The challenge of environmental technology: promoting radical innovation in conditions of lock-in.

FINAL REPORT TO THE GARNAUT CLIMATE CHANGE REVIEW

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Summary

How can we sustain global economic performance while reducing and perhaps eliminating climate impacts? This dual objective ultimately requires the innovation of radically new low- or zero-emitting energy technologies. But what is involved in such innovation, and why and how should governments support it? What are the implications for innovation policymakers?

The paper discusses the nature of the innovation challenge of climate change, develops a framework for analysing modes of innovation, applies the framework to energy technologies and analyses policies for energy innovation. The overall argument is that we are ‘locked in’ to an unsustainable but large-scale hydrocarbon energy system. Despite widespread innovation efforts and incentives, these are not yet addressing the innovation challenge on an adequate scale. Addressing these issues will involve new mission-oriented programs, coordinated by new or modified transnational agencies.

The analytical framework sees technologies not as single techniques but as multi-faceted technological ‘regimes’. Regimes involve production organisations and methods, scientific and engineering knowledge organisation, infrastructures, and social patterns of technology use. We live not with individual energy technologies but with a complex hydrocarbon regime.

Against this background we can identify three modes of innovation, with very different characteristics. They are

- Incremental innovations - upgrades to existing technologies, producing innovation within existing technological regimes, such as increases in the capabilities and speeds of microprocessors.
- Disruptive innovations - new methods of performing existing technical functions, changing how things are done, but not changing the overall regime, such as the shift from film to digital imaging.
- Radical innovations - technological regime shifts, involving wholly new technical functions, new knowledge bases, and new organisational forms, such as the transition from steam power systems to electricity.

We need environmental innovations on all three of these dimensions of innovation, but we have innovation programs and policy instruments for only the first two. There are no large integrated programs seeking regime-shifting innovation of the final type.

Current policies instruments for environmental change have four basic forms - carbon taxes or emissions constraints, subsidy and procurement measures, regulatory instruments and R&D and commercialisation programs. The first set of measures is likely to promote incremental innovation only. The second and third would also support the emergence of new technological functions. Each is very important, and will frame a context in which further change can happen. But none will in themselves lead to fundamental innovation in the hydrocarbon regime.

Regime-shifting innovation typically involves long-term and highly risky innovation programmes along multiple search paths. Such programmes have usually rested on integrated public and private action. They consist of purposive, goal-oriented changes in the overall systems of knowledge, infrastructure and use patterns that make up technological regimes. In one form or another they entail methods for solving such problems as

- the shared identification of opportunities among entrepreneurs and public agencies

- substantial resource mobilisation and commitment to develop new capabilities
- methods for the management of innovation risk and uncertainty
- sustained scientific and technological problem solving, and processes of 'collective invention'
- 'patronage' of new technologies through long development periods before they reach commercial viability
- new infrastructures and institutions
- integration of public sector and business investment commitments

Most of the core technologies of the modern world have involved such processes, very often initiated or coordinated via public agencies of various kinds. The public-sectopr roles have been necessary fofr coordination purposes, for resource commitments, and for risk management. These considerations suggest very different roles for government in climate-relevant innovation than are currently envisaged in the climate debate.

We now require new large-scale "mission-oriented" technology programs for low- or zero emissions energy carriers and technologies, resting on public sector coordination and taking a system-wide perspective. However the key point about global warming is that it results from a global negative externality, which is beyond the capabilities of any single government to resolve. Government action for technology development is also constrained by globalisation, by changing views of the legitimate roles of government, and by changing forms of the state at the present time (in particular the decline of nation states and the rise of transnational governance).

This is therefore a challenge for which global innovation policy cooperation is necessary. The paper concludes by discussing possible mechanisms and governance of such cooperation, advocating the need for a transnational agency - either wholly new or developed out of an existing agency – to act as a forum for transnational policy networks and as a mechanism for the development of a truly global innovation policy for climate change.

If these challenges are intimidating, it is worth noting that innovation outcomes on a similar scale are not unprecedented. Unforeseen energy carriers have emerged before, the most recent spectacular example being nuclear power, which was simply unenvisaged considerably less than a century ago. The challenge of landing men on the moon involved technologies that did not exist when President Kennedy formulated the objective. The technological challenge of storing energy on a large scale appears to be intractable, but our society has solved an arguably bigger storage problem, that of storing, rapidly searching and retrieving vast volumes of information. The technologies for doing this were unforeseeable only a short time ago, and were generated by the sorts of programs advocated here. Against the background of the history of technology, which is one of extraordinary innovation and diffusion, we have no reason to be pessimistic about the challenges we face with respect to energy and environmental sustainability.

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1. GLOBAL WARMING AND INNOVATION

What are the main innovation and technology policy problems in stabilising and then reducing greenhouse-gas emissions from our currently dominant hydrocarbon energy technologies? The argument of this section is that continued innovation is central to the solution of environmental problems related to energy, and that such innovation should be directed towards creating low- or zero-emission technology options. Later sections address what is involved in climate-relevant innovation, both in terms of the nature of innovation processes, and the policy support issues.

1.1 The innovation policy challenges of climate change

There are some environmentalists who argue that sustainability must mean attenuating our total energy consumption. The position suggested here, however, is that we should seek sustainable greenhouse gas emission targets, without reducing global energy consumption drastically.

The reason for this is that the people of the world will clearly seek to improve current levels of global economic development, and this will require maintaining and even increasing levels of energy consumption.[1] Achieving growth without continued greenhouse gas build-up implies that low-emissions energy innovation must occur and be multi-faceted. This can happen via reduced emissions from currently used technologies, or the development of a wide variety of low-emission technologies that may not individually have any prospect of replacing current technologies. We can also encourage life-style and consumption changes. Taken together these can have significant effects. However if rapid growth continues on the basis of hydrocarbons, the effects may be limited in relation to the overall scale of the climate problem.[2] This

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[1] In the long run, economic development is associated with decreasing energy inputs per unit of output, because growth involves shifts to lower-energy activities such as services. But if global output grows rapidly, especially in large economies such as Brazil, China and India, decreasing energy coefficients will not necessarily stabilise energy use in the foreseeable future. For a discussion, see David I. Stern, ‘Economic growth and energy’, *Encyclopaedia of Energy* Vol 2, 2004.

[2] Probably the best available overview relating the technical issues in environmental technologies to their economic costs and impacts is John M Deutch and Richard K. Lester, *Making Technology Work. Applications in Energy and the Environment* (Cambridge: CUP)

suggests that any long-term strategy must also include search for full technological alternatives to the hydrocarbon-based technologies - for low or zero emission innovations in large-scale technologies for energy production, distribution and use. These latter innovations are difficult to forecast, and likely to be radical in the sense that they will go far beyond our current knowledge bases and technological horizons.

In addressing climate change we therefore face the need for at least two distinct modes of innovation: one, which inflects existing technologies and their development paths, and a second, which creates entirely new technologies. In understanding any transitions away from our current situation, it is extremely important to recognise the specific characteristics of these different types of innovation processes. Policies directed toward encouraging one mode of innovation may be utterly ineffective towards the other. Over the past two or three decades there has been a substantial global research effort on the sources, characteristics, and directions of innovation which throws some light on these issues. The empirical and conceptual conclusions from this research are often at odds with both popular and policy understandings of innovation, but they are highly relevant to our climate predicament.[3]

In particular, radical technological change usually faces a major problem, which is that it competes with the dominant technology currently in use. Existing dominant technologies usually have powerful commercial advantages over new technologies, even if the new is potentially superior in the long run. This is certainly the case with energy technologies – at present there are no technologies that can compete with the hydrocarbon regime. So in considering new technologies it is important to distinguish between innovations and policies that in effect aim to keep the hydrocarbon technology running, while mitigating its effects, and policies that seek to change it. The argument of this paper is that our currently dominant technologies will be affected

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2004. Their very careful analyses suggest limits to the benefits to be achieved from a number of technological alternatives, and hence a need for further search.

[3] The most comprehensive single overview of the recent research effort on innovation is J. Fagerberg, D. Mowery and R. Nelson (eds) *The Oxford Handbook of Innovation* (Oxford: OUP) 2004. Previous applications of this ‘innovation studies’ effort to environmental problems include J. Alic, D. Mowery and E. Rubin*, U.S Technology and Innovation Policies – Lessons for Climate Change*, Pew Centre on Global Climate Change, 2003; and J-P. Voss, D. Bauknecht and R. Kemp (eds), *Reflexive Governance for Sustainable Development*, (Edward Elgar, Cheltenham), 2006 .

but not fundamentally changed either by economic factors (including price shifts and tax policies) or by regulatory action. This is because the relevant technologies take the form of complex interlocking systems that are characterized by long-run cumulative development. Complexity and cumulativeness underlie ‘lock-in’ – the inability to move away from technologies that are in some sense less adequate than alternatives.

This is the basic problem with hydrocarbons: we do not have simply a technological system but a social and economic one. Hydrocarbon energy carriers and technologies are a central component of the urban ecologies of the world, the location and trade patterns of global industry, and global transport patterns related to both human mobility and economic consumption: they are tied intimately to the social construction of our modes of life. In this situation, the twin policies of quantity constraints on emissions or carbon taxes change the marginal costs of one part of the system (fuel use itself) and thus impel economising behaviour including efficiency-seeking innovation. But these instruments provide neither incentives nor routes towards a change in the system itself, which is a much more complex socio-technical problem.

One practical illustration of the problem here might run along the following lines. The EU and the US economies are of broadly comparable size. Over several decades EU governments have systematically raised petrol prices through taxation, and pump prices are significantly higher than the USA: in 2003 the retail petrol price in Germany, roughly the median in Europe, averaged 1110 euros per 1000 litres, which was more than double the US retail price at that time. The result appears to be differences in fuel economy of vehicles, but no shift away from private vehicle transport in Europe. On the contrary, the EU stock of private cars in 2005 was 219.8 million in 2005, 61% higher than the USA at 136.6 million cars. However the USA has 108.8 million trucks, compared to the EU’s 31.8 million, largely deriving from the fact that many American SUVs are classified as light trucks. Adding the difference in trucks (77 million) to the US stock of cars would mean that total non-goods vehicle stocks are almost identical in the EU and the USA. In other words, the end result of significantly different fuel prices appears to be marked differences in vehicle and engine types (with extensive innovation and diffusion of diesel engines in cars in the EU, for example) and fuel economy, and differences in vehicle use patterns, but no shift away from the ownership of private vehicles for transport in Europe. This is despite the existence of high-quality public transport systems in many European cities. Sustained tax and price differences have affected the trajectories of vehicle innovation, but have had minimal impact on the scale of private-vehicle transport choices.

More generally, it is difficult to think of a carbon price that would generate systemic change, as opposed to incremental change within the existing technology. The reason is that such a price would have to render the hydrocarbon system as a whole unviable, and the wider costs of such a price policy would make it impossible to implement. Against this background, the most important environmental challenge for innovation policy is to think through the reasons for the fundamental embeddedness of the hydrocarbon system and its transport technologies, and to consider how it might be changed through the creation of alternatives. How then can radical innovation be initiated and sustained in circumstances constrained by commercially efficient and strongly embedded existing technologies?

1.2 Externalities and climate change – the results of long-run human innovation

The need for innovation lies in the fact that although the earth's climate has rather well understood natural variation, related mainly to solar activity or to the complex dynamics of the earth's orbit, current climatic trends appear to derive from the long-run impacts of technological changes. Human impacts on the environment may have deep roots in human history, but they accelerated during and after the first industrial revolution as a result of the diffusion of hydrocarbon-based energy carriers and related technologies.[4] A distinctive feature of economic evolution since the late 18th century has been persistent development and use of energy- and information-intensive technologies, and while this has had spectacular effects on technical capabilities and on human welfare, the energy dimensions of modern technologies have also had significant environmental impacts.[5]

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[4] William Ruddiman has argued that significant impacts of human activity on climate can be identified following the emergence of farming, approximately 12,000 years ago, but increased dramatically 200 years ago. W.F. Ruddiman, *Plows, Plagues and Petroleum. How Humans Took Control of Climate* (Princeton, N.J.: Princeton University Press), 2005

[5] On the changing roles of energy carriers and their relations to industrial 'development blocks', see A. Kander, P. Malanima and P. Warde, 'Energy transitions in Europe, 1600-2000', paper presented to conference on *Technological Transitions and Discontinuities*, ECIS, Eindhoven, 2008.

