THE NEW CLIMATE ECONOMY

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Working Paper

Galvanising low-carbon innovation

Jason Eis, Vivid Economics; Russell Bishop, New Climate Economy; and Philip Gradwell, Vivid Economics

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Overview

Innovation is a fundamental engine of long-term economic growth, and a critical driver for reducing emissions and tackling climate risk. There is a need to scale up innovation efforts to reduce emissions cost-effectively beyond 2030 consistent with limiting dangerous climate change, in particular through supporting research, development and demonstration (RD&D) for technologies which have not yet been deployed at scale and are unlikely to without strong government support . While private sector investment in innovation is significant for nearer-to-market technologies, private and public RD&D for low-carbon solutions remains low – around 0.03–0.04% of GDP in International Energy Agency (IEA) member countries is devoted to public RD&D for low-carbon energy.[1]

Emerging economies have a particular leadership role to play in innovation, given its importance in reducing their emissions and developing growth strategies for the future. There is a need to better target innovations to developing country circumstances, along with a corresponding need to locate more innovation activity in those countries. Yet the preponderance of RD&D expenditure today is concentrated in higher income countries and China.

By supplementing core innovation activity at the national level, international cooperation can play a significant role in achieving these greater ambitions. Cooperation can facilitate more extensive knowledge sharing across global networks of innovators, combine global capabilities across a diverse portfolio of earlier stage projects, and share costs and risks in large-scale demonstration projects. It can also play a particular role in low- and middle-income countries by linking innovation activity to early market formation, overcoming intellectual property considerations, and building institutional and individual innovation capacity. High priority fields for international cooperation are those critical to avoiding the long-term and costly lock-in of carbon-intensive

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About this working paper

This New Climate Economy Working Paper was written as a supporting document for the 2015 report of the Global Commission on the Economy and Climate, *Seizing the Global Opportunity: Partnerships for Better Growth and a Better Climate*. It reflects the research conducted for Section 2.7 of the full report and is part of a series of 10 Working Papers. It reflects the recommendations made by the Global Commission.

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New Climate Economy
c/o World Resources Institute
10 G St NE
Suite 800
Washington, DC 20002, USA
+1 (202) 729-7600

New Climate Economy
c/o Overseas Development Institute
203 Blackfriars Road
London, SE1 8NJ, UK
+44 (0) 20 7922 0300

www.newclimateeconomy.report
www.newclimateeconomy.net

infrastructure (especially in buildings, electricity networks and transport systems), delivering development and climate priorities together (notably in agriculture), and enabling longer-term options for deep decarbonisation (such as carbon capture, storage and usage, energy storage, and bioenergy).

There are a number of emerging initiatives that support these efforts. These include "Mission Innovation"[2] and the Breakthrough Energy Coalition,[3] both announced at COP21 in Paris, and the Low Carbon Technology Partnerships initiative launched earlier in 2015.[4] If funding commitments are met, cooperation focusses on where it is will most add value, and strong efforts are made to engage developing countries, these initiatives have the potential to close many of the gaps identified in this paper.

The Global Commission on the Economy and Climate recommends that emerging and developed country governments work together, and with the private sector and developing countries, in strategic partnerships to accelerate research, development and demonstration (RD&D) in low-carbon technology areas critical to post-2030 growth and emissions reduction. This includes innovation in agriculture; in longer-term solutions such as bioenergy and carbon capture, utilisation and storage; and in ways to avoid lock-in of carbon-intensive infrastructure (buildings, electricity networks, transport systems). There is also a critical need for cooperation to target or adapt innovations to developing-country needs.

1. Introduction

Innovation is a fundamental engine of long-term growth, and is crucial to making that growth sustainable. It yields new economic and greenhouse gas (GHG) abatement opportunities by introducing new or improved products, processes and methods, and adapting them to a range of local contexts.[5] Investment in research, development, demonstration (RD&D) and early market formation is a core component of innovation, and public support is a critical driver of RD&D.

The Intergovernmental Panel on Climate Change (IPCC) has shown that significant investment in, and deployment of new low-carbon technologies will be required after 2030 to achieve a pathway that keeps global warming within 2°C.[6] However, current levels of RD&D investment in energy, industry and agriculture (the main sources of GHG emissions) are not sufficient to ensure strong growth and reduce the risk of dangerous climate change, let alone to stay within the 1.5°C aspirational target announced in the Paris Agreement. For example, energy sector public RD&D as a share of GDP is currently less than half its level in the early 1980s, and private RD&D investment in the sector is also low.[7]

This working paper makes the case that greater international cooperation in RD&D can facilitate the development of products, processes and methods that will drive *both* economic growth and decarbonisation after 2030, and facilitate their adoption and adaptation in emerging and developing economies, where they will increasingly be deployed. International cooperation on RD&D should complement and enhance existing private sector and national public sector RD&D efforts by focussing on activities where such cooperation has relative advantages. It can do so by sharing costs and risks in large scale innovation challenges, linking markets and RD&D activities across borders, encouraging more extensive knowledge sharing, and supporting capacity building. International cooperation has particular value to add in some specific technology areas critical to post-2030 growth and climate action. This has particular importance for low- and middle-income countries and regions that have a low capacity for innovation, but an urgent need to "leapfrog" to new technology pathways.

There has been some progress in recent years. Significant initiatives include the energy technology focussed IEA Implementing Agreements,[8] a flexible and effective means for IEA member and non-member countries, businesses, industries, international organisations and non-governmental organisations to research breakthrough technologies; and the CGIAR (formerly the Consultative Group for International Agriculture Research) programmes of cooperative research on crop varieties tailored to developing country circumstances that can enhance productivity and resilience, and reduce emissions.

The importance of international innovation cooperation for low-carbon growth was strongly acknowledges in 2015 with the announcement of a number of new initiatives including "Mission Innovation", the Breakthrough Energy Coalition, and the Low Carbon Technology Partnership initiative (LCTPi). Assuming funding commitments are met, these newly announced initiatives could help fill the gaps in international innovation cooperation. To reach their full potential, these and additional efforts will need to focus on modes of cooperation that best complement existing national efforts, on technology areas with greatest transformative potential, and on developing countries where such technologies will be widely deployed.[9]

We begin this working paper by explaining why innovation is important for economic growth and climate change, and why RD&D is particularly needed in emerging economies. Next we examine the role of international cooperation in facilitating RD&D, including lessons learned from existing efforts and initiatives. We then analyse the broad technology areas where international collaboration may best be focused. We conclude with detailed recommendations for scaling up efforts in priority areas.

2. Innovation for growth and climate action

2.1 INNOVATION IS CRITICAL FOR GROWTH AND EFFECTIVE CLIMATE ACTION

The 2014 New Climate Economy report *Better Growth, Better Climate* made the case that innovation was important to long-run economic growth, improved wellbeing, and cost-effective climate action. Innovation drives growth by inventing novel products and services, and by improving the productivity of physical, human and natural capital. By combining these factors in new, more efficient or valuable ways, it overcomes limits to growth and sustainability. In particular, innovation enables switching from more to less carbon-intensive sources of growth by making low-carbon products and services distinct from, or better and cheaper than high-carbon alternatives.

Historically, the countries that have achieved high-income status have been those that have developed the core elements of a robust "innovation ecosystem" (described in the Section 3). This ecosystem allows the country to adopt, adapt and develop advanced technologies, and the corresponding ability to increase productivity.[10] Indeed, within OECD countries, which have relatively high levels of physical and human capital, innovation capacity/activity is one of the main reasons for differences in per capita income levels.[11]

Better Growth, Better Climate also showed how low-carbon innovation in particular can play a critical role in driving growth, both by improving resource efficiency directly, and by creating valuable spillovers that lead to the broader creation of new sources of value in the economy. Although much innovation for improving resource efficiency has already occurred, considerable room exists for additional gains even among advanced countries.[12] For developing countries, where resource productivity often remains low, and where the required technologies may need to be adapted to local circumstances, low-carbon innovation capacity will be critical to achieving these gains.

