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# How can technology significantly contribute to climate change mitigation?<sup>1</sup>

Claire Alestra (Aix-Marseille University, CNRS, AMSE, France), Gilbert Cette (NEOMA Business School, France), Valérie Chouard (Banque de France, France), Rémy Lecat\* (Banque de France, France)<sup>2</sup>

## Abstract

This paper highlights how technology can contribute to reaching the 2015 Paris Agreement goals of net zero carbon dioxide (CO<sub>2</sub>) emissions and global warming below 2°C in 2100. It uses the Advanced Climate Change Long-term model (ACCL), particularly adapted to quantify the consequences of energy price and technology shocks on CO<sub>2</sub> emissions, temperature, climate damage and Gross Domestic Product (GDP). The simulations show that without climate policies the warming may be +5°C in 2100, with considerable climate damage. An acceleration in 'usual' technical progress -not targeted at reducing CO<sub>2</sub>- even worsens global warming and climate damage. According to our estimates, the world does not achieve climate goals in 2100 without 'green' technologies. Intervening only via energy prices, e.g. a carbon tax, requires challenging hypotheses of international coordination and price increase for polluting energies. We assess a multi-lever climate strategy combining energy efficiency gains, carbon sequestration, and a decrease of 3% per year in the relative price of 'clean' electricity with a 1 to 1.5% annual rise in the relative price of polluting energy sources. None of these components alone is sufficient to reach climate objectives. Our last and most important finding is that our composite scenario achieves the climate goals.

**JEL codes:** H23, Q54, E23, E37, O11, O47, O57, Q43, Q48

**Keywords:** Climate, Global warming, Technology, Environmental policy, Growth, Long-term projections

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## Introduction

According to the Intergovernmental Panel on Climate Change (IPCC, 2022a) or the International Energy Agency (IEA, 2021) scenarios, technologies must be an important part of the mix to reach net zero greenhouse gas (GHG) emissions and limit climate warming: *'technology and technological change offer the main possibilities for reducing future emissions and achieving the eventual stabilization of atmospheric concentrations of GHGs'* (IPCC, 2007). The role of technologies relies on future innovations, but also requires their diffusion and the diffusion of past innovations. Indeed, for some technologies (for example Direct Air Carbon Capture), future innovations are expected to occur, while there may be other innovations in yet unforeseen directions (radical innovations). Obtaining the gains in terms of CO<sub>2</sub> (carbon dioxide) emissions from these technologies requires investing in the 'clean' energy infrastructure and the physical equipment that embeds them. Yet, the stock of underutilised past CO<sub>2</sub>-saving innovations is still considerable, for example in the building sector to reduce heating needs.

Energy efficiency gains entail a reduction in the utilisation of energy in power units per GDP (Gross Domestic Product) in volume. There have been significant energy efficiency gains in past decades (IPCC, 2022a), although not in the past century, as the least efficient applications have sharply increased their share, even though all individual applications have become more efficient (Ayres *et al.*, 2005). There are considerable potential gains from energy efficiency, just by adopting existing more efficient technologies: adoption of the best available technologies can avoid about 20% of the projected energy consumption and 1.5 Gt of carbon dioxide emissions by 2030 (Letschert *et al.*, 2013). One phenomenon, called the Khazzoom-Brookes postulate, may reduce the gains in terms of CO<sub>2</sub> emission from energy efficiency (cf. section 3 for a detailed analysis of this postulate).

Carbon capture, utilisation and storage technologies (CCUS) are used for various purposes, especially making more productive the extraction process, and for carbon storage, mostly in oil or gas fields. Some of these technologies are mature and already in use (cf. Sleipner oil field in Norway), while some others are at an early stage of development (Direct Air Carbon Capture, for example). Innovations in that field will be crucial for reducing of the carbon stock: the contribution is about 50% higher in the case of learning, resulting in cumulative sequestration of CO<sub>2</sub> ranging from 150 to 250 billion tons of carbon during the 21st century (Riahi *et al.*, 2004). These technologies remain a valuable option even with CO<sub>2</sub> leakage of a few percent per year, well above the maximum seepage rates that are likely from a geo-scientific point of view (van der Zwaan & Gerlagh, 2008).

Renewable energy deployment is another essential lever to limit climate change and enable sustainable development. According to the International Renewable Energy Agency (IRENA, 2022), a faster energy transition is key to reaching these goals while ensuring the stability of energy prices and supply. The report urges to diversify the current energy system, heavily reliant on fossil fuels, at a time when countries that are net importers of energy encompass 80% of the world population, and when the Ukraine crisis increases oil and gas prices. The IRENA (2022) gives a roadmap of the energy transition steps for the world to comply by 2030 with the global warming objective of 1.5°C maximum in the long run. This transformation implies electrifying end-use sectors boosting both the renewable power generation and direct usage of renewable energy in end-use sectors, developing 'clean' hydrogen (from 0.5GW in 2019 to 350 GW in 2030) and sustainable bioenergy coupled with CCUS (multiplied by three in 2030 compared to 2019). Such advances require Technological Progress (TP), targeted investments and policies like carbon pricing. Yet, for most countries, renewable power is already the less costly alternative.

