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23-14 Green innovation and the transition toward a clean economy

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ABSTRACT

To combat climate change without sacrificing long-term economic growth, innovation must be redirected toward green technologies. In this paper, we review a recent literature that has developed a directed technical change framework where innovation can be endogenously targeted either toward fossil-fuel enhancing technologies or clean energy sources (such as renewables). We provide empirical evidence of path dependence in firms' choice between green and dirty innovation. We then draw implications of this path dependence for the design of environmental policy and for economic growth. In particular, we show that our framework has distinctive implications regarding unilateral environmental policies, international cooperation, the use of intermediate energy sources such as natural gas, and the role of civil society.

JEL codes: F18, O30, O41, O44, Q43, Q54, Q55
Keywords: green growth, endogenous growth, directed technical change, climate change, innovation, environmental policy

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1. Introduction

Climate change is one of the most pressing challenges facing the world today. By now, there is a general consensus that economic activities that emit greenhouse gases such as CO_2 contribute to climate change. This observation motivates the growing chorus of voices advocating a slowdown of, and even an end to, economic growth in order to reduce emissions. However, these calls ignore the massive costs that lower growth would imply for the standards of living of billions of people around the world, and the political and social disruptions that an end to growth would bring.

Our research, in contrast, proposes that a redirection of technological change towards greener innovation can combat climate change without sacrificing long-term economic growth.

While green innovations are feasible and have the potential to significantly reduce emissions, they will not take place by themselves, unless incentives are altered in both the energy sector. This is all the more so, because of “path dependence”: decades of investments in technologies complementary to fossil fuels have made clean technologies, such as renewables, initially less productive and less profitable than fossil fuels.

We develop our key ideas in the context of a framework of directed technological change in the energy sector, where new innovation efforts could be targeted to fossil fuels or to cleaner sources of energy, such as renewables.[1] Path dependence in this framework arises from the fact that past innovations in fossil fuels make current fossil-fuel technologies more productive than cleaner alternatives and renders transition to clean technology much harder.

The framework has several distinctive implications. First, both carbon taxes (or cap and trade policies) and subsidies to green innovation can help redirect technological change and help combat climate change. Second, optimal climate policy in this framework looks very different from those in other economic models and also from those most commonly discussed in the policy debates. Specifically, it is necessary to combine carbon pricing with clean innovation (“green”) subsidies. Moreover, these policies should be immediate and frontloaded – meaning that the sooner innovation subsidies are implemented, the more effective they will be in the face of path dependence. Third, investment in green technologies may increase, rather than retard, economic growth, so combating climate change is consistent with economic growth. Fourth, there is a stark contrast to models with exogenous technology, where climate policy is hampered because of free riding by other countries which can selfishly benefit from investing in fossil fuels while some nations are adopting policies such as a carbon tax. With endogenous and directed technology, there

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[1] On models of directed technological change, see Acemoglu (1998, 2002).

can be natural complementarities, because once a set of countries start pushing the clean technology frontier, other countries will find it profitable to use these technologies. Fifth, we show that “intermediate” (less polluting) fossil fuels that reduce emissions in the short run may prevent, rather than help, transition to clean energy, because they reduce incentives to invest in green innovations. Finally, our framework also highlights a distinct role for civil society action as an additional lever to encourage green innovation.

Although we are not the only ones to emphasize the role of green innovation in tackling the climate crisis, both the academic literature and the policy discussions have not properly emphasized the critical need for redirecting technological change. In fact, the dominant approaches in economics treat technology as given, and even when they recognize the importance of innovations in combating climate change, there is insufficient attention paid to how current innovation efforts can be and should be redirected towards green technologies.

The remainder of this paper is organized as follows. In Section 2, we start with a discussion of evidence on how policy can redirect innovation and the role that “path-dependence” – the relative advantage of fossil fuels driven by past innovations – plays in this. In Section 3, we summarize the climate policy debate around climate models with exogenous growth and technology. In Section 4, we outline the implications of our framework on directed technological change and highlight how they radically differ from those that have been proposed previously. In particular, a distinctive implication of the framework is that immediate intervention reduces the cost of clean transition. In Section 5, we point out that combating climate change need not sacrifice, and sometimes may even contribute to long-term economic growth. In Section 6, we illustrate how the nature of multi-country interactions changes fundamentally in the presence of directed technology. In Section 7, we explain why “intermediate” fossil fuels, such as natural gas, that reduce emissions can nevertheless retard or even prevent transition to clean technology and harm the environment in the long run. In Section 8, we look at the role that civil society can play in promoting green technologies. Section 9 concludes.

2. Incentives for and barriers to green innovation

A first question is whether it is possible to effectively encourage green innovation and what the key barriers to such innovation are. Aghion et al.

(2016) provide answers to these questions using data from the automobile industry.[2]

The authors compile data on patents filed by automobile companies from 80 countries between 1978 and 2005. They distinguish between “green” innovations, specifically those targeted to electric vehicles, and polluting innovations, which focus on advances related to (internal) combustion engines. These different categories of innovation are identified from the International Patent Classification (IPC). For each innovator (firm or individual), the authors compute the green and polluting patent flows and stocks between 1978 and 2005.

