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EEG State-of-Knowledge Paper Series

Oxford Policy Management
Center for Effective Global Action
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The Applied Research Programme on Energy and Economic Growth (EEG) is led by Oxford Policy Management in partnership with the Center for Effective Global Action and the Energy Institute @ Haas at the University of California, Berkeley. The programme is funded by the UK Government, through UK Aid. Over the course of five years, EEG will commission rigorous research exploring the links between energy economic growth, and poverty reduction in low-income countries. This evidence will be specifically geared to meet the needs of decision makers and enable the development of large-scale energy systems that support sustainable, inclusive growth in low income countries in South Asia and Sub-Saharan Africa.

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Economic growth and development with low-carbon energy

Sam Fankhauser[1] and Frank Jotzo[2]

Synthesis paper for *Applied Research Programme on Energy and Economic Growth*

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Abstract

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The Applied Research Programme on Energy and Economic Growth (EEG) is led by Oxford Policy Management in partnership with the Center for Effective Global Action and the Energy Institute @ Haas at the University of California, Berkeley. The programme is funded by the UK Government through UK Aid. The views expressed in this paper do not necessarily reflect the UK Government's official policies.

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1. Introduction

Fossil fuel-based energy has been a driver of economic development and growth over the past 200 years. The importance of fossil fuels has been documented both over the historic long-term (Stern 2011; Fouquet 2008; Fouquet and Pearson 1998) and in the study of contemporary drivers of growth (McCulloch 2016; Stern et al 2016). The significance of modern energy for economic development is recognized in the Sustainable Development Goals, which list "access to affordable, reliable, sustainable and modern energy" as one of their objectives.[3]

However, in the future access to fossil fuel-based energy will need to be constrained because of climate change. To keep climatic changes at a (relatively) safe level, the rise in global mean surface temperatures must be kept well below 2°C, and efforts should be made to keep warming below 1.5°C. These are the objectives of the Paris Agreement, which was agreed in December 2015 and came into force in November 2016. Global warming beyond 1.5 to 2°C is associated with an increased risk of breaching potentially dangerous environmental tipping points (e.g., Drijfhout et al, 2015).

Meeting the Paris targets will not be possible without substantial contributions from developing countries. Historically, developing countries have contributed a relatively small share to global greenhouse gas emissions. However, the balance of annual emissions has shifted. Six of the top 10 emitters are now developing countries. China is by some distance the world's largest emitter, and developing countries as a block account for around 60 per cent of total annual emissions. They will be responsible for practically all emissions growth from now on.

Satisfying the energy needs of developing countries therefore has to factor in an increasingly binding carbon constraint. If global climate targets are to be achieved, developing countries will not be able follow the same carbon intensive growth path as the now-developed countries did. Decoupling economic growth from carbon emissions will require radical and sustained improvements in *carbon productivity*, that is, the amount of carbon emitted per dollar of GDP.

The extent to which this is possible is unclear. Fossil fuel-based energy has been a crucial ingredient to economic growth for decades. But modern energy, which drives growth, does not necessarily have to be fossil fuel-based energy, which causes greenhouse gas emissions. Carbon-free forms of energy are increasingly affordable. Driven by a steep experience curve and economies of scale, the cost of renewable energy has fallen precipitously (e.g. Goodall 2016; IEA 2015). Similarly, the energy efficiency of machinery and appliances is increasing steadily. These trends suggest that it is possible to decouple economic growth and greenhouse gas emissions.

In other words, rapid improvements in carbon productivity seem possible, and the long term objective of a low-carbon energy supply need not be a constraint on development. The more important question is about the *short-term adjustment costs* of moving from a high-carbon to a low-carbon economy. The low-carbon transition requires a deep structural

[3] http://www.undp.org/content/undp/en/home/sustainable-development-goals/

transformation of the energy sector, and like most structural change this is likely to be economically and politically complex and associated with short-term frictions.

Short-term adjustment costs are exacerbated by the long lifetime of energy assets, which means today's investment decisions lock in future emissions over many decades. These considerations are particularly salient for developing countries, which are investing heavily in energy infrastructure to keep up with growing demand. To avoid stranded assets, the decisions they take need to account of the future carbon constraint. Yet, the rate at which carbon-emitting assets are added to the energy system is wholly inconsistent with the 2^{o}C climate objective (Kriegler et al 2014; Pfeiffer et al. 2016).

This paper reviews the implications of the low (and eventually zero) carbon transition for economic growth and development in current low income countries. It explores the likely economic costs in the short term, but also the opportunities that might arise in terms of a cleaner, more dynamic and more sustainable growth model. The paper also reviews the policy implications of steering the developing world onto a low-carbon growth path.

The structure of the paper is as follows. Section 2 outlines the historical link between greenhouse gas emissions, energy consumption and economic growth. Section 3 explores ways to break those historical links and identifies possible pathways for a low-carbon future. Section 4 asks what following those pathways might mean for growth and development. Section 5 discusses the case for policy intervention and section 6 identifies research gaps. Section 7 concludes.

2. Carbon emissions, energy use and economic activity

We start by revisiting the basic relationship between GDP, energy consumption and greenhouse gases emissions. These links are important to understand as they inform the scope for energy sector decarbonization and the impact on economic development this might have.

An intuitive way to portray the emissions-energy-economy relationship, and the scope for emission reductions, is through the following simple identity, which is often associated with the Japanese economist Yoichi Kaya:

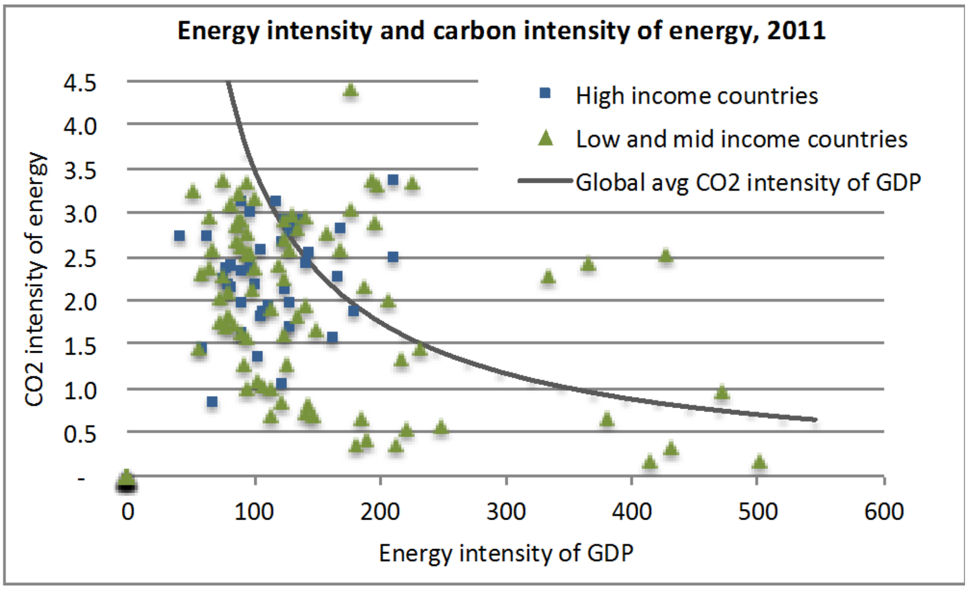
$$C \equiv \frac{C}{E} \cdot \frac{E}{Y} \cdot Y$$

The Kaya identity implies that energy-related carbon emissions, C, are a function of three factors: the carbon intensity of energy (C/E), the energy intensity of economic output (E/Y) and economic output (Y). If the objective is to curtail carbon emissions while allowing for economic growth, countries will have to drive down either their energy intensity or the carbon intensity of energy, or both.

Countries approach this task from very different starting points. Figure 1 displays the energy intensities and carbon intensities of 100 countries in 2011. It shows wide variations along both dimensions. The average energy intensity in 2011 (y axis) was 134 kg of oil equivalent per $1,000 GDP (constant 2011 PPP), with most countries in the 50 – 200 kg oil-equiv /

$1000 range. However, we also observe intensities in excess of 300 kg oil-equiv / $1000. The standard deviation over the sample is 86. The average carbon intensity of energy in 2011 (x axis) was 2.6 kgCO2 per kg of oil equivalent, with a standard deviation of 0.9. A large number of mostly developing countries are around or below the 1.0 kgCO2/kg oil-eq mark, but others have intensities in excess of 3.0 kgCO2/kg oil-eq.

