
PART V

Technology Options

22 International cooperation in advancing energy technologies for deep decarbonisation

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Climate change cannot be arrested without fundamental changes in the global energy system. Such a transformation will not be possible without major advances in a variety of low-carbon energy technologies. While carbon pricing can provide incentives for advancements in low-carbon energy technologies, more is needed to make deep cuts in global greenhouse gas (GHG) emissions in a cost-effective and politically feasible way. This is because the current state of the art for low-carbon technologies is such that they are significantly costlier than conventional fossil-based energy technologies if deployed at a larger scale. Bringing down the costs of low-carbon energy technologies will require substantial public sector investments not just in basic research, but also in pilot commercial-scale development of advanced energy technologies. Substantial gains in such efforts could be obtained from international agreement to coordinate national RD&D programmes for low-carbon energy and to share the fruits of discoveries. Such agreement promotes the provision of a public good versus negotiating over sharing the cost burden for curbing a global bad. International technology agreement can be complemented by coordinated efforts to raise international performance standards for energy efficiency and carbon intensity in key energy-using sectors.

The need for global energy system transformation

Global climate change cannot be arrested without fundamental changes in the global energy system. This can be seen from the following basic relationship explaining the influences the growth of greenhouse gas (GHG) emissions (the so-called Kaya identity):

$$\begin{aligned} & [\% \text{ rate of change in global GHG emissions over time}] = \\ & [\% \text{ rate of change in population}] + \\ & [\% \text{ rate of change in income per capita}] + \\ & [\% \text{ rate of change in energy utilised per unit of economic output (energy intensity)}] + \\ & [\% \text{ rate of change in the embodied carbon per unit of energy utilised (carbon intensity)}] \end{aligned}$$

The world's population will continue to grow over the remainder of the century, though the rate of growth will drop considerably over time. It is to be hoped that global average income per capita grows considerably over the coming decades, in order to sharply cut the percentage of individuals living in poverty and to achieve continued but more inclusive economic growth. Let us assume that population growth is about 1% per year over the next few decades, and that per capita income growth is about 3%.¹

The growth in population and per capita income will be accompanied by considerable increases in energy use, in particular by the descendants of poor populations that today use little modern energy or even lack access to it altogether. Against these trends, energy efficiency is likely to continue to improve over time. However, annual rates of improvement in energy efficiency in the order of 4% would be needed to offset the growth in population and (hoped for) income growth. This is unrealistically high; 2% is a more realistic, albeit still ambitious figure. A rate of energy decarbonisation of 2% per year then would be needed to hold GHG emissions constant. In comparison, the global carbon intensity of energy use barely changed over the period 1990–2012 according to the IEA (2014, Figure 16), and the EIA's (2013) projection without major new policies internationally is for a decrease in carbon intensity of only 0.2% per year on average up to 2040.

These calculations illustrate only what would be needed to arrest growth in GHG emissions over the next few decades. In fact, global GHG emissions must not only peak fairly soon but also fall precipitously by the end of this century to limit the increase in the global average temperature to somewhere between 2°C and 3°C, a target range seen by many as needed to avoid unacceptably high risks from climate change. To

¹ These are roughly the figures used in the Energy Information Administration's 2013 *International Energy Outlook* (EIA 2013).

accomplish this, the global energy system must be profoundly transformed into one that produces only a small fraction of the GHG emissions occurring today – even while average global income rises substantially from its current level. As shown in IPCC (2014a, Figure 7.16), low-carbon energy sources – renewables, nuclear, and fossil energy use with carbon capture and storage (CCS) – must increase from under 20% of total energy use to above 70% or even above 90% by 2100, depending on the stringency of the limit on temperature increase sought.

Such a transformation will not be possible without fundamental changes in energy technologies. The reason for this is that low-carbon energy technologies currently are not cost-competitive when implemented on a large scale. The lower ‘energy density’ of wind and solar resources per unit of capital expenditure, relative to conventional technologies, is one barrier (Kessides and Wade 2011). Even where direct costs of production are falling, as with solar photovoltaic (PV), the costs of large-scale PV use are increased by its intermittency and the challenges of coordinating such dispersed resources with the current power grid (Joskow 2011). While some very large hydroelectric resources remain to be developed, the number of economically attractive and environmentally manageable sites is inherently limited. Nuclear power remains dogged by cost overruns, public concerns, and the long time line that seems to be needed for ‘next generation’ reactors to become commercially available. ‘Second-generation’ biofuels that create fewer land-use tradeoffs and result in larger net carbon savings remain a number of years away (Cheng and Timilsina 2011). While plug-in vehicles are advancing quickly, they increase the pressure to decarbonise the power system.

All these potential pathways for decarbonisation of the energy system must bear fruit in terms of lower costs in order for dramatic decarbonisation to be economically manageable in practice. However, the ability to use carbon capture and storage appears to be especially urgent. Even some negative-emissions options are needed – in particular, growing biomass, which pulls CO₂ out of the atmosphere, and capturing the released CO₂ emissions when the biomass is burned to generate power. If CCS is not available in the portfolio of emissions mitigation options, the costs of constraining temperature increases are considerably larger (IPCC 2014b, Table SPM2). Yet, CCS remains an experimental technology, with very uncertain future prospects (see Tavoni 2015).

Challenges in achieving the transition

As it stands, the IPCC suggests that additional investments of around \$150 billion per year may be needed to move forward on a path toward decarbonisation, as well as more than twice that amount for improvements in energy efficiency (IPCC 2014b, p. 27). The International Energy Agency has estimated that \$44 trillion would be needed by 2050 in the effort to hold temperature change below 2°C (IEA, 2014), on top of the investments needed to meet growing energy demands.² Such added costs can limit the incentives for individual countries to launch programmes for energy decarbonisation, and exacerbate the debate over how the cost burden for drastically reducing global GHG emissions might be allocated.

Given that a profound change in the global energy system will be needed to reduce GHG emissions enough to stabilise the climate, and given that a high cost of decarbonisation acts as a serious barrier to unilateral and cooperative efforts to implement GHG-mitigating policies and measures, it stands to reason that technical progress in lowering the cost of decarbonisation needs to be a high priority. This is all the more important when one takes into account that the default for meeting rapidly growing energy demands in developing countries will include major increases in fossil energy, especially coal for electricity. Locking in high-carbon energy infrastructure only raises the opportunity cost of reducing emissions later, further deterring actions needed to stabilise the climate.

One way to stimulate such technical progress is by putting a price on GHG emissions. This creates powerful incentives for the development and diffusion of lower-cost, lower-carbon energy sources and technologies. With the development of such technologies, all GHG emitters can lower their costs of responding to policy (such as the need to buy allowances in the European Trading System (ETS) or to pay a carbon tax on residual emissions) by licensing the new technologies, and those who can provide cost-reducing GHG-mitigation technologies have a ready market in which they can recover their costs. Calel and Dechezleprêtre (forthcoming) show that carbon pricing in the ETS has

2 The IEA also estimates that fuel cost savings would be more than 2.5 times as large.

contributed to an increase in low-carbon innovation, though the effect is not that large given the relatively low carbon prices found in the ETS.

A key virtue of using carbon pricing to help induce development and diffusion of lower-carbon energy technologies is that it can foster competition among different approaches. Meanwhile, some of the cost disadvantages of large-scale low-carbon energy deployment will shrink through learning-by-doing as greater experience is gained with the operation of larger-scale solar photovoltaic and thermal power plants, different wind sites, and evolving technologies for growing and utilising biomass energy sources (as fuels and electricity feedstocks).

Beyond carbon pricing ...

However, more will be needed to make deep cuts in global GHG emissions in a cost-effective and politically feasible way. There continues to be resistance in much of the world to setting carbon prices that are high enough to induce major energy technology transformations, despite mounting evidence of the threats posed by climate change. Moreover, some of the cost disadvantages of low-carbon energy systems may be persistent, requiring more fundamental advances in technology than might be induced through carbon pricing alone. These include the challenges of coordinating widely dispersed and intermittent renewable electricity sources for a stable power grid (and as part of that, the development of cost-competitive power storage technologies), and the development of a ‘new generation’ of nuclear power reactors that are cost-competitive and respond to public concerns about safety as well as nuclear proliferation. The technical challenges facing the development and widespread implementation of cost-competitive and publicly accepted CCS also are quite substantial. The more basic scientific research that seems necessary to overcome the cost barriers typically is undertaken on too small a scale, if at all, by the private sector, given both the risks from failure and the difficulties in appropriating economic benefits from a basic discovery.