A first important finding points to the barriers facing green innovation. Even though combustion engines have been developing for over a century, there is no evidence of a natural switch to electric vehicles. On the contrary, in line with the path dependence ideas discussed in the Introduction, firms that have accumulated a large stock of polluting patents are more likely to continue to innovate in polluting patents. Likewise, the few firms that have built a stock of green patents are more likely to innovate in green technologies. There is also evidence of sizable contemporaneous spillovers contributing to path dependence: firms operating in countries with more polluting patents are more likely to innovate further in polluting patents. Intuitively, past innovations in polluting technologies have built up a knowledge stock that is more useful for further innovations in the same technologies than they are for nascent green technologies, such as electric vehicles.

Path dependence goes well beyond the automotive industry. For example, Noailly and Smeets (2015) provide evidence of path-dependence in the direction of innovation in the sector of electricity generation, using patent data for fossil-fuel (FF) and renewable energy (REN) technologies for 5471 European firms over the 1978–2006 period.

Path dependence constitutes a major barrier to the transition to clean energy. Because almost all countries have by now more expertise complementary to existing fossil-fuel technologies than cleaner alternatives, they have natural incentives for further investment and innovation in fossil fuels.

Against this background, Aghion et al. (2016) also show that public policy can be effective in redirecting technology. Using the geographic distribution of

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[2] Aghion, P., Dechezleprêtre, A., Hemous, D., Martin, R. and Van Reenen, J., 2016. Carbon taxes, path dependency, and directed technical change: Evidence from the auto industry. *Journal of Political Economy*, *124*(1), pp.1-51.

pre-existing patents, the authors build a measure of firm-specific fuel price, as a weighted average of country-level fuel prices and taxes. Their estimates indicate that a 10% increase in fuel prices faced by a firm raises the firm's green patenting by 10% and reduces its fossil fuel patents by 5%. These estimates suggest that higher carbon taxes that increase fuel prices faced by consumers and firms can have a powerful effect in encouraging green innovations and can counterbalance the impact of path dependence, driven by a century of fossil-fuel innovations.

The evidence in Popp (2002), Calel and Dechezleprêtre (2016), Dugoua (2023), and Acemoglu et al. (2023) also supports the role of carbon pricing in redirecting firms' innovation towards green technologies.[3]

In sum, the current state of knowledge in the energy and related sectors appears to be biased in favor of fossil-fuel technologies, due to a history of investment in these areas. This implies that unfettered markets are unlikely to generate sufficient investment in new green technologies. On the bright side, higher prices for fossil fuels and higher taxes emerge as powerful tools for redirecting technological change towards cleaner alternatives.

3. Current policy debates

Despite the broad recognition that renewables and other cleaner technologies will have to play a major role in the energy transition, much of the academic literature informing policy has so far focused on models with exogenous technologies. This focus is illustrated by the pathbreaking work of William Nordhaus, including the Dynamic Integrated Climate-Economy (DICE) model, used in numerous policy evaluations.[4] This framework introduces global warming from greenhouse gases and economic damages from a warming climate into an otherwise standard exogenous model of economic growth. It assumes that production generates greenhouse gases, the baseline technology improves exogenously, and the economy may have access to a cleaner backstop technology. Missing, however, is any possibility that policy or other factors might influence the direction of future technology.

In this framework, the only source of inefficiency is the uninternalized damages from greenhouse emissions — each producer ignores the fact that

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[3] For example, Popp (2002) shows that higher energy prices lead to more energy-saving innovations in the time series of US patents; Calel and Dechezleprêtre (2016) show that the EU-ETS led regulated firms to introduce more low carbon innovation; and Dugoua (2023) shows that the Montreal protocol led to the development of substitutes to CFCs. We discuss the evidence of Acemoglu et al. (2023) on natural gas prices and green innovation later in the paper.

[4] Nordhaus, W.D., 1992. The 'DICE' model: background and structure of a dynamic integrated climate-economy model of the economics of global warming. Cowles Foundation Discussion Papers. 1252.

their output also contributes to global warming. This modeling of climate change and market structure has a number of important implications.

First, with only one source of inefficiency, a single instrument is sufficient for implementing the optimal policy, and this single policy takes the form of a carbon tax or a carbon price, since what is needed is to make firms internalize the environmental externalities that they create with their greenhouse gas or carbon emissions (in the manner of a Pigouvian tax). Consequently, this tax is proportional to the carbon content of production.[5]

Second, with a single instrument at play, the key question turns on the level and timing of the carbon tax. Here, the simple structure of the model closely ties optimal policy to the discount rate — how costly it is to reduce consumption today in order to save the climate in the future. For the baseline discount rates used by Nordhaus, which are based on observed interest rates, optimal policy exhibits a "ramp-up" pattern – the carbon price starts at a relatively low level of approximately \$60/t CO_2 (\$2019) in 2020, which then increases over time to more than double its initial value (\$150/t CO_2) by 2050.[6] The intuition for this form of optimal policy is simple: high carbon taxes reduce GDP and consumption, and discounting implies that it is best to delay these costs by some amount.