Figure 1 Energy intensity and carbon intensity of energy, 2011



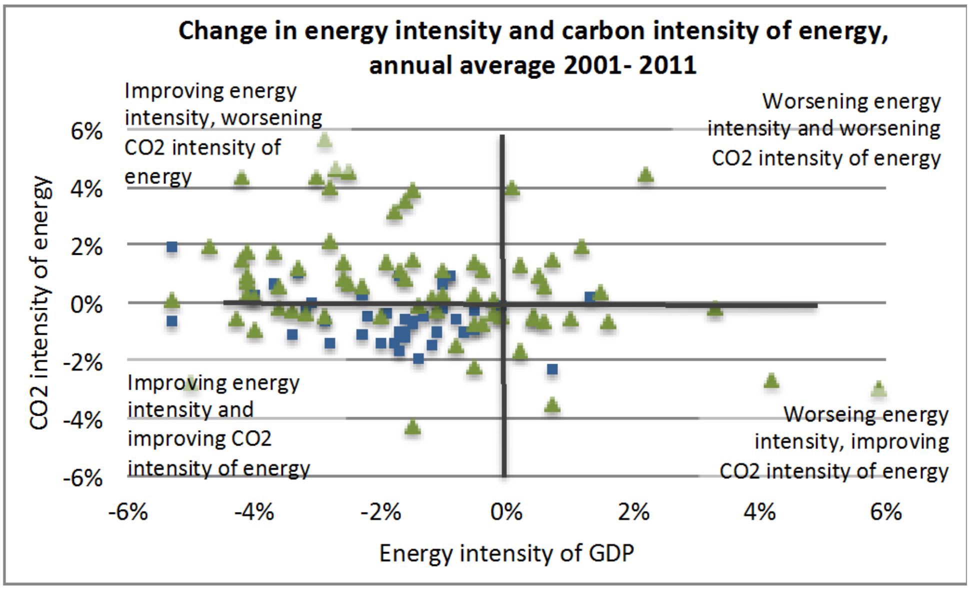
Notes: Energy intensity of GDP: Energy use in kg of oil equivalent per $1,000 GDP (constant 2011 PPP). CO2 intensity of energy: kg per kg of oil equivalent energy use. Global average CO2 intensity of GDP: 347 kg/$1000GDP(const 2011 PPP at 2011). Data: World Development Indicators 2016. Data for 2011. Data shown for 100 largest countries by population, excluding countries for which no data are available.

Combining the two indicators gives a global average carbon productivity of 347 kgCO2 per $1000 of GDP in 2011. The isoquant in Figure 1 displays different combinations of energy and carbon intensity which result in this carbon productivity. That is, countries to the top-right of the isoquant emitted above average amounts of carbon per GDP in 2011 and countries to the bottom-left had emissions below average. Since the global average is dominated by a number of large countries, most countries' carbon productivity is in fact below the global average. However, there is a significant number of developing countries whose carbon performance is worse than the global average.

The economies of high income countries on average are around 20 percent less energy intensive and 17 percent less intensive in carbon per unit of energy, compared to low and middle income countries. Although dispersion is high, income countries also tend to be more homogenous. There are fewer outliers, both in terms of energy intensity and the carbon intensity of energy. These observations suggest that carbon per GDP tends to slightly decrease at higher income levels. This corroborates earlier findings on the CO2-GDP relationship (e.g. Holtz-Eakin and Selden 1995), which suggest an environmental Kuznets curve. However, the drivers of this trend are unclear. Differences in economic structure (e.g. the role of industry) and policy choices (e.g. energy pricing, carbon policy) are all likely to be as important as income.

Figures 3 and 4 show how energy and carbon intensities have evolved over time. The rates of change are instructive to gauge the extent to which countries have been moving towards decarbonization. The figures suggest that energy intensity is improving steadily in both developed and developing countries. However, for many developing countries – and for low and middle income countries as a group – the carbon intensity of energy is still increasing. A large number of low and middle income countries find themselves in the upper left quadrant of Figure 3, with improving energy intensity but worsening (increasing) carbon intensity of energy supply. These countries are achieving better energy productivity through technical improvements and/or structural change, but are "carbonizing" their energy supply. This typically occurs through a rising role of coal in electricity supply and sometimes industry, as well as through the growth of oil use for transport in economies that are relatively low in carbon intensity of energy supply. In contrast, the majority of high-income countries are making progress in decarbonizing their energy sectors.

Figure 3 Change in energy intensity and carbon intensity of energy, 2001-2011

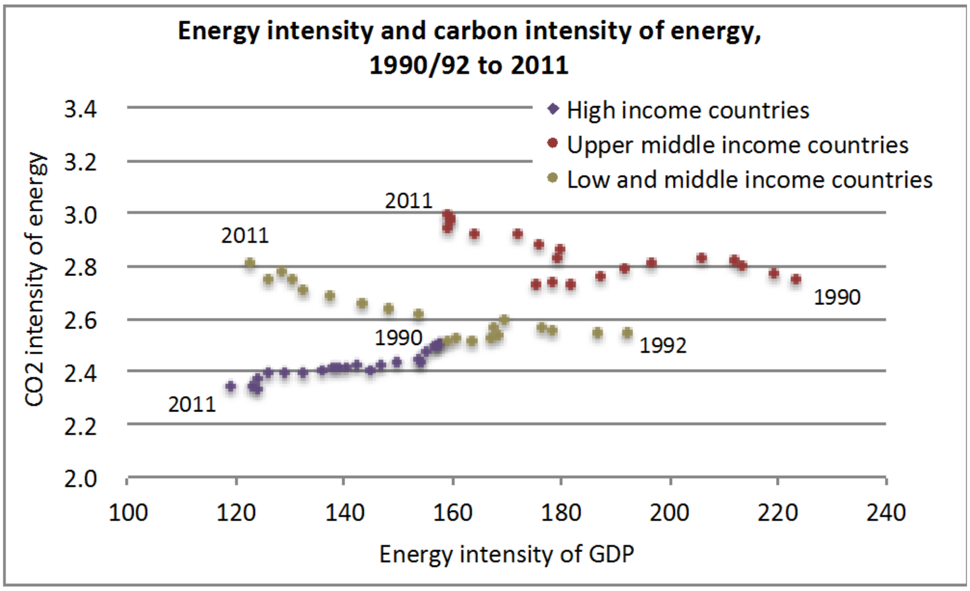


Notes: See Figure 1.

High income countries as a group improved energy productivity by 24 percent from 1990 to 2011 while reducing carbon intensity of energy by 6 percent (Figure 4). Low and middle income countries as a group have achieved a 55 percent improvement in energy productivity over two decades, and in 2011 were at the same level of energy use per dollar of GDP (adjusted for purchasing power parity) as high income countries. However energy supply became 10 percent more carbon intensive. Upper middle income countries saw similar percentage changes as low to middle income countries, but at higher levels of carbon intensity and energy intensity. Together this has meant an annual rate of improvement in carbon emissions per GDP of just under 1 percent per year globally.

More recently, significantly greater rates of improvements have been achieved. In 2014, carbon emissions per GDP decreased by 3.5 percent globally (IEA 2015), in 2015 they fell by a further 2.8 percent (PWC 2016). However, since global GDP grew by a similar amount, this has been sufficient only to stabilize global carbon emissions. They have flat-lined, rather than fallen. BP (2016) expects this trend to continue, anticipating a fall in carbon productivity of 2.6 percent a year between now and 2035 – the result of a 0.5 percent drop in carbon intensity and a 2.1 percent rate of annual energy intensity improvements.

Figure 4 Long-term trajectory of energy intensity and carbon intensity of energy, country groups



Notes: See Figure 1.

3. Pathways to a low-carbon energy sector

We next explore how a low-carbon growth path for the energy sector, which is technologically feasible and compatible with the Paris climate target, might look. The scale of action required to meet the Paris objectives is substantial. To keep the rise in global mean temperature "well below 2°C", cumulative global emissions until the end of the century must not exceed 600 to 1,100 GtCO2 (Fankhauser and Stern 2017). In comparison, annual global greenhouse gas emissions are around 50 GtCO2, of which about two thirds are related to the burning of fossil fuels (IPCC 2014). The carbon content of current fossil fuel reserves is almost 3,000 GtCO2 (Carbon Tracker 2013).

To keep within this overall carbon budget, global emissions will have to peak within the next decade and decline steadily thereafter (Rogelj et al. 2016). The current rate of reduction in carbon per GDP (described above) must more than double, to around 6.5 percent a year (PWC 2016). This rate will have to be sustained until emissions reach "net zero" (or in some scenarios go negative) in the second half of the century. "Net zero" emissions mean that there is a balance between anthropogenic emissions into the atmosphere and their removal into sinks.

