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TECHNOLOGY INNOVATION AND CLIMATE CHANGE POLICY: AN OVERVIEW OF ISSUES AND OPTIONS

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Abstract: Achieving deep reductions in greenhouse gas (GHG) emissions at acceptable social cost will involve far-reaching technological change in the energy and in other sectors. Indeed, at present this seems one of the few things on which there is international agreement in relation to climate change. There are, however, disagreements among academics and policy analysts regarding the best way to promote appropriate technological change for tackling climate change, and the implications this has for policy. There are also practical institutional challenges in devising and successfully implementing policies, both at the domestic and international levels, which will successfully promote the needed innovations. This paper attempts to explain the different views and offers a synthesis, arguing that properly understanding the economics of technology innovation offers a way forward between what seem very divergent international positions on climate change policy.

Key words: Innovation, Energy Technology, Climate Change, Research and Development, Energy Investment.

1. THE CHALLENGE OF STABILIZATION

1.1. Overview

Driven by expanding economies and populations, global energy-related carbon dioxide (CO_2) emissions are widely projected to at least double by mid century in the absence of mitigation measures(Nakicenovic et al, 2000). In sharp contrast, stabilizing greenhouse gas concentrations at almost any level will ultimately require deep reductions, suggesting radical transformation of energy systems to be a matter of when and how, not whether (Edmonds et al, 2001). Industrialised country emission reductions of 50–60% from current levels by mid century, which some governments have proposed, would bring their economies close to the current global per-capita average. This would imply roughly ten-fold decrease in national carbon intensities (relative to projected GDP) from 1990 levels. Meeting such a challenge without excessive costs clearly requires extensive innovation.

Faced with this, it is a natural temptation to place ones hope in some 'magic bullet', a radical technology breakthrough that will transform our energy systems in the way that seems to be needed. It is the core argument of this paper that this is a false hope, and a wrong-headed view of the technology challenge. The real challenge—and the real opportunity—is both far more difficult, but also far more interesting.

The first essential step is to recognize that the climate change challenge actually reaches across many different systems. It is widely recognized that the climate problem overall requires us to tackle a number of different gases and sources in addition to fossil fuels; that greenhouse gases also emanate from agriculture, land use and direct industrial process emissions. It seems less widely recognized that even within fossil fuel combustion— which account for about 80% of industrialized country greenhouse gas emissions—there are several different systems each of which involve fundamentally different processes, and which would need correspondingly diverse technological solutions.

Specifically, CO_2 emissions from energy systems are driven by energy demand in three main components (buildings, industry, and transport), supplied increasingly through three main systems (electricity, refined fuels, plus direct fuel delivery (Fig. 1)). It is fanciful to imagine that a single zero-carbon supply technology—or even a few—could radically deliver the 10-fold decarbonisation of inputs, across all the conversion systems, that would be required to deliver deep reductions in the absence of far better end-use efficiency. It is equally improbable that even radical efficiency advances could displace the need for low and zero carbon supplies. Atmospheric stabilization will require vigorous diffusion of efficient technologies and services across all three end-use sectors, combined with steady decarbonisation of the energy inputs to supply.

1.2. Global energy resources

The limiting factor in our energy systems is *not* energy resources in themselves, with or without carbon constraints. Nevertheless, the nature and distribution of resources forms an important part of the story. Energy resources are not seriously limited *in total*, and nor are low-carbon options including renewables (Table 1 and Figure 2). Rather, the constraints concern the economics of matching sources and systems to demands. Current 'proven reserves' of coal, oil and gas amount to about 100, 40 and 60 years of current production respectively. Coal could be greatly expanded with technological progress and, unlike other fossil fuels, is largely located within countries of major demand expansion (like China and the US), though transport costs (and environmental impacts) may still be significant.

In contrast, development of conventional oil resources is unlikely to more than double the presently proven conventional reserves and global production is widely expected to peak in the next 20 years or so, however unconventional resources (eg. tar sands, shales) offer major additional carbon-intensive resources. Natural gas is increasingly a fuel of choice but whilst global resources are at least comparable with oil, they are also mostly not near major demand centres and nearly half the world's potential reserves are considered as 'stranded'. Nevertheless, a quarter of global gas is now internationally

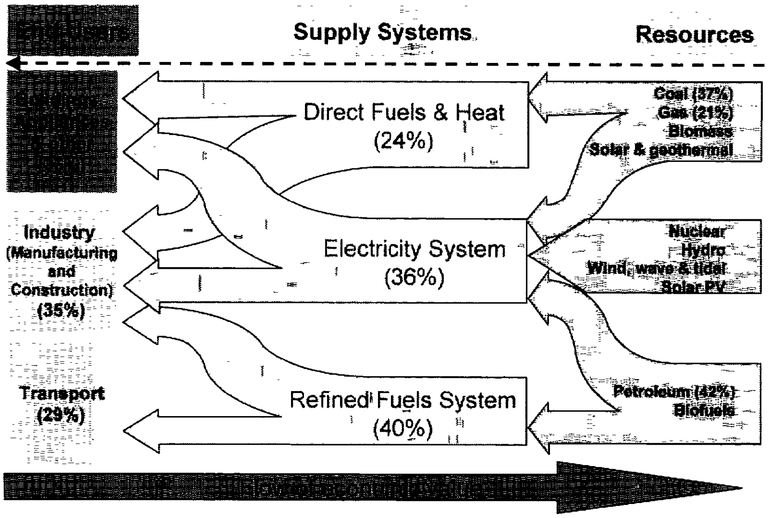

Figure 1. Main components of global energy system and CO_2 emissions.

Notes: The data show the % of global energy-related CO_2 emissions associated with the different parts of the energy system (including emissions embodied in fuels and electricity). Some small flows that comprise under 1% of global energy flows (eg. electricity and natural gas contributions to transport) are not shown. Note that patterns vary between regions (eg. industry is lower and transport higher in developed economies), and the sectors are growing at different rates (over past 30 years, energy demand for buildings : industry : transport has grown at 2.6% : 1.7% : 2.5% annual average. Non-electric energy industries' (emissions from refineries, gas etc) cited as 7% of total, are allocated here in ratio 4 : 1 : 2 to transport : industry : buildings & other. Refined fuels taken as petroleum less input to elec; direct fuels and heat is the residual.

Source data: Resources CO_2 from EIA (2002); supply systems and end-use data from IEA (2002)

traded, and the ongoing development of both pipeline and liquefied natural gas (LNG) is leading towards a global market that should stabilise prices and increase access. Limits on Uranium reserves do not pose significant constraints on plausible nuclear expansion out to mid century.

Similarly, most renewable energy sources are very large in terms of physical flows, and although various constraints limit what is feasible, the estimated global *potential* for tidal, wave and hydro are comparable to the scale of global electricity consumption, whilst most estimates of practicable wind and solar resources are substantially greater still (Figure 2 summarises various estimates). As with natural gas, key issues for delivery include the systems, and the fact that (with the minor exceptions of direct solar heating and lighting, and geothermal heating) all but one—biomass—produce primary electricity.

Table 1. Global fossil energy reserves, resources, and occurences (EJ).

	Consumption (1860–1990)		Consumption (1990)		Reserves Identified/ Potentials by 2020–2025		Resource Base/ Maximum Potentials	
	EJ	GtC	EJ	GtC	EJ	GtC	EJ	GtC
Oil								
Conventional	3,343	61	128	2.3	6,000	110	8,500	156
Unconventional	—	—	—	—	7,100	130	16,100	296
Gas								
Conventional	1,703	26	71	1.1	4,800	72	9,200	138
Unconventional	—	—	—	—	6,900	103	26,900	403
Coal	5,203	131	91	2.3	25,200	638	125,500	3,173
Total Fossil	10,249	218	290	5.7	50,000	1,053	>186,200	4,166
Nuclear [b]	212	—	19	—	1,800	—	>14,200	—
					EJ/yr		EJ/yr	
Hydro	560	—	21	—	35–55	—	>130	—
Geothermal	—	—	<1	—	4	—	>20	—
Wind	—	—	—	—	7–10	—	>130	—
Ocean	—	—	—	—	2	—	>20	—
Solar	—	—	—	—	16–22	—	>2,600	—
Biomass	1,150	—	55	—	72–137	—	>1,300	—
Total Renewables	1,710	—	76	—	130–230	—	>4,200	—

[a] Table based on SAR II, B.3.3.1, Tables B-3 and B-4.
[b] Natural uranium reserves and resources are effectively 60 times larger if fast breeder reactors are used.
— = negligible or not applicable.
Source: UNDP/WEC (2001)

