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How can technology significantly contribute to climate change mitigation?

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Abstract

This paper highlights how technology can contribute to reaching the COP21 goals of net zero CO_2 emissions and global warming below 2°C at the end of the century. It uses the ACCL model, particularly adapted to quantify the consequences of energy price shocks and technology improvements on CO_2 emissions, temperature changes, climate damage and GDP. Our simulations show that without climate policies, i.e. a 'business as usual' scenario, the warming may be +4 to +5°C in 2100, with considerable climate damage. We also find that an acceleration in 'usual technical progress' - not targeted at reducing greenhouse gas intensity - makes global warming and climate damage worse than the 'business as usual' scenario. According to our estimates, the world does not achieve climate goals in 2100 without technological changes to avoid CO_2 emissions. To hit such climatic targets, intervening only through the relative price of different energy types, e.g. via a carbon tax, requires challenging hypotheses of international coordination and price increase for polluting energies. We assess a multi-lever climate strategy, associating diverse price and technology measures. This mix combines energy efficiency gains, carbon sequestration, and a decrease of 3% per year in the relative price of non-carbon-emitting electricity with a 1 to 1.5% annual rise in the relative price of our four 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, Uncertainties, Renewable energy

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Introduction

According to the IPCC (2022a) or the IEA (2021) scenarios, technologies must be an important part of the mix to reach net zero greenhouse gas emissions (GHG) 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 as well as 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_2 (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_2-saving innovations is still considerable, for example in the building sector to reduce heating needs. In terms of technologies and their role in emission reductions, we are considering here technologies supporting (i) energy efficiency gains, (ii) carbon capture, utilisation and storage (CCUS), and (iii) non-CO_2 emitting sources of energy such as renewable energies. In its modelling of a pathway to net zero by 2050, the International Energy Association (2021) showed that transitioning to renewable energy and increasing energy efficiency will play a major role in emission reductions through 2030, with CCUS, hydrogen and electrification contributing the most to emission reductions between 2030 and 2050.

Energy efficiency gains entail a reduction in the utilization 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 (low-temperature heat and fractional horsepower motors) 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 2600 TWh, or about 20% of the projected energy consumption and 1.5 Gt of carbon dioxide emissions by 2030 (Letschert, 2013). One phenomenon, called the rebound effect, may reduce the gains in terms of CO_2 emission from energy efficiency: as energy efficiency lowers the cost of using technology, it may be used more (direct effect). Moreover, energy efficiency induces an income effect leading to an increase in overall consumption (indirect effect). Yet, it does not completely suppress the gains from energy efficiency, as the range of estimates for the size of the rebound effect is very low to moderate (Greening *et al*., 2000; Gillingham *et al*., 2016, for a literature review). The relationship between development and energy efficiency is supposed to follow an environmental Kuznets curve (Panayotou, 1993; Brock and Taylor, 2010, for a theoretical vindication): at the early stage of development, energy efficiency tends to deteriorate, but after a certain development threshold, it improves. Studies of the convergence of energy efficiency indeed find convergence among richer industrialised countries but a persistent gap at the global level (see the meta-analysis of Acar *et al*., 2018).

CCUS technologies allow carbon capture at emission or directly from the air. They 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 to its role in the reduction of the carbon stock: the contribution of carbon sequestration is about 50% higher in the case of learning, resulting in cumulative sequestration of CO_2 ranging from 150 to 250 billion tons of carbon during the 21st century (Riahi *et al*., 2004). One issue is the risk of carbon leakage from the storage location; yet, these technologies remain a valuable option even with CO_2 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 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 raising energy efficiency (by 2.5 in 2030 compared to 2019), electrifying end-use sectors - like industry (reaching a 28% share of electrification in 2030), buildings (56%), or transports (9%) - boosting both the renewable power generation (up to 65% of total electricity supply by 2030) and direct usage of renewable energy in end-use sectors (from 12% in 2019 to 19% in 2030), 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 TP, targeted investments ($1 trillion annually until 2030 for renewables) and policies like carbon pricing. Yet, for most countries, renewable power is already the less costly alternative. Indeed, between 2010 and 2020, the world weighted-average levelized cost of electricity from new units has decreased by 85% for utility-scale solar photovoltaic (PV), 68% for Concentrated Solar Power (CSP), 56% and 48% for onshore and offshore wind respectively. As an example, for Williams *et al.* (2021), carbon neutrality in the US by 2050 is affordable, at a net cost of about $1 per person per day. The authors confirm that recent declines in solar, wind, and vehicle battery prices have contributed to decarbonising the US economy at low net cost, even though they recognise that longer-term uncertainties are related mainly to fuels and CCUS in terms of technical costs and environmental impacts.

