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Will COVID-19 change the calculus of climate policy?

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Will COVID-19 change the calculus of climate policy?

Abstract: Public health experts caution that global warming increases the likelihood of novel coronaviruses and amplifies their impacts. Such contagions are virtually unique in their ability to inflict catastrophic worldwide harm. Even more alarming is the forecast that future coronavirus pandemics will be more frequent and potent. If the public comes to recognize that the pain and suffering they are currently experiencing are but another symptom of global warming, the motivation for urgent action to limit temperature rise may reach a tipping point. Navigating the current situation will require considering both existential threats jointly. Here, we present results from an integrated assessment model adapted to examine the implications of current and future pandemics for climate policy. We find that the threat of pandemics can lead to tighter temperature targets than might otherwise be justified. In a world of shrinking economic resources for reducing harm to public health and wellbeing, global warming and pandemics must be recognized as interconnected threats.

Keywords: COVID-19, climate change, integrated assessment

JEL classifications: C61, D61, Q54

1. Background

Prior to the novel coronavirus disease that began in 2019 (COVID-19), there was nearly universal agreement over the need to halt temperature rise. Yet, global emissions continued on an upward path. The international commitment was being called into question. COVID-19 has further complicated the situation. Our initial reaction to the novel coronavirus was to question whether the public had sufficient bandwidth to deal with two major threats simultaneously. But as we began to understand the troubling ties between COVID-19 and climate change, we were led to ask, what were the implications of the third novel coronavirus of the new century for climate policy?

A growing number of health experts have pointed out the clear connection between deforestation and virus emergence.^{1,2,3} Global warming contributes to deforestation due to its impact on forest decline, degradation, and collapse, thereby weakening the natural barrier separating species. The likelihood that potent new viruses will be transmitted to humans is increased. It is estimated that 25% of tropical forests have been lost creating hotbeds for animal-to-human transmissions.² This phenomenon is well known to health experts but has been widely ignored so far by political leaders. A warming planet may also amplify a pandemic's toll. An increase in the frequency of what in the past was labelled extreme climate events, such as the number and intensity of destructive hurricanes, record-shattering heat waves, devastating wildfires, and unusually severe storms, may compromise our ability to contain a novel virus by severely disrupting efforts to quarantine, shelter-in-place, and social distance.^{4,5,6}

But do we not already have sufficient justification for acting aggressively to halt temperature change? The science is unequivocal. Global warming is occurring. It is human induced. And remaining unchecked, the consequences are indeed dire.⁷ There is already ample cause to act aggressively to combat climate change. Yet, if it were not for COVID-19, we would be even further off course for meeting the Paris Climate Agreement's temperature goals.^{8,9} Some refer to this as a silver lining in an otherwise very dark cloud, but let us hope that there are better emission reduction strategies than sheltering in place. Although there was sufficient reason to reduce emissions prior to the pandemic, progress was slow. The question is "why?" Public policy experts, such as Thomas Schelling, had long suggested that substantial action would take place only when people witness with their own eyes the horrid things that are in store.¹⁰ The scientific *justification* for urgent action may exist, but the *motivation* is lacking.

2. Pandemic impacts on climate damage and GDP growth

Will pandemics provide the missing motivation required to cap temperature at desirable levels? COVID-19 provides a "here and now" catastrophic threat present for all to see, but the public must come to realize that COVID-19 is not a one-of-a-kind event.^{2,11,12} Better preparedness for extreme climate events may provide some help in containing a current

pandemic. Such stopgap measures, however, have a high likelihood of being breached. In the longer term, addressing the root causes of pandemics will be necessary. A Perspective in the New England Journal of Medicine emphasized that effectively managing both public health hazards will require an integrated science-based approach focusing on the key ties between climate change and pandemics.⁴

Scientists that use integrated assessment models (IAM) for climate policy cost-benefit analysis owe a great debt to William Nordhaus for his pathbreaking development of the DICE model.¹³ His modeling of the tradeoffs between marginal costs and marginal benefits of greenhouse gas emissions abatement provided the foundation for contemporary IAM analysis of climate policies. Our focus is on bringing pandemics into the climate policy cost-benefit calculus. Two areas where the linkages may prove particularly important are those connecting 1) pandemic damages and a warming planet, and 2) pandemics and long-term economic growth.

2.1. Damages from global warming

Damages from global warming may be characterized as market or nonmarket. Market damages reflect those which appear in national income accounts. Examples include impacts to agriculture, energy, manufacturing, coastal real estate, and tourism. Nonmarket impacts lack conventional prices and are excluded from national income accounts. Examples include impacts on human health and wellbeing, species loss, degradation of environmental quality, and the destruction of valuable ecosystems. Nonmarket damages are particularly troublesome, not only because they are difficult to value, but are often hard to quantify. Unfortunately, the climate issue is fraught with damages falling into this category.

With the need to track *total* damages geographically and intertemporally, IAM modelers who attempt cost-benefit analysis must be parsimonious in their treatment of damages. Market and nonmarket damages are typically combined into a single damage function and calibrated using expert elicitations. Multiple studies are combined through meta-analysis where global willingness-to-pay (WTP) for avoiding temperature rise is presented as a percentage of global GDP.

Diseases such as dengue fever, malaria, and West Nile and Zika viruses are included in the composite category of total damages. What makes COVID-19 different is that it is here for all to see, worldwide in scope, and rare in ability to provide massive harm to public health and wellbeing. The connections between pandemics and temperature rise may irrevocably change public motivation to curtail warming. To examine its potential as a game changer, we must isolate its disutility from that of other climate change impacts. This necessitates a second damage function.

Fig. 1 shows the two damage functions adopted for our analysis. The solid and dashed lines represent pre- and post-COVID-19 worlds, respectively. We begin with the former. Richard Tol, a leading scholar on climate damage estimation, reviewed 27 published estimates, of which 11 included a WTP to avoid a 2.5 °C increase.¹⁴ For the latter, he calculated a mean value for the global income loss of 1.3%. The 95% confidence interval is skewed in the direction of a higher WTP.

The review by Tol provides a useful starting point for estimating the damages from global warming. We have updated earlier estimates in light of recent climate-induced disasters. Extreme events appear to be occurring at a much faster rate than previously projected,¹⁵ foreshadowing worse to come.^{16,17} Indeed, there has been a debate within the climate science community over the likelihood of a particularly troublesome scenario where positive feedbacks in the climate system lead to a domino effect. Various tipping points are breached as ice sheets disappear, forests weaken and decline, permafrost melts releasing large carbon stores, and sea levels rise. As a result, an abrupt change in the planet's heat distribution system and ocean circulation may occur.¹⁸

Whether one accepts the cascading tipping point hypothesis, there is little doubt that positive feedbacks are occurring more rapidly than expected and suggest a warmer and bleaker future than that previously imagined. We have adjusted WTP estimates, accordingly. Raising the global costs of a 2.5 °C rise in temperature to 4% of global income, still well within Tol's 95% confidence interval. The revision reflects the public's growing unease and risk aversion; and is in line with other recent meta-analyses.¹⁹ It is also consistent with the implicit WTP reflected in the Paris Climate Agreement on an absolute limit to temperature rise of 1.5-2 °C.⁸ The lower curve in Fig. 1 is fitted to our revision of the estimate for avoiding a temperature rise of 2.5 °C. The quadratic rise between 2.5-5 °C is reflective of a number meta-analyses.¹⁹

Thus far, our focus has been on WTP in a pre-COVID-19 world. We now add pandemics to the list of climate-related extreme events. In order to isolate their impact on climate policy, we track them with a separate damage function, but one that is still tied to warming. The post-COVID-19 damage function not only includes a WTP to lessen damages from the current pandemic but also from future pandemics. If indeed, pandemics become more frequent and potent as many public health experts currently forecast, they may become a substantial contributor to the damages attributed to a changing climate, exceptional in their ability to pose an imminent worldwide threat.

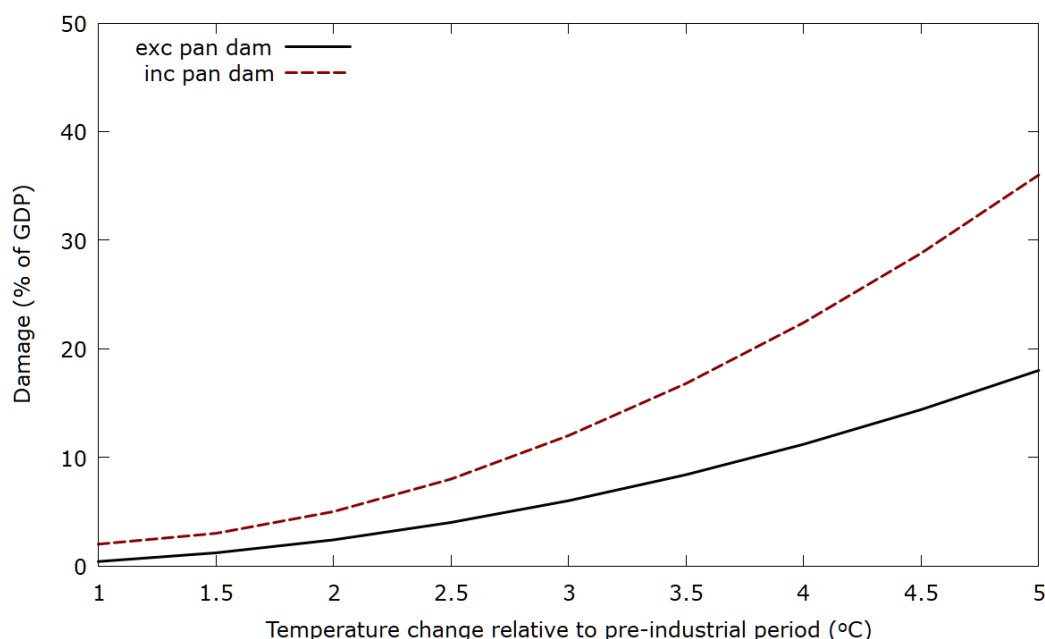
Upon what do we base these WTP estimates? How much is it worth to reduce prolonged periods of sheltering in place, quarantining, and social distancing and lessen the consequences of *repeated and more damaging* pandemics in the future? Unfortunately, there is little data upon which to base such an estimate. We are unaware of any carefully

designed surveys. We therefore will rely on casual empiricism. The U.S. pays roughly 4 % of GDP on national defense. It may be reasonable to suppose that we would be willing to pay an equivalent amount to prevent attacks by an invisible predator. The dashed line is calibrated to a WTP of 4 % to avoid a temperature rise of 2.5 °C. Coincidentally, this is the same amount that we are willing to pay to avoid all other damages due to climate change. The relationship remains comparable for both threats, post-2.5 °C. For purposes of the present analysis, we place the following bounds on pandemic damages:

- a) Pandemic damages are excluded (**exc pan dam**) from those attributed to global warming (the solid line). Policy makers fail to recognize or simply ignore the connection between pandemics and warming.
- b) Pandemic damages are included (**inc pan dam**) among those attributed to global warming (the dashed line).