...to disruptive innovation

The size and persistence of these sorts of challenges suggests that some ‘disruptive’ rather than just ‘evolutionary’ innovations in energy technologies will be needed to overcome them. While in principle such innovations could occur at any time and could come from a variety of sources, large and enduring increases in public sector R&D expenditures are likely needed in practice to raise the probability of achieving the necessary fundamental breakthroughs in low-carbon energy technology to an acceptable level. In addition, some public investment (or some other form of cost and risk sharing) will be needed in piloting commercial-scale applications of more fundamentally new technologies, in order to mitigate the economic risks of being an early mover with a new technology. For example, electricity grids that can successfully manage the integration of dispersed and intermittent resources are inherently large investments in technologies whose performance characteristics can only be fully understood once the technology has been scaled up. The same is true of large-scale CCS. Determining the economic performance of solar thermal technology on a large scale likely will require building a significant number of facilities using different specifications and operating conditions; yet each plant would cost some billions of dollars to build and would be likely deliver uneconomic power compared to alternatives while the technology is being refined.

The importance of international technology cooperation

The need for increased public sector R&D discussed above could be met by different governments funding a variety of different programmes, depending in part on their own comparative advantages (e.g. countries with high wind or solar potential, or geology favourable to CCS) as well as on their own reckonings of what technology paths may be more promising. There are, however, some significant limitations with this approach that point to the value of international cooperation in low-carbon RD&D.

One issue is the cost of greatly expanded national programmes for energy technology development. No one really knows how large these costs might be. According to

figures from the IEA,³ between 2005 and 2013, total energy-related RD&D in the OECD averaged about \$15.3 billion per year. Of that amount, about 35% was for energy efficiency and renewable energy (in roughly equal parts), just under 30% was for nuclear, and only 15% was for fossil energy. On the other hand, the percentages for hydrogen and fuel cells and for storage technologies were only about 5% each. Funding for CCS is also minimal compared to its potential importance for decarbonisation in the medium to longer term.

As noted in IPCC (2014a, Section 7.12.4), energy R&D recently has been in the order of 5% of total R&D spending – less than half the level observed in 1980. With such a small share for total energy R&D, let alone low-carbon energy R&D, there are also concerns over the scope of international R&D for low-carbon energy. No one knows which of many possible technology pathways might be successful in lowering costs as well as emissions. Because of this, it would be highly desirable to pursue a number of them simultaneously, rather than picking a few ‘winners’ early on. However, many pathways can only be adequately explored through very substantial expenditures on both R&D and commercial-scale piloting, as noted above. Keeping open a range of options for technology development and diffusion, while very desirable, is costly.

At a time of limited fiscal space for many OECD and other countries, a significant absolute increase in RD&D spending for low-carbon energy will be challenging with or without international cooperation. Another difficulty, however, is the analogue of the problem with private R&D spending falling below the socially desirable level because of inherent problems in establishing adequate incentives for knowledge creation. Because fundamental knowledge coming from expanded public-sector R&D typically would not be possible to patent (though new devices based on that knowledge could be), a portion of the benefits of any R&D increase undertaken by a particular country will ‘leak away’ to others who can make use of the resulting knowledge without sharing in the costs. Yet, technology development and transfer to developing countries will be essential for a successful global climate regime (see Coninck et al. 2015). Understandably, individual governments considering major increases in low-carbon energy R&D programmes will

3 See http://www.oecd-ilibrary.org/energy/data/iea-energy-technology-r-d-statistics/rd-d-budget_data-00488-en.

be motivated by the benefits they can secure, not the benefits for the world as a whole. Moreover, the economic and political costs of unsuccessful programmes can create a bias in favour of pursuing technology options that appear more likely to succeed or easier to implement – even though success in decarbonisation may arise from what are seen today as ‘fringe’ possibilities. This may be easier to manage when one considers a global portfolio of R&D in which activities are coordinated and costs are at least implicitly shared for a range of options.

These points highlight the potential benefit from focusing substantial attention in upcoming international climate cooperation efforts on ways to greatly expand and coordinate global RD&D activity in low-carbon energy. Agreements on coordinating research programmes to share the costs of such RD&D investing, and on arranging for broad access to successes from the R&D, add to the global public good. This compares favourably with the politics of negotiation over allocating the cost of mitigating emissions (a global public bad) through negotiating over national emissions targets.⁴

That is not to say that arriving at an international agreement for low-carbon energy technology development would be easy. There would still need to be tough discussions over funding level commitments, the means for assuring that those commitments are carried out, and rights of participants to access discoveries coming from the programme. The details of programme administration would matter greatly. Trade barriers that limit the movement of international foreign-made green technologies today would remain an issue. Nevertheless, the promise of this approach suggests that it should receive much greater emphasis in international climate policy discussions.

4 Even with ‘Intended Nationally Determined Contributions’ (INDCs) for mitigating global GHG emissions, which are figuring prominently in the run-up to the Paris COP, there is still room to debate whether any one country’s INDC is in some sense ‘adequate’. Moreover, there is reason to believe that negotiations over INDCs will have to overcome the same basic challenge to international climate agreements that has been pointed out by numerous authors, namely, the fact that among many countries coming from diverse circumstances but with a common incentive to do less while hoping others will do more, the only feasible agreements may have limited impacts on the trajectory of global GHG emissions. The nature of this challenge is thoroughly reviewed in the various essays in Aldy and Stavins (2010).

A Global Apollo Programme?

The recent call by a number of prominent authors (including Lord Stern) for a ‘Global Apollo Programme to Tackle Climate Change’ (King et al. 2015) draws welcome attention to the need for expanding international RD&D for GHG mitigation, including low-carbon energy technologies.⁵ The proposed programme calls for increased spending starting at \$15 billion per year, or about 0.02% of global GDP, rising thereafter with growth in global income. Compared to the figures on recent energy RD&D expenditures presented above, this would represent somewhat more than double the recent levels of expenditure for non-fossil energy. However, it is an order of magnitude smaller than the amounts that the IPCC and IEA have suggested for effecting a low-carbon transition. Thus, the extent to which the proposed expenditures would lower the costs of new investments in low-carbon energy is open to question. The extent to which the expenditures would bring down the cost of low-carbon energy enough to stimulate earlier retirement of existing fossil energy production capacity is even more uncertain (Evans 2015).

On the other hand, is the international community prepared to spend something close to 0.02% of global GDP per year for some time on public and private RD&D in order to effect a deep and rapid reduction in GHG emissions? Only time and increased efforts to expand global RD&D cooperation will tell.

Complementary measures: Coordination of technology standards

A useful complement to creating a programme for internationally coordinated technology development for low-carbon energy would be international agreements on various performance standards for energy-using technologies, which could help spur demand for existing and new technologies (Barrett and Toman 2010). Even with current technologies, it could be possible to stimulate demand for more energy-efficient energy-using technologies and lower their cost of production through internationally

⁵ The analogy with the programme for successfully landing people on the moon is somewhat flawed, though, since it does not fully capture the diversity of technology initiatives needed to successfully accomplish drastic reductions in GHGs.

coordinated performance standards. The result could be significant reductions in emissions at relatively manageable costs (though the costs of energy efficiency programmes continue to be debated), and without the serious political economy challenges of carbon pricing.

More ambitious measures for stimulating new technology demand could involve international agreements on sector-specific carbon-intensity performance standards. For example, countries could agree that their national electricity systems would achieve targets for GHG emissions per unit of output by specified dates. Such agreements would obviously involve different costs for different countries, depending on the nature of the agreements. However, agreements over performance standards may be easier to negotiate than carbon-reduction targets per se, in that the performance standards can be framed in terms of technology modernisation and opportunities to compete internationally in the provision and utilisation of modern technologies. The ambition of any such agreements would depend on how countries perceive the prospects for declining costs of decarbonisation over time, in particular through shared efforts to reduce the cost of low-carbon energy technologies. They would not necessarily be a substitute for coordinated international carbon pricing, but they could play a valuable role en route to such coordination.

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23 The role of renewables in the pathway towards decarbonisation

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Renewable energy technologies represent an important low-carbon alternative to hydrocarbons in all applications, from transport to electricity generation and heating. In the shorter term, developments that lower the costs of renewable energy will help lower the cost of decarbonisation efforts. In the longer term, renewables could represent the main source of energy for a zero-carbon planet. Renewables can also bring about a whole set of important ancillary benefits, such as reductions in local pollution and increased access to energy. For all these reasons, policies that lower the barriers to adopting renewable energy and that spur innovation should play a key role in a future international climate agreement.

Introduction

Renewables represent the broad category of energy flows occurring in the natural environment that can be captured for use up to their rate of replenishment. Renewables include hydropower (although typically excluded from the group of ‘new’ renewables), wind and solar energy, tidal and wave energy, ocean and geothermal energy, and biomass energy (IPCC, 2011). Renewables are a key energy option for decarbonisation, but their use as a substitute for fossil fuel energy can also result in important co-benefits, such as improvements in ‘energy security’ by diversifying the set of energy sources, reductions in local pollution, the alleviation of energy poverty, and more broadly the promotion of ‘green growth’. As renewables offer a variety of sources of energy, they are geographically distributed more widely than hydrocarbons. Thus, in principle,

renewable energy provides new possibilities for development in most regions in the world.

