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Economic growth and development with low-carbon energy

Sam Fankhauser[1] and Frank Jotzo[2]

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Abstract

Energy is needed for economic growth, and access to cheap, reliable energy is an essential development objective. Historically most incremental energy demand has been met through fossil fuels, however in future that energy will have to be low-carbon and ultimately zero-carbon. Decarbonisation can and needs to happen at varying speeds in all countries, depending on national circumstances. This paper reviews the implications of a transition to low-carbon energy on economic growth and development in current low income countries. It sets out empirical findings about trajectories for energy intensity and emissions intensity of economic growth; explores pathways to accelerate decarbonisation; reviews the theoretical and empirical literature on economic costs and co-benefits of energy decarbonisation; and assesses analytical approaches. It discusses the opportunities that might arise in terms of a cleaner, more dynamic and more sustainable growth model, and the options for developing countries to implement a less carbon intensive model of economic development.

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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). 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 came into force in November 2016.

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, 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.

This should be possible, at least in principle. 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 feasible to decouple economic growth and greenhouse gas emissions.

The more important question is about the *short-term adjustment costs* that such a shift might entail. The low-carbon transition requires a deep structural 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

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

in energy infrastructure to keep up with growing demand. To avoid stranded assets, the decisions they take need to account of future carbon constraints. Yet, the rate at which carbon-emitting assets are added to the energy system is wholly inconsistent with the 2°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, and the opportunities that might arise in terms of a cleaner, more dynamic and more sustainable growth model.

The structure of the paper is as follows. Section 2 sets out empirical findings about trajectories for energy intensity, emissions intensity, carbon emissions and economic growth of economies. 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, by way of a reviews of the theoretical and empirical literature on economic costs and co-benefits of decarbonisation. Section 5 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.

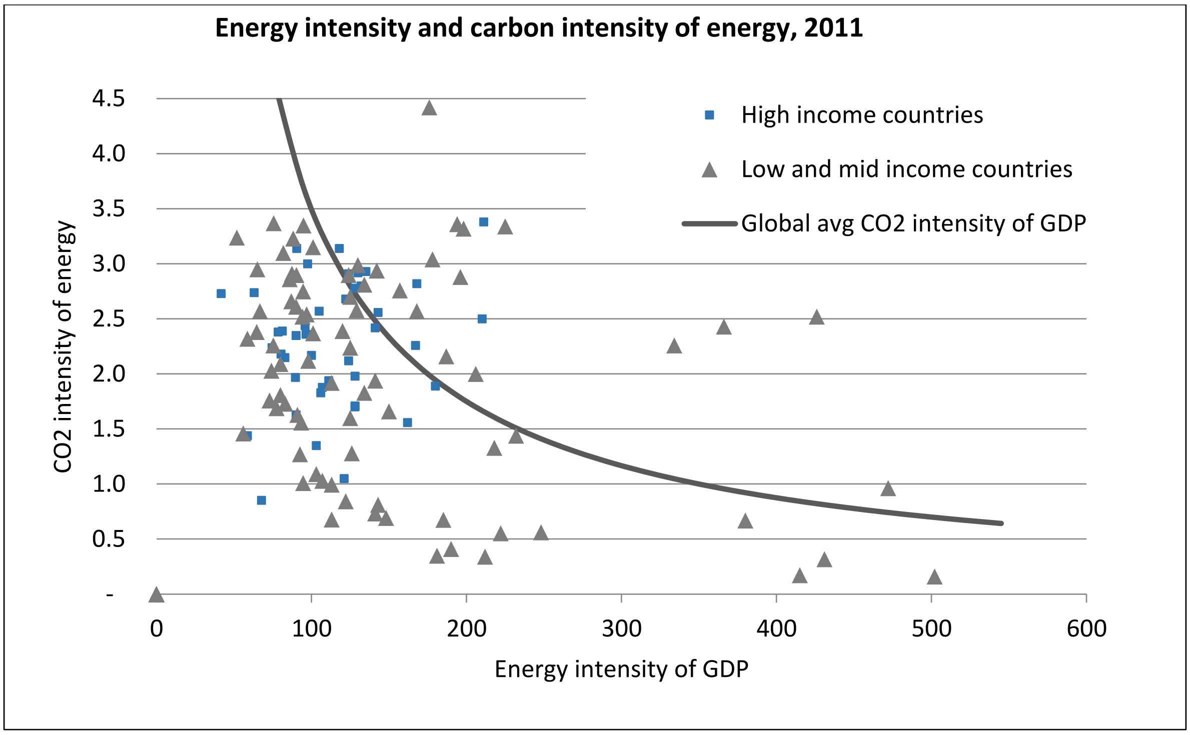
A fundamental way to portray the emissions-energy-economy relationship, and the scope for emission reductions, is through the following simple identity, which is often associated with the Japanese economist Yoichi Kaya:

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

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 $kgCO_2$/kg oil-eq mark, but others have intensities in excess of 3.0 $kgCO_2$/kg oil-eq.