Figure 1 visualizes the relationship between alternative damage assumptions and temperature rise

Fig. 1. The relationship between damages and temperature rise.



The solid line shows damages when pandemics are excluded from the impacts of climate change. The line is fitted to the results of meta-analyses and reflects recent concerns over extreme climate events and what they portend for the future.^{16,17} It is calibrated to a global WTP of 4% of GDP to avoid a temperature increase of 2.5 °C, and continues to rise quadratically, thereafter.^{14,19} We assume that damages are divided equally between market and nonmarket.²⁰ The dashed line shows damages when pandemics are included among the impacts of climate change. All pandemic damages are treated as nonmarket. They include both a WTP to contain the damages from COVID-19 and to reduce the impacts

of pandemics that health experts warn are looming in the future.² The dashed line is fitted such that at 2.5 °C the WTP is 4 % of global income. The U.S. currently spends 4 % of its national income on defense, less than 2 % on environmental protection and 16 % on health care. We assume that post-2.5 °C the WTP is comparable for each threat. We exclude the possibility that a pandemic or other climate related impacts can result in an existential event.²¹

2.2 The impact of pandemics on economic growth

There has been extensive research on the depth, length, and form of previous economic disruptions. These provide useful insights into what to expect. We have been particularly influenced by the work of Reinhart and Rogoff in designing our scenarios.²² Would the recovery be “V”, “U”, or “W” shaped? Would it be the nastiest economic crisis since the Great Depression? What would be the transient and longer-term implications for economic growth? How would the energy using and producing capital stock be affected? And so on. We may be able to draw upon past economic contractions for some guidance, however, in this instance, we may indeed be in uncharted territory.²³

We stress that a pandemic’s impact on long-term economic growth depends both on the depth and duration of the pandemic shock and, the damages to public health and wellbeing. For the magnitude of the pandemic shock, we explore three possibilities. These are not intended to be predictive, but to provide a sense of what may be in store. They include:

- a) No pandemic shock (**no pan shock**). A pandemic does not occur.
- b) A reference pandemic shock (**ref pan shock**) in which we suppose that the pandemic lasts for one year and the global economy shrinks by 10%.
- c) A maximal shock (**max pan shock**) in which we suppose that because of a failure to get the pandemic under control repeated shutdowns of the economy will be required. It takes three years for the recovery to take hold. Vaccines and/or effective therapeutic regimens become available but not before the global economy shrinks by 20%.

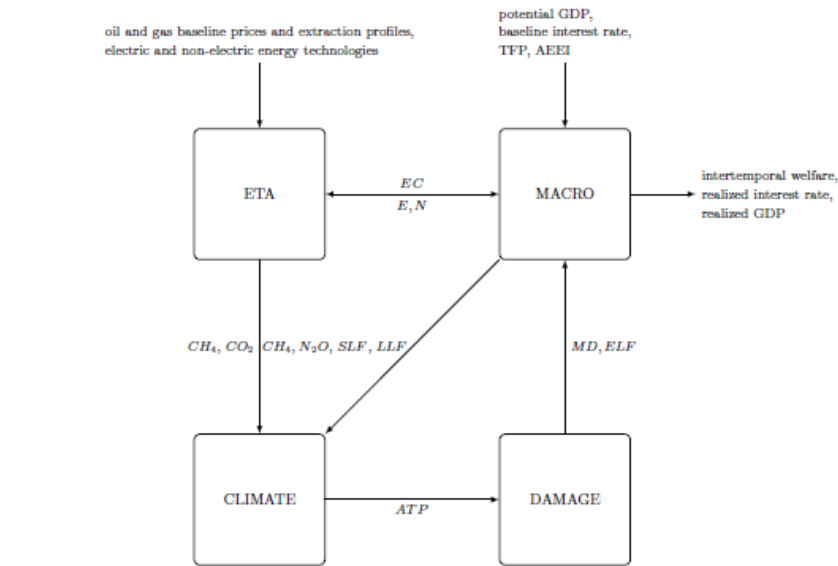
3. Integrated Assessment Framework

Our analysis is based on MERGE, an intertemporal multi-region general equilibrium model.^{24,25} The intertemporal setting reflects the need for an explicitly dynamic framework with a long-term perspective. The regional setting which incorporates major geopolitical players is a prerequisite to investigate the gains from international cooperation in climate policy. For purposes of the present analysis, the globe is divided into six geopolitical regions: **Developed**: 1) the USA, 2) the European Union plus the UK, 3) China, and 4) Other G20 Countries; and **Developing**: 5) India and 6) Rest of World.

In this section, we provide a brief non-technical overview of the model used for the present study. A detailed algebraic exposition of the model logic and its parametrization are provided in Appendices A and B.

MERGE integrates four submodules that provide a reduced-form description of the energy sector (ETA), the economy (MACRO), climate change (CLIMATE), and climate damages (DAMAGES) as shown in Fig.2.

Fig. 2. Modular structure of the integrated assessment model (MERGE)



Legend:

- EC* Energy sector costs (units of macro output)
- E, N* Electric and non-electric energy inputs to macro production
- CH₄, CO₂* Methane and carbon-dioxide emissions from the energy sector
- ATP* Actual surface temperature increase from pre-industrial
- MD, ELF* Market damage rate and economic loss factor (non-market damage)
- CH₄, N₂O, SLF, LLF* Non-energy emissions of methane, nitrous oxide, short-lived and long-lived fluorinated gases

The ETA submodule contains a bottom-up representation of each region's energy supply sector. Separate technologies are defined for each source of electric and non-electric energy. ETA determines a cost-minimizing choice of primary fuel extraction and energy technology operation to satisfy electric and non-electric end-use demands. There are introduction constraints on new technologies and decline constraints on existing technologies. ETA contains technology-specific carbon dioxide and methane emission coefficients.

The bottom-up activity analysis representation of energy supply options makes MERGE particularly suited to explore the implications of alternative technology-based viewpoints

such as different assumptions on the cost and availability of negative emitting technologies such as BECCS (bioenergy with carbon capture and storage).

Outside of each region's energy system, intertemporal consumption and savings choices are governed by an optimal growth model (MACRO). Current and future prices and quantities are determined simultaneously. Price responsiveness is introduced through a top-down production function that combines a value-added composite of labor and capital with an energy composite of electric and non-electric energy on the input side to produce a composite macroeconomic good. Differences in price-responsiveness over time are reflected with a putty-clay representation of production. Gross output is composed of different vintages so that there is a low elasticity of (energy demand) in the short run, but a higher elasticity over the longer term. Production output is used for consumption, investment, and to pay for energy system costs. In an intertemporal setting, the time paths of savings, investment and consumption are strongly influenced by the choice of a utility discount rate. The integrated assessment literature takes different views on this choice. We adopt a descriptive view where the marginal product of capital and the risk-free interest rate are given and enter the calibration of discount factors which are consistent with baseline GDP growth rates.²⁶

The CLIMATE submodule contains geophysical relationships that link together the forces affecting average surface temperature. Greenhouse gas emissions are converted to atmospheric concentrations and concentrations to radiative forcing which then translate into changes in global average temperature. Greenhouse gases are combined using global warming potentials (GWPs) in order to report CO₂e*.

With the addition of the DAMAGES submodule, MERGE can be run in a "cost-benefit" mode that accounts for climate damages, choosing a time path of emissions that maximizes the discounted utility of consumption. Utility maximization accounts for the disutility of damages due to climate change. Damages are often characterized as market or nonmarket. The former represents a direct claim on gross economic output. The latter are those not included in national income accounting and are likely to be of greater concern to high-income regions than to those with low incomes. The challenge here will be the lack of prices for measuring nonmarket damages. This will require the use of alternative techniques such as WTP.

For the treatment of nonmarket damages, we employ an "economic loss factor" (ELF), a function of both per capita income and temperature rise that enters into the discounted utility of consumption. In general, the economic loss factor is written as:

$$ELF(x) = (1 - (x/catt)^2)^{hsx}$$

where x is a variable that measures the temperature rise above preindustrial levels and there are two parameters that define the WTP to avoid temperature rise, $catt$ is the

catastrophic temperature at which all of a countries product is wiped out, and *hsx* adjusts for differing per capita incomes.

The model has been adapted for exploring impacts of a pandemic shocks and pandemic damages on climate policy. In the current version of the model climate damages can either exclude or include pandemic damages. It is included if the public comes to recognize the connection between pandemics and global warming. The model isolates pandemic damages from the other impacts of climate change to determine its impact on climate policy.

The model allows for shifts in the GDP baseline based on the size of the initial pandemic shock and pandemic damages. *BaU* implies an absence of policy to limit warming in order to reduce damages. Agents in the model act as though there is no impact on the price of energy sector emissions due to damages, i.e., they take climate damages as pure externalities. Nevertheless, climate damages feed back to the economy via GDP losses. Both the pandemic GDP shock and pandemic damages will therefore result in a smaller global economy than would occur in a pre-COVID-19 world. This in turn results in reduced energy demands, and lower temperature growth.

4. Simulation results

Our analysis is in two parts: the core analysis, and the sensitivity analysis. For the calculations, we rely on our IAM adapted for the present purposes. The model employs cost-benefit analysis to identify the welfare maximizing behavior of individual countries and groups of countries; incorporates damage functions to account for the impacts from the current and successive pandemics; includes the effects of pandemic shocks and pandemic damages on long-term economic growth; and provides details on non-electric and electric energy technologies, including the possibility of large supplies of BECCS (bioenergy with carbon capture and storage).

