Centre for Climate Change Economics and Policy

Grantham Research Institute on Climate Change and the Environment

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Path dependence, innovation and the economics of climate change

Philippe Aghion, Cameron Hepburn, Alexander Teytelboym, Dimitri Zenghelis

Abstract – *Shifting our fossil-fuelled civilisation to clean modes of production and consumption requires deep transformations in our energy and economic systems. Innovation in physical technologies and social behaviours is key to this transformation. But innovation has not been at the heart of economic models of climate change. This paper reviews the state of the art on the economics of innovation, applies recent insights to climate change. The core insight is that technological innovation is a path-dependent process in which history and expectations matter greatly in determining eventual outcomes This insight has six important implications for climate policy design. First, efficient climate policy requires direct research subsidies for inducing and/or diffusing clean innovations, combined with carbon pricing (whether by taxes or trading). Second, both public and private sector involvement is required — private market forces need to be mobilised and redirected towards cleaner energy sources by governments. Third, path dependence and system inertia imply that delaying policies that redirect innovation towards clean technologies significantly increases costs in the future. Fourth, more developed countries should act as leaders in clean technology and should subsidise access to such technologies for less developed countries. At the same time, they should consider the possibility of using border carbon adjustments against any country that would take advantage of the new environmental policies by specialising in the production and export of fossil fuel intensive products. Fifth, if a transition from coal to clean energy is to be made via intermediates (for example, gas), the use of gas (without carbon capture) should be agreed to be on a time-limited basis. Further, to avoid gas lock-in, research in fully clean technologies would need to be strongly stepped up over the intervening period, along with other supportive policies. Finally, investment in coal should not be encouraged, as its continued use is only safe if we assume the cost-effectiveness of carbon capture and storage (CCS) technologies. While much greater efforts should be taken to reduce the costs of CCS, the speed that these technologies can be developed and deployed is uncertain.*

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2 INTRODUCTION

It should be self-evident that innovation is a critical aspect of climate change policy — the costs of reducing emissions will depend on the trajectories of costs of clean technologies relative to incumbent dirty technologies (IPCC, 2014). Innovation has been fundamental for the dramatic changes in human civilisation over the last two centuries, and it will play a key part in addressing climate change. By definition, innovation involves change and requires analysis of dynamic and constantly evolving, rather than static, economies. Given the centrality of innovation to climate change economics, traditional static economic analysis can only have a residual and modest role.

What are the policy implications of incorporating the dynamics of innovation into standard models of the economics of climate change? The pace of cost reduction in clean technologies depends strongly on learning and experimentation from research and development, and experience from deployment. Costs also depend on innovation in other dimensions — how well new clean technologies integrate with each other and into new networks; whether new institutional frameworks are developed to support them; how easily financial models can be adapted to secure investment, and how quickly the labour force can learn to use them. This paper focuses on these effects, reviewing the state of the art within economics on endogenous innovation, knowledge spillovers and complementarities, and applying these insights to climate change policy.

Our starting point is that traditional tools of marginal cost-benefit analysis and trade-offs can be inappropriate and misleading (Dietz and Hepburn, 2013) and that many standard integrated assessment models of the economics of climate change do not adequately model innovation. Indeed, standard integrated assessment models suffer from a variety of problems, such as extreme sensitivity to arbitrary parameters and the inability to properly incorporate the possibility of catastrophic outcomes (Pindyck, 2013; Stern, 2013; Weitzman, 2013; Dietz and Stern, 2014). Consider, for instance, the neoclassical DICE model of Nordhaus (1994, 2007), which arguably represents the traditional approach to the climate change economics and to quantifying the costs and benefits of climate policy (or its absence). In this framework, a single consumption good is produced using capital and labour. The total productivity of these factors depends upon a single technology parameter, which is imposed and grows exogenously over time, as well as upon environmental quality. Emission intensity of production also grows exogenously. The environment is itself negatively affected by temperature, temperature increases with the emission of carbon dioxide, and the emission of carbon dioxide increases with production. Climate policy generally takes the form of a tax on carbon dioxide emissions, which induces firms to reduce emissions, but at the cost of also reducing production.

Delaying policy intervention in the DICE model thus increases short-run production and therefore short-run consumption, but at the cost of environmental degradation in the future. Future environmental degradation leads to a need to spend on abatement and adaptation in future, which reduces future consumption. Hence there is an apparent trade off – lower consumption now for higher consumption later – effectively hardwired into the model. In the DICE model, a carbon price (by tax or cap-and-trade) delivers the optimal outcome. And unless a relatively low pure time preference rate is adopted, as in Stern (2007), or damage functions with potential catastrophic impacts are employed (Dietz and Stern, 2014) intervention is relatively slow, gradual and at a modest level.

A major limitation of the DICE model, and many other integrated assessment models, is that they ignore the drivers of innovation. A number of climate economic models have attempted to incorporate innovation (see, for example, Popp (2004) and Bosetti et al. (2006), as well as a summary by Gillingham et al. (2008). However, these models usually treat innovation as an economy-wide, aggregate phenomenon rather than firm-level and sector-specific process with complex spillovers and interactions. Long-run predictions of technology costs made within integrated assessment models are usually extrapolated from recent cost trends, however, since the models do not capture interrelationships between various innovations, their estimates may bear little resemblance to the actual outcomes (IPCC, 2014). For example, it is not known how the proliferation of smart grids might affect broader innovation. Smart grids might act as an enabler of innovation in electric vehicles, and the delivery of public services such as traffic management, crime prevention, emergency services and street lighting in urban areas. Quantifying these effects ex-ante is not easy, but ignoring them is also unsatisfactory. Innovation is central to the required transformation of our energy and economic systems and it is likely that many outcomes of this innovation are currently inconceivable to us. Changes in productive innovation affect both the level and the rate of growth. Therefore, compounded innovation shocks qualitatively alter the structure of the economy and its resource intensity and make it nearly impossible to forecast aggregate technological productivity in the long run. Because most climate models treat innovation, climate impacts and mitigation effort in terms of deviations from a pre-determined trend, they miss out this compounding effect which renders long-term projections nearly useless.

Climate change can, in principle, be addressed by severely limiting production that uses fossil fuels and improving the efficiency with which they are used. But a key driver of emissions reductions will be induced product and process innovation. Much of this innovation will occur by companies and industries which, for the most part, are not heavy users of fossil fuels. Inadequate modelling of innovation has the potential to significantly bias the assessment of the cost of future low carbon technologies. For instance, increases in the price of energy inputs, relative to other goods and services, encourage innovation in energy saving.[1] In addition, if the development of new technologies prompts other cost savings, for example because new knowledge is deployed elsewhere, or because institutions and behaviours change and new cost-cutting networks are built, then the impact on costs could be magnified. Interactions between different innovations create unexpected ways of generating new products. For instance, the inventors of the World Wide Web may have found it was difficult to imagine that within 30 years anyone could develop an application that can be instantly deployed on billions of mobile phones.

