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Green innovation policies

Economics and climate change

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About the author

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David Hémous is a macroeconomist working on Economic Growth and Innovation. His work highlights the fact that innovation responds to economic incentives and that public policies should be designed taking this dependence into account. In particular, he has shown in the context of climate change policy that innovations in the car industry respond to gas prices and that global and regional climate policies should support clean innovation to efficiently reduce CO_2 emissions. His work on technological change and income distribution shows that higher labor costs lead to more automation, and that the recent increase in labor income inequality and in the capital share can be explained by a secular increase in automation. He has also shown that innovation affects top income shares. His work has been highlighted in several newspapers and magazines including Le Monde, The Economist, The Washington Post or Forbes, and it has been presented in policy circles such as COP 15 conference in Copenhagen or the French parliamentary meetings.

Abstract

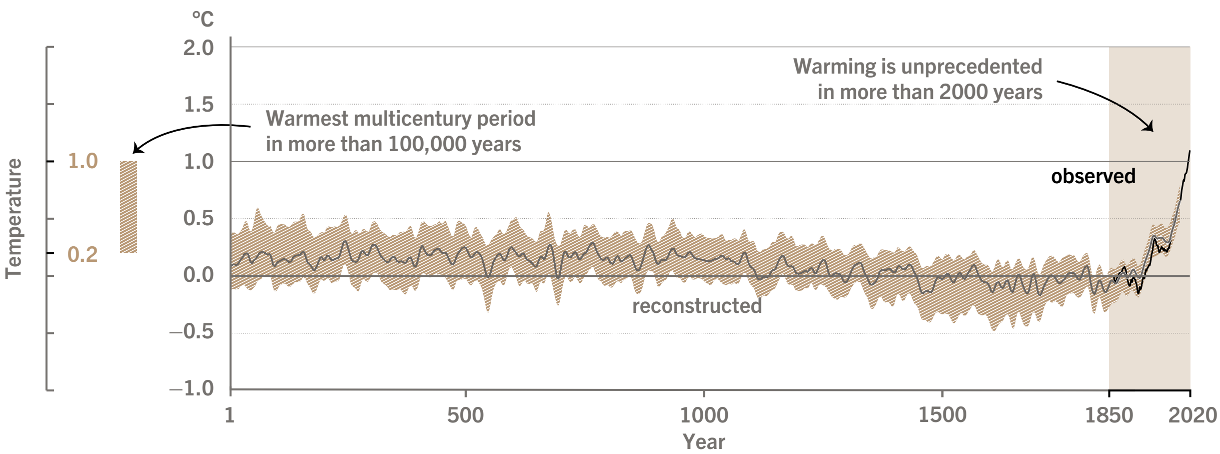
Climate change already has a negative impact on the environment and our societies, and this impact will get worse over the course of this century. How much worse? This will depend on our ability to reduce greenhouse gas emissions. Achieving the necessary reduction in emissions, while maintaining (and improving) worldwide living standards can only be achieved through innovation. Fortunately, innovation is not manna from heaven; it is conducted by scientists and firms and it reacts to market and policy incentives. It is therefore up to governments to steer it toward clean technologies. In this public paper, I will review recent economic research on the role of innovation in the design of climate policy. After a quick introduction to the challenges posed by climate change, I will show that current technological trends – though promising – are unlikely to be sufficient to limit warming to 2°C. Can policy then effectively boost green innovation? Recent evidence shows that this is definitely the case. How should global climate policy be designed to leverage this innovation response? What about unilateral policies? Some innovations are "grey": they permit the replacement of particularly dirty technologies with less dirty but still polluting ones. The shale gas revolution is an example. Can these "grey" innovations backfire?

A quick introduction to climate change

The average global temperature in the 2010s was 1.09°C higher than in the 1850–1900 period, and each of the last four decades has been warmer than the previous one: climate change is already well underway (IPCC AR6 report).[5] Figure 1 taken from the IPCC report shows that the increase in temperature and its speed are unprecedented in the last 2000 years. In fact, the Earth has probably not seen temperatures this high for the last 125,000 years. Global warming is a direct consequence of the accumulation of greenhouse gases (carbon dioxide CO_2 but also methane CH_4 and nitrous oxide N_2O) from human activities, most notably the use of fossil fuels. Figure 2 from the IPCC report shows the direct near linear relationship between the temperature increase since 1850 and the cumulative accumulation of CO_2 emissions historically, together with the warming and emissions associated with the five scenarios (denoted SSP1–1.9, SSP1–2.6, etc.) studied in the report.

The early consequences of climate change can already be felt with an increase in rare climatic events such as the floods in Germany, the heat dome in the American northwest, flooding in Zhengzhou, China, and record wildfires in Russia or California, all in 2021. More generally, a higher global temperature will be associated with higher temperatures everywhere on Earth (uneven, and particularly strong at higher latitudes), more days of extreme heat, and more rainfall. Rainfall variability will also increase with both droughts and heavy precipitations becoming more likely. To give but one example, the IPCC report argues that an extreme heat event which would have occurred only 1 in 50 years with the mean temperature of 1850–1900, is already likely to occur five times more frequently, would occur fourteen times more frequently for a mean temperature increase of 2°C, and would occur thirty-nine times more frequently for a mean temperature increase of 4°C.

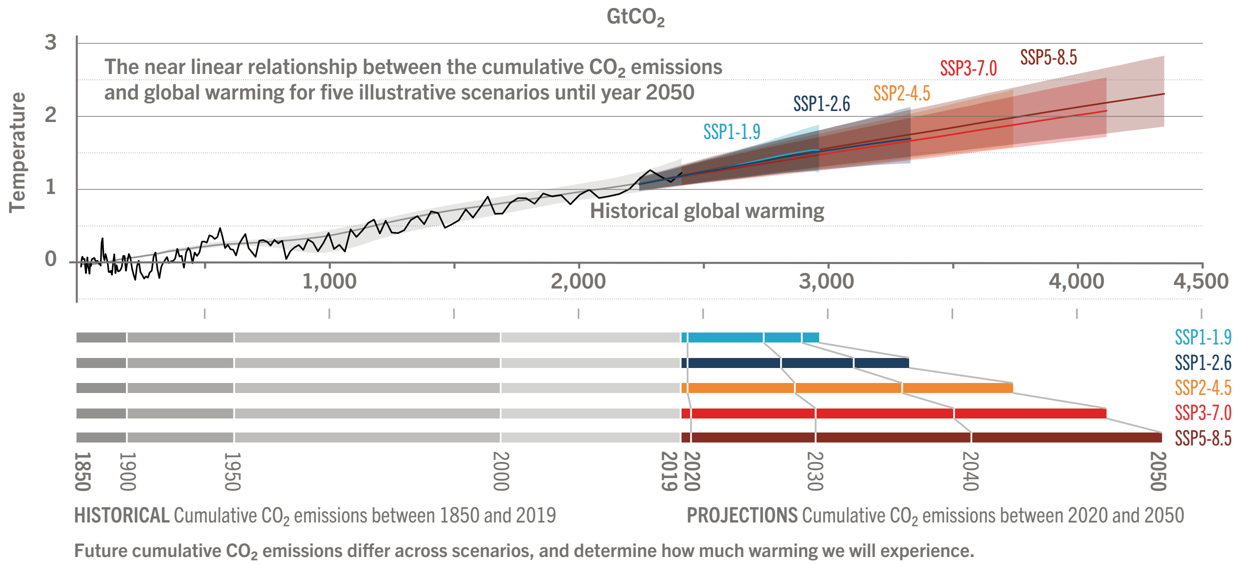
Fig. 1 **Changes in global surface temperature relative to 1850–1900**



Notes: Change in global surface temperature (decadal average) as reconstructed (1–2000) and observed (1850–2020)

Source: IPCC report

Fig. 2 Every ton of CO_2 emissions adds to global warming



Notes: The figure displays the historical increase in temperature (on the y-axis) together with the cumulative CO_2 emissions since 1850. It also projects the evolution of both CO_2 emissions and temperature until 2050 according to five scenarios studied in the report (which reflect different assumptions on economic and policy trajectories). SSP1-1.9 is the most optimistic scenario and SSP5-8.5 the most pessimistic.

Source: IPCC report

At the same time, CO_2 emissions also contribute to the acidification of oceans. Climate change directly affects ecosystems, economic production, health, and ultimately human welfare. It is bound to do so more intensely this century, but to what extent will directly depend on our greenhouse gas (GHG) emissions.

Table 1 gives an idea of the challenges ahead. The cumulative CO_2 emissions since 1850 are estimated at 2,390 Gt of CO_2. To have an even chance of limiting global warming to 1.5°C, the world can only emit 500 Gt more, knowing that emissions in 2019 alone reached 36.4 Gt. This seems impossible. To have an even chance of limiting warming to 2°C, the world can only emit 1,350 Gt more, which corresponds to thirty-seven times what was emitted in 2019: a clear challenge.

Figure 3 shows annual CO_2 emissions by world region since 1750. Global CO_2 emissions have increased at a remarkable speed between 1950 and 2012. Since then, emissions have not grown at the same rate: CO_2 emissions kept increasing until 2019 but declined in 2020 by 7% due to the Covid-19 pandemic, and a broader measure of GHG emissions including land changes shows a plateau and slight decline since the mid-2010s. Perhaps more encouraging, the graph also shows that CO_2 emissions in advanced economies (Europe and later on in the US) have been declining, while after a period of very rapid growth, even Chinese emissions have slowed down.

What should we expect for the future? Figure 4 displays different scenarios. Without any climate policies, we could expect temperature increases above 4°C with dire consequences.[I]

However, current policies should already limit warming to 2.7 to 3.1°C. Current pledges and targets by governments – if

Table 1 **Estimates of historical CO_2 emissions and remaining carbon budgets**

Global warming between 1850–1900 and 2010–2019 (°C)		Historical cumulative CO_2 emissions from 1850 to 2019 ($GtCO_2$)					
1.07 (0.8–1.3; likely range)		2,390 (± 240; likely range)					
Approximate global warming relative to 1850–1900 until temperature limit (°C)*(1)	Additional global warming relative to 2010–2019 until temperature limit (°C)	Estimated remaining carbon budgets from the beginning of 2020 ($GtCO_2$) Likelihood of limiting global warming to temperature limit*(2)					Variations in reductions in non-CO_2 emissions*(3)
		17%	33%	50%	67%	83%	
1.5	0.34	900	650	500	400	300	Higher or lower reductions in accompanying non-CO_2 emissions can increase or decrease the values on the left by 220 $GtCO_2$ or more
1.7	0.63	1,450	1,050	850	700	550	
2.0	0.93	2,300	1,700	1,350	1,150	900	

Notes: Estimated remaining carbon budgets are calculated from the beginning of 2020 and extend until global net zero CO_2 emissions are reached. They refer to CO_2 emissions, while accounting for the global warming effect of non-CO_2 emissions. Global warming in this table refers to human-induced global surface temperature increase, which excludes the impact of natural variability on global temperatures in individual years.