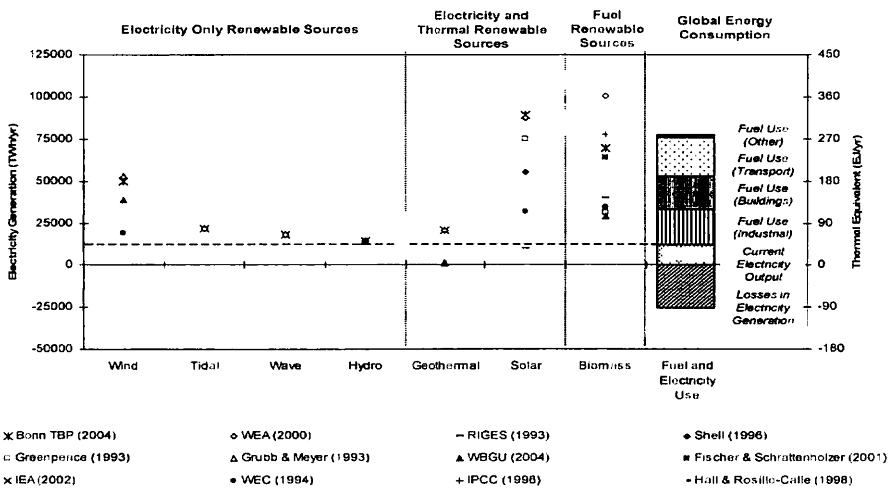

Figure 2. Global renewable energy potential estimated by various studies compared to current global energy and electricity demand.

Source: Neuhoff (2005). See source for references and explanation.

1.3. Understanding and scaling the technology options

Pacala and Socolow (2004) have introduced a useful way of thinking about the scale of the challenge and options. Stabilizing GHG concentrations below twice pre-industrial levels would require total global CO_2 emissions to peak within a couple of decades and then begin an indefinite decline. Set against a typical 'Business As Usual' projection—a world that pays no deliberate attention to global carbon and in which emissions double from the present 7 GtC/yr to 14 GtC/by by mid Century—Pacala and Socolow suggest thinking about the problem in terms of rapid expansion of seven 'wedges' of alternate technologies, each of which displaced about 1GtC/yr by 2050. Seven such 'wedges' would stabilise emissions to 2050; global reductions thereafter could stabilise CO_2 concentrations around 500 ppm CO_2, consistent with CO_2-equivalent doubling of pre-industrial concentrations.

Potential wedges come in many forms, ranging from improvements in efficiency for automobiles, appliances, and power plants, to greater shares in energy supply for nuclear energy, renewable energy, and carbon capture and storage, to enlargement of bio-carbon stocks through management of forests and soils. The wedge is a useful unit of action, because it permits quantitative discussion of cost, pace, and risk. A wedge, for example, could be a million two-megawatt wind turbines displacing coal power. Another could be two billion personal vehicles achieving 60 miles per U.S. gallon (mpg) on the road

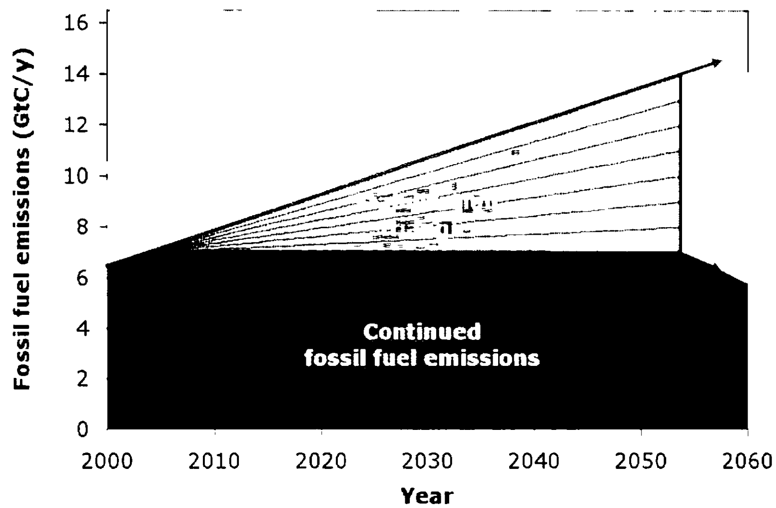

Figure 3. The "Princeton Stabilisation triangle".

Notes: As compared to a 'business as usual' future in which CO_2 emissions double from 7GtC/yr to 14GtC/yr by about mid Century, emissions stabilization requires a 'stabilization triangle' that grows to save 7GtC/yr by mid century. This can be conveniently divided into seven "wedges" of avoided emissions, each of which grows linearly from zero today to 1 GtC/y in 2054. The wedge is a useful unit for quantifying options that could make a big impact on global carbon emissions.

instead of 30 mpg. Another could be capturing and storing the carbon produced in 800 large modern coal plants.

Pacala and Socolow identified twelve such aggregated potential 'wedges' related to energy and carbon as summarized in Table 2. They claimed that "The necessary wedge technologies are already deployed somewhere in the world at commercial scale. No fundamental breakthroughs are needed. Humanity can solve the carbon and climate problem in the first half of this century simply by scaling up what we already know how to do." However, they acknowledged that every wedge is hard to accomplish, because huge scale-up is required, and scale-up introduces environmental and social problems not present at limited scale.

Table 2. Potential 1GtC/yr 'Wedges' of technological contributions.

Mitigation	1 Gt(C)/yr Global Business	Risk, Impact
Coal plant: CO_2 capture (stored, not vented: see sequestration below)	700 1GW plants	CO_2 leakage
Nuclear displaces average plant	1500 1 GW plants (5×current stock)	Nuclear proliferation and terrorism, nuclear waste
Wind displaces average plant	150×current stock	NIMBY objections Poss regional climate impacts
Solar PV displaces average plant	2000×current stock; 5×106 ha	Minimal
Hydrogen fuel	1 billion H_2 cars (CO_2-emission-free H2), displace 1 billion 30 mpg gasoline/diesel	H_2 infrastructure; H_2 storage
Efficiency, overall	8% of 2050 "expected" fossil C extraction; C-intensity of economy drops 0.2%/yr faster	Minimal
Efficiency, vehicles only	2 billion gasoline and diesel cars at 60 mpg instead of 30 mpg (or, at 30 mpg, going 6,000 rather than 12,000 miles per year).	Lifestyle (car size and power) Urban design
Geological sequestration	3500 Sleipners, at 1 Mt (CO_2)/year	Global and local leakage
Land sink	Now 1.5 Gt (C)/yr, sink becomes 2.0 Gt (C)/yr, rather than 1.0 Gt(C)/yr	Current estimate for 2050 sink is several times more uncertain
Biomass fuels from plantations	100×106 ha, growing @10 t(C)/ha-yr	Biodiversity, competing land use (200×106 ha = US agricultural area)
Storage in new forest	500×106 ha, growing @2 t(C)/ha-yr	Biodiversity, competing land use

In practice, the wedges also help to illustrate the complexity of the challenge. The 'overall efficiency' wedge is simply an aggregated statement about the acceleration of overall efficiency that could deliver a 1GtC/yr saving. Many of the other wedges involve technologies that far from commercially competitive, and face potentially huge scale-up issues. Their analysis is helpful in giving a language around which to structure discussion, and it helps to indicate that the technology challenge is diverse and complex; but it does not identify the process or strategies of innovation that could deliver such large-scale changes. This is what the rest of this paper addresses.

2. THE 'TECHNOLOGY-PUSH' VS 'DEMAND-PULL' DEBATE: SIGNIFICANCE AND EVIDENCE

2.1. *Significance of the technology-push vs demand-pull debate*

Long-term mitigation studies show consistently that assumptions about technology development are crucial to economic and policy conclusions (eg. Dowlatabadi 1998; Edmonds et al. 1999; World Resources Institute, 2000). Nevertheless, in western economies the climate policy debate is often characterized by two polarised views about technology innovation processes.

The "technology push" view holds that the primary emphasis should be on development of low-GHG technologies, typically through publicly funded R&D programmes, rather than regulatory limitations on emissions. Proponents of this view argue that, given that climate risks are a function of long-term accumulation of GHG in the atmosphere, it would be preferable to concentrate in the near term on investing in technological innovation, and adopt emissions limitations later when innovation has lowered the costs of limiting GHG emissions, rather than mandating costly reductions now (Wigley, Richels and Edmonds 1996). A paper by Hoffert et al. (2002) has become the leading articulation of this view, asserting that technologies to solve climate change do not yet exist, and calling for a grand technology programme encompassing new nuclear and space-based energy sources to solve the problem.