Assumptions other than those concerning the discount rate matter as well. How sensitive GDP is to global warming and how rapidly damages rise with increased warming are particularly important. For example, Barrage and Nordhaus's (2023) baseline finding that a 3°C increase in global temperatures over preindustrial times would be associated with a 3.1% drop in worldwide GDP may be an underestimate, and increasing potential damages would raise the optimal carbon tax level.

The most important parameter for policy, predictably, turns out to be the discount rate. For example, the influential British government report led by Lord Nicholas Stern, the Stern Review, used a similar model with exogenous technology but with discount rates chosen on ethical considerations. That is, instead of calibrating the discount rate to market interest rates, the Stern Review advocated giving a high weight to future generations in the design of welfare maximizing policies. As a result, the implied optimal policies were more aggressive and immediate.[7] With an overall discount rate between 1% and 2%

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[5] This objective can also be achieved by using quantity restrictions or cap and trade like mechanisms.

[6] Barrage, Lint, and William D. Nordhaus. *Policies, Projections, and the Social Cost of Carbon: Results from the DICE-2023 Model*. No. w31112. National Bureau of Economic Research, 2023.

[7] Stern, N.H., 2007. The economics of climate change: the Stern review. Cambridge University press.

per year as in the Stern Review, the social cost of carbon in 2020 would be as high as \$170-430/tCO_2, even in the DICE framework.

The sensitivity of the timing and level of climate policy to the discount rate is an ongoing feature of current debates. Recent efforts, such as the Climate Impacts Lab's assessment (Carleton et al., 2022), estimates from Resources for the Future (Rennert et al., 2022) and recent assessments from the U.S. Environmental Protection Agency, still crucially depend on the discount factor.[8] Low discount rates have been criticized on ethical ground for being inconsistent with other public policies particularly those that generate trade-offs across existing generations (Barrage, 2018, Eden, forthcoming).

We will next discuss how the role of disagreements on the discount factor is lessened and a very different set of insights on optimal policy emerge once we recognize the response of the direction of innovation to various government interventions.

4. The view from directed technological change[9]

When the direction of technology — specifically, the balance between innovation in fossil feel technologies and clean technologies — is decided by market forces, both the positive implications and lessons for optimal policy are sharply different from the exogenous technology benchmarks.

Suppose, following Acemoglu et al. (2012), that there are two substitutable ways of producing energy, dirty and clean, and innovation can be directed either to improving the quality of intermediate goods used in dirty production or clean production.[10]

A first result of this framework, coupled with path dependence is a simple form of a fossil-fuel trap in market economies: when the two types of energy are substitutable and we start with dirty technologies sufficiently ahead

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[8] Environmental Protection Agency (EPA), 2022. "Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances" in: "Supplementary Material for the Regulatory Impact Analysis for the Supplemental Proposed Rulemaking, 'Standard of Performance for New, Reconstructed, and Modified Sources and Emissions Guidelines for Existing Sources: Oil and Natural Gas Sector Climate Review.'" Docket ID No. EPA-HQ-OAR-2021-0317, September 2022. See, e.g., Figure 8 in Barrage and Nordhaus (2023) on reconciling these estimates based on the discount factors they use.

[9] See Acemoglu, D., Aghion, P., Bursztyn, L. and Hemous, D., 2012. The environment and directed technical change. American economic review, 102(1), pp.131-166. for details. We note that numerous earlier studies had also taken important steps towards endogenizing elements of technology in integrated analyses of the climate and the economy (see discussion in Acemoglu et al. 2012).

[10] The related framework in Acemoglu, Akcigit, Hanley and Kerr (2016) extends Acemoglu et al. (2012) by modeling firm innovation behavior and allowing clean and dirty technologies to compete across a range of energy tasks, some of which may feature much bigger gaps between clean and dirty technologies.

of clean technologies, the market will direct all innovation resources towards the dirty technology. Intuitively, when dirty technologies are far ahead of clean technologies, the market for dirty products is larger than that for clean products (and clean technologies are not cost competitive with dirty technologies), and this encourages further dirty innovation.

The framework also shows that if clean technologies were to reach parity with dirty technologies, then the market process can incentivize clean innovations. These two observations are at the heart of the normative implications of this framework.

The first implication is that optimal policy needs at least two instruments: a Pigouvian/carbon tax and a subsidy to clean innovation. There are two complementary ways of understanding this result. From a purely theoretical point of view, there are now two market failures. Firms not only fail to internalize their direct impact on the environment via carbon emissions, but they also fail to internalize their effect via the knowledge stock of the economy. In particular, investing in clean technologies today improves the productivity of clean innovation in the future, which then helps transition to clean technology. This is not because there are differential spillovers between the two types of technologies (though those might exist as well as we discussed below). The key reason is that, although there are knowledge spillovers for both clean and for dirty technologies, knowledge spillovers in the former are more socially valuable while the economy is transitioning to clean technology. Green subsidies enable those spillovers to be realized sooner and thus clean innovation to build on the transition path.[11]