The welfare benefits and environmental costs of past innovation are in fact related, because although market economies provide considerable incentives to innovation, they are characterized both by imperfect appropriability of innovation benefits, and by imperfectly assigned costs of technology use. So market systems encompass both positive and negative technological externalities, on a very large scale.[6] The positive externalities of knowledge creation are powerful drivers of growth. They play a central role both in modern theories of economic growth, and in economic histories of the spectacular growth performance of the past two hundred years.[7] Environmental problems, on the other hand, derive from the negative technological externalities. A key issue for policymakers is whether the negative externalities can be attenuated through pricing mechanisms (such as carbon taxes) and regulation (such as mandatory emissions caps) or whether they also require control by innovation efforts that extend beyond price incentives.

Some of the detrimental externalities of existing technologies are dealt with over time by economic and regulatory processes. If resources become exhausted along a predictable path where established markets exist, rising input costs generate substitution effects that can impel innovations. This may have powerful effects on types and levels of inputs, and on accompanying pollution or emission problems.[8] In addition, there are many changes that can be made via regulatory instruments, to mitigate or remove environmental damage. At the present time the main actual or proposed instruments to cope with climate change in fact fall into this category: regulations to cap emissions outputs (with tradable permits) or taxes to raise their costs. Some of these changes, combined with general impulses to cost reduction, have led over past decades to marked increases in the energy efficiency of specific

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[6] A technological externality exists when the actions of one economic actor have an effect on the welfare or the productivity of another actor indirectly (meaning other than through the price system). A familiar example of a negative technological externality is pollution. The results of fundamental science are often held to be a positive technological externality.

[7] For an overview of the theory on knowledge externalities, see B.Verspagen, 'Innovation and Economic Growth' in Fagerberg et al, op. cit, 487-513; for a historical account, J. Mokyr, *The Gifts of Athena. Historical Origins of the Knowledge Economy* (Princeton and Oxford: Princeton University Press), 2002

[8] F.R. Lichtenberg, 'Energy prices and induced innovation', *Research Policy*, 15, 1985, pp.77-87.

technologies, notably automobile engines. In emissions terms however the widening of economic activity as growth proceeds can offset these.

1.3 Why does climate change justify major innovation efforts?

While there is no attempt here to assess the evidence on climate change, or current debates on its scope, causation or potential paths, it is clearly necessary to suggest why radical (and very likely expensive) innovation policies are even being discussed. What are the potential paths, effects and costs of climate change? On the one hand, there is the scientific consensus embodied in the work of the International Panel on Climate Change (IPCC), to the effect that greenhouse gas buildup is anthropogenic and leading to global warming. On the other, there are vocal objections to the IPCC and insistent arguments against the need for any form of action, let alone the rather wide-scope policy initiatives that will be outlined below.

There are three scientific issues in dispute, and one economic question. Is the global climate becoming warmer, is it due to increased greenhouse gases, and is warming due to human activity? Beyond this is the economic question: is it worth doing anything about it? Objections to action take two forms. On the one hand there are more or less explicit lobby groups typically answering no to all three scientific questions, usually on the basis of objections to data and climate modeling results; on that basis the economic question becomes otiose. Advocates for these positions usually argue the need for ‘sound science’, and claim that there is a scientific uncertainty and hence a debate that involves competing conclusions and a lack of scientific consensus. On the other hand there are those of a more economic bent who accept that the world is becoming warmer and that human activity is responsible, but argue that the costs of seeking to mitigate climate change far outweigh any potential benefits. From this perspective, we should adapt to climate change rather than seeking to modify it. The most articulate advocate of this position is Bjorn Lomborg, who argues on the basis of a cost-benefit analysis that spending money on climate change is likely to be considerably less fruitful than seeking to reduce or eliminate malaria, for instance.[9]

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[9] B. Lomborg, *Cool It: The Skeptical Environmentalist’s Guide to Global Warming* (NewYork: Knopf) 2007; B. Lomborg (ed.) *Global Crises, Global Solutions* (Cambridge: CUP) 2004

These positions have two fundamental weaknesses. On the scientific front, we have in fact had major programs of work that by any reasonable standard have generated sound science and a scientific consensus. The ‘lobbying’ positions tend to neglect the fact that discussion of global warming has now been continuing in a serious way for a couple of decades. Sixteen years ago, William Cline, in a discussion of the scientific and economic issues stressed that

> ... an ambitious plan of firming up the science and greatly elaborating the meagre estimates of economic effects is called for over a period of perhaps no more than a decade.[10]

This is more or less exactly what subsequently happened. There has been a sustained global research program of scientific work on a very wide range of climate-related issues, none of which has disconfirmed the core hypotheses of global warming. While nothing in science is ever definitively settled, there is in fact a scientific consensus, which is summed up in the reports of the IPCC. This is not purely a scientific consensus, since publication also required unanimous political approval by UN member countries. An underlying assumption of this paper is that the IPCC work should be accepted as the basis of current policy debate on climate change: that is, that current climate scepticism is not a responsible basis for policy analysis.

This then leaves the question of the appropriate way in which IPCC work might be assessed in economic analysis. One possibility would be simply to take the mean values offered by the IPCC, and conduct some kind of cost-benefit analysis of programs for reducing these means. This is the approach of Lomborg, who concludes that potential benefits are small in relation to costs. This approach is open to a range of methodological and conceptual challenges.[11] One set of these relate to the idea that cost-benefit analyses essentially make point estimates of two states, and neglect the dynamic risks associated with transitions. Two types of risk are relevant. The first is that global temperatures may

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[10] W.R. Cline, "The Scientific Basis for the Greenhouse Effect", *Economic Journal,* Vol 101, No 407, 1991, p.918.

turn out higher than estimated: the IPCC work contains not only estimates of means for global temperature increases, sea level rises, etc, but also confidence intervals for variation around the means. That is, there are estimates of probabilities for quite substantially higher or lower temperature means; at the higher end, global impacts would be very severe. The second issue concerns the transition path to a higher-temperature world. Here there are not just risks, but uncertainties (in the sense that we cannot estimate probabilities, because we do not know what outcomes are even on the agenda). Since both the earth's climate, and ecological systems generally, are complex non-linear systems, any transition to higher mean temperatures may involve abrupt, unpredictable and irreversible shifts into new regions.[12] This implies significant risks and uncertainties that would be difficult to integrate into a cost-benefit analysis. In this case, we are in need of options for coping with events that may be highly uncertain, yet whose impacts would be very adverse. This means a need for technological options that would provide some measure of hedging against a range of potential outcomes. The question then is how to achieve these options: what kinds of new technologies would be necessary to obviate the risks posed by our current climate trajectory?

1.4 Current economic analyses of climate change and their innovation approaches

While the economics of climate change is being intensively studied at the present time, existing treatments of the innovation challenges are not strong. By far the most important recent economic and policy analysis is the *Stern Review*, which has provided a major step forward, and is probably the definitive treatment of the economics of climate change at the present time.[13] Stern argued that:

- Climate change results from an externality associated with emissions
- Impacts are global, long term and persistent
- Uncertainties and risks in impacts are pervasive

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[11] P. Dasgupta, "Standard cost-benefit analysis may not apply to the economics of climate change", review of B. Lomborg, *Cool It*, in *Nature*, 449, September 2007

[12] P. Dasgupa, S. Levin and J.Lubchenko, "Economic pathways to ecological sustainability: challenges for the new millenium", *BioScience*, 2000, 50 (4), pp.339-345.

[13] N. Stern, *The Economics of Climate Change. The Stern Review* (Cambridge: CUP), 2006.

- There is serious risk of major irreversible change with non-marginal economic effects

These conclusions suggest both a need for action to avert further climate change, and a role for public policy in doing so. However the Review contains a serious problem - the innovation dimensions of the climate change challenge are conceptualised in a simplistic way. Stern argues for a policy response aimed at abatement strategies, which would in effect provide incentives to innovation. The abatement strategy seeks to generate such incentives by changing the costs associated with carbon use, or by directly focusing on innovation via technological advances in power, heat and transport technologies. The main measures proposed by Stern are:

- Reduce demand for emissions-intensive goods and services (via carbon taxes)
- Seek fuel efficiency gains (replace coal power with extra 2 million windmills plus 7GW more nuclear)
- Develop low-carbon power, heat and transport technologies (cut carbon emissions by 25% in buildings, raise car fuel efficiency from 30 to 60 mpg)
- Reduce non-fossil fuel emissions by reducing deforestation

Significant innovation is required by all but the last of these measures. The new technologies – particularly in power, heat and transport - aimed at by Stern will certainly require policy incentives and support measures. This point is emphasized in the recent Pew Climate Change Centre report, which remarks that

> Stabilizing atmospheric concentrations of CO2 and other GHGs at a "safe" level, the international goal under the United Nations Framework Convention on Climate Change, would have profound implications for industrial and industrializing economies alike. Human activity now adds around 8 billion metric tons of GHGs to the earth's atmosphere each year, a total that is growing approximately 4 percent annually. A widely discussed goal of stabilizing atmospheric CO2 at twice the pre-industrial level by 2100 (i.e., at 550 parts per million, 65 percent higher than today's concentration) implies worldwide CO2 reductions on the order of 60 to 80 percent below projected

> "business as usual" levels for the remainder of the 21st century. Substantial reductions in U.S. CO2 emissions would require that the United States replace or retrofit hundreds of electric power plants and substantially improve the efficiency of tens of millions of vehicles. In addition, appliances, furnaces, building systems, and factory equipment numbering in the hundreds of millions might also need to be modified or replaced. Technological change on this scale cannot happen immediately. Many of the technologies needed do not yet exist commercially or require further development to reduce costs or improve reliability.[14]

The *Stern Review* approaches the innovation issue by recommending policies based on R&D and commercialisation strategies, seeing the problem essentially in terms of a low level of R&D in energy and transport sectors. This is, in effect, to deploy the so-called 'linear model of innovation', in which innovation proceeds in a more or less linear fashion from research through to engineering and applied development, and then to diffusion.

The problem – to be discussed in more detail below - is that this is an outdated and indeed discredited view of innovation. Innovation only rarely begins with R&D, and in only a very small proportion of cases might be seen as the commercialisation of some prior act of discovery founded in R&D results. The 'R&D + commercialisation' approach used by Stern is certainly popular among science lobbies and governments, but simply does not reflect the dominant processes by which most innovation has occurred historically.

The central difficulty here is that the conceptual underpinnings of the approach to innovation in the Stern Review simply do not accord with what we know about the generation of large-scale radical innovations in the advanced economies. The key challenge to be addressed, therefore, is how we can apply the concepts and methods of recent innovation research to the innovation problems of climate change.

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[14] Alic et al, *op.cit*, p.4

2. LARGE-SCALE INNOVATION: A CONCEPTUAL AND HISTORICAL FRAMEWORK

This section turns to the question of how innovation can be conceptualised and understood, and what the implications might be for future energy technologies. Continuous innovation is one of the few phenomena really distinguishing modernity from previous epochs, yet it has only rather recently begun to be studied empirically and theoretically in any detail. A survey of this work would go far beyond the scope of this paper, but this section outlines a framework for thinking about modes of innovation, drawing on some core concepts from recent innovation research. One aim here is to distinguish between forms of innovation for which strong incentives and opportunities exist in market economies and those that face more or less severe lock-in constraints. Innovation has many modalities, and a central point here is the need to recognise the complex diversity of sources and constraints that generate or inhibit different types of innovation. Policy-makers are not always aware that incentives for innovation may be highly localised in terms of what modes of innovation they are likely to produce, and this is a serious problem in seeking new technologies in the face of climate change.