This article quantifies the necessary contribution of technologies to reduce CO<sub>2</sub> emission and limit the damages from climate change, taking as a goal the declared objectives of the COP21 (2015 United Nations Climate Change Conference). In our knowledge, it is the first to use for that purpose a

model with a comprehensive endogenous modelling of Total Factor Productivity (TFP) dynamics, GDP growth and differentiation of multiple energy sources, particularly adapted to assess the consequences of energy price shocks and technological improvements on CO<sub>2</sub> emissions, temperature changes, climate damage and GDP. Hence, it provides an accurate and transparent estimation of the contribution of 'green' technologies to the energy transition and climate mitigation mechanisms. This paper also offers a global and long-term perspective, helpful for policy decisions, by contrasting the outcomes of scenarios with different 'usual' and 'green' technologies implemented individually and simultaneously until 2100. Indeed, it uses the Advanced Climate Change Long-term model (ACCL) by Alestra *et al.* (2022)<sup>3</sup>, exploiting an original and extensive database that distinguishes five types of energy, four 'dirty' in terms of CO<sub>2</sub> emissions (coal, petrol, gas, 'dirty' electricity) and 'clean' electricity. We consider three 'green' technologies: energy efficiency gains, carbon capture and a decrease in the relative price of 'clean' energy. This last component can correspond to the result of innovation or a tax/subsidy-oriented policy.

A first result of our simulations is that without climate policies, which correspond to a 'business as usual' (BAU) scenario, the warming may be almost +5°C in 2100, with major climate damage, particularly in India, China or Africa. And this evaluation may be considered optimistic, as it assumes no tipping points which can amplify the warming and consequently the damages. A second result is that 'usual' TP without impact on GHG intensity worsens the evolution of temperature and climate damage. A third result is that without technological changes that avoid CO<sub>2</sub> emissions, climatic goals cannot be reached at the end of the century. To intervene only through the relative price between the different types of energy, by increasing the relative price for the four 'dirty' types of energy, for instance by implementing a carbon tax, requires challenging hypotheses concerning the price increase of 'dirty' energy to reach the climatic goals. Energy price policies are useful but only as part of a more global climate strategy.

Technological support is essential for reaching climatic goals. According to our estimates, each of the three technology components, at the maximum of what the literature considers realistic, is not enough to reach these goals. We evaluate a mixed strategy, combining the four different types of policies together. The mix adds energy efficiency gains, carbon sequestration, a decrease of 3% per year in the relative price of non-carbon-emitting electricity to an increase of 1% per year of the relative price of the four 'dirty' types of energy. The fourth and most important result of our analysis is that the mixed scenario reaches the climatic goals according to our estimates: at the end of the century, global temperature will have increased by about 1.7°C. In this scenario, the carbon tax is helpful not only as it contributes directly to reaching the climate goals, but also to generate financial resources to finance the decrease in the relative price in 'clean' energy and the costs of energy efficiency gains and gas sequestration technologies. This fourth result is probably the most important one and, to our knowledge, appears original in the climate economic literature. It indicates through realistic simulations that ambitious climate policies mixing technological and price dimensions reach the COP21 goal of net zero CO<sub>2</sub> emissions and global warming below 2°C at the end of the current century. Yet, all countries must implement such policies as soon as possible, which is challenging.

Section 1 describes our data and ACCL model; sections 2 and 3 present and discuss estimation results of our scenarios without and with 'green' technologies, respectively.

## **1. Data and econometric model**

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<sup>3</sup> The projection tool is available online at the following address: [https://advanced-climate-change-long-term-scenario-building-model.shinyapps.io/ACCL\\_Projection\\_Tool/](https://advanced-climate-change-long-term-scenario-building-model.shinyapps.io/ACCL_Projection_Tool/)

The ACCL model is a fully transparent and free-access model, with a rich and endogenous modelling of the GDP growth dynamics. It is a user-friendly projection tool, which allows the user to run scenario-analysis to identify and quantify the consequences of energy price shocks and of technology improvements on GDP. The user can change at will all hypotheses and parameters.

### **1.1. Global framework for analysis**

The ACCL model assesses the long-run GDP effects of changes in energy prices or technologies on economic growth through two opposite channels. First, the impact on GDP growth via the impact on TFP. Then, the impact of limiting physical damage from climate change on GDP, through the abatement of CO<sub>2</sub> emissions.

ACCL uses an original and extensive database that enables 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). ACCL allows to implement global and local projections for the whole world at the 2060 and 2100 horizons.

The ACCL model adopts a supply-side approach and a long-term view. It opts for a production function approach to GDP, assuming full capacity utilisation and full adjustment of production factors to their optimum values. Short- and medium-term transition costs are only partly considered, as the consequences of climate policies are based on long-term estimates.

### **1.2. GDP before damage**

For each country, GDP is based on a Cobb-Douglas production function with two factors - capital, labour - and constant returns to scale, as in a large part of the literature (for instance the DICE model from Nordhaus, 2018). Labour (employment and working hours) is exogenous. Concerning the volume of capital, ACCL assumes that, in the long term, at the potential path, the capital coefficient (ratio of capital divided by GDP) remains constant in nominal terms (cf. Certe, Kocoglu and Mairesse, 2005).

TFP is estimated based on its structural determinants and so, depends on:

- i) The price of energy, relative to the price of GDP, which corresponds to a substitution effect. If this relative price increases, firms decrease their intermediate consumption of energy and increase their use of labour and capital production factors, per unit of GDP. Everything else being equal, this corresponds to a decrease in the TFP. This specification corresponds to that included in several models (for instance the DICE model, see Nordhaus, 2018).
- ii) The investment price relative to GDP price which corresponds to a TP effect. If this relative price decreases, it means that the same capital value corresponds to higher volume and production capacity, which is consistent with TP and implies a TFP improvement.
- iii) The average years of schooling in the working age population, to consider the contribution of education to the quality of labour input.
- iv) The employment rate which displays decreasing returns because less productive workers are more recruited (resp. fired) than others as the employment rate increases (resp. decreases).
- v) Regulations on labour and product market.