Interestingly, once innovation is taken seriously in the model, a whole set of new policy conclusions emerge, most of which are related to such knowledge complementarities or spillovers. This paper briefly surveys and discusses some of these knowledge complementarities and the policy recommendations they generate.

The remainder of paper is structured as follows. Section 3 examines the importance of path dependence in economic systems and apply more general lessons to clean innovation. Section 4 observes that for the global economy to shift to cleaner production and consumption, technology diffusion and spillovers from one country to another — including, but not exclusively from developed to developing countries — are vital. Section 5 considers the implications of the path dependence of innovation for the extent to which a transition from coal to gas could serve as a 'bridge' in moving eventually to zero-carbon technologies. Section 6 describes some of the more general potential conclusions for climate policy.

[1] For example, Newell et al. (1999) show that innovation in air conditioning reduced the prices faced by consumers following the oil price hikes of the 1970s. Popp (2002) provides more systematic evidence on the same point by using patent data from 1970 to 1994, documenting the impact of energy prices on patents for energy-saving innovations.

3 PATH DEPENDENCE AND INNOVATION

'Path dependence' is a common phenomenon in socioeconomic systems, which arises when initial conditions and their historical antecedents matter for eventual outcomes.[2] The authors have each contributed to this paper by typing on QWERTY keyboards, deliberately designed to slow down typing speeds in order to prevent early typewriters from jamming (David, 1985). Roman roads, built in England two thousand years ago, determined the location of many modern highways and railways. In continental Europe, in contrast to Britain, people now drive their cars on the right following Napoleon's declaration that, in the spirit of the revolution, horse-drawn carriages, like the common man, should keep to the right (Young, 1996).

The analysis in this paper focuses mainly on the importance of path dependence in innovation processes. First, scientists work in areas that are well funded and where other good scientists work: *research and knowledge production* are path-dependent. Second, *deployment* of innovations is path-dependent: incentives to deploy innovations that leverage existing (rather than new) infrastructure are much higher (for example, conventional cars are easier to sell than electric vehicles because there are more many petrol stations than charging stations; smart meters require smart electric grids, and so on). Finally, incentives for technology *adoption* create path dependence: if the benefits of using a product rise with the number of others using it, unilaterally switching to an alternative may be unattractive. These reasons imply that socioeconomic systems have strong inertia, and when large numbers of scientists and innovators are focusing on advancing a specific set of dirty technologies, progress is likely to be relatively rapid. Unsurprisingly, therefore, it has been difficult to shift the innovation system from dirty to clean technologies. Finally, shifting to a low-carbon economy may initially tie up factors of production and undermine the net returns from investment, potentially restricting the drivers of long-run endogenous growth. Moreover, it will take time to diffuse clean technologies, more time for this to slow and reverse emissions, and yet more time to slow down global warming because once they are in the atmosphere greenhouse gases remain there for decades or centuries, trapping heat and increasing mean global temperatures. Given all of these lags in the system, and the potential for a protracted transition to potentially inhibit the drivers of growth, delivering a change in the direction of innovation appears to be an urgent component of the transformation.

A key source of path dependence in socioeconomic systems is the presence of 'complementarities' i.e. when the payoff to the whole group from working together is greater that the sum of the payoffs of its parts. In particular, 'strategic complementarities' arise when agents make individual decisions that affect each other's welfare and one agent's greater productivity makes *all* the other agents more productive. Research and development externalities (Romer, 1990, Aghion and Howitt, 1992, 1998) and learning spillovers (Arrow, 1962) in low-carbon technologies have these features – as more scientists start addressing and thinking about clean energy, more ideas and innovations emerge such that other scientists can 'stand on the shoulders of giants' and see further in the clean energy domain.[3] However, most integrated assessment models rarely attempt to model this feature of research and development.

In deployment and adoption of clean technologies, path dependence arises specifically because of powerful network effects and high switching costs. These effects are also present with the telephone (the incentive to buy a phone rises as others buy a phone), with the Internet, and with transport systems (the incentive to buy a petrol-fuelled car rises as others buy similar cars, as this leads to more refuelling stations, which makes the car itself more convenient). In general, past decisions about technologies are going to make a difference about which technology is dominant (Grubb, 1997; Clarke and Weyant, 2002). Infrastructure is often locked-in due to switching costs (Farrell and Klemperer, 2005). A current example of the difficulty in overcoming such lock-in is the challenge of developing electric vehicle infrastructure (Eberle and von Helmont, 2010). Once electric vehicle infrastructure is in place, the incentives to conduct research and development on electric cars will increase substantially relative to fuel cell or combustion engine vehicles. Since the Industrial Revolution firms have been routinely exploiting this path dependence in technology adoption and network effects in order to diffuse their innovations and create new

[2] This contrasts 'ergodic' processes for which the long-run outcome is independent of initial conditions (Young, 1996).
[3] For example, using OECD patent data, Braun et al. (2010) find that both wind and solar technologies create knowledge spillovers at the national level. Many existing green technologies may also exhibit scale effects (Moore, 1959).

markets (Bessen, 2014). Recently, Tesla Motors Inc. released all their electric vehicle patents to the public arguing that all car companies would "benefit from a common, rapidly-evolving technology platform" (Musk, 2014). Tesla Motors would itself benefit substantially from electric vehicle infrastructure. However, incentives to invest into the infrastructure will only arise if enough firms work on electric cars, which in turn is much more likely when much of the initial research is publicly available. At the same time, incumbent networks of car dealers in certain states in the United States are acting to effectively block the sale of Tesla cars and prevent the path-dependent feedbacks that might reduce the profits of traditional car manufacturers (Surowiecki, 2014).

Path dependence also affects the effectiveness of public policies. For example, dense cities with integrated public transport require lower carbon taxes than sprawling cities in order to achieve the same reduction in emissions, because shifting the transport mode is easier. Complementary non-price policies increase the elasticity of substitution in response to carbon pricing, thus lowering the cost of emissions reductions (Avner et al., forthcoming). Complementarities are not limited to technological networks. Institutional and cultural lock-in is also prevalent. Clean technologies give rise to new industrial lobbies and constituencies, which, for better or worse, can help drive green policies and give rise to new regulatory institutions (Lockwood, 2013). For example, a city mayor who promises increased bicycle lanes, congestion charging and pedestrianisation is likely to garner more public support in a dense resource-efficient city than in a sprawling suburban one, whose citizens may instead prefer the promise of highway expansion and lower fuel costs which further lock in carbon-intensive infrastructure (Rode et al., 2012).

Incorporating these features of path-dependent phenomena – knowledge spillovers, network effects, switching costs, feedbacks, and complementarities – into economic models is difficult and often leads to a *multiplicity* of 'equilibria', which can often be Pareto-ranked (Shleifer, 1986; Krugman, 1991; Matsuyama, 1991, Redding 1996).[4] In short, there is no guaranteed unique outcome, but it is possible to say whether or not one outcome is better or worse *for everyone* than another. In the context of the economics of climate change, this means that there is a set of possible paths in which insufficient low-carbon innovation occurs and clean technologies are not adopted (Pittel, 2002). No firm has an incentive to produce clean research because it can neither pay the best scientists nor overcome the network effect of the incumbent dirty technology to deploy its innovation. The economic system stays locked in fossil fuels. In an alternative path, the system is given enough of a 'push' to overcome initial switching costs so that cleaner technologies are fully developed and adopted, eventually displacing fossil fuels.