The discussion in this section turns on five basic issues explored in the analysis of innovation, namely:

1. The role of formal Research and Development (R&D) in innovation processes, distinguishing between R&D as a source of innovation and R&D as problem-solving activity within ongoing innovation processes
2. Differences in modes of innovation, particularly with respect to the novelty of innovations in relation to existing technological knowledge, and the roles of different social actors in generating them
3. Technological complexity, and in particular the need to understand technologies not as individual artifacts but as more or less complex technical systems; the central concepts here is those of the ‘technological regime’ or ‘technological paradigm’.

4. The roles of ‘innovation systems’, meaning the roles of persistent industrial, institutional and social frameworks, in shaping or constraining paths of technological change
5. Resting on the above characteristics, are concepts of ‘path dependence’ and ‘lock-in’, each of which refers to the ways in which technological regimes and innovation systems inhibit the innovation of technological alternatives, or prevent transition away from existing technologies.

Against the background of these concepts and ideas, the paper will then turn to a discussion of different modes of environmental innovation, and how they might be supported and achieved.

2.1 The role of R&D in innovation: a source, or an accompaniment?

An influential popular view of innovation – much promoted by leading scientists, for obvious reasons – is that innovation derives from research, and especially scientific research.

This model of innovation, in which discovery processes precede the translation of research results into engineering process and then into products, very rarely describes either business-sector innovation or the wider ways in which major technologies have entered the world. A core result of modern innovation research is that R&D is generally not an originating process of innovation.[15] At the firm level, firms compete technologically not by performing R&D looking for applications, but by building new product concepts that draw heavily on existing knowledge bases. As they seek to build new products they constantly face unanticipated problems, some of which require R&D to solve. This means that R&D is best seen as a problem-solving activity within existing innovation programs, rather than a search mechanism for new discoveries. That is, innovation is usually non-linear in character: work starts, there are problems and feedbacks, there may be R&D along the way, with testing, development and market exploration going on constantly. The real problem is how new product and

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[15] A classic statement of the issue here, more than twenty years ago, was Stephen Kline and Nathan Rosenberg, “An overview of innovation”, in R. Landau and N. Rosenberg (eds) *The Positive Sum Strategy. Harnessing Technology for Economic Growth* (Washington: National

process development programs get started, and how they are continued, especially when setbacks occur.

Looking beyond R&D at the firm level, there is a question about the role of R&D in developing "big" technologies. The technological landscape of the modern world rests on major innovations that have been developed largely by agencies other than firms. Virtually all of the "core" technologies of modernity – in electronics and computing, materials, communications, transport, and industrial production methods, for example – were initiated and brought to feasibility with the heavy involvement of universities and public or quasi-public labs, and via large-scale publicly-funded technology programs. As with firm-level innovation, these programs were not R&D-driven, although much R&D was done. Rather, these can best be understood as the result of "mission-oriented" programs, aimed at producing specific technological solutions, often heavily influenced by military objectives. The implications of this will be discussed below. In any event, neither knowledge of how companies actually innovate, nor knowledge of how modern technologies actually emerged, supports the idea that we can generate significant new technologies purely via R&D programs (whether or not they are accompanied by commercialisation programs).

2.2 Technological regimes and modes of innovation: incremental, disruptive, radical

The technologies of the modern world are immensely complex, being the outcomes of long evolutionary processes of technical and organisational development. The result is that the technological landscape is a multi-faceted, multilayered array of technologies across a very wide space of technical functions. Analysing this complexity presents enormous conceptual and classificatory challenges. To keep things manageable in the face of this, what is suggested here is a simple three-level taxonomy of innovations organised around the concept of a 'technological regime'.

It was noted above that technologies are not singular, isolated artefacts. Rather, they exist within complex scientific, engineering and economic frameworks that determine the broad 'shape' of a specific technology at any point in time. This means that

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academy Press) 1986, pp.275-306; also S. J. Kline, "Innovation is not a linear process", particular technological functions are open to only a limited range of changes at any moment, and are thus ordered or structured. Innovation theory has a wide range of concepts for denoting this phenomenon – the concept of 'technological paradigms', for example, is widely used, as is the concept of 'design configuration' or the notion of 'technological system'.[16] These concepts are closely related. Here, a 'technological regime' refers to the whole complex of scientific knowledge, engineering practices, process technologies, infrastructure, and product characteristics, skills and procedures that make up the totality of a technology. However a technological regime can extend considerably further than the factors noted in this definition – for example, into education and training procedures, arenas of tacit knowledge, public procurement processes, and regulatory frameworks.

These elements of knowledge, engineering practice, education and so on serve to 'embed' the technological regime, and to constrain the possible forms of innovation. Innovation around technologies that are components of a well-defined regime is feasible only insofar as it is consonant with the structure of the regime – that is, it must be in accord with the established practices, infrastructures, and routines of the technological regime. These constraints define a particular route of technological advance, and this can be understood as the 'technological trajectory' associated with any particular regime. The technological trajectory is thus the set of feasible lines of innovation with respect to a regime. Just as the regime has inertia as a result of its systemic complexity, so does the trajectory – that is to say, innovative change is possible (and may even be very frequent), but it is ordered, structured and limited by the nature of the underlying regime.

Against this background we can identify three broad types of innovation: incremental innovation, disruptive innovation and radical innovation. These modes of innovation differ in terms of their complexity, time horizons (and hence resource commitments), sites of development, risk profiles, degree of novelty in knowledge use and learning

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Research Management, July-August, pp. 36-45, 1985.

[16] The concept of technological paradigm was introduced in G. Dosi, 'Technological paradigms and technological trajectories. A suggested interpretation of the determinants and directions of technological change', *Research Policy*, 11, 1982, 147-162.

processes, constraints, accompanying social change, and rationales for government intervention. They also face different obstacles, and it is this that is particularly important for policymakers.

2.3.1 Incremental innovation

Incremental innovation is 'localised' change within a technological regime and its associated trajectory of innovation. It consists of enhancements of existing technologies, either with respect to performance attributes or input characteristics (such as more economical use of materials), but it does not fundamentally change the core characteristics of the existing technology. Such innovation consists of improvements to pre-existing products, and it also tends to be new at the level of the enterprise but not new in any more general sense (either new to the sector or to the world as a whole). The world's biggest statistical coverage of innovation is the EU's *Community Innovation Survey*, the dataset of which covers innovation in approximately 400,000 EU firms. This shows clearly that incremental change is the dominant form of innovation in the business sector, a result that has been confirmed by similar surveys worldwide. This type of innovation may be small but should not be underestimated in its cumulative economic impacts, which can be very profound: it has been shown many times that the big productivity impacts of innovations usually follow not from first introduction, but from cumulative incremental improvements. The *Community Innovation Survey* has also shown that such innovation may have a wide range of objectives, including environmental improvements (often as a response to regulation).

2.3.2 Disruptive innovation

Secondly, there is change that disrupts and replaces the functional performance of a technological regime: it changes how things are done, but usually does not change the nature of the technological regime itself. Such change is not uncommon, and involves a replacement of existing norms of product design, performance attributes and production processes. Innovation in this sense is a reshaping of how a particular technical function is fulfilled, and it normally involves not only new products but also new systems of suppliers, of education and training. Examples are the substitution of computer-based text production for electric typewriters, or the shift from film to digital graphics. These changes generally involve the entry of new firms into an industry, and new groups of firms dominating an industry. Perhaps the most extensive studies of such change are those by Abernathy and Utterback, who emphasize a broad order to the process of change.[17] There tends to be firstly an awareness of a new technological possibility, followed by the entry of many technical solutions, followed by the emergence of a 'dominant design' that eliminates most of the variety in the new solutions, followed by a long-term shift from product to process innovation in the new technology. Examples of such functional changes, and their historical sequences, are overviewed in Table 1 below:

Table 1: Sequences of disruptive innovation

Industry	**Waves of innovation**
Text production	Manual typewriters Electric typewriters Word processors PCs with WP software
Refrigeration	Natural stored ice Machine-made ice Electro-mechanical Refrigeration Aseptic packaging
Lighting	Candles and oil lamps Distilled gas Incandescent electric lamps Fluorescent lamps Halogen
Photography	Daguerreotype Tin type Glass plates Dry plates Celluloid role film Electronic imaging

Source: James Utterback, *Mastering the Dynamics of Innovation*, (Harvard: Boston), 1994.

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[17] For an overview, see James Utterback, *Mastering the Dynamics of Innovation***,** (Harvard: Boston), 1994. A formal treatment is Steven Klepper, 'Entry, Exit, Growth and Innovation Over the Product Life Cycle', *American Economic Review*, Vol 86, No 3, pp 562-583.

This type of innovation is sometimes completely new with respect to a technical function, and new with respect to an existing industry. It is often new to the world as a whole, although in some cases it can consist of the application of existing technologies to new functions. Utterback makes a key point about this type of innovation that is highly relevant when thinking about radical innovation with environmental objectives. This is that incumbent firms within an industry only rarely undertake such innovation, and even more rarely succeed with it (for example Kodak developed digital imaging, but was unable to shift quickly enough out of film). This is because enterprises tend to be locked in to their existing areas of competence, and to their existing networks of suppliers, knowledge collaborators, customers and training apparatuses. One of the implications of this is that innovations at this level are usually accompanied by changes in industrial structure and company demographics – incumbent firms exit, and new entrants based on new knowledge bases and new capabilities come to dominate the industry.

2.3.3 Radical innovation

Finally, we have truly radical form of innovation, meaning a full-scale shift in technological regime, as a result of which large-scale changes occur in the fundamental enabling technologies of the economy. Here we are not thinking of a shift with respect to a single technical function, but rather a more encompassing change that alters the generic technologies that underpin many forms of technological and economic activity. [18] Examples of such change might be the broad movement towards mechanisation that happened as part of the first industrial revolution, the changes in agriculture associated with the use of the Haber-Bosch process and nitrogenous fertilisers, the shift first to steam power systems and then to electrification of the western economies during the late 19th and early 20th centuries, the emergence of internal-combustion vehicle technologies, or the shift towards digitalisation in the late 20th century.[19] Regime shifts of these types change the overall nature of production

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[18] R.G. Lipsey, et al, *Economic Transformation: General Purpose Technologies and Long Term Economic Growth*, (Oxford: OUP) 2005

[19] Vaclav Smil, *Creating the Twentieth Century. Technical Innovations of 1867-1914 and Their Lasting Impact* (Oxford: OUP), 2005, and Vaclav Smil, *Transforming the Twentieth Century: Technical Innovations and Their Consequences* (Oxford:OUP) 2006

and industrial location, broad patterns of technology use, social patterns of consumption, and the nature of relevant infrastructures. These major regime shifts seem to have a number of important common features. These include:

- Very long time horizons – the history of steam power, for example, suggests a period from the work of Torricelli, Pascal, Boyle, and Hooke to the first demonstrations of Papin, to the development of the Watt engine, that must be measured in centuries.[20] The introduction of the Watt engine to its widespread adoption as part of a new factory system took nearly a century.[21]
- Processes of "collective invention" through which inventors, engineers, entrepreneurs and government agencies dispersed widely in time and space work on technical problems and design configurations.[22]
- Patronage of emerging technologies and their knowledge bases either by individuals, societies or governments, which protects the new technology during the (often long) development phase.
- Niche markets through which emerging technologies are protected from the full brunt of competition while they are developed.[23]
- In the modern era, significant roles for government: government support may involve either direct support of the technology, or support for its accompanying infrastructures, or both.[24]

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[20] A. Nuvolari, *The Making of Steam Power Technology. A study of technical change during the British Industrial Revolution* (Eindhoven: ECIS) 2004

[21] N. von Tunzelmann, *Steam Power and British Industrialization to 1860* (Oxford: OUP) 1978. Von Tunzelmann showed that the Watt steam engine diffused very slowly and made minimal impact on Britain's industrial growth during the "first industrial revolution" (despite the fact that many histories of industrialisation are written with steam as the centrepiece). It was patented and introduced in 1775, but became competitive only around 1860, after about 85 years of cumulative improvements, and after related innovation in coal mining reduced fuel costs.