Figure 1 Energy intensity and carbon intensity of energy, 2011



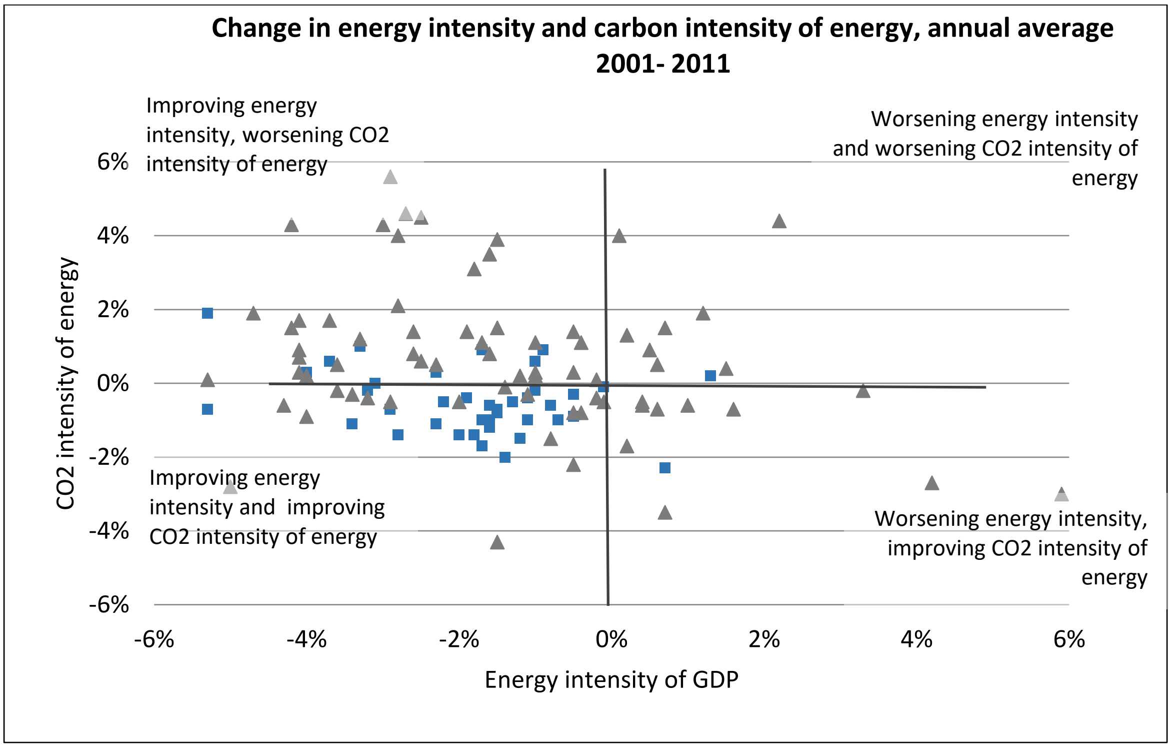
Notes: Energy intensity of GDP: Energy use in kg of oil equivalent per $1,000 GDP (constant 2011 PPP). CO2 intensity of energy: kg per kg of oil equivalent energy use. Global average CO2 intensity of GDP: 347 kg/$1000GDP (const 2011 PPP at 2011). Data: World Development Indicators 2016. Data for 2011. 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 (or carbon intensity of GDP) of 347 $kgCO_2$ per $1000 of GDP in 2011. The isoquant in Figure 1 displays different combinations of energy intensity of GDP and carbon intensity of energy 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 that have a relatively carbon intensive economy, most countries' carbon intensity of GDP is in fact below the global average (and conversely, their carbon productivity above 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 were around 20 percent less energy intensive and 17 percent less intensive in carbon per unit of energy in 2011, compared to low and middle income countries. High income countries also tend to be more homogenous. These observations suggest that carbon per GDP tends to slightly decrease at higher income levels. This corroborates earlier findings on the CO_2-GDP relationship (eg Holtz-Eakin and Selden 1995), which suggest an environmental Kuznets curve for carbon dioxide emissions. However, the drivers of any such trend are not universal. Differences in economic structure (e.g. the role of heavy versus light industry and the services sector), resource endowment (e.g. indigenous sources of energy) and policy choices (e.g. energy pricing, carbon policy) are all likely to be as important as income.

