of needs (an input from M2), adjusted to reflect the growth constraint. Since prices in CCEM are signals that do not intend to reflect market prices but rather "aggregated prices over a number of years", we suppress irrelevant oscillations by a damping factor (the ratio need/output is divided by a constant factor (currently 3). We then compute the supply output vector using the function show in Figure 7 (as seen in the equation below, the MaxCapacity formula is different for fossil (finite) and clean ("infinite") energies. The code for clean energy max capacity uses the "belief" *maxCapacityGrowth*(e,y) which gives, for any year in the future, the growth capacity (expressed in output per year) for this year. Figure 7 may look far too simplistic, which it is, but keep in mind that it applies to situation where energy is abundant and where it simply represents a linear elasticity. When energy is scare the price trend is dominated by "the other half of the equation", that is how demand decreases with price.

Equations (functions & differential state)

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

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

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

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

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

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 y, expected max capacity in Gtoe that may be added during year y (yearly production)
- ***inventory***(e,p) : expected reserves (at year 1) for fossil fuel e with a market price p
- ***threshold(***e) : part of current reserve when suppliers of e reduce their output to match 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*. (similar to the growth of clean energy but plays a minor role because fossil energies have been around for a long time).
- *sensitivity*(e) : price sensitivity factor for energy *e*. Here we need to repeat that the function shown in figure 7 is simplistic because we do not try to model the pricing strategy of fossil-fuel-producers, and because prices are dominated by the demand side (prices increase until the demand declines enough to match the possible supply).
- *co2perTon(e)* : CO2 emissions to produce one toe of energy e

3.3 Energy Consumption Model (M2)

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. Let's break the economy into slices of homogeneous ratio (*value produced / cost of required energy*). Figure 8 illustrates this idea with 10 "slices". Although this curve is the central belief of M2 and one of the core parameters of CCEM since it dictates how the economy will react if not enough energy is available in the future, it is actually difficult to sample.

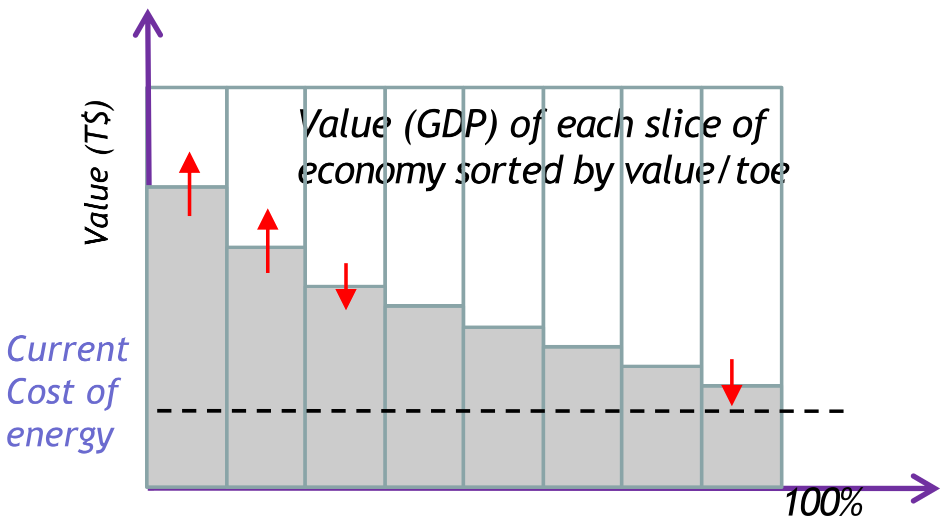

Figure 8: Sampling the energy dependency of GDP output

To simplify CCEM simulation, we represent the histogram of Figure 9 with four curves (that could be derived from this histogram if we knew it for each geographical zone):

- 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 a energy consumption share. We use the equivalent oil price to normalize these functions.
- For each region r, ***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 (on the right on Figure 9). 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 histogram of Figure 9 is not constant and evolves with time (represented with the small red arrows). 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$ / installed 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.

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

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

M2 is computed at the region level. Its input are the economic activity of the previous year, the demographic evolution, and the history of consumption for each energy source. Its output is a set of vectors, for each energy source, that represents the expected required energy for each possible market price (same discretization for demand and for supply). The computation of the energy demand goes through three steps:

- The initial demand ($R_z(e,y)$: raw needs) is assessed from previous consumption, based on economy evolution (proportional) and population evolution (linear).
- The initial demand ($N_z(e,y)$) is adjusted modulo the two "energy transition": **savings** (based on the level of efficiency that has been reached so far) is applied to reduce the need, **substitutions** produced by M3 (see next section) are applied to transfer part of the remaining needs from one source of energy to another. Since substitutions are ordered, it requires to iterate Energy in the proper order:
- 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. We first compute $R_z(e,y)$ and $N_z(e,y)$. We then compute the adjusted need, *Demand*(*e,z,y,p*), for each region and energy source. We uses the $Tr(e_1,e_2,y)$: state variable that applies one of the 6 transitions of the M3 model (see next section). It removes a share of the energy from the source (e_1) and adds it to the target (e_2). Last, we produce the energy demand vectors for all possible "discretized" prices. Note that demand reduction due to "savings" is price-independent, it corresponds to the level of energy savings investments made so far, while "cancellation" is price-dependent. By construction, the CCEM model (with its parameters) ensures that a unique price is found that matches the production (from M1) and the consumption (from M2). Once the price $P_e(y)$ is found, the capacity and the output are computed from M1.

Equations (functions & differential state)

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

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

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

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

$$\text{Demand}(e,y,p) = \Sigma_z \text{Demand}(e,z,y,p)$$

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

$$C_e(y) = \max(C_e(y-1)\ ,\ \textit{Capacity}(e,y, P_e(y)))$$

$$O_e(y) = \Sigma_z \textit{Supply}(e,z,y,p)$$

These equations used additional parametric functions that represents the "*known unknowns*" associated to M2. Once again, the first four functions names are in bold to indicate that they represent the "belief" associated to "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***(*e,y*): expected decline in energy density (gdp/conso) for zone z
- ***savings***(*z,y*): share (percent) of energy that can be saved (efficiency) with iso-output for zone *z* at year *y* (technology roadmap)
- *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
- *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 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, …). The next figure is a very simplified illustration which illustrates why some substitutions are easier than other. 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". As we shall discuss in Section 4.1, 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 represented in the figure 9 below (due to Paul Caseau).