Going further in finding solutions, Long *et al.* (2021) develop three models for California to quantify the costs of a variety of future scenarios for new sources of clean, reliable electric power. They find that renewables like wind and solar are critical to the state's path toward decarbonisation. But, as these energies depend on sunshine and wind seasonality, their solution is combining them with carbon-zero non-intermittent energy sources. These sources can be geothermal, nuclear power and natural gas that utilises CCUS technology to sequester CO_2, as well as clean fuels like hydrogen manufactured with no life-cycle emissions.

This article quantifies the contribution of technologies to CO_2 emission reduction and the limitation in damages from climate change. In doing so, it uses the Advanced Climate Change Long-term model (ACCL) built by Alestra *et al.* (2022)[2] which is particularly adapted to quantify the consequences of energy price shocks and technology improvements on CO_2 emissions, temperature changes, climate damage and GDP. It distinguishes five types of energy, four being "dirty" in terms of CO_2 emissions (coal, petrol, gas, "dirty" electricity) and one being "clean" ("clean" electricity). This model gives a particularly interesting and transparent insight into the role of technologies in the energy transition and climate mitigation mechanisms. We consider three technological channels: energy efficiency gains, carbon capture and a decrease in the relative price of the "clean" energy type. The last component of this strategy can correspond both 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 +4 to +5°C at the end of the century, with major climate damage, particularly in certain areas such as 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' Technological Progress (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_2 emissions, climatic goals cannot be reached at the end

[2] The projection tool is available online at the following address: https://advanced-climate-change-long-term-scenario-building-model.shinyapps.io/ACCL_Projection_Tool/

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. We need an increase of 3% per year for the four types of “dirty” energy, which means that these relative prices are multiplied by a factor of 11 at the 2100 horizon. Moreover, this ambitious policy has to be totally coordinated in all countries. 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 as realistic, is not be 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. Energy efficiency gains and carbon sequestration are calibrated to be realistic, in line with the literature. 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 relative price increase of the four types of “dirty” energy 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 of “clean” energy and the costs of energy efficiency gains and gas sequestration technologies.

Section 1 presents the ACCL model, emphasising the key uncertainties of the different relationships; section 2 bears on the challenges of reaching the 2°C climate goal, as the BAU case reaches 4 to 5°C and as carbon tax policies necessary to reach 2°C are very demanding; in section 3, we present the potential contributions of the three technological channels, energy efficiency gains, carbon capture, and renewable energies, separately and mixed.

1. The model ACCL to evaluate climate policies

The ACCL model is a fully transparent and free-access model, with a rich and endogenous modelling of the GDP growth dynamics. This tool is a user-friendly projection tool, designed with R-Shiny, 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.

We present first the general framework of the ACCL tool (1.1.). Then we present the evaluation of the GDP before climate damage (1.2.) and the endogenous evaluation of the global warming and of GDP damage from climate change (1.3.).

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 Total Factor productivity (*TFP*). Then, the impact of limiting physical damage from climate change on GDP, through the abatement of CO_2 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, decomposed in 31 countries and regions at the 2060 and 2100 horizons.

Scenarios built with ACCL 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 GHG emissions benefits 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. Simulations show that for each country, the best individual strategy is a BAU one and stringent climate policies for others. Hence, the global best collective strategy is 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 ACCL model adopts a supply-side approach and a long-term view. At the 2060 and 2100 chosen horizons, it accounts for a production function approach to GDP, assuming full capacity utilization 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. Estimating 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). For each country, labour (more explicitly employment and working hours) is exogenous. The quantification of the volume of capital and of the *TFP* is based on specific assumptions and relations. 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. Cette, Kocoglu and Mairesse, 2005).