The opposing "market pull" view holds that technological change must come primarily from the business sector, and is primarily a product of economic incentives. In the climate context, this view gives priority to adoption of regulatory measures such as technology-based regulatory limitations, GHG emission caps, or charges. Profit-seeking businesses will respond by innovating to produce technologies that will reduce emissions at less cost in order to gain competitive advantage over rivals.[2] From this perspective, postponing emissions limitations would simply defer the whole process of innovation required for the private sector to produce these solutions. Proponents of this approach might acknowledge various market failures with respect to the early stages of innovation; business firms may not have adequate incentive to invest in basic research because they may be unable to appropriate (through patents, etc.) the knowledge

[2] This perspective draws on a considerable literature on induced technical change (eg. reviewed by Weyant J.P. and T. Olavson (1999), with implications for policy considered eg. in Grubb et al. (1995); Dowlatabadi (1998); and Grubb, Koehler and Anderson (2002).

gained, and because the commercial payoffs may be too uncertain and long-term. But "market pull" advocates tend to assume that existing general policies (such as corporate tax breaks for R&D expenditure) are sufficient to overcome these failures.[3]

Thus, divergent perspectives on the *process* of technology change lead to directly opposing *policy prescriptions*, in many dimensions, as summarised in Table 3. It is indeed quite remarkable that so many policy-relevant issues hinge upon the view one takes of technological change processes. In the rest of this paper, I want first to argue that these views pose a 'false dichotomy' - that rather than describing a choice between 'right' and 'wrong' ways of looking at innovation, they offer instead insights into different parts of the process. Then, I look briefly at whether and if so how this might help to reconcile opposing political positions.

Before doing this, I offer one other observation. The argument about technology change processes seems to be mostly between different western schools of thought, and itself reflects the tendency of western economies—and the underlying theories upon which they are based—to draw a sharp line between the role of the State (and of regulation as its tool of implementation) on the one hand, and the role of the Market (and of private industry as the implementor) on the other. It is possible that Asian researchers, reflecting more intimate and less legalistic relationships between State and industry, may more easily accept the need for—and perhaps find ways to implement—a more integrated approach.

2.2. *Empirical evidence and learning curves*

As noted, the debate between supply-push and demand-pull views of technology change is not new; indeed it dates back many decades. In the energy sector, however, it has become sharpened by the fact that the main classical global energy system models have modeled technology change as an exogenous assumption—future technology costs are simply entered by the modeller and not affected by the abatement or carbon price assumptions in different control scenarios. This is equivalent to "supply-push", and contrasts with the accumulating evidence around market-based technology learning.

One specific technology example is illustrated in Fig. 4. This shows the declining cost of wind energy in Denmark as the industry expanded at around 25%/yr, first domestically and then internationally. Costs roughly halved during the 1990s and wind energy now appears competitive with conventional power generation at good sites around much of Europe. The technology improved dramatically, but in evolutionary ways clearly associated with the build-up of the industry.

There is abundant more widespread evidence linking technology cost reductions to increased use, through a variety of learning processes. Figure 5 illustrates historic 'learning curves' for various electricity technologies; a doubling of production volume has typically been associated with cost reductions of 10–25% in technologies during initial phases of commercialisation and deployment though there is some evidence that the learning rate declines as the market matures (McDonald and Schrattenhozer, 1999;

[3] There is far less need for regulation to create market incentives for innovation in technologies to facilitate adaptation to climate change, but there is need for publicly funded R & D in adaptation measures.

Table 3. The divergent policy implications of different technical change perspectives.

Process:	Technology-push: R&D-led technical change	Demand pull: market-led technical change
	Technical change depends mostly on autonomous trends and government R&D	Technical change depends mostly upon corporate investment (R&D, and learning-by-doing) in response to market conditions
Economic/policy implications:		
Implications for long-run economics of large-scale problems (eg. climate change)	Atmospheric stabilisation likely to be very costly unless big R&D breakthroughs	Atmospheric stabilisation may be quite cheap as incremental innovations accumulate
Policy instruments and cost distribution	Efficient instrument is government R&D, complemented if necessary by 'externality price' (eg. Pigouvian tax) phased in.	Efficient response may involve stronger initial action, including emission caps/pricing, plus wide mix of instruments, targeted to re-oriented industrial R&D and spur market-based innovation in relevant sectors. Potentially with diverse marginal costs
Timing implications	Defer abatement to await technology cost reductions	Accelerate abatement to induce technology cost reductions
'First mover' economics of emissions control	Costs with little benefits	Up-front investment with potentially large benefits
Nature of international spillover/leakage effects arising from emission constraints in leading countries	Spillovers generally negative (positive leakage) due to economic substitution effects in non-participants	Positive spillovers may dominate (leakage negative over time) due to international diffusion of cleaner technologies

Source: Adapted from Grubb, Koehler and Anderson (2002).

IEA, 2000). This reflects the fact that innovation is a product of *complex systems*, in which feedbacks from the different stages of the innovation chain and the ability to learn from market experience are crucial.

Such experience curves have in fact been used for decades in engineering consultancy analysis, but their use in large-scale energy systems analysis is proving controversial, because of their radical implications as indicated below. Critics point out that causality is not certain: has rising market share driven cost reductions, or the other way round? How important is just the time dimension—that costs decline over time because we learn as time passes? Whilst these debates are important, however, they cannot obscure the basic common-sense fact that scale and experience can be expected to reduce the cost of almost any technology. Data such as indicated in Fig.5 give the best insight we have at present into typical magnitudes, and the implications appear profound.

2.3. *Technology cost projections*

Technology cost projections are fraught with uncertainty, but combinations of engineering assessments and experience curve data give some interesting insights. The ICCEPT research group at Imperial College conducted studies for the UK government's

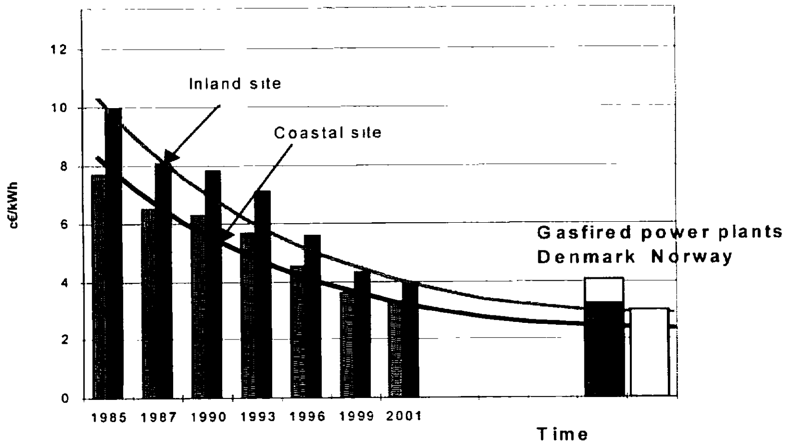

Figure 4. Cost reductions for wind energy in Denmark.

Source: Morthurst (2005).

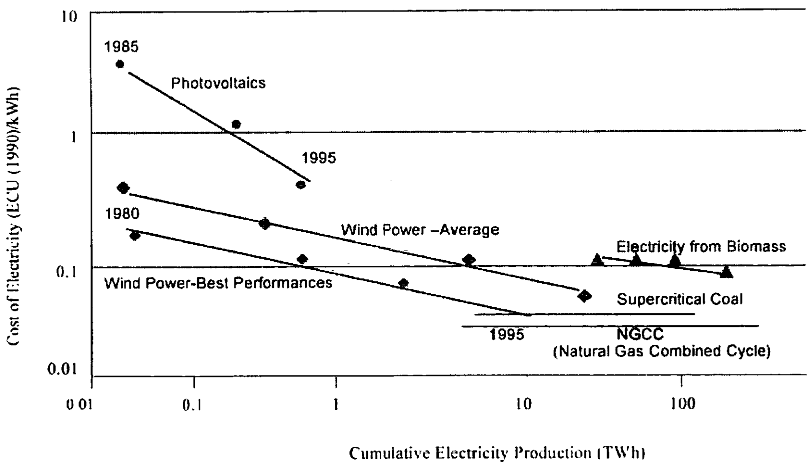

Figure 5. Historic learning curve data for energy technologies.

Source: McDonald and Schrattenholzer (1999).

Performance Intelligence Unit, and have since refined and expanded these with the results indicated in Tables 4 (for electricity generation) and 5 (for liquid fuel technologies).