*(1) Values at each 0.1°C increment of warming are available in Tables TS.3 and 5.8. in the IPCC report.
*(2) This likelihood is based on the uncertainty in transient climate response to cumulative CO_2 emissions (TCRE) and additional Earth system feedbacks, and provides the probability that global warming will not exceed the temperature levels provided in the two left columns. Uncertainties related to historical warming (±550 $GtCO_2$) and non-CO_2 forcing and response (±220 $GtCO_2$) are partially addressed by the assessed uncertainty in TCRE, but uncertainties in recent emissions since 2015 (±20 $GtCO_2$) and the climate response after net zero CO_2emissions are reached (±420 $GtCO_2$) are separate.
*(3) Remaining carbon budget estimates consider the warming from non-CO_2 drivers as implied by the scenarios assessed in SR1.5. The Working Group III Contribution to AR6 will assess mitigation of non-CO_2 emissions.

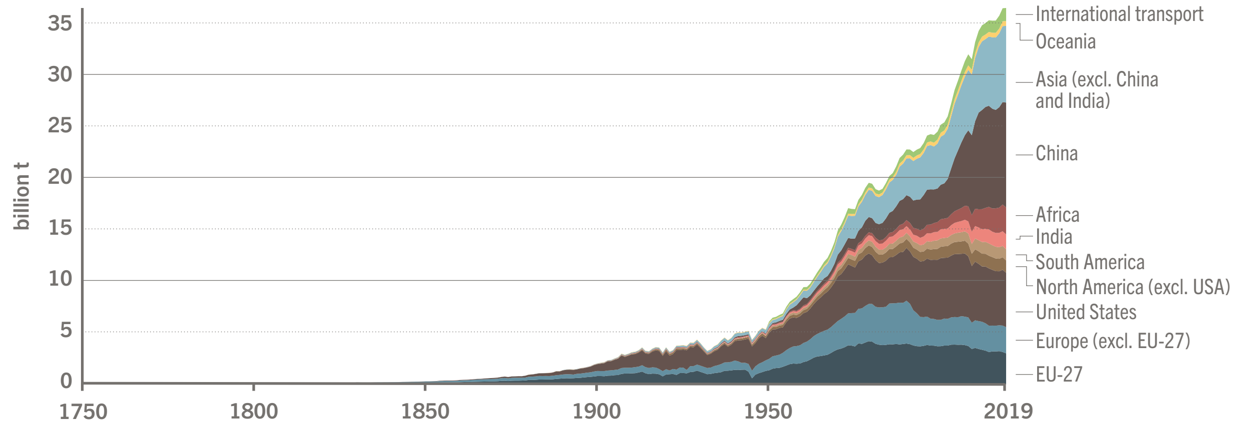
Source: IPCC report

fulfilled – would limit the mean temperature increase to 2.4°C, still very insufficient to reach the recommendation of the IPCC to limit warming at 1.5°C. To reach that goal, emissions would have to decline very rapidly and become net negative toward the end of the century. In order to limit the temperature increase at 2°C, emissions would have to start declining immediately at a rapid but regular pace. A chart like this one masks perhaps the high level of both economic and climate uncertainties that remain. Still, it gives an idea of the situation: while we are likely (though not certain) to avoid a catastrophic climate disaster, current policies are not sufficient to prevent further very significant climate change and its associated damages.

1972 United Nations Conference on the Human Environment takes place This is the UN's first major conference on international environmental issues and marks a turning point in the development of international environmental politics.

Why an economic perspective?

Fig. 3 **Annual total CO_2 emissions, by world region**

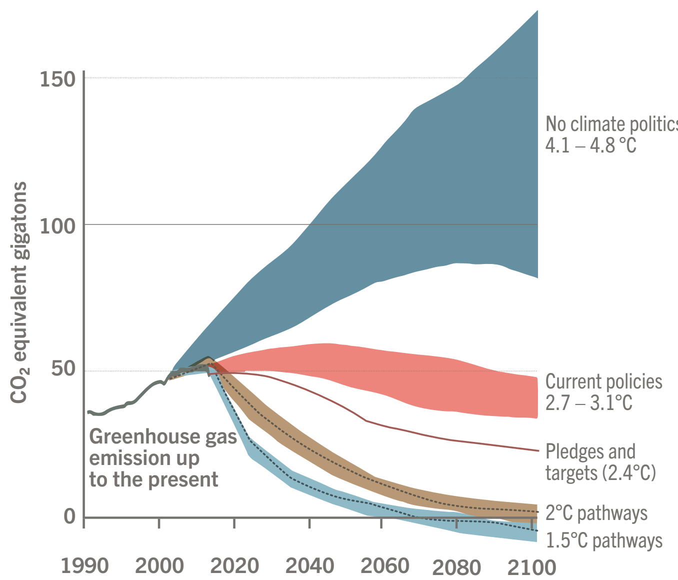


Notes: This figure measures CO_2 emissions from fossil fuels and cement production only – land use change is not included. "Statistical differences" (included in the GCP dataset) are not included here.

Source: Our World in Data based on the Global Carbon Project

Some may think that climate change is mostly a problem for natural scientists who tell us its mechanics or engineers who can develop solutions to reduce our greenhouse gas emissions. In reality, climate change is really an interdisciplinary problem and economists have a key role to play. Lionel Robbins gave a famous definition of economics as "the science which studies human behavior as a relationship between ends and scarce means which have alternative uses." Addressing the challenge posed by climate change fits squarely within that definition: the goal is to manage a carbon budget (the "scarce" means) to foster human development while limiting climate damages ("the ends") when fossil fuels can be used across many tasks in societies, in different countries and at different points in time, or simply be left in the ground (the "alternative uses"). More concretely, climate change involves trade-offs between today's income and development and tomor-

Fig. 4 **Global greenhouse gas emissions and warming scenarios**



Notes: Each pathway comes with uncertainty, marked by the shading from low to high emissions under each scenario. Warming refers to the expected global temperature rise by 2100, relative to preindustrial temperatures.

Source: Our World in Data based on Climate Action Tracker

1979 World Climate Conference takes place in Geneva This is one of the first major international meetings on climate change. Essentially a scientific conference, it is attended by scientists from a wide range of disciplines. It leads to the establishment of the World Climate Program.

row's: reducing our dependence in fossil fuels is not free, but using fossil fuels generates a negative externality on tomorrow's production and general welfare. This trade-off is apparent in developed economies but is perhaps even more salient in developing countries, which need development more urgently as industrialization with fossil fuels can lift millions out of poverty, but these people are those who are most likely to suffer more from climate damages. Therefore, an economist's first task is to think about the optimal path for carbon emissions. The second task, which is intimately linked to the first one, is to think of policies which can most efficiently achieve such a path (at the lowest possible cost to society). Economists have long advocated policy instruments which put a uniform price on carbon, so that consumers and firms internalize the costs of climate change. Third, economists analyze the costs of climate damages to production (by how much will agricultural productivity go down in Southern Spain?), to health (what is the effect of a heat wave on mortality?), to social stability (might climate change cause wars?) or – and this is even more difficult to evaluate – to natural amenities (how much should we value the loss of biodiversity?).

Innovation is key to ensure economic growth while preserving the environment, but innovation is not a silver bullet.

Fourth and more generally, reducing greenhouse gas emissions depends on human actions and requires the right incentives for consumers, firms, and governments. Understanding the link between incentives and actions is of course core to economists' work. In the climate context, this may mean designing policies to encourage consumers to switch to energy-efficient vehicles or lightbulbs, designing institutions so that governments join international environmental agreements, or designing policies which push firms to develop clean technologies.

This paper focuses in particular on the last question. How responsive is innovation to climate policy? And after answering this question, I will explain how its answer changes our approach to the second task, the design of optimal climate policy. We will see that innovation is key to ensure economic growth while preserving the environment, but innovation is not a silver bullet. First, there is not a single innovation that will reduce our dependence on fossil fuels; instead, we will need many (sometimes incremental) innovations in energy-saving technologies and in clean energy. Second, innovation is not manna from heaven, and it is not even necessarily clean. Instead, the direction of innovation responds to incentives and to policies, which means that policies should be designed taking their induced effect on clean (or dirty) innovation into account.

1988 **The Intergovernmental Panel on Climate Change is set up** The Intergovernmental Panel on Climate Change (IPCC) is a scientific and intergovernmental body under the auspices of the United Nations, providing the world with a clear scientific view on the current state of knowledge regarding climate change and its potential environmental and socioeconomic impacts.

Technology trends across countries

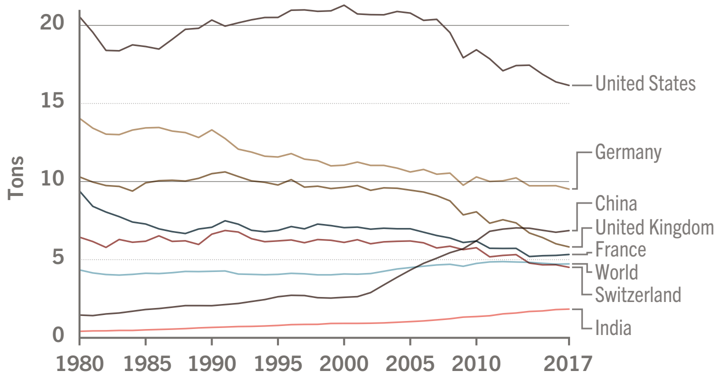
Greenhouse gas emissions have just started to (perhaps) plateau. Given this trend, the prediction of Figure 4 that we are on track to limit the temperature increase to around 3°C may seem quite optimistic, while the 2°C pathway may already appear out of reach. Yet, focusing on recent trends in certain countries delivers a more hopeful message. Now, I present a few facts on technology trends across countries.

Fact 1:

There are huge disparities in CO_2 emissions per capita even for similarly advanced economies.

