The VITAL SPARK

Innovating Clean and Affordable Energy for All

The Third Hartwell Paper

July 2013

THE LONDON SCHOOL
OF ECONOMICS AND
POLITICAL SCIENCE

The Mackinder programme

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The views expressed in this paper are those of the co-authors writing in their personal capacities alone and should not be attributed to any organisation by which any of the co-authors is employed.

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PREFACE: THE STORY SO FAR…

AT A TIME OF HIGH DRAMA in the science and the politics of climate change, the first Hartwell Paper was published in May 2010 and quickly became well known for the novelty of its approach to climate policy.[1] Distancing itself from the narratives and policy approaches that had so spectacularly collapsed at the 15th Conference of the Parties (COP15) to the United Nations Framework Convention on Climate Change (UNFCCC) in Copenhagen in December 2009, that group of Hartwell authors built upon 25 years of research and publication to advocate a different approach. This route was intended to avoid the pitfalls into which recent policies had led; and to promote in their place the radical pragmatism that has been a hallmark of the Hartwellian approach.[2]

The authors eagerly asserted that proactive action was required to reduce rapidly the weight of humanity's footprint on our planet; but the paper also emphasised that wide and sustained public support was needed for any action to be effective over the long term. The argument began from the premise, later confirmed by the International Energy Agency (IEA) in April 2013, that the "top-down" policy of targets and timetables, embodied in UNFCCC-style climate change policy, had not made significant material change in the carbon intensity (CO_2 per unit of GDP) of human civilization.[3] The authors also took the view that rather than being merely expedient, public policy to support and defend human dignity should be integral to the enterprise. The second Hartwell paper, *Climate Pragmatism,* carried these same themes to an American readership in 2011.

Building on these principles, four main arguments were popularised. The first concerned the mismatch between the character of the problem that is posed by climate change and the remedies advocated within the traditional UNFCCC-style "top-down" policy approach.

Climate change is an issue of such complex uncertainty, driven by so many ill-understood feedbacks, that it is – in the terms made famous by Rittel & Webber – a "wicked problem".[4] The special meaning of "wicked problems" as they defined it is characteristic of systems that are open, complex, and imperfectly understood. Although "wicked problems" are often formulated as though they are soluble, it is more accurate to regard them as persistent systemic conditions that can only be managed more or less successfully. As a result, the solutions that we adopt for "wicked" problems will be imperfect; they may be clumsy. It follows that the politics through which we approach "wicked" problems must be humble, avoiding that brittle, aggressive certainty that is so often a mark of modern democratic politics.

In its treatment of the "wicked" problem of climate change, the 2010 Hartwell Paper acknowledged the fact of the "climate wars" then raging (and that are still, to a lesser degree, continuing). However, the authors declined to engage in them. This 2013 paper maintains that position, because the core themes and priorities of the approach it proposes do not depend upon taking a position in this battle. To be clear, all the major temperature ensembles agree that the century trend since the late 19th century shows that the atmosphere has warmed by approximately 0.8 degrees Centigrade. The precise balance of the forces responsible is still unclear, but it would be surprising if anthropogenic emissions of greenhouse gases, (the action of which has been plain since Arrhenius published his seminal work in 1896), have not contributed to a material degree, even if we now see that the effect cannot be specified as definitively as some would argue.[5] Indeed, the welcome intensification of primary research since the 1980s in all branches of observation of the climate, in paleoclimatology and in data-processing and interpretation, has served to erode our confidence in the certainties of the 1980s-2000s, just as it has deepened our understanding. In spite of this uncertainty, it is still prudent to conclude that emissions of greenhouse gases should be rapidly reduced; but the aim of avoiding probable further anthropogenic temperature forcing becomes one reason among many. This modest and pluralistic approach has important consequences for the design of policy.

Unfortunately, combatants on both sides of the “climate wars” have tended to use arguments that focus upon short-term climate trends, observed over periods of time such as decades. These are too short to be informative, whatever their rhetorical power. As a result, the watching public has become confused. On the one hand, the above average warming trend of the 1980s and 1990s sustained a catastrophist attitude amongst "climate action" advocates; on the other, the temperature plateau of the past fifteen years has deepened the suspicions of those who allege that the entire case for human involvement in global warming is a specious fabrication. Neither position is robust, and neither can provide a helpful conceptual framing if we wish, as the Hartwell authors do, to advance a pragmatic approach to what all informed parties grant is a problem simultaneously marked by grave hazards and great scientific *lacunae*.

In this perplexing situation we must, at the outset, acknowledge the specific difficulties posed by imperfectly understood open climate systems. Foremost among these is the fact that we can never know enough to conclude that research and data gathering should cease and policy-making begin. The two activities must proceed together, with policy remaining as responsive as possible to the changing state of understanding. Furthermore, we should acknowledge that "wicked" problems such as climate change present extreme difficulties for those whose hands rest upon the levers of governmental power. The desire to do something with their power is present in most politicians, and the pressure to act is sometimes overwhelming during periods when existential anxieties dominate the public mood; but prematurely irreversible actions, immune to course correction and improvement and without the ability to identify and to open gateways to the possibility of radical invention, could be severely counter-productive.

Common sense can be quite misleading. One example, highlighted in the 2010 Hartwell Paper, was of the perverse effects of the Jevons Paradox (known academically as the "rebound effect"), which states that the energy savings that accrue from improvements in the efficiency of a process or a device do not translate symmetrically into reductions in the usage of energy.[6] On the contrary, that process may become even more attractive and widely used. Alternatively, the purchasing power released by savings in energy expenditure is likely to be used to consume goods and services that themselves require energy, and thus to erode the energy savings from efficiency measures. As Jevons argued in his famous 1866 study of the consequences of James Watts' dramatic improvements in the efficiency of steam engines, such rebound effects might even result in a net increase in energy consumption.[7] As the 2010 Paper documented, only in certain circumstances, for example in Japanese heavy industry, is there concrete historical evidence of improved energy efficiency translating directly into reduced greenhouse gas emissions.

To be sure, measures to improve energy efficiency are worth pursuing, and should indeed be encouraged: they make good economic sense globally, and in the developing world they contribute to sustainable development by freeing up energy and wealth for other uses. Yet many climate policy makers have been quick to bank hypothetical reductions in energy use and emissions through efficiency gains without reflecting on their likelihood in a particular situation or economy. Doubts on this point are increasingly being voiced, though they are not yet universal.[8]

A different sort of unwelcome surprise was seen in the real world results of attempts to shift consumer behaviour by macroeconomic interventions. The self-declared flagship policy of this sort was the European Union's attempt to create a market in carbon by legislative fiat. After a stormy voyage since its launch in 2005, the EU Emissions Trading Scheme (EU ETS) was finally holed below the water line in April 2013, having failed for several years to sustain a carbon price sufficiently stable to stimulate the desired level of private investment in low-carbon innovation, while continuing to threaten such high costs to industries that there was successful lobbying to undermine the scheme.[9] Perhaps most importantly, the ETS was not permitted to operate freely, to encourage the economy to find least cost emissions reductions. Instead many other market interventions mandated the adoption of renewable technologies, each with their own implicit and usually higher cost of carbon reduction.

In light of the complexity of the climate change issue, and evidence that attempts to produce conclusive "solutions" to such problems can cause unexpected and unwelcome consequences, the Hartwell authors promoted a second theme. This suggested that a modern climate pragmatism could take its cue from "Capability" Brown's principle of 18th-century landscape garden design: "lose the object and approach obliquely." The paper developed this insight to suggest that direct confrontation with the "wicked" problem of climate change was mistaken, and that an indirect approach was essential for success. The Hartwell method consequently embraced a range of topics aside from that of carbon-dioxide mitigation, all of which could lead obliquely and swiftly to beneficial outcomes.[10]

A third theme ran through the 2010 paper: Pielke's Iron Law of Climate Politics.[11] Named for one of the co-authors, who first spelled it out, the law holds that political economy constraints always put a limit on the "felt cost" and on the "willingness to pay" by current citizens and that policies that violate those constraints will not attain the legitimate authority to succeed, especially over the long time scales necessary to manage the wicked problem of climate change.

No climate policy which increases the felt cost of living for voters in democracies will attain legitimate authority and succeed. The proposition had fundamental implications for that suite of Kyoto Protocol era efforts to hasten adoption of low-carbon energy either through subsidies or by substantially increasing the cost of fossil fuels, both of which result in higher prices to consumers. As predicted by the Iron Law, these have not only proven to be unpopular, but have helped to fuel a counter-narrative to that of the “catastrophic imperative” in climate policy.

The first Hartwell Paper offered a legitimation for action on climate that appealed neither to existential fear nor to a critique of markets. Its fourth argument, conforming to the Iron Law, was opposed to growth restricting policies that would offer little hope to the more than 1 billion people currently without access to electricity. That was considered to be both immoral and impractical, since it was bad politics. The approach spelled out in The Hartwell Paper, and elaborated in THE VITAL SPARK, places social justice and the enhancement of human dignity at its core. In pursuit of that goal, we seek to marshal a coalition for achievable actions to reduce poverty, especially in the demographic superpowers of India, China, Brazil, Indonesia, and Sub-Saharan Africa, with the contingent but equally valuable benefit of lightening the human footprint on the planet.

This agenda of radical pragmatism, as expressed in the 2010 paper, was taken up with some enthusiasm by several state parties outside the European Union, as well as by some major industrial enterprises. Since that time there have been moves in the framing of international diplomacy that are resonant with The Hartwell Paper’s insights. Notable is the growing emphasis on “bottom-up”, national imperatives rather than international “top-down” points of departure.[12] This welcome trend is explored further in section 4.

The logic of the 2010 Hartwell paper pointed towards the need for both radical invention and incremental innovation in the generation of energy by lower-, low- and non-carbon means. There are encouraging signs that there is a growing understanding of this need. Only when power from non-carbon fuel sources is more affordable to the consumer than that from fossil fuels, without subsidy to either, will they prevail spontaneously in the world's markets and produce lasting change in the global energy mix. At present the combined role of nuclear (4.9 per cent), hydro (6.5 per cent), and other renewables (1.6 per cent) is not large, and that of non-hydro renewables – the focus of our attention in this paper – is especially small.[13]

The Vital Spark builds upon the track record of the earlier Hartwell papers. What now follows is an attempt to provide a comprehensive prospectus for constructive suggestions on how policy consistent with these principles can foster invention and accelerate subsequent innovation in the energy sector.

SUMMARY

- The Vital Spark is an attempt to learn salutary and positive lessons from the unusual decade 2003-13. **One major conclusion defines the topic of this third Hartwell paper: top-down policies directed at climate mitigation have thus far failed to achieve their objectives, and it seems likely that they never will.** Only a spontaneous and fundamentally affordable and politically sustainable energy transition can succeed. This requires both *invention* (discovery) and *innovation* (application of discoveries), with the recognition that policy agendas based on the deployment of existing technologies may be constraining, particularly with regard to invention.
- The co-authors therefore propose a range of pragmatic Building Block concepts, eleven in all, that should underpin attempts to provide all of humanity with access to energy that is both affordable and has decreasing carbon intensity and polluting consequences.
- Only a high-energy planet is morally defensible or politically viable (i). As Hartwellians argued in 2010 and still maintain, it is not acceptable to pursue policies that will leave the bottom billion of humanity without the energy services they require for wellbeing and dignity.

- However, at present, only carbon-intensive sources of energy offer a realistic prospect of such a high-energy world, with (ii) obvious hazards to the climate.
- It notes that (iii) the discovery and exploitation of new fossil fuels appear to outpace the discovery and exploitation of low-carbon energy sources now and for the near future; and that (iv) current low-carbon energy technologies are technically and economically uncompetitive.
- Therefore (v) pragmatic and (vi) open-minded and pluralistic innovation policies are essential, with the recognition that (vii) policy failures must be embraced as the necessary price of progess.
- Employing the definitions set down at the outset, the case is made that (viii) both radical *invention* and *innovation* are required, and that (ix) the deployment of nascent and maturing or entirely novel technologies alike should be undertaken as a means leading to the growth of knowledge and further invention: not an end in itself.
- Amplifying the theme of necessary pluralism, there (x) must be recognition that energy innovation must proceed by more than one pathway at once.
- The final Building Block links back to the first: it argues that (xi) broad, bottom-up social legitimation of policies is morally and practically indispensable.

- The paper then reviews the lessons of the decade 2003-13 by examining recent experiences with energy innovation in energy transitions. It explains that, historically, policy “driven” energy transitions are rare; but that the outcomes of different policy instruments and processes, especially in Europe and the USA from 2003-13, are valuable as a source of information and positive lessons.
- With an eye on pragmatic and achieveable improvements, the paper then describes Hartwellian options for National Level Actions (NLAs). It advocates ways to stimulate energy innovation through more intelligent investment. It suggests how to overcome the limitations of institutions and make incentives work as they should. Then, inspired by the growing importance of Nationally Appropriate Mitigation Actions (NAMAs), it advocates analogous and complementary “Nationally Appropriate Innovation Actions” (NAIAs).
- NAMAs and NAIAs can stimulate new processes in diplomacy. Therefore the paper next spells out Hartwellian options for International Level Actions (ILAs). It explains how
  - to understand and implement the positive lessons from the failure of the Kyoto regime;
  - to recognise and accommodate the interests of different parties in a transfer of new technology;

  - to embrace the results of an already naturally occurring global division of labour in energy innovation.