[22] See for example, P.B Mayer "Episodes of collective invention" ,US Bureau of Labor Statistics, 2003; and P.B. Mayer ,"The airplane as a collective invention" US Bureau of Labor Statistics 2006. For historical examples, J. Mokyr, *The Lever of Riches. Technological Creativity and Economic Progress*, (Oxford: OUP) 1992

[23] René Kemp, Johan Schot and Remco Hoogma, 'Regime Shifts to Sustainability Through Processes of Niche Formation. The Approach of Strategic Niche Management', *Technology Analysis & Strategic Management.* Vol. 10, No. 2, 1998, 175-195.

[24] This is discussed in more detail below.

- Substantial risk, in the sense that is has been extremely common for multiple search processes to be explored, many technological alternatives to be developed in the early phase of development, with concomitant high failure rates and frequent capital losses.
- Major changes in governance, social organisation, production methods and management, which themselves may involve long time periods.

There are those who argue that this regime-shift process is the essential form in which innovation relates to economic growth, although that appears to take too narrow a view of innovation.[25] It certainly appears that technological regime shifts on this level occur only rarely, and that between them major processes of lock-in occur. A key problem (both historically and analytically) concerns how lock-in is overcome.

The climate-change relevance of this is that the dominant generic technological regime of our time is the hydrocarbon-based energy system. In other words, the innovation problem with respect to climate change is not simply one is one of incremental change around present techniques, or even disruptive change, but full-scale 'regime change'. Such change involves not just a change in dominant firms and their associated knowledge bases, but rather a full-scale shift in scientific and technological knowledge, and associated infrastructures, and even changes in economic and technological organisation at the level of national economies. Some of the issues associated with such change will be discussed in a later section.

2.4 Innovation systems

There is a further framing concept for innovation that is relevant to understanding what types of energy innovation are feasible and likely. This is the concept of the 'innovation system', which refers to an even broader dimension of structuring and order in economic and technological activity. The basic idea is that economic behaviour occurs within rule-ordered frameworks and in the context of persistent structural features. Even the free-est of free market economies operates within structures of institutions that legitimate or exclude certain types of behaviour – such

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[25] For a powerful statement of this position, see C. Freeman and F. Louca, *As Time Goes By. From the Industrial Revolutions to the Information Revolutions* (Oxford: OUP), 2001

institutions include the corporate governance system, the system of property rights, the legal framework of contract and company law, labour market law and regulation, systems of intellectual property, and arrangements for finance and risk management of economic activity. This institutional framework tends to be embodied in and supplemented by a wide range of regulations that affect such matters as accounting procedures, health and safety rules, and environmental impacts. These institutions and rules are constraints, but they also have positive effects: they play the role of reducing uncertainty that would otherwise be endemic in economic behaviour. They play a role in shaping what kinds of innovation are and are not possible in particular environments.

In addition to these frameworks of rules, we can note at least two other areas of persistence and differentiation in economies, which have innovation impacts. One is the overall system of infrastructure. This consists of physical infrastructures – such as roads, energy supply, ports, water etc – and of knowledge infrastructures such as universities, research institutes, patent offices, and libraries. Each type of infrastructure tends to be highly capital intensive, with very long life times and therefore very long investment horizons. Such infrastructures can and do form a constraint or shaping factor in the types of innovation that may be possible within a system. A second important area of differentiation is simply the economic and industrial structure (and related technological specializations). Regional and national economies tend to have different industrial structures and technological specializations (and different trade specializations as an effect of the industrial structure) and these tend to persist over time, and to shape innovation activities.

The point of thinking in these 'systemic' terms is that successful innovation is only rarely a result of action by an individual firm. In practice, success in innovation involves complex interactions between a firm and its environment, and a major problem for government is how to understand and shape this 'environment' in order to improve the innovation performance of businesses. The innovation system affects firms within it by shaping the nature of education and training, the extent and manner in which new opportunities can be identified, the ways in which finance is mobilised and risk is managed, and the provision and governance of supporting infrastructures. Essentially the innovation systems concept has been a way to discuss policy frameworks and policy actions that can support the overall innovation environment – it is probably the most important development in innovation studies in recent years, and appears to be playing an increasingly important role in policy development globally.[26]

2.5 Path dependence and lock-in

A final element of recent innovation studies, central to the issue of climate change, concerns the phenomenon of 'lock-in'. 'Lock-in refers to the fact that inferior (in some relevant sense) technologies may be repeatedly selected in place of superior (in some sense) technologies. Incumbent but inferior technologies may face inherent advantages because they have benefited from (sometimes long) trajectories or paths of development. In this case, the competitiveness of a technology is "path dependent". [27] If there are increasing returns to the adoption of a technology (so that costs fall as users increase), or network externalities (so that benefits rise with numbers of users), then over time an incumbent technology will accrue cost-benefit advantages that cannot readily be overcome even by a potentially superior technology (in terms of performance characteristics and ultimate economics). Understanding the sources of lock-in, and understanding how it may be overcome, appears to be central in understanding transition paths to cleaner energy technologies.

From the climate change perspective there are two primary ways of looking at the sources of lock-in, and hence at its resolution. One is through the lens of history, and the other is through system effects.[28]

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[26] For an overview of the analytical use of the concept, Bo Carlsson, "Innovation Systems: A Survey of the Literature from a Schumpeterian Perspective", Paper for the International J.A. Schumpeter Society conference, Milan, Italy, June 9-12, 2004; on policy uses L. Mytelka and K. Smith, (2002) 'Innovation theory and policy learning: an interactive and co-evolving process', *Research Policy*, Vol 31, No 8/9.

[27] In this sense, lock-in is related to the concept of hysteresis in the natural sciences and economics: the idea that we cannot understand the present level of some variable or component of a system without understanding its path over time.

[28] W. Brian Arthur, 'Competing technologies, increasing returns, and lock-in by historical events, *Economic Journal*, 99 (1989) 116-131; Kenneth Arrow, 'Increasing returns: historiographical issues and path dependence, *European Journal of the History of Economic Thought*, 2000, 171-180.

Lock-in may occur simply because an existing technology has a temporal advantage.[29] Innovation is not an individual act that occurs at some point in time, and innovations are simply never introduced in their final forms. Rather, innovation is the first point of an often very long process during which a flow of performance improvements are painstakingly explored and implemented, resulting in qualitative improvements in product performance characteristics, and more importantly in sustained cost reductions. Nathan Rosenberg argues that:

> Most innovations are relatively crude and inefficient at the date when they are first recognized as constituting a new innovation. They are, of necessity, badly adapted to many of the ultimate uses to which they will eventually be put; therefore, they may offer only very small advantages, or perhaps none at all, over previously existing techniques.[30]

As a result, even when a subsequent innovation project succeeds in generating a new technology, it is likely to face a major difficulty. New products are often uncompetitive with existing products because they tend to require significant periods of post-innovation improvement and development before they can really compete. Products already in the market have benefited from often-long sequences of improvement, which may be incremental in character. That is, there are dynamic economies of scale, if we think of scale in terms of historically accrued volumes of output, rather than the volume of output at a particular point in time. This is the common phenomenon of the learning curve, down which unit costs decline over time. So new technologies may either not be developed at all, or if developed may not diffuse, simply because they are not able to catch up with the historically developed advantages of an embedded technology.

The second issue relates to system effects. Here the issue is has been raised above: a technology rarely consists of a single artifact, but more often is composed of many elements that make up a complex system. These may consist of technical elements, but

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[29] Paul David (1985) ‘Clio and the economics of QWERTY’, *American Economic Review*, Vol 75, No 2, pp.332-7

[30] Rosenberg, N., *Perspectives on Technology,* (Cambridge: Cambridge University Press) 1976.

may also involve social patterns of use and development. On the purely technical level, most technologies are complex products and processes, consisting of more of less detailed systems of interconnecting components, devices, knowledges and skills. Technical complexity of this type has grown radically over the past century or so, and the number of components in many current products is orders of magnitude greater than even twenty years ago. But technologies are also systemically connected with the social world: with patterns of education and training, with infrastructures, with forms of production organization, with modes of technology use, and with modes of consumption. These systemic aspects of technology mean that it can be very difficult to change particular technologies (such as the use of carbon-based fuels) independently of changes in the system as a whole. But system changes are considerably more difficult to initiate and sustain than changes in individual techniques. So an important problem, both for analysis and policy, is to distinguish carefully between cases where technological change is relatively unproblematic, and cases in which systemic factors generate major obstacles to change. We then need to understand in more detail the character of such obstacles, and their implications for policy foundations, policy design and implementation measures.

Both the temporal and system dimensions are important in explaining why it is that apparently superior technologies diffuse so slowly, and why regime changes take such long times. This is of course a common feature of major technological transitions: steam power has already been mentioned, but in the electrification revolution the dynamo replaced steam power only very slowly, diesel locomotives were slow to replace steam locomotives (and electrification of rail was also slow), petrol aircraft engines were slow to disappear in the face of jets, sail persisted in the face of steamships, mainframe and supermini computers persisted long after the emergence of "client/server" architectures, etc.[31] This occurs not just because the old technologies take time to disappear – rather they continue to be improved and they continue to sell

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[31] Paul David has demonstrated the system effects that created lock-in and prevented rapid diffusion with respect to several technologies: P. David, 'The Dynamo and the Computer: An Historical Perspective on the Modern Productivity Paradox', *American Economic Review*, Vol. 80 Issue 2, 355-361, and "Clio and the economics of QWERTY", *American Economic Review*, Vol. 75 Issue 2, 332.337.

long after the new technology has entered the market.[32] The remarkable fact is not that the new technologies are slow to become dominant: it is that they survive at all. How the new survives, and why and how it sometimes takes over, will be discussed below.

3 TECHNOLOGY AND INNOVATION OPTIONS FOR CLIMATE CHANGE

This section uses the framework outlined above – of incremental, disruptive and radical innovation – to look at the current modes of innovation and policy support directed towards climate technologies. Environmental innovation can be conceived very widely, but as noted above, this runs the risk of lumping many different types of action together:

> A broad definition of environmental innovations would include all measures that conserve energy and materials, and minimise the environmental load. In a broader view environmental innovation consists of new or modified processes, techniques, practices, systems and products to avoid or reduce environmental harms.[33]

Another broad definition is given by Shrivastava (1995, p. 185):

> Environmental technologies can be defined as production equipment, methods and procedures, product designs, and product delivery mechanisms that conserve energy and natural resources, minimise the environmental load of human activities and protect the natural environment. [34]

3.1 Forms of environmental innovation

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[32] On this point, applied both generally and to computing, see T. Bresnahan and S. Greenstein, 'The competitive crash in large-scale computing' in R. Landau et al (eds) *The Mosaic of Economic Growth* (Stanford: Stanford University Press), 1996, 357-397

[33] R. Kemp K. Smith and G. Becher, 'How should we study the effects of environmental regulation on innovation?', in J. Hemmelskamp, K. Rennings and F.Leone (eds) *Innovation-oriented Environmental Regulation. Theoretical approaches and empirical analysis* (Physica-Verlag: Berlin), 2000 p.60.

[34] Paul Shrivastava (1995), 'Environmental Technologies and Competitive Advantage', *Strategic Management Journal* 16: 183-200.

Current measures to reduce greenhouse gas impacts or to reduce environmental stress fall into three broad groups: measures to improve the efficiency of existing technologies, measures to contain impacts (such as carbon sequestration or direct climate intervention) and measures to create and diffuse non-hydrocarbon energy technologies for energy production and use. Each of these initiatives requires innovation, but innovation of different types, with quite different degrees of novelty and different scales of effort required.

We can classify the potential lines of climate-relevant technology advance along these conceptual lines, by distinguishing between three types of innovation and three types of emission effects. Table 2 does this drawing on a variety of sources, the most important of which is the work of the International Energy Agency.