The most striking feature of Table 4 is the diversity of very low carbon options that have medium-term potential costs broadly around 5-7c/kWh; carbon capture with storage, modular nuclear, advanced biomass, fuel cell technologies and offshore renewables

Table 4. Current and projected medium-term costs of electricity generating technologies.

Technology	Current cost (*cents/kWh*)	Medium term projections	Comments
Present fossil fuel plant			
Gas CCGT Coal	3–4 3.5–4.5	Depends on fuel prices and carbon cap/price systems	Carbon prices in range \$10–20/tCO_2 (widely projected under the EU Emissions Trading System) would add c. 0.6-1.2 /kWh to CCGT generating costs and about twice as much to coal.
Very low carbon electricity technologies			
Carbon Capture and Storage (CCS) Nat. Gas with CCS IGCC Coal with CCS	 NA NA	 4–6 5–8	Techniques known but not tested at scale.
Nuclear Power	5–7	4–8	Costs very sensitive to finance rates & construction times. Low historical learning rate.
Biomass Co-firing with coal Electricity CHP-mode	 2.5–5 5–15 6–15	 2.5–5 5–9 5–12	Costs depend on feedstock as well as conversion plant—farm/forest wastes cheaper than dedicated crops.
Wind Electricity onshore offshore	 5–8 9–12	 2–4 3–8	Costs vary with site; learning curve evidence and rapid growth with good engineering data onshore, offshore experience more limited.
Tidal Stream/Wave	13–20	< 15	Estimates from parametric models due to immaturity of technologies
Grid connected PV 1000 kWh/m^2/year (UK) 2500 kWh/m^2/year (Africa, South Asia)	 50–80 20–40	 15–25 5–15	Strong market growth and learning curve basis for cost decline; added value in applications close to end-use.

Notes : The table shows typical busbar generating costs and medium-term (generally 2020/2025) cost projections for low carbon generation. All costs inflated from time of study to 2004, and converted at purchasing power parity rates; UK£ converted at 1.5 £/\$. Cost projection methodologies in the studies are diverse. PV costs neglects offset costs (e.g. building materials displaced by PV façade).

Source: The table summarises results of survey and analysis presented in R. Gross and A. Bauen, 'Synthesis of energy technology medium-term cost projections: a technical note', ICCEPT, www.iccept.ac.uk. The principal sources are analysis and review work carried out and published as part of the UK Energy White Paper and the precursor analysis of the UK Performance Intelligence Unit.

all fall into this range. Gas turbines and onshore wind energy are probably cheaper, whilst PV is more expensive per kWh but could benefit from its small, modular nature that could enable it to compete against end-user, not wholesale, electricity prices. All these options draw upon known technologies; blue-skies breakthroughs do not seem needed in power generation, and studies that incorporate experience curve learning indicate very low carbon electricity futures need not be more costly. The choice from this portfolio would vary from region to region, and its diversity (combined with improving storage and grid management technologies over time) also suggests intermittency is not a fundamental obstacle. Paths to very low carbon electricity systems within decades seem clearly visible, if we can develop the associated industries at scale.

The situation for transport is more complex. Atmospheric stabilisation will ultimately require transport fuels with near-zero 'well-to-wheels' CO_2 emissions. The main options are biofuels, electricity, and hydrogen, the last two only helping if produced from very low net CO_2 energy sources.

Table 5 summarises costs for various biofuels. Clearly, little can compete with the cost of conventional oil production (which is only above US$10/bbl in the more remote and difficult production fields), but there do appear to be a range of options that could start to compete with oil at the traded prices seen since 2003. Cost reductions associated with the build-up of the Brazilian industry appear to have made its ethanol competitive at oil prices above about US$30/barrel, and advanced cellulosic technologies might offer similar costs, whereas ethanol from grains, and diesel from rapeseed, are projected to remain about twice as expensive (Table 5).

Table 5. Biofuels current costs and 2020 projections ($cents/litre g.e.).

Technology	Current costs	2020 Projections
Gasoline / (diesel) cost for oil crude @ c. $50/barrel (FOB Gulf cost)	35 / (37)	Dependent upon oil supplies
Ethanol from sugar cane (Brazil)	25–35	22–31
Ethanol from corn (US)	40–60	37–56
Ethanol from grain (EU)	50–80	40–65
Ethanol from cellulosic crops	50–90	27–67
Biodiesel from rapeseed (UK)	99–165	
F-T diesel from coppice (UK)		53–89

Source: See table 4.

Electric and plug-in hybrid vehicles can reduce CO_2 emissions if the electricity is drawn from CCGT or lower carbon sources. Hydrogen for fuel cell vehicles from non-carbon electricity can be costly. Vehicles fuelled with biofuels, low carbon electricity, and low-carbon hydrogen could all co-exist in a long-term transition to low-carbon transport, but both the economics and pathways appear more complex and potentially more costly than for electricity.

The need to make a transition in transport fuels is also driven by oil resource and supply security considerations. Compared to the century-timescale of the climate problem, global oil production will peak soon. Indeed, total remaining conventional oil resources contain barely a quarter of the total carbon that would have to be emitted to reach 500 ppm CO_2.

2.4. *A global systems perspective*

This points to the importance of taking an integrated, long-term and internally consistent view of the combined challenges of climate and energy provision.

The new class of models that embody technological 'learning-by-doing' suggest the range of possible emissions, for similar global economic costs, is very wide. Figure 6 shows the probability distribution of global CO_2 emissions by 2100 projected by leading studies by IIASA (Gritzevski and Nakicenovic, 2002). The most striking feature of this analysis is the 'bimodal' distribution of long term emissions at similar costs: some futures embody learning on a high-carbon, coal and synfuel-based global energy system, other futures embody learning on a gas, renewables and ultimately hydrogen-based energy system. Either of these kinds of global energy future will require huge investment and learning, and it cannot be assumed *a priori* that the carbon-intensive paths will be cheaper—they will just be very, very different in terms of the technologies, systems and resources employed.

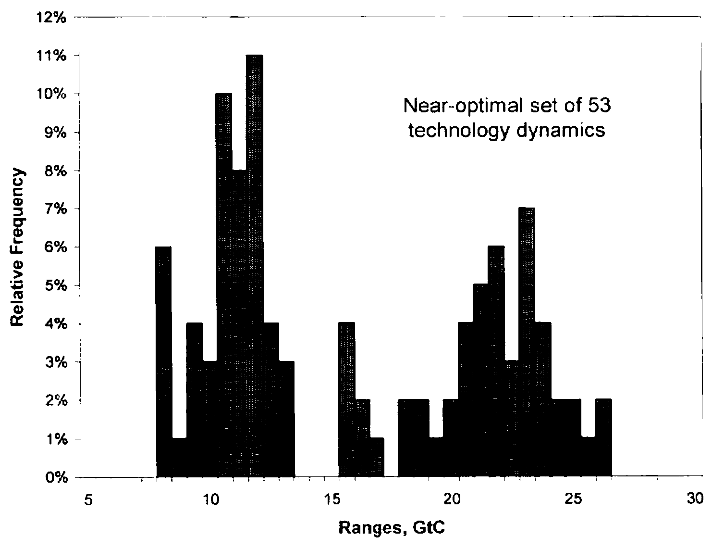

Figure 6. Results of IIASA analysis of global energy systems with induced technical change under uncertainty: range of emissions by 2100 for 53 least-cost scenarios.

Source: Gritsevski and Nakicenovic (2002).
Note : The graph show the relative frequency distribution of projected global carbon emissions at the end of the Century for the 53 scenarios in which total discounted energy system costs were within one percent of the minimum, derived from a model embodying learning-by-doing at uncertain learning rates. The cheapest scenarios were either high-carbon (with predominantly coal-based learning) or low-carbon, but not in the mid-range.

Equivalent results, in a different format, are produced by Papanathsiou and Anderson (2002), who produce a probability density of the net costs of renewables-intensive futures, and find these to be widely distributed about the zero point. In other words, given learning-by-doing at uncertain rates, renewable-intensive futures may be either cheaper or more expensive than carbon-intensive futures, depending on the choice of learning parameters, but there is no a priori basis for expecting them to be more expensive.

From a policy perspective, the key will be to ensure that investment 'beyond petroleum' does not follow the current trend towards developing higher-carbon fossil sources—heavy oils, tar sands, oil shale, and coal-derived fuels—but instead is diverted in the direction of lower-carbon energy systems. Which brings us to the policy question, of how to induce innovation in low-carbon directions.