- Politicians frequently call for “ambitious” solutions – meaning extreme or difficult solutions – in the fields of climate policy and of energy innovation. The paper explains that this is misleading interpretation of the term ambition, the Latin root of which, *ambire*, reminds us that the exploration of possibilities and securing of public support are crucial. Only this grounded interpretation of ambition will result in real, concrete results. More lurid pretences of “ambition” that lack any concept to deliver on their bold pronouncements do little good to anyone, save perhaps the ephemeral interests of the politicians who mouth them.
- The paper ends with the co-authors’ view of what an Hartwellian ambition for the future really is, which has been the underlying purpose of the entire work: **Only general prosperity can produce widespread consent for emissions reductions, and only affordable energy can deliver prosperity for all**.

INTRODUCTION: DEFINITIONS, MOTIVATIONS AND ACKNOWLEDGMENTS

This paper seeks to exploit the insights of the first Hartwell Paper of 2010 by applying its principles to the field of invention and innovation in the energy sector, which the authors judge to be an area as neglected as it is essential for human welfare and for the welfare of the planet.

Invention and innovation are not the same; but they work hand in hand. Although used interchangeably in colloquial speech, and inevitably related, there are distinctions between these two concepts that, at the outset, we must specify and defend lest imprecision lead to confusion. Etymology, as ever, provides a guide.

Invention, from its Latin root *invenire*, means to come upon, to find. The term suggests fundamental thought that makes new discoveries. It is dominant in the realm of the pure sciences, where there is more scope for dramatic discovery which can change everything in a flash – or in a “Big Bang”.

Innovation (*innovare*), on the other hand, is concerned with the reform or the alteration of something already existing, or the introduction of something new to an existing situation. Importantly, innovation enjoys an asymmetrical relationship with its close relative. Some inventions will never lead to innovation. Invention initiates.

Further invention may take place during innovation, and sometimes incremental tinkering can find the gateway to more fundamental invention; but it is more likely to be constrained by the scope of the innovatory project. Thus constrained, it is more directed towards writing variations than composing new themes. This places important limits on "learning by doing": limits that are too often neglected in current policy.

Most crucially for our present purposes, under certain conditions innovation may bring no new invention at all, but simply deploy existing inventions without any further intellectual progress. In Joseph Schumpeter's memorable phrase, while you may "add successively as many mail-coaches as you please, you will never get a railway thereby".[14] We believe that this has been the outcome of many current low-carbon energy policies, which are, in effect, only deployment for deployment's sake, regardless of whether this is innovatory in itself, or encourages innovation and further invention. This would not matter if the current state of intellectual knowledge in energy engineering were adequate to provide spontaneously competitive low-carbon energy. Sadly, it is not.

Consequently, this paper argues that policies should be reoriented, not only to ensure that there is adequate support for invention, but also that where innovation is supported – as it should be – it does not degenerate into a process of sterile deployment, but is productive of further invention. Therefore, in sum, creative innovation is mainly *innovare*, but with elements of *invenire*, in ways that we shall explore. And as a product of human choice in an arena wider than that of technology alone, energy innovation is inevitably an intensely social activity. As we shall see, when this is forgotten, things quickly fall apart.

This Hartwell paper does not describe "how to do energy innovation successfully", because no-one can give such a prescription to fit all circumstances. If they do, distrust them. There is no magic formula. Having already, in the Preface, reminded readers of the initial Hartwellian insights, and how the 2010 Hartwell paper came to conclude that innovation was our next area of work, what we do here is to describe the necessary *conditions for success* in energy innovation.

First, we lay out eleven Building Blocks that we believe should frame any successful policy for energy innovation. Then we review recent experience. We look for concrete success. We find that there is some, but not nearly enough. So we employ the Seventh Building Block, and we report positive lessons from recent failures.

Thus armed, we then return to the *fora* of politics and describe the requirements for first national and then international policy that arise from the largely cautionary lessons that we have learned.

We have been able to do this work with renewed, enlarged and indispensable funding from the Nathan

Cummings Foundation, to which all the authors gratefully acknowledge their debt. With this increased funding, a series of studies was commissioned. The enlarged Hartwell group convened for this phase of work then gathered in Vancouver, British Columbia in February 2013 to review the results and to design this paper.

It is being published in English in printed form and simultaneously in electronic form. Translations into numerous foreign languages are to follow; these will be freely available.

As Convenor and Co-ordinator of the group and as the principal writers integrating their contributions, we would like to thank all the co-authors for their diligence, and those other members of the Hartwell group who were not co-authors of this particular paper for their comments.

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1

THE ELEVEN BUILDING BLOCK CONCEPTS THAT GUIDE THE HARTWELLIAN APPROACH TO ENERGY INNOVATION

This paper is about how circles may be squared. It is about how to achieve the simultaneous and apparently conflicting objectives of a high energy, low-carbon world. We seek the means of providing large quantities of energy at low cost, and with low environmental impact.

Any programme of work, or conceptual framing, rests upon a series of Building Block concepts. These may be convictions of principle or they may be conclusions reached after research. Often, such assumptions are not made explicit. They may even be deliberately hidden in order to evade criticism. This lack of exposure is dangerous in that it not only conceals intellectual weaknesses, but also forecloses legitimate debate over core values and principles. On the principle that sunlight is the best antiseptic, this paper attempts to make explicit the assumptions on which the authors agree and which therefore form a common foundation for their approach.

(i) Only a high-energy planet is morally or politically acceptable

The need for energy with low environmental impact is, of course, widely acknowledged. But it is not being delivered. As we highlighted in the 2010 Hartwell Paper, and as has been confirmed in international climate negotiations in the intervening years, a global climate strategy that does not alleviate inequality and sustain aspirations for development will – rightly in our view – not be acceptable to the governments or populations of large developing countries. We therefore view the lack of universal access to a quantity and quality of energy sufficient for human dignity and empowerment as a policy failure, an unacceptable moral outcome and an impediment to political progress.

Most of the people alive today who are left without electricity live in South Asia and Sub-Saharan Africa, and are among the poorest in the world. The role of stable, safe, and affordable energy in bringing economic growth and development to such populations is well known and well documented; and there is no doubt that access to electricity is a prerequisite for economic and political empowerment. For this reason, and understandably, energy access has been and remains a leading political objective in the demographic superpowers of Latin America, Africa and Asia, trumping the climate change agenda. But must this be so?

The Hartwellian approach believes that it is no paradox to suggest that we can attain the objective of energy with low environmental impact only if we also create a high energy global economy with reliable energy that all can afford to buy. The case for universal energy access is not just a moral one; it is also a matter of political legitimation and pragmatism.

How can we achieve this? Hitherto, the issue has been framed – in the combative context of international climate diplomacy – as a contest between sharply different objectives: the interests of human development and those of the natural environment. Prominent Non Governmental Organisations have entered the lists on behalf of their declared special interests, to joust as champions for their conflicting causes. We must find a way to balance the values and interests of all, or be condemned to failure. We have reviewed the sadly unproductive present state of affairs and think that to do better, we need to return to first principles.

(ii) It will be hazardous to build a high-energy planet with current carbon-intensive sources

There are a number of reasons why building a high-energy planet with current carbon-intensive energy sources would be hazardous. They range from conventional national security concerns to health and emissions impacts. The latest BP Statistical Review calculates that 87 per cent of global primary energy supply comes from coal, oil, or natural gas: 30 per cent, 33 per cent, and 24 per cent respectively.[15] Using such an energy mix to provide universal access to sufficient energy for all – and to meet the greatly increased future energy demand assumed across virtually all well-researched predictions of energy demand

– would likely produce atmospheric concentrations of carbon dioxide at least double and possibly triple that of the 280 ppm of the pre-industrial era. If we add to this the increases in energy access that we believe to be necessary (and which are not currently included in the scenarios published by international energy agencies and large energy companies), the problem becomes still more acute. Smog and lung illnesses in China and India remind us that a coal-fuelled high-energy world carries severe risk to human health as well as to the health of the ecosphere.

We have no infallible way to assess precisely the climatic impact of such an increase in emissions. The outputs of computer models are subject to the obvious cautions that results are dependent upon the input assumptions, and that those results are *projections*: not predictions. Still, we can take as at least indicative the computer modelling endorsed by the Intergovernmental Panel on Climate Change (IPCC) that a doubling or more from pre-industrial levels of carbon dioxide (280 ppm) of atmospheric carbon dioxide might produce a global average temperature increase on the order of 2 degrees Celsius, and possibly a temperature increase of 4 degrees or beyond.[16] It is an hypothesis not to be taken lightly.

Therefore, rising energy demands and the needs of the energy poor must somehow be satisfied from an energy mix that is progressively lower in carbon intensity (CO_2 per unit of GDP), with the aim of becoming zero carbon or even carbon negative. But this is not straightforward. The premium global energy fuel – oil – has the manifest attractions of high energy density, precision of content, portability, temperature range tolerance, relative ease of storage, and versatility of fractions from naphtha to jet fuel. For these reasons, it has become the indispensable reference fuel of our age. It will require a remarkable breakthrough – or many – to replicate these qualities in a lower and ultimately low and zero carbon energy mix capable of being scaled to meet global demand, and to do so at prices that the least wealthy consumers, who are also those currently without access to modern energy services, can afford to pay.

Is this an unattainable goal? After study in a wide range of contributing disciplines, the co-authors of this paper have come to the view that while it will certainly be a remarkable achievement, it is not, *a priori*, an impossibility. But, as explained below, the problem is not so much the (considerable) technological difficulties, but rather the need for a different sort of energy innovation: one which will address the problem in a way that enables us to satisfy the triple requirements listed above; namely for energy that is plentiful, affordable, and of low environmental impact.

(iii) The discovery and exploitation of new fossil energy sources outpace the discovery and exploitation of low-carbon energy sources now and for the near future.

A reality check is always useful. The challenge to shift the global energy system to be lower-, low-, and ultimately zero- or negative-carbon has always been daunting. In 2011, fossil fuels, nuclear power, and hydroelectricity provided 98.4 per cent of global primary energy as opposed to "new renewables" upon which so much has been bet; and fossil fuels enjoy tremendous benefits by virtue of their incumbency. Most global infrastructure is built to support a fossil-derived energy supply, and the fossil fuel economy shapes and enriches some of the world's most powerful companies and financial institutions. In some cases it pre-occupies the fortunes of national governments, too, which is a mixed blessing. All these companies, banks, and oil-producing states – and their shareholders and citizens respectively – have strong incentives to maintain a fossil-intensive global energy mix, or indeed to expand the use of fossil fuels globally. As we have seen, these baser motives do not operate in a vacuum. Consumers and investors have strong and valid reasons to be attracted to the benefits of fossil fuels.

Renewable energy policies, even when fuelled by political drive, have so far failed to carve out a substantial market share for renewable technologies. Simultaneously, over the past decade, the successful deployment of new and improved extraction techniques for fossil fuels has changed the global energy landscape. Advances in horizontal drilling and hydraulic fracturing techniques allow petroleum producers to recover both oil and gas from previously inaccessible shale rock formations. The increase in proven oil and gas reserves in unconventional formations ("tight" rock or oil sands, for example) seem likely to compensate for the depletion of mature oil and gas fields in near-term decades. CCU (Carbon Capture and Use) will also help to purge previously exhausted oil fields, further boosting production. BP's estimates of proven oil and natural gas reserves in 2011 are 30 per cent and 24 per cent above 2001 levels, respectively. The global R/P (reserves to production) ratio for oil (ie, years remaining at that year's extraction rate) was 31 in 1981, 42 in 1991 and is 54 in 2011.[17] Or in different numbers, global oil reserves were 1,032.7 thousand million barrels in 1991 and 1,652.6 in 2011. The increase in proven gas reserves has been even more startling, from 131.2 trillion cubic metres in 1991 to 208.4 trillion cubic metres in 2011.[18] Oil boosters point to such figures and ask where the problem is. Hasn't it gone away? No.

These updated reserve figures undermine the basic assumption of the well established "scarcity peak" school which, in popular presentation at least, holds that declining fossil fuel availability will soon force the adoption of renewable energy technologies, making clean energy both necessary and economic. The political utility of the "scarcity peak" fossil-fuel argument – which, although often voiced in catastrophist language, can be seen to be no more than wishful thinking for now – is voided by a mismatch of scales. The undisputed fact is that world fossil fuel resources are, like the life of the planet, eventually finite. As John Maynard Keynes observed on a shorter time scale, "in the long run we are all dead". Although the assumption is true in the long term, that does not translate into an assumption that reserves will fall any time soon, as the BP figures show; nor that prices will rise for reasons of simple scarcity. But we must note it because perceptions are powerful in the politics of climate change.

However, there is a different and more empirical "rate peak" school of thought, which dissociates itself from the "scarcity peak" argument.[19] It correctly notes that "tight" oil and gas cost considerably more, per unit, to extract than "easy" oil and gas in mature fields, such as those in Saudi Arabia and the Gulf States, which means that while R/P ratios may be rising now, the extraction of these new supplies is at great and rising cost. So the argument goes that fossil-based energy production costs will certainly rise, although not for the primary reasons advanced by advocates of "scarcity peak". Once the investment/return ratio closes too much, recovery becomes uneconomic, and, it is suggested, "rate peak" occurs.