Low-carbon innovation can also drive critical underlying technological advances, in areas like materials science, digitalisation, and biotechnology, which contribute to the creation of new growth horizons across the economy, even as they simultaneously create new opportunities for decarbonizing specific elements of that growth. Innovation then can spur a virtuous cycle, in which growth and climate aims reinforce one another by stimulating innovation and building innovation capacity that meets both needs.[13]

Innovation is particularly important to ensuring that future growth is compatible with tackling climate change for two reasons:

- Achieving strong, decarbonised growth requires a system-wide transition to new energy sources, processes of production, land use, and forms of human settlement, and this is not possible without innovation. Across a set of models assuming limited technology,[14] the IPCC finds that stabilisation of atmospheric CO_2 at 450 parts per million (ppm; corresponding to an energy pathway consistent with the goal of limiting the global increase in temperature to 2°C) is very challenging if not impossible, and even stabilisation at 550 ppm is expected to cost on average twice as much compared to a scenario of assumed steady technology progress.[15]

- This system-wide transition would need to be achieved in a very short timescale to limit the economic and social risks of global warming beyond a dangerous threshold of 2°C,[16] putting a premium on rapid innovation.[17]

This transition is especially critical for developing and emerging economies, where achieving growth and climate action may benefit from a high degree of "leapfrogging" — skipping over the 'next' stage of growth as followed by more developed countries, through the adoption and adaptation of technologies that have not necessarily reached maturity elsewhere (e.g., smart grids or distributed power).[18] By 2020, two-fifths of the market in low-carbon and energy efficient technologies is expected to be in emerging and developing economies.[19] The cost of using readily-available high-carbon technologies now, and moving to low-carbon technologies later is likely to be very high since it would involve substantial stranding or expensive retrofitting of relatively new assets, such as high-carbon plants and equipment or other large pieces of infrastructure.[20]

Furthermore, the pace of decarbonisation will likely need to increase after 2030 given current emissions trajectories. The United Nations Environment Programme (UNEP) estimates that, for a less than 66% chance of staying within 2°C of warming, annual emissions in 2030 should decrease from 2014 levels of 53 gigatonnes of CO_2 equivalent ($GtCO_2e$) to around 42 $GtCO_2e$ by 2030 (or 39 $GtCO_2e$ for a 1.5°C pathway), and GHG levels should be net zero by 2060–2075.[21] In many cases, the innovations required to cost-effectively achieve this after 2030 trajectory have yet to be developed, and in most cases, they have yet to be demonstrated at scale. Given the time it can take to bring innovation from its early stages to full scale deployment, RD&D is required today to meet increasing abatement needs after 2030, and to help bring down the costs of existing technical and system solutions.

2.2 RESEARCH, DEVELOPMENT AND DEMONSTRATION ARE A CORE COMPONENT OF INNOVATION, REQUIRING DISTINCT PUBLIC SUPPORT MECHANISMS

The innovation process is often described as a set of activities from basic research to full-scale deployment, occurring within a complex "ecosystem" of actors (e.g., researchers, entrepreneurs, financiers, consumers, etc.), institutions (universities, firms, etc.), interconnecting networks, and social and economic conditions.[22] Other New Climate Economy (NCE) working papers in this series (e.g., on land use, cities, clean energy financing and energy efficiency)[23] focus heavily on the deployment of low-carbon solutions by 2030, and incorporate elements of innovation in this timeframe. Yet, given the critical need to also drive new technologies to the point where they can be scaled up by the market after 2030, this working paper focuses on the pre-commercial components of innovation: research, development and demonstration, as well as early market formation, including context-specific adaptations, and the feedback loops between them (all of which we term RD&D).

It is, of course, important to note that RD&D does not reflect the whole innovation process, and that deployment is essential if innovation efforts are to be successful. However, we do not focus on the on-going innovation that occurs once a product, process, or method has already reached commercial scale, nor do we focus on the important incentives for innovation created by so-called "pull" policies, whereby government uses regulations (e.g., efficiency standards) or price incentives (e.g., a carbon tax) to form a stable long-term market for new innovations.

As with other innovation related activities, RD&D faces a great deal of uncertainty,[24] with high risks and market returns that are hard to value ahead of time, and difficult to capture after the fact. Moreover, the ecosystem as a whole, so critical to the effectiveness of innovation, is generally beyond the capacity or interest of any one actor (or manageable group of actors) to create. This means markets left to themselves will consistently underinvest in RD&D vis-à-vis the social optimal, and there is a strong case for distinct public support and investment mechanisms.[25] With regard to low-carbon RD&D, the case is even stronger owing to the large, global externality involved.[26]

Based on experience, there are a number of broad criteria for how public investment can best support innovation – it should:[27]

- Rely on goal-oriented portfolio strategies and a flexible, results-driven policy design, in line with the fact that success is hard to predict, and some failure is inevitable
- Exercise discipline in its effort to crowd-in rather than crowd-out private RD&D activity, based on bespoke assessments of likely "spillover" effects, and competitive funding mechanisms which allow for the discovery of new technologies.
- Include funding for RD&D activities and physical innovation infrastructure (e.g. testing centres, demonstration facilities), and mechanisms for leveraging private sector contributions at ratios appropriate to the stage of innovation
- Include support or incentives for risk capital, and ensure an economic setting conducive to risk taking, including ease of opening and closing enterprises, and effective intellectual property rights protection
- Include support or incentives for the broader development of skills, institutional capacity, accessible and reliable knowledge bases, and networks for collaboration and knowledge exchange
- For enhanced policy coherence, ensure coordinated support across the full innovation ecosystem based on a cross-cutting strategy.

2.3 CURRENT LEVELS OF LOW-CARBON RD&D ARE TOO LOW, AND GREATER PUBLIC SUPPORT IS REQUIRED

Better Growth, Better Climate argued that current rates of climate innovation are insufficient, and recommended that governments of major economies should at least triple their public energy-related research and development (R&D) by the mid-2020s, and that bilateral donors, foundations and national governments in developing countries should collectively double the financing of crop, livestock and agro-forestry R&D in developing countries from US$15 billion in 2008 to US US$30 billion in 2030.[28] Such an increase in spending would be a step change from current trends – and indeed many major economies of the world committed to doubling of public investment in energy research at COP21 through " Mission Innovation".[29]

Public funding for energy-related RD&D in IEA member countries has been rising since a low in 1997, and was roughly US$18 billion in 2014, with about 90% of spending going towards low-carbon technologies.[30] Absolute funding in IEA member countries for energy-related RD&D increased by about 25% between 2008 and 2014, and for low-carbon energy RD&D by about 30%.[31] Moreover, this does not include significant increases in such RD&D by emerging economies, especially China, where renewable energy RD&D increased by approximately 50% between 2010 and 2014, surpassing the United States in 2013.[32]

Nevertheless, as a share of GDP in IEA member countries, current levels of energy-related RD&D are half what they were in the early 1980s, and the share of overall public RD&D expenditure on energy has fallen from 11% in the early 1980s to 3–4% over the last decade.[33] Moreover, since 2011 absolute expenditure by IEA countries has been falling steadily as public sector budgets have been squeezed.[34] While these declines are somewhat balanced by increases in China, spending on low-carbon energy RD&D growth appears to be flattening out globally with around 0.03–0.04% of GDP in International Energy Agency (IEA) member countries devoted to public RD&D for low-carbon energy.[35] In agriculture – the other major source of GHG emissions alongside energy – the latest available data shows that global public funding for RD&D was US$32 billion in 2008, and its share of overall public RD&D expenditure was 3%.[36]

Private RD&D expenditure data is sparse and so trends are difficult to identify.[37] However EU surveys of the top 2,000 global R&D spending firms suggests that R&D in energy is low relative to other sectors of the economy. Energy R&D expenditure is around 1% of sales revenue, while the average for other industrial sectors is 3% and as high as 10 and 14% in computer services and pharmaceuticals respectively.[38] Private energy R&D also focuses on high carbon technology (especially in the oil and gas sector), which received US$12.5 billion compared to US$8.7 billion for low-carbon technology in 2012. In agriculture, private R&D was also low at US$18 billion in 2008, or 1% of agricultural gross value added in that year.[39] As discussed above, market failures mean that private funding for RD&D is unlikely to be at optimal levels despite some private incentives to innovate, which will strengthen, for example, as carbon prices increase. Additional public support, whether direct or in partnership with private actors, is therefore essential to increase RD&D to more socially optimal levels.