### 1.3. Energy consumption, global warming and GDP climate damage

In ACCL, the Total Final Consumption of energy (TFC) depends on past GDP and the relative price of energy. From estimated results, an increase in the past GDP of 1% raises energy TFC by 0.97%, while a similar growth of the energy relative prices reduces energy TFC 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, del Mar Rubio-Varas & Stern (2016). The negative elasticity of energy consumption to its price reflects efficiency gains in energy consumption due to the substitution of products with high energy content for products with low energy content or energy-saving technologies.

ACCL distinguishes five distinct types of energy: coal, oil, natural gas and electricity that is derived from both 'dirty' (CO<sub>2</sub> emitting) and 'clean' (non- CO<sub>2</sub> emitting) energy inputs.<sup>4</sup> Their respective shares in the TFC of energy are computed using substitution elasticities between each couple of energy types. The pairwise substitution elasticities between coal, oil, natural gas and electricity are selected from David Stern's meta-analysis (2009), along with Papageorgiou *et al.* (2017) appraisal for the elasticity of substitution between 'clean' and 'dirty' electricity inputs (see Alestra *et al.*, 2020, for the detailed set of elasticities).

In order to consider the economic consequences of climate change, the consumption of energy is for each country translated into global CO<sub>2</sub> emissions. ACCL uses a simplified carbon cycle constituted by using a Permanent Inventory Method (PIM) to evaluate the increase in the worldwide stock of carbon dioxide by the aggregate CO<sub>2</sub> emissions. CO<sub>2</sub> sequestration by the carbon sinks of the planet (*i.e.*, natural or artificial reservoirs capturing atmospheric CO<sub>2</sub>) can be considered as a fixed proportion of the stock or of the emissions or as a fixed volume of CO<sub>2</sub> independent from emissions or stock of CO<sub>2</sub>. This allows ACCL users to introduce some non-linearity in CO<sub>2</sub> emissions, coming from specific shocks. There 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, ACCL offers the user the possibility to choose and modify at will the different coefficients. Our baseline hypothesis is to have an absorption capacity fixed at a volume corresponding to a third of the 2015 CO<sub>2</sub> emissions.

ACCL converts the resulting projections of CO<sub>2</sub> 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 & Kopp (2018). ACCL adopts a linear relation calibrated using the Representative Concentration Pathway 8.5 (IPCC, 2014).

Different types of damage can result from higher temperatures (see for instance Hsiang & Kopp, 2018). Evaluation of damage from climate change suffers from large uncertainties (see for a synthesis Auffhammer, 2018). ACCL considers them only in their direct or indirect GDP dimension. Uncertainties concerning this GDP damage are here accounted for by allowing the user to change the coefficient linking temperature changes to GDP damage. The world damage hence follows a quadratic relationship with the temperature rise, whose parameters are based on Nordhaus & Moffat's survey (2017). This worldwide damage is then broken down into local damages using the share of the OECD (2015) regional coefficients of climate-damage as a distribution key.

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<sup>4</sup> Here, 'dirty' means CO<sub>2</sub> emitting, so ACCL considers the nuclear electricity production as clean, which can of course be contested from other dimensions.

## 2. Estimation results of scenarios without 'green' technologies

### 2.1. Business-as-usual Scenario

The BAU scenario assumes no additional climate policy compared to the 2015 Paris Agreement situation, keeping prices of each energy type relative to the GDP price stable for the whole world from 2017 to 2100. The BAU scenario simulated with ACCL forecasts, at the 2100 horizon, a multiplication of the world net annual CO<sub>2</sub> emissions by a factor of four compared to their 2016 level. The global temperature rises by 4.8°C (with respect to the pre-industrial era), and climate damages correspond at the world level to a GDP loss slightly superior to 9%.

In this simulation, we assume no emergence of any tipping points, i.e. of stages where the environment cannot cope with the level of temperature increase and jumps to another state, with accelerating emissions and temperatures. Damages are higher in the case of tipping points. Dietz *et al.* (2021) wrote a literature review covering 52 papers and considering eight types of tipping points. In their main specification, the eight climate tipping points collectively increase the social cost of carbon (SCC) by about 25%. If we assume a homothetic distribution of the GDP losses over time, this means, from our BAU simulation with the ACCL model, a loss, at the world level, of about 12%.

Evaluations of a BAU scenario suffer from considerable uncertainties on all types of parameters. IPCC reports show that most of these uncertainties appear to be negative (evaluations under-evaluate climate consequences of human activities).<sup>5</sup> Tipping points correspond to one large dimension of such negative uncertainties. Hereafter, we will not consider tipping points any longer. But we have nevertheless to keep in mind that reality can be worse than what we describe.

### 2.2. 'Usual' technological progress scenario

Can 'usual' TP - without impact on GHG intensity of growth - contribute to curbing global warming? In the ACCL model, 'usual' TP impacts GDP growth in a classical way through two channels: the growth rate of TFP and the growth rate of the capital-over-labour ratio (capital deepening).<sup>6</sup> The capital deepening effect stems from the fact that the quality-adjusted price of capital equipment decreases as technology advances. These two channels are related to the investment price relative to the GDP price.<sup>7</sup> We simulate with ACCL the impact of a faster constant decrease in the investment relative price from 2017 to 2100, assumed identical in all countries and areas. We have calibrated this faster decrease to be -0.5 percentage point per year, this value corresponding to changes observed in the US during several subperiods of the XX<sup>th</sup> century (see US national account evaluation). From this 'usual' TP improvement, the global GDP increases by 34% in 2100, the two channels (TFP and capital deepening) each contributing to almost half of this increase. But as this higher GDP is associated with unchanged energy intensity, GHG emissions increase by nearly the same proportion. In consequence, compared to the BAU scenario, the temperature increases by 1.1°C in 2100. This simulation illustrates that 'usual' TP is not a solution to diminish global warming.

