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Growth impact of climate change and response policies: The advanced climate change long-term (ACCL) model¹

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Abstract

This paper provides a tool to build climate change scenarios to forecast Gross Domestic Product (GDP), modelling both GDP damage due to climate change and the GDP impact of mitigating measures. It adopts a supply-side, long-term view, with 2060 and 2100 horizons. It is a global projection tool (30 countries/regions), with assumptions and results both at the world and the country/regional level. Five different types of energy inputs are taken into account according to their CO₂ emission factors. Full calibration is possible at each stage, with estimated or literature-based default parameters. Compared to other models, it provides a comprehensive modelisation of Total Factor Productivity (TFP), which is the most significant determinant of the GDP projected path. We present simulation results of different energy policy scenarios. They illustrate both the “tragedy of the horizon” and the “tragedy of the commons”, which call for a policy framework that adequately integrates a long run perspective, through a low-enough discount rate and an effective intergenerational solidarity as well as international cooperation.

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1. Introduction

The latest report by the Intergovernmental Panel on Climate Change (IPCC, 2021) has underlined the fast deterioration of climate stability. This issue presents strong implications for policy-making, notably regarding the carbon pricing strategy in terms of efficiency, equity or political acceptance. A pigouvian tax on CO₂ emissions is often presented as the simplest and most efficient policy to reduce CO₂ emissions (see the synthesis from Gillingham and Stock, 2018), although, from a welfare point of view, it could be complemented by other policies as for instance regulation and norm setting (see Stiglitz, 2019).

Yet, the economic literature reveals a lack of consensus among economists and policy-makers concerning the impacts of climate change and the appropriate policies to face this risk. Appropriate macroeconomic modelling frameworks have emerged to quantify the economic impacts of climate change, breaking down the different mechanisms at play from fossil energy use to final damage. Amongst them, the Integrated Assessment Models (IAMs), the Computable General Equilibrium (CGE) models, the Input-Output models, Agent-based models and the Macroeconometric models (for a recent overview of these models see the NGFS Technical Supplement, 2019 and Bolton et al., 2020).

The IAMs describe not only relationships between human activities and environmental processes but also between socio-economic systems and environmental systems. The most renowned IAM is Nordhaus' Dynamic Integrated Climate and Economy (DICE) model (1991, 1994, 2007, 2013, 2018). It consists of a macroeconomic module, modelling the relationship between economic activity, GHG emissions and the costs of their reduction (through an abatement curve) and a climate module, which links the rise in concentration of GHG emissions to the increase in world temperatures (that is, the climate sensitivity). Nordhaus and Yang (1996) and Nordhaus and Boyer (2000) developed the RICE, a regional version of the DICE model with different inputs endowments (in labour, capital and energy) by geographic areas. Other examples of IAMs are the models DART (Deke et al., 2001) with a general equilibrium framework and the inclusion of agricultural productivity and sea level rise, WITCH (Bosetti et al., 2006) that considers non-cooperative behaviour between different regions, MERGE (Manne et al., 1995), PAGE (Alberth & Hope, 2006) and FUND (Tol, 2005; Waldhoff et al., 2014).

On the contrary, CGE models are dynamic general equilibrium models that describe the economy as a system of monetary flows across sectors and agents, solving numerically combination of supply and demand quantities, as well as relative prices to clear the commodity and labour market simultaneously (NGFS technical Supplement, 2019). The OECD ENV-Linkages multi country by Chateau et al. (2014) is one example of a recursive dynamic neo-classical CGE model.

Our contribution proposes a fully transparent and free-access model, the Advanced Climate Change Long-term model (ACCL), with a rich and endogenous modelling of the GDP growth dynamics. This tool is based on a supply-side approach. A major blind spot of the economic literature on climate change is Total factor productivity, which is the most significant determinant of the future path of GDP, but which is sketchily presented, usually as a deterministic trend. We present here a comprehensive modelisation of TFP, including all its major drivers. Moreover,

University of Orléans, the 6th AFSE-DGT policy evaluation conference, the 69th Congress of the AFSE, the Eco-Mod2021 conference, and the 20th International Conference on Credit Risk Evaluation for their advice on the paper. We would like to warmly thank Thomas Laboureau for his preparatory work on the model. This paper does not necessarily represent the opinions of the Banque de France or the Eurosystem. This work was supported by the French National Research Agency Grant ANR-17-EURE-0020 and by the Excellence Initiative of Aix-Marseille University - A*MIDEX.

capital intensity is endogenous. Our contribution could be classified in the Macroeconometric models family. It is a user-friendly projection tool², designed with R-Shiny, which allows the user to run scenario-analysis to identify and quantify the consequences of energy price shocks on GDP. The user can change at will all the hypotheses and parameters.

In this model, we assess the long-run effects of carbon taxation on economic growth through two opposite channels. First, the negative consequences of carbon tax, or any other regulation increasing prices of CO₂-emitting energies, on GDP growth via the impact of higher energy prices on Total Factor productivity (TFP). Then, the positive economic impact of limiting climate change consequences, through the abatement of carbon dioxide (CO₂) emissions (as the increase in the prices of CO₂-emitting energies has a deterrent effect on their consumption).

To address this question, we build an original and extensive database that enables us to estimate or calibrate most of the relationships of the model (18 developed countries and seven emerging countries among the world greatest polluters, plus six regions to cover the rest of the world). We then use these empirical findings to implement-global and local projections for the whole world, decomposed in 31 countries and regions at the 2060 and 2100 horizons, allowing for user-designed scenarios of both climate change and carbon taxation.