Figure 5 displays the evolution of CO_2 emissions per capita in the world, the US, China, India, and a few European countries since 1980. It first shows that there are huge disparities in CO_2 emissions across the world: an American produces on average three times more CO_2 emissions than a random person in the world, and close to nine times what an Indian produces. Of course, GDP per capita is much higher in the US than in India, but the correlation between income and emissions is far from perfect. Switzerland is below the world average, France is close to it (and below it once we take changes in land use into account), but clearly both countries are relatively rich. Such cross-country differences reflect differences in technologies (how electric power is produced, how well buildings are insulated, etc.) and consumption choices (what type of cars are popular, how far people live from work, etc.).

Fig. 5 **Per capita CO_2 emissions**



Notes: The figure depicts carbon dioxide (CO_2) emissions from the burning of fossil fuels for energy and cement production. Land use change is not included. CO_2 emissions are measured on a production basis, meaning they do not correct for emissions embedded in traded goods.

Source: Our World in Data based on the Global Carbon Project; Gapminder & UN

Fact 2:

Emissions per capita are declining in advanced economies (and this does not simply reflect international trade).

Second, the trend in several advanced economies is hopeful: even though the US has a very high emission rate per capita, emissions have been declining rapidly since 2008 in part thanks to the shale gas revolution (we will get back to this later in this paper); since 1980, UK emissions per capita have been nearly halved while GPD has close to doubled. Clearly, it is possible to decrease emissions while sustaining economic growth.

One may think that these cross-country differences reflect the role of trade: perhaps, the reason why France and the

1990 **The IPCC produces its first assessment report** In its first assessment report, the IPCC concludes that human emissions are adding to the atmosphere's natural component of greenhouse gases. It underlines the importance of climate change as a challenge requiring international cooperation to tackle its consequences. The report therefore plays a decisive role in paving the way for the creation of the United Nations Framework Convention on Climate Change (UNFCCC).

1992 Convention on Climate Change is adopted The text of the United Nations Framework Convention on Climate Change is adopted at the United Nations Headquarters in New York. This is the key international treaty to reduce global warming and help cope with the consequences of climate change. For the first time binding gas emissions reduction targets are set for industrialized countries.
Earth Summit in Rio Governments are invited to sign the United Nations Framework Convention on Climate Change at the Earth Summit in Rio.

UK do not pollute that much is because their citizens increasingly consume goods produced in China.

Though trade does play a role, it is not the main factor behind these differences and trends: allocating CO_2 emissions to consuming instead of producing countries gives a similar picture (though China now looks cleaner than France or the UK) with similar trends. The only exception is Switzerland which has a very high (and stable) level of consumption-based CO_2 emissions per capita. See Figure 6.

How can we then understand these vast differences in emissions per capita? A useful decomposition is Kaya identity:

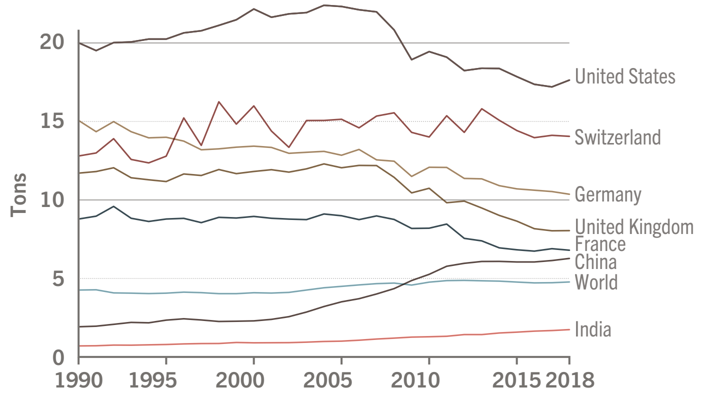
$$\text{Emissions} = \frac{\text{Emissions}}{\text{Energy}} \times \frac{\text{Energy}}{\text{GDP}} \times \frac{\text{GDP}}{\text{Population}} \times \text{Population}$$

This identity decomposes total emissions in a country in four terms: i) the emission intensity of energy, which captures how clean energy production in a country is; ii) the energy intensity, which captures how much energy is needed to produce GDP; iii) GDP per capita and iv) population. This decomposition makes sense because most (though not all) emissions are linked to the production of energy. The equation also clearly shows that to decrease emissions without sacrificing too much income or reducing population, one needs to improve energy efficiency and make energy cleaner.

Fact 3:

Energy intensity is improving across the world.

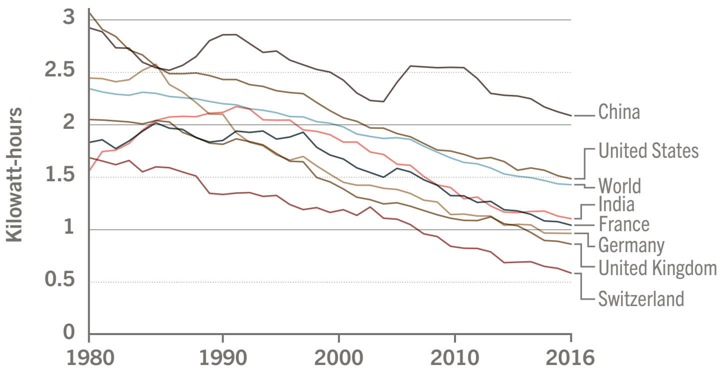
Fig. 6 **Per capita consumption-based CO_2 emissions**



Notes: Consumption-based carbon dioxide (CO_2) emissions are national or regional emissions which have been adjusted for trade (i.e., territorial/production emissions minus emissions embedded in exports, plus emissions embedded in imports).

Source: Our World in Data based on the Global Carbon Project & UN Population

Fig. 7 **Energy intensity**



Notes: Energy intensity is measured as primary energy consumption per unit of gross domestic product. This is measured in kilowatt-hours per 2011$ (PPP).

Source: Our World in Data based on BP; World Bank; and Maddison Project Database

Figure 7 displays the evolution of energy intensity: everywhere in the world, energy intensity is improving rapidly. For instance, energy intensity in the US halved between 1980 and 2016. This trend reflects innovation and adoption of energy-saving technologies but also structural change. As economies transition from energy-intensive manufacturing to less energy-intensive services, the overall energy intensity declines.

Figure 8 instead shows the emission intensity of energy production. There are again large differences in the emission intensity of energy across countries which reflect the substitution between fossil fuels and alternative energy sources, most of the time electricity produced with renewables, biomass, hydro or nuclear energy. Worldwide, there is not a clear trend toward the decarbonization of energy production. Yet, some countries have achieved rapid progress. The carbon intensity of energy decreased by 10% in just 4 years between 2012 and 2016 in the UK thanks to the massive deployment of renewable energy: wind power now accounts for close to a quarter of UK electricity. Thanks to the

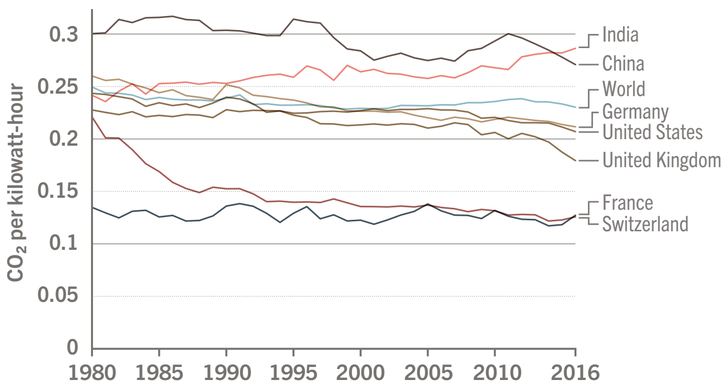
Fact 4:

There are vast disparities in the carbon intensity of energy production and no global trend toward energy decarbonization (yet).

use of nuclear power in electricity production, France managed to halve its carbon intensity in 25 years (between 1963 and 1988). To reduce emissions worldwide without losing too much economic growth, it will be essential to achieve much faster decarbonization of energy production. One piece of evidence that fast technological progress in that direction is possible (and therefore that the decarbonization of energy production can be achieved at reasonable costs) comes from the evolution of the costs of solar panels shown in Figure 9. Between 2006 and 2019, they were reduced by a factor 11.

To summarize, technological differences across the world allow for vast differences in emissions per capita despite similar levels of income. Thanks to technological progress, particularly in energy-saving technologies, emissions have now peaked in most developed economies. Yet, to limit climate change, we need to decrease emissions globally much more rapidly, which will require faster technological progress and technology adoption, particularly in substitutes for fossil fuels in energy production.

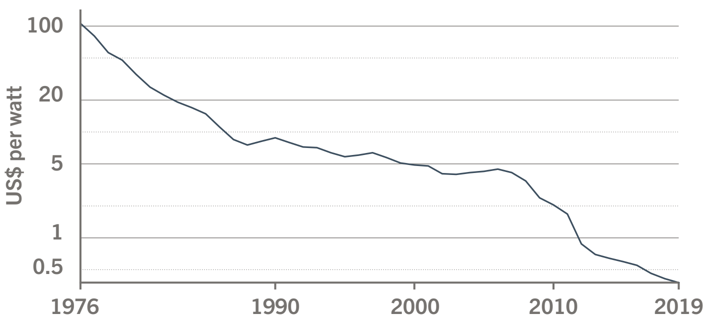
Fig. 8 **Carbon intensity of energy production**



Notes: Carbon intensity of energy production is measured as the quantity of carbon dioxide emitted per unit of energy production. This is measured in kilograms of CO_2 per kilowatt-hour.

Source: Calculated by Our World in Data based on Global Carbon Project; BP; IEA via the World Bank

Fig. 9 **Solar PV module prices**



Notes: Global average price of solar photovoltaic (PV) modules, measured in 2019 US$ per watt.

Source: Our World in Data based on LaFond et al. (2017) and IRENA Database

1995 COP1 takes place in Berlin Parties agree that commitments in the Convention are "inadequate" for meeting Convention objectives. They establish a process for negotiating stronger commitments for developed countries, thus laying the groundwork for the Kyoto Protocol.