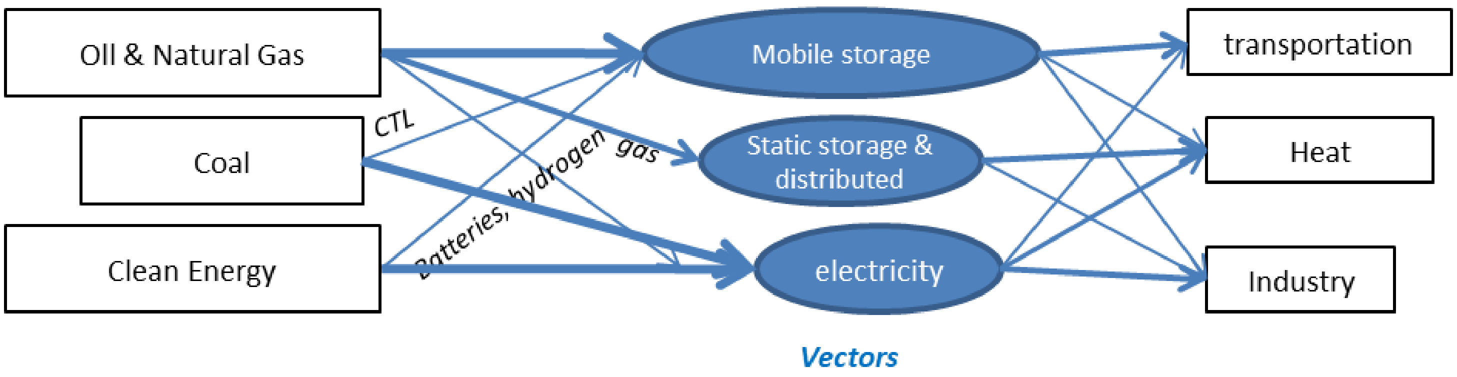

Figure 9: Understanding Energy Vectors to Assess possible substitutions

M3 uses the following **state variables** to describe the energy system year after year (the parameter y represents the current year):

- $P_e(y)$: price in $ for 1 toe for energy e, at year y
- $U_z(e,y)$: usage (constrained consumption) for zone z of energy e
- $S_z(y)$: percentage of savings reached at year y
- $CN_z(y)$: percentage of 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 CO2 tax table, for each region, that sets the CO2 tax level as a function of the CO2 concentration that has been reached. M3 may be described with the following equations. The first step is to compute the constrained energy consumption $U_z(e,y)$ for every energy source e and every zone z. Once the equilibrium price is known, we may apply the “savings and the “cancellation”. 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.
The last complex equation of 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.

Equations (functions & differential state)

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

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

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

$$Tax_z(y) = \Sigma_e\ (O_z(e,y) * \mathit{co2perTon(e)} * \mathit{CarbonTax(z,y)}$$

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

Producing the energy transition matrix is a big task (even with only 6 transitions), fortunately historical data may help for the calibration, which we discuss briefly in Section 4.1. These equations used additional parametric functions that represents the "known unknown" associated to 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
- *techEfficiency*(*z*): yearly growth of tech efficiency (cost reduction in investment to build a production capacity)
- i*nvest Price(e*): investment that is necessary to build a capacity of 1Gtoe/y at year 1
- *ftech*(*z*): expected yearly decline of *investPrice* in zone *z* (technology progress)
- *steelFactor*(*e*): part of steel cost in total cost of investment for *e*

3.5 Economy under Energy & Climate Stress Model (M4)

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 through the use of 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 10. 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.

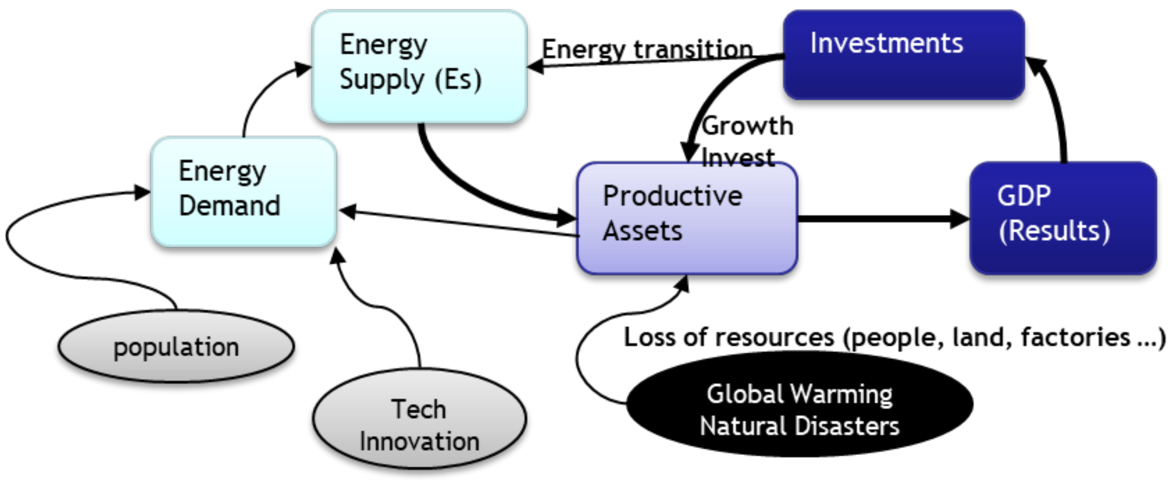

Figure 10: GDP Growth Model

The key variable here is the worldwide GPD, measured in current dollars. As we shall discuss later, there are many drawbacks to this choice (it is unclear how GDP growth and population welfare correlated, plus the value of a dollar in 2095 is quite abstract) but it has the benefit of simplicity and makes historical calibration much easier. Still, it means that 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 1500 \$/toe may mean in 2060, what matters is that the economy cannot consume more oil that is available at this time).

The input variables of M4 are the energy consumptions for all regions and all four kinds of energy sources, associated with the prices (computed by M2). From this model we also get the energy redistribution factor. From the model M3, we get the "energy investments" that are necessary to perform the desired energy transition (switching from one energy source to another and investing into energy consumption reduction technology).

The beliefs associated with M4 are described with three ratios:

- The "return on investment" factor, ***roi***(z,y), the fixed part of the results that invested and the part of the results growth that is invested (the linear regression of investments as a function of GDP and GDP growth is very simple but decent and easy to calibrate).
- The GDP impact form disasters caused by global warming (cf. Figure 4), aggregated into a function **disasterLoss**(z,T) that returns the percentage of GDP assets that are no longer operating (a farm, a plant, a city).
- The cancellation curve of M2 that we saw previously.

Because GDP 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). As shown in Figure 11, 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, Figure 11 shows how 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 (Mendelsohn, 1993), 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).