Figure 3 shows 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 2, 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 have made progress in decarbonizing their energy sectors.

Figure 2 Change in energy intensity and carbon intensity of energy, 2001-2011

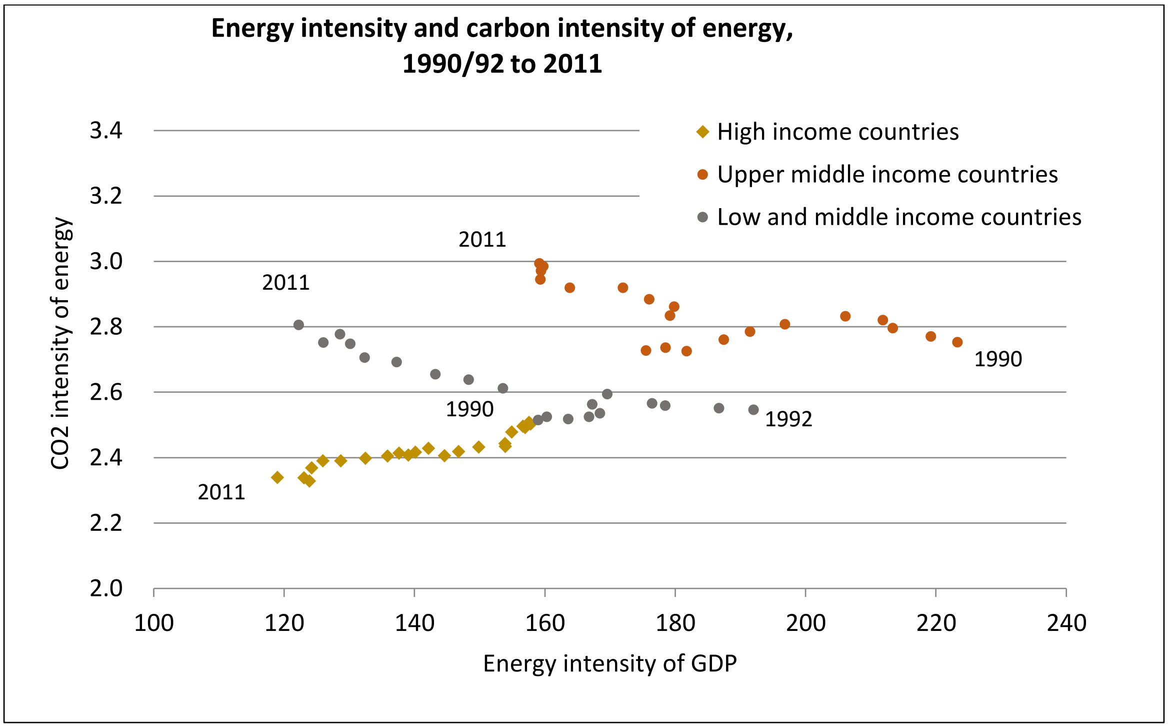


Notes: Energy intensity of GDP: Energy use in kg of oil equivalent per $1,000 GDP (constant 2011 PPP). CO2 intensity of energy: kg per kg of oil equivalent energy use. Global average CO2 intensity of GDP: 347 kg/$1000GDP (const 2011 PPP at 2011). Data: World Development Indicators 2016. Data for 2011.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

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 on average 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, on average comprised entirely of improvements in energy productivity (Table 1).

More recently, significantly greater rates of improvements have been achieved. Global carbon dioxide have remained almost unchanged during 2014, 2015 and 2016 (IEA 2017). With global GDP growth around 3 per cent each in of these years, global carbon productivity grew by around 3 per cent per year. BP (2016) expects this trend to continue, anticipating a fall in carbon intensity of GDP 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 3 Long-term trajectory of energy intensity and carbon intensity of energy, country groups



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 for 100 largest countries by population, excluding countries for which no data are available.

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 $GtCO_2$ (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 approximately double to achieve this. For example, the IEA's 2 degrees scenario has global carbon intensity of GDP falling by 5.3 per cent per year on average during 2014 and 2040, comprising of an average annual reduction of energy intensity of GDP of 3.0 per cent and a reduction of carbon intensity of 2.4 per cent per year (computed on the basis of data in IEA 2016). Carbon dioxide emissions are reduced by 2.1 per cent per year on average in absolute terms, assuming annual average GDP growth of 3.4 per cent over the period 2014 to 2040 in the IEA scenario.