There is a wealth of energy-economy models that can and have been used to simulate different emissions paths. They have been reviewed in the 5th assessment report of the Intergovernmental Panel on Climate Change (IPCC 2014) and in a series of model comparison exercises, where models are run under standardized assumptions and/or to achieve agreed climate outcomes (e.g. EMF-27 – Blanford et al 2014; LIMITS – Kriegler et al 2013; AME – Calvin et al. 2012; ADAM – Edenhofer et al. 2010). The same models are now being used to produce *shared socio-economic pathways* – a series of consistent scenarios that can feed into climate models (van Vuuren et al 2012; Riahi et al. 2016).

Most of these global models are too aggregate to reveal much about the decarbonization pathways of individual countries. However, at least for the major greenhouse gas emitters additional information is available from country-level simulations. One source of information is the UN Deep Decarbonization Pathways Project, a high-profile initiative led by prominent economist Jeff Sachs (DDPP 2015).

DDPP explores extremely rapid decarbonization paths, using detailed, country-specific and technology-rich energy-economy models. Their results suggest that extremely rapid reductions in energy intensity and the carbon intensity of energy are feasible, at least theoretically. Table 1 reproduces the results for five key emerging markets. The annual reductions listed in the table exceed past performance by at least a factor three and result in the virtual decarbonization of the energy sector by the middle of the century (Figure 5).

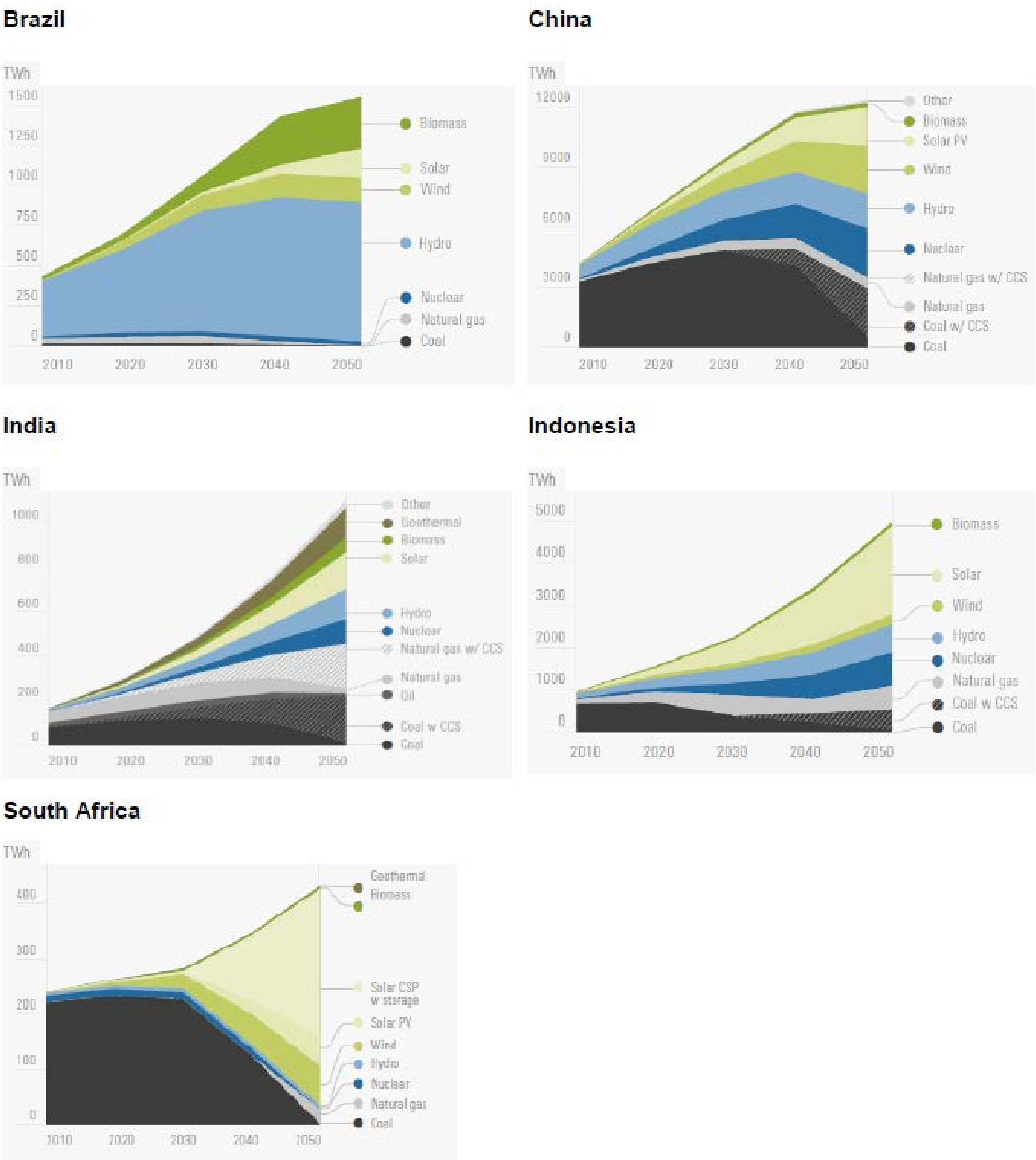
While the DDPP scenarios are extremely aggressive, they illustrate what might be possible. Each country will face its own distinctive challenges. There are clear differences for example between a country like Brazil, which has a largely carbon-free electricity sector thanks to its hydropower reserves, and countries like India and China, which rely heavily on indigenous coal. There are also fundamental differences in the decarbonization paths of low-income countries and those of high and middle income countries. In the latter, decarbonization is about changes to power generation, the redesign of electricity grids, residential energy efficiency and cuts in industry and transport emissions (e.g., CCC 2015). In the former, the decarbonization challenge is about clean electrification, the sustainable use of biomass and access to services such as heat, light and water. Despite these differences some stylized facts are beginning to emerge.

Table 1 Theoretically feasible improvements in energy and carbon intensity

	Annual rate of reduction 2010-2050		
	Energy Intensity	**Carbon intensity of energy**	**Carbon per GDP**
Brazil	-1.3%	-12.4%	-13.7%
China	-3.2%	-5.8%	-9.1%
India	-3.5%	-5.8%	-9.3%
Indonesia	-3.0%	-6.8%	-9.8%
South Africa	-1.3%	-7.7%	-9.0%

Note: Results from country-specific model simulations using linked computable general equilibrium economic models and bottom-up energy-systems models.
The following scenarios are depicted Brazil = DDPP Scenario; China = Central Scenario; India – Renewables + CCS; Indonesia = Renewable; South Africa = High Skills
Source: DDPP (2015). See also http://deepdecarbonization.org/countries/ for full country reports.

Figure 5 Deep decarbonisation pathways for key developing countries



Note: As Table 1.
Source: DDPP (2015). See also http://deepdecarbonization.org/countries/ for full country reports.

3.1 Reducing the carbon intensity of energy

Virtually all pathways to a low-carbon economy start with the rapid decarbonization of the electricity sector. The carbon intensity of energy decreases much faster than emissions in any other sector (Bataille et al 2016; Fankhauser 2013; Williams et al 2012). This is for three main reasons. First, energy is the dominant source of greenhouse gas emissions, accounting for about two thirds of global emissions. Second, low-carbon power generation is well-understood technologically. A number of low-carbon options are available, including renewable energy (wind, solar, biomass, hydro), nuclear energy and (as yet less well developed) carbon capture and storage (CCS). They create options for low-carbon power generation. Third, decarbonized electricity has an important role to play in reducing emissions in other sectors, chief among them transport, residential energy demand and perhaps some parts of industry. That is, low-carbon energy pathways go hand in hand with an increased electrification rate. “Electrification” of the economy will drive up power generation, but will reduce overall emissions if the carbon intensity of electricity is low.

The carbon intensity of energy depends on the choice of fuels, specifically the balance between the different fossil fuels, as well as the balance between fossil fuels and renewables and nuclear power. Fossil fuel currently accounts for around 80 percent of global energy supply. Coal and oil account for around 30 percent each, and gas just over 20 percent (IEA 2015). Of the remainder, the majority is from biomass, followed by nuclear power. Modern renewables such as solar thermal, solar PV and wind are growing fast but from a low base. Differences between countries are a function of resource endowments, income, the economic structure (e.g. the importance of heavy industry) but also wider socio-economic factors. Calvin et al. (2012) found that the use of solid fuels in residential energy use decreases sharply with the level of urbanization.