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<sup>5</sup> See for instance IPCC (2022a).

<sup>6</sup> Another channel is the growth of human capital, considered explicitly in ACCL. To simplify, we abstract here about this as an improvement of human capital has exactly the same type of impact as the one described concerning a decrease in the investment relative price.

<sup>7</sup> For more details concerning these relative price changes and their impact on growth through the two channels (TFP and capital deepening), see, for instance, among abundant literature, Bergeaud, Cette & Lecat (2018).

To fight against global warming, TP must be oriented and explicitly related to the goal of a decline in the stock of GHG.

### **2.3. Carbon tax scenarios**

We simulate an analytical scenario to evaluate the efforts needed without technological support to achieve the less than +2°C goal in 2100. This scenario corresponds implicitly to high carbon taxation (HCT), implemented from 2017 onwards and simultaneously in all countries.<sup>8</sup> It assumes an increase in the relative price of each of the four types of ‘dirty’ energy by 3% per year. The relative price of the ‘clean’ energy type is assumed to stay stable over the period in all countries. It implies that the relative prices of the four ‘dirty’ energy types are multiplied by a factor of 11 at the 2100 horizon. And that this climate policy is perfectly coordinated in all countries. This HCT scenario must be considered analytical and cannot pretend to correspond to a realistic one.

It appears that, in this HCT scenario, at the 2100 horizon, the annual net CO<sub>2</sub> emissions are nil, implying that such a goal of nil net emissions corresponds to very ambitious climate policies, as also emphasised by the IPCC (2022b) reports. In 2100, the HCT scenario also fulfils the objective of a maximum temperature increase of 2°C, corresponding again to very stringent political measures. Moreover, the net 2100 GDP impact is a loss of 1.5%, as opposed to a loss of 9% in the BAU scenario.

These results show that, without technological support, only scenarios with challenging assumptions like perfect coordination among countries in the immediate implementation of very ambitious climate policies, can reach the goal of an increase of less than 2°C of the temperature in 2100 with limited climate damages. It means that we need help from climate technology innovation to reach this 2°C goal.

In what follows, we will consider as the baseline scenario a worldwide low carbon tax (LCT), on top of which different types of technological innovation will be implemented. All countries implement the LCT scenario from 2017 onwards simultaneously. It assumes an increase in the relative price of each of the four ‘dirty’ energy types by 1% per year and a stability of the relative price of the ‘clean’ energy type, over the whole period and in all countries. These hypotheses mean that in this LCT scenario, the relative prices of the four ‘dirty’ energy sources are multiplied by a factor of 2.25 at the 2100 horizon. This LCT scenario has also to be considered analytical. At the same time, the relative price increase of the four ‘dirty’ types of energy appears modest in this LCT scenario compared to the one in the HCT scenario, which is more realistic regarding consumer supportability and public acceptance. To facilitate this acceptance, and as advised, for instance, by Stiglitz (2019) among others, receipts from this carbon tax can be transferred to the low-income part of the population to neutralise the anti-redistributive impact of the tax. They can also be used to finance renewable energies subvention.

### **3. ‘Green’ technology scenarios estimation results**

We consider three ‘green’ technological changes: energy efficiency gains, CCUS technologies and increased use of non-CO<sub>2</sub> emitting energies. We believe that the scenarios corresponding to these three technological changes can only be slightly concerned by the Khazzoom-Brookes postulate, also known as the Jevons paradox. This Khazzoom-Brookes postulate, described for instance in Khazzoom

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<sup>8</sup> This scenario, as the following LCT one, are detailed and already commented in ACCL (Alestra *et al.*, 2022) in which the reader can find more details.



(1980, 1987 and 1989), explains that increased efficiency in the use of some energy types (here 'dirty' ones) at the micro level can lead to higher demand for these energy types at the macro level. The price signal concerning 'dirty' and 'clean' energy types is clearly present in our simulations and no 'dirty' energy relative price declines. Consequently, we have no demand increase for these 'dirty' energy types from decreasing prices. The demand/price elasticity used in the model is econometrically estimated and accounts for all existing channels of the impact of energy price changes on energy demand implicitly at the macro level. Even more, in our mixed scenario - the only one reaching climate goals - we include the hypothesis of a higher 'usual' TP through an increase by 0.5% per year of the TFP to make it more exigent. Indeed, this higher 'usual' TP increases growth and energy demand. This hypothesis can partly correspond to the result of a slight Khazzoom-Brookes effect, if this effect appears here, which we believe is not necessarily the case.