Table 2: Modes of energy innovation

	Incremental change	***Disruptive change***	***Radical change***
Climate control technologies without emission reduction	Reduced deforestation	Sulphate emissions in atmosphere Carbon sinks	
Emission reducing innovation	Enhanced engine efficiency District heating and cooling Gas baseload power	Carbon sequestration/clean coal (including capture and geological storage) Advanced motor fuels Bioenergy Fluidised bed combustion (improved combustion efficiency) Advanced materials for transportation Advanced motor fuels Efficient combustion technologies	
Low or zero emissions technologies	Heat pumping technologies for buildings (including storage Development of existing nuclear capabilities	Geothermal energy Solar panels Wind energy systems	Fusion power Hydrogen Hydropower Ocean energy Photovoltaic power systems Concentrated solar power (orbital sun-tracking mirrors) Advanced fuel cells Advanced energy storage technologies

			(batteries, capacitors, compressed gas storage)

Sources: Various, but see in particular IEA, *Energy Technologies at the Cutting Edge* (Paris: OECD/IEA) 2005; also R. Socolow, "Stabilization Wedges: An Elaboration of the Concept" in H.J. Schellnhuber et al(eds.) *Avoiding Dangerous Climate Change* (Cambridge: CUP) 2006.

The first type of environmental innovation includes a wide range of activities and technologies, including the following:

- Pollution control technologies that prevent the direct release of environmentally hazardous emissions into the air, surface waters or soil (classic end-of-pipe technologies like fluegas-desulphurisation, car exhaust purification and biofilters)
- Waste management: handling, treatment, and disposal of waste both on-site by the producer of waste and off-site by waste management firms.
- Clean technology: process-integrated changes in production technology that reduce the amount of pollutants and waste material that is generated during technology production and use.
- Recycling: waste minimisation through the re-use of materials recovered from waste streams.
- Clean products: products that give rise to low levels of environmental impact through the entire life cycle of design, production, use and disposal. Examples are low-solvent paints and bicycles, but this would extend also to car engine efficiency increases.
- Innovations in the packaging and delivery of goods in ways that reduce the overall environmental load. Examples are low-weight packaging materials and reusable packages
- Organisational innovations such as the use of environmental management systems.

It is the case with most of these types of measures that innovation is largely incremental in the sense that it involves improvements in technologies that exist or the application of forms of knowledge that already exist. There may be problems to do with incentives for firms to develop or adopt such innovations, but the technological solutions themselves either exist or are readily foreseeable. Moreover innovations in these areas can be introduced more or less on a piecemeal basis because they fit into existing patterns of production and consumption, and into existing patterns of corporate and consumer behaviour.

The second set of measures, to do with carbon sequestration or climate engineering, is more problematic. The sequestration effort applies to a widely applicable clean-up technology that would leave existing hydrocarbon generation technologies intact. There are two main technological functions, namely carbon capture and carbon storage, for each of which there is a range of potential solutions.[35] Although there are some major sequestration activities underway (the Norwegian oil company, Statoil, is currently sequestering approximately one million tonnes per year of recovered CO2 by injecting it into a geologic formation under the North Sea associated with the Sleipner gas field) this is still a technology at an early phase. At the present time none of the major capture technologies is economically feasible, with sequestration from coal and oil power plants currently costing between $US100 and $US300 per ton of emissions. There is therefore no 'dominant' or even generally used technology, and the problem is to identify which technology or group of technologies might provide sequestration solutions. This is typical of a disruptive innovation. This is a situation – not uncommon in the history of technology – where a technical function is readily identified, but where no dominant technological solution exists, and where the emergence of a solution will probably involve some kind of more or less discontinuous change to existing knowledge and technical practice. In fact, there are a number of potential disruptive changes that would leave the existing system more or less intact while dramatically changing its functioning and the related environmental load. Apart from sequestration, another array of disruptive changes would encompass various climate-engineering solutions: sun shields, sulphate particle seeding in the stratosphere, and new methods of ocean cloud formation.

The third area of technology measures, the domain of potential radical innovation, concerns full-scale non-emitting alternatives to the hydrocarbon energy system. These

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[35] For capture, at least five basic technological principles are relevant: absorbtion, adsorbtion, distillation, gas separation and mineralisation; beyond these lie the application of new materials (including nano materials), and CO2 hydrate formation and separation. Options range from clean-up approaches to full-scale change in power technology cycles. There is also a range of geologic storage options and related technologies.

are clean products that minimise environmental impacts at all stages of the energy cycle, and – at an even more ambitious level – very low or zero emission energy production and use technologies. They imply shifts in the underlying generic technologies on which the present industrial economy is based. This is the level at which it is currently difficult to envisage change, yet it is the level at which the really significant environmental technology challenges exist. Here the scientific and technological challenges cover the spectrum from power generation to storage, distribution and use. The search options include fusion technologies for power generation, non-emitting hydrogen production and the development of a full set of hydrogen-based applications, large scale energy storage technologies (important with respect to the long term viability of current non-emitting technologies, such as windmills and solar panels, which suffer from intermittent generation), space-based solar power generation and transmission, and major global changes in urban planning, design and ecologies (with concomitant infrastructure changes). Some of the challenges here begin involve scientific and technological breakthroughs whose form cannot at present be envisioned. An important feature of each of these potential technologies is that there exist many conceivable forms that technological solutions might take: there are no clear routes forward, and so there are multiple search paths towards viable solutions.

3.2 Innovation instruments for energy innovation

What are the incentives and impulses to innovation at the three levels outline above – incremental, disruptive or radical? Current innovation policy instruments and approaches to new energy technologies are essentially focused on the incremental and disruptive modes innovation described above. Instruments are essentially of three kinds. There are price-based incentives deriving from emission caps or taxes. With more direct technology policy measures, instruments rest firstly on the idea that R&D is the central initiating aspect of innovation, and that the principal problem is to commercialise or to spread awareness of it. More relevantly, they also contain measures that promote the spread of developed but uncommercial technologies (such as solar panels) via tax credits, rebates or procurement.

The excellent Pew Report on climate change implications of US technology policies offers the following overview of US policy instruments:

Table 3: US Technology Policy Tools

Direct Government Funding of Research and Development	*Direct or Indirect Support for Commercialization and Production: Indirect Support for Development*	*Support for Learning and Diffusion of Knowledge and Technology*
R&D contracts with private firms (fully-funded or cost-shared) R&D contracts and grants with universities Intramural R&D conducted in government laboratories R&D contracts with industry-led consortia or collaborations among two or more of the actors above	Patent protection R&D tax credits Tax credits or production subsidies for firms bringing new technologies to market Tax credits or rebates for purchasers of new technology Government procurement Demonstration projects	Education and training (technicians, engineers and scientists, business decision-makers, consumers) Codification and diffusion of technical knowledge (screening, interpretation and validation of R&D results; support for databases) Technical standard setting Technology and/or industrial extension services Publicity, persuasion and consumer information

Source: J. Alic, D. Mowery and E. Rubin*, U.S Technology and Innovation Policies – Lessons for Climate Change*, Pew Centre on Global Climate Change, 2003, iii.

This array of instruments involves firstly is an overemphasis on R&D. It was argued above that a fundamental problem with the innovation perspective of the Stern Review was its reliance on an obsolete concept of innovation processes, and its emphasis on R&D and commercialisation programs as policy supports. This means that the effects are unlikely to be significant, at least within a reasonable time-period.

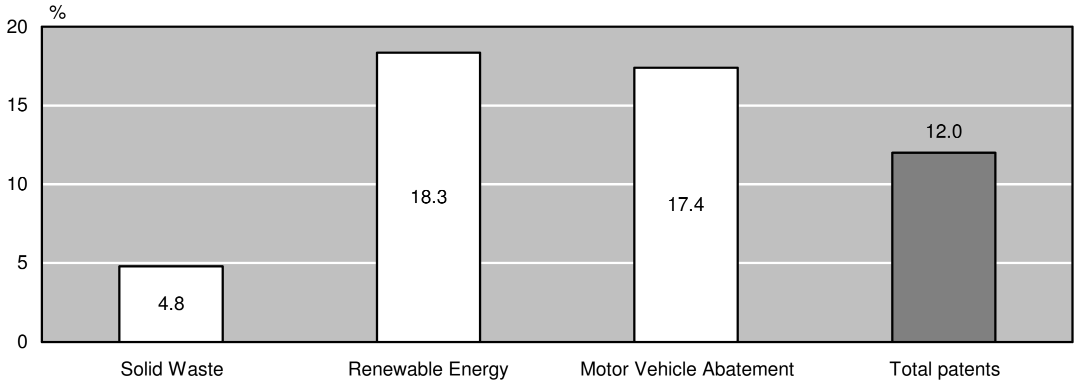
More positively it involves regulatory incentives, procurement instruments and standardisation methods that will affect and modify existing technological practices – this includes most pollution control technologies, waste management technologies, and some process-related clean technologies. Within engine technologies, price shifts for fuel will generate search for incremental fuel efficiencies; this has been very marked since the 1970s, as a result of OPEC I and II, and subsequent changes in tax regimes (notably in Europe). We already have abundant evidence that environmental innovation at this level occurs frequently, such as changes in construction methods and especially insulation as a result of fuel cost changes.

Depending on the specifics of policy design, emissions control policies based on quantity caps and treading permits, or on emissions taxes, can be expected to provide adequate incentives for this type of innovation. They may also have impacts on the diffusion of disruptive technologies mentioned above, such as solar panels, geothermal energy or wind power.

Further measures are likely to be necessary in the case of disruptive innovations. The central problems lie not in creation of functioning technologies but in getting existing techniques to an economically competitive point. Solar panels, for example, are now a well-known technology developing along a fairly clear trajectory, and there are at least twenty fairly large global producers. But they are far from being cost competitive, and clearly require many years of development before reducing their costs to levels that would enable them to compete with the main elements of the electricity grid. Policy support for continuance along these trajectories would (and in fact, do) take the form of fiscal incentives to diffusion: subsidies to production, subsidies to adoption, and public procurement. A second array of disruptive measures would be the carbon sequestration technologies referred to above. Since this relates to a direct market failure taking the form of a detrimental externality, and since there are beneficial externalities from adoption, the appropriate policies might be research support and regulation to impel adoption. Although the design and implementation of appropriate regulatory instruments is a demanding process, it is nonetheless feasible and productive. Even here, of course, system effects need to be considered, since incremental change in technological systems may require us to look far beyond the point at which we would like to promote change – into supplier industries, or demand conditions, for example.

The overall set of incentives and policy support measures are clearly having impacts on current innovation trajectories. The best evidence for this is in the patent record. Recent OECD work on patenting at the European Patent Office suggest three conclusions: firstly that renewable energy sources and mitigation of vehicle emissions are major sources of patenting at the present time. Figure 1 shows that at the present time 12% of the stock of EPO patents relate to environmental issues. However renewable energy and motor vehicle abatement technlogies make up much higher percentages. So there is strong inventive activity being revealed by the patent stock data.