Our results illustrate the “tragedy of the horizon” with net GDP losses induced by climate policies in the medium term, but a favourable net impact in the long term. Similarly, we can presume that international coordination is of significant importance since climate change is a global issue. A collective reduction of greenhouse gases (GHG) emissions would actually benefit a vast majority of countries. Yet, these social benefits can be neglected by national governments facing high individual costs to implement such a policy and fearing inaction by other emitters. Our simulations do show that for each country, the best individual strategy is a “Business As Usual” (BAU) one and stringent climate policies for others. Hence, the global best collective strategy would be the implementation of stringent climate policies simultaneously in all countries. This coordination problem comes from the fact that a climate policy has a detrimental impact on GDP through TFP decrease in the country which implements it, but a favourable GDP impact through lower environmental damage for all countries.

The rest of our paper is organized as follows. Section 2 describes the general framework of the ACCL tool. Section 3 presents the evaluation of the GDP before climate damage. Section 4 presents the endogenous evaluation of the global warming and of GDP damage from climate change. Section 5 proposes several climate scenarios, corresponding to business as usual country behavior or to the implementation of climate policies. Section 6 concludes.

2. Global framework for analysis

We adopt a supply-side approach and a long-term view. Indeed, at the 2060 and 2100 horizons which we chose, we take into account a production function approach to GDP, assuming full capacity utilization and full adjustment of production factors to their optimum values. Short- and

² We would like to thank, without implicating, Katheline Schubert and participants of the “Economic models and tools against climate change” TSE-Banque de France-ACPR conference, of the 2nd International Conference (EENR), University of Orléans, the 6th AFSE-DGT policy evaluation conference, the 69th Congress of the AFSE, the Eco-Mod2021 conference, and the 20th International Conference on Credit Risk Evaluation for their advice on the paper. We would like to warmly thank Thomas Laboureau for his preparatory work on the model. This paper does not necessarily represent the opinions of the Banque de France or the Eurosystem. This work was supported by the French National Research Agency Grant ANR-17-EURE-0020 and by the Excellence Initiative of Aix-Marseille University - A*MIDEX.

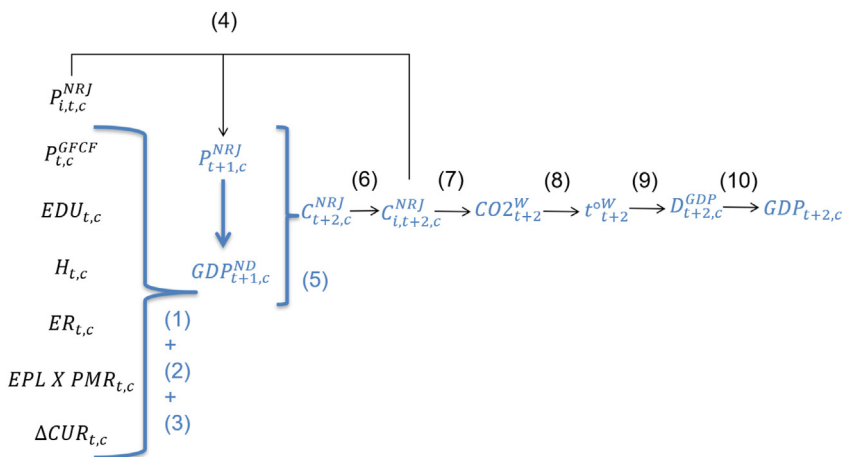


Diagram 1. Overall scheme of the projection tool.

Table 1
Main series used in the scenario tool.

Scenarios hypotheses	Results from estimated, calibrated or accounting relationships
$P_{i,t,c}^{NRJ}$: Relative energy prices	$GDP_{t,c}$ Gross Domestic Product in volume and PPP 2010
$P_{t,c}^{GFCF}$: Relative investment price	$C_{t,c}^{NRJ}$ Energy Final Consumption
$EDU_{t,c}$ Mean years of education	$CO2_{t,c}^W$ World CO ₂ emissions
$H_{t,c}$ Average hours worked per employee	$t_{t,c}^{oW}$ Increase in world temperature from pre-industrial era
$ER_{t,c}$ Employment rate	$D_{t,c}^{GDP}$ Damage to GDP from global warming in country c
$EPL * PMR_{t,c}$ Regulation index	
$\Delta CUR_{t,c}$ Change in Capacity utilization rates	

medium-term transition costs are only partly taken into account, as the consequences of climate policies are based on long-term estimates of the impact of energy prices on TFP and on energy consumption.

Diagram 1 presents the overall scheme of the projection tool. The series (cf. Table 1) defined in the scenario are in dark and resulting series are in blue. The main scenario inputs are the prices of the different types of energy relative to the GDP price. These series are meant to represent the policies that will impact the relative price of energy sources in order to curb energy consumption towards less CO₂-emitting energy types.

The other inputs are directly and mainly related to the determination of TFP, as presented in part 3.3. The resulting series stem either from estimated or calibrated relationships. GDP is based on a Cobb-Douglas production function with two factors: capital and labour. TFP is estimated based on its structural determinants as well as on relative energy prices: relationship 1 of Diagram 1 is the long-term estimates of TFP on all the series defined in the scenario mentioned above but regulations, which are used in relationship 2 as determinants of the country fixed effects estimated in relationship 1, and capacity utilization rate, which are used in short-run relationship 3. Labour is directly determined by the hypotheses on employment rates and hours worked. We endogenise the dynamics of the capital stock from the path of TFP, labour and relative investment prices. Relationship 5 relates total energy consumption to relative energy prices and GDP. The decomposition of total energy consumption into consumption of the different energy types is

based on the substitution elasticities between energy types, which are set as parameters of the scenarios (relationship 4 and 6). As energy prices influence the TFP level, our production function indirectly corresponds to one with three production factors, with an implicit substitution elasticity between energy and the other two factors not necessarily equal to one.