2.4 LEADERSHIP FROM 'EMERGING INNOVATOR' COUNTRIES[40], AND RAPID CATCH-UP BY LOW- AND MIDDLE-INCOME REGIONS ARE CRITICAL TO ADVANCING LOW-CARBON INNOVATION

Currently, there is a large difference in the maturity of innovation ecosystems across countries, reflected in where most climate RD&D activity is taking place. Advanced economies accounted for roughly 80% of world's climate patented inventions in 2000-11.[41] Moreover, in 2013 advanced economies still accounted for around 74% of total (public and private) R&D in renewable energy, followed by China with around 21%.[42]

However, 'emerging innovator' economies have become more important, with, by some measures, total levels of public energy RD&D spending by Brazil, India, Russia, Mexico, China and South Africa equal to the total of IEA member countries.[43] China leads this group with around 14% of world climate patented inventions from 2000-11, and 73% of the group's public energy RD&D expenditure, as well as demonstrated success in developing core low-carbon innovations. India has the second highest public energy RD&D expenditure in the group, with 10% of the total, followed by Brazil, with 8%. 90% of this group's public energy RD&D was delivered through State Owned Enterprises, and private RD&D levels are much lower than in advanced countries. Yet the potential for innovation in these countries is clear.

Not all countries are, or need to be, at the frontier of RD&D, but so called "absorptive capacity" enables countries to adopt and adapt innovations developed elsewhere, thereby sharing in the growth and climate benefits of innovation. In this respect, the immaturity of innovation ecosystems in low- and middle-income regions, including less developed regions in the emerging innovator countries, represents a major challenge. Such regions lack the capacity to adopt and adapt innovations developed elsewhere, or the feedback mechanisms to link their markets to global innovators. In particular, in low- and middle-income regions innovation institutions and human capital are scored 33% lower than higher income countries on an index of innovation created by the World Intellectual Property Organization.[44]

Based on the experience of countries that have developed their innovation ecosystems to a high degree, and created a strong focus on climate innovation (e.g. Japan, South Korea, Brazil and China), it takes decades to systematically establish underlying skills, institutions and knowledge networks.[45] For these countries, relatively high levels of public support were required in the beginning, as well as policies that aggressively leverage knowledge and capacity from overseas.[46] Where it is made a priority, countries can also achieve more rapid development of their innovation ecosystem in climate technologies, for example, wind turbines and solar PV in China, and biofuels in Brazil.

3. The role of international cooperation

3.1 RD&D ACTIVITY OCCURS PREDOMINANTLY AT THE NATIONAL LEVEL WITH INCREASING GLOBALISATION DRIVEN BY THE PRIVATE-SECTOR

International cooperation is not the default method for delivering innovation, nor would it make sense for it to be. Innovation systems remain primarily anchored in the national context, as one would expect given the advantages of cultural and physical proximity, and the justifiable treatment of innovation as a source of national competitive advantage. Available evidence for the US, EU, Japan, South Korea and China suggests that at least 90% of overall low-carbon RD&D activity is funded and conducted by government agencies or companies in their home countries.[47] Nevertheless, there has been significant growth in recent years in international RD&D activity,[48] driven by broader trends of globalisation and the increasing importance of emerging markets.[49]

International RD&D activity is currently driven for the most part by the private sector, rather than public initiatives. Private sector efforts are primarily led by multinational innovator companies and early-stage investors. Overall data on RD&D shows that spending by multinational innovator companies outside their home countries[50] accounts for at least 10-20% of private-sector R&D activity. In the case of smaller, high-innovation countries, over 60% of their private-sector RD&D tends to come from foreign enterprises.[51] This includes, among other things, setting up global networks of innovation centres, joint innovation projects or ventures between multiple firms in different countries, foreign investment by venture capital, and combinations of all of the above. Although data for low-carbon innovation is difficult to disaggregate, many of the most relevant subsectors (e.g. renewable energy generation and energy efficiency) show a similar pattern of internationalisation.[52]

Private sector-led international activity strengthens global innovation outcomes in various ways.

- **It leverages and builds upon international skills.** Two examples are GE's technology centres in Brazil, China, India, Israel and Germany, and Suzlon's technology development centres across India, Germany and the Netherlands. These have gained advantage by utilising international RD&D capacity and specialised skills in specific countries (e.g. GE's bioenergy R&D through its Brazilian centre)[53], while also accelerating the development of capacity and sharing of know-how across markets (e.g. wind energy know-how spreading from Europe to India via Suzlon's centres).[54]
- **It utilises and expands international networks to access knowledge spillovers and expand feedback channels from markets.** For example the World Business Council for Sustainable Development has facilitated networks in the cement and chemicals sectors, looking at both near-term and long-term technology opportunities, sharing knowledge and helping set a longer-term agenda for RD&D.[55] Similarly, the Global CCS (carbon capture and storage) Institute, which was launched by public sector initiative, has seen the active participation of private sector members.[56]

- **It successfully shares costs and risks on later-stage, generally modular and generic technologies where the complexities of coordination are small.** For example, various joint development and demonstration ventures on battery technologies have been established in recent years, including joint ventures between BASF and TODA KOGYO, and Bosch and Mitsubishi. This experience also shows the ability of the private sector to end international joint RD&D activities on a timely basis if they are deemed to bear insufficient commercial advantage, as was the case in the Innovation Co. and Continental AG battery venture.[57]
- **It effectively spreads innovation 'bets', especially at later stages of demonstration and early market formation across a larger portfolio adapted to various markets.** For example, various Silicon Valley venture capital funds have expanded their investments into early-stage ventures in emerging markets. Sequoia Capital has invested in China, Israel and India, and Accel Partners has invested in India, where both portfolios include various clean-tech companies.[58]

It is also worth noting the important interaction between domestic RD&D activity and cross-border private sector activity, with the former playing a critical role in establishing attractive conditions for the latter. Domestic RD&D capacity and programmes have helped attract private sector-led international RD&D activity, as has an openness to trade and foreign direct investment. While large countries, such as China, India and Brazil, garner much attention, there are examples of smaller countries benefiting even more from open national programmes focused on attracting international actors and resources. For example, Israel's publicly funded Yozma programme drove strong foreign investment in technology start-ups, and Singapore's Agency for Science, Technology and Research, which established 12 research centres hosting RD&D activities funded by various international sources.[59]

However, given the commercial drive behind private sector international innovation activity, it tends to contribute less to earlier stage R&D, and on its own, has not driven large-scale demonstration projects or international knowledge networks. It also tends to be concentrated in countries with mature innovation ecosystems, and with large short- to medium-term market potential – capitalising on the opportunities offered by countries that have already established core innovation capacity and institutions, and that have strong indications of early market formation. For example around 90% of US companies' overseas activity takes place in Europe, Japan, Canada, China, Brazil and India,[60] even though these countries make up less than 50% of the world's population and 70% of world GDP.[61]

3.2 PUBLIC SECTOR DRIVEN INTERNATIONAL COOPERATION HAS A CRITICAL ROLE TO PLAY, BUT REMAINS RELATIVELY SMALL IN SCALE AND LIMITED IN SCOPE

Given the importance, albeit insufficient scale, of domestic public RD&D programmes, the important and positive role of private sector led international activity, and the desire to achieve national and firm level competitive advantage, public sector driven international cooperation should enhance and complement (rather than distort and displace) national efforts. We identify five ways in which public sector driven international cooperation can deliver further growth and climate action benefits:[62]

- **Encouraging more extensive knowledge sharing across a global network of innovators** to achieve greater knowledge spillovers. Neither domestic RD&D networks (limited to national boundaries) nor private-sector networks (limited by commercial interest) are best placed to facilitate optimal levels of knowledge sharing globally.
- **Combining global capabilities in earlier stage R&D projects,** to enable a more diverse portfolio of approaches and access to specialised expertise beyond the capacity of a single country. Particular innovation challenges would benefit greatly from combining expertise across borders, whereby domestic programmes are inadequate, and private sector international efforts are too commercially (i.e. later stage) focused.[63]
- **Sharing costs and risks in large-scale demonstration projects**, often involving complex coordination across multiple actors. These are areas where it is difficult for a single country to support a sufficient number of innovation 'bets', and where private sector efforts have difficulty overcoming the coordination challenges.
- **Linking RD&D activity to early market formation**, especially in low- and middle-income regions where significant local adaptation of overseas technologies is required, and where the immaturity or small size of local markets deters private international actors. In these cases, there is often a geographic mismatch between innovation capacity and market formation, which domestic RD&D programmes have difficulty bridging, and there is insufficient near-term commercial incentive for private sector actors to fill the gap.