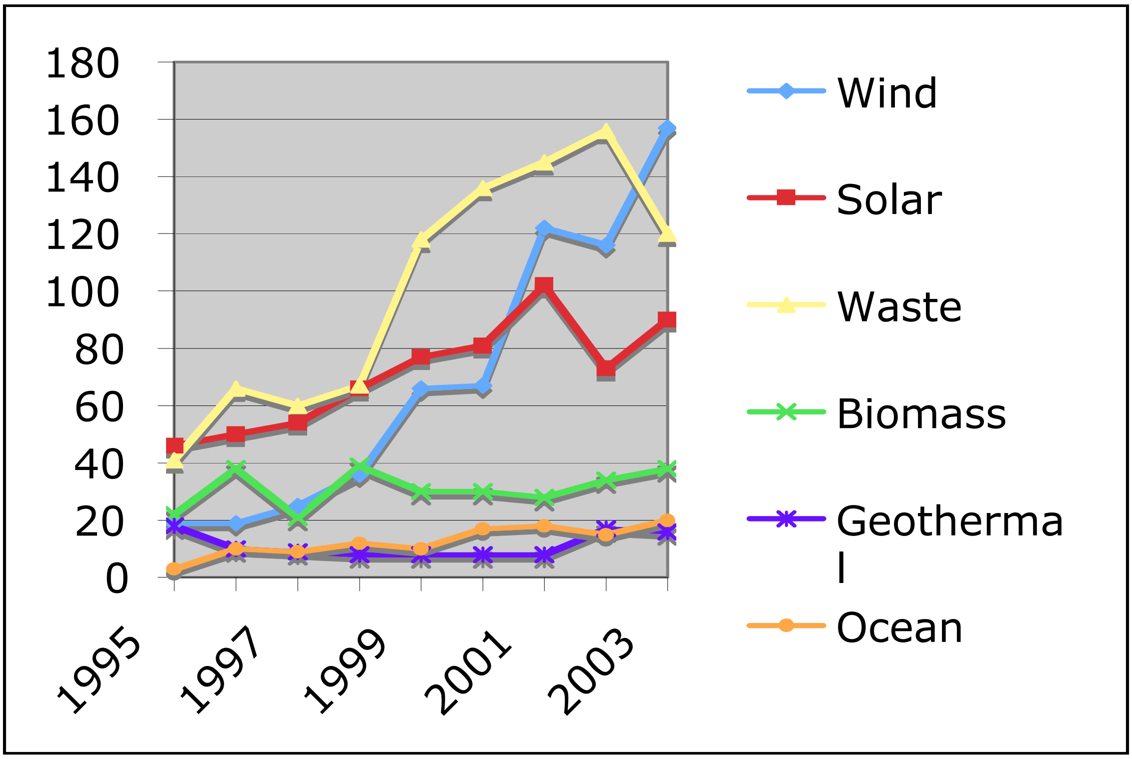
Figure 1: Shares of total EPO patents by environmental technologies.



Source: OECD Patent Database at www.oecd.org/sti/ipr-patents.

The largest category of patents is in renewable energy, and this area has been growing rapidly in recent years. Figure 2 shows how this looks among different types of renewables.

Figure 2: Patent trends: Renewable Energy patenting by Energy Source



Source: N. Johnstone and I. Hascic, “Eco-innovation, policy and globalisation”, *OECD Observer*, No 264-265 Jan 2008, pp.15-16.

At the same time there has been sharp growth in integrated emissions control technologies for vehicles: from just over 400 patent applications in 1995 to nearly 1100 in 2001. These trends in patenting suggest that both existing incentives and policy instruments are working to increase activity across the whole range of incremental and disruptive changes. Whether the current effort is big enough, or in the right directions, or whether it is getting the right policy signals, is of course still open to question. But the incentives and policies are there. The matter of support for more radical change remains outside the zone of current policies, however.

3.3 The innovation policy challenges of climate change: supporting radical search and change

The set of non-emitting technologies in the bottom right-hand panel of Table 2 above exhibits all of the characteristics of historical radical innovations: major scientific and technological challenges, extreme uncertainty about technical and economic feasibility, a multiplicity of potential technical choices and development paths, major investment risks and possibly deficits (due in part to absence of relevant investment appraisal techniques), lack of accompanying infrastructures, collective invention characteristics (with a very dispersed R&D and engineering effort globally). Yet it is here that we find the ultimate array of options for climate control, and this section turns to the issues in developing and sustaining such options.

Shifts in technological regimes have occurred in the recent past, such as computing, mobile telephony and satellite communications. What then are the characteristics of such change, and what do these characteristics imply for public policies now? Three important characteristics can be suggested. The first is that the core generic technologies of the modern world have emerged via goal-directed "mission-oriented" programs. They have not evolved piecemeal out of applied engineering efforts based on research results, but are the outcomes of purposive efforts aimed at securing pre-envisioned outcomes.[36] These 'missions" have historically had a variety of forms and

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[36] This does not at all mean that *innovators envision all of the outcomes*. Society has a persistent habit of using new technologies in ways that cause great surprise to innovators. For example, the innovators behind mobile telephony envisioned a world of mobile communications primarily for business users, and were stunned when predominantly young

coordinators. The second characteristic is that these efforts have usually been aimed not at individual technologies, but at the creation of systems of technology and use-forms: such changes as the transition to electricity were, as Thomas Hughes has put it, "systems, built by system builders".[37] The third characteristics is that the modern forms of these epochal shift have largely been initiated and sustained by governments and government agencies, utilising the innovation systems of which they are a part.

The role of government or public agencies has been pervasive, the main evidence being the histories of the technologies in question. Many of the core technologies of the modern era appear to have their origins in mission-oriented programs that involve firms as participants but not as initiators.[38] For example, the histories of computing, aerospace technologies, nuclear power, telecommunications (especially satellite-based communications and mobile telephony), biotechnology development, high-speed rail and the Global Positioning System suggest that many of our core technologies find their origins in attempts by public-sector agencies to create technologies or exploit scientific potential to fulfill new technical functions.[39] Although they involve research, often on a spectacular scale, they are in fact outcome-driven. They result

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users first began using mobiles, and then sending text messages (which were originally seen as a pager substitute for business) in large volumes. This shifting of use is a major source of technological risk and uncertainty. See Nathan Rosenberg, "Uncertainty and technological change", in T. Landau, T.Taylor and G. Wright, *The Mosaic of Economic Growth* (Stanford, Ca.: Stanford University Press) 1996, pp.334-353

[37] Thomas Hughes, 'The evolution of large technological systems', in W. Bijker, T. Hughes and T. Pinch, *The Social Construction of Technological Systems*, (Cambridge: MIT), 1989, 51-82

[38] The concept of "mission-oriented" technology policy is very useful but rather neglected. It derives from H. Ergas, "Does Technology Policy Matter?", *Technology and Global Industry*, (Washington: National Academy of Sciences) 1987, 191-245

[39] For an excellent account of one of these processes, studying the role of government in the US success in the computer industry, see Computer Science and Telecommunications Board, *Funding a Revolution. Government Support for Computing Research* (Washington USA: National Academy Press), 1999. On mobile telephony, Sven Lindmark, *Evolution of techno-economic systems: an investigation of the history of mobile communications*, Chalmers University of Technology, 2002, ISBN 91-7291-194-8 and Johan Hauknes and Keith Smith, (with Johan Hauknes) *Corporate Governance and Innovation in Mobile Telecommunications: How did the Nordic Area Become a World Leader?* Report to the European Commission, DG-Research, Corporate Governance and Innovation Project; on GPS, S. Pace et. Al, *The Global Positioning System: Assessing National Policies*, (Rand Corporation, 1995), especially Appendix B, 'GPS History, Chronology and Budgets'

from attempts to solve specific socio-technical problems, some civil but others notably military. In the modern cases governments or public sector agencies have played central roles in actually initiating and managing the development programs of the technologies referred to above. So the GPS system was developed (and continues to be run) by the US Air Force, having evolved out of long-term efforts to provide strategic bomber navigation systems; the Internet emerged out of Department of Defense attempts to create survivable computer capacity.[40] As a civil example, the Nordic mobile telephony systems emerged from the state-monopoly telecommunications services providers of the Nordic area, who through the Nordic Telecommunications Union envisaged (beginning in 1948) mobile telecoms as a solution to the major communications challenges of the region. In earlier cases, such as those involving the diffusion of steam power, the creation of electricity networks or the rise of automobile transport, governments provided enabling infrastructures, regulatory frameworks that reduced uncertainties and increased safety (and thus promoted adoption), or direct interventions to enable system benefits to be achieved. So although in Europe much electricity development was initially private in character, governments increasingly intervened (indirectly or via nationalisation) to create the network integration through which the economic benefits of the underlying innovation were realised.[41]

Is this place of the public sector in major innovations merely contingent, or is there something necessary about its role in mission-oriented technology development? This is clearly a central question for any attempt to conceptualise the nature of radical innovation.

Radical innovations as defined above involve at least six major problems that are more or less unresolvable by profit-seeking potentially innovating firms. These problems are not necessarily market failures as conventionally understood. They relate to

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[40] The role of military technology creation in the US is well-known, though it is not widely appreciated that such ostensibly civilian phenomena as Silicon Valley owe an enormous amount to military funding and decision-making. This is true of many other economies, and is under-studied; see Thomas Heinrich, “Cold War Armory: Military Contracting in Silicon Valley, *Enterprise and Society*, Vol. 3 No. 2, 247-284; for an account of the military role in the UK, see D. Edgerton, *Warfare State. Britain 1920-1970* (Cambridge: CUP) 2005

information failures, to institutional failures, to coordination failures, and to more general investment obstacles related to radical innovations. The six broad problems are:

Time horizons and financial commitment. The long time horizons and circuitous search paths involved in radical innovations make it virtually impossible for rational capital accounting and investment appraisal around these technologies, which also require long-term financial commitments that are simply beyond the ability of any profit seeking firm (under normal methods of corporate governance) to undertake.

Risk bearing and the management of uncertainty. These technologies tend to involve serious technological risks (in the sense that there are serious risks of technological failure), and economic risks (in the sense of very high probabilities of capital loss for particular projects). They also face uncertainty in the Knightian sense, since the time horizons are so long that utterly unexpected solutions may emerge that enhance or destroy particular search avenues.[42]

Indeterminate outcomes and multiple search paths. It is usually necessary not to undertake a single search path in the case of radical technologies: overlapping and multiple paths are a key feature of success in these fields (demonstrated most sharply in the US cases of nuclear weapons and computing technologies).

Social adaptation. Society does not simply adapt to new technologies, it also shapes them. But there are often social adjustments and adaptation that need to be made for a radical innovation. These may include regulation, training, changes in physical infrastructures etc.; they are beyond the capabilities of individual investing firms.

Coordination failures. Innovations occur as complex systems, which require system coordination. In some cases a dominant large firm can achieve this, but it can also be addressed either tacitly or de facto by public agencies.

Overcoming lock-in. Overcoming lock-in to a currently dominant technology typically requires the protection of niche markets, public procurement, and patronage that tend to be provided only by interested and wealthy elites or by government.

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[41] Robert Millward, "Business and Government in Electricity Network Integration in Western Europe, c.1900-1950", *Business History*, Vol. 48 No, 4, 2006, 479-500.

[42] Historically, this has been a major economic function of government: David A. Moss, *When all Else Fails. Government as the Ultimate Risk Manager* (Cambridge: Harvard University Press), 2002.

These considerations suggest a more overt role for the public sector in generating radical technologies for low-emissions energy production. Before turning to issues of policy design, we need to ask the more fundamental question: Is such a public role feasible with current forms of policy organisation?

4. POLICY RATIONALES AND INTERNATIONAL POLICY COLLABORATION

4.1 The rationale for public sector support

The previous section has indicated a range of ways in which governments have been involved in the creation and diffusion of major technologies. Of course the mere empirical fact of such involvement, even over a long historical period, does not mean that governments have any necessary role in supporting innovation, or that they should intervene in the creation of technologies. What then is the rationale for public sector intervention in support of innovation, and especially of radical innovation of the type emphasized in this paper?

The most common rationale for public intervention is that some "market failure" exists as a result of which welfare-enhancing action is possible but will not be undertaken by private profit-seeking firms or by individuals. However not all of the problems that involve governments in market economies are best understood as market failures, and this section discusses two of them, namely missing or weak institutions, and coordination problems in complex economies.

The market failure approach rests on the idea that markets can fail to produce optimal results, but it often goes on to suggest that such problems can be resolved by the creation of markets, or by taxes or subsidies that correct price distortions. In the case of public goods, where consumption is both non-excludible and non-rival (such as street lamps or defence), governments should directly provide the good. The "market creation" approach to policy usually takes two forms, each of which has limitations when applied to environmental technology issues. Firstly, it suggests that market failures can be resolved by the creation of property rights – so problems associated with beneficial and detrimental externalities can be resolved by the assignment of prices, or combination of price and property rights, which may then be traded. This of course underlies carbon-pricing policies that lead to administratively established markets. Secondly, some market failures can in principle be resolved by the creation of contingent markets, which take account of varying states of the world. So appropriate futures markets will provide incentives for forward-looking behaviour, and this is also provides incentives for innovation in fields where futures prices are rising.