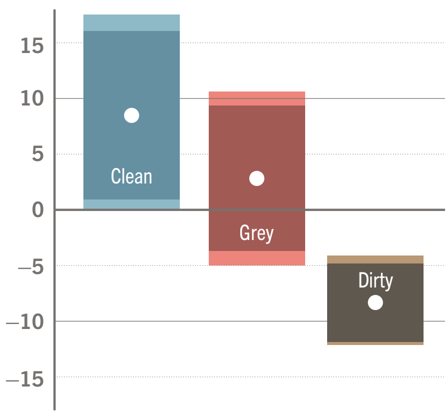
1997 The Kyoto Protocol is adopted The Kyoto Protocol is the world's first greenhouse gas emissions reduction treaty. The Protocol legally binds developed countries to emission reduction targets - an average of 5% by the period 2008–2012, with wide variations on targets for individual countries.

Can policy change technology?

This naturally raises the following question: is the pace and direction of technological change set? Or can it be affected by economic conditions and policies? Is it therefore possible to accelerate the development of green technologies? The economic literature on these questions is clear: the direction of innovation is endogenous and can be changed by policies.

The first study to show this is by Newell, Jaffe, and Stavins.[1] Looking at product characteristics, they found that the energy efficiency of home appliances changed in response to energy prices between 1958 and 1993. Technical change in air conditioners was biased against energy efficiency in the 1960s when energy prices were low, but this bias reversed after the energy shocks of the 70s. Using a time series of US patent data, another study finds that a 10% increase in energy prices leads to 3.5% more patents in energy-saving technologies.[2] Using aggregate data on GDP, energy, capital, and labor, a group of researchers compute a measure of the overall energy efficiency of the US economy.[3] They find that while there was little progress in energy efficiency before the oil shocks of the 70s, there has been steady progress since then. Therefore, various methods reach the same conclusion: higher energy prices lead to more energy savings innovation.

Fig.10 **Effect of a 10% increase in fuel prices**



Notes: The bars denote the 90% and 95% confidence interval.

Source: Aghion, Dechezleprêtre, Hémous, Martin, and van Reenen (2016)

Higher energy prices lead to more energy-saving innovation.

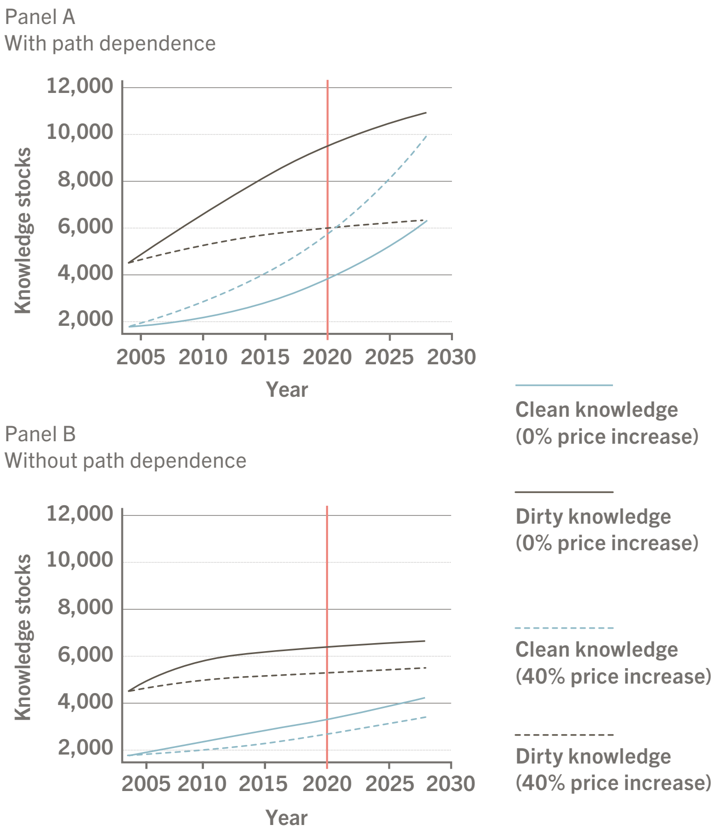
What about reducing the carbon intensity of energy? In a cross-firm study, we investigate how changes in gas prices shape innovation in the car industry.[4] To do that, we use patent data and distinguish between clean innovations which develop alternatives to fossil fuel engines (that is, electric, hybrid, or hydrogen vehicles) and dirty innovations which pertain to fossil fuel engines. Within dirty innovations, one can distinguish "grey" and "purely dirty" innovations. "Grey" innovations reduce fuel consumption of fossil fuel engines, which, however, may incentivize more driving (since it only becomes cheaper). Grey innovations will only reduce total emissions if this "rebound" effect is sufficiently small. In contrast, "purely dirty" innovations improve other aspects of fossil fuel engines, and will typically be associated with higher emissions.

The originality of our work is that instead of using aggregate data, we carry out our analysis at the firm level. This allows us to identify the causal link between an increase in gas prices and a change in the direction of innovation more clearly.[II] To compute a gas price at the firm level, we take advantage of the fact that innovators in the car industry sell their products across various national markets, and thus face different exposure to country-specific fuel price variations, depending on their sales distribution. We then compute a firm-specific fuel price as a weighted average of country-level fuel prices where the firm-specific weights reflect their sales distribution. We use the firm's patent history presample to proxy for this sales distribution. Since Toyota sells a lot of cars (and registers many patents) in Japan and the US but far fewer in Germany, the Toyota fuel price will be heavily influenced by the fuel prices in Japan and in the US, but far less by that in Germany. In contrast, Volkswagen is heavily exposed to Germany, quite exposed to the US but not much to Japan, and the Volkswagen fuel price will reflect this geographical dependence.

We then measure the effect of fuel prices on clean, grey, and purely dirty innovations using 3,412 international firms over the period 1986–2005. We find that a 10% increase in fuel prices leads to 8.5% more clean innovations and 8.3% less purely dirty innovations 2 years later, with no statistically significant effect on grey innovations (see Figure 10). In other words, innovators in the car industry react to the higher prices their customers face by redirecting their innovations away from fossil fuel engines toward alternative engines. We find similar effects if we only use fuel taxes, which are a policy instrument. Interestingly, we also find that electricity prices decrease clean innovations (which makes sense since clean engines use electricity as an input), and that public R&D subsidies to energy-saving technologies favor grey innovation (again, in line with what one would expect).

Importantly, we find evidence for path dependence in the direction of innovation both through internal and external spillovers. Internally, we find that the propensity to patent in clean innovation is greater for firms which have accumulated more clean knowledge. In addition, firms whose innovators are exposed to more clean knowledge (because of their location) also tend to undertake more clean innovation. Similarly, firms with more dirty knowledge or exposed to more dirty knowledge tend to carry more dirty innovations.

Fig. 11 **Evolution scenarios of clean and dirty patents' stock**



Notes: These graphs show the simulated evolution of the aggregate clean and dirty knowledge stocks between 2005 and 2030. The knowledge stock is the discounted sum of past patents. Fuel prices are assumed to increase at once in 2005 and remain constant thereafter. In panel A, knowledge stocks and spillover stocks are recursively updated. In panel B, we switch off the effects of past innovation stocks by the firm itself and of spillovers. In both panels we assume a 1.5 percent growth rate of per capita GDP.

Source: Aghion, Dechezleprêtre, Hémous, Martin, and van Reenen (2016)

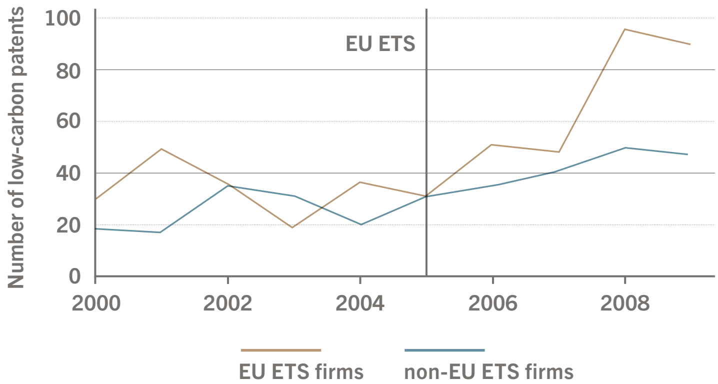
2001 President George W. Bush removes the US from the Kyoto process President George W. Bush removes the US from the Kyoto process, arguing that it puts more of the burden for reducing emissions on industrialized nations instead of developing ones.
The Marrakesh Accords The Marrakesh Accords are adopted at COP7, detailing the rules for the implementation of the Kyoto Protocol, setting up new funding and planning instruments for adaptation, and establishing a technology transfer framework to support developing countries in addressing climate change.

To illustrate how path dependence affects the trajectory of technology, we simulate the evolution of the stock of clean and dirty patents from 2005 (the last year of our analysis) under various scenarios. Figure 11 combines two scenarios, once with (panel A) and once without path dependence (panel B). The first scenario assumes that there is no change in fuel prices. Dirty technologies dominate clean technologies, and the gap widens (solid lines). In the second scenario, we assume that there is a permanent 40% increase in fuel prices. This large shock is enough to ensure that the stock of clean knowledge overcomes that of dirty knowledge in 15 years (dotted lines). Unfortunately, this is not what happened. Panel B reproduces the same exercise but removes the effect of path dependence. Without a price increase, the gap between clean and dirty does not increase as much, but at the same time, the 40% price increase is not enough to ensure that clean technologies overtake dirty ones in 15 years. Path dependence acts as a double-edge sword: it widens the gap between clean and dirty technologies in the absence of policy, but it also makes it easier for clean technologies to catch up to dirty ones in the presence of a significant policy.

Others have used the same method to generate energy price variation at the firm level and compute innovation's response in the electricity production sector.[5] They study how clean and dirty innovations respond both to fuel price and to the market size, where firm-level market size is calculated analogously. Their results support the directed technical change hypothesis: an increase in renewable market size or fossil fuel prices increases renewable innovation, and a larger fossil fuel market leads to more fossil fuel innovation. An increase in fossil fuel price also leads to a large increase in fossil fuel energy-efficiency innovations ("grey innovations").

While we use worldwide variations in fuel prices and taxes in our 2016 study, other papers focus on specific environmental policies. In particular, there is one

Fig. 12 **Number of low-carbon patents since 2000**



Notes: The figure depicts low-carbon patents by matched EU ETS and non-EU ETS firms from 2000 to 2010.

Source: Calel and Dechezleprêtre (2016)

study that examines the influence of the EU cap and trade system (European Union Emissions Trading System, EU ETS), which created an EU-wide carbon price for electricity generation and heavy industry, on innovation in 2005.[6] The EU ETS only applies to installations above certain capacities. The authors of this study take advantage of these regulatory thresholds at the plant level and compare regulated firms with unregulated firms located in the same country, operating in the same sector and of similar size. As illustrated in Figure 12, they find that the EU ETS increased low-carbon innovation (as measured by patent filings at the European Patent Office) by 10% in regulated firms relative to non-regulated firms.