TFP is estimated based on its structural determinants. The *TFP* is assumed to depend for each country on several variables:

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 (and 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. 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. It means that TP 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. Second, a *TFP* improvement channel. These two channels are taken into account in ACCL.
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. From GDP without damage to 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 estimate results, an increase in the past GDP of 1% raises energy final consumption by 0.97%, while a similar growth of the energy relative prices reduces 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, 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_2 emitting) and "clean" (non- CO_2 emitting) energy inputs.[3] Their respective shares in the total final consumption 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 carbon dioxide emissions. ACCL uses a simplified carbon cycle constituted by using the Permanent Inventory Method (PIM) to model the increase in the worldwide stock of carbon dioxide by the aggregate CO_2 emissions. CO_2 sequestration by the carbon sinks of the planet (*i.e.,* natural or artificial reservoirs capturing atmospheric CO_2) can be considered as a fixed proportion of the stock or of the emissions or as a fixed volume of CO_2 independent from emissions or stock of CO_2. This allows ACCL users to introduce some non-linearity in CO_2 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 carbon dioxide emissions.

ACCL converts the resulting projections of CO_2 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 RCP (Representative Concentration Pathway) 8.5 scenario (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

[3] As dirty means here CO_2 emitting, ACCL considers the nuclear electricity production as a clean one, which can of course be contested from other dimensions.

down into local damages using the share of the OECD (2015) regional coefficients of climate-damage as a distribution key.

2. The challenge of achieving +2°C at the end of the century

Over the last decades and even during recent years, except in 2020 at the top of the COVID-19 crisis, the net CO_2 emissions have structurally and almost continuously increased. As a result, climate change has continued, and the world will not spontaneously achieve the two goals of zero net CO_2 emissions and global warming below +2°C at the end of the century. A simplified BAU scenario simulated with the ACCL model illustrates that risk (2.1.). Other simulations with ACCL may elucidate if carbon tax policies are sufficient to reach the two goals and if such policies seem too ambitious (2.2.). If they are too ambitious, it means that achieving the two goals requires the support of technological changes.

2.1. Without climate policies, the warming may be +4 to +5°C

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, without technical climate innovation nor tipping points, forecasts, at the 2100 horizon, a multiplication of the world net annual CO_2 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%. The consequences are very different from country to country. GDP losses are higher than 20 % in India and Africa and above 15% in three more areas: Mexico, China and the rest of Asia. Conversely, the impact can be positive in two countries, Russia and Canada, as the temperature increase creates a supply-side gain from arable lands expansion. Yet, the increased occurrence of extreme events may offset this growth. The impact is negative between these two extreme situations in the other areas.

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. Abundant literature deals with the question of tipping points. Dietz *et al*. (2021a and 2021b) wrote a literature review covering 52 papers. They consider eight types of tipping points, the two potentially most damaging being the dissociation of ocean methane hydrates and the permafrost carbon feedback. In the main specification of Dietz *et al*. (2021a and 2021b), 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 global loss, at the world level, of about 12%. But the distribution of the losses is positively skewed, and Dietz *et al.* (2021a and 2021b) estimate a 10% chance of climate tipping points more than doubling the SCC, which means a global loss of 18%. Behind these global numbers, the losses are worse in some areas and can even be disastrous, as in India.

The evaluations by Dietz *et al.* (2021a and 2021b) may themselves be considered optimistic, as they do not account for possible interactions between tipping point effects: "*Tipping points can interact with each other in multiple ways. … For example, the PCF (permafrost) increases temperature, which affects all seven remaining tipping points in our study, because all of them depend on temperature.*" And as raised by Fewster *et al.* (2022), who focus on permafrost, some tipping points can appear at low-temperature change: "*In Europe and Western Siberia, permafrost peatland thaw could happen from low warming levels*". Hence, some tipping point effects can happen even before reaching a 2°C temperature increase.

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).[4] 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.

Can 'usual' TP - without impact on GHG intensity of growth - contribute to curbing global warming? The ACCL model helps deal with this question. 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).[5] 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.[6] 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 XXth 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. To fight against global warming, TP must be oriented and explicitly related to the goal of a decline in the stock of GHG. The following sections of this paper deal with such oriented (and not 'usual') TP.