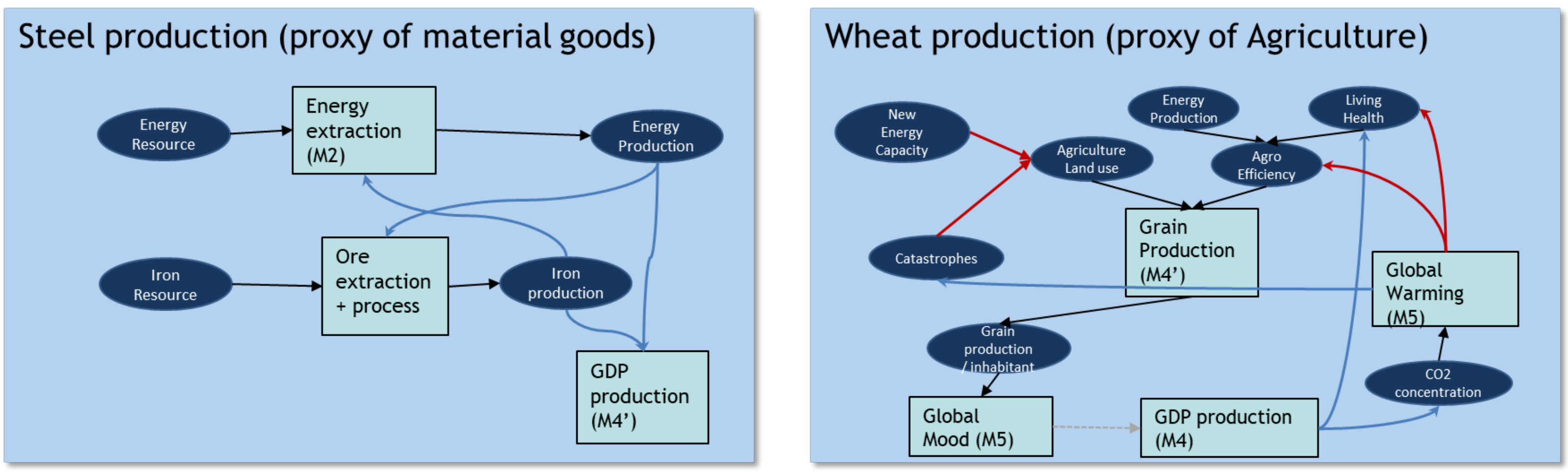

Figure 11: Introducing steel and wheat production as proxies for the "material" economy

M4 uses the following **state variables** to describe the energy system year after year (the parameter *y* represents the current year):

- $M_z(y)$: 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 $G(y) = \Sigma_z G_z(y)$)
- $I_z(y)$: amounts of investments (energy + growth)
- $IG_z(y)$: amounts of growth investments
- $SC_z(y)$: steel consummation for zone *z* at year *y*
- $SP(y)$: steel price for year *y*

The logic of M4 can be described with the following equations. We first compute the "maximum output" expected from the previous investments, and then consider the loss of productive capacity from global warming impact. The function ***impact***(*z,p*) returns the part of the GDP that is not produced when energy is lacking (cf. explanations for M2 in previous section). The new amount of total investment is computed using the previously introduced linear regression and is split between previously computed "energy investments" (to which CO2 taxes are subtracted – see model M3), and "growth investments".

Equations (functions & differential state)

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

$$GW_z(y) = \mathit{disasterLoss}(T(y – 1))$$

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

$$dGW_z(y) = (1 - GW_z(y)) / (1 - GW_z(y - 1))$$

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

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

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

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

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

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

These equations used additional parametric functions that represents the "known unknown" associated to 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 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.

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, or a more realistic output from ACCL, 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, following Bruno Latour and other research scientists (Bonnet, 2021) 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 that is built into M3 thought the *Alpha* function). 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.

The relation between CO2 emissions and CO2 concentration is kept very simple in CCEM, which is a known design limit. On the other hand, because we represent the temperature elevation as a function of CO2 concentration, we may capture some amplification loops which 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 the fact that additional methane may be released as a consequence of temperature elevation. With this respect, not taking methane concentration into consideration is a simplification that does not necessarily degrade the model relevance.

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

- AS(y): Agricultural surface on year y
- ES(y) : Areal that was transferred from Agriculture to Clean Energy Production
- WO(y): Wheat Output
- CO2(y): emission for year y in Gt
- CO2ppm(y): CO2 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 CO2 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 (the following equations represent the "logic of the model"). We compute the CO2 level from the emissions (minus the absorption capacity, a very crude abstraction). We then derive the temperature elevation from the "belief" table (IPCC(c)). For each of the four world regions (US, EU, China and RoW), we compute the associated pain level and the consequent “redirections” which are represented by coefficients (tax/cancel/redistribute) which are feedbacks to the other models.

Equations (functions & differential state)

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

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

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

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

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

$$TaxF_z(y) = \mathit{pain2Tax}(z, PAIN_z(y))$$
$$CnF_z(y) = \mathit{pain2cancel}(z, PAIN_z(y))$$
$$TrF_z(y) = \mathit{pain2transition}(z, PAIN_z(y))$$

Notice that ↑F(*y*) is a shorthand notation for the yearly increase ration F(*y*) / F(*y – 1*). These equations used additional parametric functions that represents the “known unknown” associated to M5:

- ***bioHealth***(T,y): percentage of yield evolution, which declines when temperature raises but grows with worldwide diffusion of tech and best practices
- ***agroEfficiency***(p) : decline of productivity as energy price increases
- ***painProfile***(z) : vector of 3 coefficients that define the global pain level
- ***painFromClimate***(T): step function that sets a pain level as temperature rises.
- *pain2Cancel*(z,p) : policy that sets cancel acceleration (sobriety) as a function of pain
- *pain2Transition*(z,p) : policy linear function that links pain level p to Energy Transition acceleration
- *co2Neutral* : level of emissions that is approximately balanced by nature
- *co2Energy*: percentage of CO2 emission due to fossil energy
- *co2Ratio*: additional concentration in the atmosphere from additional CO2 emission (ratio)
- IPCC(c): temperature elevation caused by concentration c, extracted from IPCC RCPs
- *satisfaction*(z,dW,dG) : heuristics that defines satisfaction from *WheatOutput* change and GDP change