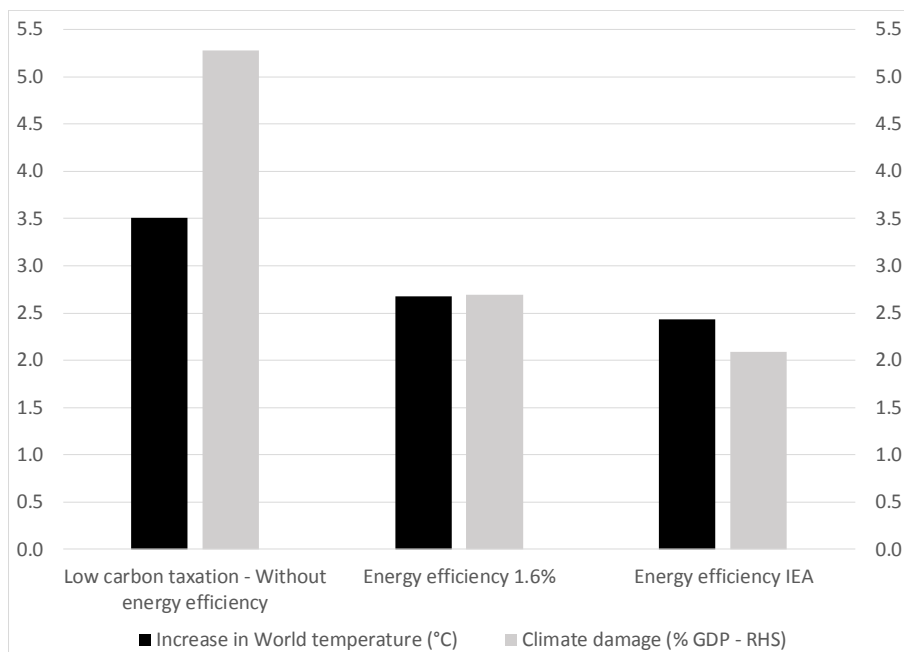
### **3.1. Energy efficiency gain scenarios**

Energy efficiency gains correspond to the decrease in the ratio of energy utilisation (in power units, e.g. MJ) to GDP in volume. Since the oil shock, advanced economies recorded energy efficiency gains, which reached 1.6% per year in the 2010s (IEA, 2021). These gains are based on innovation targeted at reducing the use of energy inputs but also on the diffusion of existing technologies and basic quality improvement. In particular, the renovation of existing buildings is the first source of energy efficiency gains in the IEA scenario before gains in transport and industry.

Energy efficiency gains can accelerate with the implementation of a carbon tax or regulations. The increase in the energy price provides incentives to invest in energy-saving innovation or renovation. Regulations already contribute significantly to energy efficiency gains with the gradual withdrawal of energy-intensive appliances or the thermal insulation of buildings.

We implement two energy efficiency gain profiles. First, a trend of gains of 1.6% per year, corresponding to the trend observed in the recent past. Second, we use the IEA (2021) energy efficiency scenario profile, which frontloads energy efficiency gains in the 2020s, as simple measures can be very quickly implemented (diffusion of energy-efficient appliances, buildings renovation...). Once these low-hanging fruits are picked up, energy efficiency gains slow down. Hence, energy efficiency gains reach 4.2% per year in the 2020s and slow down to 2.7% from 2030 to 2050. Afterwards, we return to the previous energy efficiency trend of 1.6% per year. The implementation of a carbon tax or appropriate regulations is necessary to make this latter scenario happen, as higher energy prices for the consumer are fostering investment in more energy-efficient technologies.

**Graph 1: 2100 increase in world temperature and climate damage in LCT scenario with or without faster energy efficiency gains**



Left-hand scale in °C for the increase in world temperature and right-hand scale in % of GDP for climate damage.

According to the ACCL model results (Graph 1), none of these two scenarios is sufficient to reach the less than 2°C goal in 2100. World climate damages are significantly reduced between 2% and 3% of GDP, but with a significant dispersion, as some countries and regions such as India and Africa are experiencing damages above 5%. Finally, net-zero emission are not reached in both scenarios in 2100, and global warming continues. In the 1.6% scenario, net emissions are stabilised close to 2016's level: the impact of GDP growth offsets the impact on net emissions of both the increase in CO<sub>2</sub>-emitting energy prices and the trend in energy efficiency gains. In the IEA scenario, which requires the implementation of a significant carbon tax or regulation, net emissions in 2100 are 14 Gt CO<sub>2</sub>, declining compared to 2016 but still positive.

### 3.2. Carbon capture, utilisation and storage technologies scenarios

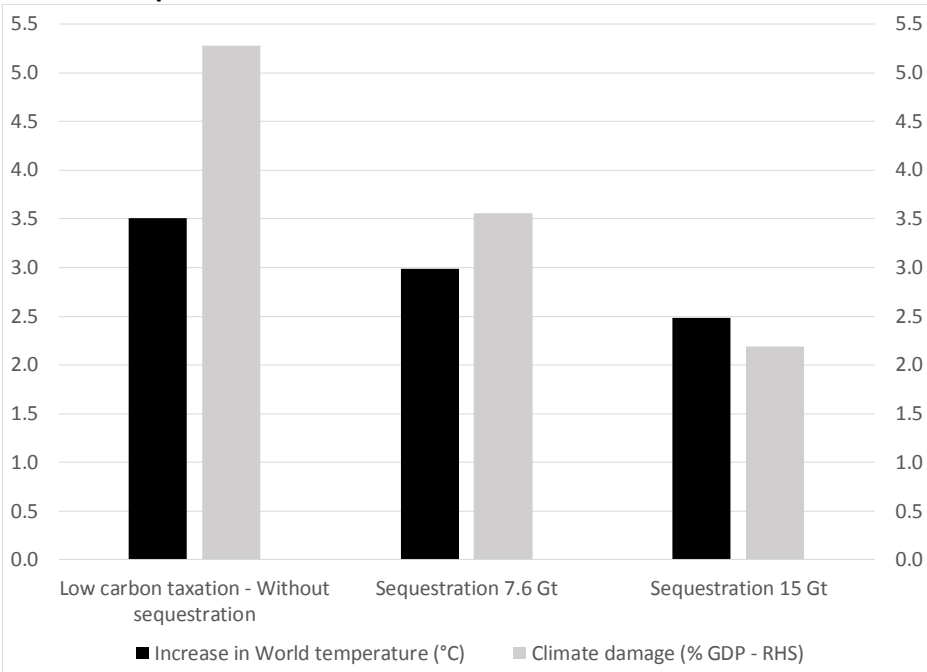
CCUS technologies which are currently mature are used for CO<sub>2</sub> capture at emission from large industrial facilities. They are particularly relevant for electricity generation, steel or cement production and natural gas treatment. The process involves first the capture of CO<sub>2</sub> by separating it from other gases. Three methods exist: post-combustion captures 80-95% of emitted CO<sub>2</sub>, it is the most mature technology and it can be easily adapted to existing facilities; pre-combustion captures a similar share of emitted CO<sub>2</sub> but it requires changes to the existing facilities; oxy-fuel combustion is the least mature technology, it requires producing pure O<sub>2</sub>, which is costly but leads to 95-99% capture. The CO<sub>2</sub> needs then to be transported and stored in gas, oil field or saline formation. It can be injected into the ocean or treated by mineral carbonation. It can also be used to enhance oil recovery by injecting it into the oil field, allowing to recover more oil than by natural production. CCUS technologies can be applied to biofuel energy production (Bioenergy with carbon capture and storage - BECCS). Direct air carbon capture and storage technologies (DACCS) comprise several distinct technologies to remove dilute CO<sub>2</sub> from the surrounding atmosphere; many materials and processes are under investigation but are far from being operational.

