16 Accelerating Technological Innovation

Key Messages

Effective action on the scale required to tackle climate change requires a widespread shift to new or improved technology in key sectors such as power generation, transport and energy use. Technological progress can also help reduce emissions from agriculture and other sources and improve adaptation capacity.

The private sector plays the major role in R&D and technology diffusion. But closer collaboration between government and industry will further stimulate the development of a broad portfolio of low carbon technologies and reduce costs. Co-operation can also help overcome longer-term problems, such as the need for energy storage systems, for both stationary applications and transport, to enable the market shares of low-carbon supply technologies to be increased substantially.

Carbon pricing alone will not be sufficient to reduce emissions on the scale and pace required as:

- Future pricing policies of governments and international agreements should be made as credible as possible but cannot be 100% credible.
- The uncertainties and risks both of climate change, and the development and deployment of the technologies to address it, are of such scale and urgency that the economics of risk points to policies to support the development and use of a portfolio of low-carbon technology options.
- The positive externalities of efforts to develop them will be appreciable, and the time periods and uncertainties are such that there can be major difficulties in financing through capital markets.

Governments can help foster change in industry and the research community through a range of instruments:

- **Carbon pricing**, through carbon taxes, tradable carbon permits, carbon contracts and/or implicitly through regulation will itself directly support the research for new ways to reduce emissions;
- **Raising the level of support for R&D** and demonstration projects, both in public research institutions and the private sector;
- **Support for early stage commercialisation investments in some sectors.**

Such policies should be complemented by tackling institutional and other non-market barriers to the deployment of new technologies.

These issues will vary across sectors with some, such as electricity generation and transport, requiring more attention than others.

Governments are already using a combination of market-based incentives, regulations and standards to develop new technologies. These efforts should increase in the coming decades.

Our modelling suggests that, in addition to a carbon price, **deployment incentives for low-emission technologies should increase two to five times globally** from current levels of around $33billion.

Global public energy R&D funding should double, to around $20 billion, for the development of a diverse portfolio of technologies.

16.1 Introduction

Stabilisation of greenhouse gases in the atmosphere will require the deployment of low-carbon and high-efficiency technologies on a large scale. A range of technologies is already available, but most have higher costs than existing fossil-fuel-based options. Others are yet to be developed. Bringing forward a range of technologies that are competitive enough, with a carbon price, for firms to adopt is an urgent priority.

In the absence of any other market failures, introducing a fully credible carbon price path for applying over the whole time horizon relevant for investment would theoretically be enough to encourage suitable technologies to develop. Profit-maximising firms would respond to the creation of the path of carbon prices by adjusting their research and development efforts in order to reap returns in the future. This chapter sets out why this is unlikely to be sufficient in practice, why other supporting measures will be required, and what form they could take.

This chapter starts by examining the process of innovation and how it relates to the challenge of climate change mitigation, exploring how market failures may lead to innovation being under-delivered in the economy as a whole. Section 16.3 looks more closely at the drivers for technology development in key sectors related to climate change. It finds that clean energy technologies face particularly strong barriers – which, combined with the urgency of the challenge, supports the case for governments to set a strong technology policy framework that drives action by the private sector.

Section 16.4 outlines the policy framework required to encourage climate related technologies. Section 16.5 discusses one element of this framework – policies to encourage research, development and demonstration. Such policies are often funded directly by government, but it is critical that they leverage in private sector expertise and funding.

Investment in Research and Development (R&D) should be complemented by policies to create markets and drive deployment, which is discussed in Section 16.6. A wide range of policies already exist in this area; this section draws together evidence on what works best in delivering a response from business.

A range of complementary policies, including patenting, regulatory measures and network issues are also important; these issues are examined in Section 16.7. Regulation is discussed in the context of mitigation more generally, and in particular in relation to energy efficiency in Chapter 17.

Overall, an ambitious and sustained increase in the global scale of effort on technology development is required if technologies are to be delivered within the timescales required. The decline in global public and private sector R&D spending should be reversed. And deployment incentives will have to increase two to five-fold worldwide in order to support the scale of uptake required to drive cost reductions in technologies and, with the carbon price, make them competitive with existing fossil fuel options. In Chapter 24, we return to the issue of technological development, considering what forms of international co-operation can help to reduce the costs and accelerate the process of innovation.

16.2 The innovation process

Innovation is crucial in reducing costs of technologies. A better understanding of this complex process is required to work out what policies may be required to encourage firms to deliver the low-emission technologies of the future.

Defining innovation

Innovation is the successful exploitation of new ideas[1]. Freeman identified four types of innovation in relation to technological change[2]:

- Incremental innovations represent the continuous improvements of existing products through improved quality, design and performance, as has occurred with car engines;
- Radical innovations are new inventions that lead to a significant departure from previous production methods, such as hybrid cars;
- Changes in the technological systems occur at the system level when a cluster of radical innovations impact on several branches of the economy, as would take place in a shift to a low-emission economy;
- Changes of techno-economic paradigm occur when technology change impacts on every other branch of the economy, the internet is an example.

[1] DTI (2003)
[2] Freeman (1992)

Many of the incentives and barriers to progress for these different types of technological change are very different from each other.

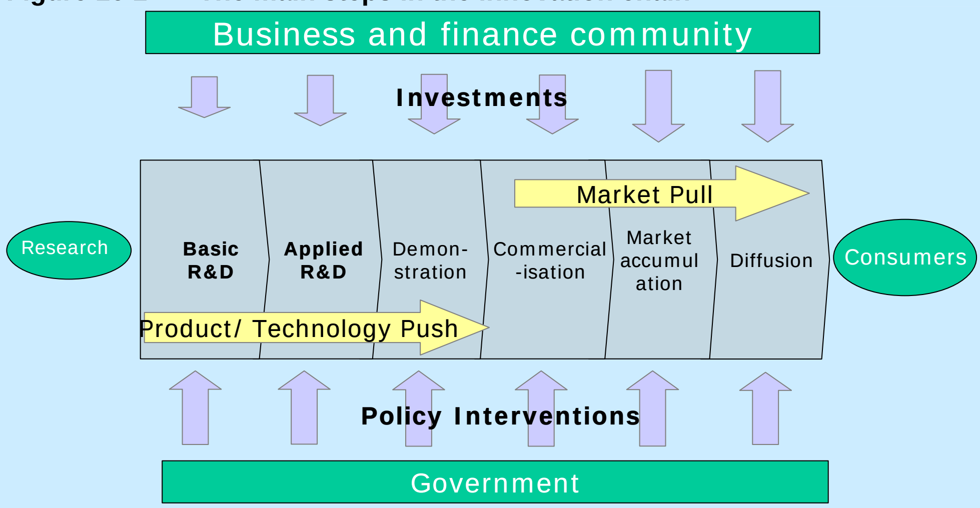
Innovation is about much more than invention: it is a process over time

Joseph Schumpeter identified three stages of the innovation process: invention as the first practical demonstration of an idea; innovation as the first commercial application; and diffusion as the spreading of the technology or process throughout the market. The traditional representation of the diffusion process is by an S-shaped curve, in which the take-up of the new technology begins slowly, then 'takes off' and achieves a period of rapid diffusion, before gradually slowing down as saturation levels are reached. He proposed the idea of 'creative destruction' to describe the process of replacement of old firms and old products by innovative new firms and products.

There is an opportunity for significant profits for firms as the new product takes off and this drives investment in the earlier stages. High profits, coupled with the risk of being left behind, can drive several other firms to invest through a competitive process of keeping up. As incumbent firms have an incentive to innovate in order to gain a competitive advantage, and recognising that innovation is typically a cumulative process that builds on existing progress, market competition can stimulate innovation[3]. As competition increases, and more firms move closer to the existing technological frontier of incumbents, the expected future profits of the incumbents are diminished unless they innovate further. Such models imply a hump-shaped relationship between the degree of product market competition and innovation, as originally suggested by Schumpeter.