In the field of innovation the most common argument around market failure concerns the alleged public good character of R&D: the view is that firms under-perform R&D, because with non-excludability and non-rivalry others can use R&D results, and the performing firm cannot therefore appropriate the full benefits. This failure is corrected through the creation of time-limited property rights via the patent system, or by R&D tax credits, or by direct subsidies to R&D. With respect to energy innovation we have already seen this approach in the *Stern Review*, which argues for R&D subsidies in transport fields and in energy production. The fundamental problem with this approach is not necessarily that it is wrong, but that it is only limitedly relevant. Two core results of modern innovation research are firstly, that outside the biomedical field, patents – while useful as an indicator – are not an important method of appropriating innovation benefits, and secondly, the performance of R&D and hence its financing issues are only single components of complex innovation processes, and are not necessarily fundamental to the problems that innovating firms face.[43]

It is not obvious, however, that we should think purely in terms of markets and market failure. It is important to remember that the “market mechanism” can be a somewhat misleading term, because markets are not in fact a mechanism: markets do not make decisions for the allocation of resources, particularly for the allocation of resources to innovation. In the private sector, the managements of business enterprises make decisions, and so what really matters are the contexts in which they make decisions, and how those contexts shape their ability to commit resources to innovation programs. These “contexts” include market signals and conjectures about their future shape, but they also include institutional constraints, and coordination obstacles. In

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[43] On the role of patenting the key work is Levin, R.C., Klevorick, A., Nelson R.R., and Winter, S., “Appropriating the Returns from Industrial Research and Development”, *Brookings Papers on Economic Activity*, 1987, 3: 783-820;

particular the absence of relevant institutions, or their particular forms of operation, or the inadequacy of linkages and hence coordination, can reinforce lock-in and inhibit firms form making innovation investments. These institutional and coordination problems can also be considered "failures", but they are problems not of markets but of the structure and operations of the innovation system; neither can they be resolved by the creation of actual or quasi markets.

Institutions are legally or customarily formed "rules of the game", that shape economic behaviour; they are usually associated with organisations that implement, manage or enforce institutional rules. Key institutions in market economies affecting innovation concern the rule-systems shaping corporate governance, the production and distribution of knowledge, and the management of risk and uncertainty. Corporate governance is typically seen as being about the principal-agent problems associated with making managers responsible to owners, and about the market for corporate control. But the system can also be seen as a set of rules and practices that govern the extent to which corporate managers can invest in the tangible and intangible assets that are needed to innovate. From this perspective the key elements of the corporate governance system would be the explicit or implicit rules that determine the stock of firm-specific innovation-relevant assets, the time horizons over which innovation investments can be made (and the expected rates of return that are required from them), and the extent to which innovation projects can take on technical or economic risk. The issue of risk and uncertainty goes beyond corporate governance and into the related areas of equity markets and corporate finance. Equity markets both reduce risk by diversifying it, and monitor and constrain the actions of management with respect to investment. These are complex issues, much debated at present. One area of debate concerns whether shareholder-value approaches to corporate governance have reduced the ability of managers to create firm-specific assets, and whether they have shortened investment time horizons. But if we look at them against the background of the broad histories of radical innovation, sketched above, it is not difficult to see that profit-seeking firms are unlikely either to take on the risks associated with radical innovation, nor the time-frames over which those risks must be borne. Nor can we envisage methods of investment or risk sharing, with our current governance arrangements that will permit investments in radical innovation. So purely on these institutional grounds there is a case that, if radical innovations are in some sense necessary, the public sector will have to play a central role in organisation and the commitment of resources. The fundamental rationale for this lies in the long time horizons and complex risk structures of radical innovation efforts.

There is also a coordination rationale for a public sector role, particularly where the problem is to overcome lock-in. Both markets and institutions are coordination mechanisms, of different types, but they can fail to work effectively. Such failures are often recognised in economics, particularly in Keynesian macroeconomic theory, where sub-full employment equilibria rest on the existence of coordination failures. These are situations in which workers would like to work and to consume (at existing wage and price levels), and firms would like to employ and produce, but no mechanism exists to overcome the inability of labour and product markets to coordinate via price signals. At this point, Keynesian arguments for public intervention come into play.

Innovation analyses, especially those seeing technologies as systems, also focus on coordination issues.[44] Both analytical and policy issues turn on the nature of the components of the innovation system, and the nature of the links between them. The links may be economic, they may involve the transmission of knowledge, and they may involve the joint use of infrastructures, and so on: the precise connections cannot be specified in advance, and often need detailed empirical investigation to uncover. Lock-in is a form of coordination problem – a situation in which change is blocked because of the absence of a coordinating mechanism or agent. In overcoming lock-in, components of the new system must be integrated in a coherent way (that is, all moving in more or less the same direction, with more or less compatible objectives) towards the development and use of the new technology that is the object of the innovation process.

By definition, systems require coordination, but they do not necessarily require a coordinating agent. Where institutions, infrastructures or inter-firm connections are well established within a particular technological framework, the coordination needed

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[44] E.g., Sven Lindmark, 'Coordinating the early commercialization of general purpose technologies. The case of mobile data communications' *Innovation Management Policy and Practice*, Vol 7 No 1.

for innovation is usually routine. But where a new technology involves a major disjunction, coordination becomes highly problematic. When innovations are radical with respect to existing procedures, engineering capabilities or technical knowledge bases they involve multiple component systems and great complexity, and here coordination becomes necessary to insure inter-operability, common technical standards, and the integration both of technologies and production organisations and skills. That is why technological historians such as Thomas Hughes write about such innovations as electricity purely in terms of system construction.[45] System builders, such as Thomas Edison, were essentially fulfilling a coordination function among disparate components of the complex new technology. These coordination issues are found in all radical technologies, but over the past century have tended to involve government because they also involve long-term financial commitment. This type of view of change within a systems context is surely relevant to environmental technologies at the more radical level. If environmental innovation is seen as a kind of end-of-pipe clean-up technology then existing organization and regulation systems are likely to be adequate. But if we see the task of environmental innovation in a more radical way, as shifting the fundamental technological systems on which the current industrial economy is based, then the coordination problems come to the forefront. A systems approach would suggest that the identification of co-ordination failures, the design of policy instruments to overcome them, and the development of relevant actors, are likely to be an important rationale for public policy intervention, and important also in deciding its scope and objectives.

4.2 National policies or transnational collaboration?

What is the way forward in developing an approach to new radical climate technologies? The discussion above has argued for mission-oriented programs and a key role for government. But there are three obvious and cogent objections to the idea that government-led mission-oriented innovation programs could conceivably address the radical innovation problems related to climate change. This section considers these

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[45] In his history of the development of electricity, Hughes emphasized the systemic elements of innovation in the electrical power system with successful innovators best seen as system managers. T.P. Hughes, *Networks of Power. Electrification in Western Society 1880-1930* (Baltimore and London 1983).

objections, and then offers a solution in the form of a global program, on the scale of the IPCC but aimed at engineering and socio-technical solutions, coordinated by an international agency. There is one objection I do not consider, namely the ritual notion that government “cannot pick winners”. This is not considered here because it is an assertion rather than a fact: the historical record – as I have noted above – suggests that governments can and do pick winners, the evidence being virtually every major technology that we use today.[46]

The first serious objection to government leadership is that the innovations described in the previous section belong to a past in which national governments could structure and deploy national innovation systems to seek particular radical innovations as solutions to perceived national problems. Ergas pointed out more than twenty years ago that the technology policies of the USA, the UK and France (and he might have added others) were “intimately linked to objectives of national sovereignty”:

> Though relying on market forces, the [capitalist] system has interacted with government ... [A primary way] relates to the harnessing of technological power for public purposes. Nation-states have long been major consumers of new products, particularly for military uses, and the need to compete against other nation-states provided an early rationale for strengthening national technological capabilities.[47]

However recent decades have been a period of fundamental transition not only in economic policy methods and frameworks but also in basic attributes of the state. Liberalisation and economic reform have been widespread across the advanced economies, though taking quite different forms (it is important to bear in mind that the Anglo-Saxon liberalisation/reform model is not the only one available, nor the only one to have been deployed). But the common themes of privatisation and deregulation have led to the disappearance of many of the institutions and organisations that

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[46] Of course governments have also picked an impressive array of losers. But then so has every serious innovating company. The reason for “picking losers” is not that either governments or firms are intrinsically bad at technology selection, but rather than real innovation involves irreducible risk of technical failure.

[47] Ergas, op.cit., 191.

supported the mission-oriented efforts of the past. These include state-owned enterprises (often monopolies) in utilities and their large research operations (which led the implementation of digitalisation in telecoms, for example). Then there are government labs of all types and technology development institutions (so-called PROs – Public Research Organisations) that have faced major governance changes that have pushed them into more market-oriented project portfolios. Finally, even the military, except in the USA, has faced downsizing and governance changes, and privatisation of development capabilities. So the practical organisational structure through which previous generations of radical technology have been developed and/or diffused now exists only in heavily modified forms that are arguably very compromised in terms of innovation capabilities. Naturally there are variations across countries – France, for example, has preserved ownership and governance structures that have enabled it to build the TGV high-speed rail system, arguably a radical system innovation (with significant climate implications also). This is something that would be impossible in the UK or the Netherlands after deregulation and privatisation of the rail systems: the organisational basis for radical transport development is simply gone, and this precludes any sort of action along the lines suggested above.

A second objection is that states have changed fundamentally in what they perceive as legitimate domains of action, and in terms of their policy capabilities for actually undertaking action. It is widely argued that the nation-state – a form of state committed to well-defined sovereignty and self-sufficient actions towards welfare and military objectives – is in decline or has indeed disappeared.[48] Be that as it may, there are now clearly recognisable constraints on what governments can or can't do, and on what they are indeed willing to attempt. Even in an era of globalisation they can support national innovation systems via investments in education systems, knowledge infrastructures, financial mechanisms and tax policies, and R&D and innovation policies. But they cannot undertake the focused government-led initiatives that created most of our current generic technologies, because such actions are now neither within their capabilities nor their legitimate realms of action.

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[48] A sustained argument along these lines is Philip Bobbit, *The Shield of Achilles. War, Peace and the Course of History* (Harmondsworth: Penguin), 2003; see also Martin Van Creveld, *The Rise and Decline of the State* (Cambridge: CUP) 1999

Finally, even if governments could do such things, why should they? It is very plain that climate change is a major global detrimental externality and that any solution to it would in effect be a global public good. It is of the essence in public goods theory that decentralised solutions are not available, and that public provision is the only efficient solution; the problems in public good theory turn not on the principle of public provision but its extent. But where the public good is global in character, then national governments are in the position that citizens would be in a society without government; adaptive behaviours are possible, but full-scale provision is not. In this case, not only do governments lack capabilities towards radical innovation, they also lack incentives.

Could the problem of developing new climate-relevant technologies be addressed at a world level? The answer suggested here is yes. If world government does not and probably cannot exist, this does not mean that collective action towards a global public good is impossible. Indeed one of the clearest trends in current public policy at the present time is the limited ceding of national sovereignty towards transnational agencies of collective action and governance. These result ultimately from a primary trend towards economic interdependence, either via formal schemes of economic integration, or via the de facto links of "globalisation". The most spectacular example of economic integration and institutional creativity is of course the European Union, where the creation of a single economic space has involved the accompanying creation of legal arrangements taking precedence over those of the Member States, a common currency, EU-level regulatory powers, the Schengen agreement (which in effect removes borders), the common R&D program FRAMEWORK (by far the largest single civilian R&D program in the world) and a range of major "Technology Platform" projects that integrate business, universities and government across the Union. Within and around this broad setup major transnational technology development programs have been undertaken rather successfully: the European high speed rail network known as Thalys, the EADS enterprise (comprising military combat and transport aircraft, helicopters, launchers and satellites and the Airbus business) and the Galileo global positioning system, for example.