4. Preliminary Computational Results

4.1 Six “*Key kNown Unknowns*” (KNU) to Characterize Beliefs

In this fourth section we present a few outputs from our preliminary simulations. This is preliminary in the sense that “median beliefs” are necessary as an input to CCEM, and this is not an easy task. What “median belief” means here is a “compilation” of web bibliography (not so simple in the sense that it represents 50 pages of notes, but with no specific validation). 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. Here are these 6 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", which is the speed at which new green capability may be added. The KPI that we use is the number of PWh that can be added in a decade. This KPI describes the ***maxCapacityGrowth***(e,y) belief of M1.
2. The "Energy intensity" is the ratio of total energy used by unit of GDP. It has been declining constantly over the years. We used the negative combined aggregate growth as a KPI, which is bound to the dematerialization belief of M2.
3. The negative energy demand to price elasticity is a KPI that describes the cancellation behavior of model M2. Economy studies separate short-term and long-term elasticity, we use long-term elasticity to calibrate the cancellation belief. This is a debated topic and this elasticity is clearly an known unknown.
4. The electrification of energy consumption is of one the heavily debated unknown, as told when we described model M3. Many non-electric energy usages, from chemistry to heavy transportation, are still difficult to convert to an electric vector. We use as the 4th KPI the electrification of energy reached in 2050, which was 16% in 2020 (here we perform a simple ratio with no conversion factor between types of primary energy – some authors multiply the green electricity product by a Carnot factor, so the percentage may appear higher).
5. The return on investment (average for each zone) is a key parameter that determines the shape of the world economy growth. We use here the world average as the 5th KNU, but there is even more uncertainty when setting up this parameter for each zone, as the relative growth of the four zones during the past three decades indicates.
6. The last KPI that we use to characterize M6 is the damage loss of GDP as a function of warming. A simplistic "pseudo-SCC" computation may be made by dividing the 21st century cumulated global warming impact (from the **disasterLoss**(z,T) table) by the total amount of CO_2 emitted during the same period. Note that we do not introduce any discounting rate in this crude ratio.

The following figure shows the value that we have obtained though the "web calibration process" described earlier, with the assistance from a few experts from the NATF. To make this more concrete, we have shown the similar values that are proposed in the IRINA +1.5C path (IRINA 2023a)

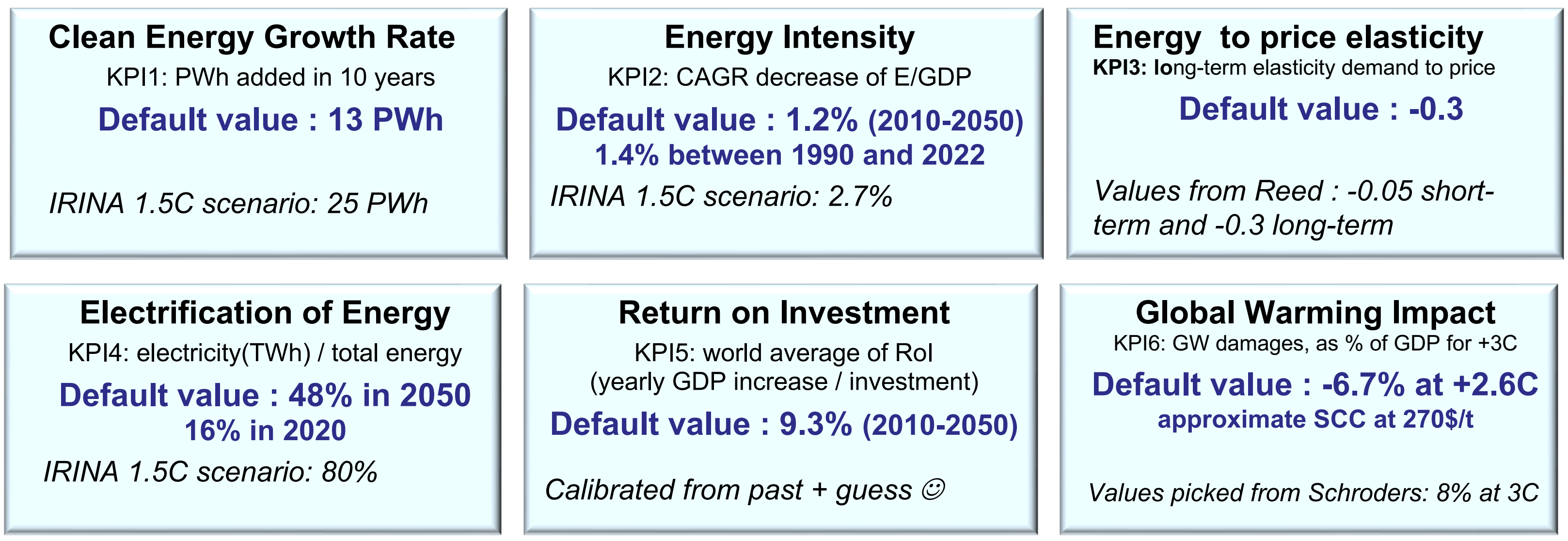

Figure 12: Six KPIs to characterize your beliefs

These six beliefs are essential to capture the world vision that you use for your simulation. Section 4.3 will illustrate this with three sets of beliefs that yield completely different global warming narratives. The fact that our energy related KNUs are more conservative than IRINA's reflects the influence of (Smil, 2022) and (Püttgen, Bamberger, 2021) on our thinking.

4.2 Simulation Outputs with "Median Beliefs"

The outcome shown in Figure 11 are just illustration of what the outcome of a simulation run looks like. The left part of the figure reports the indicators that are usually found in similar reports about earth models (see DICE or ACLL for instance): GDP, total primary energy production, CO2 emission (forcing) 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). 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 13. Our experience with previous global models (Caseau, 2012) is that we need many more simulations before we stabilize the CCEM model and feel comfortable reporting detailed computational results. It should also 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.