An expanded version of this 'stages' model of innovation that broadens the invention stage into basic R&D, applied R&D and demonstration is shown in the subsequent figure. In this chapter the term R&D will be used but this will also cover the demonstration stage[4]. The commercialisation and market accumulation phases represent early deployment in the market place, where high initial cost or other factors may mean quite low levels of uptake.

Figure 16.1 The main steps in the innovation chain[5]



This model is useful for characterising stages of development, but it fails to capture many complexities of the innovation process, so it should be recognised as a useful simplification. A more detailed characterisation of innovation in each market can be applied to particular markets using a systems approach[6]. The transition between the stages is not automatic; many products fail at each stage of development. There are also further linkages between

[3] Aghion et al (2002): Monopolists do not have competitive pressures to innovate while intense competition means firms may lack the resource or extra profit for the innovator may be competed away too quickly to be worthwhile.
[4] R,D&D (Research, Development and Demonstration) can be used for this but it can lead to confusion over the final D as some of the literature uses deployment or diffusion in the same acronym.
[5] Grubb (2004)
[6] For an excellent overview of innovation theory see Foxon (2003)

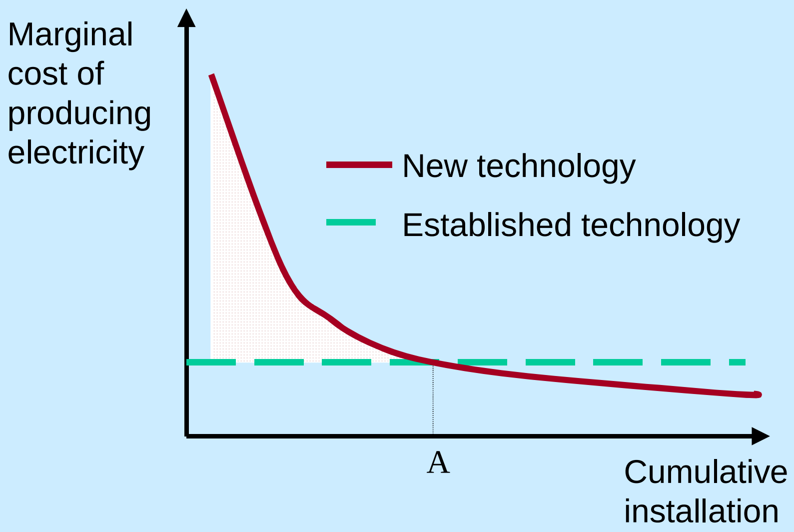
stages, with further progress in basic and applied R&D affecting products already in the market and learning also having an impact on R&D.

Experience curves can lead to lock-in to existing technologies

As outlined in Section 9.7 dynamic increasing returns, such as economies of scale and learning effects, can arise during production and lead to costs falling as production increases. These vary by sector with some, such as pharmaceuticals, experiencing minimal cost reductions while others fall by several orders of magnitude. These benefits lead to experience curves as shown in Box 9.4.

Experience curves illustrate that new technologies may not become cost effective until significant investment has been made and experience developed. Significant learning effects may reduce the incentive to invest in innovation, if companies wait until the innovator has already proven a market for a new cost effective technology. This is an industry version of a collective action problem with its associated free-rider issues.

Figure 16.2 Illustrative experience curve for a new technology



Dynamic increasing returns can also lead to path dependency and 'lock-in' of established technologies. In this diagram, the market dominant technology (turquoise line) has already been through a process of learning. The red line represents a new technology, which has the potential to compete. As production increases the cost of the new technology falls because of dynamic increasing returns, shown by the red line above. In this case, the price of the new technology does ultimately fall below the level of the dominant technology. Some technological progress can also be expected for incumbent dominant technologies but existing deployment will have realised much of the learning[7].

The learning cost of the new technology is how much more the new technology costs than the existing technology; shown by the dotted area where the red line is above the blue. During this period, the incumbent technology remains cheaper, and the company either has to sell at a loss, or find consumers willing to pay a premium price for its new product. So, for products such as new consumer electronics, niche markets of "early adopters" exist. These consumers are willing to pay the higher price as they place a high value on the function or image of the product.

The learning cost must be borne upfront; the benefits are uncertain, because of uncertainty about future product prices and technological development, and come only after point A when, in this case, the technology becomes cheaper than the old alternative. If, as is the case in some sectors, the time before the technology becomes competitive might span decades and the learning costs are high, private sector firms and capital markets may be unwilling to

[7] The learning rate is the cost reduction for a doubling of production and this requires much more deployment after significant levels of investment.

take the risk and the technology will not be developed, especially if there is a potential free-rider problem.

Innovation produces benefits above and beyond those enjoyed by the individual firm ('knowledge spillovers'); this means that it will be undersupplied

Information is a public good. Once new information has been created, it is virtually costless to pass on. This means that an individual company may be unable to capture the full economic benefit of its investment in innovation. These knowledge externalities (or spillovers) from technological development will tend to limit innovation.

There are two types of policy response to spillovers. The first is the enforcement of private property rights through patenting and other forms of protection for the innovator. This is likely to be more useful for individual products than for breakthroughs in processes or know-how, or in basic science. The disadvantage of rigid patent protection is that it may slow the process of innovation, by preventing competing firms from building on each others' progress. Designing intellectual property systems becomes especially difficult in fields where the research process is cumulative, as in information technology[8]. Innovation often builds on a number of existing ideas. Strong protection for the innovators of first generation products can easily be counterproductive if it limits access to necessary knowledge or research tools for follow-on innovators, or allows patenting to be used as a strategic barrier to potential competitors. Transaction costs, the equity implications of giving firms monopoly rights (and profits) and further barriers such as regulation may prevent the use of property rights as the sole incentive to innovate. Also much of value may be in tacit knowledge ('know-how' and 'gardeners' craft') rather than patentable ideas and techniques.

Another broad category of support is direct government funding of innovation, particularly at the level of basic science. This can take many forms, such as funding university research, tax breaks and ensuring a supply of trained scientists.

Significant cross-border spillovers and a globalised market for most technologies offer an incentive for countries to free-ride on others who incur the learning cost and then simply import the technology at a later date[9]. The basic scientific and technical knowledge created by a public R&D programme in one country can spillover to other countries with the capacity to utilise this progress. While some of the leaning by doing will be captured in local skills and within local firms, this may not be enough to justify the learning costs incurred nationally.

International patent arrangements, such as the Trade Related International Property Rights agreement (TRIPs[10]), provides some protection, but intellectual property rights can be hard to enforce internationally. Knowledge is cheap to copy if not embodied in human capital, physical capital or networks, so R&D spillovers are potentially large. A country that introduces a deployment support mechanism and successfully reduces the cost of that technology also delivers benefits to other countries. Intellectual property right issues are discussed in more detail in Section 23.4.

International co-operation can also help to address this by supporting formal or informal reciprocity between RD&D programmes. This is explored in Chapter 24.

Where there are long-term social returns from innovation, it may also be undersupplied

Government intervention is justified when there is a departure between social and private cost, for example, when private firms do not consider an environmental externality in their investment decisions, or when the benefits are very long-term (as with climate change mitigation) and outside the planning horizons of private investments. Private firms focus on private costs and benefits and private discount rates to satisfy their shareholders. But this can lead to a greater emphasis on short-term profit and reduce the emphasis on innovations and other low-carbon investments that would lead to long-term environmental improvements.