Power sector emissions can be brought down by switching from high-carbon fuels like coal to lower-carbon fuels, such as gas, and ultimately carbon-free sources of energy. This has implications in particular for coal. A consistent feature of all energy decarbonization scenarios is the sharp decline in coal-fired power (e.g. Sachs et al. 2014, Ribera et al. 2015; CCC 2015). Already in the short term, the scope for new coal investments is highly limited. According to one estimate, any coal-fired power station built after 2017 will have to be scrapped prematurely or retrofitted with carbon capture technology (Pfeiffer et al. 2016). There is no room for unabated coal in a low-carbon energy sector.

In contrast, natural gas is likely to play a substantial role over the short and medium term. However, over the long-term even gas-fired power stations will become too carbon intensive and will have to be fitted with CCS. Modern combined-cycle gas turbines emit about 350 gCO2 per kWh of electricity generated, compared with a required grid average of less than 100 gCO2/kWh in more aggressive decarbonization scenarios (e.g., CCC 2015).

Strategically used natural gas also remains important to balance load and ensure system stability. As the penetration of intermittent renewables, such as solar and wind, increases, the task of meeting power demand reliably becomes more and more difficult and the value of rapidly dispatchable power, such as hydro and gas-fired plant, goes up. Studies have found that renewable energy shares above 50 per cent of total capacity are possible, but this requires a judicious combination of dispatchable power, smart demand management and interconnection with neighboring grids (Cochran et al 2014; NREL 2012; Denholm and Hand 2011). In the UK, the costs of managing intermittency in a 100 gCO2/kWh power system are about $13 per MWh of renewable output (Imperial College London and NERA 2015).

As battery costs come down, energy storage should become increasingly cost-effective, further enhancing the scope for renewables (Goodall 2016). Cheaper storage will also enhance the attractiveness of distributed energy solutions and mini-grids, a solution that may be particularly relevant for low-income countries. In contexts where energy demand is dispersed and individual loads are low, distributed energy is a potentially competitive, if not problem-free, alternative to costly grid extension (e.g., Palit 2013; Wamukonya and Davis 2001).

These trends are illustrated in the country examples in Figure 5, which show a drastic reduction in coal use in all countries, but particularly China and South Africa, and a rapid expansion of renewable energy toward the middle of the century. The only exception among these major countries is Brazil, which already has a largely decarbonized electricity sector due to its vast hydropower reserves.

3.2 Reducing the energy intensity of GDP

Decarbonisation scenarios typically show substantial expansion in energy use, and in particular electricity consumption, in developing countries. It reflects both a large unmet demand and the growing use of electricity for activities that traditionally have used fossil fuels directly. This expansion effect more than dominates any success in increasing energy efficiency and reducing energy use per unit of GDP. Yet, deep decarbonization also requires substantial progress in this respect.

The energy intensity of an economy, and its trajectory over time, principally depends on economic structure and technical energy efficiency. Both tend to improve through the development process, but in the case of the latter progress can be accelerated through targeted interventions (EBRD, 2011; Doda 2016a).

Energy use per unit of monetized economic output as measured in GDP is relatively high in materially intensive industries such as primary industries such as mining, and many heavy processing industries such as metals and minerals processing, chemicals and cement. It can also be high in transport and agriculture. By contrast, most service industries and light manufacturing use relatively little energy per unit of output. Hence, energy intensity can be reduced through structural change, and this a typical part of the development process.

Technical energy efficiency too tends to increase as part of the development process. Efficiency improvements come about through technical improvements in specific processes and products, such as more energy efficient motors and industrial installations, as well as technological change that allows producing similar goods or achieving similar services with entirely new, less energy intensive processes.

There is a long-running debate about the extent to which observed energy efficiency levels lag behind the technical potential, that is, whether there is an energy efficiency gap. The economics literature tends to be skeptical (e.g. Allcott and Greenstone 2012), while engineering studies regularly find substantial energy savings potential.

Studies for South Africa have identified a large energy savings potential in industrial sectors as diverse as mining, iron and steel, wood products and chemicals (Howells 2006, Hughes et al. 2006). The Global Energy Assessment (IIEA 2012) estimates that a 46 per cent reduction in heating and cooling energy demand is feasible by 2050 compared to 2005. Most residential energy efficiency options concern the energy consumption of middle and high-income households, for example through more efficient lighting and appliances (McNeill et al 2008). Opportunities to save energy in low-income households are related for example to the thermal efficiency of buildings (Spalding Fecher et al 2002; Winkler et al. 2002).

However, the main benefit of these measures tends to be poverty alleviation rather than energy savings. Most households respond to efficiency improvements by increasing their comfort levels rather than reducing their energy bills. That is, there is a strong rebound effect, with lower costs leading to higher consumption (Dimitropoulos 2007).

4. The impact of energy decarbonization on economic growth

This section asks what the pursuit of low-carbon energy might do to economic growth and development. There is no doubt that a low-carbon development path will reshape the economy, and have particularly strong effects on economies and sectors where emissions intensity is high. It will force the contraction of entire industries (in particular coal mining, but also oil extraction and refining, gas extraction) transform others (such as production of energy-intensive goods) and let yet other industries grow (such as renewable or nuclear power production, and the manufacture of energy efficient equipment).

Low-carbon transformation in the energy sector has three major aspects, or “pillars” in the language of the ‘Deep Decarbonization Pathways Project’ (Sachs et al. 2014, Ribera et al. 2015, Bataille et al. 2016). The first is the low-carbon transition of the electricity supply; the second is electrification of energy using activities that currently relies on direct combustion of fossil fuels (including road transport, heating and industrial processes); the third is improvements in energy efficiency, which is essential for cost-effectiveness of decarbonization.

In most countries, a low or zero carbon electricity supply would rely to a large extent on renewable power – principally hydro, wind and solar power – though nuclear power plays a significant role in some countries, and carbon capture and storage for coal and gas fired power plants could also be important (Sachs et al 2014).

An electricity sector dominated by partly decentralized renewable generators producing intermittent power at near-zero operating costs (or short-run marginal costs) may need different market structures and will need to be regulated differently from the fossil fuel-based “centralized generator” model prevalent in most countries today. While high penetration of renewables is feasible in most grids (Cochran et al 2014), it will be necessary to incentivize electricity storage to complement intermittent renewable sources, to facilitate investment in new transmission infrastructure, and to create new markets e.g. for the provision of frequency control services that come automatically with fossil fuel powered turbines (Riesz et al. 2015).

Electric cars, particularly if they are self-driving, and homes with smart energy meters and smart appliances will give rise to new business models and changes in consumer behavior.

These changes threaten incumbent operators, provide openings for market entry, and result in new infrastructure investment. They are associated with potentially large structural adjustment costs, as labor and capital is redeployed. However, they may also open new opportunities.

The potential effects of a low-carbon transition are thus manifold and complex. Theoretical approaches identify many different factors of influence but do not offer universally applicable conclusions. Empirical modelling-based approaches provide insight, though their methodological limitations prevent them from providing definitive answers. Scope for ex-post analysis of the effect of decarbonization on economic growth is limited because many other factors affect growth, making it impossible to clearly isolate the macroeconomic effects of decarbonization. Furthermore, the scope for comparative studies between countries is limited because circumstances differ greatly and because few countries have undergone decarbonization of their energy systems.

4.1 The impact on growth: theory

A range of effects from a low-carbon transition on economic growth can be expected. The literature to date does not provide a comprehensive and universal typology. We group potential growth effects of a low-carbon transition in the following categories: effects on productivity and economic efficiency; investment and dynamic effects on growth; stranded assets and fossil fuel rich countries; and growth effects of environmental impacts.

Productivity and efficiency

Technical progress is a fundamental driver of economic growth, as it enhances the productivity of capital and labour (Färe et al 1994). Investment in low-carbon energy technologies can change overall productivity. Usually, new technologies allow greater economic output using the same level of other inputs, thus enhancing productivity. Improved “total factor productivity”, usually attributed to technological change, is a consistent factor in economic growth.

Low-carbon infrastructure and production assets by contrast could be less productive than the high-emissions alternatives. A potential example is renewable energy generation, which may have – but not necessarily does have – higher resource costs than a fossil fuel fired alternative for the production of a given amount of electricity. Consequently, in such a case investing in the cleaner technology may reduce economy-wide productivity and thereby could lower growth.