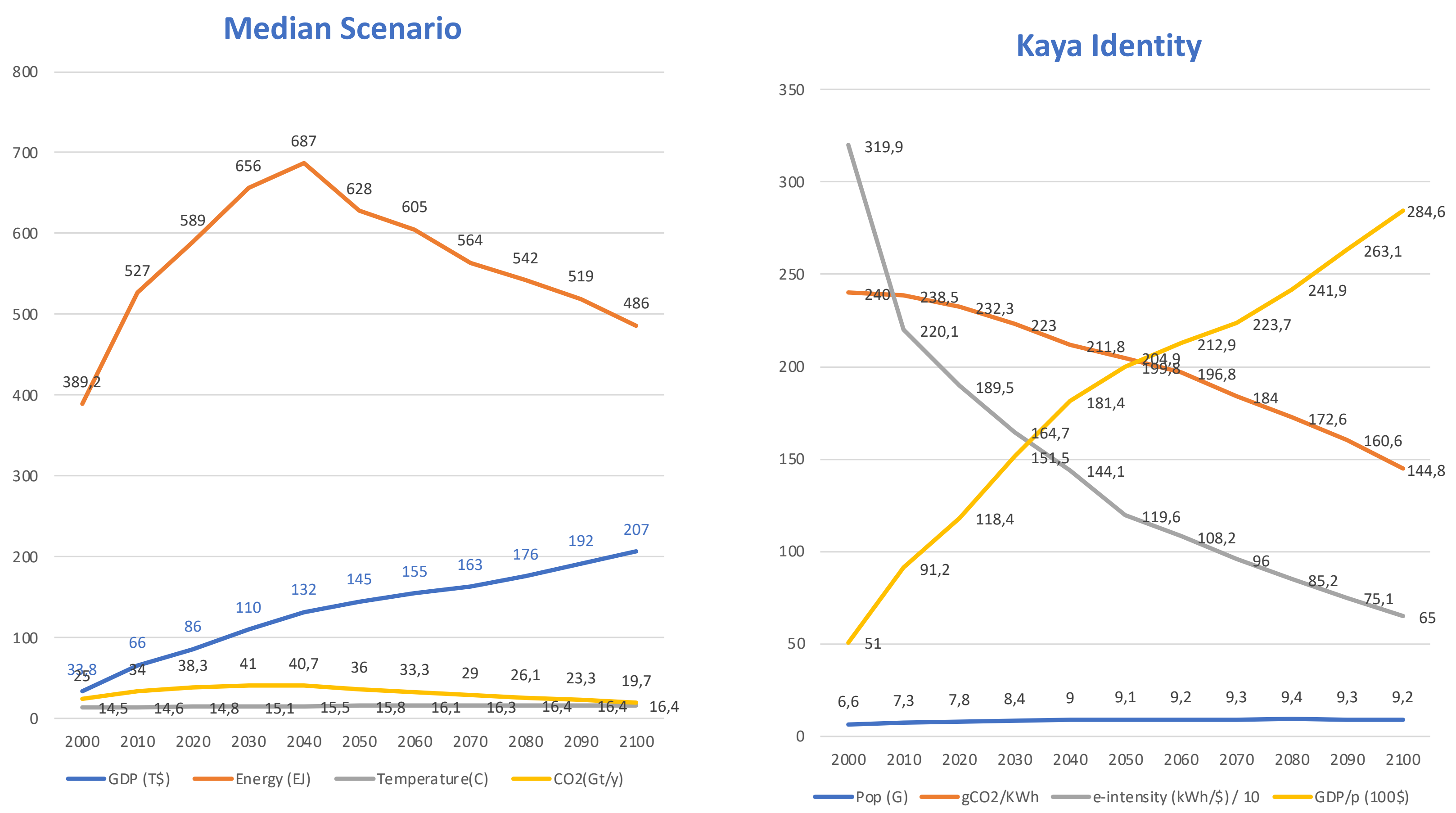

Figure 13: Outcomes from one CECM scenario (left: key KPI, right: Kaya coefficients)

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

- Be cautious about GDP figures expressed in current dollars. Nobody knows what $100 will represent in 2100.
- The evolution of the CO2 intensity of energy is the perfect illustration of the viscosity expressed by Vaclav Smil: the trend towards the decarbonization of energy is constant, but it takes time.
- The dematerialization of the economy is another underlying macro-trend, but it raises other questions: the "immaterial" economy (digital or service) adds to the material economy by taking an increasing share of the value, but it is not independent. That is why we introduced the production of steel and wheat as proxies for the material economy in version 4 of the CCEM model.

- The figures used for demographic forecasting are based on recent studies that take into account the decline in male fertility (a probable but not yet demonstrated consequence of pollution) and the impact of higher education of the female population.

4.3 Sensitivity Analysis

We will first illustrate the “sensitivity to key beliefs” analysis with two specific examples. The next figure represents the impact of the “Fossil Energy” known unknown. The left part of the figure represents 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 right part of the next figures makes the hypothesis that the reserves can be extended by a similar amount (what was added from 2010 to 2020).