2.2. Without technological support, achieving the less than +2°C goal requires ambitious and coordinated climate policies

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.[7] It assumes an increase in the relative price of each of the four types of "dirty" energy (coal, oil, natural gas and CO_2-emitting electricity) by 3% per year. The relative price of the "clean" energy type (non-CO_2-emitting electricity) 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_2 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.

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[4] See for instance IPCC (2022a).

[5] 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.

[6] 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).

[7] 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.

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 (coal, oil, natural gas and CO_2-emitting electricity) by 1% per year, and stability of the relative price of the "clean" energy type (non-CO_2-emitting electricity), 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. The LCT scenario assumes that the same increase in the relative price of the "dirty" energy types is perfectly coordinated across all countries. As the HCT scenario, this LCT scenario has 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.

In this LCT scenario, the net annual CO_2 emissions are, compared to their 2016 level, multiplied by a factor of two. We are far from a zero net emission situation and even from a stable net emission one. The temperature increases by 3.5°C (with respect to the pre-industrial era), and climate damages correspond in 2100 at the world level to a GDP loss slightly superior to 5.25%. Here again, the damages differ broadly from country to country.

3. <u>How much can technology help to reach the goal on +2°C?</u>

Different types of technology changes may contribute to reach climatic goals. We present successively an energy efficiency gains scenario (3.1), a carbon capture and sequestration scenario (3.2), a higher competitiveness of no CO_2 emitting energy scenario (3.3) and a composite scenario associating different types of technology changes (3.4).

3.1. Energy efficiency gains

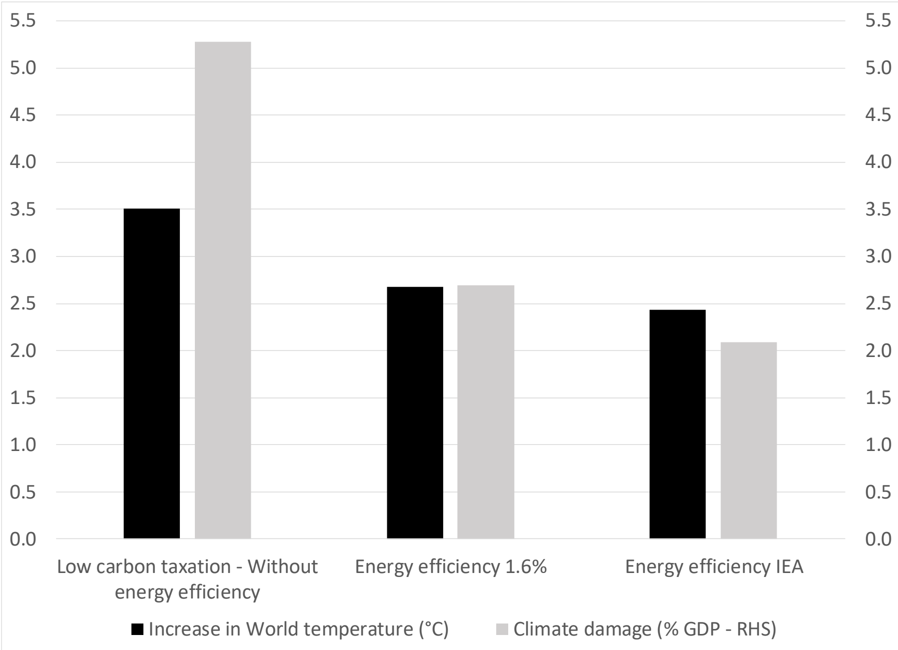
Energy efficiency gains correspond to the decrease in the ratio of energy utilization (in power units, e.g. MJ) to GDP in volume. Since the oil shock, advanced economies recorded energy efficiency gains, which reached 1.6% per year in the 2010s (IEA, 2021). These gains are based on innovation targeted 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 - to reduce heating or cooling needs is the first source of energy efficiency gains in the IEA scenario before efficiency gains in transport and industry. Part of the technological efficiency gains may be offset by a rebound effect, as more energy efficient technologies lead to substitution effect and income gains, which will be partly spend on energy consumption.