But will it? “Scarcity peak” ignores and “rate peak” underestimates the role of human ingenuity that can blossom under the right institutional conditions. The “shale revolution” that horizontal drilling and hydraulic fracturing have brought about is witness to that. Are we sure that there will be no more surprises of this kind? Rather than a diminishing supply of fossil fuels with rising prices, today’s expectation is that relatively low fossil-fuel prices (in real terms of use-value in economic activity) will remain the norm, at least over the medium-term, and especially for natural gas and coal. Global coal use increased by 5.4 per cent in 2011 experiencing the greatest absolute increase in quantity of any fuel. Although it is not wise to extrapolate from a short-term trend, it is the case that the currently falling real cost of coal is in part a consequence of the displacement of coal by gas in the US energy mix.

At the same time, mainly due to the successive shut-down of Japan’s nuclear power fleet after the Fukushima *tsunami,* by 2012 low carbon nuclear use fell by 6.9 per cent – which was the largest annual fall on record. And those who place faith in swift substitution from “renewables” must remember that all together, excluding hydroelectricity, they represented a marginal 1.6 per cent of global energy use.

A transition to “renewable” energy predicated on scarce fossil fuels and rising prices is therefore not at all certain. Any efficient social impetus for energy innovation will plainly have a source other than the “peak” arguments.

The only zero carbon source that can technically be scaled up in short order is nuclear – much faster than renewables on a similar time-frame; and while not the case in China and to a degree India, the trend in the West after the Fukushima incident is the opposite. One must remember that, at Fukushima, the nuclear fail-safe systems were largely effective: it was the inadequate protection of diesel fuel tanks for stand-by cooling generators that compounded the seriousness of the accident: a lay-out planning and low-technology fault. So what we must learn from the Fukushima incident is not only that we must make every effort to improve nuclear safety and the general all-system safety of nuclear plant sites – for there will be ever more nuclear power stations installed around the world – but that an accident can happen even in a country like Japan, with mature nuclear technology.

After the accident, investigative committees identified the causes. Some were context-specific (mis-management in the Tokyo Electric Power Company (TEPCO) and other organisations, for example); but others had wider significance. Nuclear accidents could take place in China or India: we cannot deny that possibility. So the reasons why nuclear power is not likely ever to be the sole solution for a low carbon energy transition are that not only is there the risk of accident inherent in the technology ensemble (Chernobyl, Three Mile Island, Fukushima) but also because an outage like that which Japan has just experienced can have a great impact on the pattern of global energy supply, and the global economy, once accidents like Fukushima take place. In Japan's case the ensuing shut-down not only resulted in power shortages; it also "maxed out" the country's LNG import terminals and hugely increased its coal imports. All these extra costs also decimated Japan's historic balance of trade surpluses.

(iv) Current low-carbon energy technologies are technically and economically uncompetitive

Transforming the world's energy system is one of the principal political and technological challenges of the 21st century. Perhaps it is *the* principal challenge. The low energy density of low-carbon fuels is the source of many of the technological difficulties in this proposed transition, meaning that low-carbon energy technologies must jump various hurdles before they are fit for diffusion at scale. The hurdles are numerous and significant: capital and operation and maintenance costs, integration costs arising from uncontrollable variability (intermittency) of popular wind and solar resources, and public acceptance, particularly of the oft-diffuse geographic impact of these low-density fuels. Each hurdle is high at present. The partial exception is biomass for electricity, a standard dispatchable technology, which is less discussed and more used today than is widely realised (half of all the "green" megawatt hours generated in the UK between 2002 and 2012 were from biomass related technologies). But the cultivation of fuel on the scale required poses environmental problems and land-use opportunity/cost conflicts (in particular with food production) that are equally limiting.

In the electricity sector today, the direct costs of generating electricity from renewable technologies are typically greater than simply burning fossil fuels such as gas or coal by 50-300 per cent.[20] Wind and solar power are still, in spite of some progress, comparatively capital intensive per unit of capacity (MW), and when this is combined with low load factors (around 10 per cent for solar, and around 25 per cent for wind in Europe), the costs per megawatt hour (MWh) generated are necessarily also high. Furthermore, the integration costs of uncontrollable generators are high. Large fleets of conventional generation must, currently, be retained to ensure security of supply when renewables are not available, on a cloudy, windless afternoon for example. Additional grid lines must be constructed to prevent congestion, and special rapid response plants must be constructed to correct errors in the wind and solar forecasts. Some studies conclude that these "integration" costs for even minority fractions of renewables are likely to be high – perhaps very high – and therefore to increase substantially the direct cost of energy derived from these sources.[21]

Nuclear power, which seems to be economically viable in China, where 29 units are presently being constructed, faces safety concerns associated with current light water designs and more general constraining factors, as discussed in the Japanese context, above. Current carbon capture technologies, though very interesting, are nowhere near viable today, and may add as much as 50 per cent to the cost of coal or gas power. Finally, energy efficiency, while often touted as the most cost-effective way to avoid carbon emissions, is unlikely to be a climate change panacea due to increased consumption in the developing world, not least for the reasons cited by Jevons' and noted above.[22] In fact, there is evidence to suggest that rates of energy efficiency are falling around the world due to more energy-intensive lifestyles and industrial production.[23] Even the most aggressive energy efficiency-promoting jurisdictions such as California have managed to reduce electric demand by only about 15 per cent from the baseline: a welcome improvement, but not a transformational one.[24]

As a result of these considerable hurdles, the cost of extracting and converting low density energy flows from organic cycles and delivering them to consumers has not fallen sufficiently to be remotely competitive for electricity generation with either coal or gas at current prices. The position in the transport sector is also – if not even more – bleak. The advantages as transport fuels of oil and, to a degree, LNG and CNG – for example in the Indian urban public transport fleet – (high energy density and hence miles per gallon, safely, portability, refuelling network availability etc) have not yet been challenged by false starts most especially with hydrogen and all-electric alternatives, as the very poor take-up of alternative powered vehicles shows (except as fashion or political statements in some wealthy constituencies).

(v) Relentless pragmatism, favouring simplicity, points to effective solutions

We may therefore see quite clearly that there is no convenient and powerful external argument that will propel the cause of an energy transition from high- to low-, zero- or negative-carbon sources. The transition will have to occur based on its own merits. Therefore, across all stages and scales of the innovation process, we have a bias for pragmatic solutions. The simplest solution is usually the best one. In practice, this means an approach that avoids heroic assumptions, identifies and amplifies what has been shown to work, and builds on and transfers best practices.

The Kyoto process failed to provide the greenhouse gas emissions reductions that it promised because it was unwieldy, complicated, and costly. It was built upon unrealistic assumptions about what nations are willing to or can accomplish, and it invested unfounded confidence in binding international legal agreements. Consequently, complicated mechanisms designed to transfer the costs of mitigation from developing to industrialized nations have not delivered the scale of emissions reductions in developing countries envisaged by the architects of the Kyoto Protocol. The United States refused to participate in the treaty and China, India and other major emitters who accounted for the bulk of emissions growth, were exempt. All recognised, correctly, that it would have significantly impeded economic growth and they were not willing to accept this trade-off. Furthermore, until recently the Kyoto process did not even identify – let alone provide support for – the technological means by which nations can achieve reductions of greenhouse gases.

Where countries have achieved significant emissions reductions, it is because they have followed practical solutions that do not infringe upon economic growth. In some cases they contribute substantially to it. In the United States, natural gas has been rapidly displacing coal-fired electricity, with supplementary contributions from modern renewables and improving efficiency of the U.S. automotive fleet. US energy-related CO_2 emissions are at a 20-year low.[25] Decarbonisation of the US electric power sector was made possible by the availability of low-cost, abundant natural gas and, to a much lesser extent, targeted deployment subsidies for renewable energy. In the late 1970s and 1980s France made a strategic decision to meet growing energy demand by expanding its nuclear power industry, supported by robust government subsidies. Between 1979 and 1989, French CO_2 emissions declined by some 30 per cent and have remained at low levels since. But France is (as always) a special case.

(vi) Open-minded and pluralistic policies only, please

In addition to being pragmatic and as simple as possible, policies must be technologically open-minded, with no *a* *priori* exclusion or privileging of individual technologies (picking winners or stigmatising losers). Experience in other domains, for example the Defense Advanced Research Projects Agency (DARPA) instigated by the US Department of Defense, has shown that a focus on outcomes and agnostic assumptions about paths towards these outcomes will be more effective than privileging specific technological routes. This is especially true where integration of multiple technologies is involved, as it encourages cross-disciplinary problem-solving and provides the impetus for creativity. Funding of such processes should be competitive, and funders should be prepared to support exploratory research before establishing priorities for substantive development. Furthermore, commercialisation and deployment supports for still-nascent and maturing technologies should remain innovation-centred and thus support only the level of deployment needed to ensure continued innovation and learning about the future potential of currently immature technologies and business models. Competition between still-improving technology approaches must be maintained and prematurely "picking winners" avoided.

(vii) Embracing failure is vital to achieving success

Innovation is messy. It is a dynamic, evolutionary process in which technologies fail or succeed according to their ability to thrive within prevailing market conditions, which themselves are shaped by policy and sometimes subject to frequent change. Contrary to conventional wisdom, the frequent failure of innovators is not inherently a problem, even at a wide scale. What is a problem is when a culture of stigmatising failures – or those responsible for them – discourages calculated risk-taking and drives potential innovators away from pursuing their vision. Equally problematic is the situation that arises when, lacking effective processes and incentives to examine their own failures or those of others, innovators fail to learn lessons from failure and apply these lessons to further innovation activity.

What is essential therefore is for there to be a climate that makes it safe for inventors (and policy makers) to take risks and to fail: a climate in which failure is learned from, not stigmatised; in which would-be innovators who have failed are empowered to continue trying; and in which more people are encouraged to participate in innovation in the first place. We must increase calculated risk-taking by decreasing the financial and opportunity costs of failure. We must change our very perception of failure itself. Though easier said than done, changing perceptions towards failure and increasing calculated risk-taking by decreasing the financial and opportunity costs of failure, is essential.

(viii) We need invention and innovation, working together

As several of us argued in the 2010 Hartwell Paper, expanding access to modern energy while reducing anthropogenic carbon emissions requires both rapid transfer of best available low-carbon energy technology to all and sustained improvement of low-carbon technologies. But there are two routes to that destination. In this paper, we argue for a policy focus both on incremental innovation – the gradual expansion of our technological frontier through performance improvements and cost reductions – and on radical invention that can "disrupt" existing energy markets and accelerate energy system transition.

For the purposes of managing the dual challenge of emissions reduction and energy expansion, we group energy innovations into three classifications:

- Less carbon-intensive energy technology
- Zero-carbon energy technology
- Negative carbon technology.

The first and second of these exist already, and innovation in these categories can and should be both incremental and radical. Existing technology in these categories could also be deployed widely once economically viable. In the first instance, energy conservation technology and lower- and zero-carbon energy production methods could be transferred from advanced economies with low carbon intensities to large emerging economies with high carbon intensities (CO_2/GDP). That India and China are, respectively, roughly four and five times more carbon intensive than the United States, and roughly thirteen and eighteen times more carbon intensive than world leaders such as Sweden, suggests that there is considerable room for improvement across the board.

The third technological category, negative carbon technology, may turn out to be crucial in managing global environmental systems, particularly if we remain on or near our current emissions trajectories. In their current forms, unless nuclear energy is deployed at a scale not currently envisaged, low-carbon and zero-carbon technologies are not sufficient to reduce greenhouse gas emissions in absolute terms as populations grow, economic growth continues, and industrial demand increases. Carbon Capture and Storage (CCS) and Carbon Capture and Use (CCU) technologies are the systems in question. CCU is more likely to be fruitful in the short term. Furthermore, some experiments are being conducted to invent a new chemical process of catalysis to turn CO_2 directly into new materials, including food and fabrics.

So far, efforts to move CCS technologies from the conceptual stage to demonstration and deployment have been only minimally successful, although some demonstration plants are running. CCU, however, has already been demonstrated, for example in the Canadian Athabasca oil sands. In Norway and the United States, CO_2 is extracted from process combustion and is then used to purge conventional oil fields of residual reserves (a process called Enhanced Oil Recovery – EOR). CO_2 is also used in intensive horticulture to speed plant growth, a process that, like EOR, places market value on CO_2. But efforts to develop such technologies and applications have not proceeded nearly as quickly as virtually all international energy agencies and large energy companies have assumed in their climate mitigation scenarios (or argued is necessary for climate change mitigation).

(ix) Deployment of early-stage technologies should be as a means, not an end

The innovation cycle includes research, development, testing, demonstration, adoption, and diffusion. This process is non-linear and involves numerous critical feedbacks and linkages between problems and solutions identified and trailed at each stage. The need for public support at the basic research and development level – due to the significant differential between public and private returns to investment during this stage – is a well-understood economic principle. We argue that this public-private return differential is not limited simply to the basic research and development or "invention" phase of energy innovation. Yet public support for testing and demonstration is not always forthcoming, as sums of funding required at this stage grow, sometimes by an order of magnitude; and governments often fear to be seen to fail.