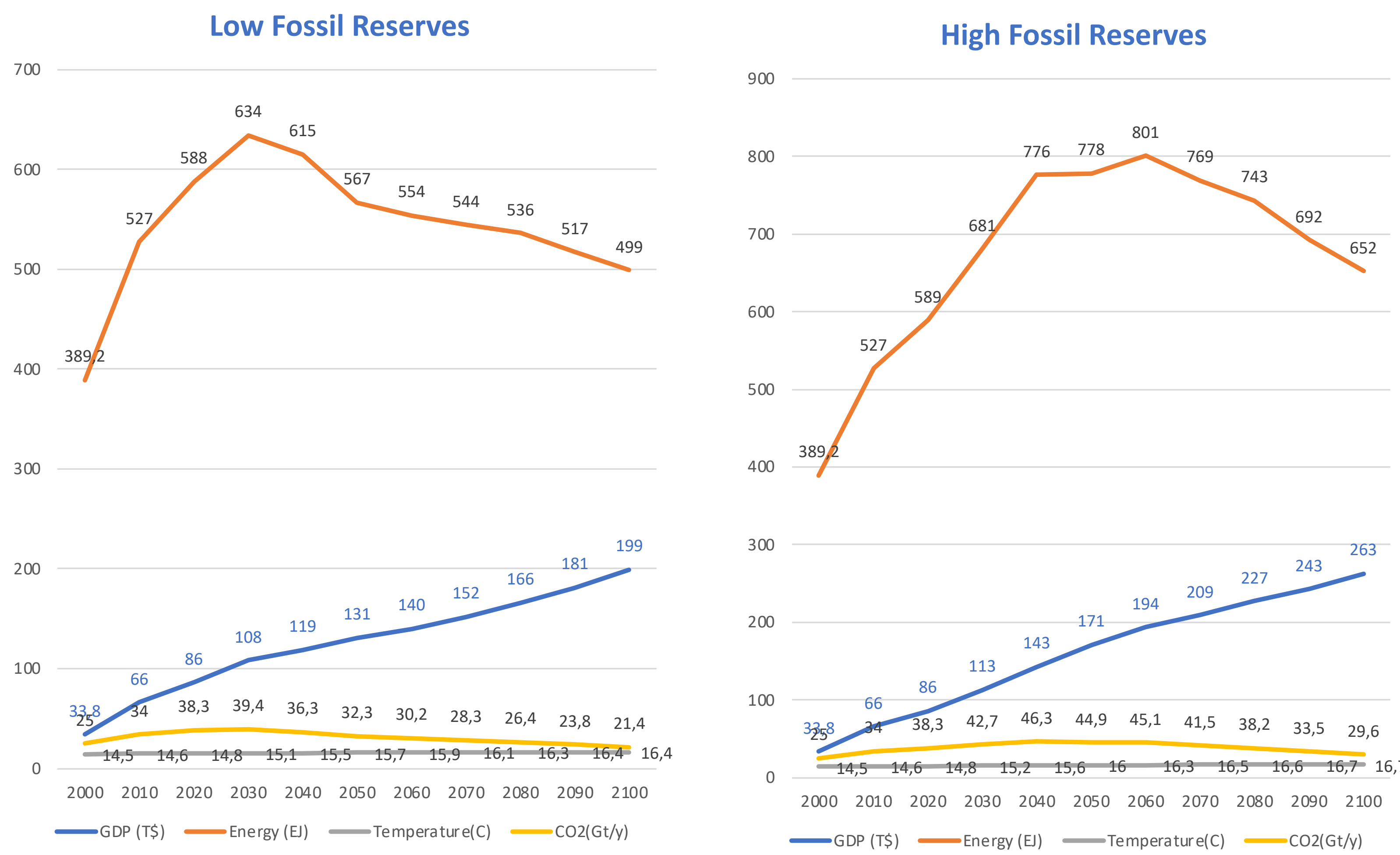

Figure 14: Sensitivity to fossil reserves

Unsurprisingly, we see that 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 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, even in a scenario of abundant energy. It is interesting to report that the impact on economic growth is stronger in Europe and the US than in China, which has made the strategic choice of abundant coal and is less dependent on the availability of oil and gas.

The next figure represents the sensitivity to carbon tax. The left simulation is performed no carbon tax, which different from the “median belief” that includes a moderate carbon tax (80 \$/t). The right simulation shows the effect of a strong carbon tax that grows from 400 to 600 \$/t as the CO2 concentration rises.

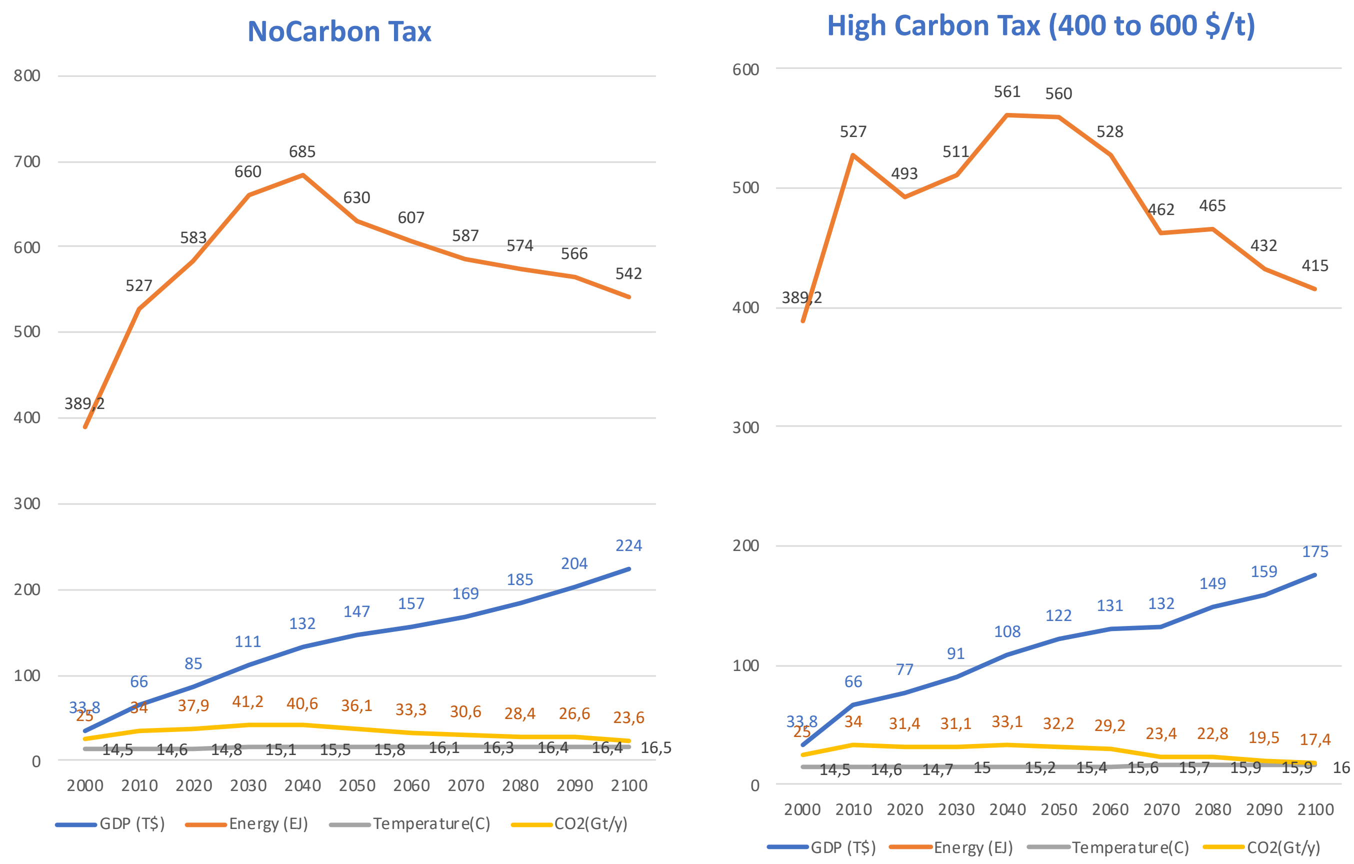

Figure 15: Sensitivity to carbon tax

These three simulations show that carbon tax works, towards the goal of reducing CO2 emissions and thus reducing global warming, but there is a clear impact on the economy output (which is the symmetrical observation from the previous figure: cheap energy fuels economy growth). A moderate carbon tax has a moderate impact on the world GDP but also a moderate impact on the emissions. A more substantial tax works better but the economic impact is large and heterogeneous. The burden is heavier on China whose energy density is higher. We will return to this observation in Section 5.

For lack of space, we shall not present a full sensitivity analysis of the key beliefs. Here is a short summary of how the key "*known unknowns*" influence the results shown in the previous section:

- Fossil Energy has a strong influence on the outcome. This was shown for oil & gas reserves with Figure 14, but it also applies to coal. The political decision to reduce, maintain or grow the coal production in the decades to come is a key "known unknown".
- Transition to Clean Energy: this is major factor, with two key parameters, the speed at which we can deploy new renewable energy capacities and the speed at which we can transition our usages (industry, agriculture, transport, etc.) from one source of energy to another. As shown in Section 4.1, our "median belief" scenario is more conservative than IRINA (IRINA 2023b).
- Efficiency and Sobriety: those are obviously important factor but they are less critical than one may think. Changes in the parameters accelerate or slow down the necessary adaptation, but they do not change the overall narrative which is approximately : we need to transition from fossil to renewable energy and this transition is difficult and expensive, which will have a negative impact on the economy (b) the more we delay, the more earth will suffer global warming with consequences which are at first less than the transition impact but will grow into a global disaster which is hard to foresee.
- Economic Growth and Price Sensitivity : these parameters have, by construction, a large impact on the outcome GDP, but a moderate influence on global warming, in the sense that (a) the actual growth is governed more by the actual available energy than the foreseen variation of return on investment (b) energy price is mostly a signal in CCEM to adjust supply and demand (with a feedback loop on steel price).