Which pathway is more likely? Economic theory indicates that the pathway selected will depend on the *expectations* of people about technologies as well as the *initial conditions* of the innovation process (Krugman, 1991; Cooper, 1999). Even if clean technologies were starting out from a low initial base, firms' expectations of a large clean-energy market in the future would be a sufficient incentive to invest in it. As enough players shift investment, the costs of clean technologies would be expected to fall as would the cost of capital in what were formerly considered niche markets. The development of new skills as well as supportive institutions and behaviours would be expected to further reduce unit costs. Naturally, if clean technologies are reasonably well developed, this change in expectations is more likely to occur. Therefore, the government has a role both in shifting the expectations (for example, by credibly committing to climate policy) or changing the initial conditions (for example, by investing in green infrastructure or funding clean energy research) in order to reduce the risk of clean technology investment and thereby help shift the economy to the low-emission pathway. Thus the knowledge that innovation is path-dependent should be an incentive for early action.

This is one of the primary insights of Acemoglu et al. (2012a), henceforth AABH. The paper applies more general economic insights from directed technical change literature (Acemoglu, 1998, 2002) to climate change, and develops a model in which, in contrast to the traditional approach of Nordhaus (1994) where productivity growth is assumed to be exogenous, productivity growth in clean and dirty technologies emerges *endogenously* from innovations. AABH construct a model where innovations can improve the efficiency of competing clean and dirty production processes, and profit-maximising researchers choose to direct their research and development

[4] Predicting outcomes in the presence of equilibrium multiplicity is further compounded by the fact that innovation is inherently a stochastic process (Acemoglu and Zilibotti, 1997; Klette and Kortum, 2004).

activities towards innovating either in clean or in dirty input sectors. The production of dirty inputs damages the environment, which in turn affects the production of the consumption good and the utility people derive from it.

AABH assume that the dirty technology enjoys an initial installed base advantage, so the innovation machine tends to work in favour of further improving the dirty technology. The reason for this is easy to understand. The existing dirty network infrastructure is already there — while the clean infrastructure is not — so there are immediate and direct economic payoffs from investing in better ways to use dirty technologies. Companies have resources to pay the finest minds to make additional innovations and the incumbent sector already employs large numbers of people. As a result, it has both a wealth of existing skills and expertise and can exercise significant political clout in influencing policies and institutions. Hence, there is path dependence in the direction of dirty technology innovation. The important conclusion is that clean technology may never displace dirty technologies unless the government intervenes, for example by subsidising clean activities and/or by taxing dirty activities.[5] While the conclusion is not dissimilar from conventional economic approaches — support for clean innovation and carbon pricing — the logic for it is strikingly different. Moreover, the urgency of action is much clearer once these path dependencies have been identified.

Policy intervention in such models, similarly to the conventional models that move the economy onto a low emissions pathway, is not free: costs are born initially in the form of final output growing slower while the innovation is transitioning from the more advanced dirty sector to the less advanced clean sector. As noted above, the tying up of additional resources necessary to trigger the transition may also inhibit the endogenous drivers of growth, especially if the transition is protracted. It will take a certain period of time before there is higher and cleaner growth, powered by a “clean innovation machine”. But once the clean technology has gained sufficient productivity advantage, the clean innovation machine can be left on its own.

Indeed, there is evidence to suggest that the clean innovation machine, when switched on and running, can be more innovative and productive than the conventional alternative. The potential for unit costs to fall as a result of learning and experience is higher for many new technologies than for long established incumbents. It is entirely conceivable that under a low-carbon innovation path with the development of storage technologies, operating costs of energy generation within this century could fall well below those associated with digging fossil fuels out of ever more remote places and transporting it across the world in pipes and ships. Moreover, the potential spillovers from low-carbon innovation to other sectors, which drive whole economy GDP, might well be higher.[6] Using data on 1 million patents and 3 million citations, Dechezleprêtre et al. (2013) find that spillovers from low-carbon innovation are over 40 per cent greater than in conventional technologies (in the energy production and transportation sectors). The importance of this effect cannot be underestimated.

As a result, carbon taxes (on dirty input and profits) may need only be *temporary* — in the sense of being required for several decades – because the energy and economic system will overtime become locked-in to a low-carbon product technology base.

Modelling of this sort suggests that a critical feature of the system transition is the extent to which the dirty and the clean technology are easy to substitute for each other (Hassler et al., 2012; Miao and Popp, 2013). If the clean technology is not a good substitute for the dirty technology (for instance, because solar power producers do not have access to the electricity grid), then different government interventions may be required compared to the case where clean technology players can establish an initial niche in the market.

This emerging line of economic analysis delivers two predictions that stand in contrast to those delivered by the standard paradigm. First, it stresses the centrality and importance of public subsidies for both the development (for example, research prizes or investment tax breaks) and deployment (for example, public infrastructure) of

[5] In particular, AABH revisit the debate between Stern and Nordhaus by arguing that even under Nordhaus’s higher discount rate, policy intervention should be immediate and at full steam.
[6] Smulders (2005) points out that growth and stable environmental quality can only be maintained if there are with non-diminishing returns to investment in new (green) knowledge capital. Popp (2002) provides some evidence that these returns may be diminishing.

clean research and development and/or patent protection to deal with the knowledge externality, in addition to the sort of carbon pricing policies emphasised by traditional models (see also Fischer and Newell, 2008; and Johnstone et al., 2010).[7] While a carbon tax alone would discourage the production of dirty input and also discourage innovation in the dirty sector,[8] using the carbon tax alone may lead to excessive consumption reduction in the short run, and it does not explicitly address the relevant knowledge externalities. Where substitution options outside the dirty sector remain limited or expensive, a carbon tax alone may also encourage innovation in efficiency in the existing dirty sector (for example, by funding innovation in more efficient combustion engines rather than electric vehicle). This not only unnecessarily erodes welfare in the short run, but also increases political and economic resistance to transition to the clean technologies.[9] Smulders (2005) notes that the role of relative price changes in inducing directed technical change might be small where input substitution options are limited.[10]

Second, properly accounting for path dependencies implies that immediate and substantial intervention in the innovation system is optimal, even under the higher discount rate assumptions made by Nordhaus (2007). The reason is that if full intervention is delayed, then as time progresses, the dirty innovation machine continues to absorb the bulk of the scientific effort, possibly even widening the gap between dirty and the clean technologies. A longer period of intervention would then be required for the clean technology to catch up and replace the dirty technology. As this catching-up period is characterised by slower growth, costs, in terms of foregone growth, will be higher if intervention is delayed. This captures an important feature of the climate policy debate: delaying action means locking in to technologies, infrastructures and behaviours that will be more costly to reverse or retrofit at scale later. By contrast, working incrementally with the depreciation cycle to replace dirty capital, as it retires, with clean capital is likely to be a more cost-effective way of managing a transition from dirty to clean production.