Another helpful intuition is that the social planner would like to reduce current emissions while also redirecting technological change away from fossil fuels towards cleaner energy. Although a high carbon tax helps achieve both objectives, if we were to rely only on a carbon tax, this would necessitate a very high tax level to have a sufficiently big impact on the direction of innovation, and such a high tax would then lead to a large reduction in current production and consumption. Using the two instruments enables policymakers to limit current economic costs while still achieving the desired redirection of technology. This conclusion contrasts sharply with the main policy lesson from

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[11] Interestingly, this logic does not extend to subsidies for energy-saving innovation. While energy-saving innovations can also help reduce emissions, energy is a complementary input to non-energy inputs and the economy is not going to undergo a transition from energy to non-energy inputs. This is why Directed Technical Change (DTC) models that focus on energy-saving versus energy-using innovation do not find an important role for R&D subsidies in the design of climate policy (see Hassler, Krusell and Olvosson, 2021, or Hémous and Olsen, 2021).

models of exogenous technology, which suggest that selecting the right level and time path of a carbon tax is sufficient for optimal policy.

A second policy implication from directed technological change is equally important. In contrast to the sensitivity of the time path of optimal interventions to the discount rate in models with exogenous policy, this framework implies that policy intervention should be immediate and front-loaded in general.[12] This is because path dependence gets worse with every day in which a decisive intervention is not undertaken, as more innovation and knowledge accumulate for the dirty technology. Therefore, the sooner the right combination of clean technology subsidies and carbon taxes is introduced, the better. In addition, the intuition provided above also suggests why after a while, interventions can be lessened: once clean technologies did catch up with dirty ones, the market process starts generating sufficient incentives for clean innovations, and the need for clean research subsidies weakens. Depending on how long the carbon stock stays in the atmosphere and how small the dirty technology sector becomes, optimal policy may even have zero carbon tax in the long run. This will be the case, in particular, when carbon emissions are sufficiently low that they do not increase the global temperature above preindustrial times.

Finally, these models also shed light on which of the two policy tools — carbon taxes or clean subsidies — are more important for transitioning to clean technology. This question is particularly important in view of the previous literature’s emphasis on carbon taxes, coupled with the inability of U.S. administrations to pass a comprehensive carbon tax, which have led to more subsidy-based policies in the Inflation Reduction Act, IRA (which is essentially a climate bill passed by the Biden administration).

The results in Acemoglu et al. (2016) imply that, perhaps at first surprisingly, clean technology subsidies are more important. In particular, limiting policy to only carbon taxes leads to significantly larger welfare losses than limiting it just to clean technology subsidies, and this remains true even when the subsidies are inefficient at the margin (e.g., some of the incentives are wasted). Intuitively, if such subsidies can manage to redirect technological change within a reasonable timeframe, then the market process will thereafter favor clean technologies, enabling rapid decarbonization. Carbon taxes are still useful, even with powerful clean technology subsidies, because they would enable lower emissions during the transition. Nevertheless, since the economy is already transitioning to clean energy, their absence creates more limited

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[12] There can be exceptions to this for sufficiently low levels of the discount rate because the same mechanism as in Nordhaus's analysis — the desire to delay costs — could become dominant, despite the new economic force introduced here.

welfare losses. In contrast, just relying on carbon taxes would either fail to secure a sufficiently rapid transition to clean energy or the very high levels required to ensure such a transition would lead to larger welfare losses as they induce sharp reductions in total energy consumption before clean technologies become competitive with dirty ones.

5. What is the cost of clean transition?

The exogenous technology benchmark ties reductions in carbon emissions to reductions in production in energy-intensive sectors, and consequently, implies that there is always a significant cost of a clean transition in terms of economic growth.

The implications of a framework based on directed technology are richer. To start with, the simplest frameworks, such as those discussed in the previous section always imply that there is a *short-run* cost, because energy consumption is shifted away from cheaper dirty inputs towards more expensive clean inputs. But acting now rather than later unambiguously helps minimize these short-run costs, because the sooner this transition is initiated, the smaller is the advantage of dirty technologies relative to clean ones.

Figure 1 illustrates this point using a calibrated version of the directed technological change model of Acemoglu et. al. (2023). [13] The two curves in the figure compare output net of climate damages under, respectively, the optimal policy and a delayed version of the optimal policy, which starts after 20 years. The laissez-faire net output (without any policy) is normalized to zero, and hence these curves depict the change in net output under the two policy regimes. The green curve shows that with the optimal policy, there is an immediate decline in output below the laissez-faire, but the economy quickly recovers and net output then far exceeds the one in the laissez-faire economy, because climate damages are brought under control. The purple curve for delayed policy, on the other hand, avoids the immediate decline in net output, but an even larger decline takes place after 20 years. Thereafter, the delayed policy never catches up to the (immediate) optimal policy, underscoring the suboptimality of delaying comprehensive climate change policies.