4.1. Core analysis

Our primary objective is to investigate how pandemic shocks affect the cost-benefit calculus of countries acting either individually or collectively. We first sketch three different futures on the business-as-usual (*BaU*) in the absence of any climate policy. The *BaU* scenarios reflect alternative assumptions on how pandemics affect climate damages and GDP growth as discussed in section 2 above. In *BaU*, climate damages are treated as pure externalities, i.e., producers and consumers within a region neglect the negative effects of their greenhouse gas emissions not only for other regions but also for themselves. The consequences for long-term economic growth, CO₂e* (energy sector) emissions, and temperature rise are shown in Fig. 3. While the social costs of CO₂e* are ignored by the agents along the *BaU*, climate damages still feed back to the national economies, affecting overall GDP and welfare.

We then devise three climate policy scenarios that reflect different degrees of international cooperation. The extent to which climate externalities (damages) are internalized will depend on the size of the coalition. For the *Statusquo* we assume no international cooperation at all, i.e., individual countries are interested solely in the mitigation costs and damages within their own borders (Nash equilibrium).²⁷ Since the cost-benefit calculus of a particular country does not include the benefits to others, its GHG emission reductions are modest. We then consider climate coalitions of different sizes. When a coalition is established it expands its scope of interest to the impacts on all coalition members. In effect, the coalition acts as a single entity that internalizes climate damages within the club while CO₂e*prices are harmonized.²⁸ We consider two scenarios for climate clubs. One denoted *Developed* where developed countries – the US, the EU, China, and other G20 – coordinate their climate policies to maximize the net benefit of the coalition. And another one denoted *Global* where all regions act together to maximize jointly global welfare. The latter scenario reflects the grand coalition leading to a first-best outcome of international climate policy. Welfare gains occur when damages are reduced (adjusted for increased mitigation costs).

Tab.1 summarizes the key scenarios under investigation.

Tab. 1. The core scenario design.

| Scenario labels | Scenario description |
|--|---|
| Business-as-usual scenarios (<i>BaU</i>) on alternative pandemic shocks | |
| <i>no pan shock/exc pan dam</i> | no pandemic GDP shock - pandemic damage excluded |
| <i>ref pan shock/exc pan dam</i> | reference pandemic GDP shock - pandemic damage excluded |
| <i>ref pan shock/inc pan dam</i> | reference pandemic GDP shock - pandemic damage included |
| Climate policy scenarios on alternative degrees of international cooperation | |
| <i>Statusquo</i> | Nash climate policy of individual countries (USA, EU, China, India) |
| <i>Developed</i> | Cooperative climate policy of developed countries |
| <i>Global</i> | Cooperative climate policy of all countries |

Business-as-usual scenarios reflect alternative pandemic shocks in the absence of climate policy. *BaU* scenario *no pan shock/exc pan dam* refers to the pre-Covid-19 world in which the public and its political leaders failed to heed the warning of health experts that devastating pandemics were imminent. What is unclear in the post-COVID-19 world is whether pandemics will be attributed to climate change. Hence, we consider two post-COVID-19 scenarios, one in which COVID-19 is not attributed to climate change (*ref pan shock/exc pan dam*) and one in which it is (*ref pan shock/inc pan dam*). Corresponding to each scenario is a unique business-as-usual global GDP growth path in which agents in the model treat damages as externalities (Fig. 3). Climate policy scenarios reflect alternative

degrees of international cooperation We investigate three levels of cooperation with their implications for global welfare (Fig.4) and temperature (Fig. 5): the *Statusquo* where countries act only in their own self-interest; developed countries act in concert (*Developed*); and universal collaboration (*Global*).

Business-as-usual implies that climate damages, whether they exclude or include those due to pandemics, are treated as pure externalities by the agents in the model. Nevertheless, damages are recognized in the welfare maximization governing societal behavior. The solid line in Panel a. of Fig. 3 shows projections of *BaU* economic growth for a pre-COVID-19 world. There was virtually no expectation among the public of imminent pandemics. In the post-COVID-19 world, we adopt the reference pandemic shock, either excluding (dashed line) or including (dotted line) pandemic damages. The comparison of the solid and dashed lines show how a pandemic shock affects economic growth. Similarly, the dashed and dotted lines show the impact of damages. The decline in GDP due to the pandemic shock and damages has a corresponding effect on energy sector emissions (Panel b. of Fig. 3). CO₂e* is used to denote emissions of carbon dioxide and methane. These two gases are combined using GWPs. The economy-wide response plays itself out both on the demand- and supply-side of the energy sector, affecting both the energy using and producing capital stock. The decline in GDP also results in a modest decline in temperature rise (Panel c. of Fig. 3).

Fig. 3. Effects of pandemics on business-as-usual (*BaU*).

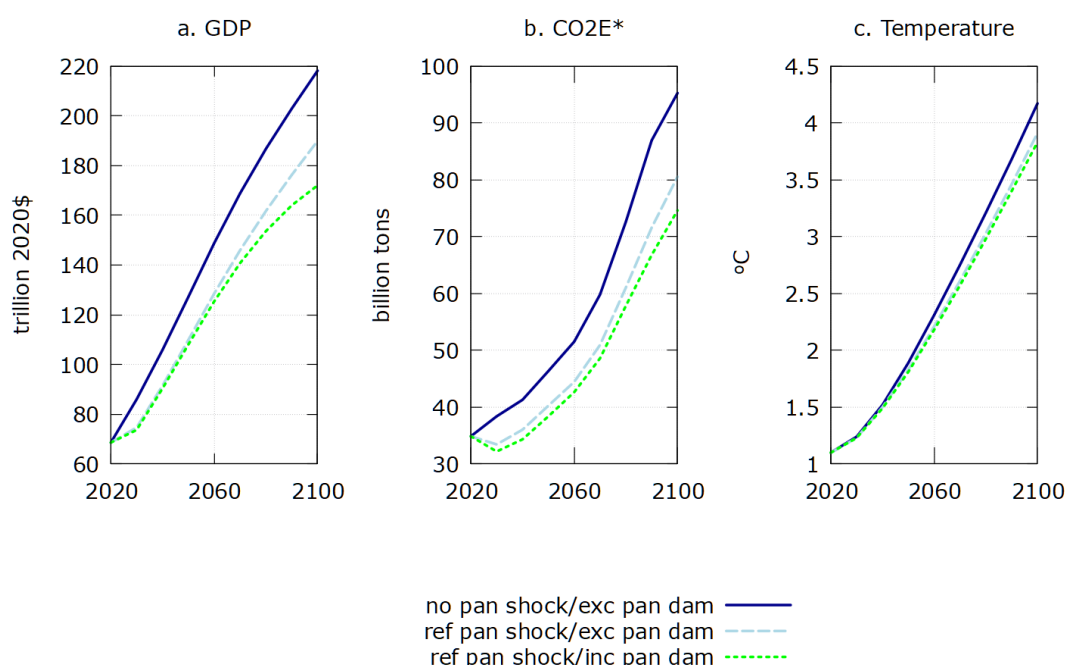
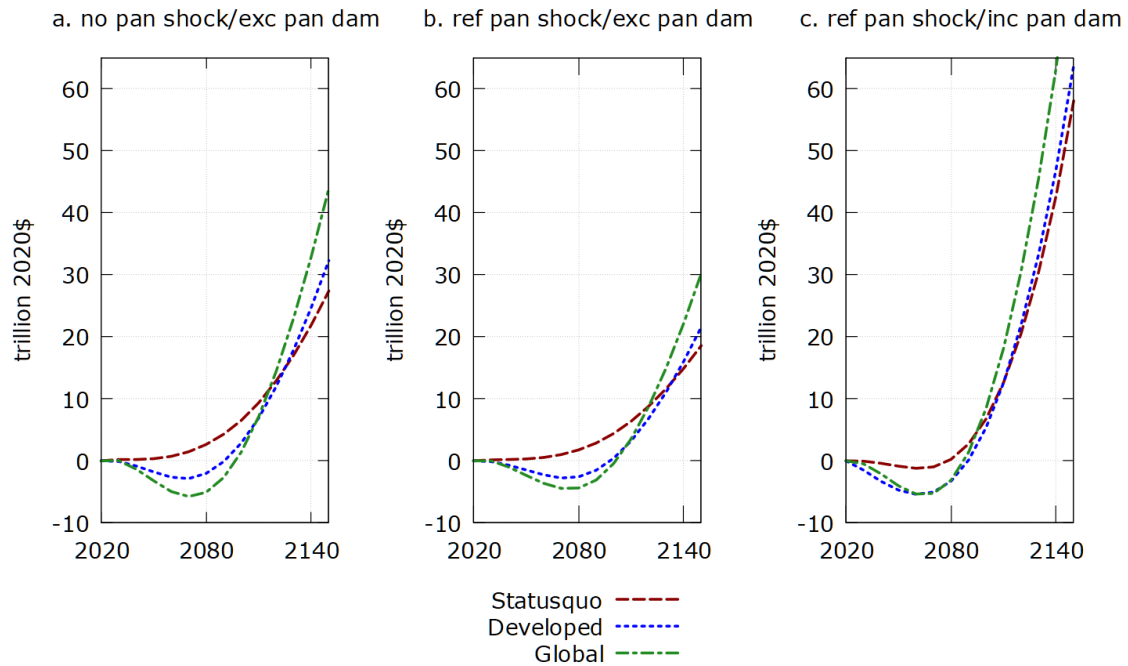


Fig. 4 reports cumulative global welfare change in trillion US\$ relative to *BaU*. The timing of benefits is due in large part to inertia in the socioeconomic system and momentum in the climate system. Here, we refer to constraints on capital stock turnover and the geophysical dynamics governing warming. The near-term investment will take time to pay off, but payoff it will. As the size of the coalition increases, so does the benefits to its members due to the global nature of the greenhouse gas externality.