There is emerging evidence for these two conclusions. Aghion et al. (2012) provide empirical evidence both for geographical knowledge spillovers (a firm's choice whether to innovate along a clean or dirty pathway is influenced by the practice of the countries where its researchers/inventors are located) and for path dependence (firms tend to direct innovation towards what they are already good at). Using cross-country patenting data from the automotive industry, they show that clean innovation is path-dependent on the firm and industry level: firms (or industries) that started out with a greater stock of low-carbon technology patents innovate at a faster rate in the future. While this is a promising confirmation of AABH's results, much empirical work on innovation in this direction remains to be done.

The case for intervention increases the risk that governments, which are necessary to shape the environment for investment and innovation, can over-reach themselves or be influenced by vested interests (Hepburn, 2010). The story of directed technical change and dynamic market failures potentially amplifies the size and duration of the consequences of policy failure, making the need for accountable institutions all the more important. Put differently, path dependence makes the costs of 'picking losers' substantial.[11] To counter this, policy instruments must be

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[7] Public subsidies to clean innovation need not be direct research and development subsidies so long as they spur clean innovation. Examples include public investments in municipal gas, smart electricity grids or electric or fuel cell vehicle infrastructure. On the other hand, direct research and development subsidies appear to have played a bigger role in nuclear and renewable energy. The authors thank Alex Bowen for pointing this to us.

[8] See Popp (2002) and Aghion et al. (2013) for evidence on the role of carbon price in redirecting technical progress towards cleaner innovation.

[9] It is for this second reason that Rozenberg et al. (2014) propose easing the burden of carbon taxation on incumbent dirty industries in the short run in favour of incentives to new clean technologies. Although, this framework raises the cost of attaining emissions reductions, they argue it is necessary in order to enhance political buy-in.

[10] Firms may pursue any innovations that hold out the prospect of reducing total costs which may boost labour saving innovation, because labour accounts for the largest share of costs, rather than innovation economising on the factor that just got more expensive. Thus carbon pricing may not induce enough of the right sort of innovation and direct support for green research and development may be even more necessary.

[11] Helm (2012) forcefully argues that the EU 2020 energy and climate package has created 'bad' path dependence including large rents for vested parties and significant lock-in of expensive offshore wind and current generation solar at the expense of new renewables with brighter prospects. He also argues that this has caused renewed demand for coal.

market-based, transparent and non-discriminatory as possible. For example, rather than picking winners with research grants, the government could offer relatively favourable tax treatment to firms involved in clean technology, underwrite national green infrastructure projects, and support *basic* scientific clean energy research. However, sometimes choices must be made, and it is not impossible for publicly funded, publicly run and publicly accountable research institutes to make good strategic choices, spurring profitable innovation in sectors considered too risky by the private sector. Public research institutes have also shown a good track record in spurring profitable innovation in sectors considered too risky by the private sector. Technology spillovers from public spending on defence research and development are commonly credited as responsible for the Internet, the touch screen, GPS and Apple's Siri technology, among other things (Mazzucato, 2011). Some strategic choices must be made in apportioning scarce public resources to develop and deploy clean technologies, especially where multiple policy objectives exist in addition to reducing climate risk (for example, energy security, particulate pollution, improved efficiency, reduced congestion and fiscal reform through lower fuel and energy subsidies and carbon pricing). Ideally, institutions should be robust to regulatory capture and capable of learning from successes and failures of past policy decisions. Such institutions could design of policy instruments that can limit lobbying, rent seeking, and government capture by low-carbon industries – sometimes called the 'technology pork barrel' (Cohen and Noll, 1991).

4 PATH DEPENDENCE AND GLOBAL ACTION

The effects of path dependence described in section 3 have particular implications for global challenges such as climate change. At the heart of current approaches to climate change is the international coordination of climate policy intervention. As the benefits of reductions in carbon dioxide emissions will be global, countries have a short-term incentive to free-ride on the efforts of others, avoiding the costs of interventions. Theoretically, free-riding should be an unenlightened strategy because climate negotiations are a long-run game, potentially thought of as an 'iterated prisoners' dilemma' (Barrett, 1990; Ward 1996), where an uncooperative country this year could end up experiencing diplomatic, political or economic 'punishment' in the future. However, no country has yet been 'punished' for (the lack of) its emission reduction policies. What if other countries are not intervening to support a switch to clean technologies? Does it still pay to intervene unilaterally? Is it good policy to make actions conditional on the level of other countries' commitments? The answers depend in part on how well different countries are able to pick up and use new technologies developed abroad (Grossman and Helpman, 1991).

Many developing countries have so far objected to setting mandatory targets for reductions in carbon dioxide emissions. Why, they argue, should they be subject now to environmental criteria that developed countries did not follow when they were at a comparable stage of development? Factoring in directed technological change – as this paper argues is necessary – sheds new light on how countries should debate and negotiate the implementation of a global environmental policy. While some emerging countries, such as China or Brazil, also form a part of the global innovation machine, many emerging-market countries are more likely to merely imitate or adopt clean technologies previously invented in the developed countries.

Building on Cohen and Levinthal's (1990) work, Acemoglu et al. (2013) observe that there are complementarities between low-carbon research in developed and in less developed countries. Indeed, developing countries now make up 61 per cent of global clean energy investment and China has already surpassed the United States and the European Union (NSF, 2014; Mathews, 2014). There are also many examples of technology diffusion through markets including mobile phones, affordable laptops and indeed fossil fuels, for example hydraulic fracturing and liquefied natural gas. If developed countries direct their own research and development efforts towards clean technologies, and then facilitate the diffusion of new clean technologies to emerging markets, they will go a long way towards overcoming global climate change.[12] In other words, government intervention in developed countries could kick-start the 'green innovation machine', which in turn will set in motion the "green imitation machine" in developing countries to adopt cleaner technologies developed by the technology leaders. The higher

[12] The Green Climate Fund and Technology Mechanism established at the Conference of the Parties of the UNFCCC in 2010 are steps towards this.

the spillovers from the developed green innovation machine to the developing countries, the more active is the green imitation machine in developing countries working to implement clean technologies rather than dirty ones. This makes a case for unilateral policy intervention – pricing carbon and subsidising green R&D – by the developed countries, facilitation of technology transfers from the developed to less developed countries, and improvement of the capacity of developing countries to effectively absorb cutting-edge technology.