Rapid rates of reduction 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 data is the UN Deep Decarbonization Pathways Project, an initiative of co-ordinated national-level bottom-up studies (Sachs et al. 2014, Ribera et al. 2015, Bataille et al. 2016).

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 economies. The annual reductions listed in the table exceed past performance by at least a factor three and result in a largely decarbonized energy sector by the middle of the century.

While the DDPP scenarios are very ambitious, 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. We discuss them next.

Table 1 Annual rates of change in energy and carbon intensity: historical and scenarios

	Energy Intensity of GDP	Carbon intensity of energy	Carbon emissions intensity of GDP
World, 1990-2014	-1.0%	0.0%	-1.0%
World, 2014-2040, IEA 2 degrees scenario	-3.0%	-2.4%	-5.3%
DDPP scenarios, selected countries, 2010-2050			
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
Data computed from IEA (2016); DDPP (2015). See http://deepdecarbonization.org/countries/ for full DDPP 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). In the longer term, 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, interconnection with neighboring grids and energy storage (Cochran et al 2014; NREL 2012; Denholm and Hand 2011; 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 alternative to costly grid extension, though it poses its own challenges (e.g., Palit 2013; Wamukonya and Davis 2001). In areas where rural electrification is still underway, such as India and much of Africa, off-grid electrification using solar power and storage is increasingly becoming a viable option (Sandwell et al 2016).

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 change through the development process in a way that increases aggregate energy productivity (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. Structural change can also be a policy objective, as in China's goal for modernization of the economy (Teng and Jotzo 2014).

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. Progress can be accelerated through targeted interventions.

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).

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. Embarking on a low-carbon development path can reshape an economy, and will 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 power production) and the manufacture of energy efficient equipment). Such changes threaten incumbent operators, provide openings for market entry, and result in new infrastructure investment. The transition can bring large structural adjustment costs, as labor and capital is redeployed. However, it also opens 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. In the absence of a comprehensive and universal typology in the literature, 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' (eg Wing 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.

Policy interactions

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. 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 (including carbon taxes and emissions trading schemes where governments sell permits to polluters) can 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 (Bovenberg and de Mooij 1994, Carraro et al 1996). Conversely, a 'tax interaction' effect of levying a carbon tax on top of existing taxes tends to be welfare reducing (Goulder 1995), specifically via distortions arising from changes in relative prices including for labour (eg 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 (eg 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 (Caldecott et al 2014, Rozenberg et al 2014). 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.

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). 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

The energy production sector, and the cost of energy in overall production, is typically just a few percent of total GDP or overall production costs. So even if energy costs increased greatly in a low carbon transition, the (first order) impact on the economy in terms of additional costs would not be very large, compared to underlying economic growth over time.

The insight is broadly borne out by model results. 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, for example under the Stanford Energy Modeling Forum (EMF, e.g. Weyant et al 2006). 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

Modelling results of the economic impacts of emissions reductions are sensitive to a number of factors, including parameter choices (e.g. technology costs, substitution elasticities), the timing of climate change mitigation (early action versus later action), the degree of international cooperation and the choice of policy instruments (eg 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), and the possibility of induced technological change is not usually modelled (Scrieciu et al 2013, Wing 2006).

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. In the model, 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. Factors that may improve economic outcomes, discussed above, as a rule are not explicitly factored into economic modelling of climate change mitigation action.

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 that models typically ignore structural rigidities, particularly in the labour market, which can either increase costs (under full employment) or reduce them (if there is excess labour). Further there are synergies between climate policy and other environmental objectives, from reduced water and air pollution from fossil-fuel extraction and burning to the preservation of the world's forests, all of which can bring economic and broader social benefits.

5. Conclusions

Climate change imposes an increasingly binding constraint on the use of fossil fuels. Some authors 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 review evidence from the literature that in sum suggests that it makes sense for developing countries to start decarbonizing their energy systems early, although the speed of decarbonization will depend on individual circumstances. 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 large share of renewable energy. As the cost of renewable energy technologies further declines and storage technology becomes cheaper, decarbonization of electricity systems becomes not just technically but also economically feasible. 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. Decarbonization of economies in line with strong global mitigation objectives requires a much more rapid improvement in emissions intensities than currently observed. Modelling studies suggest this is possible. However it will take a significant effort in improving technical efficiency in the energy sector, structural change away from heavy industries, decarbonization of the electricity sector and shifting of most energy use to low-carbon electricity.

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 (Bowen and Fankhauser 2017), although it will and should differ according to national and regional circumstances.

Significant gaps in knowledge remain on how low-carbon energy affects economic growth and development. 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 a carbon constraint to documenting the benefits of a clean technology transformation.

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