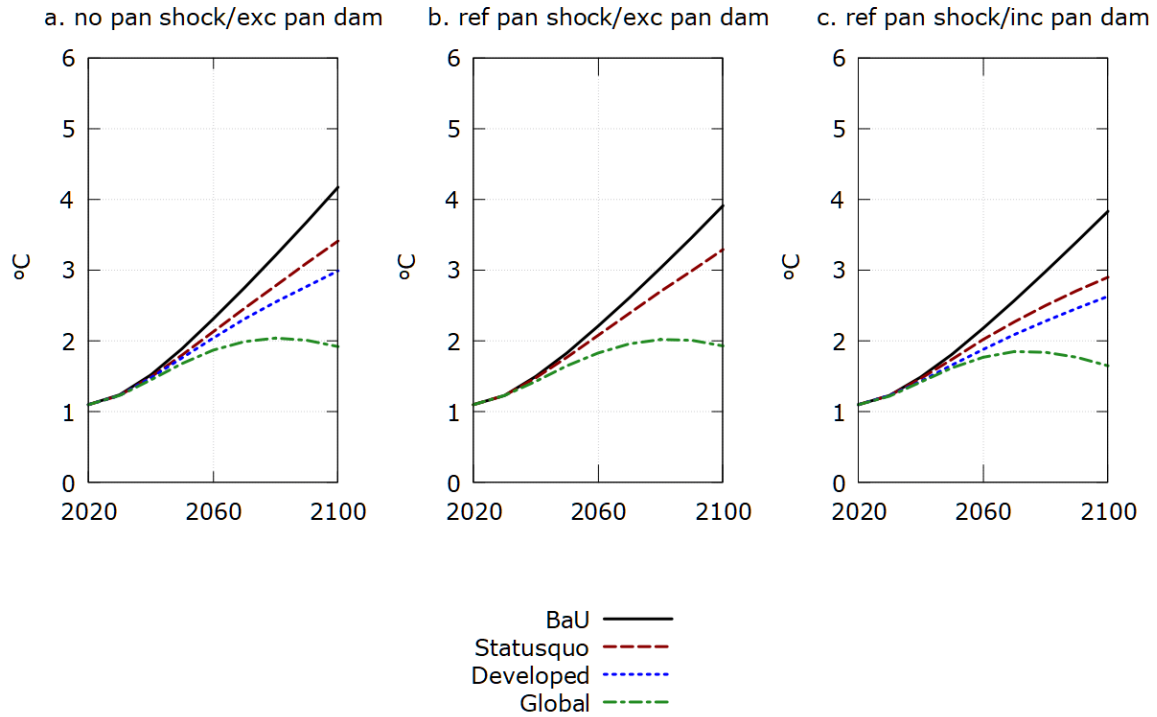
Fig. 4. Present value of net benefits (discounted to 2020 at 2% per year).



Each panel in Fig. 4 contains a comparison of alternative levels of cooperation for dealing with the climate externality. *Statusquo* reflects a world where each individual region acts purely in its own self-interest, maximizing welfare within the region, but ignoring the climate damages of its action on other regions. The “Developed” country coalition reflects a world where a sub-global climate coalition (USA, EU, China, other G20) cooperatively internalizes the climate externality within the boundaries of the coalition. The global coalition reflects a first-best world where all countries work together to combat global warming thereby fully internalizing the climate externality. The global welfare gains from internalizing the climate externality at these different levels of cooperation are stated relative to the respective *BaU*. Panel a. represents the pre-COVID-19 world in which climate policy excludes the possibility of future pandemics. Panel b. assumes a post-COVID-19 world experiencing a reference pandemic shock but excluding pandemic damages. The decline in net benefits (relative to a.) is due to the lower GDP growth rate. Panel c. considers a world in which the reference pandemic shock and the associated pandemic damages are included in the welfare maximization. The increase in net benefits (relative to b.) is the result of the shift to the higher damage curve.

Fig. 5 shows the corresponding effect on average global temperature rise. The results suggest that the goal of capping temperature rise will be difficult to achieve if developing countries remain outside the coalition.

Fig. 5. Welfare maximizing temperature paths.



The importance of global participation in the coalition is clear. It is the only coalition where temperature rise is capped before the end of the century. The level at which the global peak occurs does appear to vary across panels, but the differences are relatively small. This is because of the inertia in the socioeconomic system and momentum in the climate system. There are physical limits on the rate at which temperature growth can be halted. These limits can be relaxed by the availability of large supplies of bioenergy with carbon capture and storage (BECCS). This negative emissions technology – although more costly than a number of zero emitting technologies (e.g., nuclear) – is used in substantial quantities in the Global coalition. We assume BECCS availability consistent with the mean level implementation reported in IPCC.²⁹ This explains the overshoot and decline

4.2. Sensitivity analysis

We investigate the sensitivity of these results to assumptions underlying long-term economic growth; the availability of bioenergy with carbon capture and storage (BECCS); and the risk-free market rate of return. In Fig. 6, the focus is on welfare gains from global coalitions. In Fig. 7, we examine the corresponding effect on temperature paths.

We begin by exploring the potential impacts of two factors influencing long-term economic growth: the short-term pandemic shock and pandemic damages. Both are matters of

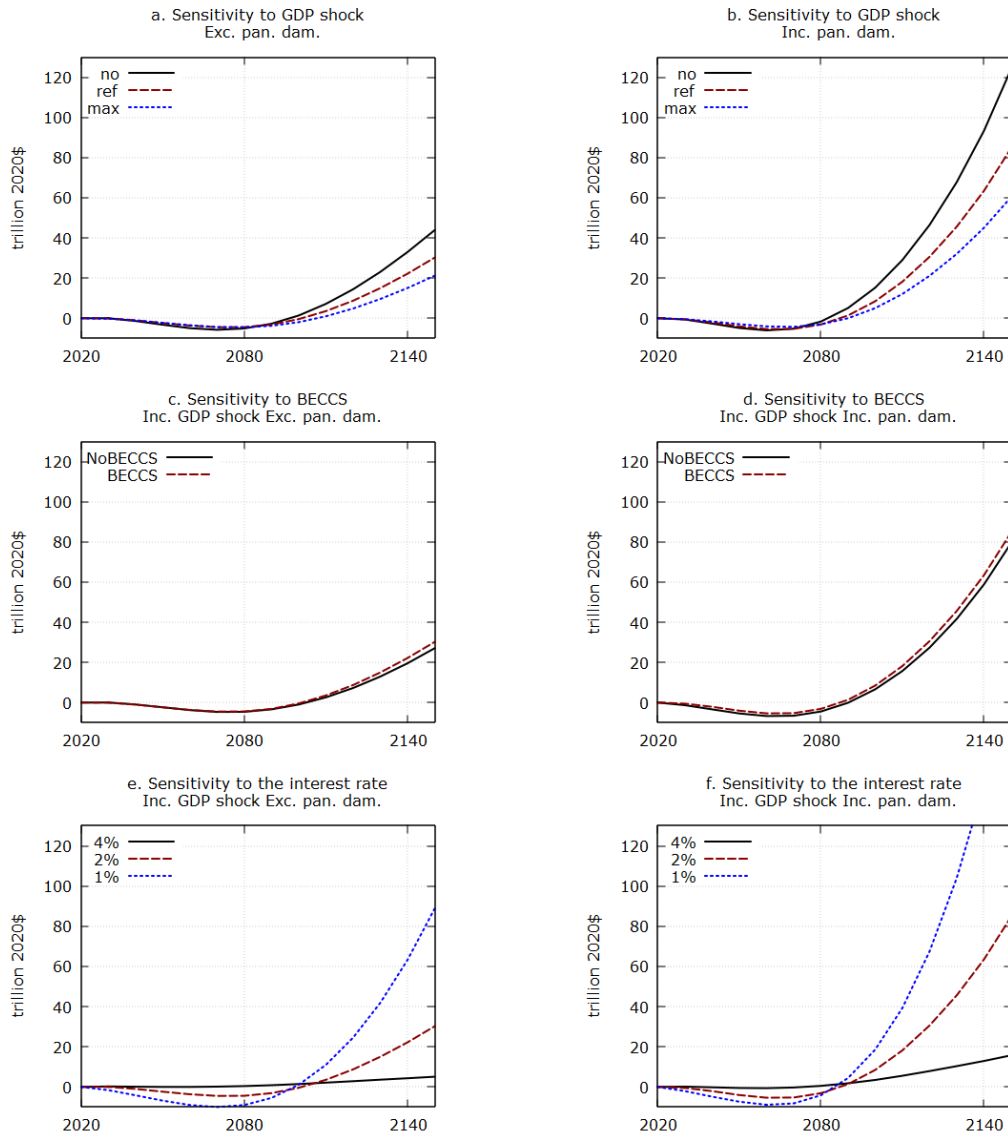
considerable conjecture. The goal is not to be predictive but to generate low, medium, and high scenarios for long-term economic growth. Both factors influence future economic growth and both need be considered.

Next, we examine the assumption of ample supplies of BECCS, the only negative emitting technology included in the analysis. The IPCC has cautioned that “Afforestation and bioenergy may compete with other land uses and may have significant impacts on agriculture and food systems, biodiversity, and other ecosystem functions and services (high confidence).”³⁰ In fact, some scientists suggest that BECCS should not be employed at all.^{31,32,}

Finally, we explore the sensitivity of the results to the choice of market interest rate. Investments in the environment often involve balancing costs today and benefits accruing in the distant future. Global warming is frequently chosen as a primary example. In an optimal growth model, risk-free market rates of return are often used as discount rates. However, economists, philosophers, and ethicists continue to debate the appropriateness of the market rate of interest when evaluating projects involving externalities and time frames extending into the far distant future.³³ In the present analysis, we adopt a 2 % market interest rate. For sensitivity analysis, we explore interest rates of 4 % and 1 %.