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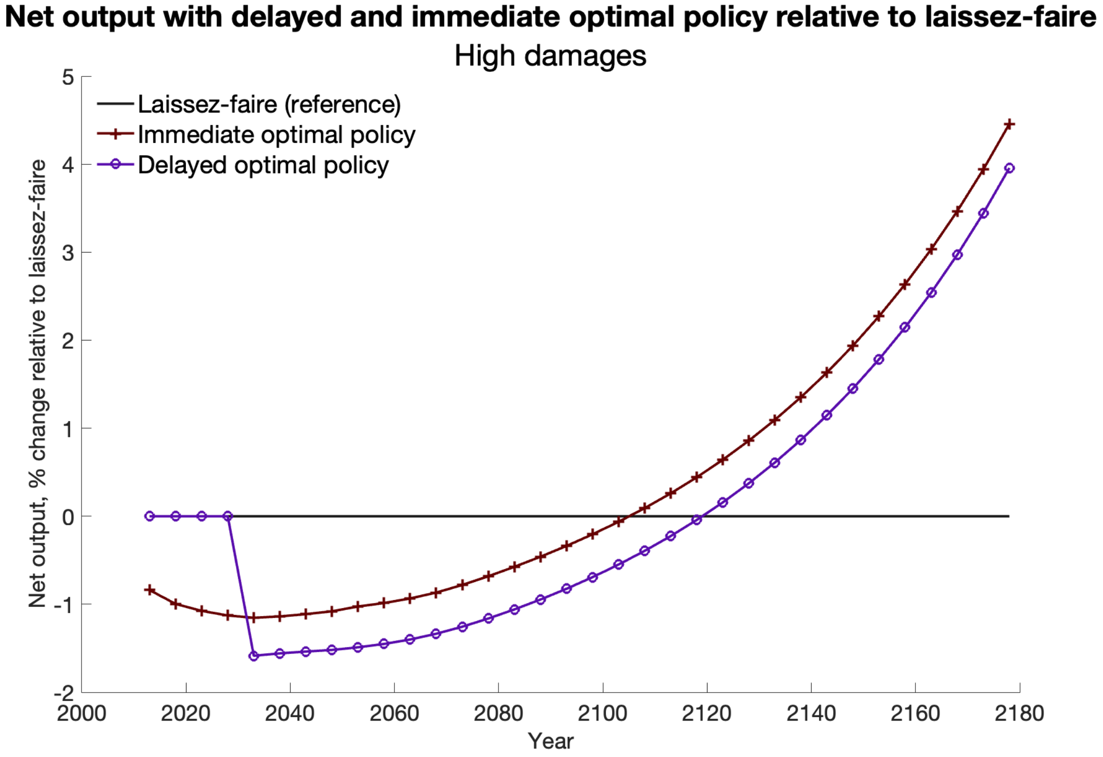
[13] Acemoglu et al. (2023) calibrate an economy with directed technological change and coal-based, natural-gas based and green-based energy to electricity data from the United States. Here, we use the version of the model with a 1% discount rate and high climate damages. In addition, to account for U.S. emissions outside of the electricity sector, we exogenously impose the same change in non-electricity emissions as in electricity emissions.

Figure 1



Note: The costs of delaying intervention for 20 years in the baseline calibration in Acemoglu et al. (2023). The two curves show the changes in output net of climate damages under optimal climate policies and a delayed version of optimal climate change policies, in both cases relative to net output in the laissez-faire economy, which is normalized to zero.

More generally, the medium and long-run implications of implementing optimal policies depend upon the technological opportunities. If the growth potential of clean technologies is the same as that of dirty technologies, economic growth can go back to its pre-climate policy level after the process of redirecting technology is completed,. If, on the other hand, there are fewer growth opportunities in clean technologies, long-run growth can slow down. Conversely, however, if clean technologies have greater room for long-run innovation, growth could even accelerate after a transition to clean technology.

Although we do not have enough information to say anything definitive about these long-run possibilities, there are two reasons why post-transition growth may be no less, or even possibly greater, than before. First, after sufficient advances have been made, renewables may be cheaper than fossil fuels, because they do not require costly extraction of resources, such as coal, oil or natural gas. A recent comprehensive assessment by Arkolakis and Walsh (2023) finds evidence in support of this presumption, showing that many regions of the United States may get significantly lower energy prices after the energy transition triggered by the IRA. Second, Dechezleprêtre, Martin and Mohnen (2014) estimate that clean technologies generate more knowledge spillovers for other innovations, which would also be another source of faster growth after a clean transition.

Even the short-run growth costs may be more nuanced in general. Michael Porter (1991) has suggested that a clean transition can lead to faster growth. Acemoglu (2010) provides a simple framework in which this claim can be assessed, and proves that under some simple conditions and starting from no or very little environmental regulation, an energy transition can improve productive capacity and thus lead to an expansion of output, because transition to cleaner technologies can boost investment and the rate of technological progress. Intuitively, in the Acemoglu (2010) model, there is a strong form of "scarcity is the mother of invention" channel. When there is a shortage of relevant inputs, this triggers more investment and thus more growth. The beginning of a clean transition creates such a scarcity, because clean energy is scarce (and firms are discouraged from using the abundant dirty energy), and this can induce more rapid growth.

To sum up, the current literature suggests that the medium-run and long-run growth implications of the energy transition are uncertain, and yet there are good reasons to suspect that, such a transition will not be as bad for economic growth as models with exogenous technology suggests.