In the short term, a shift towards renewables and improvements in these technologies have the potential to lower the cost of transitioning out of fossil fuels, thus making it more attractive for countries to adopt more ambitious INDCs. In the longer term, renewables provide the main technological means for reducing global emissions to zero, and so can help shape the ambition for setting long-term global temperature targets.

For all these reasons, policies related to renewables (either easing their adoption, lowering integration barriers, or promoting innovation in the next generation of technologies) should play a key role in future international climate negotiations.

This chapter provides an introduction to renewable energy technologies, describing their future technical potential (Section 1); reviewing their key role in addressing the GHG-mitigation challenge (Section 2); and, finally, discussing in Section 3 the main bottlenecks to the large-scale penetration of these technologies and the policies needed to help overcome these bottlenecks.

It is important to keep in mind that, following a period that has seen an unprecedented drop in the cost of new renewables (and solar modules in particular), a generalised trend change in the regulatory environment of several countries might result in a slowdown of future investments (IEA, 2014). As a result, renewables might run the risk of falling short of the levels required by deep decarbonisation scenarios. As argued here, international climate negotiations could counteract this trend by providing the predictable and long-term signals that will be needed to secure a sustained growth in these technologies.

1 Renewables today and their technical potential

In 2013, renewables represented about 22% of total electricity generation, with hydropower producing the lion's share, and roughly 13% of the world's total primary energy supply, the vast majority of which came from biomass alone. The deployment of renewables power capacity is expected to rise globally to 2550 GW in 2020 (a growth of 50%), with more than half of this new capacity expected to be installed in non-

OECD countries. The International Energy Agency projects that, thanks to this growth, by 2020 power supplied by renewables will grow from 22% to 25%. A further 50% growth by 2030 is shown in the projections presented in Table 1.

Table 1 Global installed capacity of renewables in 2000, 2010 and 2014, and projections for 2030 (GW)

Renewable technology	2000		2010		2014		2030 (IEA projections)	
Hydropower	781.73	(92.8%)	1027.60	(76.2%)	1172.00	(64.1%)	1670.00	(41.4%)
Wind energy	17.33	(2.1%)	196.33	(14.6%)	369.60	(20.2%)	1173.00	(29.1%)
Solar energy	1.23	(0.1%)	40.05	(3.0%)	179.64	(9.8%)	900.00	(22.3%)
Bioenergy	33.72	(4.0%)	72.54	(5.4%)	94.53	(5.2%)	245.00	(6.1%)
Geothermal energy	8.32	(1.0%)	10.98	(0.8%)	12.41	(0.7%)	42.00	(1.0%)
Tidal, wave, ocean energy	0.27	(0.0%)	0.27	(0.0%)	0.53	(0.0%)	6.00	(0.1%)

Notes: Relative share in parentheses.

Source: IRENA (<http://resourceirena.irena.org/>); 2030 projections from IEA (2015).

Table 1 gives estimates and projections for the cumulated installed capacity of different renewables technologies for various years. Wind and solar capacity have grown most rapidly, in response to the large reductions in the costs of solar PV modules, which fell by a half in several countries over the period. Most of this cost reduction was due to innovative changes in the production structure developed by Chinese manufacturers.

Roughly 50% of renewable installed capacity is currently located in the top five countries in terms of renewables deployment: China, the US, Brazil, Germany and Canada. However, most of the future instalment is expected to be concentrated in developing countries, where energy demand will grow the most in the next decades.

Underlying the projected numbers for 2030 presented in Table 1 is the assumption of an increase in investments in renewable energy technologies in the power sector from US\$270 billion in 2014 to \$400 billion in 2030, resulting in a more than threefold increase in the installed capacity for both wind and solar. Notwithstanding the current growth trend in renewables investments, renewables are projected to face a transition period in response to a change in the policy regime of most countries (IEA, 2014). Although it might be affected by international climate negotiations, new generation,

capacity additions and investment in renewable power are all expected to level off through 2020. As far as biofuels are concerned, production and consumption in the US, the EU and Brazil are now slowing down after a period of very rapid expansion, mainly due to changes in policies in reaction to the peak in land demand and general equilibrium implications on crop prices that previous policies have caused. To meet the IEA's projections for 2030, a change in this recent policy trend would be required.

Renewable energy technologies can potentially cover the full spectrum of human energy needs; they can be used to produce electricity and heat, and provide energy for transportation. The IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation concluded that the aggregated global technical potential for renewables as a whole is significantly higher than global energy demands although there is great uncertainty regarding assumptions on land use availability that have to account for issues like biodiversity, food security, water limitation, and soil degradation (IPCC 2011).¹

2 The projected role of renewables in a decarbonised future

Simulations from global energy economy models suggest that renewables are fundamental both in the short to medium term as well as in the second half of the century (Clarke et al. 2014).

Those renewables options that are largely confined to the electricity sector (e.g. wind and solar) and to heat generation are projected to be especially important in the first part of the century. Each option contributes to keeping mitigation costs down and to facilitating decarbonisation by enriching the portfolio of technological alternatives and allowing a diversification of energy sources. In the short term, coupling renewables penetration with gas power generation is seen as the most promising solution, which would help maintain the flexibility of the power system.

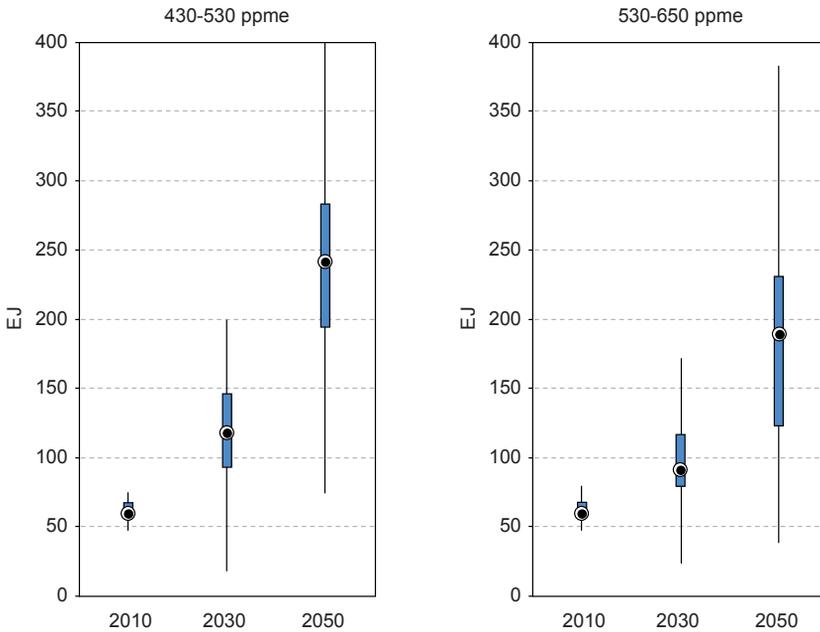
¹ The complexity of such intricate interactions scales up the uncertainty surrounding the potential deployment levels of biomass for energy, which is estimated to be in the range of 100 to 300 EJ by 2050 (for the sake of comparison, 112 EJ is the primary energy consumption of North America in 2012 was 112 EJ).

Wind and solar technologies might have a less critical role in the longer run. Around 2050 and beyond, the effort to keep the average global temperature in line with a 2°C or 2.5°C target is such that ‘negative emissions’ technologies in moderating mitigation costs (Krey et al., 2013). Indeed, in the longer term, the technological option of combining biomass generated power with carbon capture and storage (CCS) gains a prominent role as it allows for the production of carbon-neutral power while, at the same time, generating ‘negative’ emissions. The idea is to generate power using carbon-neutral sustainable biomass and then capture CO₂ at the plant level and store it underground in geological sites (see the chapters in this book by Tavoni and Barrett and Moreno-Cruz). Most projections that do not incorporate such a technological option either report costs of decarbonisation that are at the higher end of the scale, or fail to find a combination of technologies that would deliver stringent climate targets (i.e. scenarios leading to about 450 ppm CO₂eq) (Azar et al., 2006; van Vliet et al., 2009, 2012; Krey et al., 2013).

Figure 1 summarises projections of renewables primary energy from multiple integrated assessment model (IAM) simulations for two representative future years (2030 and 2050) under two climate scenario classes (the left-hand panel reports the range of model results for 430-530 ppme, approximately in line with a 2°C temperature target, while the right-hand panel reports results for 530-650 ppme, or approximately 3°C).