3. A CLOSER LOOK AT ENERGY-ENVIRONMENTAL INNOVATION PROCESSES AND POLICIES

3.1. *Integrated perspectives: the innovation chain*

This analysis paints a complex picture. Innovation is clearly needed, but not necessarily radical blue-skies technology breakthroughs. At the same time, the innovation required to develop low carbon options is unlikely to arise without government direction; industries are not going to risk large amounts of capital on potentially risky scaling-up of low carbon technologies without good reason. What therefore does all the above imply for policy?

A good place to start is to learn from history and recognise that innovation policy is not easy. As cited by Fri (2003), there has been a tendency to 'throw technology at social problems, and that has certainly been true of energy', with at best mixed results.[4] It is thus crucial to understand the innovation process, and the potential role of policy.

First, the debate between 'supply push' and 'demand pull' needs to resolved by recognizing that innovation is a complex phenomenon which in reality encompasses both perspectives. Whilst engineers tend to focus upon R&D, economists since Schumpeter have tended to break innovation down into three components (invention, innovation, and diffusion)—but even this is inadequate. The tendency to add more "D's" (development, demonstration, diffusion ...) does not really capture the essential qualitative changes involved in the various steps. Viewed more closely there are in fact at least six distinct stages to energy technology innovation in a market economy (Fig. 7(a)):

- *basic research and development;*
- *technology-specific research, development and demonstration;*
- *market demonstration* of technologies to show to potential purchasers and users that the technology works in real-world applications, and tests and demonstrates its performance, viability and potential market;

[4] 'Synthetic fuels, the breeder reactor, fusion power, most renewable technologies, and the persistence of the fuel cell option testify to this tendency. For the most part, however, these programmes have been either expensive failures or only slightly less expensive technological successes that serve limited markets' (Fri, 2003)

- *commercialisation* – either adoption of the technology by established firms, or the establishment of firms based around the technology;
- *market accumulation* in which the use of the technology expands in scale, often through accumulation of niche or protected markets;
- *diffusion* on a large scale.

The chain is not necessarily linear—university spin-out companies may well be established to conduct the market demonstration, for example—and there are constant feedbacks. Each stage involves technology improvement and cost reduction, but the principal barriers and driving forces change across the different stages. 'Technology push' elements dominate early stage research, whilst 'market pull' is increasingly important as technologies evolve along the chain.

This framework helps to reveal the conflict between the technology push and demand pull views as a false dichotomy. In effect, 'supply-push' perspectives are true for the early stage R&D, whilst 'demand-pull' apply in later stages, closer to market. From a finance and public policy perspective, indeed, it is useful to condense the innovation chain into three main components (Fig 7(b)): at one end, the new technology RD&D stages, the main issues concern the funding and management of publicly-financed technology RD&D; at the opposite end, what matters are policies that affect the economic returns to private investors. In the middle, the challenge is the transition from publicly to privately financed operations.

The innovation literature highlights other important findings. Innovation is a product of complex systems, in which feedbacks from the different stages of the innovation chain and the ability to learn from market experience are crucial (Shelton & Perlack, 1996). Also, major innovations involve co-evolution of technologies and institutions that support them. Together, these factors tend to favour incumbents ('lock-in'), making it hard for new technologies to enter ('lock-out') (for review see Sanden and Azar, 2004). In this sense, the framework indicated by Fig.7 is highly simplified; it can be considered as an 'intermediate complexity' approach to the innovation problem, complex enough to capture some key features, but simple enough to be useful in thinking about some of the major policy issues.

3.2. Innovation in the energy sector

The way in which some of these basic principles of innovation play out in practice varies radically between different sectors. Information technology and pharmaceuticals, for example, are both characterized by high degrees of innovation, with rapid technological change financed by private investment amounting typically to 10–20% of sector turnover (Neuhoff, 2005). However this offers a dramatic contrast with power generation, for example, where the same fundamental technology has dominated for almost a century and private sector RD&D has fallen sharply with privatisation of energy industries to the point where it is under 0.4% of turnover (Margolis and Kammen, 1999).

There may be several reasons for this low inherent innovation-intensity. Processing large amounts of energy may inherently involve big capital investment and long timescales, which naturally increases risk and deters private finance; each stage in the

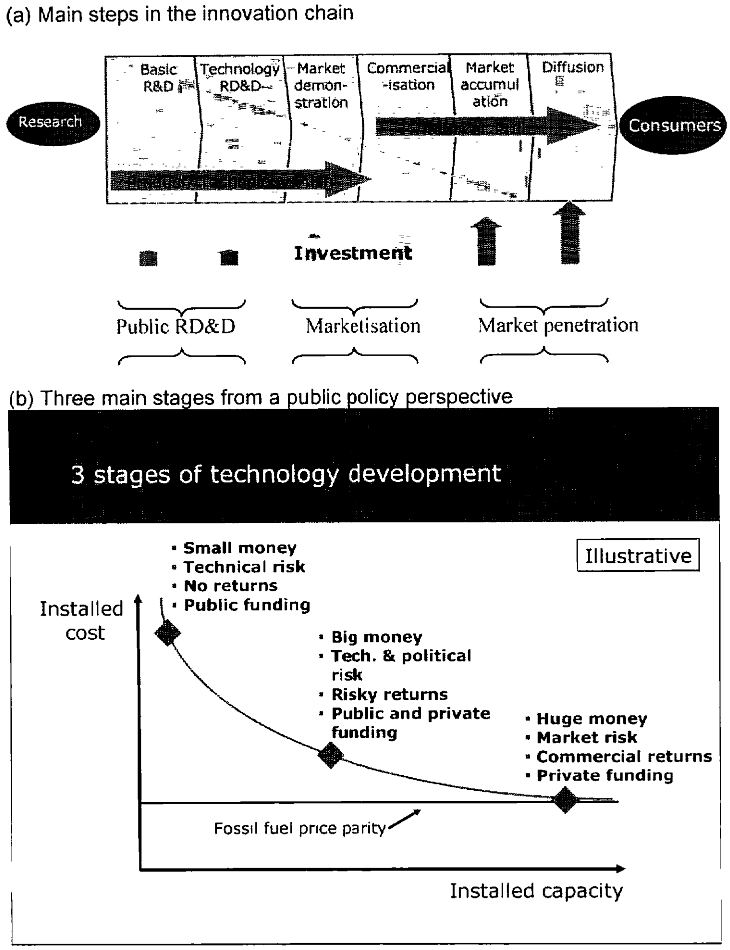

Figure 7. The innovation chain.

innovation chain can take a decade, and diffusion is equally slow. Perhaps more fundamentally however, the R&D-intensive sectors (like IT and pharmaceuticals) are ones in which competition is essentially all around product differentiation (a better computer/mobile phone; a better drug) whereas innovation in power generation is basically about efficiency and price in delivering the same product (electrons). This is a far weaker driver. And compared to a new product that captures public imagination and commands a large market combined with a high price premium, price-based competition has dramatically less scope for offsetting big risks against the prospect of huge rewards.

Note that the problem is particularly relevant in the power sector, and in buildings; the oil sector is characterized by much higher innovation, not least because the huge rents in the sector can fund large risk-taking, whilst vehicles certainly involve product competition even if fuel consumption is generally a minor part of the competitive appeal. Unfortunately, most of the oil sector's risk-taking is currently still in higher-carbon directions; and it is power generation and building energy use that remain the larger source of global CO_2 emissions.

Thus, climate technology policy is seeking radical innovation in one of the least innovative sectors in the whole economy. The incentives for low-carbon innovation, whose value depends upon uncertain government policies to internalise carbon costs at some point, are still weaker.

Public R&D is not a satisfactory substitute. Global public sector energy RD&D expenditure has halved since the mid 1980s (Margolis and Kammen, 1999) not only because the perceived oil crisis recede, but because several expensive forays into large-scale energy technologies failed to deliver commercial products (Cohen and Noll, 1991). There are many reasons for this – intrinsic obstacles to technologies successfully crossing from the stage of publicly-funded demonstration to becoming a basis for commercially viable industries. The result is the now well-documented 'technology valley of death', in the central stages of the innovation chain (eg. Murphy and Edwards, 2003).

Public RD&D fails to bridge the gap in either quantity or its linkage to commercially exploitable results: innovation is sparse and energy technologies founder because of the very different needs of private and public sectors (Murphy and Edwards, 2003; Foxon, 2003).

3.3. *A framework for narrowing the innovation gap*

All this sets the context for thinking about low-carbon innovation policy. Government has a key role across the innovation chain, but its role changes radically along the innovation path and the appropriate extent of involvement may vary greatly between different sectors.

At one end, government finances basic and applied technology R&D, and some proof-of concept demonstration, in order to lay a foundation of publicly-available ideas for others to work with.