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 in the ACCL model LCT scenario. First, we implement a trend of energy efficiency 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



Note: Low carbon tax (LCT) scenario with an increase in carbon-emitting energy prices by 1% a year. Faster energy efficiency gains of 1.6% per year or following the IEA scenario. 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, meaning that the triggering of tipping points cannot be excluded. 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 positive impact of GDP growth offsets the negative impact on net emissions of both the increase in CO_2-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_2, declining compared to 2016 but still positive.

3.2. Carbon capture, utilization and storage technologies

CCUS are technologies that separate CO_2 from other gases at emission or directly from the air, use it in extraction or industrial processes or store it in natural facilities. It excludes biological carbon sequestration such as forestry or fertilization of oceans.

CCUS technologies which are currently mature are used for CO_2 capture at emission from large industrial facilities. They can be particularly relevant for electricity generation, steel or cement production and natural gas treatment (CO_2 can account for as much as 70% of a gas field). The process involves first the capture of CO_2 by separating it from other gases. Three methods exist: post-combustion captures 80-95% of emitted CO_2, it is the most mature technology and it can be easily adapted to existing facilities; pre-combustion captures a similar share of emitted CO_2 but requires changes to the existing facilities; oxy-fuel combustion is the least mature technology, requires producing pure O_2, which is costly but leads to 95-99% capture. The CO_2 needs then to be transported and stored in gas, oil field or saline formation; it can be injected into the ocean; it can be 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_2 from the surrounding atmosphere; many materials and processes are under investigation but are far from being operational.

CCUS are energy-intensive and costly technology, which is why they did not develop although they could have been implemented for decades. Although involving a sizeable initial investment, they cost 15 to 25 USD per ton of CO_2 captured (IEA, 2019), 100 to 200 USD per ton of CO_2 for BECCS and 600 to 1000 USD per ton of CO_2 for DACCS (Fuss *et al*., 2018). Substantial uncertainties remain on the future course of these costs, especially for the most recent technologies. In particular, Fuss *et al*. (2018) estimate that the costs for DACCS can decrease to 100-300 USD/tCO_2 as technologies advance. So far, two major projects use CCUS: in 1996, the Sleipner oil field in Norway, following the implementation of a CO_2 tax on offshore extraction; in 2015, The Quest project in Canada launched to tackle carbon emissions in the oil sands. Globally, large scale CCUS facilities capture more than 30 million tons of CO_2 per year (IEA, 2019).

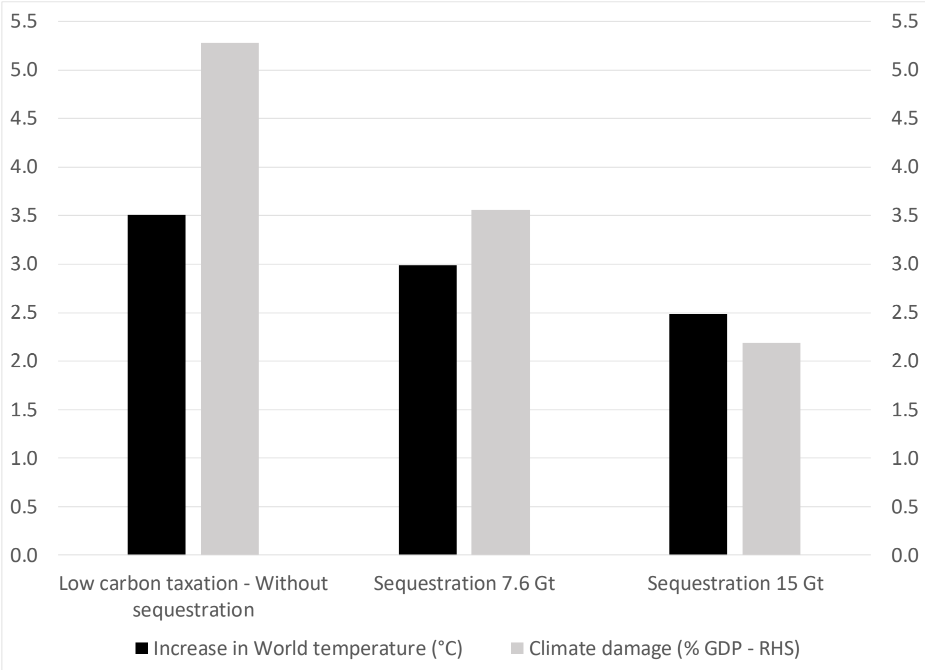
Projections of CCUS use in 2050 net-zero scenarios are 15 Gt CO_2 per year for the median of IPCC scenarios and 7.6 Gt CO_2 for the IEA (2021) scenario.[8] If emissions are about 30 Gt CO_2 in 2050, they will capture between a quarter and half the emissions. These scenarios crucially hinge on the implementation of CO_2 tax, which is set at 250 USD/t CO_2 in the IEA scenario for advanced countries. Given their cost, a CO_2 price is needed to set the proper incentive to implement these technologies.