- **Building institutional and individual capacity** in low- and middle-income regions where knowledge and resources are insufficient. While domestic policies in these regions are critical to driving this capacity building, international cooperation can enhance these global efforts by facilitating access to international expertise and supplemental resource. Private sector led efforts can help accelerate this process, but they are not well suited to building basic capacity, the benefits of which they find hard to capture.

These five areas explicitly supplement domestic RD&D programs, and private sector led international endeavours. In the absence of public sector support for such international cooperation, we stand to lose the benefits of knowledge spillovers at a global scale, of cost and risk reductions through diversification of efforts, and of faster skills and technology diffusion to low- and middle-income regions. Although difficult to quantify , the extent of these benefits is likely to grow as a far greater number of countries are making significant investments in RD&D, and as market size and growth is more balanced globally.[64] Governments can use international cooperation to gain access to these benefits, which complement their national innovation strategies. Similarly, the private sector, which is at the forefront of the globalisation of innovation, can utilise public sector international cooperation to expand the scope, and improve the effectiveness, of its own efforts.

However, despite this complementary role for public sector driven international cooperation, analysis of major programmes shows that under 2% of overall publicly funded R&D goes through this channel.[65] US and EU energy-related R&D data suggests a similarly low proportion for international cooperation in low-carbon RD&D.[66] There are three broad approaches to public sector driven international cooperation, all of which can serve as major channels for international RD&D funding:

- **National innovation programmes directly supporting RD&D activity by overseas entities** – for example, the EU Horizon 2020 funding for "third country" participants,[67] which funds RD&D carried out by innovators in other countries as part of core EU research programmes; or the UK's Newton Fund, which directly funds science and innovation partnerships in 15 countries to promote the economic development and welfare of those countries.[68]
- **Direct government-to-government (G2G) cooperative programmes supporting joint activity** – for example, the U.S.-China Clean Energy Research Center (CERC), which takes joint government funding and applies it to a jointly defined RD&D program in four technology areas (buildings energy efficiency, advanced coal and CCS, clean vehicles, and energy and water) with participants from both countries;[69] or the various multi-lateral programmes through the IEA Implementing Agreements (see Box 2).
- **Intergovernmental or non-governmental organisation (IO-NGO) programmes supporting international activity** – for example, CGIAR (formerly Consultative Group on International Agriculture), which channels funds from various government and non-government donors into RD&D for agriculture in developing countries; or the World Bank Climate Innovation Centres, which applies its government donor funds to centres in developing countries.

Across all of these forms of international cooperation around 200 climate change related initiatives were examined for this analysis to see where gaps exist.[70]

Of the five ways that international cooperation can add value, efforts have predominantly supported **knowledge sharing and network formation** across countries, with almost all initiatives having this as a primary or secondary goal.[71] Various technology and/or region specific initiatives exist with some overlap in membership and mission. For example, multiple platforms related to CCS exist with a focus on different aspects of knowledge sharing, and different types of stakeholders: the Carbon Sequestration Leadership Forum is a ministerial level group of 23 countries with a broad facilitation role; the IEA Clean Coal Centre has a more limited membership but with a focus on much more technical knowledge sharing and networking; the Global CCS Institute has very broad participation, and has come to serve as an umbrella network supporting a wide breadth of initiatives and more focused networks. Similar examples exist in other technology areas have also emerged to keep pace with technological development (e.g. the IEA International Smart Grid Action Network, which brought existing activities under one network, was established only in 2011), and in many areas some gaps exist in geographic coverage, and arguably, private sector participation, especially SMEs.

Although knowledge sharing initiatives and networks generally garner less participation from low- and middle-income regions, some do specifically target these regions, most commonly with a focus on knowledge brokerage and encouraging RD&D in areas of local relevance, especially agriculture. Examples of initiatives including or aimed at low- and middle-income regions include the African Technology Partnership Network, which has created various platforms for collaborative and innovative policy research and knowledge brokerage; and the Renewable Energy Cooperation Network for the Asia-Pacific, which aims to facilitate technology transfer and promote R&D collaboration.[72]

Related to this, international cooperation has pioneered mechanisms to enable greater patent sharing and to mitigate intellectual property (IP) rights issues, including patent landscaping, voluntary patent pools, and IP management plans (see Box 1). These mechanisms are important to enabling RD&D collaboration among advanced and emerging innovator countries, as demonstrated by the emphasis given to them in the CERC.[73] They also play a role in enabling technology adoption and adaptation in low- and middle-income countries that often lack the resources to acquire technologies without financial and technical support.[74] Nevertheless, in both cases progress has been slow, and results have been mixed. In the case of CERC, for example, filing of joint patents between Chinese and US researchers has been extremely limited despite IP management plans. Another example is the GreenXchange, established as a patent pool for technology patents related to sustainability, but de-activated after three years.[75]

Programmes that c**ombine global capabilities through earlier stage RD&D project implementation** are less numerous than knowledge sharing and networks, but represent the largest share of spending by international cooperation initiatives. These have generally undertaken targeted, small-scale RD&D cooperation across a wide range of low-carbon technologies. They most often focus on technology challenges of universal interest, although in some cases, they have focused on challenges specific to a local or regional context. Such cooperation has been driven through a plethora of approaches. For example, the EU cooperates in this way by opening its Framework Program to "third countries", by establishing co-funded bilateral programmes (e.g. with the US, China, India and Brazil), by participating in multilateral programmes (e.g. those agreed through the IEA Implementing Agreements), and by contributing to international organizations that fund such programs.

Most advanced and emerging innovator countries have established a number of bilateral joint RD&D programmes, and there is some evidence of increasing momentum for such programs. For example, in November 2014 the U.S.-China Clean Energy Research Center was expanded to cover joint research on clean vehicles, building energy efficiency and clean coal.[76] An even larger group of countries achieves such cooperation through the expanding activities of international organisations. For example, the various IEA energy technology initiatives have expanded the number of non-IEA participants by 7.5 times since 1995,[77] and the newly established Low Carbon Technology Partnerships initiative is seeking to catalyse new international public private partnerships to drive research, development, demonstration and deployment across a number of broad technology areas.[78]

Programmes to **share costs and risks in large-scale demonstration projects** are much less common. There are a few nationally-driven programs that have strongly supported international participation, such as the UAE's Masdar City, which aims to be the world's first zero-carbon city at a construction cost of around US$20 billion, and is being developed in partnership with international private firms and NGOs. There are also a small number of government-to-government cooperation initiatives supporting medium-scale demonstration in areas such as CCS or industrial processes: for example, some of the projects on advanced coal under the U.S.-China CERC, and a recent initiative between Norway and the Czech Republic to support CCS pilots in the latter.[79] Most notably, there is the International Thermonuclear Experimental Reactor (ITER) project, which is the only case of international cost and risk sharing for a very large-scale and uncertain technology. ITER's scale and ambition far exceeds any other cooperation project, involving the EU, India, Japan, China, Russia, South Korea and the US, with a budget in excess of US$20 billion, spent over multiple decades. To date, cooperation in RD&D implementation tends to focus on specific technological opportunities rather than larger scale system-level innovation involving various interacting technologies.

Relatively fewer initiatives have focused on **linking RD&D to early market formation**, and facilitating the adaptation and development of technologies suited to the local context in low- and middle-income regions, especially outside of agriculture. The most prominent examples would be CGIAR and some of the IEA Implementing Agreements (see Box 2). Another example is the Climate Technology Program pioneered by the World Bank, establishing Climate Innovation Centres that support domestic SMEs to adapt and develop locally relevant technologies in Kenya, Ethiopia, South Africa, Ghana, Morocco, India, Vietnam, and the Caribbean.[80] Finally, a few non-governmental efforts, such as the C40's efforts related to bus rapid transit or electric buses, have focused on linking the demonstration and development of new technologies to developing country markets.

Fewer initiatives also exist whose primary purpose is to **strengthen institutional and individual RD&D capacity** in low- and middle-income regions. UNESCO has a number of broad initiatives on science and technology policy and capacity building,[81] and there have been various government led initiatives (e.g. China's Africa and ASEAN Science and Technology Partnerships) with a strong capacity building component across a variety of technology areas but without a strong focus on low-carbon innovation. The largest number of RD&D capacity building programs in low and middle-income regions focus on agriculture (e.g. RUFORUM, START and the IDRC), but again with relatively little focus on low-carbon innovation. Recently, the UNFCCC's Climate Technology Centre and Network has been established with a strong focus on providing capacity building support to least developed countries, although its activities are still being ramped up. Overall, the scale of these efforts remains very small relative to the capacity needs of low- and middle-income regions, and their impact, while positive, remains marginal.