At the opposite end, governments need to define and enforce a basic regulatory structure which can reward innovators, most notably, a functioning system of product patents that allows companies that invest in developing a unique product to be protected from copying by rivals for some defined duration. In addition to rewarding innovators, market-side policies can act to sift out the best and guide the underlying research effort (Loiter and Norberg-Bohm, 1999).[5]

[5] 'Weak demand-side policies for wind energy risks wasting the expenditure of public resource on research programs aimed at technological innovation. When these programs operate without the benefit of a market to test the results or provide guidance for future efforts, they are less likely to succeed (Loiter and Norberg-Bohm, 1999 p. 85).

In the case of innovation oriented towards a 'public good' like climate change mitigation, obviously 'market pull' is inoperable unless governments adopt regulations that increase the market value of low carbon technologies, most obviously through carbon taxes or cap-and-trade systems; such emission control regulations provide market based incentives to underpin the diffusion of low-carbon technologies, and hence provide signals that innovation in this direction can ultimately expect more reward.

For many sectors of the economy, public policy of the kinds indicated may be adequate. In pharmaceuticals, for example, the 'public good' of better medicines is automatically matched by the large-scale purchase of better drugs by national health authorities, private health practices, or direct private purchase; and patenting of discrete, chemically-unique drugs provides strong protection for the manufacturers; thus the 'market pull' forces reach deep into the innovation chain. For the information technologies, product differentiation built on a strong base of publicly-funded basic research provides a similarly strong combination.

As we have seen however, the energy industries—and particularly utilities and many end-uses—are not like this. The classical policies at the ends of the innovation chain do not address the core 'technology valley of death' problems in the central stages. Public R&D cannot drive commercial uptake, market pull forces are weak because product differentiation is not a key market driver, and the promise of emission controls does not form a credible, long-term basis of sufficient security against which most firms could take substantial risks in the face of sceptical shareholders. In addition to the technical and financial risks, the political risk of such markets—real or perceived—further undermines those who might wish to try. Neither public R&D nor prime reliance on carbon pricing / cap-and-trade will achieve the far-reaching, long-term innovations required to address climate change.

Thus for a big, long term problem like climate change, emission constraints need to combine with R&D and a range of targeted supports to promote technology investment through different stages of the innovation chain. This broad conclusion is becoming more widespread (IEA, 2003); the next section attempts to delve in a more structured way into the implications.

3.4. *A classification of policies for narrowing the innovation gap*

To foster technologies right across the innovation chain requires policies that bridge the 'technology valley of death' and, where successful, can carry technologies on into the phase of large-scale diffusion. Fig. 8 indicates three such classes of policies, combined with a generic need for 'internalisation': *Market Engagement programmes* move a 'trial technology' from public R&D funding to engagement with the private sector; *Strategic Deployment policies* build market scale and thereby buy-down the cost of technologies; and *Barrier Removal* aims to establish a 'level playing field' through removal of regulatory and institutional barriers that generally favour incumbent technologies.

In addition, *internalisation policies* may operate in different ways at many stages of the innovation chain. The classical examples, towards the end of the chain, are emission cap-and-trade or emission taxes, which seek to internalise the environmental damage associated with incumbent technologies and thereby improve the economics of alternatives.

However, 'learning-by-doing' earlier in the innovation process is from an economic perspective also an expression of external benefits, to the extent that the knowledge becomes available to all future developers. Long-lived investment in infrastructure consistent with low-carbon futures is another potential aspect of "internalisation" in current policies, and helps to illustrate that the weight given to such internalisation efforts may well vary according to the longevity of the investments and the options that they open up. For a global and long-lived problem like climate change, the indirect benefits of lower-emitting investments in terms of the knowledge creation, infrastructural and option effects, may far outweigh the direct benefits; indeed some ten years ago, based on a highly simplified optimal control model, I argued that these indirect benefits could be at least seven times the simple "avoided damages" value of emission controls (Grubb, 1995).

Overall this is consistent with the findings of innovation systems research, which indicate that the innovation effort cannot be separated from the goal: the instruments to accelerate innovation cannot be developed separately from those associated with the long-term environmental aim, rather policy needs to be explicitly informed by "back-casting" from the long-term vision of low carbon energy systems.

Rather than work linearly through the innovation chain—which in any case, as indicated is not a linear process—it is more rigorous to work in from either end, and explore the gaps that remain. I first clarify a little the nature of market engagement and barrier removal, and then focus upon strategic deployment.

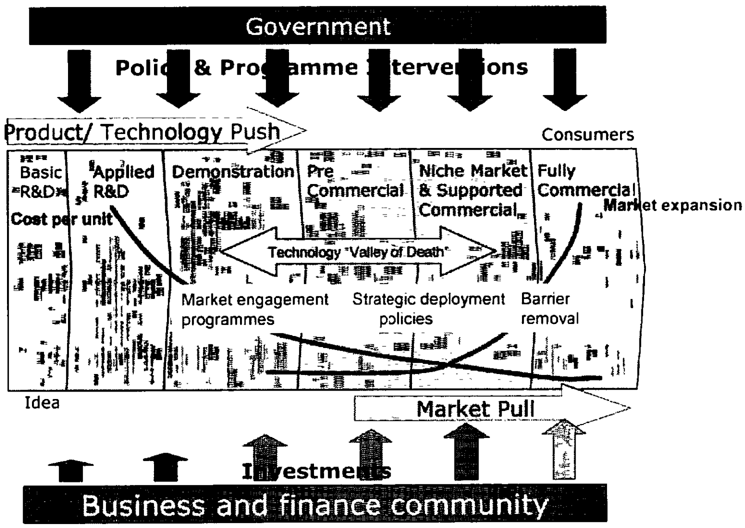

Figure 8. Activities for spanning the innovation chain.

Market engagement programmes help move technologies from the domain of public finance to private sector engagement. There can be several elements to these, some already familiar, others less widely developed:

- *technology incubators* are quite familiar as government-funded organisations specialising in developing companies out of (usually) university-based ideas;
- *acceleration programmes* 'field test' technologies, in circumstances of actual use, in numbers which provide useful data on performance in the target applications. This also helps to 'debug' the technologies, and give private investors and potential users confidence in the practical performance of the technologies and associated companies. This is akin to 'beta testing' in the software industry. Recent examples include the Carbon Trust's accelerator programmes on micro-CHP and smart metering technologies.

At the other end, many new technologies face barriers due to the way current markets have become structured to suit incumbent technologies, and incumbents often may not bear their full external costs. Examples include adverse subsidies, incumbent's lobbying power, and regulations that *de facto* discriminate – a classic example being the way in which many short-term trading markets in liberalised electricity systems discriminate against the variable nature of wind production. Since barrier removal tends to be very market-specific (for an overview of market barriers to intermittent renewable electricity sources, see Neuhoff 2005), I do not address these further.

For many energy-demand-side technologies in particular, this combination may be adequate because so many demand-side technologies appear cost-effective. In these cases intervention—whether formally through removal of barriers, or other measures such as subsidies and technology-forcing standards—has clear potential to yield direct net benefits. Examples of "technology-forcing" demand-side policies (such as some of the Japanese top-runner programmes, which could be considered in this category) can frequently deliver net economic savings over project lifetimes. There is no evidence that energy efficiency technologies have any less potential for innovation than supply technologies; it is just that current practice is further from the best of existing technologies, and in many cases the investments required are not as large and lumpy as generating technologies. In such cases, Market Engagement measures that just help to 'demonstrate and debug' technologies for markets, and accelerate diffusion through removing or otherwise circumventing barriers, may in combination suffice to span the innovation chain.

It is a central contention of this paper that accelerating innovation in low-carbon supply technologies is more problematic, however, because power production inherently involves:

— long timescales;

— multiple political risk (large physical installations are bound to attract opposition, and the incentive of carbon pricing is only slowly and hesitantly being implemented in practice);

— very weak market drivers, derived from marginal price differentiation for a homogenous product (electrons), which in turn often sells into a regulated market in which governments may well regulate profits.

Many power technologies also are inherently 'lumpy'—large units. This deters any but the most brave—or foolhardy—power company from diverting a significant portion of its turnover to ventures that are inherently large and risky and may not yield returns for decades—returns which, in any case, could then be subject to government regulation on profit margins.

That is why governments have found themselves increasingly moving towards policies that help to make the final, central link in the innovation chain, which I now consider more closely.