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 damage 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_2 emissions are not reached, even in 2100, with 26 (IPCC scenario) to 35 (IEA) Gt CO_2 equivalent still emitted each year. Moreover, as temperatures are significantly above 2°C, the triggering of tipping points (cf. section 2.1) can still be possible. Finally, as energy prices increase only at a 1% a year pace, carbon taxation remains too low

8 This includes 985 Mt CO_2 per year through DACCS and 1,4 Gt CO_2 per year through BECCS. For DACCS and BECCS, Fuss *et al.* (2018) estimate that their potential is 0.5–5 Gt CO_2 per year each by 2050 and for DACCS, which technologies may continue to improve, between 10–15 Gt CO_2 per year by 2100 (Fuss, 2017; Smith *et al.,* 2016a; McLaren, 2012; National Academy of Sciences, 2015) with some seeing much higher potentials beyond 40 Gt CO_2 per year (Lenton, 2014).

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



Note: Low carbon tax (LCT) scenario with an increase in carbon emitting energy prices by 1% a year. Sequestration of CO_2 through CCUS technologies according to the IEA (7.6 Gt a year) or the IPCC (15 Gt a year) scenarios. Left-hand scale in °C for the increase in world temperature and right-hand scale in % of GDP for climate damage.

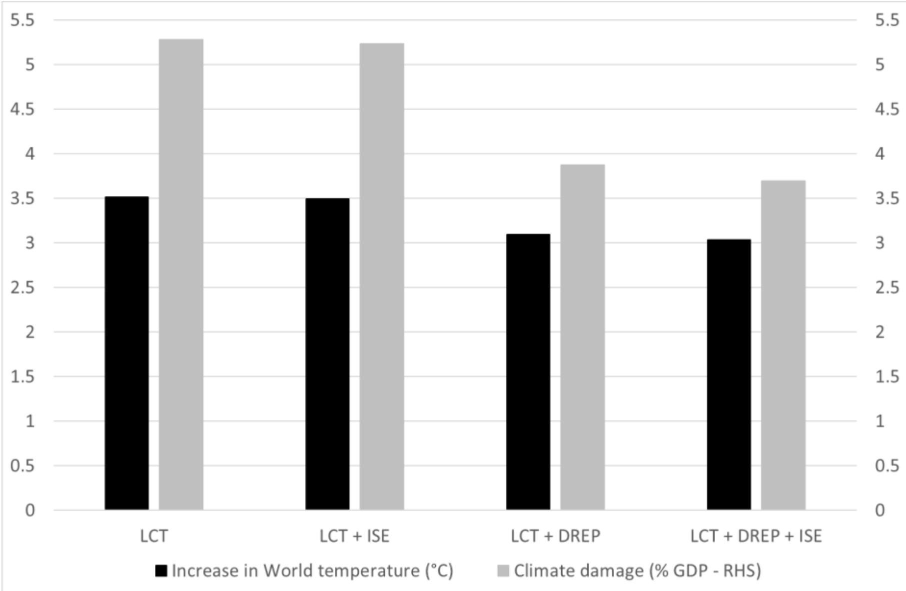
3.3. Increased competitiveness and use of non-CO_2 emitting technologies

According to the International Renewable Energy Agency (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 (PV), 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, even from existing coal plants to a certain extent. 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.