CCUS are energy-intensive and costly technologies, which is why they did not develop although they could have been implemented for decades. Substantial uncertainties remain on the future course of these costs, especially for the most recent technologies. Projections of CCUS use in 2050 net-zero scenarios are 15 Gt CO<sub>2</sub> per year for the median of IPCC scenarios and 7.6 Gt CO<sub>2</sub> for the IEA (2021)

scenario. A CO<sub>2</sub> price is needed to set the proper incentive to implement these technologies: higher energy prices decrease energy consumption, but increase energy producers' benefits without providing any incentive for them to bear the cost of these investments, contrary to a tax related to CO<sub>2</sub> emissions.

In the LCT scenario, estimates using the ACCL model for sequestration on the scale of the IPCC and IEA scenarios are not sufficient to reduce temperature increase below 2°C in 2100 (cf. graph 2). As the relationship between GDP damages and temperature is non-linear, world climate damages are significantly reduced, but not in all regions: damages in India, in Africa or in the Middle East are still highly significant, above 5% in the IEA scenario. Net zero CO<sub>2</sub> emissions are not reached, even in 2100. Finally, as energy prices increase only at a 1% a year pace, carbon taxation remains too low in many areas to trigger the investment necessary to reach carbon sequestration at the level envisaged in the IPCC and IEA scenarios.

**Graph 2: 2100 increase in world temperature and climate damage in LCT scenario with or without technological carbon sequestration**



Left-hand scale in °C for the increase in world temperature and right-hand scale in % of GDP for climate damage.

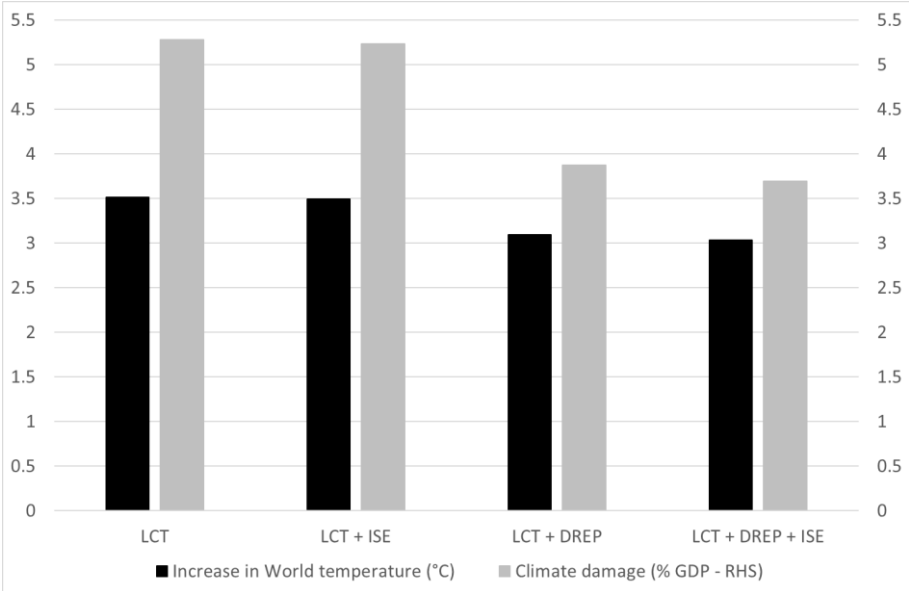
**3.3. Increased use of non-CO<sub>2</sub> emitting energies**

According to the IRENA (2021), renewable technologies are increasingly competitive. Depending on renewable sources, the electricity cost dropped from 48% (offshore wind) to 85% (utility-scale solar photovoltaics) between 2010 and 2020. In 2020, despite the pandemics, the cost reduction persisted and ranged from 16% for concentrating solar power to 7% for utility-scale solar photovoltaics yearly. For Way *et al.* (2021), this drop is in line with past trends as they show that for several decades the costs of solar photovoltaics, wind, and batteries have dropped (roughly) exponentially at a rate near 10% per year. According to the authors, future energy system costs will be determined by a combination of technologies that produce, store and distribute energy. Their costs and deployment will change with time due to innovation, economic competition, public policy, concerns about climate change and other factors.

The electricity costs of all renewable technologies are now comparable to those of new generation capacity from fossil fuels. Raising awareness about climate change, potential innovations such as renewable hydrogen, modern biomass or improved storage capacities and the redirection of public subsidies towards cleaner power generation may foster this improvement in renewable feasibility and affordability in the future.