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[8] Scotchmer (1991)
[9] Barreto and Klaassen (2004)
[10] The agreement on Trade Related Intellectual Property Rights (TRIPs) is an international treaty administered by the World Trade Organization which sets down minimum standards for most forms of intellectual property regulation within all WTO member countries.

16.3 Innovation for low-emission technologies

The factors described above are common to innovation in any sector of the economy. The key question is whether there are reasons to expect the barriers to innovation in low-emission technologies to be higher than other sectors, justifying more active policies. This section discusses factors specific to environmental innovation and in particular two key climate change sectors – power generation and transport.

Lack of certainty over the future pricing of the carbon externality will reduce the incentive to innovate

Environmental innovation can be defined[11] as innovation that occurs in environmental technologies or processes that either control pollutant emissions or alter the production processes to reduce or prevent emissions. These technologies are distinguished by their vital role in maintaining the 'public good' of a clean environment. Failure to take account of an environmental externality ensures that there will be under-provision or slower innovation[12].

In the case of climate change, a robust expectation of a carbon price in the long term is required to encourage investments in developing low-carbon technologies. As the preceding two chapters have discussed, carbon pricing is only in its infancy, and even where implemented, uncertainties remain over the durability of the signal over the long term. The next chapter outlines instances in which regulation may be an appropriate response to lack of certainty. This means there will tend to be under-investment in low-carbon technologies. The urgency of the problem (as outlined in Chapter 13) means that technology development may not be able to wait for robust global carbon pricing. Without appropriate incentives private firms and capital markets are less likely to invest in developing low-emission technologies.

There are additional market failures and barriers to innovation in the power generation sector

Innovation in the power generation sector is key to decarbonising the global economy. As shown in Chapter 10, the power sector will need to be at least 60% decarbonised by 2050[13] to keep on track for greenhouse gas stabilisation trajectories at or below 550ppm CO_2e.

For reasons that this section will explore the sector is characterised by low levels of research and development expenditure by firms. In the USA, the R&D intensity (R&D as a share of total turnover) of the power sector was 0.5% compared to 3.3% in the car industry, 8% in the electronics industry and 15% in the pharmaceutical sector[14]. OECD figures for 2002 found an R&D intensity of 0.33% compared to 2.65% for the overall manufacturing sector[15]. Unlike in many other sectors, public R&D represents a significant proportion, around two thirds of the total R&D investment[16].

The available data[17] on energy R&D expenditure show a downward trend in both the public and private sector, despite the increased prominence of energy security and climate change. Public support for energy R&D has declined despite a rising trend in total public R&D. In the early 1980s, energy R&D budgets were, in real terms, twice as high as now, largely in response to the oil crises of the 1970s.

[11] Taylor, Rubin and Nemet (2006)
[12] Anderson et al (2001); Jaffe, Newell and Stavins (2004) and (2003)
[13] This is consistent with the ACT scenarios p86 IEA, 2006 which would also require eliminating land use change emissions to put us on a path to stabilising at 550ppm CO_2e
[14] Alic, Mowery and Rubin (2003)
[15] Page 35: OECD, (2006)
[16] There are doubts as to the accuracy of the data and the IEA's general view is that private energy R&D is considerably higher than public energy R&D (though this still represents a significant share).
[17] Page 33-37: OECD (2006)

Figure 16.3 Public energy R&D investments as a share of GDP[18]

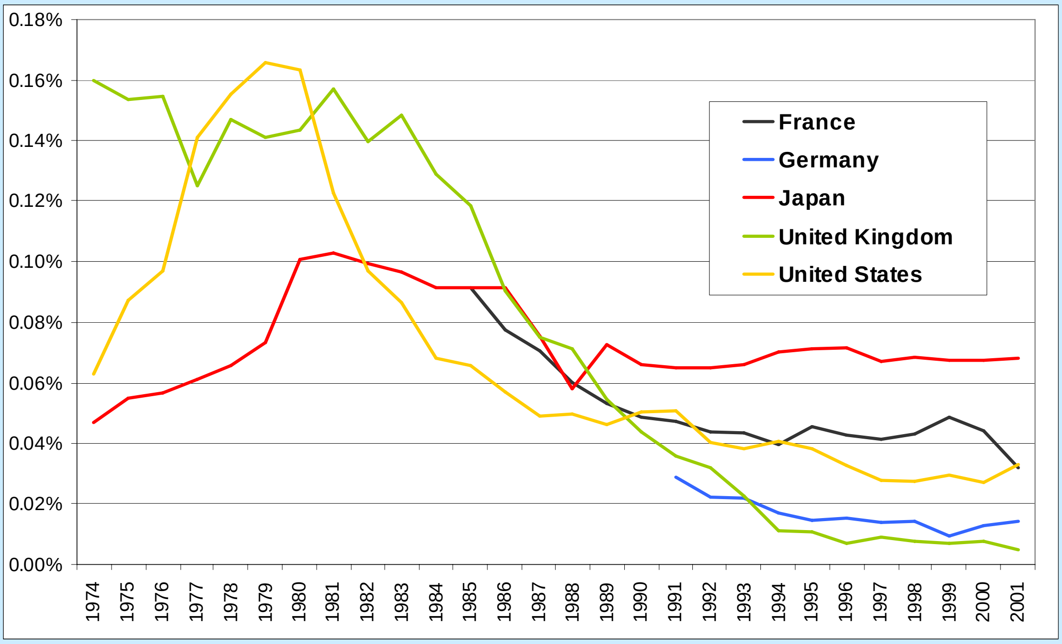
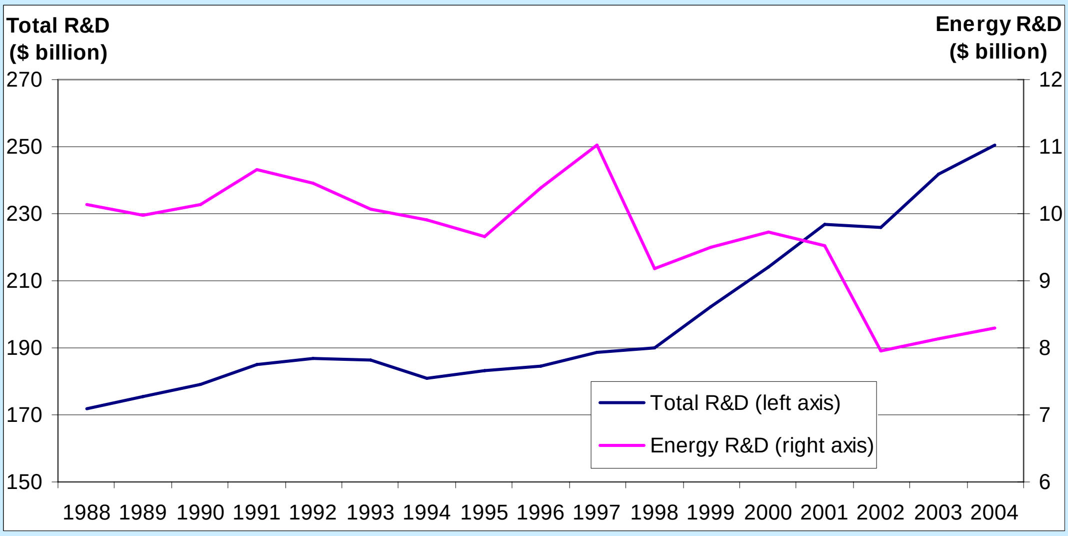


Figure 16.4 Public R&D and public energy R&D investments[19]