The following figure (Figure 16) 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 much higher GDP output than the previous scenario and, as a consequence, much 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 thinking from some thinkers associated to the Singularity University, such as Peter Diamandis and his best-seller "Abundance". 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 13).

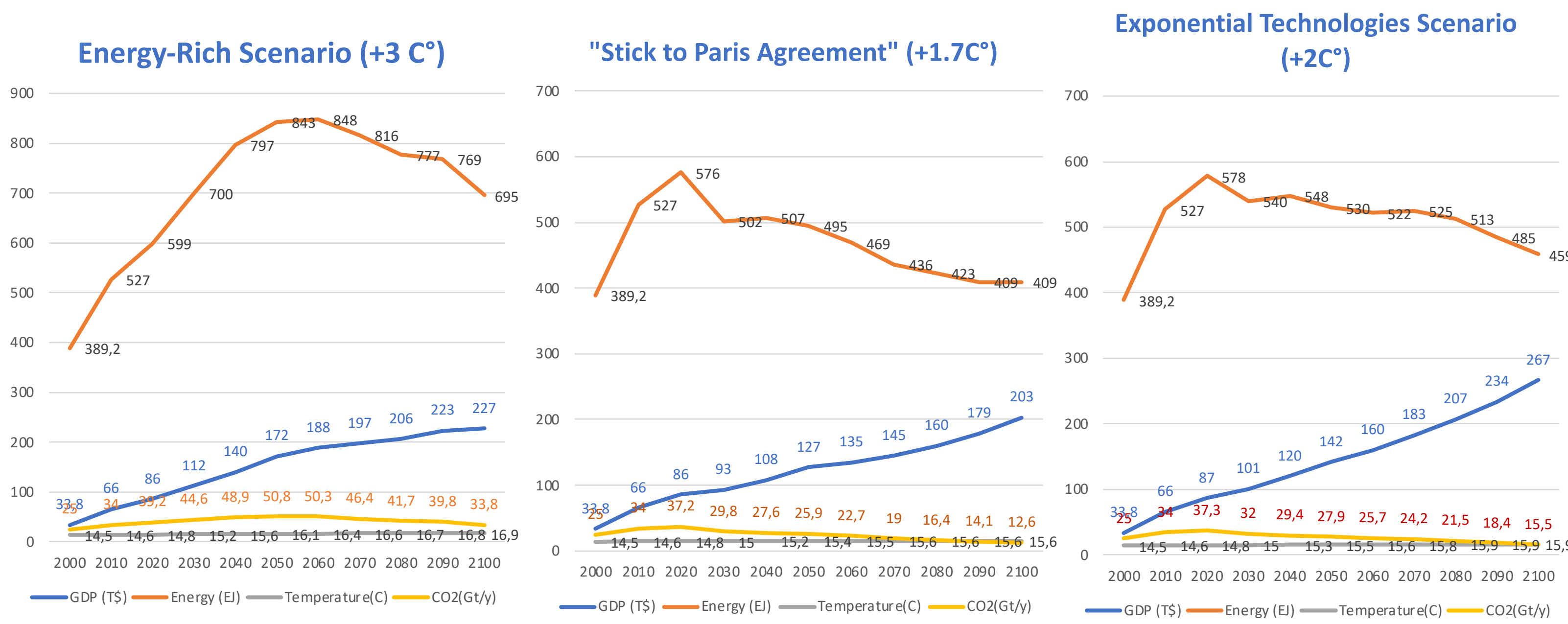

Figure 16: Different beliefs produce different outcomes

These outcomes illustrate the capacity of CCEM to reproduce a large scope of mental model. It helps to see that implicit beliefs are often the main reason for which different serious, motivated and educated scientists propose very different forecasts and recommendations from their earth model simulations. As mentioned earlier, this is a first preliminary computational result, where the ecological redirection is not triggered (our goal is to calibrate CCEM against other earth models before we exploit the full added power of the M5 model – cf. Section 4). Still, it is interesting to notice that the first and second scenarios are quite unrealistic because they produce a large amount of "pain" that is bound to trigger ecological redirection. The first scenario, because the temperature reaches +3C, comes with a large set of catastrophes from global warming. The second scenario, because it creates both an energy shortage and huge price increases (the second caused by the first) would also produce lots of societal and economy stress (remember that societal balance has been bought for decades with economic growth). This is the reason why CCEM has been extended with ecological redirection.

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 CO2 output and CO2 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:

- 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.
- Wars, conflicts, and social uprising are somehow out-of-scope, as soon as their scale is large enough to disrupt the world economy significantly. This is a design limit for such earth models. A way to address this question partially in a future version of the model would be to include a feedback loop between the "pain" level and the economic outcome (gdp).
- 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 citizen 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).

These are perspectives to extend the model in the future. Even with the current scope of version 4 of CCEM, there are several open questions, such as:

1. How to better capture the difference between the four zones in terms of economic growth ? The current model allows to differentiate RoI (return on investment) and investment ratio (share of GDP that is invested), but this is not convincing to explain the different gdp growth of US, China and Europe between 2010 and 2020.
2. To understand the balance of power between geographic zone, we need a model for the impact of protectionism. The current model uses the "balance of trade" graph to extrapolate the influence of each block over the economy of each other (cf. Model 4 equation), but this is rather conservative. If strong protectionism occurs in the 21st century as a consequence of rising tensions, we need a way to evaluate the possible GDP impact (cf. section 5.3 when we discuss game theoretical approaches).
3. How to model the dependency between the material part of the economy, such as agriculture or steel, and the immaterial part, such as services or digital ? Although agriculture, food and related industries is approximately 5% of the US economy, a complete failure of that sector would stop the economy, not reduce the GDP by 5%. The growth of "immaterial services" that fuels the GDP growth that we see in Section 4's simulation, is only meaningful if the material side of the economy is still functioning. Part of this dependency should be capture with our KNU #6 (damages of global warming should not limit to direct damages but indirect as well), but it also probably necessary to include, as a utility function, the impact of material proxies such as agriculture or steel into the satisfaction of the workforce.