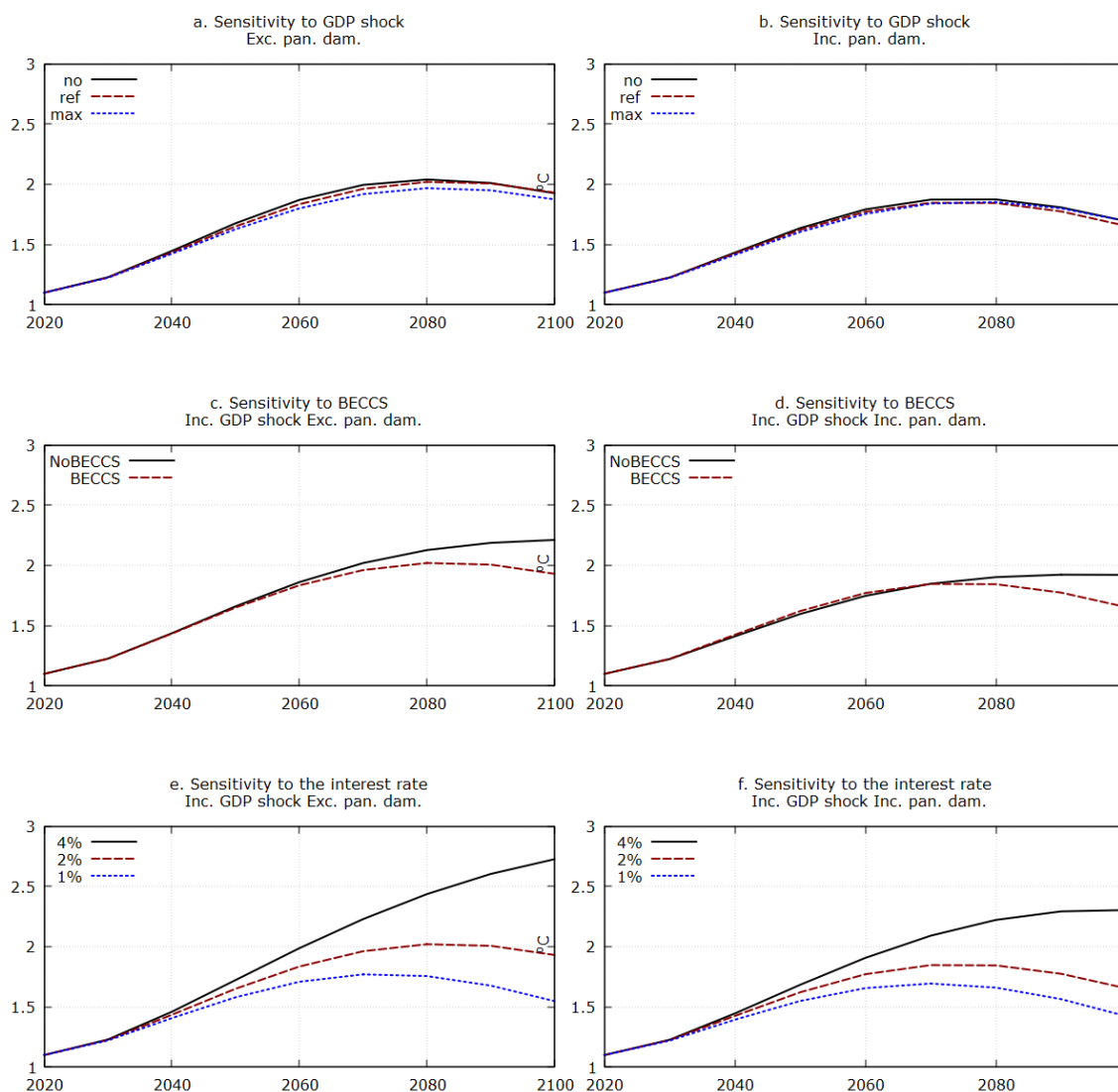
We begin our discussion of welfare gains from global cooperation in Fig. 6. with the top row focusing initially on the differences within each box. The smaller the pandemic shock, the larger the global economy and its ensuing emissions. The benefits from emissions reduction are highest in the case of no pandemic shock. When we move from a. to b., the net benefits increase substantially. Because of the higher damages, there is a higher payoff from emissions reduction. Turning the middle row, BECCS does not have much impact on the welfare maximizing path. There are physical limits on its availability which are binding even in the absence of a pandemic shock. Its alternatives are a host of zero emitting technologies some of which are less costly in terms of energy generation, but do not have negative emitting capabilities. Although the value of BECCS increases when pandemic damages are included, its availability does not. Finally, the bottom row examines the sensitivity of the results to the assumed risk-free market rate of interest. With a 4% rate, less weight is place on the distant future. Upfront abatement costs play a larger role. Conversely, a lower interest rate increases the weight placed on future generations.

Fig. 6. Sensitivity analysis for welfare gains from a global coalition (compared to *BaU*).



The magnitude of the pandemic shock has little impact on temperature within a. and b. as can be seen from Fig. 7. This is consistent with the corresponding net benefits curve from Fig. 5. Net benefits do not begin to diverge until post-2100. Prior to that the temperature path is constrained largely by the inertia in the human system and momentum in the climate system. However, note that there are discernable differences in 2100 between a. and b. This is due to the higher damages in the latter. Turning to BECCS, this negative emitting technology increases the rate at which CO₂ is removed from the atmosphere. Without BECCS, welfare is maximized at a higher temperature level. Notice that with or without BECCS the temperature path is lower when pandemic damages are included in the calculus. Finally, the impact of the risk-free market rate of interest is profound both within and across damages scenarios. As the weight placed on future generations is diminished, the temperature limit is relaxed. Conversely, the temperature limit is tighter when pandemic damages are included in the calculus.

Fig. 7. Wealth maximizing temperature paths.



5. Conclusions

In a pre-COVID-19 world, there was already sufficient justification for aggressively reducing greenhouse gas emissions. Yet, the pre-COVID-19 global emissions trajectory suggested a lack of commitment to implement the measures being called for. This could all change if the public came to realize that curtailing global warming can help diminish the toll of future pandemics. For this to happen, however, people must first recognize that the third appearance of a novel coronavirus in the new century is not just a matter of bad luck. Health experts have been warning that pandemics are likely to increase both in frequency and potency. If their worries are unheeded, the next pandemic could be even more catastrophic. We asked earlier, does the public have the bandwidth to deal with both climate change and novel coronaviruses simultaneously? It may have no choice.

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Appendix A. Algebraic Model Summary

MERGE is an economic equilibrium model formulated in GAMS (Bisschop and Meeraus (1982), Bussieck and Meeraus (2004)). It is solved as a sequence of (integrable) nonlinear optimization problems based on sequential joint maximization (Rutherford, 1999) using CONOPT3 (Drud, 1994). Within each iteration step, the Negishi-weighted discounted utility of consumption across all regions is maximized. The Negishi weights are adjusted iteratively so that – as the model solution converges towards an economic equilibrium – each region will satisfy its income-expenditure constraint.

The model is formulated in discrete time. In general, integrated assessment models that are operated in cost-benefit mode must be solved over very long-time horizons in order to provide a consistent accounting of both the costs and benefits of climate policy. The overall model horizon is dictated by the climate submodel which is typically run over 200-300 years. When all submodels are solved as a simultaneous system, the long horizon of the climate submodel demands for a relatively sparse level of modeling detail in the economic and energy submodels in order to keep the optimization algorithm tractable. We can relax the dimensionality constraints by running the economic/energy submodels and the climate/damage submodels on different time scales. A shorter horizon in the economic model then expands the scope for policy-relevant details on model dimensions such as regional or technological disaggregation.

In the present analysis, the first endogenous year is 2030. The economic and energy submodels operate on a *decadal* time step from 2030 through 2150, while the vari-

ables in the climate and damage submodels are tracked on an *annual* time scale from 2030 thorough 2250. In order to properly capture the benefits of greenhouse gas mitigation in the later years of the energy-economy horizon we project post-terminal consumption and damages from 2160 to 2250.¹ In a similiar vein, the capital stock in the first post-terminal period ($t = 2160$) is targetting to provide steady-state growth as described in [Lau et al. \(2002\)](#).

Below we provide an algebraic description of MERGE. For each of the four submodels we first list the decision variables in tabular form and follow with equations that contain the respective model logic and explanatory text.

A.1 Economic Submodel (MACRO)

A.1.1 Welfare

MERGE maximizes global welfare as the sum of Negishi-weighted regional welfare. The latter is defined as the discounted utility from consumption over time subject to an intertemporal elasticity of substitution (ζ) adjusted for the economic loss factor of climate damages (ϵ_{tr}):

$$W = \sum_r \omega_r \log \left(\sum_t \delta_{tr} (\epsilon_{tr} C_{tr})^\zeta \right)^{1/\zeta}$$

A.1.2 Market clearance for macro output

The output of macroeconomic production in each region and time period is used for current consumption, investment to build up capital stock and for energy expenditures that represent the total cost of extracting energy resoruces and supplying elec-

¹In time periods beyond the economic projection period (from 2160 to 2250), consumption is constrained by projected output net of market damages and projected energy costs.

Table A.1: Indices, Variables and Parameters in MACRO

| | |
|------------------|--|
| Indices | |
| t | Index for time periods |
| r | Index for regions |
| Variables | |
| W | Global (Negishi) welfare |
| C_{tr} | Consumption (\$T) |
| I_{tr} | Investment (\$T) |
| EC_{tr} | Energy cost (\$T) |
| Y_{tr} | Production (\$T) |
| K_{tr} | Capital stock (\$T) |
| E_{tr} | Electric energy (TKWh) |
| N_{tr} | Non-electric energy (EJ) |
| Y_{tr}^N | New vintage production (\$T) |
| K_{tr}^N | New vintage capital stock (\$T) |
| E_{tr}^N | New vintage electric energy (TKWh) |
| N_{tr}^N | New vintage non-electric energy (EJ) |
| ϵ_{tr} | Economic loss factor (non-market damages) |
| μ_{tr} | Market damage rate |
| Parameters | |
| ω_r | Negishi weights |
| ζ | Intertemporal elasticity of substitution |
| Δ_{tr} | Discount rates |
| λ | Capital survival factor |
| δ | Depreciation rate |
| $\psi_{t+1,r}^s$ | Next period investment coefficient (investment maturation factor in subsequent period) |
| ψ_{tr}^c | Own period investment coefficient (investment maturation factor in current period) |
| ϕ_{tr} | Productivity parameter |
| α_{tr} | Baseline value-add share in composite production |
| β_{tr} | Baseline energy value share in composite production |
| κ_{tr} | Baseline capital value share in Cobb-Douglas value-added composite |
| θ_{tr}^e | Baseline electricity value share in Cobb-Douglas energy composite |
| ρ | Substitution elasticity between energy composite and value-added composite |

tric and non-electric energy.