Notwithstanding the huge uncertainties that characterise this range of IAM results, including over breakthroughs in renewables technologies, the average required expansion by mid-century in the more stringent climate scenarios (left-hand panel) is projected to be a threefold increase relative to today’s levels. *This would represent a level of primary energy supplied by renewables in 2050 that is roughly half of today’s total primary energy* (and a third for the more moderate climate stabilisation scenarios).

Figure 1 Model-based projections of primary energy from renewables



Notes: Average of estimates from integrated assessment models (IAMs). In each box, the central mark is the median, the edges of the box are the 25th and 75th percentiles, and the whiskers extend to the most extreme data points not considered outliers (corresponding to 99% if the data are normally distributed). Primary energy is the energy contained in raw fuels. Note that today's total primary energy global consumption (including fossils and nuclear) is 567 EJ, projected to grow to 612 and 643, by 2020 and 2030, respectively (IEA 2015).

Source: Author's elaboration of the IPCC AR5 Working Group III database (<https://secure.iiasa.ac.at/web-apps/ene/AR5DB>).

3 Limits to actual deployment

Below I review the uncertainties that could prevent the deployments of renewables.

Costs evolution

The major bottleneck slowing down the materialisation of the huge technical potential of renewables is, first and foremost, related to their transformation cost relative to the incumbent, fossil-fuelled technologies.² Although costs of both solar and wind power

² Hydropower is the most mature of the renewables technologies and the only one for which costs are competitive. However, most of the hydropower potential, except for in Latin America and Africa, is already tapped and most projections are pessimistic with regards to the possible growth in the role of hydropower.

have decreased substantially in the last five years, grid parity³ is still some way off, especially if fossil fuel prices were to remain low. Indeed notwithstanding regional variabilities due to resource availability, besides hydropower, it is only onshore wind that may be competitive with coal or gas power production. While in the case of wind technologies, the main source of cost reduction might come from improvements in assemblage and material costs as well as learning effects, solar, biomass-based and ocean technologies might still foresee drastic cost reductions due to major technological breakthroughs.

Three main (and not mutually exclusive) strategies could make renewables more competitive. The first is mainly based on directly funding public research and development (R&D) programmes or incentivising private R&D efforts in renewables technologies. The second is a set of strategies based on demand-side promotion schemes. Public policies directed to renewables deployment that include standards, energy certificates and feed-in tariffs not only promote the adoption of renewables, but also play a critical role in spurring additional innovation in these technologies (Johnstone et al., 2010). The third strategy would be to directly price carbon emissions, thus penalising the competitive, incumbent technology and again spurring adoption of and innovation in renewable technology. Though the debate over the relative merits of these strategies is far from being settled, it is increasingly evident that a combination of the three will likely be required. In addition, a key to success will be the adoption of a long-term policy strategy that will secure the commitment to the required investments.

Multiple recent studies have collected expert assessments of the probabilistic evolution of the cost of carbon-free technologies in response to R&D efforts – the first of the three strategies – by means of structured protocols and interviews (so-called ‘expert elicitations’). These studies gather the probabilistic distributions of future costs of renewables technologies and how these distributions might be affected by R&D investments (Baker et al. 2008, 2009, Anadón et al. 2012; Bosetti et al. 2012, Fiorese et al. 2013, 2014).⁴

3 Grid parity occurs when an alternative energy source can generate power at a levelised cost of electricity (LCoE) that is less than or equal to the price of purchasing power from the electricity grid. The term is most commonly used when discussing renewable energy sources, notably solar power and wind power (en.wikipedia.org/wiki/Grid_parity).

4 Tidal and wave energy, ocean and geothermal energy technologies have not yet been covered by expert elicitation surveys.

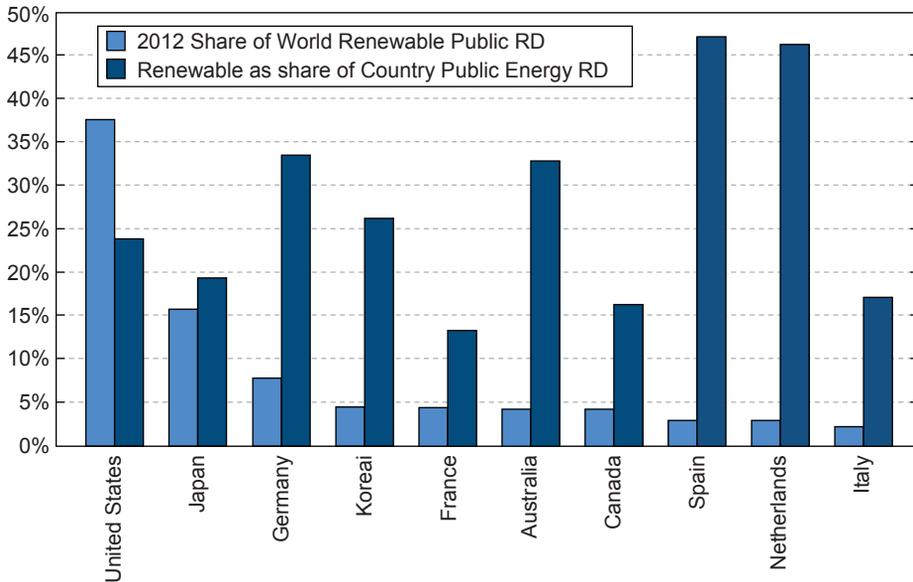
A summary of these studies (Bosetti et al. 2015) reports that overall renewable technologies costs are projected to decrease in the coming 15 years, and that experts expect these costs to be responsive to current levels of public R&D efforts. These elicitation also support the notion that R&D investments will often not reduce the uncertainty surrounding costs; rather, uncertainty is likely to stay the same or increase with larger investment in R&D as the range of technological possibilities expands (Bosetti et al. 2015). Solar PV technologies are to have the largest relative cost reductions, both under current public R&D funding as well as under increased R&D funding. Notwithstanding this expected trend, all reported median values for 2030 costs (and, in most cases, 10th percentile values) imply levelised costs of electricity still higher than coal- or gas-generated power (reported medians of solar PV LCoE cluster around \$0.1 per kWh, in 2010 US dollars).

Elicitations for biofuels and biopower for 2030 also suggest that to become competitive with their fossil-fuelled competitors, public R&D efforts in renewables in OECD countries (see Figure 2) might not be enough, and policies that either internalise the external costs of carbon emissions or that work as demand-side promotion schemes will be necessary.

To get a sense of the magnitude of these investments, the dark blue bars in Figure 2 show each country's public contribution to renewables R&D as a share of its total public energy R&D (including fossils and nuclear). Contribution to R&D of renewables remains within the range of 13-20% for most countries, except for a few outliers (Australia, Germany, the Netherlands, Spain).

If we look at the private side of R&D investment, the Bloomberg New Energy Finance databases report, for the period 2004-2011, an average corporate R&D investment in renewables of around \$3.5 billion, with solar receiving the largest share (around 60%) and wind following at just under 20% (Frankfurt School-UNEP Centre/BNEF, 2014). To put this number into perspective, in 2011 the R&D expenditure by Exxon Mobil alone was more than \$1 billion. In addition, the energy sector is traditionally one of the sectors with the lowest levels of R&D expenditure as a ratio of net sales (less than 1%, while, for example, the R&D expenditure level in the drugs and medicine sector is in the order of 10%).

Figure 2 Share of renewables in public R&D expenditures of selected OECD countries, 2013



Source: Author's calculation from OECD Energy R&D dataset (2013 data).

Looking at patenting activities (see Popp et al., 2011), an indicator of the output of innovation, the US, Japan and Germany again emerge as the most innovative countries in renewables technologies.

On the second set of policy instruments (demand-side promotion schemes), evidence from multiple countries is becoming available. Supported by long-term policy frameworks, renewable investments have increased from multiple financing sources. Energy markets, in particular futures markets for electricity, span forward only a few years, whereas renewables are capital-intensive investments with a life-time of 20-30 years. This market failure, together with the lock-in of fossil fuels, has been the main motivation for these demand-side promotion schemes (Edenhofer et al., 2013) which have been fundamental for the adoption of solar PV and wind throughout Europe and that this has, in turn, been critical for the decrease in the cost of these technologies.

Several factors have contributed to the declining trend in demand-side promotion schemes throughout the developed world. In the case of biofuels, it is mainly related to the realisation of failures in the original policy schemes. In the EU and Japan,

uncertainties remain over the evolution of the renewable policy framework, the feed-in tariffs schemes, and the prospected investments towards grid integration across countries. In the US, the EPA regulation on existing power plant emissions could help support renewables going forward, although renewable portfolio standards are debated in several states (see the chapter by Burtraw in this book).

In developing countries, most policy frameworks have traditionally emphasised electrification. Starting from Brazil and China (two major markets for renewables today), as well as India, policies to promote renewables adoption and to cope with barriers to their use have been increasingly important in accelerating deployment and attracting investment to this sector, while in Africa electrification remains a huge challenge (see the chapter by Mekkonen in this book).