Consumption by energy types and by country/regions yields a path of the global CO₂ emissions (relationship 7). The relationship between the GHG stock and global temperature increase compared to the pre-industrial era (relationship 8) is calibrated on the Representative Concentration Pathway of the [IPCC \(2014\)](#). GDP damage from temperature increase is calibrated on [Nordhaus and Moffat \(2017\)](#)' meta-analysis of studies and derived at the country/region level using [OECD \(2015\)](#) estimates as a distribution key. GDP damage is assumed to be non-linearly related with temperature increases (relationship 9). We assume that GDP damage from temperature increases does not affect the energy consumption stemming from GDP, as it results from it. Indeed, this damage may appear non-linearly through time and hence may not slow down energy consumption.

Subscript i energy, t for year and c for country; series defined in the scenario in dark and resulting series in blue; estimated relationship numbers in blue and calibrated or accounting ones in dark.

Relationships 1, 2, 3 and 5 are estimated on a sub-sample of advanced countries. Estimate results are used for other countries/regions, for which no existing or sufficiently long time-series are available. This may create a bias for emerging countries, which are further from the productivity frontier and for which some coefficients may be, compared to those estimated for advanced countries, higher (e.g. education) or lower (e.g. regulations).

3. Estimating GDP before damage

3.1. Estimating GDP

The GDP evaluation is based on a supply-side model, at the country level. We assume a usual two-factor (capital and labour) Cobb-Douglas production function, with constant returns to scale, as in a large part of the literature (and for instance the DICE model from [Nordhaus, 2018](#)):

$$Q_{c,t} = TFP_{c,t} \cdot K_{c,t-1}^{\alpha} \cdot (N_{c,t} \cdot H_{c,t})^{1-\alpha} \quad (1a)$$

Where c and t variable indexes indicate for which country c and which year t the variable is considered. Q is the volume of GDP, TFP the total factor productivity, K the volume of capital installed at the end of the year, N the employment, i.e. the number of workers, and H the average number of hours worked per year and per worker. α is the elasticity of output Q to capital K and we assume constant elasticity over time for all countries with the calibration: $\alpha = 0.3$ as in other studies (see for example [Bergeaud et al., 2016](#), or [Fouré et al., 2013](#), among others).

Relation 1 can be expressed in logs and growth rate terms:

$$\Delta q_{c,t} = \Delta tfp_{c,t} + \alpha \cdot \Delta k_{c,t-1} + (1 - \alpha) \cdot (\Delta n_{c,t} + \Delta h_{c,t}) \quad (1b)$$

where x corresponds to the logarithm of the variable X ($x = \log(X)$), and Δx is the usual approximation for the growth rate of X . ($\Delta k_{c,t-1} - \Delta n_{c,t} - \Delta h_{c,t}$) is the change of the capital intensity, which corresponds to the capital deepening mechanism.

To build a scenario, for each country c , employment N and working hours H are exogenous. The quantification of the volume of capital K and of the TFP is based on specific assumptions and relations.

3.2. Estimating the capital stock

Concerning K , the volume of capital, we assume that in the long term, at the potential path, the capital coefficient (ratio of capital divided by GDP) remains constant in nominal terms (cf. [Cette et al., 2005](#)):

$$\Delta pq_{c,t} + \Delta q_{c,t} = \Delta pk_{c,t} + \Delta k_{c,t-1} \quad (2a)$$

Where P_Q is the GDP price ($pq = \log(P_Q)$) and P_K the price of investment in fixed productive capital ($pk = \log(P_K)$).

As in [Cette et al. \(2005\)](#), we observe in nominal terms in the US a notable stability in the capital coefficient over the last few decades. The stability assumption, thus, seems realistic.

From relation 2a, we obtain the relation 2b, which is used to build long-term capital scenarios:

$$\Delta k_{c,t-1} = \Delta pq_{c,t} + \Delta q_{c,t} - \Delta pk_{c,t} \quad (2b)$$

We could assume a short-term over-decommissioning of capital due to the faster capital obsolescence triggered by environmental policy implementation. Such environmental policy could make obsolete some capital components quicker than previously expected without policy. Due to this short-term capital over-decommissioning, the capital growth rate could be lower than the growth rate given by relation 2b, for some time. But in our supply approach, the appropriate level of capital would not be changed in the long-term, which means that the transitory lower capital growth rate would be followed by an equivalent transitory higher capital growth rate. For this reason, as we consider climate policy impacts at a long-term horizon, we do not consider a possible short-term impact of climate policy on the decommissioning rate.

3.3. Estimating TFP

Total factor productivity, estimated in log level, depends on several variables. We estimate in two steps the long-term relation.³

In a first step, the log of TFP is assumed to depend on the following variables:

- The log of the price of energy relative to the price of GDP. This corresponds to a substitution effect: if this relative price increases (resp. decreases), firms decrease (resp. increase) their intermediate consumption of energy and increase (resp. decrease) their use of labour and capital production factors, per unit of GDP. Everything else being equal, this corresponds to a decrease (resp. increase) of the TFP . Then, we expect a negative coefficient for this variable. Our choice of specification corresponds to that included in several models (and for instance the DICE model, see [Nordhaus, 2018](#)). An alternative could have been to specify a three-factor production function (as [Fouré et al., 2013](#), among numerous others, see this paper for a survey). Implicitly, our specification is equivalent to such a three-factor production function: the coefficient of the relative price of energy can be considered as equivalent (in absolute value) to an implicit substitution elasticity between energy and the combination of the two other factors (labour and capital). This impact on TFP, which relies on a substitution effect within the production

³ The projection tool is available online at the following address: <https://advanced-climate-change-long-term-scenario-building-model.shinyapps.io/ACCL.Projection.Tool/>

function, is estimated on past energy price hikes, which did not involve any redistribution of the proceed of the increase.