But equally, a low-carbon energy transition can result in additional innovation that in turn can result in productivity raising technological change. The new energy technologies may lead to more productive capital and labour than the old technologies they replace, in addition to being cleaner. Insofar as innovation-led productivity enhancements are the result of policy to cut emissions, they are described as 'induced technological change' (e.g. Barker et al 2006).

Analysis of the historical relationship between energy and economic growth (Stern 2011) has shown a close linkage between energy use and GDP growth, and that energy can impose a strong constraint on the growth of the economy when energy is scarce, while its effect on economic growth is lower when energy is abundant. In addition to the considerations about productivity, this may imply that a shift from potentially scarce sources of energy (such as oil and gas) to intrinsically abundant renewable energy sources reduces the vulnerability to growth-reducing energy constraints.

Energy efficiency improvements unambiguously raise productivity, as less input is needed to provide the same product or energy service (Fowlie and Phadke 2016). However, gains from energy efficiency are counteracted by the 'rebound' effect, which has energy demand increasing as a result of falling implicit prices per unit of energy service used. The effect on aggregate economic output depends among other factors on the nature of the additional energy services used, and recent reviews conclude that there is no strong evidence that the rebound effect is very large. The longer-term macroeconomic relationships are not well understood (Dimitropoulos 2007). However, the rebound effect tends to be much smaller than the underlying efficiency improvement (Gillingham et al 2013).

Further, the rebound effect will generally be welfare enhancing as it is an expression of greater consumption of energy services. It can also be argued that rebound is associated with induced innovation and productivity growth (Gillingham et al 2015), shifting the focus back on the overall productivity effect of energy efficiency improvements rather than the effects on energy consumption.

Another important aspect is interactions of low-carbon policies with existing policies. A shift to clean energy driven by policy measures interacts with existing taxes, subsidies and regulations. If the pursuit of low-emissions activities and reinforces existing, distorting policies then this will reduce economy-wide efficiency. If on the other hand the policy drive towards clean energy goes in the opposite direction as existing, economically distorting policies, then this may increase efficiency. A general 'tax interaction' effect of levying a carbon tax on top of existing taxes tends to be unambiguously welfare reducing (Goulder 1995).

An example is a carbon tax in the face of fossil fuel subsidies: subsidies for fossil fuels lead to inefficiently high fossil fuel use, so reducing fossil fuel use will enhance economic efficiency, regardless of environmental and other effects, and up to a point where the effect of the carbon tax is equal to that of the fuel subsidy.

Some policy mechanisms to support low-carbon energy systems may also bring in net fiscal revenue, allowing governments to lower existing taxes and thereby reduce economic distortions. This in turn could yield a "double dividend" of environmental and economic efficiency, however benefits from revenue recycling might be reduced or negated by the 'tax interaction effect', namely distortions arising from changes in relative prices including for labour (e.g. Bovenberg and Goulder 1995, Parry et al 1999). Nevertheless, ‘environmental tax reform’ has been found in some analyses to be potentially efficiency enhancing (eg Ekins et al 2012).

A further potential impact on productivity and growth of climate change mitigation policy is that a shift towards a cleaner economy will also mean a change in economic structure, for example away from mining and fuel extraction and associated industries and towards engineering and manufacturing. Insofar as productivity growth differs between such sectors, the structural change may also result in higher or lower productivity over time. The effect of such impacts can in principle be represented in computable general equilibrium models, however the resulting estimates suffer from a lack of information about the future relative productivity in different sectors of an economy.

Investment and dynamic effects

The shift to a low-carbon energy system has implications for the extent, nature and timing of investment in the energy system. Zero-carbon energy options (for example wind, solar, hydro or nuclear power) tend to require greater up-front capital investments than fossil-fuel using options (e.g. coal or gas fired power). In turn, fossil fuel based energy sources typically have higher ongoing operating costs due to the cost of fossil fuels, reflecting investments and operating costs in upstream industries such as mining, fuel extraction and fuel transport.

Consequently, both the composition of investments and the time profile of investment differs between conventional and low-emissions energy sources. The higher up-front investment required for typical clean energy installations would increase GDP in the short term, unless it solely displaces other investments. Investment in ‘green’ infrastructure was undertaken as a form of fiscal stimulus following the economic slowdown of the late 2000s, including in China and the United States (Barbier 2010).

The longer term effect of clean energy investment on growth depends, among other factors, on whether additional short term investment for clean energy productivity is compensated by lower investment later on, and on productivity effects from structural change. Neither the direction nor the magnitude of the impact are clear a priori.

Stranded assets and fossil fuel rich countries

There is a risk that high-carbon energy infrastructure may become unusable (or ‘stranded’) before the end of its expected lifetime, on account of stringent future carbon constraints. High-carbon infrastructure may enjoy a present-day cost advantage, however this advantage may be reduced or turned into a cost disadvantage if there is a significant risk that it will not be able to be used for its full lifetime. If global emissions are to remain with the carbon budget that would keep global warming to two degrees or then many existing and yet to be built fossil fuel installations would be stranded.

Fossil fuel producing countries are particularly strongly exposed to the risk of stranded assets. More generally, fossil fuel rich countries stand to lose the value of their resource base. If there is a global transition to a low carbon energy system would leave large shares of fossil fuel reserves “unburnable” (McGlade and Ekins 2015). The prices of hydrocarbons still extracted would decline with declining global demand, and with them the resource rents to fossil fuel producing countries. Carbon capture and storage technology could mitigate the effects on global fossil fuel demand to some extent but would not fundamentally alter the fact that decarbonization means substantially less demand for fossil fuels, especially in light of slow progress with the technology (Scott et al 2013).

The prospect of fossil fuels losing their economic value in a decarbonizing world economy suggests fossil fuel rich countries should employ strategies to guard against the risk of deep reductions in the value and contribution to economic growth of their fossil fuel resources. The primary risk management strategy is to diversify the economy by strengthening non-fossil fuel sectors, be they other resources sectors, or manufacturing and services. This may be achieved through a variety of policy interventions, from changes in the tax system to investments in infrastructure and human capital.

Other strategies include the establishment of resource revenue funds, investing in other sectors and countries with the expectation of having financial resources available once the resources lose their value. Norway’s fiscal management of its petroleum resources is a well known example of this approach (Holden 2013).

Avoided climate change and other environmental impacts

The ultimate purpose of climate change mitigation including the transition to low-carbon energy is to limit future climate change, and in turn to safeguard future economic prosperity.

Assessing the possible economic effects of future climate change, and the benefits and costs of avoided climate change, is the subject of a literature that is beyond the scope of this paper. It is important however to keep in mind that the long term goals of avoiding damages and minimizing risk, including to economic growth, are the core objective of a low carbon transition. The future benefits are difficult to quantify but could be very large, including through the insurance effect of reducing the risk of catastrophic climate change (Weitzman 2014).

Transitioning to cleaner energy technologies also has so called ‘co-benefits’, namely benefits other than reduced climate change. In particular, low carbon energy means less local air pollution and therefore lesser adverse health effects which are economically costly.

Local air pollution from fossil fuel combustion is a major cause of morbidity and mortality in some locations, including many population centres of the developing world. For example the damages from the use of coal in the United States have been estimated at up to half a trillion dollars per year, higher than the direct costs of producing electricity from coal (Epstein et at 2013). Air pollution from fossil fuel combustion is an emblematic environmental and health problem in many developing and industrializing countries. Air pollution leads to very large economic losses due to illness and premature deaths, with estimates that air pollution in Northern China shortens life expectancies by five years (Chen et al 2013).

Improvements in air quality will tend to have positive effects on growth and development, especially through higher labour productivity and reduced health system costs.

Other co-benefits can include improved energy security due to relatively greater reliance on domestic or local energy sources (Valentine 2011). Energy security can be strengthened under a low carbon energy system in a physical sense because energy production tends to be more distributed, with less reliance on long distance energy transport and trade. Economic energy security can also be improved, as non-fossil energy is not directly subject to price fluctuations in markets for coal, gas and oil.

In many circumstances, co-benefits are an important driver of policies that will result in lower carbon dioxide emissions. China is an example where co-benefits in terms of health, energy security and economic diversification come together and are thought to have shaped policy (Teng and Jotzo 2014). The United States' clean power plan (Bushnell 2015) established under President Obama is primarily framed in terms of carbon dioxide emissions reductions, but can also be seen in the context of concerns about local pollution.