System integration

Even if recent developments in the evolution of renewables costs were to be replicated in the near future, a second, major obstacle is becoming increasingly important – system integration. In the face of stable and growing demand, renewables are an energy source that is unpredictable and highly variable over timescales that might range from seconds to years (IPCC, 2011). System integration issues are important barriers to deployment and they will require investment in innovation (most notably, for storage technologies), investment in new infrastructures, and institutional changes to account for required changes in the energy markets. The larger the share of renewables in the system, the more pressing these issues will become.

In order to meet power demand at each moment in time, either complementary technologies supporting enough flexibility in dispatch or energy storage systems are required. Gas power plants, with their flexibility, are the best complement to increases in the share of renewables in the grid, at least in the short term. For storage technologies, the most prominently discussed technologies are either based on pumping water or air pressure, or on large batteries, including networks of smaller batteries, such as those employed in electric drive vehicles. Finally, renewables could also be better managed by using demand-side response practices.

Lack of predictability and lack of flexibility can also put pressure on energy markets, which are currently based on marginal cost pricing; hence, large penetration of renewables could lead to low and even negative pricing, which in turn could lead to reductions in overall sectorial investments (Edenhofer et al., 2013).

Environmental issues

Other environmental and social issues should be kept in the picture when designing policy that implies penetration of renewables technologies on a massive scale. This is particularly critical in the case of large-scale penetration of biomass usage, both for power production and for biofuels. Indeed, diffusion of energy crops exerts pressure on other land uses, ranging from food crops to forestry, and, in principle, threatens biodiversity. Land use is also one of the major potential issues associated with large-scale deployment of solar technologies (together with the issue of toxic waste and lifecycle GHGs emissions for solar), but it is overall much less of a concern than in the case of biomass.

The modest potential for hydroelectric energy still available, hydroelectric development will play only a minor role in the future of renewables.

Environmental risks from ocean energy technologies appear to be relatively low, although the technology is too immature for any definitive evaluation. Finally, in the case of wind, the environmental footprint of the technology is relatively low.

4 The way forward

Even though renewables will become more competitive, their future development is still closely linked to public policies aimed at stimulating innovation, actual deployment and carbon pricing. In particular, long-term and stable policy frameworks and market signals will be crucial for large-scale deployment of renewables. This is in contrast to the uncertainty recently affecting the renewables regulatory environment (in particular, in the EU, Japan and the US). This general trend in the policy environment could be reversed by an international climate agreement that establishes a long-term global

commitment to internalising the costs of carbon emissions or that includes some form of commitment to renewables deployment.

Indeed, any international climate agreement implying a mid- to long-term commitment to fossil fuel emissions mitigation and an appropriate carbon price would help to provide this signal. In addition, policies and technologies aimed at increasing power system flexibility will be particularly important. In the longer term, policies fostering innovation and key technological breakthroughs in storage technologies, third generation PV, algae-based biodiesel or third generation biofuels, as well as other technologies still far from any commercial application, will play a more important role.

As discussed by Toman in his chapter in this book, an international agreement with the objective of coordinating national R&D programmes for renewables and sharing the resulting knowledge (for example, with special patent rights for open knowledge or facilitated licensing) could represent an important step forward in dealing with these longer-term innovation issues. This would be particularly relevant for high-risk technologies with large potential but that are still far from any commercial implementation.

However, as we have discussed, most experts believe that innovation policies alone would fall short in delivering the required price cuts in the short to medium term. Rather, demand-side promotion schemes could play a crucial role, as well as policies favouring international transfer of technologies. Since in the coming decades the largest share of the global energy demand growth will be located within fast-growing developing countries, technological transfers will play a key role. Indeed, notwithstanding China and Brazil, most of today's renewables installed capacity and know-how is located in developed countries. Similarly, the largest share of investments in R&D, as well as the largest effort in terms of complementary policies to spur the diffusion of renewables has, so far, mainly taken place in the developed world. As discussed in detail by de Coninck et al. in their chapter in this book, agreements and policies promoting the transfer of technology and know-how to developing countries will therefore be extremely valuable in the deployment of renewables.

In addition, as discussed by Buchner and Wilkinson in their chapter, specific programmes designed to reduce the risk-return ratio of renewables investments and

explicitly targeting developing countries, whereby risk is shared with public (national or international) institutions, could nurture a thriving market for renewables in developing countries.

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24 Carbon capture and storage: Promise or delusion?

Massimo Tavoni

Fondazione Eni Enrico Mattei (FEEM) and Politecnico di Milano

Fossil fuels currently dominate the global energy mix, and there is no indication of a significant reversal of this trend in the near future. The recent decline in oil prices, the revolution in extraction of gas and oil, and the abundance of global coal resources suggest that whatever strategy will be devised to deal with climate change, it will have to confront a large supply of competitive fossils. To this end, the possibility to sequester and store CO₂ geologically offers an important way to decouple fossil fuel use from greenhouse gas emissions. It could also provide incentives to engage fossil fuel producers in international climate action. CCS, if coupled with biological sources, also offers the potential to remove CO₂ from the atmosphere and is a technology that will be needed in the future if ambitious climate targets will need to be attained. Yet, the commercialisation of large-scale CCS plants has proven much more difficult and slower than originally envisioned. This chapter explores the importance of CCS for short- and long-term climate policies, drawing quantitative insights from the scenarios recently collected for the IPCC Fifth Assessment Report. It confronts the predictions of the models with the engineering assessment of the cost and performance of the technology, both in its current form and for different assumptions about technological progress in the foreseeable future. We conclude with a set of policy recommendations aimed at promoting the development of a large-scale and well functioning CCS programme.

1 Why CCS?

Carbon capture and storage (CCS) is a technology which allows capturing waste CO₂, transporting it to a storage site, and depositing it in such a way that it will not go into the atmosphere, for example in a geological or oceanic storage site. The key

distinguishing feature of CCS is that it makes extraction and combustion of fossil fuel energy sources compatible with climate mitigation objectives. This is an important characteristic, because fossil fuels provide abundant sources of energy now and for the foreseeable future. As testified by the shale natural gas boom that occurred in the US in the past decade as well as in the recent drop in oil prices, fossil fuels remain extremely competitive. Although the estimates of fossil reserves and resources are highly uncertain, it is safe to say that the total fossil fuel reserves contain sufficient carbon, if released, to warm the planet well above any safety threshold (Rogner et al. 2012). This is particularly true for coal, which scores the highest among fossil fuels both in terms of reserves and carbon intensity.¹ Thus, CCS could effectively allow for the procrastinated use of fossil fuels while limiting – if not eliminating – their impact in terms of greenhouse gas emissions. Moreover, CCS can in principle be coupled with non-fossil energy sources, such as biomass, thereby possibly allowing CO₂ to be absorbed – rather than emitted – in the atmosphere. This would create a ‘negative emission’ technology, which could help remove some of the CO₂ that has already been or will be put into the atmosphere. Finally, by making emissions reduction strategies compatible – at least to a certain extent – with fossil fuels, CCS can have important repercussions on the climate negotiation process. In the remainder of this brief chapter, we explore the role of CCS for climate stabilisation, and discuss the current status of the technology and its role for climate and energy policy.

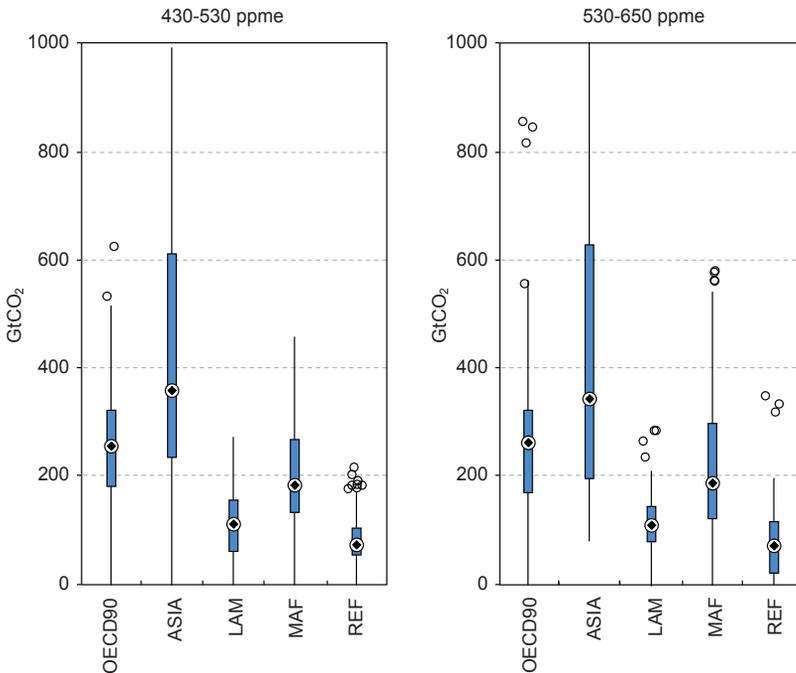
2 CCS and climate stabilisation

In order to provide information about the importance of CCS as a climate stabilisation strategy, let us look into the results of the scenarios recently produced for the Working Group III of the IPCC Fifth Assessment Report (see IPCC 2014, Chapter 6). These scenarios are generated by integrated energy economic models and describe possible realisations of the energy systems throughout the entire century, under different assumptions about climate policy. Figure 1 reports the total amount of CO₂ that would need to be captured via CCS for different climate policy objectives, and five