Despite a considerable number of initiatives, our review of current international cooperation suggests a number of gaps:

- **International cooperation does not sufficiently cover key RD&D challenges.** Cooperation has been late to emerge in some technology areas, and it has not played a major role in system-level innovation involving various interacting technologies, or in catalysing large-scale demonstration projects. Section 4 examines specific technology needs in more detail.
- **Participation by developing countries remains low**, especially in RD&D implementation programs combining global capabilities or sharing RD&D costs and risks, although participation is increasing quickly for emerging innovator countries.
- **Few efforts make the critical link between market formation and RD&D** in relation to markets in low- and middle-income regions where there is least incentive for private sector players to bridge the "valley of death".
- **There remains a relative dearth of efforts to support capacity building** in low- and middle-income regions, and the available support has not catalysed a major shift in partner countries toward strengthening local innovation ecosystems.
- **Progress has been slow in resolving IP rights issues**, whether in terms of managing IP in joint programs among advanced and emerging innovator countries, or in terms of facilitating access to IP among low- and middle-income regions.[82]

Finally, while it is impossible to define optimal levels of international cooperation, the very small proportion of countries' low-carbon RD&D budgets channelled through such efforts, and the existence of a number of critical gaps, strongly suggest that current levels are inadequate. This is also consistent with other such recent assessments.[83]

Box 1

Intellectual Property Rights and international collaboration:

Intellectual property rights normally secured through legally enforced patenting can be important for stimulating innovation by providing commercial incentives to invest in risky technologies. Other methods of protecting intellectual property include strong internal processes for confidentiality, non-disclosure agreements and non-compete contractual clauses. Both public and private investment in RD&D is often shaped by industrial policy and the development of industrial competitiveness relative to other countries (e.g. as was the case with Danish wind energy deployment in the 1980s and 1990s) and competitors. Without IPR protections there is a risk of reducing the incentive for such investments.

Yet IPR protection also presents significant barriers to the development of environmental technologies due to cost (proprietary products cost more than generic ones), access (owners of IPR can restrict licenses to given manufacturers and countries), and capacity (where countries with weak legal structures can struggle with IPR and patent issuing). Moreover, in some technology areas, such as software, there is significant debate about whether existing IPR protections inherently inhibit innovation, with the negative effects on competition outstripping the positive incentives provided by temporary protections. Even where innovation is occurring through collaboration IPR issues remain an important barrier.

In recent years, many potential solutions have been developed for protecting IPR while also promoting IP dissemination. Examples include voluntary patent pooling, open source innovation and open licensing agreements. For example, an Eco-Patent commons launched in 2008 by IBM, Nokia, Pitney Bowes, Sony and the World Business Council for Sustainable Development (WBCSD) has collected 100 environment related patents pledged by companies to be made available for free use by all.[84] Another prominent examples is Tesla Motors Inc. who in June 2014 announced that it would open the company's patents for electric cars freely. Experience in other areas, such as infectious diseases, shows that multilateral financing to cover licensing fees or to buy out patents on key technologies of public interest can be useful if designed well.

Box 2

International Cooperation at two ends of the spectrum[85]

The IEA Implementing Agreements (IEA-IA) and CGIAR (formerly the Consultative Group on International Agriculture Research) are two of the longest standing (each with around 40 years of operation), and largest scale, international RD&D cooperation efforts. Both have evolved and improved over time, increasingly leveraging multiple benefits from cooperation. Nevertheless, they started with very different objectives, and despite some convergence, offer insights into quite different frameworks for cooperation.

The IEA Implementing Agreements are flexible, demand-driven mechanisms that provide a legal framework through which governments, businesses, and NGOs can share the costs and benefits of RD&D collaboration in energy technologies. This relatively bottom-up approach has helped ensure the benefits of collaboration to all participants, and allowed for significant adjustment over time. Moreover, the umbrella oversight provided by the IEA ensures that endeavours are adequately connected where worthwhile. Activities typically include some combination of expert networks, knowledge sharing on research results and programmes, database development, modelling and systems analysis, basic and applied research, technology development and pilot plants, as well as the development of codes and standards to facilitate market diffusion. Since the 1970s, the IAs have shifted their focus from fossil fuels to low-carbon technologies, with a steady expansion in the technology areas covered. There are currently about 40 IAs, with most having annual budgets in the tens of millions of dollars. The private sector has been involved since early on, and grown over time, although it remains dominated by large companies. Expansion in the participation of developing country governments and businesses has taken place mostly over the last decade, and has further to go. In 2006, the IEA collaborated with the UNFCCC to establish the Private Financing Advisory Network, a public-private partnership to facilitate financing for early stage clean energy projects in developing countries. This represents an important expansion to its innovation cooperation efforts toward linking RD&D and market formation in developing countries, while facilitating the requisite adaptation in local markets.

CGIAR is both more centralised and more dispersed. It consists of a network of 15 R&D centres located in low- and middle-income countries, drawn together by a strong central office and fund. It channels around US$1 billion per year in RD&D activities (accounted for around 10% of agricultural R&D for development), with core and project funding coming from a combination of governments, inter-governmental organizations (especially the World Bank), and non-governmental organisations (especially the Bill and Melinda Gates Foundation). This creates stronger mechanisms for top-down guidance, priority setting and evaluation, balanced by bottom-up determination and management of specific RD&D projects. Its major focus has been on applied research, development and demonstration, and the adaptation of existing technologies for developing country markets, it is also incorporates knowledge sharing and network building, and innovation capacity building as integral parts of its work. CGIAR began with, and has maintained a single focus on agriculture and on developing countries. In contrast to the IEA, it has been relatively late and slow in involving the private sector, a gap it has worked to close over the last decade. In addition, it is still in the process of incorporating low-carbon agriculture more extensively into its portfolio. In contrast to the IEA, its strong, top-down, core funding model has allowed it to mobilise resources consistently over long periods of time against major innovation challenges, without needing to align interests across many participants on a project by project basis. At the same time, it has compensated for this lack of project by project 'checks and balances' by establishing very strong monitoring and evaluation mechanisms to ensure efforts deliver impact.

The key lessons learned from both these initiatives are summarised in Section 3.3, alongside lessons from a broader set of initiatives.

3.3 EXISTING INTERNATIONAL COOPERATION EFFORTS OFFER A NUMBER OF INSIGHTS INTO HOW SUCH COOPERATION CAN BE INCREASED

To determine how to best extend existing efforts, we examine what is known about how cooperation can be most successful. Overall, there is very little evaluation of international RD&D cooperation efforts, whether qualitative or quantitative, and differences in evaluation methods make comparison very difficult. Thus, rather than make overly-specific suggestions for the design of future efforts, we distil seven design principles for successful collaboration from experience to date.[86]

1. Provide sufficient scale to ensure the foundations of a robust innovation ecosystem. Large national innovation systems have generally established a set of foundations that support a broad range of national RD&D programs: robust priority setting processes, systems for quality assurance and evaluation, mechanisms for IP management and sharing, frameworks for independent scientific advice, channels for market feedback, and so on. International cooperation initiatives are often too small, or too arms-length from national innovation systems to establish these foundations. The European Union has made strides to overcome this in its Horizon 2020 program by fully integrating its international cooperation initiatives into its core innovation programs, and seeking a direct link to partners' national innovation programs.[87] This has enabled it to leverage national capacities (e.g. knowledge networks, tracking and monitoring systems) and align enabling policies (e.g. related to IP rights) to better facilitate effective collaboration. Moreover, the European Union's official international cooperation strategy has also clarified where cooperation is in the national interest, and hence provided a stronger basis for significant funding allocations. In the cases of CGIAR and IEA Implementing Agreements, the need for such foundations was discovered and developed in stages, in response to experience. Over time, the scale of both programs has grown sufficiently to establish these foundations – for example, CGIAR's Independent Evaluation Arrangement and Scientific and Partnership Council;[88] and the IEA Implementing Agreements' mechanisms for identifying prior IPR and its Experts' Group on RD&D Priority Setting and Evaluation.[89] Both examples also point to the importance of core funding as a way of ensuring such basic foundations are in place. Finally, it is worth noting that a need for scale does not mean that related international cooperation efforts should automatically seek consolidation (see the principle 6 below).