4.2 The impact on growth: empirical modelling

There is a long tradition in energy modelling to study the impact of a carbon constraint in the energy sector on economic output. Many of these energy-economy models predate the debate on climate change and have their origin in energy sector planning. Others have their roots in computable general equilibrium (CGE) analysis of economic production and consumption as a result of policy change such as trade rules. All relevant models include some form of estimates of abatement costs and marginal abatement costs, that is, the incremental cost of reducing emissions by an additional ton.

Philosophies of different approaches are diverse and different types of models offer different insights. Bottom-up models are more suitable for energy sector study. Macroeconomic models and CGE models offer more insights on economic and output effects (Kolstad 2014).

Quantitative results

In considering quantitative model results, it is worth considering broad magnitudes of possible economic effects. The cost of energy is typically just a few percent of overall production costs. So even if energy costs doubled under a low carbon transition, the (first order) impact on the economy in terms of additional costs would not be very large.

The insight is broadly borne out by model results. On the whole, modelling of mitigation costs suggest that the economic cost of decarbonisation is relatively small, relative to broader growth trends, perhaps a few percentage points between now and the middle of the century. This compares to expected continued underlying economic growth that would have global economic output perhaps doubling over the same period of time.

However there is considerable variation between models, scenarios and (within the same scenario) different countries and sectors. There are also significant limitations to the conceptual approach and practical implementation of low-carbon energy scenarios in economic models.

A number of model comparison exercises exist where different models are run on standardized assumptions to better understand sensitivities and answer empirical questions through ensembles of models. These model based analyses omit a number of the factors listed above that may result in lower economic cost or economic benefits, as they typically model only the costs of reducing emissions not the benefits, and in many cases have only limited representation of productivity enhancing effects.

The IPCC 5th Assessment Report (IPCC 2014) summarizes the economic cost estimates as consumption losses in cost-effective scenarios between 2.1 and 6.2 percent relative to the model baseline at 2050 for 450ppm or 2 degree compatible scenarios. This equates to annualized reductions in GDP growth between 0.06 and 0.17 percent. Imperfect policy implementation – for example if large sources of emissions reductions remain untapped or the explicit or implicit carbon price differs greatly between sectors and countries – can significantly raise the modeled cost of achieving a given emissions target.

Specific modelling comparison exercises have come to broadly similar conclusions.
The EMF-27 modelling comparison (Kriegler et al 2014) puts discounted consumption costs of 450ppm scenarios at between 0.9 to 3.3 percent of GDP from now until the end of the century. The RECIPE modelling comparison project (Luderer et al 2011) found costs of 1.4 percent or less in reduced global consumption over the 21st century.

4.3 Limitations

Results are sensitive not only to parameter choices (e.g. technology costs, substitution elasticities) but also to assumptions about the timing of climate change mitigation (early action versus later action) and the degree of international cooperation and policy instruments (e.g. a global carbon tax that would minimize costs is often assumed, although this does not appear a realistic prospect in practice).

Energy-economy models have been criticized on a number of fronts. A first shortcoming is that they tend to neglect the dynamic benefits of innovation, endogenous learning and investment (Aghion et al 2014). Representation of the sources of technological progress (and thus productivity growth) is difficult and often done in a partial fashion in existing models (Clarke et al 2008).

Among the most important issues that modelers must address in constructing and interpreting approaches to technological change are those surrounding the “sources” of technological change. Technological change arises from a variety of interacting sources, including publicly funded R&D, privately funded R&D and learning-by-doing.

A second major shortcoming is that structurally, modelling exercises compare a carbon-constrained world with an unconstrained (or less constrained) base case. The base case is by definition the better economic outcome, as the economy is less constrained. Hence such models are by design set up to report a cost of reducing emissions, irrespective of the factors that may improve economic outcomes, discussed above).

A related criticism is that the models by focus on marginal changes when the problem at hand is one of system-wide and non-marginal change (Stern 2016; Fankhauser and Stern 2017). Other critics point out the typical lack of modelling of environmental side-benefits as well as of structural rigidities, which can either increase costs or reduce them if there is excess labour (Barker et al 2006). There are notable synergies between climate policy and other environmental objectives, from reduced fossil-fuel pollution (air and water) to the preservation of the world's forests. Air pollution is a key environmental problem in most major cities. The Global Burden of Disease project estimates that in 2010 close to 7 million people died globally from the effects of ambient and household air pollution (Lim et al. 2013). These are environmental priorities that would and should be pursued in their own right. However, the low-carbon transition offers opportunities for synergies and coordination (Fankhauser and Stern 2017).

5. Policy requirements and barriers

This section explores the role of the state in the low-carbon transformation. We have seen that dealing with climate change requires deep structural change. Unlike other market transformations, such as that caused by information technology, this structural change is not driven exclusively by market forces. The low-carbon transition is primarily a policy driven transformation.

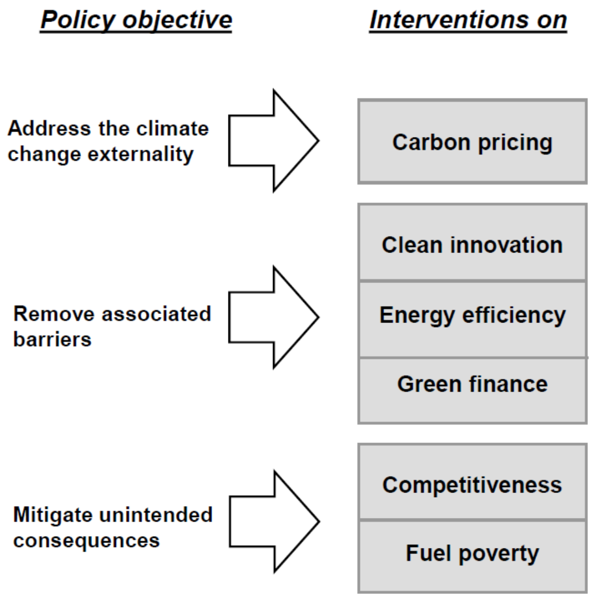
Policy intervention is motivated by the need to correct a fundamental market failure (Stern 2007): the fact that the (potentially massive) economic, social and environmental costs of greenhouse gas emissions are not reflected in the price of fossil fuels. Without government intervention to "internalize the climate change externality" the emitters of greenhouse gases have no incentive to control their carbon output.

This is not the only issue that requires government intervention. Fankhauser and Stern (2017) point to a long list of associated problems that hold back the low-carbon transition, including failures in capital markets, the societal benefits of low-carbon innovation, network issues, barriers preventing the uptake of energy efficiency measures and related environmental externalities like air pollution and the destruction of the natural environment.

There are also policy distortions, not least the subsidization of fossil fuels and the underpricing of energy (OECD 2015; Coady et al. 2015). Carbon policy is not enacted in isolation. The energy sector is already heavily regulated and low carbon measures come on top of existing rules and regulations. This can exacerbate the overall costs of regulation but, as noted above, there may also be synergies.

Following Bowen and Fankhauser (2017) we group the requirements for public policy into three sets of measures (see Figure 6). The first group concerns interventions to discourage carbon emissions. For most policy makers this means putting a price on carbon. The second group concerns policies that deal with additional market failures in areas such as clean innovation, energy efficiency and financial markets. Addressing them will make carbon pricing policies work more efficiently. The third group of interventions mitigates the wider socio-economic impacts of carbon policies.

Figure 6: Low-carbon market failures and key policy interventions



Source: Bowen and Fankhauser (2017).

5.1 Putting a price on carbon

The first group of policies is concerned directly with the climate change externality. For economists this is the first and foremost intervention and at its core is the need to put a price on carbon emissions.

Carbon pricing has proven an effective tool to incentivize emission reductions with very limited effects, so far, on competitiveness (Dechezleprêtre and Sato 2014). Putting a price on carbon has been shown not just to reduce emissions (Ellerman et al 2007; Convery et al. 2008), but also to encourage innovation in low carbon technologies (Calel and Dechezleprêtre 2016).

There are two main pricing instruments: emissions trading (also known as cap and trade) and carbon taxation. Another option would be carbon offsets, or baseline-and-trade systems. However, following the collapse of the Clean Development Mechanism they are restricted to niche markets.[4] Of course it is also possible to directly regulate carbon

[4] Under a baseline and trade systems, eligible projects can earn and sell "emission reduction credits" if their emissions fall below a pre-agreed baseline. This contrasts with cap-and-trade, where the regulator issues a set number of emissions allowances or permits, which are traded on the market. In some systems regulated firms may cover their emissions either through allowances or credits obtained through an offset project.

emissions by imposing emissions standards, for example on the amount of CO_2 permitted in electricity generation. While many regulators have gone down this route, command-and-control regulation is less unlikely to result in an efficient outcome than market-based instruments (Bowen 2014).