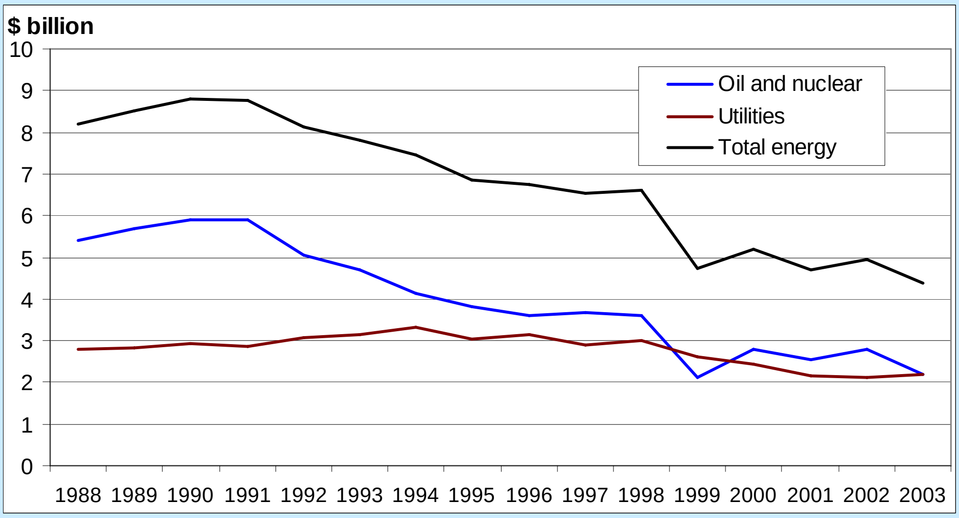


Private energy R&D has followed a similar trend and remains below the level of public R&D. The declines in public and private R&D have been attributed to three factors. *First*, energy R&D budgets had been expanded greatly in the 1970s in response to the oil price shocks in the period , and there was a search for alternatives to imported oil. With the oil price collapse in the 1980s and the generally low energy prices in the 1990s, concerns about energy security diminished, and were mirrored in a relaxation of the R&D effort. Recent rises in oil prices have not, yet, led to a significant increase in energy R&D. *Second*, following the liberalisation of energy markets in the 1990s, competitive forces shifted the focus from long-term investments such as R&D towards the utilisation of existing plant and deploying well-developed technologies and resources - particularly of natural gas for power and heat, themselves the product of R&D and investment over the previous three decades. *Third*, there

[18] Source: IEA R&D database http://www.iea.org/Textbase/stats/rd.asp Categories covered broken down in IEA total Figure 16.8
[19] OECD countries Page 32: OECD (2006)

were huge declines in R&D expenditures on nuclear power following the experiences of many countries with cost over-runs, construction delays, and the growth of public concerns about reactor safety, nuclear proliferation and nuclear waste disposal. In 1974, electricity from nuclear fission and fusion accounted for 79% of the public energy R&D budget; it still accounts for 40%. Apart from nuclear technologies, energy R&D budgets decreased across the board (Figure 16.8).

Figure 16.5 Trends in private sector energy R&D[20]



The sector's characteristics explain the low levels of R&D

There are a number of ways to interpret these statistics, but they suggest that private returns to R&D are relatively low in the sector. There are four distinct factors which help explain this.

The first factor is the nature of the learning process. Evidence from historical development of energy-related technologies shows that the learning process is particularly important for new power generation technologies, and that it typically takes several decades before they become commercially viable. Box 9.4 shows historical learning curves for energy technologies.

If early-stage technologies could be sold at a high price, companies could recover this learning cost. In some markets, such as IT, there are a significant number of 'early adopters' willing to pay a high price for a new product. These 'niche markets' allow innovating companies to sell new and higher-cost products at an early profit. Later, when economies of scale and learning bring down the cost, the product can be sold to the mass market. Mobile phones are a classic example. The earliest phones cost significantly more but there were people willing to pay this price.

In the absence of niche markets the innovating firm is forced to pay the learning cost, as a new product can be sold only at a price that is competitive with the incumbent. This may mean that firms would initially have to sell their new product at a loss, in the hope that as they scale up, costs will reduce and they can make a profit. If this loss-making period lasts too long, the firm will not survive.

In the power sector, niche markets are very limited in the absence of government policy, because of the homogeneous nature of the end-product (electricity). Only a very small number of consumers have proved willing to pay extra for carbon-free electricity. As cost reductions typically take several decades this leaves a significant financing gap which capital markets are unable to fill. Compounding this, the power generation sector also operates in a highly regulated environment and tends to be risk averse and wary of taking on technologies that may prove costlier or less reliable. Together, these factors mean that energy generation

[20] Source Page 35 OECD (2006); For US evidence see Kammen and Nemet (2005)

technologies can fall into a 'valley of death', where despite a concept being shown to work and have long-term profit potential they fail to find a market.

For energy technologies, R&D is only the beginning of the story. There is continual feedback between learning from experience in the market, and further R&D activity. There is a dependence on tacit knowledge and a series of incremental innovations in which spillovers play an important role and reduce the potential benefits of intellectual property rights. This is in strong contrast with the pharmaceutical sector. For a new drug, the major expense is R&D. Once a drug has been invented and proven, comparatively little further research is required and limited economies of scale and learning effects can be expected.

The second factor is infrastructure. National grids are usually tailored towards the operation of centralised power plants and thus favour their performance. Technologies that do not easily fit into these networks may struggle to enter the market, even if the technology itself is commercially viable. This applies to distributed generation as most grids are not suited to receive electricity from many small sources. Large-scale renewables may also encounter problems if they are sited in areas far from existing grids. Carbon capture and storage also faces a network issue, though a different one; the transport of large quantities of CO_2, which will require major new pipeline infrastructures, with significant costs.

The third factor is the presence of significant existing market distortions. In a liberalised energy market, investors, operators and consumers should face the full cost of their decisions. But this is not the case in many economies or energy sectors. Many policies distort the market in favour of existing fossil fuel technologies[21], despite the greenhouse gas and other externalities. Direct and indirect subsidies are the most obvious. As discussed in Section 12.5 the estimated subsidy for fossil fuels is between $20-30 billion for OECD countries in 2002 and $150-250 billion per year globally[22]. The IEA estimate that world energy subsidies were $250 billion in 2005 of which subsidies to oil products amounted to $90 billion[23]. Such subsidies compound any failure to internalise the environmental externality of greenhouse gases, and affect the incentive to innovate by reducing the expectations of innovators that their products will be able to compete with existing choices.

Finally, the nature of competition within the market may not be conducive to innovation. A limited number of firms, sometimes only one, generally dominate electricity markets, while electricity distribution is a 'natural' monopoly. Both factors will generally lead to low levels of competition, which, as outlined in Section 16.1, will generally lead to less innovation as there is less pressure to stay ahead of competitors. The market is also usually regulated by the government, which reduces the incentive to invest in innovation if there is a risk that the regulator may prevent firms from reaping the full benefits of successful innovative investments.

These barriers will also affect the deployment of existing technologies

The nature of competition, existing infrastructure and existing distortions affect not only the process of developing new technologies; these sector-specific factors can also reduce the effectiveness of policies to internalise the carbon externality. They inhibit the power of the market to encourage a shift to low-carbon technologies, even when they are already cost-effective and especially if they are not. The generation sector usually favours more traditional (high-carbon) energy systems because of human, technical and institutional capacity. Historically driven by economies of scale, the electricity system becomes easily locked into a technological trajectory that demonstrates momentum and is thereby resistant to the technical change that will be necessary in a shift to a low-carbon economy[24].