- The log of investment price relative to GDP price. This corresponds to a technical progress effect: if this relative price decreases (resp. increases), it means that the same capital value corresponds to higher (resp. smaller) volume and production capacity, which could go with technical progress implying at the same time *TFP* improvement (resp. deterioration). The underlying idea is that quality improvements in investment in terms of productive performance are at least partly incorporated into the measurement of investment prices in national accounts through hedonic or matching methods. This is mainly done for ICT since this investment benefits more than others from performance improvements (for a summary on these aspects, see [Cette et al., 2005](#)). This means that technical progress decreasing the relative investment price impacts *GDP* level and growth through two channels. First, a capital deepening channel, the same capital nominal value corresponding to a higher capital volume and then to a higher production capacity. This channel is taken into account by the previous relation 2b. Second, a *TFP* improvement channel, which is taken into account through *TFP* relation 3. Thus, we expect a negative coefficient for this relative investment price variable in the *TFP* relation, which corresponds to the second mentioned channel.
- The average years of schooling in the working age population, to take into account the contribution of education to the quality of labour input. This contribution is calibrated at a 5% return by year of schooling, estimated in [Bergeaud et al. \(2018\)](#) on the same database. This return falls within the range of estimates of “Macro-Mincer” equations such as [Barro and Lee \(2010\)](#).
- The employment rate that displays decreasing returns because less productive workers are more than others recruited (resp. fired) as the employment rate increases (resp. decreases). This impact is estimated in other studies (see [Bourlès and Cette, 2007](#) for surveys and estimates) and the related coefficient is expected to fall within the range -0.75 to -0.25 .

Thus, the estimated relation is the following:⁴

$$\begin{aligned}
 tfp_{c,t} = & -0.023^* \cdot [pen - pgdp]_{c,t-1} - 0.370^{***} \cdot [pinv - pgdp]_{c,t-1} \\
 & + 0.05 \cdot EDUC_{c,t-1} - 0.401^{***} \cdot ER_{c,t-1} + FE_c + 0.007^{***} \cdot I_{1985,t} \\
 & - 0.011^{***} \cdot I_{2012,t} + \alpha_0 + \varepsilon_{c,t}
 \end{aligned} \tag{3}$$

Where *pen*, *pgdp* and *pinv* correspond to the log of energy, *GDP* and investment price indexes, *EDUC* is the average years of schooling, *ER* is the employment rate. The indexes *c* and *t* (or *t-1*) indicate the country and the year. *FE_c* is a country fixed effect. As there is a general intercept (α_0), there is no fixed effect for one of the countries, which is here the US. $I_{T,t} = \text{Max}(0; t-T)$ are variables which allow us to take into account some possible *tfp* common trend breaks for all countries in our sample starting from different years *T*.

This relation 3 is estimated using the OLS method on a panel of 18 developed countries⁵ over the period 1980–2017.

All coefficients have the expected sign. A decrease by one percent of the relative price of energy or of investment would decrease *TFP* by, respectively, 0.02% and 0.37%. Two global TFP trend

⁴ In this equation and in the following ones, *: $p < 0.05$; **: $p < 0.01$; ***: $p < 0.001$.

⁵ A short-term error correction model (ECM) relation has been estimated, based on residuals coming from the long-term estimate. As simulations are built over a very long period (with a horizon of 2060 or 2100), this short-term relation will not be used and simulations will be based only on the long-term relation here presented.

breaks are estimated, a positive one in 1985 just at the starting point of a largely synchronised global growth recovery, and a negative one in 2012 after the financial crisis. In [Alestra et al. \(2020\)](#), several robustness tests are conducted, showing in particular limited impacts of slight changes in the dates of the *TFP* trend breaks or dropping employment rate from the explanatory variables, but more significant impact of dropping country fixed effects, which captures unobserved country characteristics, in particular in terms of technical progress.

In a second step, we estimate the impact of regulations on labour and product market on the *TFP* level. A large body of literature investigates the productivity impact of product and labour market imperfections and of the anti-competitive regulations establishing and supporting them (see [Cette et al., 2018](#), for survey). As shown in numerous papers, this impact could be large (see for instance [Cette et al., 2016, 2018](#)). Country fixed effects estimated in the previous relation capture all the factors that may structurally impact *TFP* and are not explicitly taken into account in relation (3), for instance regulation, the quality of management, corruption, etc.

The estimated relation is the following simple one:

$$FE_c = -0.108^* .REGUL_c + \beta_0 + \varepsilon_c \quad (4)$$

Where $REGUL_c$ corresponds to the chosen regulation indicator.

Several types of regulation indicators built by the OECD have been tried. As there is no time dimension in the estimates, and considering the availability period of the OECD indicators, we have used the average level of the regulation indicators over the period 1998–2013. These indicators are based on detailed information on laws, rules and market settings. The OECD product market indicators (here *PMR* for Product Market Regulations) aim to measure to what extent competition and firm choices are restricted when there is no *a priori* reason for government interference (see [Koske et al., 2015](#)). They take into account different domains, as state control or barriers to entry. The OECD *EPL* (Employment Protection Legislation) indicator aims to measure the procedures and costs involved in dismissing individual workers with regular contracts and workers on temporary contracts (see [OECD, 2013](#), for more information).

The best results have been obtained on crossed product and labour regulation indicators, which correspond to the idea of a possible complementarity between the *TFP* impacts of these two types of regulations. As expected, regulations have a negative impact on *TFP* through the estimated fixed effects. Concerning *PMR*, it focuses on barriers to trade and investment, and concerning *EPL* it takes into account only regulations on individual dismissals. Robustness tests are presented in [Alestra et al. \(2020\)](#).