3.5. Strategic deployment: instruments and economics

Probably the most controversial area lies in the terrain where technologies are proven and in principal commercially available, yet they remain trapped in the cycle of small volume and hence high costs. The response here is policies for 'strategic deployment'—policies that, in one way or another, support the larger scale deployment of these emergent technologies, in view of the strategic advantages to be gained by building up these industries and 'buying down' the cost curve. The principal empirical justification for such policies is to be found in the 'experience curves' summarised in section 2.

Strategic deployment generally requires regulation that incentivises adoption of technologies that would otherwise be uneconomic, so as to secure the benefits of learning-by-doing and other scale economies. Consumers generally bear the costs. Of the three categories of 'bridging' programmes and policies, strategic deployment is likely to be the most controversial because it generally involves direct government intervention (as opposed to funded programmes) for which classical economics does not yet offer a widely-accepted theoretical basis.

The classic examples are policies to support renewable energy deployment, notably:

- *feed-in tariffs*, as adopted particularly in continental Europe, which mandate a specific (premium) price to be paid for electricity generated from renewable sources such as wind energy;
- *renewable obligations*, known in north America as *portfolio standards*, which require utilities to source a certain percentage of their electricity from renewable sources generally through systems of tradeable certificates;
- other *technology or fuel mandates*, such as the long-standing requirement in Brazil cars to run entirely or partly on ethanol.

Some of the pros and cons of these different approaches are analysed in Butler and Neuhoff (2005).

Strategic deployment of a low carbon supply technology generally has to 'buy down' its cost, to the level of higher carbon alternatives (whose costs may also decline, but more slowly as an incumbent technology) plus the gradual incorporation of carbon costs, after which it generates profits (Fig.9). Development of the Danish wind and Brazilian biofuels industries each required sustained government support over decades.

The Danish subsidies totalled $1.3bn, and Danish wind companies now earn more than that each year (Carbon Trust, 2003). At current oil prices, Brazil may soon similarly recoup its investment in biofuel technology.

The learning investment required for other supply technologies may be greater. RD&D totalling several $bn has brought IGCCs—which are a pre-requisite for most power-generation carbon capture and storage technologies—ready for 'small fleet' deployment requiring $0.5–7.5 bn subsidy depending on the programme scale and instrument (Rosenberg et al, 2004). Based on learning curve data, investment in the range of US $20–100 bn could bring PV costs down to compete with bulk power supply at the point of end-use in many countries; the resulting strategic benefit-cost ratios are sensitive to assumptions but potentially high even without incorporating carbon prices (Neuhoff 2005; van der Zwaan, 2004). Overall, global studies by the IEA (2002) estimate that learning investments totalling $400bn over the next three decades could deliver low carbon electricity systems globally. This is less than a tenth of the sectors' projected needs for generation investment over the same period, and the IEA's 'alternative' high efficiency, low carbon scenario requires less total cumulative investment because the reduced electricity demand also reduces the need for infrastructure.

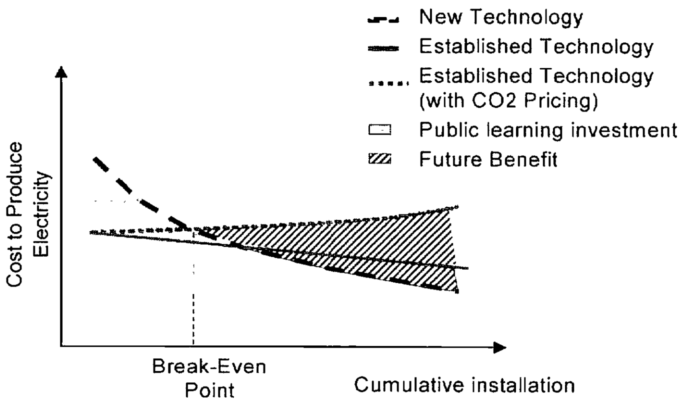

Figure 9. Strategic deployment costs and subsequent benefits, including potential impact of rising CO_2 prices.

Notes : The grey area illustrates the strategic deployment subsidies needed to secure learning-by-doing cost reductions, declining per unit until a break-even point is reached, after which new technologies produce electricity below the costs of established technologies (whose costs may also decline, but generally more slowly since they are already developed and deployed at scale), with potential benefits as indicated in the striped area. The time to break-even, and the longer term gains, will also depend upon the emergence of policies that reflect environmental damages. In economic terms, the up-front subsidies seek to internalise the benefits of strategic learning, which to a large degree is an external, public good.

Source: (Neuhoff, 2005).

The earlier stage of most transport options precludes such quantification. However the potential cost of bioenergy development is dwarfed by the £235bn annual agricultural subsidies in the OECD (OECD, 2004), whilst efforts to maintain oil supplies in the face of declining reserves are projected to require $3trillion investment to 2030, with a growing proportion going to develop and convert higher carbon resources (IEA, 2003c). Development of gas and coal supply systems is projected to require similar investment. In total, the IEA projected that the energy sector will require $16tr investment over the coming three decades, irrespective of carbon constraints.

The conclusion of section 2 above was that the key to low carbon futures is to channel a growing share of such subsidies and 'frontier investments' into lower carbon, rather than higher carbon, infrastructure and learning. To achieve this, public RD&D and carbon cap-and-trade systems will need to be complemented by the full armoury of market engagement, barrier removal, and strategic deployment policies.

4. SOME BRIEF OBSERVATIONS ON INTERNATIONAL STRATEGIES

A key question, to which answers are far from clear, is how much of this effort needs (or could benefit from) direct international cooperation. The answers will depend partly upon other aspects of the international context. If the Kyoto system does move forward, with more countries taking on emission caps over time, the fact that countries commit to limiting emissions will help to provide incentives for them to adopt measures to promote low carbon technologies particularly towards the diffusion end of the innovation chain. Indeed, such an ongoing process would itself increase the willingness of major strategic companies to invest in low carbon innovation, because a future with ongoing (and probably strengthening) low carbon incentives, whether cap-and-trade or other mechanisms, becomes more likely.

Conversely, if a Kyoto-like system did not survive, this would place far greater stress on the need for international technology cooperation to deliver 'on the ground' changes not only to develop technologies and help them through the mid stages of the innovation chain, but to develop incentives for the large-scale diffusion of myriad efficient end-use as well as low carbon supply technologies.

Overall, the IEA (2003) does conclude that "much more could be done in this respect". The options can most usefully be broken down by function corresponding roughly to the early, middle and late stages of the innovation chain.

4.1. Funded international RD&D programmes

Because of potential scale economies, cooperative specialization, and mutual learning, there is wide scope for beneficial international collaboration in publicly funded R&D for innovation in low-GHG emission and sequestration technologies as well as adaptation technologies.

The task is not easy. Any "open call" public expenditure on technology promotion may be faced by a flood of applications from those who believe they have the answer, if only governments would fund it sufficiently; and from companies that scent a chance of free money for something they might have done anyway. Critics—especially economists—can point to long lists of government-sponsored technology failures, some of them astonishingly expensive, due to phenomena that social scientists well recognise in terms of institutional capture. As one cynic put it, 'governments are bad at picking winners, but losers are good at picking governments'.

Some of the institutional problems in public R&D may be amplified in the context of international technology programmes, where the goal of cooperation among countries is bedevilled by unavoidable issues of international rivalry. Every government would like its own industry / technology to receive support from international sources, especially if there is a significant prospect of it delivering commercial success, and is reluctant to spend on technologies of other countries. In addition, as technology nears commercial applicability, issues of intellectual property can become highly sensitive, leading to the reverse of cooperation as participants seek funding from the common pool whilst holding back their most commercially valuable ideas from public scrutiny. As a result, the easiest focus for international technology programmes is often technologies, such as fusion power, that no one realistically expects to be commercially viable in the foreseeable future. Good management, set against clear criteria and firm accountability mechanisms, is essential. Clear attention must be paid to the goals of the programme (object, scope, and time horizon including proposed path towards commercial application); the basic R&D strategy and mechanism, extent of participation by different countries; and issues of institutional form, governance, and accountability mechanisms.

In addressing these questions, one can draw on a considerable body of historical experience and ongoing programmes in the energy and international environmental fields. The International Energy Agency has now accumulated almost 30 years experience of coordinating OECD efforts on energy, including an extensive set of 'Collaborating Agreements' on specific technologies; a number of success stories are report in IEA (1999). These programmes have now extended beyond the OECD to incorporate a number of developing countries, though they remain tiny compared to the scale of the challenge.

There may always be some risk that large-scale international programmes acquire substantial institutional autonomy: if national programmes can be hard to terminate if the results do not fulfil the initial hopes, international ones can be even more difficult. International RD&D programmes may have a useful role, but they are certainly not a panacea and do not in themselves address the core challenges associated with turning technological ideas into viable large-scale industries.