6. Is global cooperation necessary for the energy transition?[14]

A common concern is that, even though climate change is a global problem, each nation would have an incentive to free ride on the green policies of other countries. For example, European carbon taxes may increase the cost of goods such as steel in these countries, which may then incentivize other nations to expand steel production and also refrain from their own carbon taxes. Existing estimates suggest "leakage rates" in the range of 5-25%, meaning that a 1% reduction in carbon emissions in a group of regulated countries tends to lead to a 0.05-0.25% increase in emissions from unregulated countries (see Branger and Quiron, 2014).

An obvious solution to this is international coordination and cooperation, so that all countries are effectively regulated. But this has proven to be difficult and a number of countries have instead turned to unilateral policies with local carbon markets, such as EU-ETS in the case of the European Union and the IRA for the United States. How does endogenous and directed innovation affect the effectiveness of unilateral policies?

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[14] See Acemoglu, Aghion, and Hémous (2014) and Hémous (2016).

To start with, the pollution haven effect associated with unilateral carbon pricing may become exacerbated when innovation is endogenized. Following the implementation of a unilateral carbon tax, the production of energy-intensive goods moves from regulated to unregulated countries. In addition to the adverse direct effects for carbon emissions, this industrial relocation also complicates the energy transition in the regulated countries, because the flight of energy-intensive goods shrinks the market for cleaner technologies in the regulated country. Moreover, with the expansion of the production of energy-intensive goods in unregulated countries, the incentives to further invest in dirty technologies in these countries are also strengthened. As an example, if steel production moves from Europe to India in response to European carbon taxes, this reduces incentives to innovate in clean energy technologies, such as electric-arc-furnaces (EAF), and the European steel sector, while boosting the incentives to invest and innovate in conventional, dirty technologies, such as blast-oxygen-furnaces (BOF), in the Indian steel industry. Both of these effects reduce the efficacy of unilateral policies.

In contradistinction to this first adverse effect, a unilateral “green industrial policy’’ targeting redirection of technology can also gain strength in the global context. If such a policy can redirect technology in the regulated countries, then via international knowledge spillovers, it starts affecting the menu of technologies available in unregulated economies. If clean technologies advance sufficiently rapidly, then producers in the unregulated countries will ultimately find it optimal to switch to clean technologies themselves. Once again using the example of steel, if EAF powered by renewables or other methods of producing steel with low emissions become sufficiently cheap compared to BOF, then production in India will also switch away from BOF. This global linkage then potentially increases the reach of unilateral policies adopted in regulated countries and could ultimately reduce emissions in both regulated and unregulated economies.

Put differently, when innovation is endogenous and directed, the international trade-off changes qualitatively. Put simply, with exogenous technology, anti-carbon emission policies across countries are “strategic substitutes” (the more a set of countries adopts these policies, the weaker are incentives for others to do so), while with endogenous technology they may become “strategic complements” (the more a leading set of countries invest in clean technologies, the more others are incentivized to do likewise).

The underlying reason for this is the same path-dependence we emphasized before: advances in clean technology create a stock of knowledge for other countries to build on and further develop their own clean technology sector.

This discussion does not imply, however, that global redirection towards clean technologies will take place by itself. Nor is it necessarily sufficiently powerful to avert climate disasters. In fact, the same insights also suggest a new set of policy levers that can play an important role in redirecting technology: measures to facilitate flow of clean technology knowledge across countries. For example, facilitating developing countries to build on patented or non-patented advances in clean technologies may be one way of enabling this global redirection.

7. Intermediate sources of energy and energy transition

Despite major advances in renewable technologies, several major technical challenges stand in the way of increasing the share of renewables in energy production. Most important are those related to the intermittency of the supply of renewables and difficulties in storage. In this context, a popular idea is to rely on "intermediate" sources of energy, such as natural gas, which have a flexible supply and are less polluting than coal or oil. For example, per unit of energy natural gas today emits about 30% less CO_2 than oil and 50% less than coal. The growth in the supply of natural gas from a variety of sources, most notably from the shale reserves, have recently boosted the world production of natural gas. A natural question is whether reliance on these intermediate fuels can in fact facilitate the energy transition.

The existing data show a clear reduction in the carbon content of U.S. energy after the shale gas boom, together with an accelerated decline in overall U.S. carbon emissions, indicating that the shift from coal and oil towards natural gas has been a boon to the environment.

Reality is more complex, however. Concurrently with the shale gas, we also see a major diversion of innovations away from renewables, which had witnessed a high level of innovative activity in the early 2000s. The evidence suggests that this reduction in renewable innovation was caused by lower natural gas prices.

Is this adverse redirection of innovation a price well worth paying for the short-run reductions in carbon emissions? The answer to this question depends on how much cleaner than coal and oil natural gas is and the long-run effects on technology.

In Acemoglu et al. (2023), we build a model of directed technology with three sources of energy – coal, shale gas and renewables – and allow technology to be directed between fossil fuels and renewables.[15] The model confirms that a shale gas boom is beneficial in the short run, when technology is given. But it also shows that lower natural gas prices will redirect innovation away from renewables towards fossil fuels. Most worryingly from the viewpoint of transitioning to clean technology, the model shows that a significant reduction in natural gas prices can create a new fossil fuel trap: With high natural gas prices, the economy would have converged to clean technology because of sufficient innovation in renewables, but after the decline in natural gas prices, this transition grinds to a halt.