[21] Neuhoff (2005).
[22] Source: REN21 (2005) which cites; UNEP & IEA. (2002). Reforming Energy Subsidies. Paris. www.uneptie.org/energy/publications/pdfs/En-SubsidiesReform.pdf Also Johansson, T. & Turkenburg, W. state in (2004). Policies for renewable energy in the European Union and its member states: an overview. *Energy for Sustainable Development* 8(1): 5-24.that "at present, subsidies to conventional energy are on the order of $250 billion per year" and $244 billion per annum between 1995 and 1998 (34% OECD) in Pershing, J. and Mackenzie (2004) Removing Subsidies.Leveling the Playing Field for Renewable Energy Technologies. Thematic Background Paper. International Conference for Renewable Energies, Bonn (2004)
[23] WEO, (in press)
[24] Amin (2000)

Despite advances in the transport sector, radical change may not be delivered by the markets

Transport currently represents 14% of global emissions, and has been the fastest growing source of emissions because of continued growth of car transport and rapid expansion of air transport. Innovation has been dominated by incremental improvements to existing technologies, which depend on oil. These, however, have been more than offset by the growth in demand and shift towards more powerful and heavier vehicles. The increase in weight is partly due to increased size and partly to additional safety measures. The improvements in the internal combustion engine from a century of learning by doing, the efficiency of fossil fuel as an energy source and the existence of a petrol distribution network lead to some 'lock-in' to existing technologies. Behavioural inertia compounds this 'lock-in' as consumers are also accustomed to existing technologies.

Certain features of road transport suggest further innovative activity could be delivered through market forces. Although there is no explicit carbon price for road fuel, high and stable fuel taxes[25] in most developed countries provide an incentive for the development of more efficient vehicles. Niche markets also exist which help innovative products in transport markets to attract a premium. These factors together help to explain how hybrid vehicles have been developed and are now starting to penetrate markets, with only very limited government support: some consumers are content to pay a premium for what can be a cleaner and more fuel-efficient product. There is also a small number of large global firms in this sector, each of which have the resources to make significant innovation investments and progress. They can also be less concerned about international spillovers as they operate in several markets.

Incremental energy efficiency improvements are expected to continue in the transport sector. These will be stimulated both by fuel savings and, as they have been in the past, by government regulation. Both the hybrid car, and later, the fuel cell vehicle, are capable of doubling the fuel efficiency of road vehicles, whilst behavioural changes - perhaps encouraged, for example, by congestion pricing or intelligent infrastructure[26] - could lead to further improvements.

Markets alone, however, may struggle to deliver more radical changes to transport technologies such as plug-in hybrids or other electrical vehicles. Alternative fuels (such as biofuel blends beyond 5-10%, electricity or hydrogen) may require new networks, the cost of which is unlikely to be met without incentives provided by public policy. The environmental benefit of alternative transport fuels will depend on how they are produced. For example, the benefit of electric and hydrogen cars is limited if the electricity and hydrogen is produced from high emission sources. Obstacles to the commercial deployment of hydrogen cell vehicles, such as the cost of hydrogen vehicles and low-carbon hydrogen production, and the requirement to develop hydrogen storage further, ensure it is unlikely that such vehicles will be widely available commercially for at least another 15 to 20 years.

In Brazil policies to encourage biofuels over the past 30 years through regulation, duty incentives and production subsidies have led to biofuels now accounting for 13% of total road fuel consumption, compared with a 3% worldwide average in 2004. Other countries are now introducing policies to increase the level of biofuels in their fuel mix. Box 16.1 shows how some governments are already acting to create conditions for hydrogen technologies to be used. Making hydrogen fuel cell cars commercial is likely to require further breakthroughs in fundamental science, which may be too large to be delivered by a single company, and are likely to be subject to knowledge spillovers.

The development of alternative technologies in the road transport sector will be important for reducing emissions from other transport sectors such as the aviation, rail and maritime sectors. The local nature of bus usage allows the use of a centralised fuel source and this has led to early demonstration use of hydrogen in buses (see Box 16.1). In other sectors, such as aviation where weight and safety are prominent concerns, early commercial development is unlikely to take place and will be dependent on development in other areas first. The capital stock in the aviation, maritime and rail sectors (ships, planes and trains) lasts several times

[25] There are exceptions in the case of biofuels with many countries offering incentives through tax incentives.
[26] Intelligent infrastructure uses information to encourage efficient use of transport systems. http://www.foresight.gov.uk/Intelligent_Infrastructure_Systems/Index.htm

longer than road vehicles so this may result in a slower rate of take-up of alternative technologies. The emissions associated with rail transport can be reduced through decarbonising the fuel mix through biofuels or low carbon electricity generation. In the aviation sector improved air traffic management and reduced weight, through the use of alternative and advanced materials, can add to continued improvements in the efficiency of existing technologies.

Box 16.1 Hydrogen for transport

Hydrogen could potentially offer complete diversification away from oil and provide very low carbon transport. Hydrogen would be best suited to road vehicles. The main ways of producing hydrogen are by electrolysis of water, or by reforming hydrocarbons. Once produced, hydrogen can be stored as a liquid, a compressed gas, or chemically (bonded within the chemical structure of advanced materials). Hydrogen could release its energy content for use in powering road vehicles by combustion in a hydrogen internal combustion engine or a fuel cell. Fuel cells convert hydrogen and oxygen into water in a process that generates electricity. They are almost silent in operation, highly efficient, and produce only water as a by-product. Hydrogen can produce as little as 5% of the emissions of conventional fuel if produced by low-emission technologies.[27]

There are several hydrogen projects around the world including:

- Norway: plans for a 580km hydrogen corridor between Oslo and Stavanger in a joint project between the private sector, local government and non-government organisations. The first hydrogen station opened in August 2006
- Denmark and Sweden: interested in extending the Norwegian hydrogen corridor
- Iceland: home to the first hydrogen fuelling station in April 2003 and it is proposed that Iceland could be a hydrogen economy by 2030
- EU: trial of hydrogen buses
- China: hydrogen buses to be used at the Beijing Olympics in 2008
- California: plans to introduce hydrogen in 21 interstate highway filling stations

Innovation will also play a role by addressing emissions in other sectors, reducing demand and enabling adaptation to climate change.

Innovation has enabled energy efficiency savings, for example, through compact fluorescent and diode based lights and automated control systems. Furthermore, innovation is likely to continue to increase the potential for energy efficiency savings. Energy efficiency innovation has often been in the form of incremental improvements but there is also a role for more radical progress that may require support. Some markets (such as the cement industry in some developing countries including China and building refurbishment in most countries) are made up of small local firms not large multinationals, which are less likely to undertake research since their resources and potential rewards are smaller. In addition, R&D, for example, in building technologies and urban planning could have a profound impact on the emissions attributed to buildings and increase climate resilience. Chapter 17 discusses energy efficiency in more detail.

[27] E4tech, (2006)

Box 16.2 The scope for innovation to reduce emissions from agriculture

Research into fertilisers and crop varieties associated with lower GHG emissions could help fight climate change[28]. In some instances it may be possible to develop crops that both reduce emissions and have higher yields in a world with more climate change (see Box 26.3).

Another important research area in agriculture will be how to enhance carbon storage in soils, complementing the need to understand emissions from soils (see Section 25.4). The economic potential for enhanced storage is estimated at 1 GtCO2e in 2020, but the technical potential is much greater (see Section 9.6).

Research into sustainable farming practices (such as agroforestry) suitable to local conditions could lead to a reduction in GHG emissions and may also improve crop yields. It could reduce GHG emissions directly by reducing the need to use fertilisers, and indirectly by reducing the emissions from industry and transport sectors to produce the fertiliser[29].