¹ For reference, the emission factors for electricity generated by coal is close to 1,000 grCO₂/kWh, with natural gas being around 600 grCO₂/kWh.

representative regions. These numbers represent the economically optimal CCS strategy in the context of the global transformation of the energy sector needed to achieve climate stabilisation roughly consistent with 2°C and 3°C temperature targets (left and right panels, respectively), as foreseen by integrated assessment models under a wide range of assumptions about policy implementation and alternative low carbon mitigation options. The figure illustrates the importance of CCS as an emission reduction strategy. Despite differences across regions, models, and policies, the average quantity of CO₂ captured and stored throughout the entire century is in the order of hundreds of GtCO₂. By comparison, current CO₂ emissions are in the order of 35 GtCO₂ per year. Summing up the regional contributions, the global sequestered CO₂ would exceed 1,000 GtCO₂, an amount similar to the total carbon budget compatible with keeping temperature increase below 2°C.

Figure 1 Projections for cumulative CO₂ capture by region under two policy scenarios, 2010-2100.



Notes: LAM stands for Latin and Central America, MAF for Middle East and Africa, REF for Reforming Economies or Economies in Transition. Black dots are the medians, thick bars show the 25-75 percentiles, and thin bars extend to 99 percentile, outliers are shown as circles.

Source: Author's elaboration using the AR5 IPCC WGIII database.

The convenience of CCS under a climate policy regime is that it can be applied to different fossil sources, such as gas and coal, as well as to biological ones, as previously discussed. This flexibility makes CCS appealing for different levels of climate policy stringency, as shown in Figure 1. The capacity of biomass and CCS (commonly referred to as BECCS) to generate net negative emissions – at least in theory – by capturing the CO₂ stored in the biomass and sequestering it underground provides additional incentives in favour of CCS. Although the costs of BECCS and other negative emission technologies are currently above those of conventional mitigation technologies (e.g. above \$100 per tCO₂), models foresee a large role for CO₂ removal, especially during the second half of the century, when carbon prices will rise to sufficiently high levels. Despite its potential, it remains unclear whether BECCS can deliver the CO₂ absorption rates foreseen by economic optimisation models, when considering the technological and institutional limitations and the need to provide CO₂-neutral biomass. The uncertainties around the potential of negative emissions are therefore huge (Azar et al. 2013, Tavoni and Socolow 2013, Fuss et al. 2014).

These large uncertainties are also reflected in the wide range of the scenario results in Figure 1, which includes cases in which models have assumed that CCS would not be available, as shown by confidence interval bars including no CO₂ captured. Such analysis has further revealed that among all mitigation technologies, CCS is the one with the highest economic value – foregoing or banning CCS would lead to a significant increase (i.e. a doubling or more) in the economic costs of achieving a given climate stabilisation, especially for the most stringent mitigation scenarios (Tavoni et al. 2012, Kriegler et al. 2014: 27). Although a broad portfolio of low-carbon technologies is needed to achieve climate stabilisation, CCS stands out as one of the most important since it is the only one that would allow continued use of fossil energy sources.

3 Status of and prospects for the technology

The climate stabilisation scenarios call for a massive scaling up of CCS over the next several decades, a requirement that stands in stark contrast to the limited deployment of CCS observed in reality. At the time of writing, approximately 14 pilot CCS

projects are operating, four of which are for enhanced oil recovery.² Several others have been announced, but an equally large number have been cancelled. One of the obvious reasons for this is the high capital costs of these technologies compared to conventional ones. For example, the US government's recent decision to pull the plug on the FutureGen project resides in the fact that, despite the \$1 billion of federal money, investors remained wary of the economic viability of the carbon capture project. It is also due to the fact that cheap natural gas and the falling costs of renewable energy sources currently provide more economical solutions for reducing CO₂ emissions. In addition, public support for CCS remains a critical factor for its development – CCS involves infrastructure as well as storage sites, both of which require public acceptance. In Europe, adverse public acceptance has recently led to the cancellation of two CCS projects in the Netherlands and in Germany. Moreover, CCS alone would not eliminate other kinds of pollution coming from coal combustion, such as those responsible for local air quality. Last, but not least, if CO₂ were to leak from the reservoirs where it is stored, the benefits of CCS would be undone. Although current tests do not seem to indicate leakage to be a particularly critical issue, the long-term effects of storing CO₂ are not yet fully understood. Looking ahead, by 2020 the number of CCS projects in operation is expected to double, but this will mostly come from demonstration plants, with the aim of recovering oil (de Coninck and Benson 2014).

4 Policy issues and gaps

The gap between the currently observed rates of investment in low-carbon technologies and the actual levels needed for the transition towards a low-emission society is particularly significant in the case of CCS. Despite recent changes in the energy markets, coal and gas remain the dominant technologies in power generation (globally 40% and 23%, respectively), especially in the developing world (Steckel et al. 2015). As a result, developing a technology that is able to limit the CO₂ emitted by fossil fuel plants seems particularly valuable. In order for this to happen, several things would need to change at the policy level. First of all, the technology remains unproven at the

2 See http://sequestration.mit.edu/tools/projects/index_pilots.html.

required scale. Several countries have embarked on or announced pilots, but more will be needed in order to test and demonstrate which among the different designs works best. Low natural gas prices now offer an additional and technologically easier way of testing whether CCS works, since this does not require the complicated gasification process needed for coal. Second, research and development is needed to close the cost gap between plants with and without CCS. Currently, the cost of CO₂ capture appears to be around \$100 per tCO₂, well above the carbon prices discussed in policy contexts. Expert elicitation studies indicate that R&D could reduce the additional CCS cost to a few cents per kWh by the year 2030, if incentives (see below) to innovate were in place (Baker et al. 2009). However, despite some considerable R&D investments in the recent past, CCS plants have not materialised as expected, highlighting the many enabling conditions that are needed to demonstrate CCS. These include climate policies that provide the appropriate economic incentives to sequester CO₂ – even if CCS develops further economically and technologically, it will always require a significant economic incentive in order to be viable and to compete with alternatives. Last but not least, several other enabling conditions will also need to be met at the same time in order for CCS to flourish: public and political support, trust of investors, and a transparent procedural justice (de Coninck and Benson 2014).

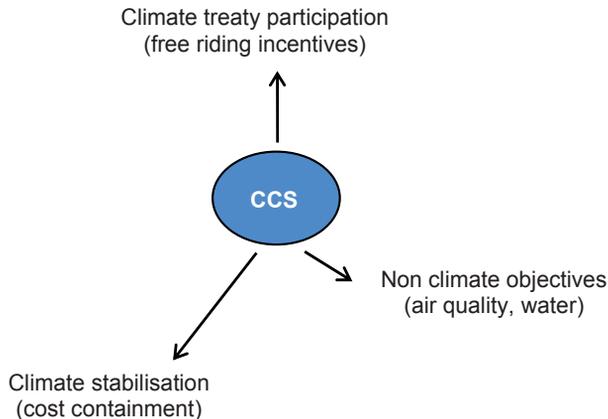
5 CCS in the context of climate negotiations

The barriers outlined above represent significant obstacles, which will not be easily overcome in the next few years. CCS might indeed never materialise at the scale foreseen by the scenarios depicted in Figure 1. In light of this uncertainty, to what extent should CCS be an important part of the current negotiation process? One thing we know now is that keeping the option open is vital for climate strategies. As shown in Figure 2, CCS represents one of the few levers that can be used to engage fossil fuel-rich countries in climate mitigation efforts, and to reduce the risks of carbon leakage via trade and intensified extraction of fossil fuels in anticipation of stringent climate legislation. The biggest challenge for international climate policy is to ensure participation and overcome free-riding incentives. If a climate coalition that reduces emissions is formed, non-participants have an economic incentive to increase fossil fuel consumption (see also the chapter by Fischer in this book). A possible way to overcome this conundrum,

as recently highlighted by Harstad (2012), would be to buy fossil fuel deposits in the non-participating countries. However, this would require significant political capital and would have equity considerations (see the chapter by Collier in this book). CCS has the potential to achieve the same results and with higher chances of being successful. In order to do so, a technology agreement aiming at developing and commercialising CCS in all the major fossil fuel-rich countries (and especially countries rich in coal) could enrich the climate agreements, which as currently discussed are focused on the demand side of emissions quotas. Sufficient R&D investments aimed at reducing the currently high mitigation costs of CCS would be also needed in order to engage fossil-endowed countries and thus reduce the free-riding incentives.