4. From GDP without damage to global warming and GDP climate damage

4.1. Calculation of the total final consumption of energy

We start by estimating the relationship between the Total Final Consumption of energy (*TFC*) and the previous *GDP* and the Relative Price of Energy (*RPE*), on historical data for the most developed countries. Here, the *TFC* is considered as a proxy for energy use. Again, we chose to conduct the regression on these countries, as we need relatively long time series for the estimate, while we only need a few data points for the rest of the world on which we apply the estimated coefficients to uptake the simulations.

We thus build a panel database from 1980 to 2015 for 18 countries, using past data on the *TFC* of energy, in thousand tons of oil equivalent (*ktoe*) on a net calorific value basis, drawn from the [IEA \(International Energy Agency\) Headline Global Energy Data \(2017\)](#). We conduct the logarithmic regression detailed in the Eq. 5. Robustness checks (see [Alestra et al., 2020](#)) demonstrate that our relationship holds (the price coefficient only slightly changes) when adding a trend variable or constraining the GDP elasticity to be equal to one.

$$tfc_{c,t} = 0.965^{***} \cdot gdp_{c,t-1} - 0.670^{***} \cdot rpe_{c,t-1} + \mu_0 + \varepsilon_{c,t} \quad (5)$$

Where *tfc* is the log of the total final consumption of energy, *gdp* the log of the Gross Domestic Product, *rpe* the log of the relative prices of energy, and ε the error term, for countries (or regions) *c* and year *t*.

Corroborating our expectations, we find a positive relationship of the log of the total final consumption of energy with the log of the lagged *GDP* and a negative one with the log of the lagged relative prices of energy, both with an elasticity less than unity. Hence, an increase of the past *GDP* by 1% should raise energy final consumption by 0.97%, while a similar growth of the energy relative prices should reduce energy final consumption by 0.67%, all other things being equal. The sign and magnitude of this first coefficient are similar to what can be found in the literature, for instance [Csereklyei, Rubio-Varas and Stern \(2016\)](#). The negative elasticity of energy consumption to its price reflects efficiency gains in energy consumption due to substitution of products with high energy content to products with low energy content or energy saving technologies.

4.2. Computation of the relative price of energy

RPE is derived from the relative prices of each types of energy weighted by their respective shares in the total consumption of energy.

$$RPE_{c,t} = \sum_i [RPE_{c,i,t} \times \Omega_{c,i,t}] \text{ where } \Omega_{c,i,t} = \frac{TFC_{c,i,t}}{TFC_{c,t}}$$

Where Ω_i is the share of the energy of type *i* in the total volume of the final consumption of energy. Data on energy prices come from the [IEA Energy Prices and Taxes database, second quarter 2018](#): we chose a nominal index of total energy end-use prices (taxation included) for both industry and households, covering all types of energy, with the base year 2010. To calculate the relative prices of energy, we divide these data by the *GDP* deflator (index base 2010) from the [OECD Economic Outlook \(2018\)](#) database.

We distinguish five distinct types of energy: coal, oil, natural gas and electricity that is derived from both “dirty” (CO₂ emitting) and “clean” (non-CO₂ emitting) energy inputs.⁶ Their respective shares in the total final consumption of energy are computed using Eq. (6).

$$\Delta \Omega_{c,i,t} = \Omega_{c,i,t-1} \cdot \sum_j [\Omega_{c,j,t-1} \cdot \sigma_{i,j} \cdot (\Delta rpe_{c,j,t} - \Delta rpe_{c,i,t})] \quad (6)$$

Where Δ is the variation within the time interval considered and $\sigma_{i,j}$ the pairwise elasticities of substitution between energy types, for all the various energy sources $i \neq j$.

⁶ These countries are Australia, Austria, Belgium, Canada, Switzerland, Germany, Denmark, Spain, Finland, France, the United Kingdom, Italy, Japan, The Netherlands, New-Zealand, Portugal, Sweden, the United States.

We select estimates of the pairwise substitution elasticities between coal, oil, natural gas and electricity from [Stern’s meta-analysis \(2009\)](#), along with [Papageorgiou, Saam, and Schulte \(2017\)](#) appraisal for the elasticity of substitution between “clean” and “dirty” electricity inputs (see [Alestra et al., 2020](#) for the detailed set of elasticities). Therefore, knowing the projections of the *TFC* of energy, the past shares of each energy type in the final consumption, the substitution elasticities between energy types and the average annual growth rates of the projected relative prices of each energy type, we found the amount consumed for each energy source, until 2100, at the national and regional scales.

4.3. Converting energy consumption in CO₂ emissions

In order to consider the economic consequences of climate change, the consumption of energy is translated into global carbon dioxide emissions according to the Eq. (7):

$$CO2_t = \sum_{i,c} TFC_{i,t,c} \cdot \gamma_i \quad (7)$$

Where *CO2* is the world carbon dioxide emissions (in tonnes of CO₂) and γ_i the default emissions factors for the energy of type *i* (see [Alestra et al., 2020](#) for the detailed set of default emissions factors).

Projected emissions have thus been computed based on the past levels of total emissions from all sources adjusted by the yearly change in energy emissions, computed as the sum, across countries and energy sources, of the energy consumptions by energy types, weighted by their corresponding emissions factor. This implies that emissions stemming from non-energy sources such as animal husbandry are supposed to increase in a similar proportion as emissions from energy consumption⁷ and hence, that regulations preventing greenhouse gas emissions evolve in a similar way across sectors. Historical data on total CO₂ emissions arisen from fuel combustion, in million tons of carbon dioxide (Mt of CO₂), have been drawn from the [IEA Headline Global Energy Data \(2017\)](#). Default emission factors for fossil fuels and - both “CO₂-emitting” and “non-CO₂-emitting” - electricity have been collected from the [CoM \(Covenant of Mayors for Climate and Energy\) report \(2017\)](#).