These results are illustrated by Figure 2, which is reproduced from that paper. The figure depicts the evolution of the share of scientists (or more generally, the share of innovation inputs) devoted to clean technologies with or without the shale gas boom (Panel A), and the effects of the shale gas boom on emission levels and output net of climate damages (Panels B and C) in the baseline calibrated version of the model. It confirms that the shale gas boom was large enough to potentially derail an otherwise ongoing transition to clean energy.

More specifically, Panel A shows that after the boom the share of innovation resources devoted to clean technologies drops significantly and starts declining towards zero. Panel B, on the other hand, depicts the short-run and long-run implications of the shale gas boom: emissions fall at first, because shale gas is cleaner than other fossil fuels. However, owing to the redirection of technology away from renewables, emissions start increasing steadily after the shale gas boom (relative to the no shale gas boom benchmark). Panel C then shows the net output implications.

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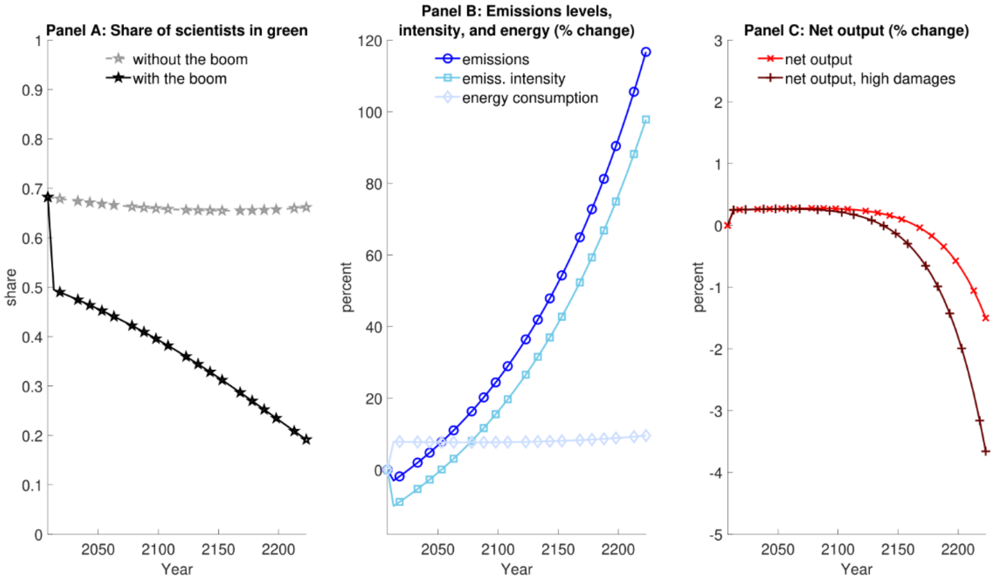
[15] Acemoglu, D., Aghion, P., Barrage, L. and Hemous, D., 2023. Climate Change, Directed Innovation, and Energy Transition: The Long-Run Consequences of the Shale Gas Revolution. Working Paper.

Figure 2

The fossil-fuel trap and the shale revolution



Note: Acemoglu et al. (2023). This figure shows the dynamic effects of the shale gas boom in laissez-faire in our baseline calibration. Panel A depicts the allocation of scientists with and without the shale gas boom. While innovation is increasingly directed toward green technology without the boom, it moves toward fossil-fuel technologies with the boom. Panel B shows the changes (in %) in emission intensity, energy consumption and emissions in the electricity sector that result from the shale gas boom. The boom is associated with an initial decline in emission intensity that is reversed over time. As a result, emissions eventually rise following the boom. Panel C shows the effect on net output of the boom for two calibrations of the damage function. The boom eventually decreases net output.

Moreover, our analysis suggests that the observed carbon emission reductions, dynamics of energy plants, and innovation responses in the data are consistent with the U.S. economy being in this type of fossil fuel trap, which has severe welfare consequences.

These results are a cautionary tale for strategies that rely on intermediate fossil fuels. They also highlight why policy is critical during this transitional period. Under the optimal environmental policy (consisting of a carbon tax and green subsidy as explained above), a shale gas boom always leads to sizable welfare gains, because it enables emission reductions in the short run, while optimal policy would ensure that the long-run green transition is not disrupted.[16]

8. **The role of civil society: consumers, competition, and green innovation**

The recognition of the central role that the direction of innovation plays in the future of climate change naturally opens the way to a broader discussion

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[16] In this context, note that this calibration and the analysis in Acemoglu et al. (2023) do not incorporate the implications of the recent IRA policies, and it would be interesting to explore whether the IRA is sufficient to ensure the reallocation of sufficient innovation resources to clean technologies in the face of the shale gas boom.

of factors affecting the direction of technology. The recent book by Acemoglu and Johnson (2023) emphasizes the role of social factors, ideologies, and civil society in the direction of innovation more broadly.[17] For example, they argue that developing more "pro-worker" technologies would be socially beneficial, but these technologies are hampered by a strong focus on automation and cost-cutting both in the corporate and the tech world. These priorities can shift with regulation as well as by changes in norms and priorities of businesses and society at large and civil society action. These issues are particularly important in the context of climate change.