There are two main obstacles limiting the transition from basic R&D to diffusion that suggest a need for public financing at intermediate stages of innovation. The first obstacle to be crossed is the so-called "technological valley of death". It is encountered when the capital required to turn science into a potentially profitable product or to undertake pilot projects is not forthcoming due to a high risk of failure. The second obstacle is the difficulty of finding finance to support the demonstration of technologies at scale, sometimes referred to as the "commercialization valley of death".[26]

The trap in which promising early-stage technologies lie stranded is particularly grim for energy technologies because they generally have high capital and infrastructure costs. Crossing such "valleys of death" cannot be accomplished in the absence of public support and policies that encourage later private sector investment; but this support must be tailored in such a way that it does not result in sterile deployment for deployment's sake, terminating further incremental innovation or invention. This is a key characteristic of the Hartwellian approach.

(x) Recognise that energy innovation must proceed by more than one pathway at once

Innovation is generally understood as "the successful implementation of a new idea". However, as we observed at the outset, this popular definition in fact conflates innovation and invention. Sometimes innovation has come about directly because of a new invention – by a single discovery – but innovation is almost always the result of a combination of factors of which a new invention is only one. It may be argued plausibly that Apple's success in personal computer and telecommunications devices derives more from innovation in human interaction – and from its business model – than from the technological characteristics of its devices. The GSM standards agreed jointly by industry and the EU provided the matrix for all the innovations that opened up access to mobile data. The interplay between technology, systems and human choice is understood in the area of Information and Communications Technology, where profound intended or unintended changes in the way people utilise technology are routine: "social networking" is perhaps the most significant recent example.

All aspects of the innovation process require investment, but different stages of the process need different types and levels of support. Furthermore, investment in innovation depends on wider cultural and institutional contexts from which the knowledge and skills that support and sustain the activities of innovating organizations derive. Therefore, the uneven and localised nature of the innovation process is one of its key characteristics, which means that – given the uncertainty inherent in innovative experiments and ventures – conducting multiple, parallel research, development, demonstration, and deployment (RDD&D) efforts is not inherently wasteful and may in fact be the most effective way of exploring a radically new technological frontier.

The powerful implications of this for low-carbon energy innovation are clear. No single technology, technology class, research pathway, or RDD&D investment strategy will unlock the technologies needed to address the challenge of producing affordable, reliable, scalable low-carbon energy technologies. Multiple innovation pathways are needed, as well as greater coordination between on-going and prospective parallel efforts.

(xi) Broad, bottom-up social legitimation of policies is morally and practically indispensable

Innovation means rethinking how we provide energy and therefore how we may go beyond and beneath our current arrangements. Analyses of the type provided by energy systems and integrated assessment models mainly focus on large-scale systems. For example, these studies suggest that the major technological changes needed in energy systems are 1) to increase electrification (eg, of transportation, heating and cooling, and other energy services) as much as possible 2) to substantively de-carbonize electricity production and 3) to develop biofuels and other transport systems that are low- or no-carbon. However, the systems required for those without access to modern energy services don't fit that formula because they are to be developed in a challenging variety of contexts, from sparsely populated areas to dynamically growing cities, from areas without infrastructure to areas with abundant but poorly functioning infrastructure, and from needs for irrigation to education to transportation in developing industries.

There is no simple prescription available. One size does not – cannot – fit all. As the 18th-century Anglo-Irish politician and thinker Edmund Burke correctly observed, "The circumstances are what render every civil and political scheme beneficial or noxious to mankind." The nuclear power that Sweden employs to light its cities during the dark winters is not a solution for distributed micro-power in savannah villages in the sun belt of sub-Saharan Africa. A simple pulley system may be the best transport option for a steep slope in Rio de Janeiro, much better than an engineered road and vehicles. Short-sighted attempts to promote specific technologies in spite of local circumstances will invariably fail because they miss this basic but essential insight.

Contextual specificity is not only a sound principle of technical design; it is also a precondition for the acceptance of policies and technologies by those from whom decision makers derive their legitimacy to act. Indeed, as we will discuss below, the indispensability of broad, bottom-up social legitimation for fresh policies is the main salutary lesson of the failures of the years 2003–2007, when international climate policy was at its apogee. In the years which just preceded the banking crash of 2008, politicians felt less inhibited in playing free with their constituents' money, and taxpayers and consumers were themselves less attentive in monitoring government levies and spending. Once that mood of general public well-being had evaporated, the willingness to sanction the legislation of expansive and expensive programmes was lost with it.

We need an alternative way forward. To be sure, people are concerned about climate change and its impacts. But declared attitudes are not always consistent with actions or, crucially, willingness to pay. A workable approach must genuinely engage the public in a transparent discussion of the costs, the benefits, and the hazards of proposed solutions. This of course means accepting the possibility that the public will not agree to what the policy-makers propose. But it is only if policy has been subjected to this assay that politicians and legislators can understand the limits of tolerance they can realistically expect from their electorates. With this knowledge, policies can be implemented in ways that attract rather than erode public support.

2

RECENT EXPERIENCES WITH ENERGY INNOVATION IN ENERGY TRANSITION

(i) Mandated or "driven" energy transitions are difficult and unusual, although not impossible

Energy transitions are long-term affairs. Since the rise of coal power in the late 18th century, the global energy system has been on a slow but steady path of decarbonisation, as coal, oil, and gas have sequentially succeeded biomass and one another as the reference fuel in the energy mix.[27] Over the intervening centuries, the amount of carbon emissions generated by the production of a unit of value (GDP) has fallen, on average, by 1.3 per cent per year, primarily as a result of improvements in energy efficiency and this fuel switching process.[28] The challenge now is to accelerate this background rate of decarbonisation: to hasten the transition of the global energy system towards a lower and ultimately zero- or negative-carbon state.

Energy innovation happens continuously, at all spatial and temporal scales. Businesses and individuals make choices daily to improve their circumstances; on a longer time scale, industrial enterprises invest and governments create policies that together shape infrastructure spanning continents. While the frenzy of innovation at smaller scales is often the most visible, and may create the expectation of rapid systems change, the emergent behaviour of the global energy system marches to a slow, multi-generational drum.[29]

Human societies have undergone two major energy transitions. The first was from hunter-gather societies to settlement-based agricultural societies, eight to ten thousand years ago. Energy use, dominated by biomass, increased by two orders of magnitude and climbed steadily afterwards.[30] The second transition, the industrial revolution, began about two hundred years ago. It saw hydrocarbon energy sources – fossil fuels – augmenting humanity's continued use of biomass, the latter mainly for food and fibre.

Within this second energy transition, a clear pattern of the global primary energy market share is evident. The global energy mix is moving from a high-carbon, low-energy density energy mix to a low-carbon, high-energy density mix.[31] This dynamic nature of the global energy system is not well recognized, as is revealed by the frequent use of the term business-as-usual, which suggests that the energy system is static and unchanging. On the contrary, it is the usual business of all players in the system – individuals, businesses, industries, and governments – to innovate constantly. The pattern of the energy system that we observe is an emergent property of the aggregate of that innovative activity. Viewed globally, this process plays out over a multi-decadal time scale.

Future innovation ideas and policies need to be compatible with this multi-scale environment and must be cognisant of the slow drum-beat of change in global primary energy use. The current "industrial revolution" energy transition began in 1800. It will likely require the remainder of this century to complete. The resulting population of 8-10 billion (according to UN projections), living increasingly in dense urban settlements, need to be served by high-energy density primary energy sources with low-carbon attributes. But it may not happen as soon as some would wish, and though we seek in this paper for ways to speed it up, the truth is that it is not clear how much this long-run process can be accelerated.

To be sure, governments can try to impose energy transitions. Examples of such mandated energy transitions include Germany's *Energiewende* and state adoption of renewable portfolio standards (RPS) in the United States. *Energiewende* represents Germany's somewhat self-contradictory commitment to transitioning towards a carbon-free – and uranium-free – future through the subsidising of wind and solar technologies combined with the decommissioning of nuclear power. In the USA, state adoption of RPS requires utilities to acquire a specific percentage of their generation from renewable sources. Qualifying renewable facilities are provided with production and investment tax credits.

It is not our contention that mandated policies are fatally flawed *sui generis*. There are examples of considerable success such as nuclear initiatives in Sweden and France or geothermal energy in Iceland, all of which achieved decarbonisation rates of 3 per cent per annum sustained for a decade or more. But each of these benefitted from unusual political dispensations (French centralisation and Scandinavian social cohesion) which are not widely found. The wider experience suggests that mandated policies are often ineffectual, and they sometimes produce unintended consequences. The German *Energiewende* policy has promoted significant wind and solar deployment with the perverse effect in the short run of displacing nuclear and gas-fired generation in favour of more carbon-intensive coal-fired generation. As nuclear and gas-fired power generation have declined, coal and lignite generation have increased. The end result is that there has been no net change in fossil fuel-fired production between 2011 and 2012. Of course, it may be that Germans accept this philosophically as just a strange twist in the winding pathway of the particular model of energy transition that they are currently exploring. But that is not entirely clear. What is plain that the *Energiewende* hasn't yet created a viable renewable sector, while loading consumers with charges; and the emissions savings gained by this route have been dwarfed by the impact of cheaper gas elsewhere.[32]

In the United States, state-imposed renewable portfolio standards increase the amount of intermittent energy resources, which must be backstopped by conventional generation, usually gas-fired units.[33] As more intermittent energy resources are added to the system, maintaining grid reliability becomes increasingly difficult and expensive, with growth in management costs being significantly non-linear.

There are other examples of the difficulty of mandated energy transitions. In order to accelerate the deployment of existing renewable energy technologies, the EU and some national governments used a mixture of legislation and direct funding to create lucrative markets. These were intended to give the favoured "renewables" a handicapped advantage in the market, and were predicated on the "peak energy" assumption that fossil fuel prices would continue to rise, driven by rising global demand and a possible "peak" in production. This amounted to a 3 trillion Euro futures contract on high fossil fuel prices. It is a wager that, since 2009, worldwide but especially in the USA (benefitting from the effects of shale gas flows), has not succeeded.[34]

Instead, the effect of all these interventions has been to create a market characterised by policy uncertainty and investor behaviour typical of bubble markets.[35] The key feature of bubble markets is that investors are mainly driven by rent-seeking: deriving profit by manipulating the social or political regulatory environment in which economic activities occur, rather than by creating or adding value. Such a contortion results in the "locking in" of favoured technologies before they have matured, because the incentive to invent and innovate is snuffed out by competing attractions.

Thus, Europe's provision of generous income support subsidies for the deployment of existing technologies resulted in flaccid industries. Companies in the subsidised low-carbon sector were vulnerable to Chinese competition able to under-cut European prices for a range of reasons, including across-the-board lower wages and – a point of savage irony – lower energy costs due to the availability of cheap coal and the absence of carbon penalties. Indeed, it can be reasonably argued that the principal economic focus in the European renewables market has not been on improving technologies, but rather on securing land-use change and long-term politically guaranteed income streams.

While the importance of these matters for climate policy is sufficiently obvious, the social implications also deserve our attention. Since the European renewables industries are dependent on markets that are the creation of policy mandates, their employees are in effect state employees, but without the security usually attributed to such positions. If, as seems likely, the policies are economically unsustainable and vulnerable to distressed policy correction, these jobs are at risk on short notice.

(ii) What are the positive lessons of the decade 2003-2013?

While the recent record of low-carbon energy policy has been largely one of failure to achieve significant decarbonisation – confirmed by the IEA's recent report that the carbon intensity of the global economy has remained virtually static for the past twenty years – there have been notable successes.[36] Still more importantly, costs have not fallen sufficiently to give a reasonable prospect of the sectors being independent of subsidy even in the medium term. (Subsidy, it must be recalled, is not simply direct income support. It embraces lower or zero connection charges, and the fact that the integration costs of renewables are almost always socialised over the rest of the system – as in Britain.)

However, the experiment in the mandated deployment of low carbon energy has yielded a vast body of data relating to the performance and systems integration of renewable technologies, particularly in the electricity sector (much is also being learned in the fields of transport and heating fuels). Even though a great deal of this information is not yet fully available to analysts, it is clear that investors and innovators alike can learn enormously from full disclosure of such data. Therefore one positive lesson to be drawn from that experience hitherto is that any future developments that are funded from consumer levies or taxation must be completely transparent.

The importance of this data resource should not be underestimated. The energy sector in most countries, even in long-standing liberal democracies, has been characterized by secrecy and obscurity. The low-carbon experiment has exposed the industry to unprecedented public scrutiny, and created a context in which consumers are pressing to know more about the conduct and behaviour of energy providers and their regulators. This is a unique opportunity to prise open a previously cloistered industry, which would ultimately foster invention and innovation in the general interest.

Indeed, while it is common for governments and NGOs to lament the lack of public awareness of climate change, we think that a second positive lesson is that the experience of the last decade, certainly in relation to energy, indicates that a remarkably sophisticated debate can be created within a short period of time and the right institutional frameworks and incentives. The results of that discussion cannot be predicted, but this is a hazard that is far outweighed by the benefits of engaging as many minds as possible. In this extraordinary development, data gathering and disclosure will be a key element, firstly to provide material for investors and innovators, but also as part of the process of securing broad public consent to the changes and experiments necessary, a point that we discuss further in relation to our understanding of the term “ambition” in these endeavours.