We use a simplified carbon cycle constituted by using the Permanent Inventory Method (PIM) to model the increase of the worldwide stock of carbon dioxide by the aggregate CO₂ emissions. The flexibility of our tool offers the user the possibility to take account other climate-experts modelling of the carbon cycle.⁸ Our PIM is depicted by the accounting relation 8:

$$StockCO2_t = (1 - \rho_1) \cdot StockCO2_{t-1} + (1 - \rho_2) \cdot CO2_t - \rho_3_t \quad (8)$$

Where *StockCO2* represents the worldwide stock of carbon dioxide (in giga tonnes of CO₂), *CO2* the world carbon dioxide emissions (converted in giga tonnes of CO₂), whereas ρ_1 and ρ_2 are the coefficients of CO₂ sequestration by the carbon sinks of the planet (*i.e.*, natural or artificial reservoirs capturing atmospheric CO₂) as a fix proportion of the stock or of the emissions and ρ_3

⁷ As dirty means here CO₂ emitting, we consider the nuclear electricity production as a clean one, which could of course be contested from other dimensions.

⁸ According to FAO, total emissions from global livestock represent 14.5 percent of all anthropogenic GHG emissions, of which 80% is not related to fossil fuel consumption, and hence are not taken into account in our estimates of CO₂ emissions.

another type of possible CO₂ sequestration independent to both emissions and stock of CO₂. This parameter allows also the user of our software to introduce some non-linearity in CO₂ emissions, coming from specific shocks. For instance, the large possible CO₂ emissions from permafrost if the temperature increase exceeds some threshold. Historical data for the stock of carbon dioxide are obtained from the world cumulative 1751–2014 gigatonnes of CO₂ in [Marland et al. \(2017\)](#). It appears to be no consensus in the scientific literature on the optimal way to model carbon dioxide sequestration, as well as on the precise value of its estimate. Therefore, we offer the user the possibility to choose and modify at will the different coefficients. By default, ρ_1 and ρ_2 are null as we set a fixed amount of annual CO₂ sequestration that is equals to a third of the 2015 carbon dioxide emissions.

4.4. Translating the stock of carbon dioxide in temperature rise

We convert the resulting projections of CO₂ emissions stock in a global warming of the Earth. Literature is not consensual concerning this relation, as shown by the large surveys from [Matthews et al. \(2018\)](#) or [Hsiang and Kopp \(2018\)](#). We adopt the linear relation 9 calibrated using the RCP (Representative Concentration Pathway) 8.5 scenario ([IPCC, 2014](#)).

$$Temp_t = \eta_1 \cdot StockCO2_t \quad (9)$$

Where $Temp$ is the increase in world temperatures from the pre-industrial era (in degree Celsius) and $\eta_1 = 0.0008$.

4.5. Global and regional climate-induced GDP damage

Different types of damage can result from higher temperatures (see for instance [Hsiang and Kopp, 2018](#)). Evaluation of damage from climate change suffer from large uncertainties (see for a synthesis [Auffhammer, 2018](#)). We consider them only in their direct or indirect *GDP* dimension. Uncertainties concerning this GDP damage are here taken into account by allowing the user to change the coefficient linking temperature changes to GDP damage.

Relation 10 describes how we finally obtain the economic damage generated by climate change, defined as “the fractional loss in annual economic output at a given level of warming compared to output in the same economy with no warming” (see [Covington & Thamotheram, 2015](#)).

$$D_{c,t}^{GDP} = D_t^{GDP} \cdot \frac{\omega_c}{\omega} \quad (10)$$

With $D_t^{GDP} = \theta_1 \cdot Temp_t + \theta_2 \cdot Temp_t^2 + \theta_3 \cdot Temp_t^4$

Where D^{GDP} are the climate-induced damage as a percent of *GDP*, ω_c and ω respectively the [OECD \(2015\)](#) regional and aggregate coefficients of climate induced damage.

The world damage hence follows a fourth degree equation with the temperature rise. Following the DICE model from [Nordhaus, 2018](#), we use by default a quadratic relationship ($\theta_3 = 0$), but the user can model tipping points in the damage function through θ_3 .⁹ Our default estimates ($\theta_1 = 0.6$ and $\theta_2 = -0.6$) are based on [Nordhaus and Moffat’s survey \(2017\)](#). They reviewed 36 estimates from 27 papers and concluded, using a statistical method, that a 3 °C temperature increase (in comparison with pre-industrial levels) would diminish income (computed as a percentage of

⁹ For a comprehensive review of the carbon cycle see [Joos et al. \(2013\)](#) for [IPCC \(2014\)](#).

global aggregate *GDP* by 2.04% (+ or -2.21), while a 6 °C warming scenario would imply a reduction of *GDP* by 8.06% (+ or -2.43), with respect to a scenario without global warming. This worldwide damage is then broken down into local damages using the share of the [OECD \(2015\)](#) regional coefficients of climate-damage (ω_c) in the [OECD \(2015\)](#) aggregate coefficient of climate induced damage (ω)— both at the 2060 horizon of the OECD study-, as a distribution key.

5. Global warming scenarios

The ACCL tool allows to perform simulations of climate change scenarios. For each country and region of interest, all the economic, energy and environmental hypotheses proposed by default can be modified by the user. Baseline specifications and scenarios are systematically offered, based on the estimated relationships, as well as the parameters and series paths documented beforehand.

In the scenarios below, we consider for each type of energy the same change in relative price in all countries/regions, assuming a coordinated climate policy (but leading to different carbon taxes expressed in volume). The default values for our scenarios can be found in [Alestra et al. \(2020\)](#).

5.1. Four climate scenarios

Four analytical scenarios are simulated: no climate policy (i.e. “Business As Usual” scenario), decrease of non-CO₂-emitting energy relative price (thanks to technological progress or subsidy), and low or high carbon taxation¹⁰.