Thus, using our ACCL model, we project three scenarios between 2017 and 2100 in addition to our 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_2 and non-CO_2 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 is lower than what is observed currently on some renewable technologies, but over the course of the whole century, it is likely that this decreasing trend will slow down as easiest innovations are exhausted. Moreover, 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: Low carbon tax (LCT) scenario with an increase in carbon-emitting energy prices by 1% a year. Increased Substitution Elasticity (ISE) scenario with a substitution elasticity of 2.5 between CO_2-emitting and non-CO_2-emitting electricity. Decrease in Renewable Energy relative Price (DREP) scenario with a reduction of the relative price of carbon-emitting electricity by 3% a year. 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_2 and non-CO_2 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 COP 21 goals as global temperatures still rise by 3°C, and the climate damage decreases the world GDP by close to 3.7% in 2100. We also notice some 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 and the necessity of multi-lever climate strategies

Our previous results show that a single-lever strategy is not enough to limit global warming below 1.5 or 2°C (compared to the pre-industrial era) by the end of the century, especially in the case of faster TP not targeted at CO_2 emission reduction. 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_2 sequestration and the expansion of renewable technologies.

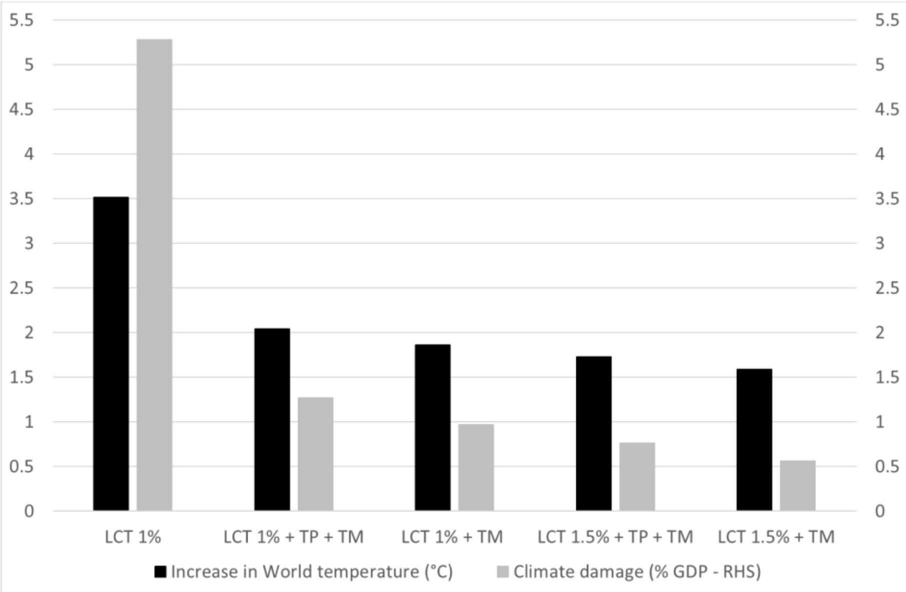
The IPCC (2022b) develops five Illustrative Mitigation Pathways (IMPs) that entail the necessary emissions reductions to reach the COP21 temperature target, all of them combining various climate change strategies in different sectors (energy, agriculture and forest, buildings, transport, industry). These 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), especially for developing countries.

We consider four composite scenarios combining our LCT scenario, the global rise of the relative price of CO_2-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, just as in section 2.1. We assume a 0.5 percentage point constant decrease in the investment relative price from 2017 to 2100 in all countries and areas. It impacts GDP growth both through the growth rate of TFP and the growth rate of the capital-over-labour ratio (capital deepening). 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_2 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). In each case, we chose the values that we consider the most plausible. We do not include the ISE scenario (cf. section 3.3) as our baseline coefficient is already relatively high, and thus, marginally increasing; it has little effect on our outcomes. The user can simulate alternative specifications using our projection tool.