The EU is not a special case. Even where countries have retained strongly national claims in terms of policymaking and sovereignty they have almost without exception (and without much debate) in practice signed up to a myriad of forms of transnational governance and regulation. These have been both global and regional. Probably the most important has been the WTO, with the key instruments being both the GATT and the special treaties surrounding it, notably TRIPS, TRIMS, and GATS.[49] These are active regulatory forms, with provisions taking the force of law; it is noteworthy that without much fanfare they successfully contained and reversed important unilateral initiatives by the Bush administration on trade policy. Then there are the specific policy forums, such as the G8, behind which lie major consultative organisations such as the OECD and the International Energy Agency (IEA), and the economic agencies such as the World Bank, IMF and the banking and financial regulators. Some parts of the UN system are very important, especially the World Health Organisation. This is not the place for a full list, let alone a full discussion of these agencies, but it is safe to say that they are now a dominant mode of formal and informal governance in the world. Informal, because around these agencies exist networks of policymakers, regulators and administrators who discuss, consult, generate and use common data resources, share information, and coordinate. As Anne-Marie Slaughter has remarked, "These government networks are a key feature of world order in the twenty-first century, but they are underappreciated, undersupported, and underused to address the central problems of global governance".[50] That is not to say that these organisations and networks are unproblematic and selfless in their operations and dynamics.[51] But they do offer a route towards the global coordination that is necessary for radical technology development in the face of climate change.

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[49] These agreements cover intellectual property, investment measures and trade in services respectively. The TRIPS agreement dramatically extends intellectual property protection and if fully implemented will have strong impacts on global innovation patterns.

[50] Anne-Marie Slaughter, *A New World Order* (Princeton University Press: Princeton and Oxford) 2004, 1.

[51] For a pathbreaking study of the developmental dynamics of a number of international organisations, see Michael Barnett and Martha Finnemore, *Rules for the World. International Organisations in Global Politics* (Ithaca and London: Cornell University Press) 2004

4.2.1 Global technology development for global climate change

In an influential set of works, Wolfgang Reinecke has argued that governments have lost not only the ability to enact policies on globally-relevant issues, but also to implement national policies within borders that globalisation is rendering porous. They should therefore “delegate tasks to other actors and institutions that are in a better position to implement global public policies – like the World Bank and the IMF, but also business, labour and nongovernmental organizations”.[52]

Foremost among such tasks is the search for technological innovations that mitigate climate change. The innovation challenge exhibits the potential complexities of most radical innovations: long time horizons, the need for major risk-bearing and uncertainty management, the need for prolonged financial commitments, the need for multiple and overlapping search paths, complexity and hence coordination challenges etc. Taken together these suggest the need for public leadership and management. The global public good aspects suggest a need for one or more transnational agencies to address the tasks.

The immediate policy tasks might be:

- To finance and support a major program of problem definition, opportunity identification, option selection and program design through an existing international policy agency. This might involve a solution task force on the scale of the IPCC, involving scientists and engineers, civil servants and other stakeholders. One obvious way would be to extend the remit of the IEA into this task.
- To map global scientific and engineering resources that are actually or potentially available, and to propose a “conceptual design” for appropriate coordination and governance mechanisms to integrate them
- To negotiate agreements on financing, risk sharing and arrangements for appropriation of direct benefits from new technologies across partner countries.

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[52] Wolfgang H. Reinecke, “Global Public Policy”, *Foreign Affairs*, 76 (1997), 132; see Slaughter, op.cit., 262

- To establish a coordinating agency, or to extend the terms of reference of an existing agency, and to provide the knowledge resources, capabilities and long-term finance to support a global coordination effort, and to design the appropriate program structures

In other words, the problem now is not to rush into a large-scale international program, but to explore – as systematically but as rapidly as possible – the modes through which this can be developed. There are already frameworks through which this can be attempted, such as the remnants of the Kyoto process. The challenge of a large-scale global climate technology programme would very likely revitalise this, and take it away from the contentious issues from which it has suffered in the past. A key problem will be how to integrate the social and technological dimensions of change, and how to envisage and manage the transition processes that will be necessary. Significant work has already be done in this area in the Netherlands, where groups of researchers in well-organised networks have been studying environmental 'transition management' issues for several years. Although they have not focused on the radical change issues advocated here, they have produced major work on the issues and methods involved in technological transitions to sustainability.[53]

4.2.2 National and regional policy agencies in the global context

Since climate change results from a global externality it is generally agreed that policies to ameliorate it must be global in character. The analysis of radical innovation presented above leads to an argument for new agencies and instruments at a global level, to undertake the missions of large-scale innovation that are involved. However this does not mean that national or regional jurisdictions do not have central roles to play; but it is important to be clear about what actions are appropriate to what levels of government. And even where some policy actions are best carried out at national or regional levels, there remains a need for global coordination in the content of policy.

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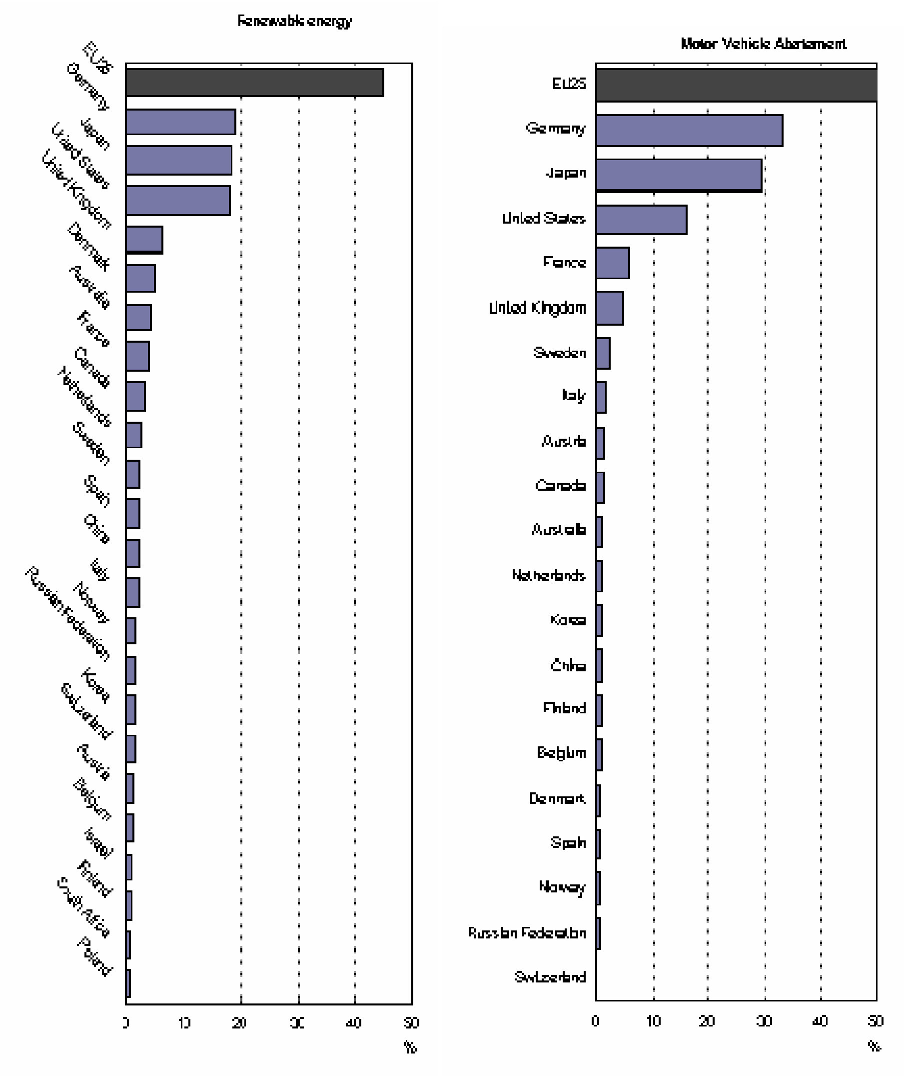
[53] F. Geels, *Technological Transitions and Systems Innovation*, (Cheltenham: Edward Elgar), 2005; R. Kemp, D. Loorback and J. Rotmans, 'Transition management as a model for managing proceses of co-evolution', *International Journal of Sustainable Development and World Ecology*, 14, 2007, 78-91; R. Kemp and J. Rotmans, 'Managing the transition to sustainable mobility' in E. Boelie et al, (eds) *System Innovation and the Transition to Sustainability: Theory, Evidence and Policy* (Cheltenham: Edward Elgar) pp.136-67.

Some of the more extreme analyses of globalisation argue that national or regional policies are ineffective in the new global context of enhanced foreign direct investment, global capital mobility, significant labour mobility and global norms of product quality and standards. This is to neglect the importance of the “innovation system” for the innovating firm. It was suggested above that firms do not produce or innovate alone, but in the context of the economic institutions and knowledge organisations of their local societies. Many of the core elements of innovation systems are not constrained or even much affected by globalisation. These include education systems, health and safety regulatory frameworks, tax policies, the provision and functioning of physical and knowledge infrastructures, risk management institutions, and much standards setting activity. Certainly there are some global constraints emerging from competition frameworks, and there are very definite government budget constraints. But within those constraints, national and regional governments still have considerable freedom of maneuver with respect to the structuring and functioning of the innovation system. These affect virtually all of the policy instruments that affect incremental and disruptive modes of innovation; and it is the case that these policies often present major challenges of design and implementation which are being resolved at national or regional levels. The most important of them are the array of carbon pricing policies. But also significant are regulation and procurement measures to induce adoption of disruptive technologies such as solar panels, wind power or geothermal energy.

The fact that this key policy arena can be national or regional in character does not mean they have no international dimension. Simply because any local emission affects the global greenhouse gas situation, there needs to be coordination on efforts towards the relevant innovations. At the moment there is little in the way of global coordination and there appear to be more or less sharp differences in efforts across countries. One possible indicator of this is the patent record: the EU is specialising far more in environmental technologies than any other major economy, as Figure 3 suggests.

Figure 3: Patent shares: Patent Collaboration Treaty filings on motor vehicle emissions abatement, and renewable energy at the EPO



Source: OECD: *Patent Compendium 2007*, Table 3.7.

The data above obviously needs to be normalised by population or GDP, but the EU and USA are of comparable size, and so it seems probable that there are some major imbalances in current innovative efforts. The general point here is that even where there are national and regional policy support functions, especially around incremental and disruptive innovations, there is a need for international coordination and agreement.

Turning to the more ambitious policies associated with mission-oriented programmes for radical innovation, it is not clear that only national governments should be involved in the direction, finance and governance of such programmes. The main reason for this is that such programmes cannot consist merely of innovation programmes, in the sense of bringing new technologies to the point of technical and economic feasibility. They must also involve diffusion and application, and in this there will be complex problems of transition management, involving the integration of new technologies with social patterns of organisation and technology use.

5 CONCLUSION

The argument of this paper has been that a major element of the innovation challenge of climate change, namely the need for full-scale alternatives to hydrocarbon technologies, is being neglected. It is not difficult to see why this should be – the problems involved in radical innovation in energy technologies are daunting. Any serious innovation programs will be long term, expensive, highly uncertain in outcome, and must be transnational – indeed global - in character. The process must involve search for technologies that are currently either very distant or not even on our technological horizons, accompanied by complex social and political initiatives to overcome our locked-in dependence on the hydrocarbon regime.

If these challenges are intimidating, it is worth remembering that innovation outcomes on a similar scale are not unprecedented. Unforeseen energy carriers have emerged before, the most recent spectacular example being nuclear power, which was simply unenvisaged considerably less than a century ago. The challenge of landing men on the moon involved technologies that did not exist when Presdient Kennedy formulated the objective. The technological challenge of storing energy on a large scale appears to be intractable, but our society has solved an arguably bigger storage problem, that of storing, rapidly searching and retrieving vast volumes of information. The technologies for doing this were unforeseeable only a short time ago, and were generated by precisely the sorts of programs advocated here. It is worth remembering that highly intelligent, well-informed and technically skilled people were deeply sceptical about the possibilities for development of this information technology or its widespread use, even after it had been shown to be technically feasible. Against the background of the history of technology, which is one of often extraordinary innovation and diffusion across a very diverse array of technological regimes, we have no reason to be pessimistic about the challenges we face with respect to energy and environmental sustainability.