The technology transfer model outlined above implies that developing countries still need to invest in low-carbon innovation in order to benefit from knowledge spillovers from developed countries.[13] But, crucially, policies that promote low-carbon innovation in developed countries may not lead to socially optimal emission reduction unless there are additional interventions that support the transfer and deployment of clean technologies in developing countries. This is because developing countries might acquire a comparative advantage in producing with the dirty technology, and thus specialise in the production of dirty goods. It is therefore critical that clean technologies are made available and affordable to poor countries (Acemoglu et al., 2013).[14] Moreover, if developed and developing countries trade freely, carbon taxes and research subsidies in developed countries could create 'pollution havens' in developing countries. Developing countries may specialise in dirty production and export their goods to the rest of the world. In this case, border carbon adjustments (or the threat of introducing them) may be necessary for developed countries to engage in unilateral environmental policy that could eventually be emulated by developing countries and thereby help deliver a speedier resolution of this global environmental problem (Hemous, 2012, Helm, 2012, Helm et al., 2012).[15]

5 DIRECTED INNOVATION AND ENERGY TRANSITION: FROM COAL TO GAS TO RENEWABLES? [16]

The previous sections of this paper have stressed the path dependence of innovation systems. In addition, political, institutional and behavioural systems are path-dependent. The political economy of shifting away from dirty to clean energy is incredibly challenging (Giddens, 2009; Steves and Teytelboym, 2013). Fossil fuel interests are politically influential and are entwined with our tax system (Pearce, 2006). Ansar et al. (2013) calculate that fossil fuel companies make up a large proportion of listed stock exchanges (11 per cent of S&P500 and 20 per cent of FTSE) and comprise a sizeable proportion of Western university endowments and public pension funds (2-5 per cent). Unsurprisingly, political lock-in and path dependence are highly relevant to developing policy recommendations. These concepts are also typically absent from conventional integrated assessment models (Dumas et al., 2014).

Although the need to eventually move away from dirty energy is now broadly understood, opinions differ as to the optimal dynamic strategy to be followed. There is debate between several views. Broadly speaking, one view is that intermediate sources of clean(er) energy, such as gas, should be immediately explored and developed in order to 'escape' from coal while scaling back investment in renewable energy, such as wind or solar, in the short run (Helm, 2012; Jacoby et al., 2011; Brown and Krupnick 2010). A competing view is that using these intermediate sources of energy will simply delay the desirable transition to fully clean and safe energy sources

[13] As pointed out to us by Alex Bowen, developing countries need innovations that are more appropriate to their stage of development. Moreover, Dechezleprêtre et al. (2012) provide evidence to the effect that technology transfers work best among countries at similar development levels.

[14] It is debatable whether border carbon adjustment or similar instruments would be legal under WTO law (see Fischer and Fox (2012) for a review).

[15] Alternatively, developed countries could engage in supply-side policies by buying and preserving fossil fuels, pushing up their prices and thus giving developing countries a clear price incentive to switch to cleaner technologies (Harstad, 2012). However, as Collier and Venables (2014) note, a higher price also triggers greater exploration for fossil fuels. Carbon price remains the desirable policy because it increases consumer prices and reduces producer prices. Border carbon adjustments and supply-side policies will also imply markedly different distributions of costs and benefits of the global clean energy transition.

[16] The ideas discussed in this section draw partly on Acemoglu et al. (2012b, 2014).

(CCC, 2012), and that we should focus on transitioning directly to clean energy. A third view favours investment in technologies which allow the continued use of fossil fuel infrastructure by either removing carbon emissions (for example, through end-of-pipe technologies such as carbon capture and storage (CCS)) or by ameliorating the impacts of growing atmospheric concentrations of greenhouse gas on the climate (for example, through so-called 'geo-engineering', whereby particulates or other substances are injected into the atmosphere to reflect solar radiation) (Gibbins and Chalmers, 2008; Keith, 2000).[17]

There is an inadequate empirical basis to comprehensively reject any of these views just yet. On one hand, innovating in (shale) gas extraction to replace coal energy could reduce climate damage in the short or medium term, especially if gas development will not significantly reduce technological progress in low-carbon and renewable energy (for example, because returns to renewable energy innovation are already sufficiently high, (Acemoglu, 2012b, 2014)). On the other hand, innovating in gas extraction may delay the transition to fully low-carbon and renewable energy technologies, and result in more pollution.

Investment in CCS and geo-engineering similarly prolong the viable life of coal infrastructure. As argued above, the rate at which the cost of fully clean technology falls will depend on the scale of research and deployment and its ability to integrate into new complementary networks. Again, investing in intermediate sources of fossil fuel energy, such as gas, or in forms of carbon capture, might conceivably delay or disrupt this process, reducing the ultimate market size for renewable technologies, shifting expectations and making renewable technologies more difficult to develop in the future.

Contrary to the claims made by both sides of this heated debate, the plausibility of the "gas as a bridge" cannot be conclusively answered ex-ante. A whole host of factors are relevant, not least energy security, domestic reserves, relative local costs, international rebound and competitiveness effects (as prices adjust to changes in demand), methane leakage, pollution from coal-based alternatives and so on, and the importance of these factors vary from one location to another. Further, some modelling suggests that large-scale use of gas without other climate policy will have limited impact on emissions (McJeon et al., 2014). However, an analysis that incorporates directed technical change and path dependence in innovation adds another useful perspective. Dislodging incumbent coal interests with renewables alone is likely to be extremely difficult given the strength of the lock-in effect, particularly on the timeframes required to give reasonable probabilities of limiting temperature increases to below two degrees Celsius. In contrast, gas, which has roughly half the emissions of coal if fugitive emissions are controlled, is now dislodging coal in some markets already, without significant government support (Helm, 2012). This is because the technological advances in horizontal drilling and fracturing — substantially funded by government in earlier decades — have significantly reduced extraction costs at a time when the alarming costs to health and local pollution of coal are being recognised and factored in through regulation around the world (BP, 2013, Vengosh, et al., 2014).

However, even if gas were to succeed in partially displacing coal — and European experience suggests that this is not guaranteed[18] — path dependence suggests two major reasons for caution. First, an energy transition via gas partially discourages intense research in renewables (including in areas such as energy storage) making it more expensive to catch up in the future (Acemoglu et al. 2012b, 2014). Second, lock-in of gas-based

[17] Very few modelled mitigation scenarios consistent with greenhouse gas stabilisation at 450 ppm CO_2e exclude carbon capture and storage (CCS) in the portfolio of technologies, and if they do the pathway is modelled as a lot more expensive e.g. IEA (2012) estimates that, in a 2 degrees scenario without CCS, the cost of meeting emission constraints in the electricity sector will be 40 per cent higher. Therefore most players include it among the portfolio of technologies that require research and development support. More generally, the extent to which resorting to gas as an intermediate source of energy extraction helps to mitigate the emission problem depends upon how gas is extracted and also about the coal technology that it is meant to replace (Bassi et al., 2013).