2. Clearly define the scope and respective roles grounded in mutual advantage. In addition to the broad bases of success (outlined above), it is critical to clearly define the scope and objectives of cooperation in alignment with participants' priorities. This includes clearly defined roles and responsibilities, as well as timelines and milestones, which in turn enable clear measures of progress for evaluation. The IEA has noted this as a key success factor across its implementing agreements, and as an important factor in enabling the successful expansion of these agreements to new participants.[90] For example, defining the scope of the IEA Demand Side Management Implementing Agreement in close coordination with the needs of India helped ensure India's commitment as the first non-member country to serve as a project lead. Similarly, the Clean Coal Centre Implementing Agreement established a robust yet efficient process for enabling full participant engagement in RD&D priority setting. As a result, it too succeeded in drawing in a number of IEA non-member participants, and it remains one of the longest running international cooperation efforts.[91]

3. Provide long-term commitments to establish trusted and effective relationships between innovators. Innovation is not a linear process, and success relies largely on the unpredictable outcomes of a robust ecosystem of actors who have formed long-term working relationships. While much of the gain from international cooperation flows from bringing together different perspectives it takes time to overcome differences in culture and working style, and to navigate new networks.[92] Successful cooperation through initiatives like CGIAR[93] and the IEA's Implementing Agreements[94] demonstrate that achieving such robust interconnections requires a decade long initial commitment. Establishing the basis of cooperation through joint priority setting, and bottom-up assessments of mutual interest, can take a year or more, so a long-term commitment can be critical to ensuring a coherent approach and clear synergies with national programs.[95] Importantly, experience suggests that overcoming difficulties the of IP management and sharing depends as much on the confidence created through long-term partnerships and trust as on well-designed approaches.[96] Initiatives that have had much shorter timeframes and insufficient funding, like the Asia-Pacific Partnership on Clean Development and Climate (APP), appear to have been cut off just as they were beginning to achieve such robust interconnections.[97] This also suggests that expanded cooperation should seek to leverage existing efforts where possible.

4. Balance technology-led and challenge-led approaches, with an emphasis on enabling discovery. Technology-led approaches have dominated both national and international RD&D activity. These have an inherent advantage in that research expertise tends to be technology based, hence, identifying and pairing researchers is easier. Nevertheless, experience has shown that such an approach can also limit the scope of RD&D initiatives, either overly limiting the types of technological solutions considered for complex challenges and/or excluding innovation that requires coordinated development of various technologies (e.g. low-carbon agriculture or low-carbon cities). Sometimes it does both. Based on this experience, as well as the desire to balance the predominance of technology-led approaches, a number of major cooperation initiatives, such as CGIAR and the Bill and Melinda Gates Foundation have moved toward programs guided by "grand challenges."[98] It is important to note, that under either approach, RD&D programs work best when they seek to achieve a general goal, with complete neutrality in terms of a specific project or technology. In this regard, even "technology-led" approaches should (and generally have) focused on a broad technology area (e.g., wind energy) rather than on a specific technology solution. Here too, there is considerable value to core funding that enables some flexibility in shifting priorities as unexpected outcomes emerge.

5. Encourage open and deep private sector participation. The private sector drives most international innovation activity today, and successful public sector cooperation initiatives have sought to gain from the private sector's capacity and dynamism, and from its focus on reaching end markets. CGIAR, for example, continues to increase its involvement of the private sector, recognising the importance of private sector advances, and the waste created by undertaking RD&D in relative isolation from it.[99] Deep engagement with, and participation from the private sector can also help address IP rights issues to all parties' mutual benefit, as demonstrated by the efforts of the Bill and Melinda Gates Foundation and its Global Access approach.[100] RD&D activities also benefit from the private sector's strength in both gathering "user" feedback, and informing users of the benefits of new technologies.[101] In international cooperation this has perhaps even greater importance, as innovators will often be translating technologies to relatively unfamiliar market contexts, and successful cooperation should enable linkages between the private sector and broader stakeholders.[102] Conversely, the opportunity for new market access is a key driver of private sector interest in such cooperation efforts, as highlighted by private sector participants in the U.S.-China CERC.[103] It remains a persistent challenge to ensure that private sector participation is as open and competitive as possible, especially with regards to the participation of Small and Medium Enterprises (SME's). International RD&D programmes have begun to make greater use of innovation competitions and SME-focused initiatives with promising results – for example, the Bill and Melinda Gates Foundation Challenge Exploration grants in health, and the World Bank's Climate Innovation Centre's initiative.[104]

6. Foster as many different and competing efforts as is feasible. Experience from cooperation programmes shows the benefit of creating as many competing projects as is feasible, linked through knowledge sharing.[105] Large, all-inclusive, multinational efforts risk crowding out, or reducing incentives for RD&D activities more broadly, and suffer from innate inefficiencies. They make sense only when there are overwhelming benefits to pooling expertise and funding (as is arguably the case for the International Thermonuclear Experimental Reactor).[106] Moreover, very large projects limited to one specific location (e.g. Masdar City) can limit the replicability of findings to broader settings.[107] Similarly, a diversity of projects helps ensure ample experimentation, which adds significant value when multiple (networked) technologies must be developed simultaneously in many contexts with a high level of uncertainty about the optimal combinations. Different approaches are also sometimes required for different groups of partners. For example, effective cooperation arrangements between two advanced countries will differ from effective partnership arrangements between an advanced and less developed country, and a one-size-fits-all approach can limit participation, as was historically the case for the IEA Implementing Agreements.[108]

7. Catalyse capacity building through national institutions with mutual commitments. Almost all international cooperation efforts demonstrate the importance of sufficient RD&D capacity to successful participation. Decades of experience bear out that effective technology absorption (or "transfer") depends critically on such capacity. Moreover, experience suggests that several levels of capacity building are required, including not only individual scientific and entrepreneurial skills, but also organisational and institutional capacity, and at community and national levels.[109] With sufficient resources, international cooperation has shown success in direct training programmes, such as the IDRC's African Institute for Mathematical Sciences, as well as in capacity building integrated into research programs, as in many CGIAR initiatives.[110] Nevertheless, the depth and scale of the capacity building required points to the importance of approaches that leverage and enhance the effectiveness of national capacity-building institutions, and that involve a strong commitment of resources from partner governments. Experience from initiatives like RUFORUM and START, both agriculture initiatives in Africa, has shown the importance of approaches that build inter-institutional networks, cheaply scalable learning programs, and the training capacity of local institutions; and that emphasise co-funding mechanisms.[111]

4. Priority technologies for climate RD&D through international collaboration

4.1 GREATER LOW-CARBON RD&D IS NEEDED ACROSS A WIDE ARRAY OF TECHNOLOGY AREAS, WITH A NUMBER OF CRITICAL GAPS

A wide range of technologies will be required to deliver climate and growth outcomes, and the best technology to use in a particular situation will vary according to its supply chain and the pre-existing system of other technologies. Moreover, specific technologies have different RD&D needs, subject to rapid shifts, and a great deal of uncertainty. In both national and international efforts, policy makers should avoid 'picking winners' and focus more on advancing broad technology areas, with the openness and flexibility to accommodate the uncertainty of innovation.

Given the role of public policy in RD&D, and the particular benefits of international cooperation, we believe it is possible to identify broad technology areas where further cooperation could be particularly valuable – creating a portfolio of RD&D efforts that expands the abatement options in the future, and enables a greater diversity of low-carbon pathways across more regions. In this section we identify priority areas by considering innovation needs across the main sources of emissions: energy, industry processes, and in the "agriculture, forestry and other land use" sector,[112] which are summarised in Table 1 and described below.[113]

The IEA *Tracking Clean Energy Progress* report considers the current status, recent trends and innovation needs of 19 technologies that could reduce energy and industry process emissions. These account for around 75% of GHG emissions at present.[114] Currently, none of these technologies are considered fully on track, and progress is limited in many cases.[115] Technologies that are particularly off track are (1) nuclear, because policy and financing concerns are holding back deployment; (2) more efficient coal-fired power, because the use of inefficient technologies is not yet sufficiently restricted; (3) carbon capture, use and storage (CCUS), because only a small number of applications exist despite the huge need; and (4) buildings, building envelope and appliance technologies, as these are not being adapted to local conditions and are adopted too slowly despite their cost-effectiveness. In addition, the collective development of some urban systems technologies (transport systems, electric vehicles, district heating and cooling, smart grids, energy storage, and hydrogen) offers a particular challenge due to network effects and coordination challenges.