Other subsidiary benefits are worth noting. The pace of systems change can be very rapid if adopters believe investment to be worthwhile. Indeed, there is good reason to think that when the attractiveness of a technology is more than skin-deep, adoption will spread very quickly indeed. The example of shale gas exploitation, given below, demonstrates this in another context.

While modern biomass may be limited in its ultimate deployment, it is interesting and important to note that it is the heavy lifter in the renewable electricity sector, and that it has made its way almost unnoticed by the public. In the UK, for example, as earlier noted more than half of all "green" megawatt hours of electrical energy generated between 2002 and 2012 were from biomass sources. The biomass case also suggests that once affordability is reached and the problem of uncontrolled variability is tackled, and low-carbon technology is competitive, growth in other technologies could be prompt.

A third major positive trend of the last decade has been the rising level of acceptance of the energy innovation imperative by politicians and policy makers. Although battles continue to rage over the relative importance of the deployment of existing technologies and the development of new ones as government funding priorities, the notion that energy innovation is key to addressing climate change now enjoys considerable support. Political winds are ever-shifting, but at least for now the consensus on energy innovation seems to cross the political boundaries, creating new and potentially productive alliances. Politicians in polarised political systems are far more likely to agree on measures to improve energy technology than other sorts of climate-oriented policies, such as carbon pricing.

A good example is of the strong bipartisan governmental support for ARPA-E, the US Department of Energy's newly established energy technology development arm. This effort has sustained support across the political spectrum because it taps into a vision shared by all US politicians: of the US as an innovative, world-leading technology producer. Unlike the US cap-and-trade bill of 2009/2010, which failed to gain passage even after enormous concessions by its sponsors and supporters, ARPA-E embodies the desire, shared by politicians and the public, to achieve industrial competitiveness, national renewal, and "blue sky" innovation.

Simultaneous with the rise of political support for energy innovation has been a significant expansion of scientific and technical attention towards the challenge of developing low-carbon energy. This has been driven partly by improved funding, through initiatives such as ARPA-E and, more expansively, through increased funding from national scientific bodies such as the National Sciences Foundation in the US, the Engineering and Physical Sciences Research Council (EPSRC) in the UK, and analogous bodies elsewhere. Such funding has permitted a generation of new energy-related research projects to begin. It has also attracted scientists and engineers from a diverse array of disciplines, from computational biologists modelling algal growth, to power systems engineers working on electrical grid demand response, to a new generation of nuclear scientists developing advanced, passively safe nuclear designs including fast reactors and small modular reactors (SMRs).

A further positive development in lower-carbon energy – and an instructive example of how innovative technologies can be brought to market at scale – is the development of technology to unlock vast quantities of natural gas from previously uneconomic shale deposits, particularly in the United States.

Natural gas, including shale gas, is a cleaner fuel than oil or coal. It can be burned more efficiently, with significantly reduced emissions of greenhouse gases per kilowatt-hour generated. Furthermore, it is low in sulphur, and does not produce the levels of black carbon from imperfect combustion typical of coal or oil. This latter point is a particularly valuable characteristic given the increasingly clear role played by black carbon as a local environmental pollutant, a risk to human health and as an agent which, by deposition upon it, accelerates the melting of ice.[37]

Gas can substitute relatively easily for coal in power generation and its considerably lower release of carbon dioxide (around 40 per cent that of coal, per unit of electricity generated) means that it has the potential to deliver significant net emissions reduction, assuming minimal natural gas leakage between well and generator.

The United States government has laid the institutional and regulatory groundwork for a massive expansion of shale gas exploration and exploitation over the past twenty years: through a combination of federally-funded geological research, the availability of GPS navigation (itself a by-product of government defence investments), public-private collaboration on demonstration projects, and R&D priorities set and exploited through the American Gas Institute.[38] Other factors, such as the nature of land-tenure in the USA, (mineral resources are owned by the territorial land-owners), combined with tax policy support for unconventional technologies and the buccaneering of wildcat drillers to prove the first major new fields have also helped drive this expansion. The shale gas boom has in recent years reached new and unforeseen heights, transforming the United States in the process.

To the consternation of those who had become used to deriding the United States as a “climate change pariah” for its refusal to sign up to the Kyoto Protocol process, the shale gas revolution has helped enable the US to reduce its power sector’s carbon emissions faster than any other country worldwide between 2005 and the present. Its performance is well ahead of the European

Union, which had prided itself on leading global climate diplomacy but where, as noted earlier, the actual effect of its aggressively promoted "green" energy policies has arguably been culturally, socially and politically – as well as economically – counterproductive: in nice Hegelian form, the dogmatic and uncompromising presentation of this thesis has predictably conjured up its equivalent antithesis. Nor have the opportunity/costs of pursuing these options been negligible. Nor should one discount the discouraging effect of presenting an economically uncompelling example to the developing world.

Furthermore the cost of energy for industrial purposes in the US compared to other regions, including China, dropped significantly. There was an initial oversupply that is now being corrected by the market; but at one point in 2012 gas was trading at $2 mmbtu (million British Thermal Units) in the USA and $14 mmbtu in Europe — a spread exacerbated by the difficulty and cost of transporting natural gas overseas.[39] As a result, more energy intensive industries have begun to return to the USA, bringing manufacturing jobs in their wake. The heavy chemical industry has been in the lead, reanimating the previously depressed economies of states like Ohio.[40] Given coal's vast market share in global electricity generation–in particular in the large developing economies where energy demand growth is likely to be highest – expanding the substitution of gas for coal could deliver meaningful global emissions benefits. However, shale gas should not be regarded as a "destination" fuel: a final stop in our global energy transition. At most, it can provide a "gas bridge" generating the wealth and the public consent that will make it possible to reach still lower-carbon electricity.

In addition to improving the carbon emissions profile of the United States, and strengthening its economy, the development and maturation of shale gas extraction technology offers further insights into how best to encourage similarly rapid progress in other fields. In the 1980s and 1990s, when private R&D was low and risks to industry high, the federally-supported Eastern Gas Shales Project, the federally-coordinated Gas Research Institute, and federally-administered tax incentives in the United States filled the investment gap – bridged the investment "valley of death" – and prompted sustained private interest and investment in longer-term shale gas development. They provided a secure policy environment, which gave innovators sufficient confidence to invest their own efforts and resources, as well as a crucial early investment support that the market would probably not have provided on its own.[41]

The economic payoffs of these efforts have been enormous. Even the most generous estimates of federal spending on decades of shale gas development have been repaid many times over in the form of increased domestic energy production, lower energy costs, increased economic activity, and additional tax revenue. Estimates of shale gas investments total more than $10 billion over several decades, including $473 million in R&D support, but the direct gains to US consumers from the shale revolution have been estimated at over $100 billion each year.[42] And this does not even include the substantial macroeconomic effects of low-cost energy and new jobs, or the geopolitical dividend that comes from producing a larger share of energy domestically.

(iii) What were the principal failures of the decade 2003-2013?

The experiences of the last decade have revealed that the principal failing of current policy mechanisms is the fact that bureaucratic preference has been permitted to replace real world experience in the selection of technologies. To the extent that taxpayer or consumer funds are used to fund technological initiatives, it should be used not to support individual companies or technologies, but rather to support key strategic technological platforms such as technology-agnostic test-beds, basic science and R&D activity, demonstration support, and competitive, innovation-focused deployment regimes.[43]

More broadly, a central lesson to be learned from the experiments of the last decade is that a failure to bear in mind the economic interests of consumers, industrial, commercial, and domestic, has weakened international climate change policy by stimulating consumer hostility and resistance. In the United Kingdom, for example, government admits that the direct consumer costs of its climate policies will be about £7.6 billion a year in 2020,[44] with the details of these costs now regularly producing front page headlines in mass circulation papers.[45] This risks not only a consequent collapse of public confidence, but a potentially universal loss of faith in an entire set of protocols. Policies that respect the economic sensitivities of their supporting populations will be more likely to produce innovations that are durable and attractive at a global level (an expansion of the simple truth of Pielke's Iron Law). This has profound implications for how national and international policies are constructed, and it is to these challenges that we now turn.

3

HARTWELLIAN OPTIONS FOR NATIONAL LEVEL ACTIONS

(i) Stimulate energy innovation through more intelligent investment

Technologies may involve the manipulation of inanimate materials and natural forces, but they are above all human systems. The history of technology shows that technology development is a process characterized by both supply push and demand pull. The lone inventor is usually a fiction, but even he or she – or, more likely, teams of inventors and innovators – produce an artefact that is modified in development and use and set in a context of new infrastructures and rules. These processes in turn stimulate further innovations in supporting systems and artefacts, forming what Rip and Kemp call a "socio-technical" system.[46]

Successful energy innovation policy must be able to account for this. It must install institutions and incentives that foster organic, bottom-up innovation whilst providing the top-down organising principles that enable complementary ideas and assets to be integrated. It should provide the landmarks for ambition, funding and the sharing of risk and reward.

Innovation in energy provision will require the right relationships between discovery and problem-driven research, demonstrators, prototype deployments, human behaviour and societal evolution. Given the great diversity of disciplines involved, the essential "eco-system" is unlikely to happen by chance.

Contrary to popular assumptions and those of most policy-makers, technology does not have an over-riding prescriptive power. If that over-riding power is granted, as we have seen, the results are more likely to be different from what was intended and often unpleasantly so. It is when this plethora of factors are balanced in counterpoint to each other that a truly self-sustaining technology is liable to be fashioned.

Sectoral characteristics must speak: what works in ICT may not transfer to nanotechnology, and so forth. So too must national and local context: geography, infrastructure, workforce skills, venture capital, industrial policy, market forces, political institutions, cultural norms and traditions of expertise must all be taken into account to achieve true success and popular legitimacy. It is therefore encouraging that research on technical innovation is increasingly focused on national systems of innovation, emphasizing the interdependence of these factors.[47] Only national sovereign actors are empowered to make decisive interventions: the shale gas story told in section 3 illustrates that.

The overall aim for national innovation policy must be to generate conditions in which private and public organizations engage in the ways suggested, and principally "up-stream." To expand such conditions will require better targeting of innovation-oriented spending. Given recent negative experiences in the subsidy-driven deployment of various renewable technologies, national innovation policies should be targeted towards driving down the future cost of promising technologies rather than deploying expensive, immature technologies at scale. We recognise, however, that deployment is a necessary component in the process of technological maturation. Thus, we favour a strategy with a bias towards the most rapid improvement of technology rather than the widest possible early deployment. This means that for immature and swiftly changing technologies, deployment should be pursued as a means to reduce cost and improve performance, not simply as an end in itself.

Another challenge lies in the timing and sequencing of actions, both for innovation and deployment. On the one hand, pushing deployment action into the future may allow relevant technologies to become more affordable, making unit-costs of low-carbon technology – and therefore emissions mitigation – less costly. This is so in the case of renewable energy: unit costs of energy from gas plants with carbon capture and storage (CSS), advanced biofuels, off-shore wind turbines, and solar cells are projected to go down substantially. On the other hand, the present economic crisis means idle capacity, not least in the labour market, as well as historically low interest rates. This suggests pushing forward "no-regrets" investments such as energy-efficient retrofitting of building stocks and the modernisation of transmission and distribution networks.[48] Such investments will stimulate economic activity without resulting in the long-term lock-in of costly, suboptimal technologies.

Demonstrations are particularly important because the demonstration phase is currently a bottleneck: a rate-limiting step in the process of commercializing new, low-carbon energy technologies. During demonstration, low-carbon technologies can be tested for "scalability", not primarily to achieve environmental goals but rather as a means of driving down production and management costs so as to bring technologies closer to market competitiveness and, by extension, spontaneous market adoption.

Only once technologies have passed this step should deployment at scale be pursued. Once pursued, such levels of deployment should be driven largely by broad, market-based, instruments targeting externalities or resource scarcity, rather than technology-specific policies designed to incentivise widespread deployment of a favoured technology.

This framework is presented in a linear fashion, but it must be recognized that technologies and information and learning do not progress linearly through this process. Numerous feedbacks exist within and between each process. Effective innovation networks will integrate and embed these policies and stages within national innovation systems.

(ii) Overcome the limitations of institutions and make incentives work as they should

Public authorities, government institutions, and civil society are all party to the process of incentivising decarbonisation because a low-carbon economy is ultimately a public good unlikely to be delivered without government involvement. The question is not whether government should participate in the provision of this public good, but how. On which level, and with what instruments, should government policy measures operate so that they help and do not hinder? There is now considerable experience in the use of certain types of incentives, but results have been mixed. We have an opportunity to look imaginatively at the levers to hand and to develop strategies for encouraging beneficial innovation.

At present, most private firms have limited incentives to undertake innovation that leads to cleaner or more affordable energy, unless they receive some guarantee of return in markets that would otherwise be too risky. But remove that risk entirely and we immediately face problems of rent-seeking (as discussed in section 2 (i)). Subsidies can easily distort markets with unintended consequences and therefore should be used sparingly and with care. Where they are used, they should be structured to foster and demand innovation and to minimise rent-seeking.[49] Other incentives such as funding for demonstrators, soft loans, guarantees linked to future purchasing plans, and sharing of risk/return should all be considered and deployed where sensible. Alongside this, one of the most important ways to incentivise investment is consistency in government and regulatory policy.