2005 **The EU's Emissions Trading System is launched** The European Union Emissions Trading System, the world's first and largest emissions trading scheme, is launched as a major pillar of EU climate policy.
The Kyoto Protocol enters into force

Introducing an economic climate policy innovation framework

The previous section established that the direction of innovation responds to economic conditions and policies. In fact, policymakers and climate scientists have long argued that overcoming the challenges of climate change requires the development of clean technologies. Yet, the economics literature on climate change has focused on models with exogenous technological change for a long time, i.e., where policies had no effect on the pace of technological development. This is, for instance, the case of the DICE model of William Nordhaus, which earned its author a Nobel Prize, where technological progress in a "backstop" technology which can substitute for fossil fuels occurs at a constant rate regardless of human actions.[7] In such a model, the optimal policy for tackling climate change is a carbon tax which incentivizes society to use less energy and abate emissions.

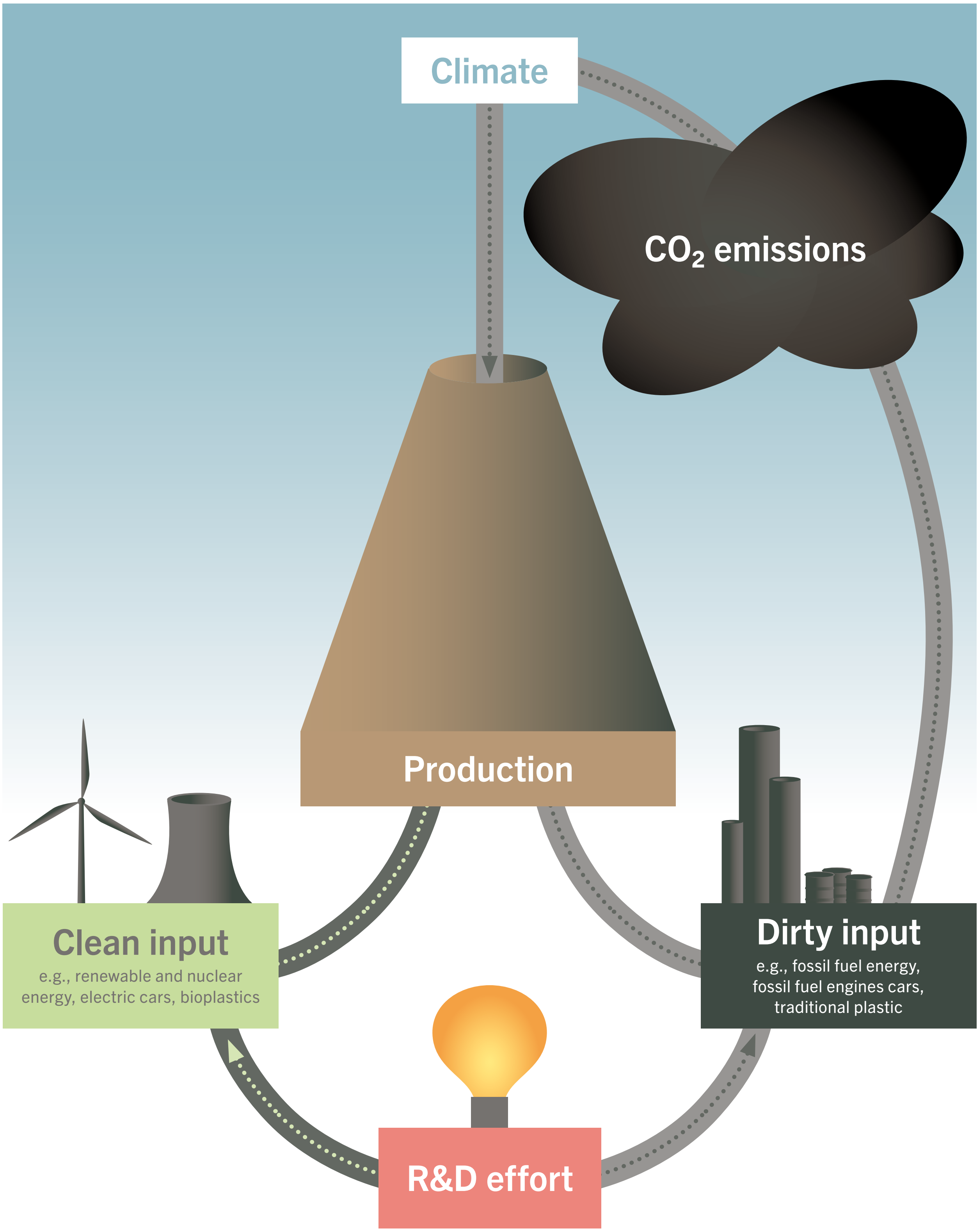
In contrast, we develop a framework (henceforth AABH, after the authors of the study) in our own work to analyze climate policy when the direction of innovation is endogenous.[8] We consider an economy that produces a good with a dirty input or a clean input which can replace it. This framework is particularly suited to think about changes in the carbon intensity of energy, for instance through the substitution between renewable or nuclear energy and fossil fuels in electricity production or the choice between electric and fossil fuel vehicles, but it also applies to the choice between traditional plastics and bioplastics. Scientists/entrepreneurs can choose between improving the clean or the dirty technologies. They allocate their efforts to the sector where they can earn the largest wages/profits.[III] The production of the dirty input generates CO_2 emissions which degrade the environment and eventually diminish welfare.

Figure 13 illustrates the set-up. The framework delivers four main lessons. First, in laissez-faire (without any governmental intervention), there is path dependence in the direction of innovation. If the dirty technology is initially more advanced, that is, fossil fuel energy is cheaper than clean energy, then the dirty sector will be larger: the economy will rely more on fossil fuels than on clean energy. In fact, since the two inputs are substitutes, the more advanced sector will also earn higher revenues. Innovations which improve the dirty input (think about better turbines for natural gas power plants) will then have a larger market than innovations which improve the clean input (think about better blades for windmills). Entrepreneurs will then favor innovation in the dirty sectors and hire more scientists to do research in those sectors. In line with the results of our empirical study on the car industry described in the previous section,[4] the economy exhibits path dependence. This explains in particular why one should not expect clean technologies to really kick-off without policy intervention.

The second lesson is that it is possible to redirect innovation and reduce emissions. Direct subsidies to clean research will push scientists toward undertaking clean innovations. A carbon tax reduces the market for the dirty input and

2007 The IPCC's fourth assessment report is released The report represents the largest and most detailed summary of the climate change situation ever undertaken, created with the help of a large number of contributors, both scientists and governmental representatives. The headline findings of the report were: "warming of the climate system is unequivocal" and "most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations."

Fig. 13 **The AABH economic climate policy innovation framework**



Source: own work

2010 The Cancún Agreements are adopted The Cancún Agreements is a comprehensive package adopted by governments to assist developing nations in dealing with climate change. The Green Climate Fund is established.

increases the market for the clean input. This reduces contemporaneous emissions, but it also indirectly redirects innovation toward clean technologies. Interestingly, a temporary intervention can have permanent consequences on the trajectory of innovation. If research subsidies are maintained sufficiently long so that clean technologies actually become better than dirty ones, then the same market forces which were pushing toward dirty innovation beforehand will now favor clean innovation in the future, rendering future subsidies useless. Again, path dependence acts as a double-edged sword. With technological progress occurring in clean technologies, emissions will decrease over time provided that the clean and dirty inputs are sufficient substitutes (a permanent carbon tax will be necessary otherwise).

Third, policy should be more frontloaded than in a world where technological progress is exogenous (i.e., the policy intervention should be less progressive). Redirecting innovation from an advanced dirty to a laggard clean technology is not free. While economic growth can in principle continue at the same rate as before once clean technologies are sufficiently ahead of the dirty ones, the catch-up phase involves significantly less growth: production increases much less when an economy relearns how to produce energy cheaply using a different technology instead of learning how to make the current type of energy even cheaper. Delaying the energy transition increases its costs because the gap between dirty and clean technologies will widen, leading to a prolonged catch-up phase later on with reduced growth. The prediction of a frontloaded policy stands in contrast with the usual recommendation of a progressive carbon tax, which results from models with exogenous technological progress such as DICE.

Fourth, the optimal policy is not limited to a carbon tax but also involves subsidies to clean research. Economists often argue that a carbon price is the most important and perhaps the only tool necessary to tackle climate change. In AABH, we argue that this exclusive focus is misguided. Clean research subsidies are equally important. Innovation generally involves externalities, so it is not surprising that the optimal policy involves research subsidies, but what is more surprising is that it requires specific subsidies to clean research (in addition to any general research subsidy) even in the presence of an optimal carbon tax. The reason for this result is that the private value of an innovation and its social value have different time horizons.
The social value of an innovation corresponds to the sum of all its discounted benefits from the time of innovation onwards. The private value of an innovation is more short-sighted. A first reason is that patents expire and an innovator can be copied, or they can be replaced by future innovators who develop even better products. A second reason is today's innovators enable future innovators to build on their work (i.e., future innovators will not have to start from scratch). This is true for both dirty and clean innovations, but the optimal policy requires an energy transition so while dirty technologies dominate today, clean technologies will dominate in the future. As a result, a large share of the social value of clean innovation is backloaded: part of the value of developing better wind turbines today results in the fact that they will enable even better wind turbines in 100 years. This is not true for dirty innovation: the value of having developed better gas turbines today will be low in 100 years, as fossil fuels will not be in use anymore.[IV]

Building on AABH by modelling firm dynamics, a group of researchers was able to calibrate their model to the US energy sector, using patent data on clean and dirty energy innovations.[9] As AABH, they find that in laissez-faire, the economy would favor dirty innova-

2011 COP17 takes place in Durban In Durban, governments clearly commit to a new universal climate change agreement by 2015 for the period beyond 2020, where all will play their part to the best of their ability and all will be able to reap the benefits together.