[18] The UK, Germany, and the Netherlands all have seen past shifts to gas in their power systems that have been even more rapid than that of the US in recent years; yet both Germany and the Netherlands are now building coal plants and mothballing gas plants, and coal remains a major part of the energy mix in the UK. To the extent that coal is eventually squeezed from the energy mix in these countries, it is likely to be driven by (local and global) pollution regulations, not solely by a "dash for gas."

infrastructure may then become a problem, given that this infrastructure is also potentially long lived. There is a risk that gas may become as hard as coal to dislodge. To alleviate these concerns, governments would need to credibly signal to the private sector that gas (without CCS) will be not subject to a favourable regime in the medium run, for instance from 2030 (Helm, 2012). The private sector would then invest in gas capital assets (fields, power plants etc.) on the basis that they could make an economic return over the coming 15-year period, but potentially no longer. In some jurisdictions, given the lead times for key pieces of capital infrastructure such as LNG terminals, this may not be feasible.

Similarly, the logic of path dependence leads to tentative speculations about the role of CCS, again an area for further research. Conventional analyses suggest that CCS dramatically lowers the cost of constraining global mean temperature increases to within two degrees centigrade (see Figure 7.17 in the Final Draft of the Report and Figure 13 in the Technical Summary, IPCC, 2014). Further, investment in CCS might be considered as insurance against possible high costs of ambitious efforts to transition away from fossil fuels directly to renewables. Although CCS is likely to be more expensive than many renewables (Committee on Climate Change, 2011) and perhaps only viable in certain locations at certain times (for example where carbon storage costs are low and where intermittency problems from renewables are significant) it allows greater flexibility along the low-carbon path. There is a vast number of existing coal plants that are valuable for security as well as cost reasons. For these to continue functioning while aiming for anything like a 450-550ppm CO2e greenhouse gas stabilisation target, CCS or similar carbon management technology appears important (Allen et al. 2009). One of the challenges is that, unlike renewables, innovation in CCS requires demonstration projects that are necessarily large and ‘lumpy’, which may reduce the incremental pace of learning. Nevertheless, further research, development and deployment of CCS, alongside other forms of carbon sequestration such as reforestation, land use change and air capture, is warranted. A similar argument applies to geo-engineering, though the risks associated with this array of technologies are higher and therefore their appeal commensurately lower (see Doda, forthcoming). However, path dependence in innovation implies that pursuing geo-engineering and CCS vigorously might reduce the incentive to urgently push for renewables. This risk is unlikely to be sufficient to abandon research and development in these sectors altogether, especially if policy accounts for ‘moral hazard’ issues, but this is an area for further research.

6 CONCLUSIONS

This paper has argued that conventional economic integrated assessment models inadequately treat the most important element of climate policy — path dependence of clean energy innovation. Introducing path dependence of innovation into the climate change debate has important implications for the design of appropriate environmental policies. In particular the above discussion suggests that:

(i) A suitable policy to fight climate change should combine a carbon tax (or cap-and-trade scheme) with direct support for research, deployment and adoption of low-carbon innovation.

(ii) Both governments and private sector can play important roles: private market forces need to be mobilised and redirected towards cleaner energy sources by governments, but clearly governments cannot substitute for the market. In an ideal world, government intervention would be credible, transparent, and non-discriminatory, avoiding pork-barrel politics and industry capture.

(iii) Governments must act now: even for very high discount rates, delaying policies that would redirect innovation towards clean energy sectors and activities will result in much higher costs in the future.

(iv) More developed countries should act as technological leaders in implementing new environmental policies, and they should subsidise the access to new clean technologies by less developed countries. At the same time, they should consider the possibility of using border carbon adjustments against any country that would take advantage of the new environmental policies to specialise in the production and export of fossil fuel intensive products.

(iv) The logic of path dependence has relevance to the debate about whether a transition from coal to clean energy via intermediates (for example, gas) should be supported. Intermediates may warrant support, so long as it is time-limited and that research in fully clean technologies is strongly stepped up over the intervening period.

(v) Even though support for research into technologies to capture and store carbon and 'geo-engineering' methods is justifiable, investment in coal should not be encouraged in the belief that these emerging technologies will prolong its useful life. Path dependence in innovation implies that a clear signal to redirect investment towards clean energy sectors now is likely to significantly reduce costs later.

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8 REFERENCES

1. Acemoglu, D., 1998. Why Do New Technologies Complement Skills? Directed Technical Change and Wage Inequality. *Quarterly Journal of Economics*, 113(4), pp. 1055–1089.
2. Acemoglu, D., 2002. Directed Technical Change. *Review of Economic Studies*, 69(4), pp. 781–809.
3. Acemoglu, D., and Zilibotti F., 1997. Was Prometheus Unbound by Chance? Risk, Diversification, and Growth. *Journal of Political Economy*, 105(4), pp. 709-751.
4. Acemoglu, D., Aghion, P., Bursztyn, L., and. Hemous D., 2012a, The Environment and Directed Technical Change. *American Economic Review*, 102(1), pp. 131-166.
5. Acemoglu, D., Aghion, P., and Hemous D., 2013. The Environment and Directed Technical Change in a North-South Model. *Mimeo*.
6. Acemoglu, D., Aghion, P. and Hemous D., 2014. Climate Change, Directed Innovation, and Energy Transition: Should We Escape From Coal Through Gas? *Mimeo*.
7. Acemoglu, D., Akcigit, U., Hanley, D., and Kerr W., 2012b. Transition to Clean Technology, *Mimeo*.
8. Aghion, P., and Howitt, P. W., 1992. A Model of Growth through Creative Destruction. *Econometrica*, 60(2), pp. 323-351.
9. Aghion, P. and Howitt, P. W.,1998. *Endogenous Growth Theory*. London: MIT Press.
10. Aghion, P., Dechezleprêtre, A., Hemous, D., Martin, R., and Van Reenen J., 2012. *Carbon Taxes, Path Dependency and Directed Technical Change: Evidence from the Auto Industry*, NBER Working Paper No. 18596.
11. Allen D. T., Torres, V. M., Thomas, J., Sullivan, D. W., Harrison, M., Hendler, A., Herndon, S. C., Kolb, C. E., Fraser, M. P., Hill, A. D., Lamb, B. K., Miskimins, J., Sawyer, R. F. and Seinfeld, J. H., 2013. Measurements of methane emissions at natural gas production sites in the United States. *Proceedings of the National Academy of Sciences*, 110(4), pp. 17768–17773.
12. Allen, M. R., Frame, D. J. and Mason, C. F., 2009. The case for mandatory sequestration. *Nature Geoscience*, 2(12), pp. 813-814.
13. Ansar, A., Caldecott, B. and Tilbury, J., 2013. *Stranded assets and the fossil fuel divestment campaign: what does divestment mean for the valuation of fossil fuel assets?* Oxford: Smith School for Enterprise and the Environment Report.
14. Arrow, K. J., 1962. The Economic Implications of Learning by Doing. *Review of Economic Studies*, 29(3), pp. 155-173.
15. Avner, P., Rentschler, J. and Hallegatte, S., (forthcoming). Carbon price efficiency: lock-in and path dependence in urban forms and transport infrastructure, *Mimeo*.
16. Barrett, S., 1990. The Problem of Global Environmental Protection. *Oxford Review of Economic Policy*, 6(1), pp. 68-79.
17. Bassi S., Rydge, J., Khor, C. S., Fankhauser, S., Hirst, N., and Ward, B. 2013. *A UK Dash for 'Smart' Gas*. Policy Brief. London: Centre for Climate Change Economics and Policy and Grantham Research Institute for Climate Change and the Environment, London School of Economics and Political Science.