There are some existing guidelines and best practices. Incentives and subsidies for fossil fuels should be abolished. Energy efficiency should be incentivised, particularly where it can be done at "negative cost", not because this will result in a one-to-one emissions reduction, which generally will not occur (see the earlier discussion of the Jevons Paradox), but because it makes good economic sense. It can be popular amongst the public if implemented consensually and to clear co-benefit.

The same is unlikely for a uniform global carbon price. This has been advocated in part as an alternative to global carbon trading systems that have dominated international experimentation heretofore, and have by and large failed.[50] But though a universal carbon tax might be less complicated, its agreement and successful implementation seem just as far-fetched as a global trading system, or indeed a global treaty on climate. Domestic carbon taxes are a more plausible approach: if low and hypothecated, as we recommended in the 2010 Hartwell Paper, such taxes could become a useful way of raising funds for clean energy invention and innovation.

Incentives should also be in place for improving the environmental and technical performance and decreasing the cost of currently existing fossil energy sources, as discussed in the previous section. Where high carbon energy is needed and is the only realistic option in the short term, (for example in poor countries committed to expanding their power supply but lacking other options for large-scale baseload power generation), policy incentives should be predicated on the use of state-of-the-art technologies such as fluidized bed combustion, ultra-supercritical coal-fired generators, or the substitution of gas for coal. Gas substitution may soon be viable in South Africa and Brazil, for example. These developments can become bridges to otherwise unreachable places. It is, in our view, short-sighted and self-defeating to deny ourselves these bridges on the basis of an undifferentiated anathema proclaimed upon all fossil fuels.

On the local and regional level, different incentives will work for different contexts. In all cases, public support is crucial and can only be won if climate policies are attractive to communities. Side payments could offer a pragmatic solution in such debates, as could ownership arrangements that provide greater financial and social incentives to local stakeholders who would otherwise oppose projects. For example, in Great Britain there is strong opposition to wind farms, which is largely absent in Germany. Whereas British wind farms are owned by big utility firms, and neighbours, who pay a significant environmental cost, see no benefit, Germany has a long history of substantive ownership by co-operatives that serve to return wealth to those most affected by a development. Such local ownership will not resolve all conflicts of interest, and it may also expose local owners to investment risks of a kind that are unreasonable given their particular circumstances. Nevertheless, local involvement is a key principle that deserves more than the lip service it currently receives from government. Here, the case of mineral rights ownership in the US shale gas revolution is instructive.

(iii) Pursue "Nationally Appropriate Innovation Actions" that satisfy many national requirements

Each nation state has its own national priority agenda. In resource-poor Japan, which relies on imported fossil fuels for its energy supply, the highest priority of politicians is to develop a secure supply of non-imported energy. This is why Japan (in its 2010 energy policy) set a national objective of generating a 50 per cent share of its power supply from nuclear power. It is also why, following the *tsunami* damage to the nuclear site at Fukushima and the subsequent wobble in public support for nuclear power, it is exploring the development of sub-sea methane hydrates for the medium to long term as well as vigorously reforming governance of its nuclear sector and at last improving interconnectivity between the Eastern and Western sections of the Japanese electricity grid from 1 to 2-3 GW.

Individual circumstances and varying conditions – environmental, social, political – mean that countries choose to focus on differing areas of technology. In China, which has a rich domestic coal supply but now faces serious air pollution problems due to particulate emissions from coal power stations, the clean usage of domestic coal may be a higher priority than energy security. In Sweden, where supply is secure and relatively clean due to an abundance of existing nuclear and hydroelectric power stations, declining costs and building an export market may be higher priorities than in energy-poor nations elsewhere.

The elementary point that these cases make is that each nation's technological innovation agenda will be directed primarily by its perceived national priorities and not necessarily by international policy goals such as greenhouse gas emissions reduction. The extent to which the reduction of greenhouse gases will be considered a priority problem in any individual country will be principally a function of the degree to which that goal overlaps with other, more pressing domestic priorities.

Nor is that political fact of life unwelcome. Today we can see that considerable greenhouse gas mitigation has, in fact, taken place as a result of policies primarily directed towards other, higher priority goals such as job creation, energy security, industrial development, social objectives or domestic competitive advantage. This is a virtuous dynamic, insofar as it provides additional political openings for an effective reduction of humanity's global impact.

Such openings have largely been absent in recent years. Their scarcity is what prompted the 2010 Hartwell Paper to call for an “oblique” approach to climate change, giving priority to actions with different prime motivation, but with the contingent benefit of reducing human impact on the environment. The pursuit of unconventional gas development technologies in Japan and clean coal technologies in China – policy approaches not motivated primarily by climate change concerns – are instructive. Not only do these policy approaches help these countries address national priorities, thereby gaining democratic legitimacy and the support of politicians, but they also promote beneficial climate change outcomes by improving technology that limits the worst practice use and negative consequences of coal.

The discovery that domestic policy actions can be harnessed in the service of a general lightening of the weight of humanity’s footprint suggests a strategy of privileging local and national-level solutions while optimizing them for maximal global impact.

The simultaneously local and global characteristics of the innovations needed to address climate change translate into the pursuit of “Nationally Appropriate Innovation Actions” (NAIAs) as an important stepping-stone for future activities around which global actors can unite. Such a programme would include efforts as diverse as the Brazilian rural electrification programme *Luz para todos* (“light for all”), and US investments in high-tech energy innovation through ARPA-E – all of which employ local resources to achieve local priorities but have contingent global benefits.

Perhaps the most promising aspect of the NAIA approach is that it is compatible with the international diplomacy of global climate change under the auspices of the UNFCCC. For years this well-meaning process has been mostly fruitless, and it shows few signs of improvement. But the sunk political capital and institutional inertia that scaffold the entire process mean that it is with us to stay, at least in the medium-term. Therefore, we should take advantage of the opportunity to harness the good intentions that remain within it to re-direct the process with procedural reform and to refresh it with new ideas.

NAIAs harmonize particularly well with the emerging discourse on Nationally Appropriate Mitigation Actions (NAMAs), which, after the Durban COP meeting, are rapidly displacing the Kyoto Protocol type of global treaty model as the preferred direction of the geopolitical majority of UNFCCC participants. In a global policy model based on NAMAs, NAIAs will serve as the vehicles through which individual countries implement their nationally agreed commitments. These will form the substance of a successful future international discourse, which is politically desirable, and will also achieve success in both mitigation of emissions and adaptation to climate change.

Just how this may be done is discussed in more detail in the next section.

4

HARTWELLIAN OPTIONS FOR INTERNATIONAL LEVEL ACTIONS

(i) Understand and implement the positive lessons from the failure of the Kyoto regime

The hybrid offspring of a nuclear arms control treaty and the US Sulphur Trading regime, with added features from the Montreal Protocol on CFCs, the Kyoto Protocol was always maladapted for the nature of the “wicked” problem that it was supposed to solve.[51] Beyond the fundamental structural mismatch, there were three additional reasons of diplomatic practice why the Kyoto protocol failed.

First, the top-down nature of the approach did not give adequate consideration to the unique situations of individual countries, specifically the differential ability and willingness to pay more for low-carbon energy provision than fossil fuel alternatives.

Secondly, the economic power balance between developed countries and developing countries changed dramatically during the fifteen years between 1997, when the protocol was agreed, and 2012, when the protocol was to begin its second commitment period.

Finally, the emissions reductions the protocol prescribed were unrealistic in the absence of low-carbon technology capable of meeting them at costs deemed sufficiently affordable by political leaders and their constituencies.

All of these factors combined together to create a widespread perception amongst politicians that adherence to the Kyoto Protocol would damage national economic competitiveness and destroy wealth, and that the level of damage would be disproportionate to the real-world impact that the Protocol could have on global emissions. Nor were they wrong. Following the economic crisis of 2007/2008, many countries decided that the impacts of Kyoto on national competitiveness, real or perceived, were no longer politically or economically affordable. Emerging economies such as China and India took the view that their economic development would be constrained if they committed to obligations under the Protocol, while developed countries, most prominently the United States, thought that the lack of commitment by those countries would be unfair and would dilute the agreement's effectiveness.

In countries that had signed the protocol, the expense of meeting targets with existing low-carbon technology – and the perception that doing so was decreasing competitiveness with non-signatories – reduced enthusiasm and political support. Together, these factors resulted in diplomatic gridlock, the erosion of institutional momentum within the UNFCCC, and the rejection of the second commitment period by several important emitter countries including Japan, Canada, and Russia.

What lessons does this history teach for the design of a more modest but possibly more successful reform of the UNFCCC diplomatic process? We see seven.

First, the international process should adopt a bottom-up approach to decreasing global carbon intensity by reducing carbon intensities across all industries, sectors, and countries. The technologies used to achieve these reductions in carbon intensity need to be identified by each industry, and shared and adopted widely in locally appropriate forms. Carbon intensity goals for each industry and sector can be calculated on the basis of their current carbon intensity, their potential to apply existing, commercially available technology, and prevailing and projected rates of technological improvement. Aggregating the targets of all industries and sectors can then result in bottom-up, self-chosen targets for individual countries. Recognising the reality of sovereign power is what may enable it to succeed. When targets are self-chosen in collaboration with competitor companies across industries, sectors, and countries, the likelihood of them being met is greater.

Second, the international process should abandon top-down target setting and instead embrace a wider range of progress indicators such as sectoral decarbonisation targets, R&D spending targets, and carbon intensity targets. A pragmatic approach, giving more respect to sovereign power, has already been tested with considerable success in the emissions field. In 2007, leaders of the Asia-

Pacific Economic Cooperation (APEC) forum agreed to a 25 per cent energy intensity improvement goal by 2030. Four years later, meeting in Honolulu, and responding to contextual shifts and changed technological and economic conditions, they agreed to raise the improvement goal to 45 per cent by 2035.[52]

Third, the framework must be structured to induce sufficient carbon intensity improvements in a transparent manner with institutionalized Measurement, Reporting, and Verification (MRV) standards and peer-review methodologies –though without necessarily being legally binding. Results are more important than modalities. Past UNFCCC negotiations show that the pursuit of "legally binding" commitments for their own sake is not productive. The US and China are together responsible for over half of global carbon emissions, and neither is likely to accept any legally binding agreement.

Again, the APEC example is instructive. The energy intensity commitments that countries have accepted are not legally binding, though they are supported by strong peer-review measures. When the goals of a country are not achieved, the peer-review process does not impose penalties on the failing country. If this were the case, several key participants would probably not have agreed to participate. Rather, countries failing to meet targets are offered detailed policy recommendations informed by best practice from other participating countries.

Fourth, a future framework will involve an expanded set of actors across all scales and types: global, regional, multilateral, bilateral, and sectoral. While the UN should still play a role in fields such as rule-making or the management of peer review processes, there will be a larger executive role for other agents. There will be a role for regional processes such as the East Asia Low Carbon Growth Partnership, Energy Efficiency Initiatives in the East Asia Summit, and APEC. There will be a role for sectoral processes such as APP/GSEP, or low carbon initiatives by international industry associations such as steel, cement, chemical and aluminium), or for bilateral credit mechanisms, such as Japan's, discussed below. There may also be a role for Sino-American agreements both on collaborative RD&D and to seek to phase out HFCs – assuming that Sino-American relations in general remain sufficiently open (which they may not) to permit this type of diplomacy. Embracing such "fragmentation" is a positive step toward pragmatism governing the diplomatic process, and hence towards concrete results.

Fifth, it must at least be acknowledged that the trajectory of global emissions will almost certainly overshoot an atmospheric carbon dioxide concentration of 450ppm in the next few decades. It is irresponsible to ignore the possibility that this could happen. On 9th May 2013, the Mauna Loa Observatory confirmed that the Keeling curve, which has measured global atmospheric carbon dioxide concentrations since 1958 (when the level was 318 ppm), had passed a daily average of 400 ppm. A positive consequence of candour is that it will concentrate minds and funding more on the search for low-carbon technology to slow this trend and negative carbon technologies capable of reversing it for the latter half of the 21st century.

Sixth, there should be more effort devoted to the invention of next generation low-carbon technologies. To date, international negotiations have put disproportionate emphasis on the transfer of existing technologies rather than the development of new ones. The debate on technology transfer has often been dominated by fruitless discussion over Intellectual Property Rights (IPR). There is considerable room for international collaboration among interested parties from both developed and developing countries. Again, much of this could be better handled outside the UN, through existing multilateral and bi-lateral channels.

Seventh, the resilience and safety of vulnerable countries and populations as CO_2 levels continue to rise will commensurately increase in importance. Acknowledging the potential failure of stringent mitigation is a moral and political prerequisite if we are to take prudent actions to adapt to climate change. Moreover, as we highlighted in the 2010 Hartwell Paper, the imperative for adaptation is not just a future concern, it is also a vital issue for the present. Many populations are maladapted to their current climatic conditions, and we need to improve all communities' resilience to the vagaries of extreme weather, whatever its cause.

The second commitment period of the Kyoto protocol covers less than 20 per cent of global emissions, and enthusiasm and commitment seem to decline by the day. At Doha, in practice the UNFCCC process crossed a bridge from the old regime to the new. While vested interests at the UNFCCC have a continuing commitment to a top-down, target-oriented approach, in fact that old regime was a one-issue process and this approach is now a dead end. Furthermore it is unclear, and not agreed within UNFCCC, who pays the costs either of proposed actions or even the continuation of the UNFCCC process. One hundred and ninety nations were present in Doha, but there was no strong pushback from governments at Doha against the recognition of the need for new directions, a marked contrast with the situation only a few years previously.