The BAU (for Business As Usual) scenario assumes no carbon taxation and so, we set the annual evolution of the relative price of each energy type to zero for the whole world from 2017 to 2100. The DREP (for Decrease of Renewable Energy relative Price) scenario is identical regarding all the different CO₂-emitting energy sources, but it displays an average annual decrease of -2% for the relative price of non-CO₂-emitting electricity in the entire world and over the whole time period. This decrease in the relative price of renewable energies may correspond to the effect of a subsidy or of technological progress, which reduces their production costs. With the LCT (for Low Carbon Tax) or HCT (for High Carbon Tax) scenarios, we introduce a climate policy that raises annually the relative price of coal, oil, natural gas and CO₂-emitting electricity by 1% for LCT and 3% for HCT, in each country/region, for the whole period. The four considered scenarios are analytical and cannot pretend to correspond to realistic ones. They help appreciating the properties of the ACCL tool and considering very contrasted climate situations.

The economic hypotheses do not depend on the chosen climate policy scenario. The reduction in the relative price of investment is the main driving force of our TFP growth, alongside the improvement in the average education level of the population. Indeed, we define by default and for all countries/regions, a convergence of the average education level towards the country, in our database, with the highest level of education (Australia with about 13 years of schooling), thus reached in 2060 and then, a stagnation for the remaining period (2061–2100). Regarding the hours worked per employee, the employment rate or the regulation index, we suppose no variation as these effects are not among the ones we want to test.

[Chart 1](#) presents the simulated World CO₂ net emissions in the four scenarios. It appears that, at the 2100 horizon, the net annual CO₂ emissions are, compared to their 2016 level, multiplied

¹⁰ A “too-little, too-late” scenario is also available online at: <https://advanced-climate-change-long-term-scenario-building-model.shinyapps.io/ACCL.Projection.Tool/>.

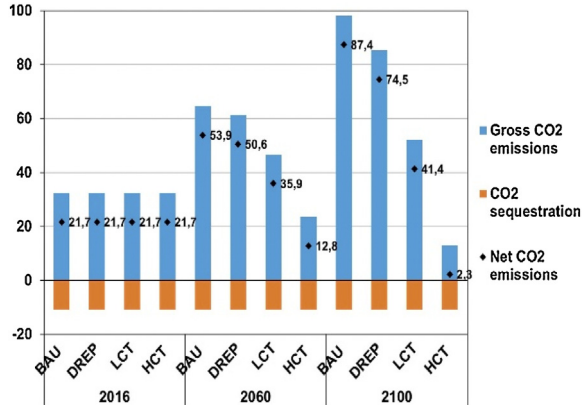


Chart 1. World CO₂ emissions (in giga tonnes of CO₂).
 Note: BAU (Business As Usual Scenario), LCT (Low Carbon Taxation Scenario), DREP (Decrease in Renewable Energy relative Price), HCT (High Carbon Taxation Scenario).

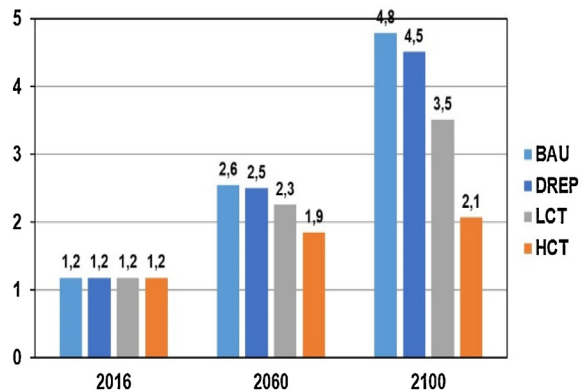


Chart 2. Global change in temperature (in °C). With respect to pre-industrial era.
 Note: BAU (Business As Usual Scenario), LCT (Low Carbon Taxation Scenario), DREP (Decrease in Renewable Energy relative Price), HCT (High Carbon Taxation Scenario).

by a factor 4 in the BAU scenario, 3.5 in the DREP scenario and 2 in the LCT scenario. Net emissions are nil in 2100 in the HCT scenario, which means that the goal of nil net emissions corresponds to very ambitious climate policies, as also emphasised by the IPCC's (2018) special report.

Chart 2 presents the global change in temperature (with respect to the pre-industrial era) of our four climate scenarios. At the 2100 horizon, the temperature increases by 4.8 °C in the BAU scenario, 4.5 °C in the DREP scenario, and 3.5 °C in the LCT scenario. The goal of an increase by 2 °C of the temperature would almost be reached in the HCT scenario, which means here again that such goal corresponds to very ambitious climate policies.

Chart 3 presents the impacts on Global GDP level of our four scenarios, compared to a situation without climate damage and climate policies. In the BAU scenario, this impact corresponds to the climate damage and, at the 2100 horizon, the GDP loss is almost 11%. In the three other

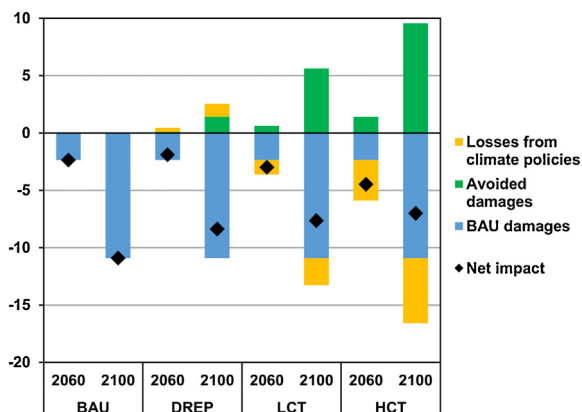


Chart 3. Impacts on Global GDP level (in % of GDP).