Macro output net of climate (market) damages hence equals consumption plus investment plus energy costs:

$$\sum_r Y_{tr}(1 - \mu_{tr}) = \sum_r C_{tr} + I_{tr} + E C_{tr}$$

In the post-terminal period ($t \geq 2160$) of the economic submodel the values of Y_{tr} , I_{tr} , and $E C_{tr}$ are fixed; μ_{tr} and C_{tr} are endogenous in order to approximate the post-terminal benefits of greenhouse gas mitigation that is undertaken within the time horizon of the economic submodel.

A.1.3 Putty-clay production

Production of the macroeconomic output in each region depends upon four inputs: labor, capital, electric energy, and non-electric energy. There are constant returns to scale with respect to these four inputs. New vintage production for period t in region r is described as nested constant-elasticity-of-substitution (CES) function²:

$$Y_{tr}^N = \phi_{tr} \left(\alpha_{tr} (K_{tr}^N)^{(\kappa_{tr}\rho)} + \beta_{tr} ((E_{tr}^N)^{e_{tr}} (N_{tr}^N)^{1-e_{tr}})^\rho \right)^{1/\rho}$$

In each period we can define aggregate output, capital, electric and non-electric energy based on new vintage values according to:

$$Y_{tr}^N = Y_{tr} - Y_{t-1,r} \lambda$$

²We normalize inputs with respect to labor such that we can omit labor as an explicit variable

$$K_{tr}^N = K_{tr} - K_{t-1,r} \lambda$$

$$E_{tr}^N = E_{tr} - E_{t-1,r} \lambda$$

$$N_{tr}^N = N_{tr} - N_{t-1,r} \lambda$$

In the equations defining new vintage quantities and capital survival parameter λ represents the one period (10 year) survival share, i.e.

$$\lambda = (1 - \delta)^{10}$$

in which δ is the annual depreciation rate of capital.

A.1.4 Capital accumulation and targeting

The evolution of capital depends on depreciation and new investment. Investments made in period t mature both in period t and $t + 1$. The stock-flow accounting relationship for capital (equation of motion for the capital stock) can be expressed as:

$$K_{tr} = \lambda K_{t-1,r} + \psi_{tr}^s I_{tr} + \psi_{t-1,r}^c I_{t-1,r}$$

Without any terminal constraint, the capital stock at the end of the model's horizon would have no value and this would have significant repercussions for investment

rates in the periods leading up to the end of the model horizon. In order to correct for this effect and assure invariance of model results with respect to the model's time horizon, an appropriate terminal condition for the projected capital in the post-terminal period must be specified. Following [Lau et al. \(2002\)](#), we target the capital stock in the first post-terminal period ($t = 2160$).

A.2 The Energy Submodel (ETA)

A.2.1 Market clearance for electric and non-electric energy

Total demand for electric energy must be satisfied by the sum of power generation across all electric supply technologies adjusted for the intermediate demand of electricity used in the generation of liquid fuels (here: hydrogen):

$$E_{tr} = \sum_{i \in \mathcal{E}} Q_{tri} - \sum_{i \in \mathcal{L}} a_i Q_{tri}$$

Likewise, total demand for non-electric energy must be satisfied by the sum of non-electric energy supplied by non-electric technologies:

$$N_{tr} = \sum_{i \in \mathcal{N}} Q_{tri}$$

Table A.2: Indices, Variables and Parameters in ETA

| Indices and Sets | |
|------------------|---|
| t | Index for time periods |
| r | Index for regions |
| i | Index for technologies and fuels (aliased with j) |
| k | Index for resource type (CNV - conventional, UNC – unconventional) |
| l | Index for market shares (penetration level) of electricity from intermittent renewable technologies |
| g | Index for greenhouse gas |
| \mathcal{I} | Set of all technologies and fuels (see Table B2-B4) |
| \mathcal{E} | Set of electric energy supply technologies (see Table B2) |
| \mathcal{N} | Set of non-electric energy supply technologies (see Table B3) |
| \mathcal{L} | Set of refined liquid fuels (see Table B4) |
| \mathcal{X} | Set of exhaustible (fossil fuel) resources (oil, gas) |
| \mathcal{R} | Set of renewable energy technologies for power generation (see Table B2) |
| \mathcal{R}^* | Set of intermittent renewable energy technologies without storage (see Table B2) |
| \mathcal{B} | Set of biomass-fired power technologies (see Table B2) |
| \mathcal{C} | Set of coal-fired power technologies (see Table B2) |
| \mathcal{G} | Set of gas-fired power technologies (see Table B2) |
| (GHG) | Set of greenhouse gases (GHG) |
| Variables | |
| E_{tr} | Electric energy demand (TKWh) |
| N_{tr} | Non-electric energy demand (EJ) |
| EC_{tr} | Energy cost (trillion dollars) |
| EX_{trki} | Extraction (production) of fossil fuel i from resource type k (EJ) |
| EXC_{rki} | Extraction cost index (intertemporal) |
| X_{tri} | Exports of fuels (EJ) |
| M_{tri} | Imports of fuel (EJ) |
| $XC R_{tr}$ | Exports of carbon rights (Gt CO ₂ e) |
| $MC R_{tr}$ | Imports of carbon rights (Gt CO ₂ e) |
| TPE_{tri} | Total primary energy consumption of fuel i (EJ) |
| Q_{rti} | Production of energy by technology i (TKWh or EJ) |
| PA_{trj} | Premature abandonment of technology i (TKWh or EJ) |
| QIR_{trl} | Cumulative electricity production of intermittent renewables at market share (penetration level) l (TKWh) |

Table A.3: Indices, Variables and Parameters in ETA (cont.)

| Variables | |
|------------------------|---|
| $CE_{t,r}$ | Carbon dioxide emissions (Gt CO ₂ e) |
| $ME_{t,r}$ | Methane emissions (Gt CO ₂ e) |
| $TE_{t,g}$ | Global emissions by greenhouse gas (Gt CO ₂ e) |
| $CME_{t,g}$ | Energy-system emissions from carbon and methane (Gt CO ₂ e) |
| Parameters | |
| a_i | Electricity requirement for non-electric technology ³ |
| h_{tri} | Heat rate (EJ per TWh) |
| ψ | Primary energy requirement factor for synfuel production from coal |
| σ^x | Elasticity of substitution in resource extraction |
| η^x | Elasticity of transformation in resource supply over time |
| $\bar{E}XC_{rki}$ | Baseline extraction cost index |
| $\bar{E}X_{trki}$ | Baseline extraction of resource by resource type (EJ) |
| θ_{rki}^x | Value share of resource rents in supply |
| θ_{trki}^x | Value share in the resource supply profile |
| \bar{B}_{tr} | Upper bound on biomass resources (EJ) |
| λ_r^C | Maximum market share for coal-fired power generation |
| c_{xtrki} | Extraction cost coefficient (\$ per EJ) |
| c_{rtrki} | Resource cost coefficient (\$ per EJ) |
| c_{otri} | Technology operation cost coefficient (\$ per MWh) |
| c_{gtri} | Grid integration cost coefficient (\$ per MWh) |
| $c_{atри}$ | Technology abandonment cost coefficient (\$ per MWh or EJ) |
| c_{ttri} | Transportation cost coefficient for fuel exports (\$ per EJ) |
| c_{ctri} | Carbon coefficient (tCO ₂ per MWh or EJ) |
| m_{ctri} | Methane coefficient (tCO ₂ per MWh or EJ) |
| gwp_g | Global warming potential by greenhouse gas |
| \overline{oem}_{trg} | Exogenous other GHG emissions outside the energy system (Gt CO ₂ e) |
| \overline{cem}_{tr} | Exogenous CO ₂ emissions from cement production (Gt CO ₂ e) |

A.2.2 Liquid fuels market

On the market for liquid fuels, the supply of liquid fuels ⁴ must cover the demand for liquids in direct use (e.g. transportation and heating) and oil-fired power generation:

$$\sum_{i \in \mathcal{L}} Q_{tri} = Q_{tr, \text{lqdu}} + h_{tr, \text{oil-f}} Q_{tr, \text{oil-f}}$$

The three types of refined products are perfect substitutes except as inputs to oil-fired electricity generation. Only refined oil based on conventional crude oil may be used to produce electricity:

$$Q_{tr, \text{petro}} \geq h_{tr, \text{oil-f}} Q_{tr, \text{oil-f}}$$

A.2.3 Primary energy accounting

The demand for total primary energy carriers – crude oil, natural gas, and coal – are determined by the input requirements for these fuels in the respective electric and non-electric technologies. Primary energy demand for crude oil is entirely in refining. As we assume that international trade in refined oil products is negligible, crude oil demand equals output from petroleum refineries:

$$TPE_{tr, \text{oil}} = Q_{tr, \text{petro}}$$

Primary energy demand for natural gas arises from direct use technologies (e.g.,

⁴Recall that the set of liquid fuels (\mathcal{L}) includes petroleum-based liquids (PETRO), biomass-based and natural gas liquids (LQDX and coal-based synthetic liquids (SYNF).

heating and cooking) and gas-fired electricity generation:

$$TPE_{tr,gas} = Q_{tr,gsdu} + \sum_{i \in \mathcal{G}} h_{tri} Q_{tri}$$

Primary energy demand for coal includes coal for direct use, the conversion into synthetic fuels, and coal-fired electricity generation:

$$TPE_{tr,coal} = Q_{tr,cldu} + (1 + \psi) * Q_{tr,synf} + \sum_{i \in \mathcal{C}} h_{tri} Q_{tri}$$

A.2.4 Exhaustible resources and biomass resource constraint

Extractable resources (set \mathcal{X}) includes crude oil and natural gas. Oil resource types include conventional and unconventional deposits (e.g., oil sands in Canada). For the initial ETA baseline calibration, supplies of crude oil and natural gas are upper-bounded by exogenous profiles reflecting expert expectations on fuel market developments. The solution of the baseline ETA calibration provides information on the value of resource extraction along the time path, which can be used to calibrate a reduced-form Hoteling model of supply for exhaustible resources. Aggregate supply of resource over time is then determined by the elasticity of substitution (σ^x) between the inputs to extraction and the resource stock, while resource supplies are allocated across time with an elasticity of transformation η^x :

$$\left(\theta_{rki}^x + (1 - \theta_{rki}^x) \left(\frac{EX_{rki}}{\bar{EX}_{rki}} \right)^{1-1/\sigma^x} \right)^{1/(1-1/\sigma^x)} = \left(\sum_t \theta_{trki}^x \left(\frac{EX_{trki}}{\bar{EX}_{trki}} \right)^{1+1/\eta^x} \right)^{1/(1+1/\eta^x)} \quad \forall i \in \mathcal{X}$$