Graph 4 summarises the results obtained with our ACCL model. In the absence of a new technical breakthrough, the combination of an increase in CO_2-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_2 emissions remain positive at the end of the century. Raising the carbon tax to an annual 1.5% of the relative price of CO_2-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). According to our simulations, it contains climate adverse consequences on the world economy below unity, with and without TP, except in Africa or some Asian countries like India, where the local loss is now lower than 2% of their GDP. In this scenario, global net CO_2 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, all those ambitious measures are costly to develop and implement. Energy efficiency, carbon sequestration and renewable technologies require subsequent financial incentives and call for a widespread and significant carbon tax. An increase in energy prices, as we currently observe with the war in Ukraine, affects energy consumption behaviours by inciting to energy sobriety or the recourse to alternative energy sources. But as long as it is not funding climate mitigation investments, research and development, as the revenues from a carbon tax might, it is unlikely that we meet the technological advances of our scenarios. Furthermore, investments in CCUS technologies by energy producers require a tax related to CO_2 emissions, as higher energy prices only increase their benefits and provide no incentive for them to bear the cost of these investments. As we do not compute a "too-little, too-late" scenario in this paper[9], 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 (see discussion in section 2.1), 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: Low carbon tax (LCT) scenario with an increase in carbon-emitting energy prices by 1% or 1.5% a year. Technical progress (TP) implies an annual 0.5 percentage points decrease in the investment relative price. Technology mix (TM) consists of energy efficiency gains of -1.6% per year, CO_2 sequestration through CCUS technologies according to the IEA (7.6 Gt a year) and a reduction of the relative price of non-carbon-emitting electricity by 3% a year. Left-hand scale in °C for the increase in world temperature and right-hand scale in % of GDP for climate damage.

Conclusion

The aim of the paper is to highlight how technological changes can contribute to reaching the goal of net zero CO_2 emissions and global warming below 2°C at the end of the current century. We have used the ACCL model, which is particularly adapted to quantify the consequences of energy price shocks and of technology improvements on CO_2 emissions, temperature changes, climate damage and GDP. Available in free access, this tool allows such evaluations at a global level and at the country or economic area level. It distinguishes five types of energy, four being "dirty" in terms of CO_2 emissions (coal, petrol, gas, "dirty" electricity) and one being "clean" ("clean" electricity).

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[9] A "too-little, too-late" scenario is available by default in our online projection tool. See also, as a benchmark, on the Network for Greening the Financial System (NGFS) Scenarios Portal, a "Too little, too late" scenario which assumes that a late transition fails to limit physical risks.

A first result of our simulations is that without climate policies, corresponding to a BAU scenario, the warming may be +4 to +5°C at the end of the century, with major climate damage, particularly in certain areas such as 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 impact on temperature and climate damage. A third result is that without technological changes that avoid CO_2 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, leads to reaching climatic goals only under challenging hypotheses concerning the price increase of “dirty” energy. We need an increase of 3% per year for the four types of “dirty” energy, which means that the relative prices are multiplied by a factor of 11 at the 2100 horizon. Moreover, this ambitious policy has to be totally coordinated in all countries. Energy price policies are useful but only as part of a more global climate strategy.

Technological support is essential for reaching climate goals. Three technological channels are considered: energy efficiency gains, carbon capture and a decrease in the relative price of the “clean” energy type. The last component of this strategy can also be the result of innovation or a tax/subsidy-oriented policy. According to our estimates, each of these components, at the maximum of what the literature considers as realistic, is not enough to reach the climate goals. We evaluate a mixed strategy, combining the different types of single 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 to 1.5% per year of the relative price of the four “dirty” types of energy. Energy efficiency gains and carbon sequestration are calibrated to be realistic, in line with the literature. The fourth and most important result of our analysis is that the mixed scenario leads to reaching the climate 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 relative price increase of the four types of “dirty” energy 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 of “clean” energy and the costs of energy efficiency gains and gas sequestration technologies.

The main message of this analysis is 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 messages from IPPC (2022b). Nevertheless, such a program appears very challenging. Indeed, it depends on the actual acquisition of such technologies and its implementation needs to start immediately and be 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 next generations in the future. However, it seems that, since the COP21 agreement in 2015, we are going this way and we need to change course as soon as possible if we want to catch the green-tech train.

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