Research into livestock feeds, breeds and feeding practices could also help reduce methane emissions from livestock.

In addition to using biomass energy (see Box 9.5), agriculture, and associated manufacturing industries, have the potential to displace fossil-based inputs for sectors such as chemicals, pharmaceuticals, manufacturing and buildings using a wide range of products made from renewable sources.

Direct emissions from industrial sectors such as cement, chemical and iron and steel can also benefit from further innovation, whether it is in these sectors or in other lower-carbon products that can be substitutes. Innovation in the agricultural sector, discussed in a mitigation context in Box 16.2 above, can also help improve the capacity to adapt to the impacts of climate change. New crop varieties can improve yield resilience to climate change[30]. The Consultative Group on International Agricultural Research (CGIAR) will have a role to play in responding to the climate challenge through innovation in the agricultural sector (see Box 24.4). The development and dissemination of other adaptation technologies is examined in Chapter 19.

16.4 Policy implications for climate change technologies

Policy should be aimed at bringing a portfolio of low-emission technology options to commercial viability

Innovation is, by its nature, unpredictable. Some technologies will succeed and others will fail. The uncertainty and risks inherent in developing low-emission technologies are ideally suited to a portfolio approach. Experience from other areas of investment decisions under uncertainty[31] clearly suggests that the most effective response to the uncertainty of returns is to develop a portfolio. While markets will tend to deliver the least-cost short-term option, it is possible they may ignore technologies that could ultimately deliver huge cost savings in the long term.

As Part III set out, a portfolio of technologies will also be needed to reduce emissions in key sectors, because of the constraints acting on individual technologies. These constraints and energy security issues mean that a portfolio will be required to achieve reductions at the scale required. There is an option value to developing alternatives as it enables greater and potentially less costly abatement in the future. The introduction of new options makes the marginal abatement cost curve (see Section 9.3) more elastic. Early development of economically viable alternatives also avoids the problem of ‘locking in’ high-carbon capital stock for decades, which would also increase future marginal abatement costs. Policies to encourage low-emission technologies can be seen as a hedge against the risk of high abatement costs.

[28] Norse (2006).
[29] Box 25.4 provides further examples of sustainable farming practices.
[30] IRRI (2006).
[31] Pindyck and Dixit (1994)

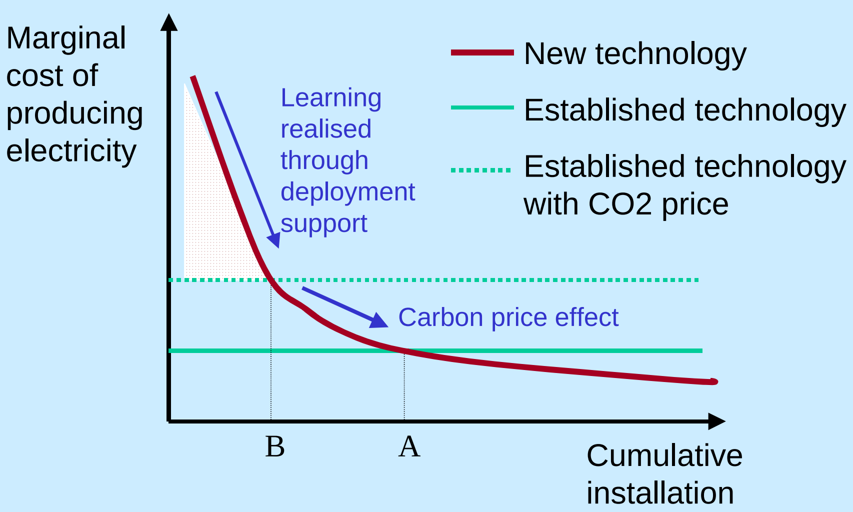
There are costs associated with developing a portfolio. Developing options involves paying the learning cost for more technologies. But policymakers should also bear in mind links to other policy objectives. A greater diversity in sources of energy, for instance, will tend to provide benefits to security of supply, as well as climate change. There is thus a type of externality from creating a new option in terms of risk reduction as well as potential cost reduction. Firms by themselves do not have the same perspective and weight on these criteria as broader society. The next section looks at how the development of a suitable portfolio can be encouraged

Developing a portfolio requires a combination of government interventions including carbon pricing, R&D support and, in some sectors, technology-specific early stage deployment support. These should be complemented by policies to address non-market barriers.

Alongside carbon pricing and the further factors identified in Chapter 17, supporting the development of low-emission technologies can be seen as an important element of climate policy. The further from market the product, given some reasonable probability of success, the greater the prima facie case for policy intervention. In the area of pure research, spillovers can be very significant and direct funding by government support is often warranted. Closer to the market, the required financing flows are larger, and the private returns to individual companies are potentially greater. The government's role here is to provide a credible and clear policy framework to drive private-sector investment.

The area in the innovation process between pure research and technologies ready for commercialisation is more complex. Different sectors may justify different types of intervention. In the electricity market, in particular, deployment policies are likely to be required to bring technologies up to scale. How this support is delivered is important and raises issues about how technology neutral policy should be, which will be discussed later in this chapter in Section 16.6.

Figure 16.6 Interaction between carbon pricing and deployment support[32]



This diagram summarises the links between two of the elements of climate policy. The introduction of the carbon price reduces the learning cost since the new technology, for example a renewable, in this illustrative figure becomes cost effective at point B rather than point A, reducing the size of the learning cost represented by the dotted area. Earlier in the learning curve, deployment support is required to reduce the costs of the technology to the point where the market will adopt the technology. It is the earlier stages of innovation, research, development and demonstration which develop the technology to the point that deployment can begin.

[32] In this figure the policy encourage learning but firms may be prepared to undertake investments in anticipation of technological progress or carbon price incentives.

Across the whole process, non-market barriers need to be identified and, where appropriate, overcome. Without policy incentives when required, support will be unbalanced, and bottlenecks are likely to appear in the innovation process[33]. This would reduce the cost effectiveness at each other stage of support, by increasing the cost of the technology and delaying or preventing its adoption.

Uncertainties, both with respect to climate change and technology development, argue *for* investment in technology development. Uncertainties in irreversible investments argue for postponing policies until the uncertainties are reduced. However, uncertainties, especially with respect to technology development, will not be reduced exogenously with the 'passage of time' but endogenously through investment and the feedback and experience it provides.

Most of the development and deployment of new technologies will be undertaken by the private sector; the role of governments is to provide a stable framework of incentives

Deployment support is generally funded through passing on increased prices to the consumers. But it should still be viewed, alongside public R&D support, as a subsidy and should thus be subject to close scrutiny and, if possible, time limited. The private sector will be the main driver for these new technologies. Deployment support provides a market to encourage firms to invest and relies on market competition to provide the stimulus for cost reductions. Both public R&D and deployment support are expected to have a positive impact on private R&D.

In some sectors the benefits from innovation can be captured by firms without direct support for deployment, other than bringing down institutional barriers and via setting standards. This is particularly so in sectors that rely on incremental innovations to improve efficiency rather than a step change in technology, since the cost gap is unlikely to be so large. In these sectors firms may be comfortable to invest in the learning cost of developing low-emission technologies.

Firms with products that are associated with greenhouse gas emissions are increasingly seeking to diversify in order to ensure their long-run profitability. Oil firms are increasingly investing in low-emission energy sources. General Electric's Ecomagination initiative has seen the sale of energy efficient and environmentally advanced products and services rise to $10.1 billion in 2005, up from $6.2 billion in 2004 - with orders nearly doubling to $17 billion. GE's R&D in cleaner technologies was $700m in 2005 and expected to rise to $1.5 billion per annum by 2010.[34] Indeed in a number of countries the private sector is running ahead of government policy and taking a view on where such policy is likely to go in the future which is in advance of what the current government is doing.