At the same time, there have been positive developments in some low-carbon energy technologies. For example solar photovoltaic module costs have fallen around 400% since 2000,[116] onshore wind capacity factors have increased by around 25% since 2002,[117] and battery costs have halved and energy density increased by a third between 2011 and 2014.[118]

The agriculture, forestry and other land use sector accounts for the remaining 25% of current emissions.[119] For many of the mitigation options in the sector, the primary challenge is one of localising the technology, with an emphasis on adaptation to local circumstances, demonstration and early market formation. However RD&D is required to improve yields so that increasing food demand can be met while also releasing pressure on forests and other valuable ecosystems. More RD&D is also required for bioenergy, where the use of residues and wastes requires innovation to reduce costs, and where bioenergy crops are needed that are appropriate to the local context and do not conflict with local food production. Bioenergy innovation is particularly important because the combination of bioenergy with carbon, capture, and storage, known as BECCS, is necessary for emissions stabilisation at 450 ppm in many modelling scenarios. That is to say, without BECCS there are few credible or cost-effective mitigation pathways to limit warming to 2°C (as discussed further in Section 4.2). Significant RD&D is also needed for adaptation to climate change in the agriculture, forestry and other land use-related sector.

Table 1

Status of energy, industry or agricultural mitigation technologies for achieving long term 2°C target[120]

	Technology	Current status	Recent trends	Innovation need
Electricity	Renewable power	🟠	↑	Cost reductions especially in offshore wind and primary innovation for solar thermal and ocean power
	Nuclear power	🔴	~	Deployment constraints are primarily due to policy and financing issues
	Gas-fired power	🟠	~	Deployment constraints are primarily due to failure to compete with cheap coal
	Coal-fired power	🔴	~	Enforcement of design principles for maximum efficiency, flexibility and for carbon capture and storage readiness
	Carbon Capture and Storage (CCS)	🔴	↑	Primary innovation in separation, both pre and post combustion routes, storage and effect on flexibility
Industry	Industry	🟠	~	For industry in general: greater adoption of best available techniques and energy monitoring
	Iron and steel	🟠	~	Efficiency through process integration, use of process gases and CCS
	Cement	🟠	~	Urban planning, intelligent transport systems, shift to low-carbon modes, especially for road freight
Transport	Road transport	🟠	~	Urban planning, intelligent transport systems, shift to low-carbon modes, especially for road freight
	Fuel economy	🟠	↑	Understanding of driving patterns, consistency between tested and real fuel economy
	Electric and hybrid-electric vehicles	🟠	↑	Lower battery costs, charging infrastructure
	Hydrogen vehicles	🟠	~	Primary innovation in all aspects, particularly costs of vehicles and infrastructure
	Aviation	🟠	~	Primary innovation required in advanced biofuels and materials for efficiency, efficient routing and taxiing
	Shipping	🟠	~	Primary innovation required in propulsion systems, adoption of Best Available Techniques for efficiency, efficient docking and port services
Buildings	Buildings	🔴	~	Lower cost technologies, localisation of codes, certification and knowledge, renovation
	Building envelope	🔴	~	Localisation of materials and knowledge, commoditisation of advanced materials
	Appliances and equipment	🟠	~	Lower cost technologies, market engagement strategies, localisation of standards

Energy networks	Co-generation and district heating and cooling	●	~	Urban planning and creation of heating and cooling networks and interconnection between networks
	Smart grids	●	~	Forward compatible smart meters and technology, international standards but localised technology
	Energy storage	●	↑	Primary innovations in high temperature thermal storage, scalable systems, flexible charging
Heat	Renewable heat	●	~	Removal of non-economic barriers for residential applications, lower cost for industrial use and better storage
Agriculture	Climate smart agriculture	●	~	Localisation of current Best Available Techniques. Primary innovation to increase yields and lower costs of bioenergy.

Note: "Current status" considers whether a technology is "on track" (a green circle), which, for all technologies except for aviation, shipping and agriculture, means that development and deployment is in line with the IEA's 2°C scenario over the next decade. The medium performance status is "improvement, but more effort needed" (an orange circle), and the worst performance is "not on track" (a red circle). "Recent trends" describes progress on technology penetration, market creation and RD&D developments, where ↑ means positive recent developments and ~ means limited recent developments.

Source: New Climate Economy based on various sources.[121]

4.2 INTERNATIONAL COLLABORATION HAS A PARTICULARLY IMPORTANT ROLE TO PLAY IN FIVE MAJOR TECHNOLOGY AREAS

All low-carbon technology areas require further innovation if they are to deliver necessary abatement opportunities. However, limited resources for publicly supported international collaboration should be focused where the impact will be greatest. The analysis so far points to three criteria to identify focus areas:

- **Technology status.** Some technologies require significant RD&D before they can be deployed at the scale necessary to achieve mitigation targets, they do not have sufficient policy initiatives or market incentives to drive development.
- **After 2030 importance.** Public support is essential in cases where failure to innovate will substantially restrict abatement options, as the recently launched Mission Innovation Programme made clear.[122] However, an even longer-term view is needed as options for abatement after 2030 are furthest from market and require fundamental innovations that have little prospect of development by the private sector.
- **Benefit of cooperation.** As explained in Section 3.2, we identify five ways in which public sector driven international cooperation on innovation can deliver growth and climate action benefits: by enhancing knowledge sharing; coordinating a portfolio of approaches; facilitating cost and risk sharing; linking RD&D to early market formation; and capacity building.

Applying these criteria to low-carbon technologies, we identify five priority areas for international cooperation on RD&D (summarised in Table 2). These areas are aligned with priorities set by recent initiatives, such as the Mission Innovation Programme and the breakthrough Energy Coalition,[123] although we go a somewhat further in focussing on key areas, and in justifying that focus:

Agriculture and bioenergy is a priority area for collaboration as many of the mitigation techniques developed need to be shared and localised, while technology requirements need to be better fed-back from local markets (where agriculture is an important part of livelihoods) to centres of RD&D. This is particularly important for high-tech innovations in agriculture, for example scientific improvements in seeds or livestock feed. CGIAR is the leading example of international cooperation in this area, but, as *Better Growth, Better Climate* argued, R&D funding for agriculture and forestry in developing countries is insufficient and needs to double to US$30 billion by 2030. Furthermore, BECCS is a key component of many low emissions scenarios, with some studies suggesting that a delay in its availability could increase total discounted mitigation costs by 64% to 2100.[124] The Breakthrough Energy Coalition also identified agriculture as a priority area. Therefore, given significant needs in developing countries and major after 2030 importance, along with a current positive, albeit small, example of international cooperation, Agriculture and Bioenergy is a priority area.

Buildings and construction, including building envelope technologies, are projected to deliver 10% of cumulative energy emissions reductions between the IEA's 6°C and 2°C scenarios by 2050.[125] However, the IEA considers these areas to be significantly off-track.[126] At the same time, urgent action is needed to enable the technologies to be deployed, especially in emerging economies, as the IEA projects that these will account for over half of the increase in buildings energy demand to 2050. Rapid innovation is therefore needed to avoid locking into a high carbon trajectory, which could result in greater climate change and require expensive retrofit later on. International cooperation can aid this by sharing knowledge and developing capacity in rapidly urbanising countries. For example the World Green Building Council currently connects 100 national councils to disseminate best practices.[127] A coordinated portfolio of approaches would also be valuable so that lessons are learned from a range of experiments. The lessons from successful experiments can then be rapidly formulated into standards, where applicable.

Electricity networks, such as smart grid and energy storage technologies, are essential in enabling widespread deployment of variable renewables. The development of individual components has acquired some momentum, but there are very few efforts testing the integration of a full suite of supply and end-use technologies into a network at the scope and scale expected to be required in coming decades. The main examples to date of such integrating efforts were only established in 2010 by theGlobal Smart Grid Federation, which focuses on knowledge sharing and facilitating public, private and non-governmental organisation collaborations,[128] and the IEA's International Smart Grid Action Network, which develops standards and coordinates government-to-government cooperation.[129] Collaboration can provide benefits here through knowledge sharing and experimentation across a wider range of configurations. It can also enable a degree of standardisation that would allow different components of the network to be combined at a lower cost. However, virtually no efforts examine the network-related trade-offs involved across a range of local settings. Innovation is required here to avoid a bottleneck in the deployment of renewable energy and end-use efficiency.