18. Bessen, J., 2014. *History Backs Up Tesla's Patent Sharing*. Harvard Business Review Blog, 13 June 2014. [online] Available at: http://blogs.hbr.org/2014/06/history-backs-up-teslas-patent-sharing/
19. Bosetti, V., Carraro, C., Galeotti, M., Massetti, E., and Tavoni, M., 2006. WITCH: A World Induced Technical Change Hybrid Model. *Energy Journal*, Special Issue on Hybrid Modeling of Energy-Environment Policies: Reconciling Bottom-up and Top-down, pp. 13-38.
20. BP, 2014. *BP Energy Outlook 2035*. Available online: http://www.bp.com/en/global/corporate/about-bp/energy-economics/energy-outlook.html
21. Braun, F. G., Schmidt-Ehmcke, J. and Zloczysti, P., 2010. *Innovative Activity in Wind and Solar Technology: Empirical Evidence on Knowledge Spillovers Using Patent Data*, CEPR Discussion Paper No. 7865.
22. Brown, S. and Krupnick, A., 2010. *Abundant shale gas resources: long term implications for US natural gas markets.* Discussion paper. Washington D.C: Resources for the Future.
23. Clarke, L. E. and Weyant, J., 2002. Modeling induced technological change: an overview, appeared in Grübler, A., Nakicenovic, N. and W. Nordhaus (eds.), *Technological Change and the Environment*, Washington, DC: Resources for the Future Press.
24. Cohen, L. R. and Noll, R. G., 1991. *The Technology Pork Barrel*. Washington D.C: Brookings Institution Press.
25. Cohen, W. M., Levinthal, D. A.., 1990. Absorptive Capacity: A New Perspective on Learning and Innovation. *Administrative Science Quarterly*, 35(1), pp. 128-152.
26. Collier, P. and Venables, A.J., 2014. *Closing coal: economic and moral incentives*. Grantham Research Institute on Climate Change and the Environment Working Paper No. 157..
27. Committee on Climate Change, 2011. *Costs Of Low Carbon Generation Technologies 2011 - Renewable Energy Review,* Technical Appendix. [online] Available at: http://archive.theccc.org.uk/aws/Renewables%20Review/RES%20Review%20Technical%20Annex%20FINAL.pdf
28. Committee on Climate Change, 2012. *The need for a carbon intensity target in the power sector. Policy* letter. [online] Available at: http://www.theccc.org.uk/publication/letter-the-need-for-a-carbon-intensity-target-in-the-power-sector/
29. Cooper, R. 1999. *Coordination Games*. Cambridge: Cambridge University Press.
30. David, P., 1985. Clio and the Economics of QWERTY. *American Economic Review*, 75(2), pp. 332-337.
31. Dechezleprêtre, A., Perkins, R., and Neumayer, E., 2012. *Environmental Regulation and the Cross-Border Diffusion of New Technology: Evidence from Automobile Patents*. Centre for Climate Change Economics and Policy, Working Paper No. 73, February.
32. Dechezleprêtre, A., Martin, R., and Mohnen, M., 2013. *Knowledge spillovers from clean and dirty technologies*, Grantham Research Institute on Climate Change and the Environment Working Paper No. 135.
33. Dietz, S. and Hepburn, C., 2013. Benefit-cost analysis of non-marginal climate and energy projects. *Energy Economics*, 40, pp. 61-71.
34. Dietz, S. and Stern, N., 2014. *Endogenous growth, convexity of damages and climate risk: how Nordhaus' framework supports deep cuts in carbon emissions*. Centre for Climate Change Economics and Policy Working Paper No. 180 and Grantham Research Institute on Climate Change and the Environment Working Paper No. 159.
35. Doda, B., (forthcoming). *Why is geoengineering so tempting*? Grantham Research Institute on Climate Change and the Environment Working Paper.
36. Dumas, M., Rising J. A., and Urpelainen J., 2014. Path Dependence, Political Competition, and Renewable Energy Policy: A Dynamic Model, *Mimeo*.
37. Eberle, U., and Von Helmolt, R., 2010. Sustainable transportation based on electric vehicle concepts: a brief overview. *Energy and Environmental Science*, 3, pp. 689-699.
38. Farrell, J. and Klemperer, P., 2005. Coordination and Lock-In: Competition with Switching Costs and Network Effects, appeared in Armstrong, M. and R. Porter (eds.), *Handbook of Industrial Organization*, 3, Amsterdam: North-Holland.
39. Fischer, C., and Fox, A. K., 2012. Comparing Policies to Combat Emissions Leakage: Border Carbon Adjustments versus Rebates, *Journal of Environmental Economics and Management*, 64(2), pp. 199-216.