Summing up, CCS would not provide significant benefits outside the climate ones. However, it remains an incredibly important option for climate policymakers, both in terms of providing incentives to participation in a broad climate treaty, as well as for ensuring climate stabilisation is attained at a minimum societal cost.

Figure 2 CCS and environmental policy goals, schematic representation



Note: The lengths of the arrows represent the potential benefit of CCS for three selected policy goals.

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25 The alternatives to unconstrained climate change: Emission reductions versus carbon and solar geoengineering

Scott Barrett and Juan Moreno-Cruz

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Having failed to limit emissions, negotiators began discussing adaptation about ten years ago. With the 2°C target likely to be crossed later this century, this chapter argues that it is now time to consider solar and carbon geoengineering as well. Carbon geoengineering offers the option of a true backstop and provides a ceiling to the costs of managing climate change. Solar geoengineering is a clear fall back, though it is unable to prevent all climate change impacts, and may have impacts of its own that cannot be foreseen. Both technologies are large engineering projects. Unlike emissions reductions, their use does not require large behavioral changes. However, solar geoengineering in particular poses problems for governance.

For centuries, humans have been extracting carbon from below the ground and ultimately dumping it into the atmosphere. The fraction of carbon emissions that is not captured by the terrestrial biosphere and the oceans accumulates in the atmosphere, some of it staying there for thousands of years. The fraction absorbed by the seas creates ocean acidification, causing corals to die. The amount absorbed by the terrestrial biosphere increases net primary productivity and changes the chemical composition of soils. The fraction accumulated in the atmosphere increases global temperatures and alters precipitation patterns, causing droughts and a rise in the sea level.

There are four ways in which the world can limit the negative impacts of climate change. First, we can *reduce the flow of emissions* – that is, we can reduce the amount of CO₂ we add to the atmosphere (relative to ‘business as usual’). Second, we can

reduce the consequences of climate change through *adaptation*. Third, we can reduce concentrations, or the stock of CO₂ in the atmosphere, by removing CO₂ directly from the atmosphere, a process we call *carbon geoengineering*. Finally, we can reduce temperatures by blocking some incoming solar radiation, a process we call *solar geoengineering*.

The primary focus of climate negotiations has always been on the first approach – reducing emissions. But because these efforts to limit emissions have failed, increasing attention has been given to the second approach – adaptation. Both approaches are on the agenda for COP 21 in Paris.

We believe that the continued failure to reduce emissions and the eventual ineffectiveness of some adaptation interventions will inevitably cause countries to consider the other two approaches. Indeed, both geoengineering approaches have already been taken up by the IPCC (2012) and have been the subject of numerous scientific inquiries, including investigations by the National Academies in the US (McNutt *et al.* 2015a, 2015b) and the Royal Society in the UK (Shepherd *et al.* 2009). As both approaches will also have profound effects worldwide, we believe that they will ultimately have to be considered by climate negotiators.

According to the latest IPCC assessment report (IPCC 2014), it will be very difficult to meet the agreed goal of limiting mean global temperature change to 2°C relative to pre-industrial levels in the long term without exceeding the concentration level likely to limit temperature change to this level for some period of time (a situation the IPCC describes as “overshooting”). Countries may come to tolerate an increase in temperature above this target level, but if efforts to limit emissions continue to falter, or the temperature change associated with these concentration levels turns out to be higher than expected, their attention may turn to using solar geoengineering to prevent the temperature from continuing to rise. The same IPCC report says that to meet the 2°C goal in the long term, with or without overshooting, CO₂ may need to be removed from the atmosphere. The report emphasises the option of ‘bioenergy with carbon capture and storage’, but

the scale of this approach is limited.¹ As concentrations continue to increase, it may become necessary for countries also to contemplate deploying industrial techniques for removing CO₂ directly from the atmosphere.

In this chapter we focus on carbon and solar geoengineering and how they compare and interact with the mainstream option of reducing emissions so as to limit climate change. Since efforts to reduce emissions may continue to fall short, we also compare the two geoengineering approaches with the option of *unconstrained* climate change.

Comparison of the options

Emission reductions are the most conservative intervention to limit climate change. They simply involve not putting something into the atmosphere that isn't currently there.

To reduce emissions, countries must either prevent the CO₂ associated with fossil fuel combustion from entering the atmosphere – a process known as carbon capture and storage (CSS) – or they must reduce their consumption of fossil fuels. CSS is expected to be costly and may encounter local political resistance, due to concerns about the safety of CO₂ storage (Tavoni 2015). Fossil fuel consumption can be reduced at relatively little marginal cost initially, either by increasing the efficiency of energy use (conservation) or by switching to alternative energy sources like solar, wind, and nuclear power. However, to limit global mean temperature change, atmospheric concentrations must eventually be stabilised, meaning that fossil fuel consumption will have to cease entirely. Achievement of this goal will require a radical change in the global energy system. It will also be beset by free-riding problems, since it is very difficult to enforce an agreement to limit emissions. Finally, as the effort would affect production costs and

1 To be precise, the IPCC says, “[m]itigation scenarios reaching about 450 ppm CO₂eq in 2100 typically involve temporary overshoot of atmospheric concentrations, as do many scenarios reaching about 500 ppm to about 550 ppm CO₂eq in 2100. Depending on the level of overshoot, overshoot scenarios typically rely on the availability and widespread deployment of BECCS and afforestation in the second half of the century” (IPCC 2014: 12). A concentration level of 450 ppm CO₂eq will only have a ‘likely’ chance of limiting temperature change to 2°C, whereas a concentration level of 500 ppm CO₂eq with a temporary overshoot of 530 ppm CO₂eq before 2100 is ‘about as likely as not’ to keep temperature change below 2°C (IPCC 2014: 10).

fossil fuel prices in global markets, efforts to stabilise concentrations will be vulnerable to ‘trade leakage’ (Fischer 2015).

Carbon geoengineering methods aim to capture and remove CO₂ from ambient air. This approach reduces the concentration of CO₂ in the atmosphere *directly*. Like emissions reductions, carbon geoengineering affects the temperature very slowly; it is not a ‘quick fix’. Compared to reducing emissions, carbon geoengineering will likely be very expensive. However, in contrast to emission reductions, carbon geoengineering technologies can be scaled up to limit atmospheric concentrations to virtually any level, making this approach the only true backstop technology for addressing climate change. Also unlike emission reductions, carbon geoengineering allows a single country or small ‘coalition of the willing’ to stabilise atmospheric concentrations unilaterally. Using this technology, achievement of a stabilisation target does not require large-scale international cooperation, and is less vulnerable to free riding than efforts to reduce emissions.² As it operates outside the international trade system, it is also protected from trade leakage.

Solar geoengineering methods aim to reflect a small fraction of incoming solar radiation back out into space, counteracting the effect on temperature of rising concentrations of greenhouse gases. Solar geoengineering can lower the global mean temperature quickly and at relatively little cost, but its effects on radiative forcing are different from those of the approaches that limit greenhouse gas concentrations. Solar geoengineering would also do nothing to limit ocean acidification. Solar geoengineering *is* a ‘quick fix’ for global mean temperature change, but is not a true fix for ‘climate change’ (Barrett et al. 2014). It might also have potentially damaging side effects. Like carbon geoengineering, solar geoengineering can be done unilaterally or by a coalition of the willing, and is not hampered by trade effects. Unlike carbon geoengineering, however, solar geoengineering is expected to be cheap to deploy.

2 The marginal cost of air capture will be approximately constant. So long as the global social cost of carbon exceeds the marginal cost of air capture, it will pay a subset of countries to fund air capture as a joint venture. This funding arrangement will be self-enforcing since, once enough countries drop out of the joint venture, the remaining countries will no longer have a collective incentive to fund air capture on their own, creating an incentive for countries not to drop out. In other words, countries need only *coordinate* financing of air capture.

Together, both of these geoengineering technologies provide a powerful frame for how we should think about climate policy and governance. Reducing emissions requires changing behaviour worldwide – a goal that, despite receiving unprecedented diplomatic attention, has so far seemed beyond our grasp. Unconstrained climate change is usually assumed to be the ‘default’ option, but as Table 1 shows, there are other options. The main thing that distinguishes solar and carbon geoengineering from emission reductions is that both approaches can be implemented as projects. In both cases, a decision has to be made to deploy them, and to pay for them, but no effort is needed to change behaviour or the global energy system.