Transport systems are a part of transport abatement innovation that should benefit significantly from new international collaboration as such systems are complex and large enough that a single city cannot undertake a portfolio of approaches. Therefore, knowledge, risk and cost sharing is especially important for cost-effective RD&D, as is the coordination of a portfolio of approaches across cities. Such RD&D support is crucial as the IEA projects that transport could provide 19% of cumulative energy emissions reductions between its 6°C and 2°C scenarios by 2050.[130] Much of this will come from new fuel technology, such as electric vehicles or even hydrogen, which require new fuelling networks to be integrated into the transport system. Furthermore, infrastructure and urban planning to manage travel patterns and modal choice will be necessary to manage transport demand, and could provide 35% of urban abatement opportunities in 2030.[131] Current international collaborations, such as the C40 Cities initiative and the Association of Local Governments for Sustainability, provide platforms for knowledge sharing. However, they do not provide a platform for cooperating on more fundamental RD&D. Efforts to build capacity in emerging and developing countries could be increased, given that 85% of transport infrastructure additions projected to 2050 will occur in non-OECD countries.[132]

Carbon capture, usage and storage (CCUS) is a key technology, particularly after 2030, for which innovation is not currently on track. Without CCUS many mitigation scenarios find stabilisation at 2°C to be impossible or extremely costly. Studies suggest that a major delay in its availability could increase total discounted mitigation costs by 138% to 2100.[133] If CCUS is available, it is likely to play a significant role in GHG abatement, especially after 2030. The IEA projects that CCUS could provide 13% of cumulative energy emissions reductions between its 6°C and 2°C scenarios by 2050.[134] The majority of deployments are required in non-OECD countries, which will need around 2.5 times more CCUS for power than OECD countries after 2025.[135] Current international cooperation efforts on CCUS, such as the Carbon Sequestration Leadership Forum, the IEA Clean Coal Centre and the Global CCS Institute, demonstrate the appetite for collaboration on CCUS. However, further action is required as progress has been slow and current cooperation efforts are not facilitating cost and risk sharing to the extent that is needed. However, further action is required as progress has been slow and current cooperation efforts are not facilitating cost-and-risk sharing to the extent needed. They could also encourage a larger portfolio of projects, especially in non-OECD countries, given that current efforts are focused in limited geographic areas where conditions are optimal and complexity is minimised. That will not be the case for the majority of CCUS facilities.

Table 2
Five technologies are priority areas for collaboration to deliver innovation

Technology	Technology status	After 2030 importance	Benefits of international cooperation
Agriculture and bioenergy	On track except bioenergy	High, especially bioenergy	Linking markets to RD&D, knowledge sharing, capacity building
Buildings and construction	Not on track	High	Linking markets to RD&D, knowledge sharing, capacity building
Electricity networks	Components on track, system is not	High as a key enabler	Share costs and risks, knowledge sharing, capacity building
Transport systems	Not on track	High	Linking markets to RD&D, knowledge sharing, capacity building
Carbon capture, usage, and storage	Not on track	Very high	Share costs and risks, knowledge sharing

Source: Global Commission on the Economy and Climate, 2015. Seizing the Global Opportunity: Partnership for Better Growth and Better Climate. Available at: http://2015.newclimateeconomy.report/wp-content/uploads/2014/08/NCE-2015_Seizing-the-Global-Opportunity_web.pdf.

5. Conclusions and recommendations

Innovation is crucial for achieving positive growth and climate outcomes, and it is fundamentally in the interest of economies at all levels of development. Yet too little innovation is now taking place globally, with a particularly large gap in innovation capacity and activity in low- and middle-income countries. Greater and more effective international cooperation related to public RD&D is needed, cooperation which must complement and leverage private sector and national level efforts, and existing initiatives.

The Global Commission on the Economy and Climate recommends that emerging and developed country governments work together, and with the private sector and developing countries, in strategic partnerships to accelerate research, development and demonstration (RD&D) in low-carbon technology areas critical to post-2030 growth and emissions reduction. This includes innovation in agriculture; in longer-term solutions such as bioenergy, and carbon capture, utilisation and storage; and in ways to avoid lock-in of carbon-intensive infrastructure (buildings, electricity networks, transport systems). There is also a critical need for cooperation to target or adapt innovations to developing-country needs.

Developing these strategic partnerships will require a broad reorientation of national innovation systems toward international cooperation. Given the hundreds of existing initiatives, and the time and resources required to establish effective foundations for such partnerships, new initiatives should build on existing platforms. At the same time, diverse and competing approaches should be fostered, recognising the uncertain nature of innovation, and the national and private interests that drive it. Finally, these strategic partnerships should focus on activities where international cooperation has most value and be linked through robust knowledge sharing and networking initiatives.

On this basis, governments, international organisations, non-governmental organisations, and private sector actors should launch new or expanded partnerships around three broad pillars:

1. **Demonstration projects to tackle large-scale innovation challenges**, prioritising carbon capture, utilisation, and storage; electricity networks; and urban transport systems. These projects should accelerate the development of interdependent technologies, enable testing in a breadth of local conditions, and advance the institutional capacity and value-chain formation required for at-scale deployment. The dearth of existing projects means this would require materially scaling up and internationalising related efforts, or launching completely new efforts.

2. **RD&D programs to tackle diverse and local innovation challenges**, prioritising buildings and human settlements and agriculture and bioenergy. These programs should create diverse RD&D projects to test and provide feedback on technologies against multiple outcomes (social, economic and environmental), support locally adapted technologies, and align local conditions to facilitate deployment. In agriculture and bioenergy, the focus should be on significantly expanding existing efforts to more thoroughly incorporate low-carbon objectives. In buildings and human settlements, substantively new programs are required.

3. **A significant expansion of projects in low- and middle-income regions**, where much future deployment will take place. Such projects should aim to achieve leapfrogging by these regions to more efficient, low-carbon development pathways, to allow firms with significant innovation capacity to access these growing markets, and to enable innovators in these countries to develop local solutions and support deployment.

To enable low- and middle-income regions to participate in such strategic partnerships and achieve low-carbon, high growth development pathways, the Commission also recommends that:

4. **Governmental and non-governmental organisations support improved innovation governance, capacity building and early market formation in these regions.** In turn, to replicate the success of emerging innovator countries, those low- and middle-income regions should focus on establishing robust low-carbon innovation ecosystems that pro-actively leverage international capacity and resources. This would have the following broad areas of focus:

    - **Innovation governance and capacity building programmes.** These should combine grant-based support with local co-funding and may be set up as complementary elements to the strategic partnerships described above. They should work with countries to establish effective national innovation strategies and institutions and to test and scale up more efficient methods for building individual skills and institutional capacity.

    - **Knowledge access and networks.** Knowledge networks should be increased to encompass broader geographic participation, with the accompanying expansion of technological scope, and widening of feedback from researchers through to users. They should also support the identification of patent "bottlenecks", and the establishment of patent pools or effective licensing arrangements that meet the needs of these countries.

    - **Early market formation.** Concessional lending-based programs should take on higher levels of technology risk and more deeply engage policy-makers to ensure policy and regulatory arrangements conducive to market formation. This would extend the portfolio of investments by major international and bilateral lenders to include, for example, carbon capture and storage in power and industrial facilities, packages of advanced smart grid technologies, and packages of advanced low-carbon buildings technologies and construction methods.

Despite the uncertainty of innovation outcomes, these recommendations would make large strides toward establishing levels of innovation activity across all countries required to meet our long-run growth and mitigation goals. If achieved, there would be a much better chance of achieving the deep emissions reductions required after 2030, while also opening up strong, low-carbon growth pathways to emerging and developing countries.

ENDNOTES

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ABOUT THE NEW CLIMATE ECONOMY

The Global Commission on the Economy and Climate, and its flagship project The New Climate Economy, were set up to help governments, businesses and society make better-informed decisions on how to achieve economic prosperity and development while also addressing climate change.

In September 2014, the Commission published *Better Growth, Better Climate: The New Climate Economy Report*. Since then, the project has released a series of country reports on the United States, China, India and Ethiopia, and sector reports on cities, land use, energy and finance. In July 2015, the Commission published *Seizing the Global Opportunity: Partnerships for Better Growth and a Better Climate*. It has disseminated its messages by engaging with heads of governments, finance ministers, business leaders and other key economic decision-makers in over 30 countries around the world.

The authors

Jason Eis, Vivid Economics

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