Both broader technological changes and developments in the energy sector have been shaped by the business climate that prioritized "shareholder values" and short-term measurable performance, such as stock market returns. Ideas powerfully articulated by Milton Friedman, and to some extent before him by Arthur C. Pigou, pushed against broad notions of corporate social responsibility.[18] This emphasis was rooted in both the belief that a single objective — maximizing profits — was likely to lead to better behavior by managers, and it was also fostered by a general trust in the efficiency of the market economy where each actor selfishly followed their private objectives.

These ideas are less compelling, however, when there are important market failures (such as in the area of environmental externalities) and the direction of technology is endogenous. There may also be limits to what markets can achieve in general without some notion of good corporate behavior.[19]

A good illustration of the role of civil society in redirecting firms' innovation towards clean technologies, is provided in a recent paper by Aghion, Benabou, Martin and Roulet (2023), which shows that when it comes to energy and energy-intensive products, consumers appear to have a significant power to influence corporate decisions. In particular, when consumers demand cleaner products, companies tend to deliver them.[20] This highlights the role of consumer preferences and civil society action encouraging consumers to act in unison, for example, in refusing to reward companies that offer slightly cheaper but much more polluting products.

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[17] Acemoglu, D. and S. Johnson. 2023. *Power and Progress: Our Thousand-Year Struggle over Technology and Prosperity*, Public Affairs, New York.

[18] Friedman, M., 1970. "The Social Responsibility of Business is to Increase Its Profits," New York Times Magazine, September 13, 1970, 32-33, 122-124; Pigou, A.C., 1920. The Economics of Welfare. London: Macmillan.

[19] Bénabou, R. and Tirole, J., 2010. Individual and corporate social responsibility. Economica, 77(305), pp.1-19.

[20] Aghion, P., Bénabou, R., Martin, R. and Roulet, A., 2023. Environmental Preferences and Technological Choices: Is Market Competition Clean or Dirty?. American Economic Review Insights, 5, pp. 1-20.

Additionally, market structure may matter majorly when it comes to the effects of consumer preferences and action. For example, if there is only a single automobile producer specializing in "gas guzzlers", it may be difficult to shift this company to electric cars, given its accumulated expertise in fossil-fuel technologies. However, in a more competitive market, new entrants can be more responsive to consumer preferences.

Aghion et al. (2023) provide evidence consistent with this pro-climate effect of competition. They measure consumers' environmental concerns using survey responses among consumers and proxy competitiveness by openness to international trade. They estimate that pro-environment consumer attitudes foster innovations in electric engines more in highly competitive markets.

The analysis in Aghion et al (2023) suggests that informing consumers of the carbon content of the goods they consume, and other measures that might facilitate civil society action in support of climate change policies, could play a major role in redirecting firms' innovation towards clean technologies and could be an important complement to more traditional. The authors also find that if: (i) prosocial attitudes were to increase by the same amount as they declined between 1998-2002 and 2008-2012; (ii) product market competition were to increase to the same extent as it increased between these two periods, then the share of clean innovations would increase by 5.4 points. Finally, this in turn is equivalent to the effect of a 17 percent worldwide rise in fuel prices, while avoiding the deleterious effects that fuel price increases can have on public opinion, as illustrated by the French "Yellow Vests" (*gilet jaunes*) movement. As Aghion et al put it: "grassroots and public campaigns to promote citizens' environmental responsibility could be a viable alternative policy option, especially where markets can be expected to become more competitive".

Moving beyond consumer preferences to look at civil society action more generally, broader changes in norms and attitudes may have powerful effects on the direction of technology when they start altering the priorities of corporate executives, for example, encouraging even large energy companies to commit to a green transition.

9. Conclusion

In this essay, we have argued that the nature of the global warming challenge and solutions thereto change fundamentally when technology is endogenous and directed. The market economy may be even more difficult to shift away from fossil fuels without decisive policy action, because a century of investments in fossil fuels and fossil fuel-using technologies creates a steep disadvantage for cleaner sources of energy. Nevertheless, the right policy action has the potential to alter this rapidly and fundamentally. The form of optimal policy in the presence of directed technological change is notable: Rather than just relying on a carbon tax (or more generally a carbon price), this perspective suggests that subsidies to green innovation have to be a central part of the policy framework. This is because in such an environment (and, we have argued, in the real world), the climate challenge necessitates a major redirection of technology away from fossil fuel stores renewables and other clean energy sources.

Even more radically, directed innovation brings many social determinants of technology choice into center stage. Priorities of corporate executives, norms and visions of tech leaders, and civil society organization and mobilization can play an important role in redirecting technology.

This perspective implies that there are many richer aspects of technological choices, which should be systematically studied in the future. In essence, a more holistic approach, incorporating the various levers that can redirect technological change and the roles of the political economy, sociological and cultural factors impacting the direction of innovation, is needed to gain a broader understanding of the climate challenge and solutions thereto.

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