5.2 Redirections and Human Happiness Proxies

Simulations from section 4 do not include redirections yet. The main reason is that the "pain" function (which may be seen as the complement of "population satisfaction") is not mature enough. As show in Section 3.6 (Model 5), pain is a composite function of multiple signals:

- Gdp growth, or absence of growth, or decline. We use the evolution of the gdp per person as the input driver.
- Wheat production per person, used as proxy for agriculture's health.
- Energy scarcity, using the amount of activities that are "canceled" because of the energy unavailability at a reasonable price (for that activity)
- Pain from the disasters caused by global warming (cf. Section 2.3, we use a composite "painFromWarming" parametric function that represents the cumulative effects of direct impact, fear and compassion).

An open question is how the impact of global warming on health and life expectancy (from sickness to accidental deaths) should be represented. This is, unfortunately, one of the key feedback loops from global warming to Earth population. In addition to "pain", it would make sense to add an explicit representation of life expectancy, which is a classical approach for most SDEM. Another open question that we raised in the previous section is the representation of the "material side" of the economy. In the current model, the steel production impacts the energy transition but does not impact the global outcome nor the population satisfaction.

The current version of the model uses pain/satisfaction as the signal that causes political reaction from each zone's governance: the unsatisfaction of the population "forces" its governing bodies to make some policy changes (redirection). As stated earlier, an open question is to see if we add, in the spirit of many earlier SDEM, a feedback loop that decreases the outcome when pain raises. In a world of technology and artificial intelligence, this is a debatable point, but it remains an open question. Redirection is defined in CCEM (model 5) as a reaction that is triggered by "pain" along three directions:

- Forced sobriety, which we call "cancel acceleration" in CCEM. Renouncing CO2 producing activities, such as combustion engines cars or private jets.
- Increasing the CO2 taxes, which can apply locally or at the border. This aspect is not yet taken into account in CCEM, whereas the EU proposal for CBAM (Carbon Border Adjustment Mechanism) shows that it may occur soon.
- Accelerating, or slowing down, the energy transition policies, as well as the energy redistribution policy (cf. the "Alpha" parameter in M4). The transition matrix that is given as an input to CCEM (one of the "key belief") is taken as the set of maximum transition flows. Similarly, the rate for deploying renewable energy is considered the highest achievable for technology and operations reasons. Each zone's policy is defined by how close to this maximum value they aim to reach.

The redirection policy of each block is currently defined as a vector of coefficients that are the parameters to a stepwise linear model (the steps are represented in the *painFromClimate* function shown in model 5). This model defines for each direction (sobriety, taxes, energy transition) a *min* and a *max* level, and a linear coefficient that helps to select a value between *min* and *max* depending on the pain level.

5.3 GTES: Game-Theoretical Evolutionary Simulation

This last section intends to give a very brief overview about the next bigger step with CCEM, which is to embed the simulation with the GTES framework. GTES is an approach designed to approach models with lots of unknowns, both about the problem at hand and the strategies of the multiple players in a complex system. GTES has been developed 20 years ago and used with many similar complex system models (Caseau, 2012). The GTES (Game Theory and Evolutionary Systems) framework is designed to study models through simulation, extracting properties from the model by learning through examples. Combining three techniques, GTES uses sampling, search for Nash Equilibrium (Caseau, 2009), and local search. The framework is an intersection of economic modeling, game theory, evolutionary game theory, and local search techniques, with a focus on the path to equilibrium as much as the equilibrium itself. GTES applies to problems for which a model is conjectured, but with far too many unknown parameters to be useful for a direct simulation. It also addresses the behavior of a set of actors/players, who try to maximize some form of objective function. GTES separates these unknown parameters into three families:

1. Parameters that are not related to the actors but represent the environment. The GTES approach is to sample these parameters using a Monte-Carlo simulation. With CCEM, our "known unknowns" fit precisely that category. Randomization allows to accept richer inputs for our key beliefs (distributions versus heuristic choices such as those show in Section 4.1).

2. Parameters that represent the objective function, i.e., the strategy of the actors. These are the control parameters for the model, those for which a "game theory strategy matrix" is desired. For CCEM, the strategy represents the macro goals for each zone: GDP growth, population satisfaction, world temperature, organized with weights that capture the priorities (which are not the same for each zone).

3. So-called "tactical parameters" that are assigned to each actor, but are "controlled" by the strategy parameters, in the sense that each actor may be assumed to learn the optimal value to best fit its objective function. This is where the "evolutionary algorithms" (or any form of local optimization and meta-heuristic) kick in: GTES solves each optimization sub-problem to find the "best behavior" for each actor according to its strategy parameters. For CCEM, the "tactical parameters" are the "redirection policies" that we defined in the previous section.

GTES uses local search and randomization to "shake" the underlying mathematical model during the simulation, making model tuning more demanding than producing a simple simulation. GTES helps to focus on the strategic goals of the zones (as we perceive them as a "world modeler") and let the machine finds the redirection policies that are best suited to the goals and the reaction of other zones. This is why the search for possible Nash equilibriums is interesting: no player (zone) can define its strategy irrespectively of the other zone's reaction.

GTES is well suited as a framework to explore CCEM models because it supports the following:

- Explicit modeling of the fact that "beliefs" are unknown, replacing the "trends" that we have shown in this paper by "cones", and using randomization to explore these cones. Note that using Monte-Carlo simulation for earth model, such as DICE, is a classical method.
- Introduction of the "multi player" aspect of world governance, recognizing that each regional zone may have different long terms goals, different constraints and different tools at its disposal. In our case, it is a great tool to explore, for instance, the benefit of a possible "EU green policy" if it played in a world where other players have different agendas. It is also the proper framework to look at the effects of trade barriers or extra-territorial carbon taxes such as CBAM.

6. Conclusion

CCEM is a work in progress, with its 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. CCEM code is already accessible on GitHub (https://github.com/ycaseau/GWDG).

The first contribution of CCEM is the explicit representation of "beliefs", within a common simulation framework. Any earth model that is complete enough uses parameters to describe known unknowns, since energy/economy/climate modeling is complex and must use hypotheses by construction. The design specificity of CCEM is emphasize five of these "key unknowns" and to make them explicit and modular constructs. Playing with them becomes easier and simulation may use used as a "workbench" to assess one's own beliefs.

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, see Aufhammer 2018). 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. As explained in Section 5, the present model for redirection is still under development.

Last, CCEM may be seen as a "meta-model", that is a glue between two or more (sophisticated and detailed) models. What we described as "beliefs" may as well be the result of a more detailed model that simulate one of the five dimensions described in the paper. This is precisely what we did with the IPCC warming model in our sub-model M5. The "CO2 concentration to temperature" tables that we extract from the various RCPs are a coarse approximation. Each of the five beliefs could be produced by a separated, more detail model, making CCEM a possible "coupling modular architecture" for earth models.

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