Extraction of oil and gas must be sufficiently high to cover domestic primary energy

demand plus net exports:

$$\sum_{j \in \mathcal{J}} EX_{trji} = TPE_{tri} + X_{tri} - M_{tri} \quad \forall i \in \mathcal{X}$$

The availability of biomass to cover demands from biomass-fired electricity generation is limited exogenously:

$$\frac{Q_{tr, \text{lqdx}}}{htrt_{\text{lqdx}}} + \sum_{i \in \mathcal{B}} Q_{tri} \leq \bar{B}_{tr}$$

A.2.5 International energy trade

On international energy markets, net exports of interregionally tradeable energy goods (crude oil and natural gas) must be balanced with net imports:

$$\sum_r X_{tri} = \sum_r M_{tri} \quad \forall i \in \mathcal{X}$$

A.2.6 Technology constraints for intermittent renewables

Electricity generation from renewable intermittent energy technologies without storage options are subject to additional grid intergration costs that depend on the specific level of penetration. Discrete levels of penetration are provided as a fraction of overall power generation such that the cumulative quantity of electricity from renewable intermittent technologies without storage options $QIR_{(T,R,L)}$ at a specific penetration level (indexed (IR)) is given as:

$$QIR_{trl} \leq \ell_l \sum_{i \in \mathcal{E}} Q_{tri}$$

Total production of intermittent renewables must equal the sum of penetration-specific production from intermittent renewables across all penetration levels

$$\sum_{i \in \mathcal{R}^*} Q_{tri} = \sum_{l \in \mathcal{R}} QIR_{trl}$$

A.2.7 Market shares, expansion and decline rates

Technology deployment is limited by different physical, institutional, regulatory and even social aspects, e.g., the time needed to build the technologies, the rate at which people can be trained to build new technologies, the rate at which renewable technologies can be integrated into the grid, the availability of supplies (steel, concrete, wires, etc.), the time to accomplish regulatory aspects or to gain social acceptance, etc. In order to control the dynamic evolution of technologies within the energy system beyond direct cost competition there are constraints on market shares, expansion and decline. Market share constraints provide upper bounds for energy supply from technologies specified as a maximum share in aggregate energy supply. Expansion and decline constraints define upper and lower bounds on technology deployment as expansion or decline rates between production in subsequent periods.

In the current application of MERGE, market share constraints apply to direct use of gas for heating and transport (GSDU), biomass-based and natural gas liquids (LQDX), gas-fired electricity production, coal-fired electricity production, and nuclear power.

Natural gas is limited to 50% of the non-electric energy market:

$$Q_{tr,gsdu} \leq \frac{1}{2} \sum_{i \in \mathcal{N}} Q_{tri}$$

Biofuels and natural gas liquids are limited to 20% of the non-electric energy market:

$$Q_{tr,lqdx} \leq \frac{1}{5} \sum_{j \in \mathcal{N}} Q_{trj}$$

Gas-fired power generation is limited to supplying 50% of the electric energy market:

$$\sum_{j \in \mathcal{G}} Q_{trj} \leq \frac{1}{2} \sum_{j \in \mathcal{E}} Q_{trj}$$

Coal-fired power generation is limited to supplying a region-specific fraction of the electric energy market:

$$\sum_{j \in \mathcal{C}} Q_{trj} \leq \lambda_r^C \sum_{j \in \mathcal{E}} Q_{trj}$$

Nuclear power plants of generation II and III can provide no more than 50% of regional generation:

$$Q_{tr,nuc-1} \leq \frac{1}{2} \sum_{j \in \mathcal{E}} Q_{trj}$$

There are decline and expansion constraints across electric and non-electric technologies.

Output of a technology in a subsequent period can not decline by more than depreciated output in the current period (here: a depreciation rate of 4% per annum over a 10-year period) unless there is costly premature abandonment:

$$Q_{tri} \geq (1 - (0.04)^{10}) Q_{t-1,ri} - PA_{tri}$$

Output in subsequent period is limited to an exogenous growth rate (here: a growth rate of 7.2% per annum over a 10-year period) over the current output plus a certain fraction (here: 4%) of total supply:

$$Q_{tri} \leq (1.072)^{10} Q_{t-1,ri} + 0.04 * Q_{T-1,r,i}$$

A.2.8 Energy cost accounting

The energy system submodel is solved as a cost-minimization problem, i.e. demands for electric and non-electric energy emerging from the economic submodel are met at least cost way subject to the above-mentioned feasibility constraints. Energy system cost $EC_{t,r}$ in region r and period t are calculated as:

$$\begin{aligned}
 EC_{tr} = & \underbrace{\sum_{ki \in \mathcal{KL}} c_{xtrki} EX_{trki} + \sum_{rki} EXC_{rki} c_{rtrki}}_{\text{Resource extraction costs}} \\
 & + \underbrace{\sum_{i \in \mathcal{L}} c_{otri} Q_{tri}}_{\text{Costs for operation of energy technologies}} \\
 & + \underbrace{\sum_{i \in \mathcal{L}} c_{atри} PA_{tri}}_{\text{Costs of premature technology abandonment}} \\
 & + \underbrace{\sum_{i \in \mathcal{R}} c_{gtri} QIR_{tri}}_{\text{Costs for grid integration of renewable electric generation}} \\
 & + \underbrace{\sum_{i \in \mathcal{L}} c_{ttri} EXPRT_{tri}}_{\text{Costs for transportation of fuel exports}}
 \end{aligned}$$

A.2.9 Greenhouse gas emission accounting

Total greenhouse gas (GHG) emissions – in CO₂ equivalents – are composed of energy-related GHG emissions based on the technology combination obtained by the energy submodel and a non-energy GHG emissions baseline (e.g. methane emissions from agriculture), which is assumed exogenously.

Carbon emissions in the energy system are determined by the carbon coefficients and the production levels for each electric and non-electric technology:

$$CE_{tr} = \sum_{i \in \mathcal{I}} c_{rti} Q_{tri}$$

Methane emissions in the energy system emerge from the extraction of total primary energy:

$$ME_{tr} = \sum_{f \in \mathcal{F}} mc_{rf} TPE_{trf}$$

Greenhouse gases outside the energy system are taken as exogenous including +CO₂ emissions from cement production $CEM_{t,r,"CO_2"}$ and other greenhouse gases OE_{trg} covering nitrous oxide N_2O , short-lived fluorinated gases SLF and long-lived fluorinated gases LLF .⁵

Global emissions by time period and greenhouse gas are given as the sum of emissions within

⁵Short-lived F-gases correspond to hydrofluorocarbons (HFCs) with a lifetime of less than 100 years. Long-lived F-gases include HFCs with lifetimes greater than 100 years, SF₆ and perfluorocarbons (PFCs).

and outside the energy system⁶:

$$TE_{tg} = \begin{cases} \sum_r CE_{tr} + \overline{cem}_{tr} - 0.9 * Q_{tr, \text{cem-ccs}} & g = \text{CO}_2 \\ \sum_r ME_{tr} & g = \text{CH}_4 \\ \sum_r \overline{oem}_{trg} & g \notin \{\text{CO}_2, \text{CH}_4\} \end{cases}$$

Accounting for potential exports and imports of carbon emission rights via international emissions trading, regional emissions from the energy system are defined in CO_2 -equivalent terms as⁷:

$$CME_{tr} = CE_{tr} + ME_{tr}gp_{\text{CH}_4} - MCR_{tr} + XCR_{tr}$$

A.3 The Climate Submodel (CLIMATE)

The climate submodel builds on a so-called box model where the complexity of the climate system is reduced to five boxes (ranging from the lower ocean to the upper atmosphere) linked by fluxes. The stocks of greenhouse gases within each box is determined by distributed lag processes to account for the inertia of the different components of the climate (such as the biosphere or ocean systems). The inertia of the climate system is modeled through a series of linear difference equations. The accumulation of greenhouse gases in the upper atmosphere determines radiative forcing. The latter in turn drives the potential temperature increase – after time has elapsed for the climate system to come into equilibrium.

The CLIMATE submodel is operated with annual time steps and takes up the decadal emissions from the energy submodel (ETA). A linear interpolation is used to convert emissions by

⁶We allow for removal of CO_2 emissions from cement through a repsective CCS technology with an efficiency factor of 0.9

⁷Greenhouse gas emission constraints such as NDCs provide then an upper bound on regional emissions

Table A.4: Indices, Variables and Parameters in Climate

| | |
|------------------|---|
| Indices and Sets | |
| r | Index for regions |
| y | Index for years ((2020,...,2250)) |
| g | Index for greenhouse gas |
| b | Index for CO ₂ decay boxes |
| (GHG) | Set of greenhouse gases |
| (GHG) | Set of CO ₂ decay boxes ((b_1, b_2, b_3, b_4, b_5)) |
| Variables | |
| CO_{2yb} | Stock of CO ₂ in each box at each time (billion tons) |
| S_{yb} | Atmospheric stock (billion tons) |
| RF_{Gyg} | Radiative forcing (W per m^2) |
| RFT_y | Total radiative forcing from GHGs net of aerosol effect (W per m^2) |
| EQT_y | Equilibrium temperature increase from 1850 (°C - associated with RF) |
| OTP_y | Ocean temperature (°C increase from 1850) |
| ATP_y | Global mean temperature (°C increase from 1850) |
| Parameters | |
| δ_b | Annual rate of decay in each box of carbon cycle model |
| θ_b | Fraction of CO ₂ e emissions accruing to each box (sums to 1) |
| $\theta_{t,y}$ | Interpolation weight for converting decadal emissions into annual emissions |
| κ_g | Interaction term of radiative forcing between N ₂ O and CH ₄ |
| ω_g | Concentration units per stock unit |
| rf_g | Radiative forcing factor |
| $barc_g$ | Equilibrium concentration of greenhouse gas |
| $montreal_y$ | Positive effect of Montreal Protocol gases (W per m^2) |
| $sulfur(y)$ | effect of sulfur aerosols in watts per square meter |
| rf_v | Average volcanic and solar radiative forcing 1850 - 2020 (RCP) (W per m^2) /-0.2189/, |
| ℓ_{se} | Annual lag in actual temperature response |
| ℓ_{so} | Annual rate of process moving surface air temperature towards ocean temperature |
| ℓ_{os} | Annual rate of process moving ocean temperature towards surface air temperature |
| ι | Linear conversion for equilibrium temperature from radiative forcing; |

decade to annual emissions:

$$EMIT_{y,g} = \sum_t \theta_{t,y} TE_{t,g}$$

A.3.1 Greenhouse Gas Stocks and Concentrations

The extra-equilibrium stock of CO₂ in each box is determined by:

$$CO2_{y+1,b} = \underbrace{(1 - \delta_b) CO2_{yb}}_{\text{Decay from the previous period (sinks)}} + \underbrace{\theta_b EMIT_{y,CO_2}}_{\text{Accumulation of current emissions}}$$