2012 **COP18 takes place in Doha** Governments agree to speedily work toward a universal climate change agreement by 2015 and to find ways to scale up efforts before 2020 beyond existing pledges to curb emissions. They also adopt the Doha Amendment to the Kyoto Protocol, adding new emission reduction targets for participating countries for 2012–2020.

tion. In contrast, under the optimal policy, nearly all innovation efforts need to be immediately allocated to the clean sector. This is achieved thanks to large clean research subsidies, which decline as clean technologies progressively catch up. The carbon tax rises progressively as a share of the dirty energy price before declining once emissions are sufficiently low. Relying solely on a carbon tax instead of a combination of both a carbon tax and research subsidies generates welfare losses (equivalent to 1.9% of consumption every year), as the initial carbon tax needs to be much larger to generate a technology transition.

To summarize, the AABH framework implies that, without policy intervention, innovation is likely to be directed toward fossil fuel technologies instead of the clean technologies that could substitute for them (renewables, electrification). Policy instead should redirect innovation from dirty toward clean technologies. This can be achieved with a combination of clean research subsidies and carbon taxes, and ideally, policy should be frontloaded to engineer a rapid and immediate transition. Of course, the AABH framework is quite simplistic and ignores a lot of heterogeneity in the real world. In the following, we analyze how its lessons can be extended (or not) to other situations: the development of energy-saving technologies, unilateral policies in the absence of a global agreement, and the use of a bridge technology (natural gas), which is less polluting than a dirtier one (coal) but still generates emissions.

Endogenous energy-saving innovation

While AABH focus on the development of technologies which can decrease carbon intensity in the economy, Figure 7 (page 10) shows that energy intensity has been steadily improving over time. This begs the question: should government use the same tools to support energy-saving innovation as energy decarbonization? Perhaps surprisingly, the answer is: not necessarily.

Energy is very complementary to other inputs in the economy, that is, there is little room for substituting energy with more capital or more labor: so much so that in the short-run energy consumption moves one for one with GDP and can be used as an early indicator of economic activity. Imagine then that for one reason or another, energy-saving technology were to lag behind other technologies (say labor-saving technology), the price of energy would increase a lot, while the use of energy would remain the same. As a result, the energy sector would command a higher share of total revenues, which would prompt more energy-saving innovation. Therefore, there is not the same path dependence feature as with the choice between clean and dirty technologies in energy production.[V] Instead, the economy tends to feature a balance between energy-saving and energy-consuming innovations.

Similarly, a carbon tax (or an oil shock) will lead to more energy-saving innovation. Yet, the reasoning that we used to explain the importance of clean research subsidies does not apply here: there are already significant incentives to develop energy-saving technologies and we should not expect the other types of innovation to be useless in 100 years. Therefore, while public intervention is crucial to the development of clean alternatives to fossil fuel energy, carbon pricing can do the heavy lifting for the development of energy-saving technologies. Whether the optimal policy also involves subsidies to energy-saving innovations or not depends on details of the market structure and the innovation technology itself.

Unilateral policies

Our AABH framework abstracts from international considerations, meaning that it applies either to a country in isolation or to the whole world with a global agreement. In reality, international climate negotiations have failed to produce global policies. While the Kyoto Protocol established binding targets for some countries, its successor, the Paris Agreement, let countries determine their targets themselves despite the ambitious objective of limiting warming to below 2°C above preindustrial levels. Article 3 stipulates that "as nationally determined contributions to the global response to climate change, all Parties are to undertake and communicate ambitious efforts […] with the view to achieving the purpose of this Agreement." As a result, climate policies take the form of unilateral actions by countries (or group of countries) which are more or less ambitious.

In this context, "carbon leakage" is a major concern. Carbon leakage occurs when the implementation of a climate policy designed to reduce CO_2 emissions in one country leads to an increase in emissions in other countries without a similar policy. This is an example of what is generally known for other pollutants as a pollution haven effect. Leakage is a direct result of international trade: as the cost of (dirty) energy increases in regulated countries, production of energy-intensive goods relocates to unregulated countries and the regulated countries end up importing more energy-intensive goods from the unregulated ones.[VI] Various forms of carbon tariffs or carbon border adjustments have been suggested to reduce leakage: for instance, the EU proposal from July 2021 plans to add a carbon border adjustment to the EU-ETS cap and trade system.

Economists have used numerous detailed models of the world economy to estimate leakage rate: that is by how much a reduction in emissions in one country tends to be undone by an increase in others. The estimates tend to be roughly consistent: a meta-study found rates of 5% to 25%,[10] other research found rates between 15% and 30% for a tax on developed economies.[11] Importantly, these models are static, that is they only look at the short-term effect of policies, and take technology as given.

In extreme cases, unilateral carbon taxes may even backfire and increase total emissions.

Is carbon leakage a bigger problem in the long run, once technology has had the time to adjust? Can unilateral policies achieve the necessary reduction in CO_2 emissions? I shed light on these questions by adapting the AABH framework to a 2-country, 2-sector set-up, which distinguishes between a regulated and an unregulated country, and between an energy-intensive and a non-energy-intensive sector.[12] This highlights the crucial role that innovation plays both in the positive and normative analysis of unilateral climate change policies.

On the positive side, I find that taking innovation into account makes carbon leakage worse. Intuitively, if the regulated country implements a carbon tax without any border's adjustment, production of the energy-intensive good

2013 COP19 in Warsaw Parties agree on a timeplan for countries to table their intended contributions for the new global climate agreement and for ways to accelerate efforts before 2020. They set up a mechanism to address losses and damage caused by climate change in vulnerable developing countries. They also enhance the implementation of measures already agreed (for instance on climate finance) and transparency of reporting on emissions.

2014 The IPCC's fifth assessment report is released The report provides an overview of the state of knowledge concerning the science of climate change, emphasizing new results since the publication of the previous AR4 report. The report refers to the "clear and growing" human influence on the climate, warning that if left unchecked, climate change will increase the likelihood of severe, pervasive, and irreversible impact on people and ecosystems.

increases in the unregulated country, and with it, emissions. This is the well-understood pollution haven effect, but with endogenous technology, this leads to further changes. In the unregulated country, the increase in the market for energy-intensive goods incentivizes more innovation in the energy sector. And, if that country does not implement a carbon policy, innovation in the energy sector is likely to be directed toward dirty technologies. As a result, emissions in the unregulated country increase further. At the same time, the market for energy in the regulated country decreases, which limits innovation in that sector, including potentially clean innovation. To give a concrete example, the EU-ETS system may reduce steel production in the EU and increase steel production in China.

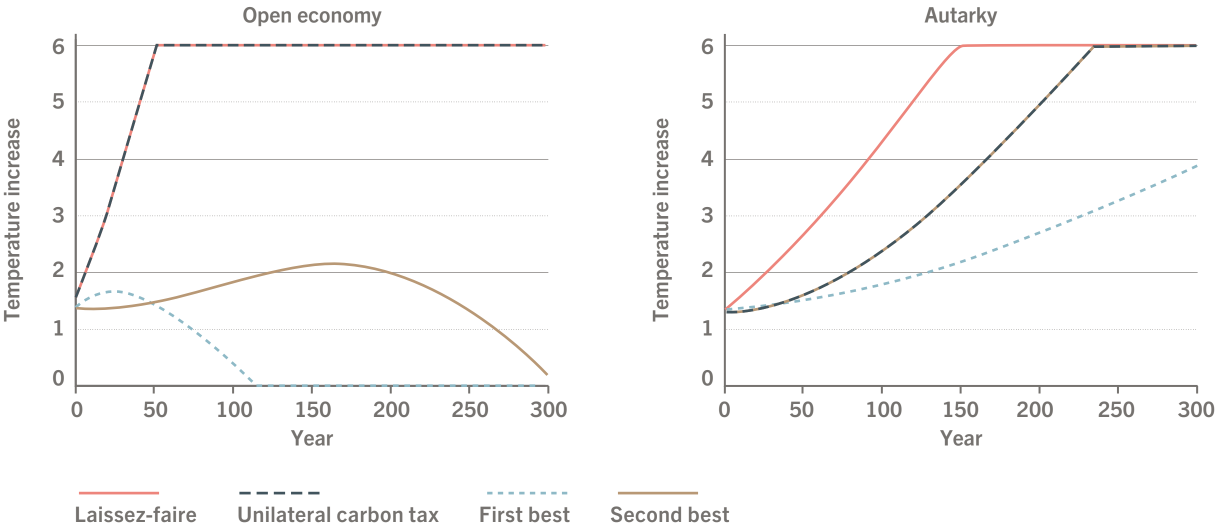
Supporting clean innovation is as important as carbon taxes in unilateral climate policies.

This increases the demand for energy in China, which encourages fossil-fuel-based innovations there, while the reduced market for energy in Europe can slow down the development of renewables here. In extreme cases, unilateral carbon taxes may even backfire and increase total emissions.

Yet, a unilateral "green industrial policy" can reduce emissions in both the regulated and the unregulated countries in the long run. Such a policy combines clean research subsidies with trade policy and carbon taxes with the goal of supporting clean energy innovation in the regulated country. The development of clean technologies in the regulated country (i.e., cheap, clean energy), potentially accompanied by tariffs on energy-intensive goods, can limit the move of energy-intensive goods toward unregulated countries. In principle, it can even reverse this move: as the regulated country invests in clean energy technologies, the pattern of comparative advantage shifts and the regulated country becomes the one exporting energy-intensive goods (while still producing those in a clean way), so that emissions end up decreasing in both countries. Knowledge spillovers can also help: if clean innovation is sufficiently fast in the regulated country, then the unregulated country will start adopting clean technologies, so that its energy-intensive sector will also become cleaner over time. Of course, to have a large effect on the rest of the world, the regulated country (or group of countries) must be sufficiently large. In other words, if the EU invests sufficiently in clean energy and protects its energy-intensive sector, then energy-intensive industries will not move to other countries, and instead other countries will start adopting clean technologies developed in the EU.

Is international trade good or bad for the environment then? In this framework, it really depends on policy. If no policy is in place, then trade increases economic growth and therefore emissions growth as well, leading to a fast rise in temperature. If the "wrong" policy is in place, that is, if the regulated country only implements a carbon tax, then trade is again bad for the environment: it generates carbon leakage and the decrease in emissions in one country is accompanied by an increase elsewhere. Yet, if the right policy is implemented, trade is good for the environment: a unilateral green industrial policy allows the regulated country to export energy-intensive goods, which reduces emissions abroad, which would be impossible without trade. In other words, trade can be used to expand the reach of climate policy. Figure 14 illustrates these notions by comparing the evolution of temperature in a world with trade (open economy) and without trade (autarky), when the

Fig. 14 **The evolution of temperature in a world with trade and without trade**



Notes: The figure depicts the evolution of temperature (from 2008 onwards) under various scenarios and policies. In the left panel, international trade is possible between developed and developing countries; while in the right panel, trade is shut down. The first best line denotes the temperature path under the optimal policy in each setting. The second-best line denotes the temperature path under the optimal unilateral policy in developed economies. The unilateral carbon tax line denotes the temperature path when developed economies can only implement a carbon tax. The laissez-faire line denotes the temperature path when neither developed nor developing countries implement any policy.