Three scenarios are added to our LCT carbon tax scenario: ISE (Increased Substitution Elasticity), DREP (Decrease in Renewable Energy relative Price) and a combination of the two. The ISE scenario implies a global rise in the elasticity of substitution between CO<sub>2</sub> and non-CO<sub>2</sub> emitting electricity from 2 to 2.5. We calibrate both values according to the range of substitution elasticities given by Papageorgiou *et al.* (2017). This level of elasticities corresponds to a better provision of ‘clean’ electricity, facilitated by increased storage capacities of renewable power, for example. The DREP scenario represents a 3% annual reduction of the price of non-carbon-emitting electricity relative to the GDP price on the world scale. This relative price is divided by about 13, which is approximately a 92% decrease over the whole period. It can reflect public subsidies towards renewable energy sectors, but we focus on the case of TP diminishing their production costs and so their price.

**Graph 3: 2100 increase in world temperature and climate damage in LCT scenario with increased substitution between electricity sources and decreased price of ‘clean’ electricity**



Note: Left-hand scale in °C for the increase in world temperature and right-hand scale in % of GDP for climate damage.

Graph 3 shows that simulations adding the increased substitution elasticity between CO<sub>2</sub> and non-CO<sub>2</sub> emitting electricity to the LCT scenario only has a tiny impact on restricting the global temperature increase (+3.5°C compared to the pre-industrial era) or the climate damage (-5.2% of GDP) at the end of the century. This result can be explained by the limited increase in substitution elasticity in the scenario due to an already relatively high value – although consistent with the literature – of this elasticity in the baseline scenario. Indeed, we do not alter the substitution coefficient between coal and natural gas, for example, while natural gas has a lower emission factor than coal. On the contrary, combining LCT and the decrease in the relative price of ‘clean’ electricity diminishes global warming (+3.1°C) and its adverse consequences on the world GDP more significantly (-3.9% of GDP). The best-case scenario is the combination of carbon taxation on polluting energy sources and TP making renewable power both cheaper and more feasible. Yet, we find that such a scenario is not enough to achieve the COP21 goals as global temperatures still rise by 3°C, and the climate damage decreases the world GDP by almost 3.7% in 2100. We also notice

synergy between DREP and ISE settings when combined (and still added to LCT) as their total impact is higher than the sum of their effects independently.

### 3.4. Composite scenarios

Our previous results show that a single-lever strategy is not enough to limit global warming below 1.5 or 2°C. Hence, to reach this climate goal, governments must consider implementing multiple strategies simultaneously to limit energy consumption, encourage substitution towards less polluting energy sources and reduce GHG emissions. The policy toolbox at their disposal contains (but is not limited to) taxing carbon, providing incentives or issuing regulations to support energy efficiency, CO<sub>2</sub> sequestration and the expansion of renewable technologies.

The IPCC (2022b) develops five illustrative mitigation pathways to reach the COP21 temperature target. These mitigation options encompass renewables resort, CCUS, technological enhancement, energy efficiency, low resource demand and sustainable resource management. The IPCC recommends international cooperation and coordination. The report also highlights the crucial role of policy design in tackling trade-offs and synergies between these mitigation measures and accounting for the national context (technological, environmental, institutional, socio-economic and cultural conditions).

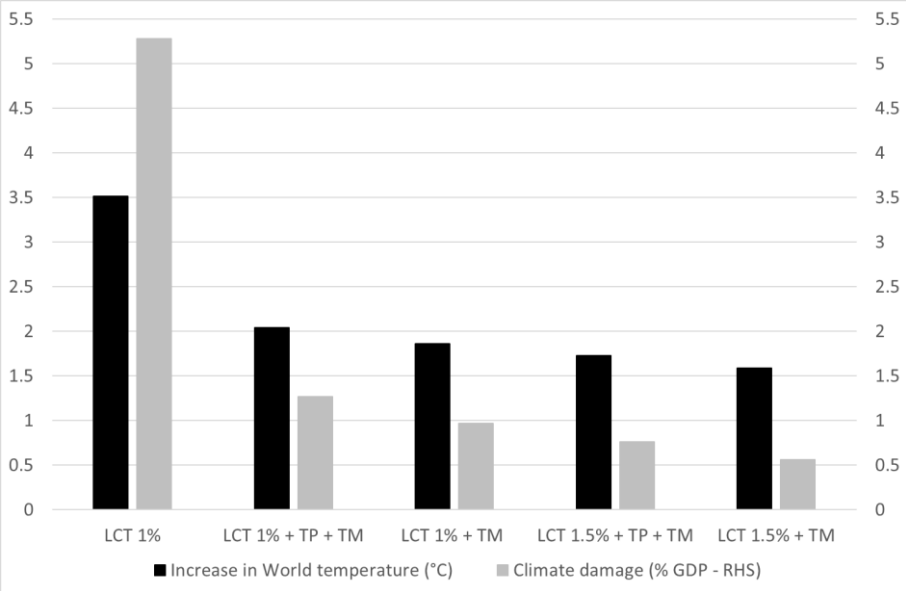
We consider four composite scenarios combining our LCT scenario, the global rise of the relative price of CO<sub>2</sub>-emitting energy sources by 1 or 1.5% a year for the whole period, with either or both the 'usual' TP and a 'green' technology package. On the one hand, the 'usual' TP hypothesis represents a technological shock that is not specifically oriented toward climate goals. We assume a 0.5 percentage point constant decrease in the investment relative price from 2017 to 2100 in all countries and areas. On the other hand, the 'green' Technology Mix (TM) is a combination of the different technological hypotheses presented in section 3, which are directly oriented toward the objective of a decline in the stock of GHG. We keep our calibration based on IEA (2021) for the energy efficiency gains of 1.6% per year and the CO<sub>2</sub> sequestration through CCUS technologies of 7.6 Gt a year, and our decrease in the relative price of non-carbon-emitting electricity by 3% a year (all of them assumed identical for the entire world and time span). We do not include the ISE scenario as it has little effect on our outcomes. The user can simulate alternative specifications using our projection tool.