The total extra-equilibrium stock of CO₂ is determined by summing over all boxes.

$$S_{y+1,g} = \bar{s}_g + (1 - \delta_g) * (S_{yg} - \bar{s}_g) + \left(\sum_b CO2_{y+1,b} \right) \Big|_{g=CO_2} + EMIT_{y,g} \Big|_{g \neq CO_2}$$

A.3.2 Radiative Forcing

For CO₂, radiative forcing is proportional to the logarithm of stock. There are similar but more complex forcing terms for N₂O and CH₄. The term κ_g approximates interaction effects in radiative forcing between these two gases. Forcing from f-gases is linear in stock.

$$RFG_{y+1,g} = rf_g \left\{ \begin{array}{ll} \log\left(\frac{S_{y+1,g} \omega_g}{\bar{c}_g}\right) & g = \text{CO}_2 \\ (\sqrt{S_{y+1,g} \omega_g} - \sqrt{\bar{c}_g})(1 - \kappa_g) & g \in \{\text{CH}_4, \text{N}_2\text{O}\} \\ S_{y+1,g} & g \in \{slf, llf\} \end{array} \right.$$

Non-Kyoto forcing is calibrated to IPCC median estimates for 2005. Total forcing equals Kyoto greenhouse gas forcing plus Montreal gas forcing less cooling effects of sulfur aerosols:

$$RFT_{y+1} = \sum_g RFG_{y+1,g} + \text{montreal}_y - \text{sulfur}_y$$

A.3.3 Lagged Temperature Responses

Equilibrium temperature is proportional to the aggregate radiative forcing induced by greenhouse gases and average volcanic and solar radiative forcing:

$$EQT_{y+1} = \iota(RFT_{y+1} + rf_v)$$

Actual temperature increase from pre-industrial is determined by a lagged response to equilibrium temperature. There is an exponential decay in the differential between actual and equilibrium:

$$OTP_{y+1} = \ell_{os} ATP_y + (1 - \ell_{os}) OTP_y$$

Table A.5: Indices, Variables and Parameters in Damage

| | |
|-----------------|--|
| Indices | |
| t | Index for time periods |
| r | Index for regions |
| Variables | |
| ϵ_{tr} | Economic loss factor (non-market damages) |
| μ_{tr} | Market damage rate |
| Parameters | |
| md_4 | Market damage rate at a temperature increase of 4 °C |
| nmd_1 | Non-market damage rate at a temperature increase of 1 °C |
| ζ | Elasticity of damage with respect to global mean temperature change) |
| $hsx_{t,r}$ | Exponent in non-market damage function (hockey-stick parameter) |

$$ATP_{y+1} = \ell_{se} EQT_y + \ell_{so} OTP_y + (1 - \ell_{se} - \ell_{so}) ATP_y$$

A.4 The Damage Submodel (DAMAGE)

The CLIMATE submodel determines market and non-market damages as a function of the change in global mean temperature from pre-industrial levels (°C increase from 1850).⁸

Market damages are a quadratic function of global mean temperature change calibrated to losses a change in global mean temperature at 4 °C:

$$mu_{tr} = \overline{md}_4 * \left(\frac{ATP_t}{4} \right)^2$$

Non-market damages are calibrated to losses at a global mean temperature change of 4 °C, an elasticity of damage with respect to global mean temperature change(ζ) and an exponent

⁸The respective values appear as damage coefficients in the MACRO submodel – see C.1

describing the role of per-capita income ($h s x_{tr}$)⁹:

$$\epsilon_{tr} = \left(1 - n m d_1 (AT P_t)^\zeta\right)^{h s x_{tr}}$$

⁹The hockey-stick parameter $h s x_{tr}$ is a function of per-capita income and determines how sensitive the losses are to a change in the actual temperature. It approaches unity (from below) as income rises such that for high-income countries, the economic loss is quadratic in terms of the temperature rise

Appendix B. Base-Year Parametrization

MERGE is calibrated to the base-year 2020. All economic values are reported in US dollars of constant 2020 purchasing power. Calibration of the macroeconomic submodel only requires a relatively sparse dataset for the regional economies such as the initial capital-GDP ratio, the annual percent depreciation, elasticities (between capital and labor as well as between electric and non-electric energy inputs), value shares (for capital, electric energy), energy reference prices, existing tax rates on electric and non-electric energy. Data input for the energy submodel is more comprehensive: Apart from base-year statistics for primary and secondary energy carriers as well as energy resources, current and future technologies must be described through cost and capacity coefficients (including decline and expansion rates).

Table B.1 summarizes the geopolitical regions that are currently incorporated in MERGE. Tables B.2 and B.3 lists the electric and non-electric technologies included in the model. Table B.4 describes the refined liquid fuels incorporated in the model beyond primary fossil fuels (coal, gas, and crude oil). ¹⁰ Tables B.5 and B.6 provide key assumptions on non-electric and electric technologies.

¹⁰In Tables B.1-B.4 we also provide the acronyms to the respective regions, technologies, and fuels in the model.

Table B.1: Regions

| Label | Description |
|-------|--|
| USA | United States |
| CAN | Canada |
| EUR | Europe |
| CHINA | China |
| INDIA | India |
| OG20 | Other wealthy and G20 Countries [†] |
| ROW | Rest of world |

[†] Region OG20 includes Australia, New Zealand, Mexico, Chile, South Korea, Japan and Russia.

Table B.2: Electric Technologies

| Label | Description |
|-----------|--|
| HYDRO | Existing hydroelectric |
| NUC-1 | Nuclear generation with once-through fuel (Generation II and III), |
| NUC-ADV | Generation IV nuclear generation (breeder or fusion), |
| OIL-F | Oil-fired electric |
| GAS-F | Gas-fired electric |
| GAS-CCS | Gas-fired electric with carbon capture and storage |
| COAL-F | Coal-fired electric |
| COAL-CCS | Coal-fired electric with carbon capture and storage |
| INTRNW-LC | Intermittent renewable (wind or solar) – no storage |
| INTRNW-HC | Intermittent renewable with storage (backstop) |
| BIOMASS | Biomass |
| BECCS | Biomass with carbon capture and storage |

Table B.3: Nonelectric (End-Use) Technologies

| Label | Description |
|--------|---|
| CLDU | Coal for direct use – (industrial only) |
| GSDU | Natural gas for direct use |
| LQDU | Liquid fuels for direct use |
| NEB-HC | Non-electric backstop |

Table B.4: Refined Liquid Fuels)

| Label | Description |
|-------|---|
| PETRO | Petroleum-based liquids (includes tight oil, shale oil, extra-heavy oil, field condensate, and bitumen) |
| LQDX | Biomass-based and natural gas liquids (other liquids including natural gas plant liquids, liquids from renewable sources (biofuels, including ethanol, biodiesel, and biomass-to-liquids) |
| SYNF | Coal-based synthetic liquids |
| H2 | Hydrogen based on electrolysis |

Table B.5: Non-Electric Energy Technology Assumptions for USA in 2020

| Fuel | Cost (\$/GJ) | Carbon Emission Coefficient (kg CO ₂ /GJ) |
|--|-----------------|---|
| Coal (for direct use) | 2.5 | 88.4 |
| Petroleum (cost rises with extraction) | 3 | 73.0 |
| Natural Gas (cost rises with extraction) | 5 | 50.2 |
| Synthetic Liquids | 15 | 111 |
| Biofuels | 10 | 0 |
| Non-Electric Backstop | 25 | 0 |

Table B.6: Electric Technology Assumptions for New Vintages for USA in 2020

| Technology | Model Year Available | Market Cost (\$/MWh) | Non-Market Cost (\$/MWh) | Carbon Emission Coefficient (Million tons C O ₂ /TWh) |
|--|----------------------------|----------------------------|--------------------------------|---|
| Coal (without CCS) | | 74 | | 947 |
| Oil-fired [†] | | 40 | | 410 |
| Coal (with CCS) [¶] | 2030 | 113 | 10 | 95 |
| Natural Gas (without CCS) [†] | | 56 | | 353 |
| Natural Gas (with CCS) [†] | 2030 | 81 | 43 | |
| Nuclear ^{¶†} | | 65 | 10 | |
| Nuclear - Advanced ^{¶†} | 2050 | 97 | 10 | |
| Hydro | | 30 | | |
| Waste and other renewables | | 50 | | |
| Biomass with CCS [§] | 2030 | 104 | 10 | -205 |
| Intermittent renewables [‡] | | 60 | | |
| Backstop renewable | | 203 | | |

[¶] We assume that the cost of nuclear and CCS generation has a market and non-market component. The latter, which is calibrated to current usage in the case of nuclear, rises proportionally to market share and is intended to represent public concerns about environmental risks in the technology. (In the case of nuclear, the represented concern can extend to security risks and risks associated with the nuclear fuel cycle.)

[†] The market cost for these generation technologies excludes fuel prices. Fuel prices faced by these technologies are a function of the market for each respective fuel.

[‡] Intermittent technologies are subject to grid integration costs when providing greater than 5% of a region's electricity: \$5/MWh when providing 5%-10% of a region's electricity, \$7.5/MWh when providing 10-20%, and \$15/MWh when providing greater than 20% of a region's electricity.

[§] Biomass with CCS is treated as a transition technology which is only available during the 21st century.

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