Source: Hémous (2016)

regulated country is the group of countries with binding targets according to the Kyoto Protocol and the unregulated country is the rest of the world. The graph looks at various scenarios: laissez-faire, carbon taxes in the regulated country only, second best (which means the optimal policy in the regulated country only) and first best (i.e., the global optimal policy). The exact numbers should be taken with a grain of salt, though, as the model is more illustrative than quantitative. The graph shows that in laissez-faire or if the regulated country implements only a carbon tax, temperature rises much faster in the open economy than in autarky. In contrast, when the regulated country implements the right set of policies (carbon tax but also clean research subsidies and a trade tax), trade allows a significant reduction (and eventual reversion) of the temperature increase.

What does it mean for a small, committed country – perhaps like Switzerland? While the previous analysis focuses on two large countries, some of its lessons apply: even if Switzerland were to become carbon neutral tomorrow, the effect on the path of global temperature would be very small. If, instead, Switzerland were to develop and export better solar panels or new carbon capture technologies, then it could potentially help reduce emissions abroad significantly. This is not to say that a domestic carbon tax is useless in a country like Switzerland: playing one's part can help with reaching a global agreement which remains the best way to reduce emissions, and local carbon pricing has a measurable effect on innovation. But, adopting carbon border adjustments with unregulated countries is justified, and supporting clean innovation is as important as carbon taxes in unilateral climate policies.

2015 **Paris Agreement is adopted** The Paris Agreement on fighting climate change is the first-ever universal, legally binding global climate deal. The objective of the agreement is to maintain the increase in global temperatures well below 2 degrees Celsius above preindustrial levels, whilst making efforts to limit the increase to 1.5 degrees. The agreement aims to ensure global greenhouse gas emissions peak as soon as possible, and to balance emissions and removals of greenhouse gases in the second half of this century. Furthermore, the agreement addresses the adaptation to climate change, financial and other support for developing countries, technology transfer and capacity building, as well as losses and damage.

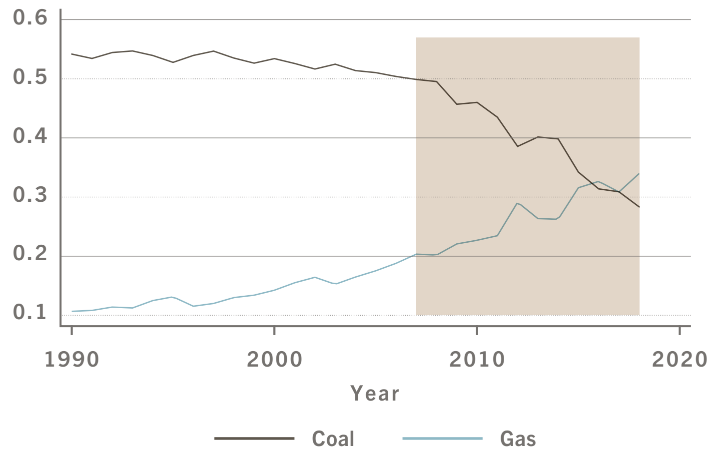
When innovations backfire – lessons from the shale gas revolution

As illustrated in Figure 5, US emissions per capita have decreased considerably since 2008. One of the major reasons behind that result is the shale gas revolution. Before 2003, US shale gas production was less than 4 billion cubic feet (bcf) per day. This number rose to 9 in 2008 and exploded to 30 bcf a day only 4 years later in 2012 thanks to the massive deployment of hydraulic fracking and horizontal drilling. Today US shale gas production is around 70 bcf a day. As a result, US total natural gas production has increased by more than 50% between 2008 and 2018. This sudden abundance of a fossil fuel resource has had profound implications on the US energy sector and its emissions.

First, as illustrated in Figure 15, natural gas has displaced coal as the main source of electricity generation in the US. While more than 50% of US electricity was generated by coal before 2009 and the shale gas revolution, this number has now dropped to below 30%, and natural gas has simultaneously risen from 20% to above 30%.

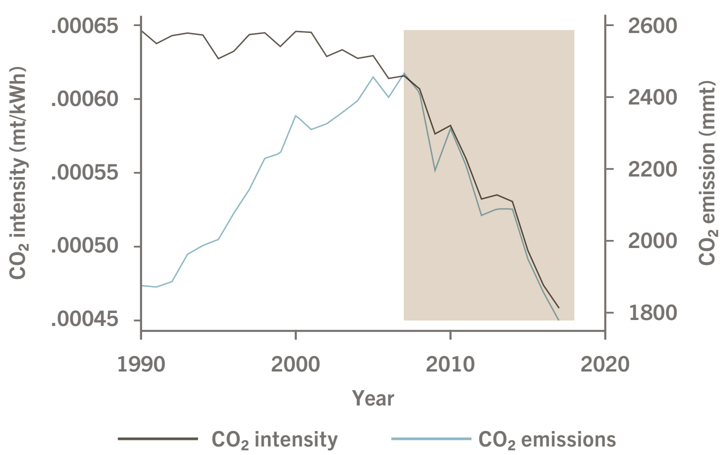
Second, this has directly led to a reduction in the carbon intensity of energy in general and electricity in particular (as reported in Figure 16) in the US. Of course, natural gas generates CO_2 emissions but it is 60% cleaner than coal. Therefore, the substitution of coal with natural gas is the major factor behind the considerable drop in the carbon intensity of US electricity which has been reduced by around a quarter in the 10 years following the shale gas revolution. Figure 16 further shows that total CO_2

Fig. 15 **Fuel shares in US electricity generation**



Source: EIA

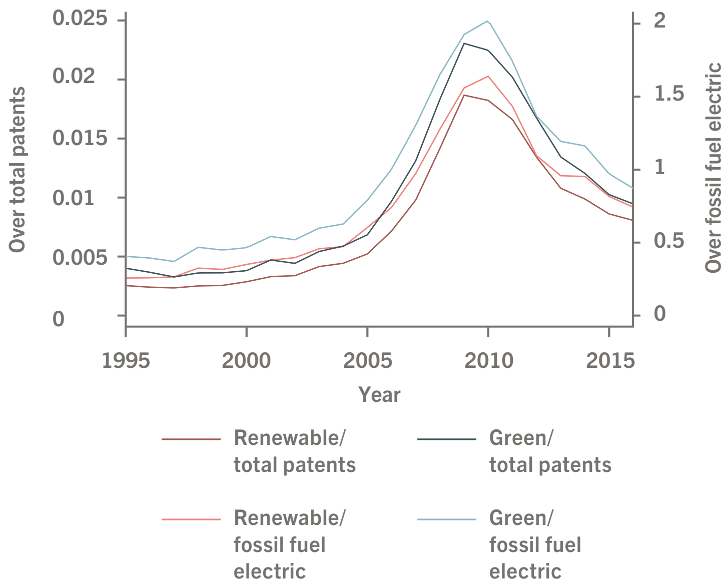
Fig. 16 **CO_2 emissions in US electricity generation**



Source: EIA and EPA

emissions from electricity generation not only stopped growing but have also been decreasing by around a quarter over the same time period. This brings CO_2 emissions from the electricity sector below

Fig. 17 **Spectacular reversed trend in renewable and green patents in the US**



Source: Acemoglu, Aghion, Barrage, and Hémous (2021)

what they were in 1990. Part of the early decline was due to the Great Recession, but while the US economy has recovered from it, emissions have kept declining. It is important to highlight that the only reason why the shale gas revolution could lead to a decline in emissions is because it substituted for a more polluting energy source (coal). A similar expansion of natural gas would not lead to emission reductions in countries with a much cleaner energy mix in electricity production. As a matter of fact, the carbon intensity of the US in 2019, 417 g/kWh, is still an order of magnitude higher than that of France (55 g/kWh) or Switzerland. At the same time, green innovation in electricity has collapsed.[VII] We document this perhaps surprising fact in a recent study.[13] Figure 17 shows that, in the US, renewable patents and green patents (which also include nuclear and biofuels patents) have declined as a ratio of total patents. This is not because patenting in electricity in general has declined. Renewable and green patents have also declined as a ratio of dirty patents in electricity, which are the patents associated with power plants using fossil fuels. These dirty electricity patents do not include patents in extraction technology, so there is no mechanical relationship between the shale gas boom, which resulted from innovations in extraction, and this pattern which focuses on innovation in power plants. In the 2000s, clean innovation was steadily growing relative to dirty innovation in the electricity sector and from 2008, there were more renewable patents than patents associated with fossil fuels in the electricity sector. In 2011, this trend spectacularly reversed.

Could the shale gas revolution explain this pattern? The timing is certainly suspicious: the trend reversed 2 years after the beginning of the boom, which corresponds to the typical time lag between economic changes and the response of innovation as measured by patents.[VIII] In our study, we conduct a simple analysis of 15 countries over the time period 1978–2016 and show that more generally, the ratio of clean over dirty innovation in the electricity sector is negatively correlated with the price of natural gas.[13] The magnitude of this relationship is consistent with the pattern observed during the shale gas revolution.[IX]

We then analyze the long-run macro consequences of the shale gas revolution by expanding the AABH framework to include a choice between a very dirty energy input (coal) and a less dirty one (natural gas). We calibrate our model to the US electricity sector. The shale gas revolution generates an unanticipated decline in natural gas prices and we look at its consequences on emissions, innovation, and production. Figure 18 reports the results when the economy is in laissez-faire. We find that the shale gas boom initially generates a decline in emissions relative to a counterfactual world where it would not have happened (i.e., where the exploitation of shale gas would have been banned).