The options shown in Table 1 are not mutually exclusive. The more we succeed in reducing emissions, the less carbon geoengineering will be required. The more we succeed in doing both of these things, the less tempting it will be to use solar geoengineering. At a fundamental level, all of these options are substitutes. They are, however, imperfect substitutes, as they operate on different stages of the carbon/ climate cycle. From the perspective of reducing climate change risk, there is a case for deploying all of these technologies as part of a portfolio of options (Keith 2013, Moreno-Cruz and Keith 2013). For example, solar geoengineering could be used to limit temperature increases while some combination of emission reductions and carbon engineering is used to limit concentrations to a ‘safe’ level. Under this arrangement, solar geoengineering would be used to limit the risk from climate change, and the other interventions used to limit the risk from solar geoengineering.

Table 1 Comparison of the options for limiting climate change

Options	Objective	Costs	Risks	Unknowns	Collective action
Unconstrained climate change	Not an intended outcome, but a consequence of failure to limit emissions	Low	High	Many	Not achieved
Substantial emission reductions	Reduce the flow of CO ₂ into the atmosphere.	High	Low	None	Difficult
Carbon geoengineering	Reduce the concentration of CO ₂ in the atmosphere	Very high	Moderate	Few	Coalition of the willing
Solar geoengineering	Limit solar radiation reaching the lower atmosphere	Low	High	Many	Easy, apart from governance

The simple economics of carbon and solar geoengineering

Various methods have been proposed for removing CO₂ from the atmosphere. The one emphasised in the latest IPCC “Summary for Policymakers” report is land-based biomass capture and storage. This works like ordinary CSS at the power plant level, with the difference being that biomass is a renewable resource, and biomass growth takes CO₂ out of the atmosphere. If the CO₂ associated with burning the biomass is not captured, the CO₂ is essentially recycled from the trees into the air and back again. However, if the CO₂ emitted by burning the biomass is captured and stored, CO₂ will be removed from the atmosphere. This approach may prove useful, but it will inevitably be limited in scale. Other technologies have been considered, including ocean fertilization and increases in ocean alkalinity. However, these approaches are speculative, pose risks to the environment, or can only operate on a limited scale.

The most important carbon geoengineering technology is industrial air capture – a process by which a chemical sorbent such as an alkaline liquid is exposed to the air, removing CO₂. The process involves not only trapping the CO₂, but recycling the sorbent, and storing the captured CO₂. To be effective, the energy required to operate such ‘machines’ would need to be carbon-free, and this is one reason why the approach may prove expensive. Estimates of the cost vary from \$30/tCO₂ (Lackner and Sachs 2005) to over \$600/tCO₂ (Socolow *et al.* 2011).

Given current and future estimates for the social cost of carbon (calculated without regard to either form of geoengineering), if the costs of industrial air capture turn out to be as high as \$600/tCO₂, then the approach is unlikely to be used on any meaningful scale. If the cost turns out to be below \$200/tCO₂, then it might be deployed at scale this century. If air capture turns out to be as cheap as \$30/tCO₂, then this technology would be a ‘game changer’. This is because the global social cost of carbon is almost certainly already above this value. As the social cost of carbon for individual countries is currently well below \$30/tCO₂, no country is likely to deploy air capture machines unilaterally on a large scale any time soon. However, a coalition of countries would have an incentive to deploy this technology on a large scale. Of course, it would also be desirable for emissions to be reduced at a marginal cost below the marginal cost of air capture, but even if these emission reductions were not forthcoming, it would still pay to deploy air capture. Moreover, as the scale at which air capture can be deployed is independent of the emissions of the countries doing it, air capture by a ‘coalition of the willing’ could suffice to stabilise concentrations. Unfortunately, we don’t know the true value of the marginal cost of air capture; almost no research has gone into development of this technology. In our view, it is imperative that this situation be corrected. It is very important for the world to know the marginal cost of the only backstop technology for limiting climate change, as this value establishes a ceiling on the price of carbon.

Some solar geoengineering options, like the placement of reflective disks in space, are so technically challenging and expensive that they are almost certain never to be deployed. Other options, especially the injection of sulfate aerosols into the stratosphere, are so cheap that cost is likely to play almost no role in the decision to deploy them. A recent paper estimates that it would cost less than \$8 billion per year ‘to alter radiative forcing by an amount roughly equivalent to the growth of anticipated greenhouse forcing over the next half century’ (McClellan *et al.* 2012). This cost is so low that the economics of solar geoengineering appear truly ‘incredible’ (Barrett 2008). Indeed, it could easily pay a large number of countries to deploy solar geoengineering unilaterally.

The ‘cost’ that is likely to matter more concerns the risk of using this technology. Some risks, such as the possibility of added ozone depletion, are known (Crutzen 2006). Others are unknown. Research into this technology is sure to reveal more information about its effectiveness and the processes governing its functioning (Keith *et al.* 2010,

Keith 2013). However, we won't know the full effect of deploying this technology at scale until we do it.

Geoengineering governance

Because the economics of solar geoengineering are so attractive, there has been concern that countries will be only too inclined to use this technology. In simple game theory terms, if anyone can use it, everyone can use it, and the country most likely to use it will be the one who desires the biggest change in the global mean temperature (Moreno-Cruz 2015, Weitzman 2015). That is, solar geoengineering introduces the possibility of 'free driving', a situation virtually opposite that of reducing emissions, which entails free riding. With free driving, policies are needed to rein in those who want to pursue climate engineering without consideration of the interests of the broader global community.

However, this assumes that countries have a *right* to use solar geoengineering as they please, and international law generally requires countries to take due regard of the effects of their actions on other countries. Moreover, other countries may be able to react to an attempt to deploy geoengineering unilaterally. They could deploy 'counter-solar-geoengineering', throwing particles into the stratosphere intended to warm rather than cool Earth, or releasing short-lived and powerful greenhouse gases like difluoromethane that would have a similar effect. More likely, they could use other measures such as trade sanctions or, possibly, the threat of military action. It is probably more realistic to assume that countries will need to negotiate the use of geoengineering. As matters now stand, however, there are no rules for whether, how, and when geoengineering can be deployed – or for which countries get to decide. The risk of not negotiating these issues, let alone settling them, is that countries may feel that they are free to act more or less without restraint.³

Carbon geoengineering can also be done unilaterally, but because of its likely high cost, this approach is unlikely to be attempted at scale by anything less than a substantial

³ Analyses of the governance of solar geoengineering are still fairly primitive; examples include Schelling (1996), Barrett (2008, 2014), Victor (2008), Ricke et al. (2013), Lloyd and Oppenheimer (2014) and Weitzman (2015).

coalition of countries. Moreover, this approach addresses the root cause of climate change, and so poses fewer risks than solar geoengineering. For both reasons, the governance of carbon geoengineering has not been a major concern. If this technology were deployed on a large scale, a decision would need to be made as to the desired level of atmospheric concentrations, but this is little different from the decision countries have already made to reduce their emissions so as to limit global mean temperature change. Countries would also need to agree how to share the substantial costs of carbon geoengineering. However, this is a relatively simple matter – countries frequently agree on cost-sharing arrangements for costly enterprises. For example, every three years, over 190 countries agree on how to fund the United Nations (Barrett 2007).

Conclusions

Just as the failure to limit emissions has brought adaptation onto the agenda of climate negotiations, so we believe the time has come for negotiators to consider the roles that solar and carbon geoengineering can play in addressing climate change.

If the 2°C goal were truly sacrosanct, then it seems unreasonable to ignore approaches that are capable of limiting temperature change directly or of limiting concentrations directly, especially as the IPCC's analysis suggests that even with a turnaround in the success of emission reduction efforts, overshooting of the 2°C goal is very likely. Should efforts to reduce emissions continue to fall short, the case for considering these alternative approaches will only increase over time.

The decision to use, or not to use, carbon and solar geoengineering will have consequences, and our view is that these consequences should be evaluated and the results of such analyses used to justify these decisions.

First, there should be collective funding of R&D into the costs and risks of carbon geoengineering. If the true cost of this approach is as high as \$600/tCO₂, then the approach can be disregarded this century. If the true cost turns out to be closer to \$30/tCO₂, however, then this technology will be a game changer.

Second, there should also be collective funding of R&D into the feasibility, effectiveness, and risks of solar geoengineering. At least as important, countries should

begin to discuss governance of such research and of the possible future deployment of this technology (the distinction between research and deployment may not always be obvious). The risk of not doing this is that countries will feel that they are free to act more or less without restraint. A key focus should be on obtaining a consensus about these things, as excessively restrictive rules are likely to cause the countries that are most enthusiastic about geoengineering not to accept the rules but to strike out on their own.

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