R&D and deployment support have been effective in encouraging the development of generation technologies in the past

Determining the benefits of both R&D and deployment is not easy. Studies have often successfully identified a benefit from R&D but without sufficient accuracy to determine what the appropriate level of R&D should be. Estimating the appropriate level is made more difficult by the broad range of activities that can be classed as R&D. Ultimately the benefits of developing technologies will depend on the amount of abatement that is achieved (and thus the avoided impacts) and the long-term marginal costs of abating across all the other sectors within the economy (linked to the carbon price), both of which are uncertain.

However, some evidence provides indications of the effectiveness of policy in promoting the development of technologies:

- **Estimates of R&D benefits**. Private returns from economy-wide R&D have been estimated at 20-30% whilst the estimated social rate of return was around 50%[35].

[33] Weak demand-side policies risk wasting R&D investments see Norberg-Bohm and Loiter (1999) and Deutch (2005)
[34] Source GE press release May 2006:
http://home.businesswire.com/portal/site/ge/index.jsp?ndmViewId=news_view&newsId=20060517005223&newsLang=en&ndmConfigId=1001109&vnsId=681
[35] Kammen and Margolis (1999)

While it is private-sector not public-sector R&D that has been positively linked with growth, the public-sector R&D can play a vital role in stimulating private spending up to the potential point of crowding out[36]. It also plays an important role in preserving the 'public good' nature of major scientific advances. Examples of valuable breakthroughs stimulated by public R&D must be weighed up alongside examples of wasteful projects.

- **Historical evidence**. Examining the history of existing energy technologies and the prominent role that public R&D and initial deployment have played in their development illustrates the potential effectiveness of technology policy. Extensive and prolonged public support and private markets were both instrumental in the development of all generating technologies. Military R&D, the US space programme and learning from other markets have also been crucial to the process of innovation in the energy sector. This highlights the spillovers that occur between sectors and the need to avoid too narrow an R&D focus. This experience has been mirrored in other sectors such as civil aviation and digital technologies where the source has also been military. Perhaps this is related to the fact that US public defence R&D was eight times greater than that for energy R&D in 2006 (US Federal Budget Authority). Historical R&D and deployment support has delivered the technological choices of the present with many R&D investments that may have seemed wasteful in the 1980s, such as investments in renewable energy and synfuels, now bearing fruit. The technological choices of the coming decades are likely to develop from current R&D.

Box 16.3 Development of existing technology options[37]

Nuclear: From the early stages of the Cold War, the Atomic Energy Commission in the US, created primarily to oversee the development of nuclear weapons, also promoted civilian nuclear power. Alic et al[38] argue that by exploiting the 'peaceful atom' Washington hoped to demonstrate US technological prowess and perhaps regain moral high ground after the atomic devastation of 1945. The focus on weapons left the non-defence R&D disorganised and starved of funds and failed to address the practical issues and uncertainties of commercial reactor design. The government's monopoly of nuclear information, necessary to prevent the spreading of sensitive information, meant state R&D was crucial to development.

Gas: The basic R&D for gas turbine technology was carried out for military jet engines during World War II. Since then developments in material sciences and turbine design have been crucial to the technological innovation that has made gas turbines the most popular technology for electricity generation in recent years. Cooling technology from the drilling industry and space exploration played an important role. In the 1980s improvements came from untapped innovations in jet engine technology from decades of experience in civil aviation. Competitive costs have also been helped by low capital costs, reliability, modularity and lower pollution levels.

Wind: The first electric windmills were developed in 1888 and reliable wind energy has been available since the 1920s. Stand-alone turbines were popular in the Midwestern USA prior to centrally generated power in the 1940s. Little progress was made until the oil shocks led to further investment and deployment, particularly in Denmark (where a 30% capital tax break (1979-1989) mandated electricity prices (85% of retail) and a 10% target in 1981 led to considerable deployment) and California where public support led to extensive deployment in the 1980s. Recent renewable support programmes and technological progress have encouraged an average annual growth rate of over 28 % over the past ten years[39].

Photovoltaics: The first PV cells were designed for the space programme in the late 1950s. They were very expensive and converted less than 2% of the solar energy to electricity. Four decades of steady development, in the early phases stimulated by the space programme, have seen efficiency rise to nearly 25% of the solar energy in laboratories, and costs of commercial cells have fallen by orders of magnitude. The need for storage or ancillary power

[36] When public expenditure limits private expenditure by starving it of potential resources such as scientists OECD (2005)
[37] Alic, Mowery and Rubin (2003)
[38] Alic, Mowery and Rubin (2003)
[39] Global Wind Energy Council http://www.gwec.net/index.php?id=13

sources have held the technology back but there have been some niche markets in remote locations and, opportunities to reduce peak demand in locations where solar peaks and demand peaks coincide.

Public support has been important. A study by Norberg-Bohm[40] found that, of 20 key innovations in the past 30 years, only one of the 14 they could source was funded entirely by the private sector and nine were totally public. Recent deployment support led the PV market to grow by 34% in 2005. Nemet[41] explored in more detail how the innovation process occurred. He found that, of recent cost reductions, 43% were due to economies of scale, 30% to efficiency gains from R&D and learning-by-doing, 12% due to reduced silicon costs (a spillover from the IT industry).

- **Learning curve analysis**. Learning curves, as shown in Box 9.4 and in other studies[42], show that increased deployment is linked with cost reductions suggesting that further deployment will reduce the cost of low-emission technologies. There is a question of causation since cost reductions may lead to greater deployment; so attempts to force the reverse may lead to disappointing learning rates. The data shows technologies starting from different points and achieving very different learning rates. The increasing returns from scale shown in these curves can be used to justify deployment support, but the potential of the technologies must be evaluated and compared with the costs of development.

16.5 Research, development and demonstration policies

Government has an important role in directly funding skills and basic knowledge creation for science and technology

At the pure science end of the spectrum, the knowledge created has less direct commercial application and exhibits the characteristics of a ‘public good’. At the applied end of R&D, there is likely to be a greater emphasis on private research, though there still may be a role for some public funding.

Governments also fund the education and training of scientists and engineers. Modelling for this review suggests that the output of low-carbon technologies in the energy sector will need to expand nearly 20-fold over the next 40-50 years to stabilise emissions, requiring new generations of engineers and scientists to work on energy-technology development and use. The prominent role of the challenge of climate change may act as an inspiration to a new generation of scientists and spur a wider interest in science.

R&D funding should avoid volatility to enable the research base to thrive. Funding cycles in some countries have exhibited ‘roller-coaster’ variations between years, which have made it harder for laboratories to attract, develop, and maintain human capital. Such volatility can also reduce investors’ confidence in the likely returns of private R&D. Kammen[43] found levels changed by more than 30% in half the observed years. Similarly it may be difficult to expand research capacity very quickly as the skilled researchers may not be available. Governments should seek to avoid such variability, especially in response to short-term fuel price fluctuations. The allocation of public R&D funds should continue to rely on the valuable peer review process and this should include post-project evaluations and review to maximise the learning from the research. Research with clear objectives but without over-commitment to narrow specifications or performance criteria can eliminate wasteful expenditures[44] and allow researchers more time to apply to their research interests and be creative.

Governments should seek to ensure that, in broad terms, the priorities of publicly funded institutions reflect those of society. The expertise of the researchers creates an information asymmetry with policymakers facing a challenge in selecting suitable projects. Arms-length

[40] Norberg-Bohm (2000)
[41] Source: Nemet, in press
[42] For an example Taylor, Rubin and Nemet (2006)
[43] Kammen (2004)
[44] Newell and Chow (2004)

organisations and expert panels such as research-funding bodies may be best placed to direct funding to individual projects.