Note: BAU (Business As Usual Scenario), LCT (Low Carbon Taxation Scenario), DREP (Decrease in Renewable Energy relative Price), HCT (High Carbon Taxation Scenario).

scenarios, the net GDP impact corresponds to the sum of three components: the BAU damage, the TFP losses from climate policy, the avoided damage from a lower temperature increase than in the BAU scenario. In the DREP scenario, losses from climate policy are in fact gains, as energy price decreases. On the opposite, they are effective losses in the two carbon tax scenarios (LTC and HTC). Adding these three components, the net GDP impact at the 2100 horizon would be a loss of approximately 8.4% in the DREP, 7.6% in the LTC and 7% in the HCT scenario. The gap in net GDP losses between the two carbon tax scenarios is small, as the higher price increase of the CO₂ emitting energies in the HCT scenario compared to the LTC one results both in higher avoided damage and higher losses from the climate policy.

The BAU scenario and the two carbon tax scenarios illustrate what has been named the “tragedy of the horizon” by [Carney \(2015\)](#). At the 2060 horizon, the net GDP impact is more detrimental in the LCT scenario than in the BAU one, and in the HCT scenario than in the LCT or the BAU ones. Indeed, losses from climate policies are higher than the avoided damage at this horizon. At the longer 2100 horizon, on the opposite, the net GDP negative impact is lower in the LCT scenario than in the BAU one, and in the HCT scenario than in the LCT and the BAU ones, losses from climate policies being themselves lower than avoided damage. This result implies that the sign of the actual net value of intertemporal GDP impact of climate policy implementation could depend on the discount rate. For very high values of the discount rate, climate policy implementation aiming at avoiding climate GDP impact could become irrelevant. Of course, for plausible values of the discount rate, the implementation of climate policies is highly relevant.

The “tragedy of the horizon” would be lowered (but would not disappear) from an increase of the convexity of the damage relation 10. If we assume that this relation is more than quadratic ($\theta_3 < 0$) then the net GDP impact of the climate policies corresponding to scenarios LCT and HCT could become positive and not more detrimental than in the BAU scenario before the 2060 horizon.

[Chart 4](#) presents the impacts on GDP at the country/regional level of the HCT scenario compared to the BAU scenario. It appears that the countries/regions that would benefit the most from the implementation of an ambitious climate policy would be those which are the most damaged in the BAU scenario. The gain is even slightly negative (more precisely non-significant) for numer-

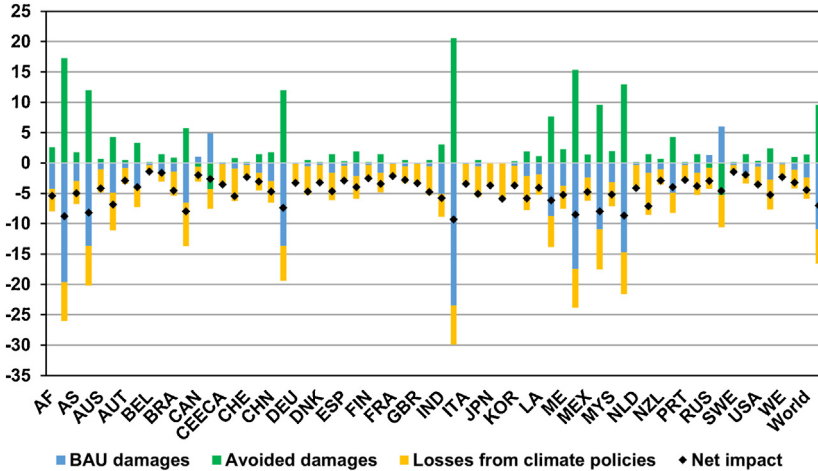


Chart 4. High Carbon Tax scenario (HCT) - Consequences on GDP (in % of GDP). For each country, first bar: 2060, second bar: 2100.

ous developed countries. This illustrates what is usually called the “tragedy of the commons”: to avoid high losses from global warming in some countries, mainly developing ones, climate policies have to be implemented in all countries and even countries where the gain from these policies could be small. It means that, in order to be efficient, climate policies need coordination and solidarity between countries.

6. Conclusion and policy implications

This paper presents a fully parametrizable tool to simulate the impact of climate change and of mitigation policies in a long-run, supply-side perspective. This tool emphasizes the effectiveness of energy price signals, which reduce the consumption of CO₂ emitting energies and, hence, could prevent major damage from climate change. As pointed by [Gillingham and Stock \(2018\)](#), a pigouvian tax on CO₂ emissions is the simplest and most efficient policy to reduce CO₂ emissions.

The proposed simulations illustrate the two tragedies of these mitigating policies. First, the “tragedy of the horizon” is reflected by the negative impact of mitigating policies in the medium run, even when accounting for the climate change damage avoided thanks to these policies. Hence, climate change requires a policy framework that adequately takes into account the long run, through a low-enough discount rate and an effective intergenerational solidarity. Second, the “tragedy of the commons” is reflected by the wide dispersion of climate change damage. Developing countries are among the most affected, while mitigating policies have to be implemented by all countries and especially by developed countries, with low climate change damage but high contribution to CO₂ emissions.

These scenarios remain optimistic, with mostly downside risks listed in the scientific literature. In particular, the relationship between CO₂ and temperature may not be linear, with several sources of tipping point, such as thawing permafrost, disruption of the thermohaline circulation, shift in El Niño–Southern Oscillation. . . On the positive side, we can mainly list potential technological improvement in CO₂ sequestration, not only at emissions but also for the existing atmospheric stock.

For all of these reasons, many environmental economists believe that contemporary values of the SCC are lower bounds of the true ones and so, that public policies are not bold enough, which our simulations fully support.

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