Graph 4 summarises the results obtained with the ACCL model. In the absence of a new technical breakthrough, the combination of an increase in CO<sub>2</sub>-emitting energy prices by 1% a year and the technology mix divides worldwide net carbon emissions by 14, keeps global warming below 2°C and limits climate damages to 1% of the world GDP in 2100. The GDP loss of India is still above 2%, and global net CO<sub>2</sub> emissions remain positive at the end of the century. Raising the carbon tax to an annual 1.5% of the relative price of CO<sub>2</sub>-emitting energies, still as a complement to the 'green' technology package, ensures that the world meets the COP21 target in terms of global temperature rise (here, +1.59°C) at the end of the century, and even in the case of technical innovation (+1.73°C). In this scenario, global net CO<sub>2</sub> emissions are null in the presence of 'usual' TP and even negative in its absence.

Moreover, we consider the 1.5% LCT scenario more realistic to fund public expenditures and to provide incentives for the private sector to implement the 'green' technology mix we present. Indeed, energy efficiency, carbon sequestration and renewable technologies require subsequent financial incentives and call for a widespread and significant carbon tax. As we do not compute a

'too-little, too-late' scenario in this paper<sup>9</sup>, we suppose countries undertake these actions immediately. This assumption seems difficult to meet considering the current geopolitics, especially since the great challenge of our scenarios is that they rely on international coordination at the world level. For all those reasons and the absence of tipping points in our model, our estimates for global temperature and climate change damage must be considered lower bounds.

**Graph 4: 2100 increase in world temperature and climate damage in LCT scenario with 'usual' TP and/or a 'green' TM**



Note: Left-hand scale in °C for the increase in world temperature and right-hand scale in % of GDP for climate damage.

**Conclusion and policy discussion**

The paper highlights how technological changes can contribute to reaching the COP21 goal of net zero CO<sub>2</sub> emissions and global warming below 2°C at the end of the current century. It shows that only a composite scenario adding technological action to a realistic increase in the relative prices of 'dirty' energy leads to reaching the climate goals. This result is consistent with the main message from Aghion *et al.* (2021) and the IPCC (2022b) mitigation pathways encompassing renewables resort, CCUS, technological enhancement, energy efficiency, low resource demand and sustainable resource management. As a comparison, in its modelling of a pathway to net zero by 2050, the IEA (2021) shows that transitioning to renewable energy and increasing energy efficiency will play a considerable role in emission reductions through 2030, with CCUS, hydrogen and electrification contributing the most to emission reductions between 2030 and 2050. The IRENA (2022) gives a roadmap of the energy transition steps for the world to comply by 2030 with the global warming objective of 1.5°C maximum in the long run. This transformation implies raising energy efficiency, electrifying end-use sectors - like industry, buildings, or transports - boosting both the renewable power generation and direct usage of renewable energy in end-use sectors, developing 'clean' hydrogen and sustainable bioenergy coupled with CCUS. Such advances require TP, targeted investments and policies like carbon pricing. Our results are consistent with the findings of the innovation economics literature transposed to climate change (see Aghion *et al.*, 2019 for a review;

<sup>9</sup> A 'too-little, too-late' scenario is available by default in the online ACCL tool. See also in [\(NGFS\) Scenarios Portal](#) a 'Too little, too late' scenario which assumes that a late transition fails to limit physical risks.

Acemoglu *et al.*, 2016 for a corresponding example of an endogenous microeconomic growth model). These papers emphasize the necessity to combine carbon pricing with research subsidies, the required cooperation between the public and private sectors and the cost of delaying policies, the need for 'green' technological transfers from northern to southern economies and the importance to favour renewables over fossil fuels with CCUS to transition to 'clean' technologies. On the other hand, Acemoglu and Rafey (2023) highlight the risk from geoengineering breakthrough that might dissuade private investment in usual 'clean' technology via the diminution in future carbon taxes.

Simulation results of the composite scenario indicate that ambitious climate policies mixing technological and price dimensions reach the COP21 goal of net zero CO<sub>2</sub> emissions and global warming below 2°C at the end of the current century. Yet, all countries must implement such policies as soon as possible, which is challenging. It is thus critical (1) to adopt a stringent carbon tax to decrease energy consumption and encourage substitution towards less polluting energies, (2) to incentivise and support 'green' innovations in compliance with biodiversity, and (3) to generalise already existing underutilised 'green' technologies. Relevant policies encompass well-targeted subsidies or tax cuts, the development of specialised training and human capital, the revision of the legal framework (including patents or regulations), the emergence of funding solutions (e.g. facilitated loans, shared financing), investments in innovation centres and support structure for 'green' businesses... The provision of such public goods can be financed via tax revenue (e.g. those from carbon taxation) and by redirecting funds traditionally oriented towards polluting energies and activities, for example. However, this program appears very challenging. Indeed, its implementation needs to start immediately, coordinated in all countries, an assumption difficult to meet considering the current geopolitics. A late or incomplete implementation means that efforts will have to be stronger in a second phase to compensate for higher gas emissions during the delay or that we concede less ambitious climatic goals. These two situations correspond to a failure and clearly express that we renounce losing a small part of comfort and quality of life in the present for a high price, in terms of climate damage, for the next generations in the future.

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