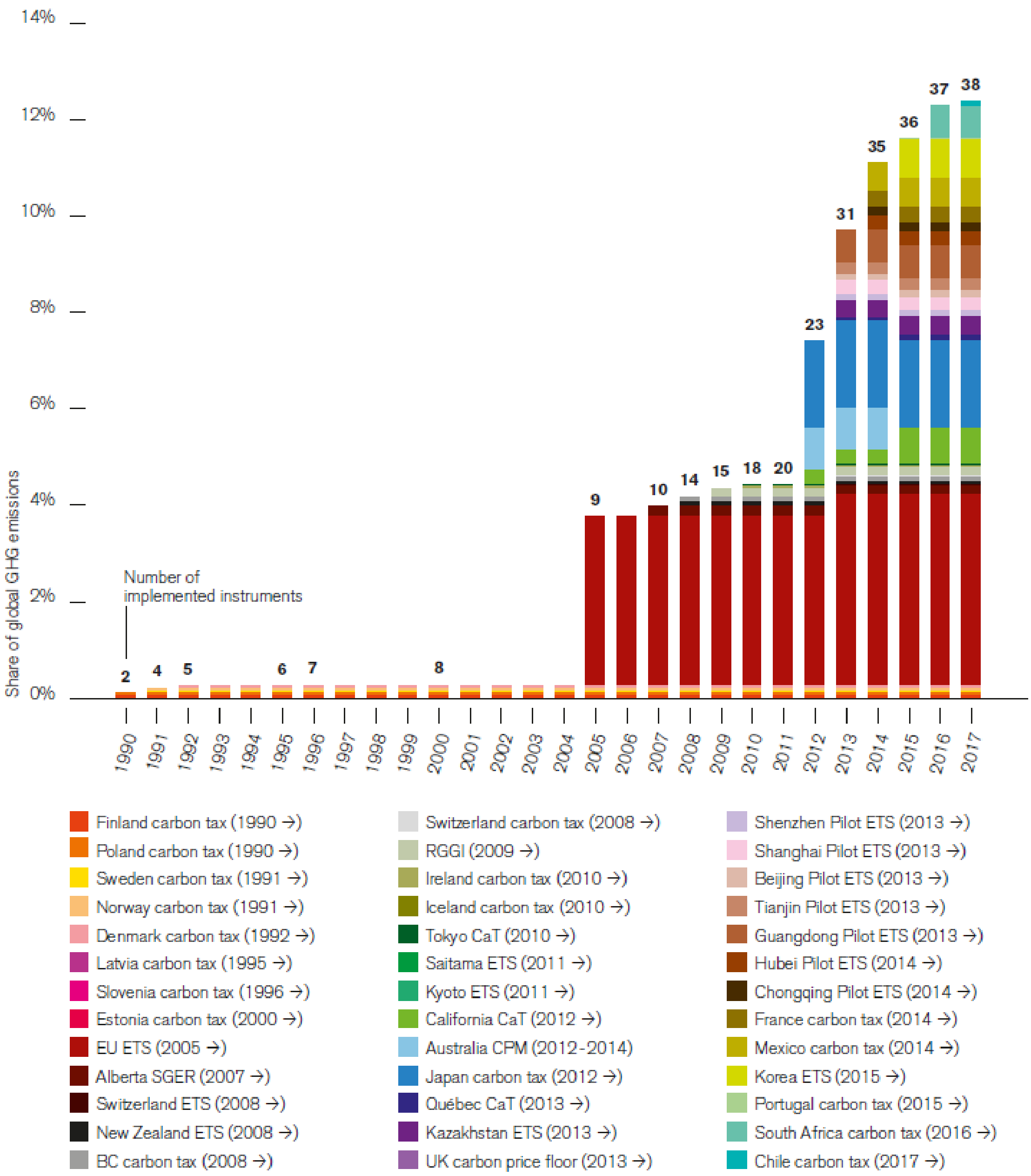
The two main carbon pricing methods have both been implemented in practice. British Columbia has gained much praise for its revenue-neutral carbon tax, which returns all proceeds to businesses and individuals. Sweden has taxed carbon since 1991 and at relatively high levels, although there are extensive exemptions. Carbon is also taxed in, among other countries, Australia, Chile, Ireland and the UK (Figure 7). The cap-and-trade world is dominated by three prominent schemes: The EU Emissions Trading Scheme, California's Cap and Trade Program and China's provincial trading pilots. However, carbon is also traded in New Zealand, South Korea, Kazakhstan the North-East US, Tokyo and Quebec.

Switzerland has both taxation and a trading scheme, and indeed regulators increasingly opt for hybrid schemes that combine features of both systems, such as trading schemes with a price collar (Fankhauser and Hepburn 2010; Kollenberg and Taschini 2016). Doda (2016b) similarly finds that the best way to respond to business cycle fluctuations is to design carbon taxes a bit like permit systems and vice versa.

From an environmental point of view, the choice between tax and trade is a choice between two forms of risk. Taxes offer certainty over the cost of compliance (the tax rate), but there is a risk emissions may not come down as expected. Trading schemes offer certainty over emissions (the cap), but compliance costs are unpredictable. Weitzman (1974) has shown that the choice between those two forms of uncertainty comes down to the shape of the climate change damage function. (The argument was extended to climate change by Hoel and Karp 2001). If damages increase steeply with emissions it is better to be certain about those emissions and set a cap. Conversely, if damages are relatively constant it is better to tax.

For practical purposes the choice between trading and taxing is often a secondary question. The more pressing real challenge is to impose a price on carbon in the first place and set this price at the appropriate level. The political economy of carbon pricing has often favored trading schemes since they create a valuable new asset (emissions permits) that can be used to pacify reluctant industries. However, taxation too creates revenues (tax receipts) that can be used to create a politically acceptable outcome.

Figure 7: The emergence of carbon pricing internationally



Source: World Bank (2015).

5.2 Removing associate barriers

Carbon pricing works better if it is accompanied by complementary policies to remove additional market failures, such as those related to energy conservation, low-carbon innovation and the functioning of capital markets. The supply and demand response to a given carbon price signal will be higher if associated barriers are addressed through separate measures (Bowen and Fankhauser 2017).

A sufficiently high carbon price would in principle be capable of overcoming any related market failures. However, the prices required may be unacceptably high, with considerable distributional consequences. Similarly, generous support for energy efficiency and clean technology could in principle compensate for a low or absent carbon price. This has political economy advantages. Such support often comes in the form of subsidies, which tend to be more acceptable politically than a corrective carbon price.

However, in reality these additional measures are complements, rather than substitutes for a carbon price. They are put in place alongside carbon pricing to address additional market failures.

More specifically, support for low-carbon technologies is justified by the societal spillovers from clean energy innovation, which tend to be higher than those of conventional energy innovation (Dechezleprêtre et al 2016), and by inertia and path dependence in energy innovation (Aghion et al. 2016). Supporting clean-tech innovation requires a combination of environmental policies (addressing environmental externalities) and R&D policies (addressing innovation-related market failures) along the full "innovation chain" from research to development, demonstration and deployment (Grubb 2014; Popp 2010; Popp et al. 2010; Newell 2010).

Similarly, energy efficiency standards, planning rules and building codes address behavioral barriers, information asymmetries and other market failures that hold back the uptake of energy efficient technologies (Gillingham and Palmer 2014; Gillingham et al 2009; Howarth and Andersson 1993). The experience with energy conservation policies goes back to at least the 1970s and the first oil price shock and over the years policy makers have experimented with many interventions. Price incentives, supplier obligations, trading schemes and advisory services all feature. However, a crucial role is played by straightforward regulation, such as energy efficiency standards, planning rules and building codes.

A third set of barriers relates to the ability of financial markets to provide low carbon finance. Private capital will generally flow if the risk-return profile of low-carbon opportunities is at least as attractive as that of high-carbon alternatives and other asset classes. Pricing carbon emissions at the appropriate level will go a long way in securing this. However, there is evidence that the flow of capital to low-carbon opportunities is hampered by a series of additional barriers and financial market imperfections, even after climate change and related externalities have been corrected (BNEF 2013). Some of these barriers are specific to low-carbon investment, while others are generic to the functioning of financial markets, but affect low-carbon finance particularly severely (Vivid Economics 2014). For example, low-carbon finance is a particularly severe barrier for market participants that already suffer from limited access to finance, such as small and medium-sized enterprises (Beck and Demirguc-Kunt 2006).