4.2. International public-private partnerships for incubation and acceleration

The second type of international coordination would be around the creation and acceleration of industrial involvement in low carbon technologies. Drawing on domestic 'market-engagement' analogies, these would probably require some co-financing of operations that helped either to 'incubate' new technology companies to the point where they could go to international venture capital markets for support, or at least help to 'de-risk' technologies through large scale field trials perhaps in several countries.

If the competitive dilemmas of international financing of such close-to-market activities prove too great, another approach to explore could be based around mutual commitment to actions, rather than actual mutual funding. For example, the UK Carbon Trust has proposed a 'stepping stones' agreement in which different countries agree to take lead responsibility for nurturing certain technology areas, particularly with reference to the mid stages of the innovation chain. Obviously, the technology areas would be differentiated according to national interests and comparative advantage. For example, the US might take a leading role with respect to sequestration, the UK take the lead on marine renewables, perhaps Japan would have a leading role on various categories of energy efficient technologies.

Agreeing the areas, and monitoring effective delivery, could be problematic. In its weakest form, such an agreement could be little more than dressing up, in international clothes, the actions that countries are already taking. From a diplomatic standpoint this is an advantage, greatly increasing the prospects for achieving a deal. Given the scale of the challenge however, it may be unclear how far such an agreement would go towards solving the problem, particularly if advanced as a substitute for emission constraints. As a contribution towards, and preparation for future rounds of, emission constraints, however, this may be one of the more promising avenues for international discussion.

4.3. International agreements on strategic deployment and barrier removal

The third class of international agreements could address the later stages of the innovation chain, concerning scale-up, large-scale learning-by-doing and diffusion policies. Examples of technologies ready for this stage include:

- advanced technologies (such as gasification) for generating electricity from coal and biomass - a suite of technologies whose accelerated deployment will bring higher efficiency, reduced emissions, and compatibility with carbon dioxide capture and storage technologies;
- advanced low-energy building technologies, where the markets are impeded by numerous barriers associated with the construction industry and rental markets;
- the more advanced primary renewables, notably PV, where potential scale economies remain large, and wind energy, where onshore deployment involves local learning and is a significant contribution to emission reductions, and offshore remains a major stimulus to related industrial innovation.

The scale involved, and the need for facility siting and economic sustainability, may make this beyond the scope of public-only finance except in limited circumstances. The most obvious example is the World Bank-UNDP-UNEP Global Environmental Facility, and associated World Bank and other carbon-related funds.[6] These are not explicit

[6] The World Bank Carbon Fund finances GHG-reduction projects that will generate commercially valuable emission reduction credits under the Kyoto Protocol's Clean Development Mechanism.

International trade in such credits, and of emission allowances pursuant to emissions trading systems, can provide funding for commercial development and application of new technologies to reduce greenhouse gas emissions. Thus, GHG regulatory/trading systems can both supply funds for R&D and create regulation-induced market demand for technological innovation. (Stewart and Wiener 2003).

technology programmes, but have made a significant effort to promote technology development in certain areas (such as biomass energy development and solar PV); more specific technology funds (such as bioenergy fund) have recently been added.

The major issues for strategic deployment, however, involve national legislation, and an international agreement would need to focus either on technology deployment targets, or on the specific regulatory mechanisms (such as feed-in tariffs or renewable portfolio systems) that would support deployment.

An additional—or softer—version of such agreements would be to focus on barrier removal. Some barriers—such as adverse subsidies that support fossil fuel technologies - are easy to identify, but politically difficult to remove (attempts have been made through various fora, including under the UNFCCC). Others may be quite subtle, and concern the regulatory specifics of electricity markets, for example.

Additional and often more general barriers impede the diffusion of more advanced technologies in many developing countries (IPCC, 2000). This topic has received more international attention in the climate change negotiations than other aspects, and the Kyoto Protocol embodies stronger language than its parent UNFCCC on the need for all countries to foster 'enabling environments' for private sector investment in environmentally sound technologies, and establishes a standing Expert Group on Technology Transfer. Agreements on barrier removal may be a modest, but useful complement to other measures and—perhaps more easily than some others—could readily be built upon the existing international climate negotiation processes.

4.4. *Summary of international options*

Table 6 attempts to summarise these various options, according to the classification developed in this paper. The main point is to emphasis that calls for international technology agreements as a solution to climate change need to be better defined. There are in fact many options, appropriate to different stages and aspects of the problem. Each of the eight options in Table 6 has merit; each has problems and limitations; each could usefully be explored further.

International technology cooperation is an area with important potential, but simply calling for technology cooperation as a solution to climate change is not adequate: what matters is the detail, as to which stage of the innovation chain agreements might address, which instruments would be employed, what kinds of technologies might benefit, and the form that agreements might take—as well as their political viability and ultimate impact. That, most immediately, is the international challenge of low carbon technology.

5. CONCLUSIONS

Innovation is central to tackling climate change, and this paper has sought to review the evidence around the innovation processes relevant to the energy sector, and the implications this may hold for national and international policy responses to climate change. Three big messages emerge.

The first is confirmation that "dentified" technologies do hold the *promise* of tackling climate change, not through any single 'silver bullet' but through a potentially rich portfolio of options matched to the various major sectors of energy production, conversion, and use. Whether expressed through the "wedges" analysis of about a dozen major options, or through the global system modelling studies, this core and hopeful message is consistent. Yet considerable innovation will be required to sift the options, improve performance and deliver them on a large scale.

Table 6. Options for international technology cooperation.

Option	Objectives
Public technology RD&D agreements	
Clean Energy R&D Fund	To provide specific R&D support to technologies whose high development cost cannot readily be borne by public funds in a single country.
Clean Energy Demonstration Fund	To provide development and demonstration support to technologies with global applications but where economic development benefits are primarily local, avoiding international IPR concerns.
Marketisation funds and agreements	
Clean Energy Venture Capital Fund	Provide venture and development capital for smaller firms with climate related technological innovations
Climate Technology Leaders Fund	Offer an investment incentive to large companies to differentiate themselves within their sector by virtue of their adoption of leading-edge, higher-risk technologies
'Stepping stones' agreement	Agree differentiated steps that countries would take to nurture technologies appropriate to their interests through the central stages of the innovation chain
Market standards, penetration and diffusion agreements	
Strategic deployment agreement	Agree national targets or measures for deployment of low-carbon technologies that are commercialized but not yet cost-competitive, and need to build up scale economies
Barrier removal agreement	Remove barriers to more rapid penetration of low carbon technologies, for example adverse subsidies or regulatory impediments
International Investor Initiative on Climate Risk	Mobilise mainstream institutional investors (such as pension funds) behind deployment of leading technologies or selective investment based upon carbon performance of companies
Technology transfer agreements	International agreement, as already developed under the UNFCCC/Kyoto Protocol and the associated Expert Group on Technology Transfer (EGTT), with emphasis upon accelerating north-south dissemination of clean technologies. The existing process and EGTT mandate covers: needs assessment; technology information; enabling environments; capacity-building and specific technology transfer mechanisms (Yamin and Depledge, 2004)

Second, the need for innovation is not synonymous with public technology RD&D expenditure, or the hope for blue-skies breakthroughs—the innovation process is altogether more complex, and more interesting. Technologies and systems have to evolve through many stages to build viable and cost-effective low carbon industries out of the seeds—mostly already planted - of low carbon ideas. Engagement with, and investment by, the private sector is critical, but the effective transfer of publicly-funded ideas into the private sector industries remains a big challenge.

Third, although measures of 'carbon pricing' (cap & trade, or taxes) offer an important element in securing such low carbon investment, adequate innovation will not emerge simply through this route. Energy production industries are overwhelmingly oriented towards fossil fuels and the conversion and end-use sectors—particularly power generation and buildings—are some of the least innovative sectors in modern economies. Changing this will require active policies that span the innovation chain. To put it more simply, carbon caps are necessary, but not sufficient.

In relation to the international politics, this suggests that understanding innovation may offer a very important contribution to the international process. The US administration, and many major multinational companies, have stressed the importance of technology as a response. Many others have stressed the need for real emission constraints. Both are right, but the current Kyoto system reflects only the latter. Kyoto has a missing element; and addressing that could offer a constructive basis for political engagement.

In the final section, this paper has outlined the additional complexities in considering international technology-oriented responses. The main point is a call for clarity: there are many different possible kinds of technology cooperation, and some are more credible, and more useful, than others. The challenge now is to identify which approaches might offer a realistic, substantive contribution to solving the climate problem.

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