Some European nations – distinct from the EU secretariats – are seeking new ideas. The governments of developing countries seem to be changing their positions, becoming more constructive and pragmatic. Many green activist groups continue to reject all new ideas; but some may accept the need for change.

The prominence of NGOs highlights a specific problem with the UNFCCC. International negotiations – for example, world trade talks – tend to be chaotic in their nature, but climate change negotiations are "super, super chaotic" Part of the reason for this is that governmental negotiators are not just interacting with the negotiators of other governments, but with individuals throughout global society who are now able to observe the discussions almost in real time through modern media, and to interject in those negotiations through equally well-publicised expressions of public opinion. With so many unregulated inputs, the negotiation process – unsurprisingly – becomes more than merely complex. A football game in which the field is occupied not only by several teams at once but also the spectators, all of them attempting to play the ball, is hardly likely to be an easy match to follow, let alone referee.

Rescuing something from this situation, and overcoming the super chaotic nature of the interaction, has become all the more important because the Kyoto Protocol process is dying, and has been for several years. However, and in spite of its known weaknesses, the goals of the UNFCCC – to increase international collaboration and national efforts to reduce the dangers of climate change and increase societal resilience to its impacts – remain of the utmost importance.

The traditional UNFCCC toolkit, included the deployment agenda, Cap and Trade (C&T), the Clean Development Mechanism (CDM), technology transfer, and a unifying focus on CO_2 equivalents. It is inadequate. Evolution towards Nationally Appropriate Innovation Actions ("pledge-and-review" NAMAs and now NAIAs) is the appropriate route, with each nation undertaking as much as it can to reduce its own emissions as rapidly as possible while meeting its development imperatives. However, improving ambition and the ability to increase national mitigation and adaptation objectives rests on invention and innovation, and will fail without it. That is to say that without the improvement of existing technological options and the development of new ones, there will be little appetite for more ambitious attempts to reduce emissions since to achieve them at costs that taxpayers and consumers are willing to bear, will be manifestly infeasible.

The "theory of change" at the core of the UNFCCC is a Politics of Limits (resulting in inappropriate tools such as Cap and Trade and the Clean Development Mechanism), and has not been successful. Instead we should establish a "theory of change" that promotes innovation and Nationally Appropriate Innovation Actions. Whether or not the UNFCCC continues, a new framework is needed that offers a more compelling, efficacious, and politically saleable pathway forward.

At one time, there was a strong US wish to shift the primary focus from the UNFCCC to the Asia-Pacific Partnership (APP), seconded most strongly by Australia and Japan.[53] Progress was made: industry had a verification process and a list of ways to calculate emissions for specific forms of energy. But the APP was cancelled when President Obama came into power, and there was also a change of government in Australia. Its replacement is the Clean Energy Ministerial, which is more technical than diplomatic or social-scientific. The Global Superior Energy Partnership (GSEP) has been initiated under the Clean Energy Ministerial. GSEP does not have sufficient political backing yet to move forward, but there is potential because it involves fewer countries than the UNFCCC and therefore suffers less from the intense chaos referred to above.

The Japanese announcement at Durban that it would henceforth focus upon bi-lateral and smaller group initiatives was influential in changing the terms of the debate. It also showed that if countries show cooperative achievement outside the UNFCCC, it may influence negotiators within it, and could also influence the developing countries that are major emitters.

Ambitious pragmatism defines a path forward for sustainable growth to a high-energy planet with a low environmental footprint. The seven lessons from the Kyoto Protocol experience, outlined above, can help give shape to this more viable diplomatic process – a bridge to the future. But caution is necessary. We must not repeat the mistake of the Kyoto era and construct "a bridge too far": negotiators and diplomats must see the bridge as viable. Especially, we must resist the standard temptation to see new solutions as necessarily "high tech" or implemented from the top down.

(ii) Recognise and accommodate the interests of different parties in a transfer of new technology

No global emissions reductions strategy will succeed without the transfer of low-carbon technology from early-adopting nations, either in the developed or developing world, to those countries lagging behind. Significantly greater attention and institutional energy must therefore be invested in next-generation technology transfer schemes.

Such schemes could take many forms. One potentially promising model is an evolution and simplification of the CDM system: the bilateral credit agreement. Under this model, countries with advanced low-carbon technologies provide state-of-the-art technology to lagging countries in exchange for a share of the resulting emissions reduction "credits". This model was announced by Japan at the Durban COP as its preferred way forward. Such schemes are not currently allowed within the Kyoto Protocol's Clean Development Mechanism (CDM), despite their clear benefits. These include a lower bureaucratic burden for the issuance and distribution of credits than currently exists under the CDM, as well as applicability to a wider variety of low-carbon technologies, including CCS/CCU and ultra-efficient coal-fired power plants, which can scale back significantly the impact of otherwise unabated fossil fuel use. Such bi-lateral credit schemes hold particular interest for energy-intensive economic sectors, where prevailing technology in many of the largest global economies lags far behind the best available technology, sometimes by decades.

Across all technology-oriented negotiations through the UNFCCC, Intellectual Property Rights (IPR) have emerged as one of the most critical – and most contentious – issues. While developed countries tend to insist that it is absolutely necessary to maintain strong IPR arrangements to provide incentives for technology development, developing countries assert that such arrangements are the most damaging obstacle to effective technology transfer. Free licensing of green technologies under such instruments as the Agreement on Trade Related aspects of Intellectual Property Rights (TRIPS), they argue, is at once morally, politically, and economically attractive.

What is lacking in this debate is recognition of the fact that, despite the hyperbole of some advocates, we simply do not currently possess sufficiently high-performance, low-cost, and low-carbon energy technology to ensure a sustainable supply of low-carbon energy at affordable prices to the billions of people whose support is required if the policy is to succeed. Energy technology innovation must be promoted, and common sense says that IPR is essential to protect profitability. Without that assurance, not enough private sector money will flow into energy innovation R&D. So there is a trade-off, and the temptation to over-ride the secure market incentive structures must be avoided.

An underappreciated aspect of this debate is that most of the energy-saving and low-carbon energy technologies needed in the coming decades will be assemblies of knowledge, not isolated technologies such as the chemical compositions of individual drugs. Consequently, industrial sectors with remarkable success stories to their credit, (and the pharmaceuticals industry is an obvious one), have only limited relevance as models. The energy innovations that we are seeking will be systems of systems: a combination of many materials and forces, all of which "plug into" existing socio-technical structures. Therefore, transfer in energy technologies involves the transfer of complex manufacturing and operational know-how in addition to the simple licensing of patents. This is a process that can only be achieved by close, mutually constructive cooperation between providers and recipients of new technologies.

For this reason, if the monopoly of new and important technologies by companies in developed countries really hinders technology transfer – as developing world governments argue it does – a resolution will only be achieved through consultative processes deemed acceptable by all stakeholders. Compulsory licensing, an often discussed alternative, will fail because while it may force the transfer of technology patents, these patents will not be accompanied by the critical operational understanding necessary to manufacture and operate the technologies in question or to integrate them into existing complex socio-technical systems.

(iii) Embrace the results of an already naturally occurring global division of labour in energy innovation.

While new energy system technologies have historically flowed from West to East and North to South, today's energy technology innovation ecosystem is much richer and more multi-directional. That is in part because most energy system growth is outside the West and much innovation is likely to occur where new systems are actually being built. It is also because global knowledge production is itself becoming more widely distributed.

Strong energy demand growth in China has led to rapid and large-scale construction of modern grids, renewable energy systems, and advanced nuclear power. It has also seen experimentation with energy efficiency, synthetic fuels, and Carbon Capture and Sequestration (CCS) and Carbon Capture for Use (CCU). Ambitious global energy companies have begun to buy up innovative technologies and practices and induce new ones, and China's scientific research establishment is growing – and increasing its ties to the West. As a result, China remains a useful global test-bed and incubator for new technology, some of it Western in origin but improved in use due to China's need, speed, cost advantage, and liquidity. Elsewhere in Asia, South Korea has emerged as a nuclear power innovator to supply its own growing demand, and is building nuclear units abroad at reportedly competitive rates. Japan is aiming to export advanced nuclear technology and expertise to the Gulf States, to south-east Asia and to some western countries, including Poland and Turkey.

But innovation learned through the experience of building and using a new system – rather in the way that the 19th century railway innovators did – is not the whole story. The United States remains a global hub for upstream scientific innovation and in some cases limited early commercial deployment (some of it financed by China) of advanced nuclear energy, CCS and CCU, energy storage, low carbon liquid fuels, and advanced renewables. The USA is also still a major global knowledge centre for materials science, the simulation and control specialties, and the design and engineering expertise that supports broad energy innovation.

Of course, China and the US are not the only potential global innovation sources. Despite stagnant energy demand, environmental and social policies have led Japan and parts of Europe to attempt to integrate into their grids large – perhaps unachievable – amounts of variable renewable resources such as wind and solar power. That effort, whatever its challenges and results, is likely to yield substantial innovations in grid operation and load-balancing technology along the way. Parts of the Arab Middle East appear poised to pour billions of dollars into advanced nuclear power and solar, as well as carbon use for enhanced oil recovery. Israeli start-ups are making substantial advances in vehicle electrification and solar water heating.

What is now needed is a more considered international division of labour for energy innovation, forged from precisely these sorts of separate but complementary initiatives. Different technologies will require different treatment, and different countries will contribute according to their capacities. For target technologies still in basic research stages, highly-funded international research consortia similar to the mega-cyclotron initiatives of CERN may be suitable. Such initiatives share large burdens internationally and integrate a wide base of human and financial resources. That reduces risk and redundancy and enhances cooperation. Candidate technologies for this sort of early-stage effort include “blue sky” technologies such as nuclear fusion, space photo-voltaic, and microwave electric transfer.

For target technologies that are in more advanced development, and for which the principal challenges are more applied, regional, national and private sector development initiatives should be conducted. In parallel, global *fora* for information sharing and progress reports – such as the APEC initiatives highlighted previously – should promote both competition and collaboration among projects, thereby accelerating the development process.

Sectoral approaches should also be advanced, in particular for the most energy intensive industry sectors such as power, steel and cement. Because energy experts in these industry sectors have common technological backgrounds, it is possible to pursue mutual benchmarking and technology transfer solutions. Sectoral base approaches can promote the rapid global diffusion of the best available technologies and the development of new, sector-appropriate low-carbon technology. The Asia Pacific Partnership on Clean Energy and Climate (APP), discussed previously, hosted such sectoral taskforces, and produced meaningful achievements. Members from the power and steel sectors conducted intensive peer review and energy diagnosis exercises, using common calculation methodologies for carbon intensity and energy efficiency developed under the APP Steel Task Force. Best practice and technology handbooks were also developed to be shared by members. The value of this approach is that these handbooks were developed by the industry experts who actually use and operate the relevant technologies, thereby assuring practicality and effectiveness. The calculation methodologies developed under APP have since been standardized through the International Organisation for Standards as ISOs, which will allow them to diffuse further beyond APP member countries.[54]

CONCLUSION

(i) The future of ambition

“Ambition” is one of those words that politicians most love. They appropriate it to their causes because it resonates with optimism and it touches with a friendly glow every subject to which it is applied. It inspires confidence. In adversarial political combat, it also has the useful quality of wrong-footing opponents because to claim ambition for one’s own position is, by implication, to tar one’s opponent with its doleful opposite.

Talk of “ambition” has been at the centre of climate policy debates of recent years, where it has become the measuring stick by which each country’s commitment to climate change action – and, by implication, its moral virtue – is assessed. But we would argue that this dominant usage of “ambition” has been anything but ambitious. It has been a case of wishful thinking. As has been noted in this paper, it has appealed to a triumph of the will that confuses hope with fact, declaratory statements with action, and acts of legislation with real-world results.

We believe that such rhetoric has not been helpful. It also reveals a radical misunderstanding of what productive ambition can be.

Productive ambition implies, as the Latin root suggests (from *ambire*, to walk about, to visit and seek the political support of), the careful investigation of possibilities and, crucially, the acquisition of public consent in order to produce meaningful, tangible results. Bearing this in mind, a relentless pragmatism may be the most ambitious approach, precisely because it is indirect and governed by the need for public agreement. These are key Hartwellian principles. In the terms of "Capability" Brown's philosophy, by opening our eyes and our minds to the wide range of opportunities that line the oblique pathways that are less travelled – *ambire* – we improve our chances of lightening the human footprint on the planet while creating a more prosperous world. In the 2010 Hartwell Paper, we pointed to options that have since gained traction. This paper has been filled with examples of that. In this 2013 sequel, we have again sought to offer a guide to good practice, this time not in the realm of politics but in that of invention and innovation.