40. Fischer, C., and Newell, P., 2008. Environmental and technology policies for climate mitigation, *Journal of Environmental Economics and Management*, 55(2), pp. 142–162.
41. Gibbins, J. and Chalmers, H., 2008. Carbon capture and storage. *Energy Policy,* 36(12), pp.4317-4322.
42. Giddens, A., 2009. *The Politics of Climate Change*. London: Polity Press.
43. Gillingham, K., Newell, R. G. and Pizer, W. A., 2008. Modeling endogenous technological change for climate policy analysis, *Energy Economics*, 30(6), pp. 2734–2753.
44. Grossman G. and Helpman, E., 1991. *Innovation and growth in the global economy*. London: MIT Press.
45. Grubb, M., 1997. Technologies, energy systems and the timing of CO2 emissions. *Energy Policy*, 25(2), pp. 159–172.
46. Hassler, J., Krusell, P., and Olovsson, C., 2012. *Energy-Saving Technical Change*, NBER Working Paper No. 18456.
47. Harstad, B., 2012. Buy Coal! A Case for Supply-Side Environmental Policy, *Journal of Political Economy*, 120(1), pp. 77 - 115.
48. Helm, D., 2012. *The Carbon Crunch: How We're Getting Climate Change Wrong – and How to Fix It*. London: Yale University Press.
49. Helm, D., Hepburn, C. and Ruta, G., 2012. Trade, climate change and the political game theory of border carbon adjustments. *Oxford Review of Economic Policy*, 28(2), pp. 368-394.
50. Hemous, D., 2012. Environmental Policy and Directed Technical Change in a Global Economy: The Dynamic Impact of Unilateral Environmental Policies, *INSEAD Working Paper 2012/123/EPS.*
51. Hepburn, C., 2010. Environmental policy, government and the market. *Oxford Review of Economic Policy*, 26(2), pp. 117-136.
52. Howarth, R. W., Santoro, R. and Ingraffea, A., 2011. Methane and the greenhouse-gas footprint of natural gas from shale formations, *Climatic Change*, 106(4), pp. 679-690.
53. International Energy Agency (IEA), 2012. *Energy Technology Perspectives (ETP) 2012 - Pathways to a Clean Energy System*, Paris: IEA.
54. IPCC, Intergovernmental Panel on Climate Change, 2014. *Climate Change 2014: Mitigation of Climate Change, Fifth Assessment Report*, Working Group III.
55. Jacoby, H.D., O'Sullivan, M.O. and Paltsev. S., 2011. *The influence of shale gas on US energy and environmental policy.* MIT Joint Program on the Science and Policy of Global Change Report No. 207. Cambridge M.A: Joint Program on the Science and Policy of Global Change.
56. Johnstone, N., Haščič I. and Popp, D., 2010. Renewable Energy Policies and Technological Innovation: Evidence Based on Patent Counts. *Environmental and Resource Economics*, 45(1), pp. 133-155.
57. Keith, D.W., 2000. Geoengineering the climate: history and prospect. *Annual review of energy and the environment,* Vol. 25, pp.245-284.
58. Klette T. J. and Kortum, S., 2004. Innovating Firms and Aggregate Innovation. *Journal of Political Economy*, 112(5), pp. 986-1018.
59. Krugman, P., 1991. History versus expectations. *Quarterly Journal of Economics*, 106(2), pp. 651-667.
60. Lockwood, M., 2013. The political sustainability of climate policy: The case of the UK Climate Change Act. *Global Environmental Change*, 23(5), pp. 1339–1348.
61. Mathews, J. A., 2014. *Greening of Capitalism: How Asia Is Driving the Next Great Transformation*. Palo Alto: Stanford University Press.
62. Matsuyama, K., 1991. Increasing Returns, Industrialization, and Indeterminacy of Equilibrium. *Quarterly Journal of Economics*, 106(2), 617-650.
63. Mazzucato, M., 2011. *The Entrepreneurial State*. London: Demos.
64. McJeon, H., Edmonds, J., Bauer, N., Clarke, L., Fisher, B., Flannery, B. P., Hilaire, J., Krey, V., Marangoni, G., Mi, R., Riahi, K., Rogner, H. and Tavoni, M., 2014. Limited impact on decadal-scale climate change from increased use of natural gas, *Nature*, 514(7523), pp. 482–485.
65. Miao, Q. and Popp, D., 2013. *Necessity as the Mother of Invention: Innovative Responses to Natural Disasters*, NBER Working Paper No. 19223.
66. Moore, F. T., 1959. Economies of Scale: Some Statistical Evidence. *Quarterly Journal of Economics*, 73(2), pp. 232-245.
67. Musk, E., 2014. *All Our Patent Are Belong To You*. [online] Available at: http://www.teslamotors.com/blog/all-our-patent-are-belong-you.

68. Newell R. G., Jaffe, A. B. and Stavins, R. N., 1999. The Induced Innovation Hypothesis and Energy-Saving Technological Change. *Quarterly Journal of Economics*, 114(3), pp. 941-975.
69. Nordhaus, W., 1994. *Managing the Global Commons: The Economics of Climate Change*. London: MIT Press.
70. Nordhaus, W. D., 2007. The Challenge of Global Warming: Economic Models and Environmental Policy in the DICE-2007 Model, *Mimeo*.
71. National Science Foundation (NSF), 2014. *Science and Engineering Indicators 2014*, Chapter 6, Figure 6-41.
72. O'Sullivan F., and Paltsev, S., 2012. Shale gas production: potential versus actual greenhouse gas emissions. *Environmental Research Letters*, 7(4), pp. 044030.
73. Pearce, D., 2006. The political economy of an energy tax: The United Kingdom's Climate Change Levy. *Energy Economics*, 28(2), pp. 149-158.
74. Pindyck, R., 2013. Climate Change Policy: What Do the Models Tell Us? *Journal of Economic Literature*, 51(3), pp. 860-72
75. Pittel, K., 2002. Sustainability and Endogenous Growth, Bodmin: Edward Elgar Publishing
76. Popp, D., 2002. Induced Innovation and Energy Prices. *American Economic Review*, 92(1), pp. 160-180.
77. Popp, D., 2004. ENTICE: endogenous technological change in the DICE model of global warming. *Journal of Environmental Economics and Management*, 48(1), pp. 742–768.
78. Redding, S., 1996. The low-skill, low-quality trap: strategic complementarities between human capital and R & D. *Economic Journal*, 106(435), pp. 458-470.
79. Rode, P., Stern, N. and Zenghelis, D., 2012. *Global Problems: City Solutions*, in Burdett, R. and P. Rode (eds.), Urban Age Electric City Conference, p. 5, London School of Economics.
80. Romer, P., 1990. Endogenous technological change. *Journal of Political Economy*, 98(5), pp. S71–S102.
81. Rozenberg, J., Voigt-Schilb, A. and Hallegatte, S., 2012. *Transition to Clean Capital, Irreversible Investment and Stranded Assets*, World Bank Policy Research Working Paper No. 6859.
82. Shleifer, A., 1986. *Implementation Cycles, Journal of Political Economy*, 94(6), pp. 1163-90.
83. Smulders, S., 2005. Endogenous technological change, natural resources and growth, in Simpson, R. S., Toman, M. A., and R. U. Ayres (eds.), *Scarcity and growth revisited*, Chapter 8, Washington DC: Resources for the Future.
84. Stern, N., 2007. *The Economics of Climate Change: The Stern Review*. Cambridge: Cambridge University Press.
85. Stern, N., 2013. The Structure of Economic Modeling of the Potential Impacts of Climate Change: Grafting Gross Underestimation of Risk onto Already Narrow Science Models. *Journal of Economic Literature*, 51(3), pp. 838-59.
86. Steves, F. and Teytelboym, A., 2013. *Political Economy of Climate Change Policy*. Smith School for Enterprise and the Environment Working Paper No. 13-02, October.
87. Surowiecki, J., 2014. *Shut up and Deal*, The New Yorker Blog, 21 April 2014. [online] available at: http://m.newyorker.com/talk/financial/2014/04/21/140421ta_talk_surowiecki
88. Vengosh A., Jackson, R. B., Warner, N., Darrah T. H. and Kondash, A., 2014. A Critical Review of the Risks to Water Resources from Unconventional Shale Gas Development and Hydraulic Fracturing in the United States. *Environmental Science & Technology*, 48(15), pp. 8334–8348.
89. Ward, H., 1996. Game theory and the politics of the global warming: the state and beyond. *Political Studies*, 44(4), pp. 850–871.
90. Weitzman, M, 2013. Tail-Hedge Discounting and the Social Cost of Carbon, *Journal of Economic Literature*, 51(3), pp. 873-82.
91. Young, H. P., 1996. The Economics of Convention, *Journal of Economic Perspectives*, 10(2), pp. 105-122.