5.3 Addressing wider economic consequences

A structural transformation is never easy and almost always imposes short-term costs. Additional policies are needed to deal with rigidities and the wider socio-economic consequences of the low-carbon transition. Bowen and Fankhauser (2017) highlight three interrelated concerns.

The first concern is economic rigidities. In the labour market there may be frictions both in terms of labor mobility and wages (Bowen and Kuralbayeva 2015). There are also rigidities in the capital stock. Carbon-intensive capital is often long-lived and assets might get stranded unless investment decisions are sufficiently forward-looking (Pfeiffer et al. 2016). We have already encountered the inertia in research and innovation above (Aghion et al. 2016). Because of these rigidities, redeploying capital and labour in a low-carbon direction is likely to be difficult in the short term.

A second concern is the impact of asymmetric carbon policies on firm competitiveness. Countries that have more stringent carbon policies than their trading partners might see their industries lose market share. Although this is a frequently expressed concern, most empirical studies suggest that existing climate policies have so far had little effect on firm performance (see Dechezleprêtre and Sato, 2014). Moreover, as the number of countries with adequate carbon regulation grows the international playing field becomes increasingly level.

The third concern is the impact of carbon policies on relative incomes. Carbon policies hit particularly hard heavy energy users and people who spend a larger proportion of their income on goods and services that require more energy along their supply chains to produce. Unfortunately, it turns out this makes carbon policies regressive – that is, lower-income groups take a proportionately larger hit. The regressivity is particularly acute for emissions associated with domestic energy usage, food and housing.

Strategies to reduce structural adjustment costs and unwanted distributional consequences are therefore an essential part of the policy mix.

6. Research needs and knowledge gaps

This section identifies key areas for future research. Although climate policy has been studied intensely for many years, there are significant knowledge gaps. There are a number of areas where further research is crucial to inform the quest for a low-carbon transition.

A first crucial gap concerns the development of new tools. Authors like Stern have called for a new generation of models to better reflect the structure and scale of the climate change problem (Stern 2016; Fankhauser and Stern 2017). Most energy-economic models have been designed for the analysis of gradual change over time, and most existing analysis is geared towards assessment of marginal change. Meeting the "well below 2^{o}C" challenge of Paris by contrast would require rapid change in energy systems, in particular very large amounts of investment in zero carbon energy supply. Such non-marginal change is only now beginning to be evaluated in the theoretical and model-based literature, with an increased emphasis on the Schumpeterian dynamics of innovation, investment and "creative destruction" (Aghion et al. 2014). Further research could synthesize the emerging knowledge on rapid decarbonisation of energy systems in developing countries, and identify robust conclusions for development and growth that can help guide policy.

Another knowledge gap concerns the evaluation of climate change policies. Policy makers across the world are experimenting with policies to reduce emissions, promote energy efficiency and support clean innovation (see e.g., Nachmany et al 2015). These efforts could be a fertile ground to apply the policy evaluation techniques of modern micro-economics. Yet, strong, credible empirical evidence of how well different policy interventions work is only starting to emerge, and most of it is in developed countries. Less is known about effective energy efficiency policies than there is about carbon pricing and renewable energy support. But even in these latter categories there are important knowledge gaps on which support mechanisms actually work.

A further knowledge gap concerns the political economy of climate policy. We know a fair amount about the desired policy mix to incentivise emission reductions, but insights are still scarce on how to manage low carbon energy transitions politically, in particular in developing countries. One aspect of such analysis might be the more systematic study of the business and growth opportunities of low-carbon energy (see e.g. Fankhauser et al. 2013). We know a fair amount about the negative impacts of climate policy on the competitiveness of carbon-intensive industries (e.g. Dechezlepretre and Sato 2016), but much less about the likely winners.

A linked concern is knowledge gaps about the implications of carbon policies for income distribution and opportunities for the poor. The impact of climate policy on low-income households is still poorly understood. Further research could explore the distributional impacts of low-carbon policies and identify policy designs that meet distributional objectives, including options that are suitable for developing countries.

A final research gap concerns fossil fuel rich countries. The global low-carbon transition poses particular challenges to developing countries that have large fossil fuel endowments, and in particular to coal exporting nations. Their challenge is two-fold. First, they need to overcome the green paradox (Sinn 2012) and make sure reserves remain in the ground. Second, fossil fuel rich countries need to diversify their economic base, so that their development trajectory can remain robust in the face of global decarbonization. Experiences exist with natural resource transitions including shifts away from the coal sector in developed countries, but knowledge about how the transition away from coal could unfold and best be managed in developing countries is very limited. An obvious strategy is economic diversification, however there are significant challenges in identifying suitable transition policies and identifying suitable trajectories for transition that balance the objective of maximizing fossil fuel rents with limiting the exposure to risk of stranded assets and in fossil fuel extraction. Further research could compile lessons from past fossil fuel transitions, focusing on economic aspects; propose objectives, frameworks for analysis and criteria for the evaluation of policy options; and identify possible policy approaches that developing country fossil fuel exporters could consider, in particular coal exporting countries.

7. Conclusions

Climate change imposes an increasingly binding constraint on the use of fossil fuels. Some commentators see in this an opportunity for “green growth”, that is, for a new kind of economic development that is resource efficient, clean, protective of the natural environment and resilient to climate extremes (New Climate Economy 2014; Hallegatte et al. 2012; Bowen and Fankhauser 2011). However, fossil fuel-based energy has been such a powerful engine of growth that it seems fair to ask, in the words of Dercon (2012), whether “green growth is good for the poor”.

In this paper we argue that it makes sense for developing countries to start decarbonizing their energy systems early, although the speed of decarbonization will depend on individual circumstances (for example, the size of indigenous fuel reserves). Energy assets are long-lived, which means anticipating a future carbon constraint will often be cheaper than risking stranded assets that have to be scrapped early. Developing countries, with their low stock of existing energy assets, have the opportunity to leapfrog to new, more productive technologies straight away, as they have done with mobile telephony.

Modelling results at the macro (country) level show that deep decarbonization pathways are feasible technologically, while sector studies suggest that power grids can absorb a relatively large share of renewable energy. As storage technology becomes cheaper that share should go up further still. The window for new coal-fired power generation (the most polluting form of electricity) is closing particularly rapidly. In many cases, a clean energy transition will bring a range of additional benefits for growth and development via innovation, removal of market failures, and other benefits such as reduced local air pollution and improved energy security.

The logic of early decarbonization should not obscure from the fact that the structural changes this requires are difficult politically and associated with short-term adjustment costs. Energy sector decarbonization requires at least a doubling of the current rate of growth in carbon productivity (carbon per GDP) from around 3 per cent a year to at least 6.5 per cent a year.

Comprehensive change in the energy sector will need a suitable policy and incentive framework to be compatible with economic growth and development objectives. The key aspects of the policy mix are by now well known. Energy needs to be priced appropriately, which means a strong carbon price signal along with the removal of fossil fuel subsidies where they exist. Policies and measures must be in place to overcome barriers to energy efficiency. Policy support is also required to promote clean innovation both at the level of research and (perhaps more relevant to developing countries) at the level of deployment.

In implementing such policies, countries need to be aware if the wider socio-economic consequences of their actions. The policy mix must include measures to protect vulnerable members of the community and ensure that low-carbon strategies do not impinge on poverty alleviation goals. This may require a particular focus on keeping electrification progressing apace, and to ensure that the poor have access to affordable energy. International support – including through grants, loan finance and technical expertise – should be available to help the transition.

The particular approaches to strategy and implementation will and should differ according to national and regional circumstances. Part of the consideration in customizing approaches is the political economy of change in the energy system. Incumbents in the energy industry typically hold more influence than new entrants, and governments need to be conscious of these influences. The protection of existing commercial interests may not coincide with the long term national interest, and the interests of low-income groups need to figure prominently for low-carbon transitions to be politically sustainable.

Significant gaps in knowledge remain on how low-carbon energy affects economic growth and development. The paper highlights a number of areas where further research is crucial to inform the quest for a low-carbon transition. Some of them are methodological, relating for example to the need for "non-marginal" models that better capture the economic implications of the deep structural changes required. Others relate to the better understanding of climate policies, both in terms of evaluating different policy designs and understanding political economy dynamics. A more philosophical suggestion relates to a shift in research focus, from studying the costs of the low-carbon transition (e.g. in terms of competitiveness) to documenting its benefits. After all, this is what green growth is about.

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