(ii) Ambition for the future

This paper has, we trust, been ambitious in the productive and radical sense, as it has reviewed and sought to identify errors in popular and political assumptions about innovation, and it has argued in favour of certain suggested corrective actions on various institutional levels. The eleven Building Blocks upon which the Hartwellian approach to energy innovation is set out have been explored. With these as our foundation, our conclusion is that many of the recent policy-driven efforts to accelerate the deployment of new energy technologies have been unsuccessful because the conceptual framing of the enterprises was too narrow. This framing mistook that which is necessary (engineering innovation and invention) for that which is sufficient (a full engagement with the multiplicity of differing contexts in which and the variety of peoples and purposes for whom energy is to be provided). Material social change that is capable of enduring is first and foremost about human choice. Therefore, we explained, a much wider and more systematic assessment process is required to achieve legitimacy in the eyes of those affected by any such technological changes, as without this public credibility there is no hope that the developments could be successful and sustainable in the long-term.

If we wish the world's populations to spontaneously and permanently prefer low-carbon technologies, it is essential that these sources are as economically productive as the higher-carbon alternatives – or at least very nearly so. (After all, there is evidence of some willingness to pay for environmental improvements – just not a vast and/or involuntary amount). Policies must therefore ensure that while inventors and innovators have maximum freedom to experiment, there is never any doubt that the aim of their work is to deliver improved cost efficiency. Only general prosperity can produce widespread consent for emissions reductions, and only affordable energy for all can deliver prosperity.

Humanity was able to see earthrise for the first time in December 1968, through the cameras of the Apollo 8 astronauts: our Earth shimmering against the blackness of space, the only point of colour that the astronauts could see, anywhere. The eleven Building Block concepts that we have described, which can support the energy transitions that humanity now needs, draw upon that sense of commonwealth which comes from understanding the indivisibility of our collective fate which was so effectively and elegantly expressed in those famous photographs. The tasks that are involved in achieving this technological breakthrough in a world of “wicked” problems greatly exceed in complexity the challenge of putting men in space. But the simple insight that the Apollo 8 astronauts brought back to Earth can help us to understand both why and how we may progress.

NOTES

1 *The Hartwell Paper: A New Direction for Climate Policy after the Crash of 2009*, lse.ac.uk/researchAndExpertise/units/mackinder/theHartwellPaper/Home.aspx

2 M.E.Caine & S.Rayner (eds), *The Hartwell Approach to Climate Policy,* Oxford: Earthscan, 2013 (Forthcoming).

3 "Tracking Clean Energy Progress", *IEA*. April 2013. www.iea.org/etp/tracking/.

4 H. Rittel & M. Webber, "Dilemmas in the General Theory of Planning", *Policy Sciences* 4, 1973, pp. 154-59.

5 S. Arrhenius, "On the influence of carbonic acid in the air upon temperature of the ground", *The London, Edinburgh & Dublin Philosophical Journal and Journal of Science*, Fifth Series, April 1896.; J. Otto, "Energy budget restraints on climate response", *Nature Geoscience*, 19 May 2013

6 J. Jenkins. "Energy Emergence: Rebound and Backfire as Emergent Phenomona," Breakthrough Institute 2011, http://thebreakthrough.org/blog/Energy_Emergence.pdf

7 W.S. Jevons, *The Coal Question* (2nd ed.), London: MacMillan, 1866.

8 The IEA, the IPCC, and the UK DECC have attempted to sustain unrealistic claims for the impact on greenhouse gas emissions of energy efficiency; these have been successfully disputed in, amongst others, Jenkins, "Energy Emergence: Rebound and Backfire

as Emergent Phenomena", 2011; Maxwell, "Addressing the Rebound Effect, a report for the European Commission DG Environment", 2011; REF, "Shortfall, Rebound, Backfire: Can we rely on energy efficiency to offset climate policy costs?", 2012.

9 "ETS.RIP?", *The Economist*, pp. 67-68, 20 April 2013.

10 For example, the 2010 paper recommended priority attention to reduction of black carbon from partial combustion. Since then, the importance of black carbon in high latitude ice melting has been more thoroughly documented, notably in D. Shindell, "Simultaneously Mitigating Near-Term Climate Change and Improving Human Health and Food Security", *Science* 335 (6065), 13 January 2012, pp.183-189.

11 R. Pielke Jr, *The Climate Fix: What Scientists and Politicians Won't Tell You About Global Warming*, New York: Basic Books, 2010.

12 See The Copenhagen Accord, 18 December 2009; ADP Workstream 1: 2015 Agreement, Submission of the United States, 11th March, 2013

13 Oil, coal and natural gas currently comprise 87 per cent of the global primary energy mix. All figures from *BP Statistical Review of World Energy*, BP, 2012.

14 J. Schumpeter, *The Theory of Economic Development: An Inquiry into Profits, Capital, Credit, Interest, and the Business Cycle*, Cambridge: Harvard University Press, 1934 pp. 54

15 *BP Statistical Review of World Energy*, BP, 2012.

16 *Climate Change 2007 – The Physical Science Basis Contribution of Working Group I to the Fourth Assessment Report of the IPCC*.

17 *BP Statistical Review of World Energy*, BP, 2012.

18 *ibid*

19 B. Plumer, "Peak oil isn't dead: An interview with Chris Nelder", *The Washington Post*, 13 April 2013, www.washingtonpost.com/blogs/wonkblog/wp/2013/04/13/peak-oil-isnt-dead-an-interview-with-chris-nelder/

20 See US Energy Information Administration, "Levelized Cost of New Generation Sources" in *Annual Energy Outlook, 2011*, Table 1. Central estimates include: combined cycle gas ($63-66/MWH); coal ($94-109/MWH); advanced coal with CCS ($136/MWH); advanced nuclear ($113/MWH); onshore wind ($97/MWH); offshore wind ($243/MWH); Solar PV ($210/MWH); Solar Thermal ($311/MWH).

21 See, for example, A. Purvins, "Challenges and options for a large wind power uptake by the European electricity system", *Applied Energy* 88(5), May 2011, pp. 1461–1469; P. Denholm and M. Hand, "Grid flexibility and storage required to achieve very high penetration of variable renewable electricity", *Energy Policy* 39(3), March 2011, pp.1817-1830; MIT Energy Initiative Symposium, "Managing Large-Scale Penetration of Intermittent Renewables", April 20, 2011, http://web.mit.edu/mitei/research/reports/

intermittent-renewables.html; Idaho Power, "Wind Integration Study", February 2013, www.idahopower.com/pdfs/AboutUs/PlanningForFuture/irp/2013/windIntegrationStudy.pdf; C. Gibson, "A Probabilistic Approach to Levelised Cost Calculations for Various Types of Electricity Generation" *Institute for Engineers and Shipbuilders in Scotland,* Edinburgh, 2011, www.iesisenergy.org/lcost/.

22 Energy Outlook 2030, BP, January 2013, www.bp.com/extendedsectiongenericarticle.do?categoryId=9048887&contentId=7082549.

23 See *BP Statistical Review of World Energy*, 2012; Data from World Bank, 2012: World Bank Databank, http://databank.worldbank.org/.

24 J. Sweeney and A, Sudarshan, "Deconstructing the Rosenfeld Curve", http://piee.stanford.edu/cgi-bin/htm/Modeling/research/Deconstructing_the_Rosenfeld_Curve.php#Project%20AbstractHe. Another, more recent, study suggests the effect of California energy policies was essentially zero. See A. Levinson, "California Energy Efficiency: Lessons for the Rest of the World, or Not?", http://isites.harvard.edu/fs/docs/icb.topic1121559.files/January%2030%20-%20Arik%20Levinson/CaliforniaEnergy.pdf.

25 U.S. energy-related CO_2 emissions in early 2012 lowest since 1992', U.S. Energy Information Administration (EIA), 1 August 2012, www.eia.gov/todayinenergy/detail.cfm?id=7350.

26 J. Jenkins and S. Mansur, “Bridging the Clean Energy Valleys of Death”. *The Breakthrough Institute*, November 2011.

27 V. Smil, *Energy at the Crossroads*, Cambridge: MIT Press, 2003.

28 See H. Ausubel. and H.D. Langford (eds), *Technological Trajectories and the Human Environment*. Washington: National Academy Press, 1997; A. Grubler, N. Nakicenovic, and W.D. Nordhaus, *Technological Change and the Environment*. Washington: RFF Press, 2002.

29 V. Smil, *op cit*

30 H. Haberl, “The Global Socioeconomic Energetic Metabolism as a Sustainability Problem”, *Energy* 31(1), January 2006, pp. 87-99.

31 J.H. Ausubel, “Energy and Environment: The light path”, *Energy Systems and Policy* 15, 1991, pp. 181-188.

32 M. Lynas, “A Squandered Opportunity: Germany’s Energy Transition”, *The Breakthrough Institute*, 17 January 2013.

33 A. Sopinka and L. Pitt, “Variable Energy Resources: VERy Interesting Implications for the Western Interconnect”, *The Electricity Journal*, 26(5), 2013. http://dx.doi.org/10.1016/j.tej.2013.04.015.

34 P. Atherton, “Future of Utility Finance in the 2010s”, speech to Future Energy Strategies, 1 May 2012.

35 Such behaviour was famously described in C.Mackay, *Extraordinary Popular Delusions and the Madness of Crowds*, 1st edn, 1841.

36 “Tracking Clean Energy Progress”, *IEA*. April 2013. www.iea.org/etp/tracking/.

37 D. Shindell, “Simultaneously Mitigating Near-Term Climate Change and Improving Human Health and Food Security”, *Science* 335 (6065), 13 January 2012, pp. 183-189.

38 A. Trembath. “Where the Shale Gas Revolution Came From,” *Breakthrough Institute,* May 2012.

39 U.S. Energy Information Agency (EIA) *Natural Gas Data*, www.eia.gov/naturalgas/.

40 “Coming Home”, *The Economist*, 19 January 2013.

41 A. Trembath, “Where the Shale Gas Revolution Came From”, *The Breakthrough Institute*, 23 May 2012.

42 National Energy Technology Laboratory, “DOE’s Unconventional Gas Research Programs 1976-1995: An Archive of Important Results”, U.S. Department of Energy, January 2007, www.netl.doe.gov/kmd/cds/disk7/disk2/Final%20Report.pdf; E.D. LaFeher, “The Effects of Section 29 Tax Credit on Energy and the Environment: A Cost-Benefit Analysis”, Journal of Energy and Development 17, 1993, pp. 1-22; R. Ames, “The Arithmetic of Shale Gas,” *Yale Graduates in Energy Study Group*, June 2012, http://papers.ssrn.com/sol3/papers.cfm?abstract_id=2085027.

43 See Jenkins, “Beyond Boom and Bust”, *The Breakthrough Institute,* April 2012; “Utilities: Powerhouses of Innovation”, *Eurelectric*, 8 May 2013.

44 www.gov.uk/government/news/government-agreement-on-energy-policy-sends-clear-durable-signal-to-investors

45 See for examples, “£286 Green Tax on Energy Bills”, *Daily Mail* 27 March 2013; and “Revealed: true cost of wind farms”, *Sunday Telegraph* 16 June 2013.

46 A. Rip and R. Kemp, “Technological change”. In E.L. Malone and S. Rayner (eds), *Human Choice & Climate Change, Volume 2: Resources and Technology*, Columbus: Battelle Press, 1998.

47 C. Freeman and F. Louca, *As Time Goes By: From the Industrial Revolutions to the Information Revolution*, Oxford: Oxford University Press, 2001.

48 “Multiple benefits from investing in energy efficient renovation in buildings”, *Copenhagen Economics*, 2012.

49 For a detailed discussion of how this may be done, see Jenkins, “Beyond Boom and Bust”, *The Breakthrough Institute,* April 2012

50 D. Helm, *The Carbon Crunch*, Oxford: Oxford University Press, 2012. *The Economist* is now seen to be nailing its colours to a universal carbon tax: “Tepid, timid,” The Economist, pp. 16-17, 29 June 2013

51 The precise nature of the disjuncture between the Kyoto Protocol and the climate change issue

was explained in G.Prins & S. Rayner, “The Wrong Trousers”, 2007 and G. Prins and S. Rayner, “Time to ditch Kyoto”, *Nature* 449, 2007, pp 973-975. This work led to the launch of the first phase of the Hartwell initiative, and the evolution of the analysis therein is further explained in M.E.Caine & S.Rayner (eds), *The Hartwell Approach to Climate Policy*, Oxford: Earthscan, 2013 (Forthcoming).

52 “APEC Energy Overview”, *APEC*, 2011, http://aperc.ieej.or.jp/file/2012/12/28/Overview2011.pdf.

53 The APP’s activities can be studied at greater depth at www.asiapacificpartnership.org/english/default.aspx

54 ISO 14404-1 for Blast Furnace process and ISO 14404-2 for Electric Arc Furnace process were published in March 2013.

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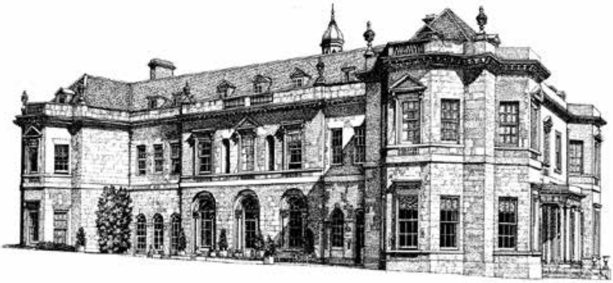

Hartwell House in Buckinghamshire, where the Royal Meteorological Society was founded in 1850 and where the Hartwell group was originally formed and has continued to meet since 2009.

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