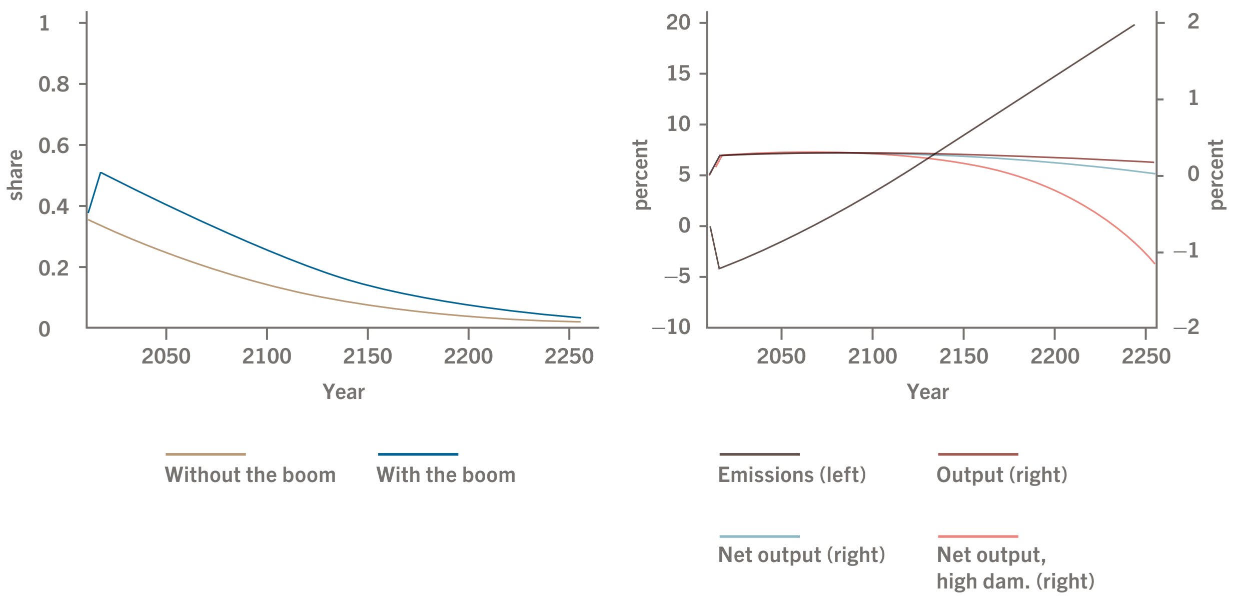
2017 **President Donald Trump announces his intent to withdraw the United States from the Paris Agreement**
COP23 takes place in Bonn COP23 makes significant progress toward clear and comprehensive implementation guidelines for the Paris Agreement, which will make the agreement operational.

2018 **UN IPCC releases its 1.5° special report** The United Nations Intergovernmental Panel on Climate Change (IPCC) releases a report investigating the impact of a 1.5°C rise in temperature (above preindustrial levels). It concludes that emissions will have to be reduced more than scientists originally estimated.
COP24 takes place in Katowice COP24 in Poland ends with mixed results. Countries agree on a deal putting the Paris Agreement into practice, but leave core issues about a global carbon trading system and how to respond to warnings of a temperature rise beyond 1.5°C unresolved.

Fig. 18 **Effect of the shale gas revolution**

Panel A: Share of scientists in fossil fuels

Panel B: % change



Notes: This figure illustrates the effect of the shale gas revolution. The left panel depicts the share of scientists within the electricity sector working on fossil fuel technologies (the remaining share works on clean technologies) under two scenarios: when the shale gas revolution happens and in a counterfactual world without the shale gas revolution (or if shale gas exploitation had been banned). The right panel shows the effect of the shale gas boom on emissions (left axis), output gross of climate damages and output net of climate damages for a medium estimate and a high estimate of damages (right axis).

Source: Acemoglu, Aghion, Barrage and Hémous (2021)

Yet, it also generates a reallocation of R&D efforts away from clean technologies and toward fossil fuel technology.[X] This is true on impact but also over the subsequent years. Clean technologies (related to renewables and nuclear) develop more slowly with the boom than without, and dirty technologies (related to fossil-fuel-based power plants) develop more quickly. This effect compounds over time, so that within a few decades the shale gas boom actually generates an increase in emissions: the economy relies less on coal than without the boom, but it also ends up relying less on clean technologies. Of course, the longer the horizon, the more speculative the analysis is, but the Figure shows that over time, the shale gas boom could generate a substantial increase in emissions. The figure also depicts the effect on output. Since the boom is associated with technological improvement in extraction technologies, it initially generates an increase in output. Yet, this is only a one-time increase (i.e., it does not change long-run output growth), and a small one reflecting the small share of the electricity sector in GDP in the US. The figure further depicts the effect on output net of

Bridge technologies may divert innovation away from actually clean technologies and reduce emissions today at the expanse of increasing emissions tomorrow.

climate damages in a low- and in a high-damage case. In the high-damage case, the increase in emissions in the long run is sufficiently large that the shale gas boom ends up generating substantial GDP losses.

What should the government do then? Banning the use of shale gas is not the best response since the shale gas revolution still initially represents a win for both the environment and the economy. Instead, the optimal policy is to allow the development of shale gas while mitigating its long-run consequences by increasing the carbon tax and subsidies to clean research so as to avoid the collapse in green innovation documented earlier on. To summarize, this analysis shows the dangers of the development of “bridge technologies” such as natural gas, which are cleaner than the most polluting technologies (here coal) while still generating CO_2 emissions. Such bridge technologies may divert innovation away from actually clean technologies and reduce emissions today at the expanse of increasing emissions tomorrow.

2019 **COP25 takes place in Madrid** The longest COP conference on record concludes with an agreement on increased carbon cutting, but disappoints as decisions on a global carbon trading system, clarity on concrete emission cuts and a system to channel new finance to the most vulnerable countries are postponed to the next COP in Glasgow.
The Green Deal The EU Commission presents the Green Deal. Using the European Climate Law, it aims to make Europe climate neutral by 2050.
EU to become climate neutral by 2050 EU leaders agree to make the EU climate neutral by 2050 during a European Council meeting in Brussels.

2020 European Climate Law The European Parliament approves the Climate Law to make the EU and all member states climate neutral by 2050. It sets a more ambitious 2030 emissions reduction target to 60%.

Conclusion

The recent decline in green innovation is a clear reminder that policy is key to direct innovation toward decarbonization. Innovation has the potential to combine the necessary decline in greenhouse gas emissions with sustained economic growth; and it responds largely and rapidly to price signals. This is true both for a carbon tax but also, in the opposite direction, for a decline in the cost of fossil fuels. As a result, climate policy should be designed not only in view of reducing polluting activities today with instruments such as a carbon tax, but also in order to incentivize clean innovation. As we have seen, this means that governments should

1. use front-loaded subsidies to clean research,
2. implement unilateral green industrial policies in the absence of a global agreement and
3. accompany the potential deployment of bridge technologies with renewed support for clean innovation.

Of course, tackling climate change is a complex problem, and this paper omits a number of interesting questions. One is whether it is economically in a country's best interest to act unilaterally and develop clean technologies which can reduce emissions worldwide. On one hand, such endeavor allows a country to build a comparative advantage in sectors which are bound to become more important over time: the next "oil countries" are likely to be those able to deliver cheap clean energy to the world. On the other hand, there is no guarantee that an early edge in clean technologies will survive and pay off: for example, Germany and the US were the world leaders in solar photovoltaic cells in the 2000s, but they have since been overtaken by China.

Another important issue is society's acceptance of climate policy. While youth demonstrations send a message to governments that they need to speed up the energy transition, attempts to implement measures such as carbon taxes have also generated violent backlash as illustrated by the "yellow vest" movement in France. A policy focused on innovation may be easier to accept, but as important as innovation is, economic analysis also emphasizes that emissions should start declining now and carbon pricing is the right tool to achieve reductions in the short-term.

Notes

I. To give just one example: Carleton et al. (2021) estimate that under a high emission rate scenario (RCP 8.5, which predicts a temperature increase of around 4°C), the number of deaths associated with extreme temperatures only would be around 75 per 100,000 per year (taking adaptation into account).[14] This is of the same order of magnitude as all deaths from infectious diseases pre-Covid. By comparison under a moderate emissions scenario (RCP 4.5, which predicts a temperature increase below 3°C), this number is only 11 per 100,000.

II. A positive correlation between fuel prices and clean innovations at the country level may not be so informative: it could be that governments raise fuel taxes when clean cars become better, or that countries with a greater environmental commitment both support R&D in clean cars and raise fuel taxes without a direct effect of the latter on the former.

III. Of course in reality, scientists may also be driven by other motives than income to develop clean technologies. Yet, the results of the previous section show that economic incentives play a large role in directing innovation.

IV. Similarly, innovations in steam engines for cars from the early 1900s generate very little value today, while innovations in the combustion engine from the same period still generate a lot of value, since they enabled better combustion engines today.

V. In contrast, if clean energy technologies lag behind dirty energy technologies, there is less demand for clean energy, and the revenues of the clean sector are lower (despite the larger price). This is because clean and dirty energies are substitutes.

VI. Note: Leakage can also occur directly through trade in fossil fuels: a carbon tax in a given country reduces local demand for oil, which decreases its global price, which in turn encourages oil consumption in other countries.

VII. At first glance, a decline in green innovation seems to contradict the reduction in the cost of renewables, notably solar, documented in Figure 9. Yet, the decline in the cost of solar may reflect the delayed adoption of innovations occurring before the collapse of green innovation. In addition, part of the decline is also due to a decrease in labor costs following the move of production to China.

VIII. This is the time lag used in Aghion et al., 2016.[4]

IX. A similar trend, notably for photovoltaic innovation (but not so much wind power), exists in Europe, suggesting that other factors have also probably contributed to the decline in green innovation (see Popp, Pless, Hascic and Johnstone, forthcoming).[16]

X. In this version of the model, a clean transition does occur and the shale gas boom slows it down. In other versions, there is no clean transition without policy intervention and the shale boom accelerates a specialization in dirty innovation. The pattern that ultimately emerges depends on assumptions on policy and on the future costs of extracting coal and natural gas.

2021 COP26 takes place in Glasgow

Source:
European Parliament A GUIDE TO CLIMATE CHANGE NEGOTIATIONS . www.europarl.europa.eu/infographic/climate-negotiations-timeline/index_en.html#event-2019-12-13

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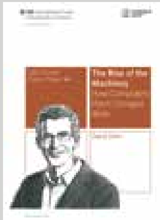

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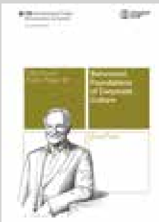

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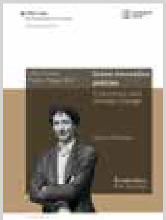

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