Three types of funding are required for university research funding.

- Basic research time and resources for academic staff to pursue research that interests them.
- Research programme funding (such as research councils) that directs funding towards important areas.
- Funding to encourage the transfer of knowledge outside the institution. The dissemination of information encourages progress to be applied and built on by other researchers and industry and ensures that it not be unnecessarily duplicated elsewhere.

Research should cover a broad base and not just focus on what are currently considered key technologies, including basic science and some funding to research the more innovative ideas[45] to address climate change. Historical examples of technological progress when the research was not directed towards specific economic applications (such as developments in nanotechnology, lasers and the transistor) highlight the importance of open-ended problem specification. There must be an appropriate balance between basic science and applied research projects[46]. Increases in energy R&D (as discussed in the final section of this chapter) can be complemented by increased funding for science generally. The potential scale of increase in basic science will vary by country depending on their current level and research capabilities[47].

There may also be a case for demonstration funding to prove viability and reduce risk. An example of this is the UK DTI's 'Wave and Tidal Stream Energy Demonstration Scheme' that will support demonstration projects undertaken by private firms. This has many features to encourage the projects and maximise learning through provision of test site and facilities and systematic comparison of competing alternatives. Governments can help such projects through providing infrastructure. Demonstration projects are best conducted or at least managed by the private sector.[48]

Energy storage is worthy of particular attention

Inherent uncertainty on fruitful areas of research ensures governments should be cautious against picking winners. However, some areas of research suggest significant potential through a combination of probability of success, lead-times and global reward for success. Priorities for scientific progress in the energy sector should include PV (silicon and non-silicon based), biofuel conversion technologies, fusion, and material science.

As markets expand, all the key low carbon primary energy sources will run into constraints. Nuclear power will be confined to base-load electricity generation unless energy storage is available to enable its energy to follow loads and contribute to the markets for transport fuels. Intermittent renewable energy forms with backup generation will face the same problem. Electricity generation from fossil fuels with carbon capture and storage will likewise be unable to enter the transport markets unless improved and lower cost forms of hydrogen storage or new battery technology are developed. Solar energy can in theory meet the world's energy needs many times over, but will, like energy from wind, waves and tides, eventually depend on the storage problem being solved.

The analysis of the costs of climate change mitigation in Chapter 9 provides further confirmation of the need for an expansion of RD&D activities in energy storage technologies. A failure to develop such technologies will inevitably increase the costs of mitigation once low-emission options for electricity generation are exploited. In contrast, success in this area will

[45] For some examples, see Gibbs (2006)
[46] Newell and Chow (2004)
[47] In 2004 the UK Government published a ten-year Science and Innovation Investment Framework, which set a challenging ambition for public and private investment in R&D to rise from 1.9% to 2.5% of UK GDP, in partnership with business; as well as the policies to underpin this. An additional £1 billion will be invested in science and innovation between 2005-2008, equivalent to real annual growth of 5.8% and to continue to increase investment in the public science base at least in line with economic growth. http://www.dti.gov.uk/science/science-funding/framework/page9306.html
[48] Newell and Chow (2004)

allow low-emission sources to provide energy in other sectors, such as transport. Current R&D and demonstration efforts on hydrogen production and storage along with other promising options for storing energy (such as advanced battery concepts) should be increased. This should include research on devices that convert the stored energy, such as the fuel cell.

In the case of applied energy research, partnership between the public and private sectors is key

It is important that public R&D leverages private R&D and encourages commercialisation. Ultimately the products will be brought into the market by private firms who have a better knowledge of markets, and, so it is important that public R&D maintains the flow of knowledge by ensuring public R&D complements the efforts of the private sector.

The growth and direction of private R&D efforts will be a product of the incentives for low-emission investments provided by the structure of markets and public policies. Public R&D should aim to complement, not compete, with private R&D, generally by concentrating on more fundamental, longer-term possibilities, and by sharing in the risks of some larger-scale projects such as CCS. In many areas the private sector will make research investments without public support, as has been the case recently on advanced biofuels (see Box 16.4).

Box 16.4 Second generation biofuels

Cellulosic ethanol is a not-yet-commercialized fuel derived from woody biomass. In his 2006 State of the Union address, Bush praised the fuel's potential to curb the nation's "addiction to foreign oil". A joint study by the Departments of Agriculture and Energy[49] concludes that U.S. biomass feedstocks could produce enough ethanol to displace 30 percent of the nation's gasoline consumption by 2030.

In May 2006, Goldman Sachs & Co became the first major Wall Street firm to invest in the technology. Goldman Sachs & Co invested more than $26 million in Iogen Corp., an Ottawa-based company that operates the world's first and only demonstration facility that converts straw, corn stalks, switchgrass and other agricultural materials to ethanol. Iogen hopes to begin construction on North America's first commercial cellulosic ethanol plant next year.

In September 2006 Richard Branson announced plans to invest $3 billion in mitigating climate change. Some of this will be invested in Virgin Fuels, which will develop biofuels including cellulosic ethanol.

The OECD[50] found that economic growth was closely linked to general private R&D, not public R&D, but that public R&D plays a vital role in stimulating private spending. There is evidence[51] from the energy sector that patents do track public R&D closely, which suggests that they successfully spur innovation and private sector innovation. R&D collaboration between the public and private-sector is one way of reducing the cost and risks of R&D.

The public sector could fund private sector research through competitive research funding, with private sector companies bidding for public funds as public organisations currently do from research councils. Prizes to reward innovation can be used to encourage breakthroughs. Historically they have proved very successful but defining a suitable prize can be problematic[52]. An alternative approach, as suggested for the pharmaceutical sector, is to commit to purchase new products to reward those that successfully innovate.[53]

[49] US Departments of Agriculture and Energy (2005)
[50] OECD (2005)
[51] Kammen and Nemet (2005)
[52] Newell and Wilson (2005)
[53] Kremer and Glennerster (2004)

Box 16.5 Public-private research models - UK Energy Technologies Institute[54]

In 2006, the UK launched the Energy Technologies Institute (ETI). It will be funded on a 50:50 basis between private companies and the public sector with the government prepared to provide £500 million, creating the potential for a £1 billion institute over a minimum lifetime of ten years.

The institute will aim to accelerate the pace and volume of research directed towards the eventual deployment of the most promising research results. ETI will work to existing UK energy policy goals including a 60% reduction in emissions by 2050.

The ETI will select, commission, fund, manage and, where appropriate, undertake research programmes. Most investment will focus on a small number of key technology areas that have greatest promise for deployment and contributing to low-emission secure energy supplies.

16.6 Deployment policy

A wide range of policies to encourage deployment are already in use.

In addition to direct emissions pricing through taxes and trading and R&D support, there are strong arguments in favour of supporting deployment in some sectors when spillovers, lock-in to existing technologies, or capital market failures prevent the development of potentially low-cost alternatives. Without support the market may never select those technologies that are further from the market but may nevertheless eventually prove cheapest. Policies to support deployment exist throughout the world including many non-OECD countries[55]. China and India have both encouraged large-scale renewable deployment in recent years and now have respectively the largest and fifth largest renewable energy capacity worldwide[56].

There is some deployment support for clean technologies in most developed countries. The mechanism of support takes many forms though the costs are generally passed onto the consumer. The presence of a carbon price reduces the cost and requirement for deployment support. Deployment support is generally a small component of price when spread across all consumption (see Box 16.7) but does add to the impact of carbon pricing on electricity prices. Policymakers should consider the impact of deployment support on energy prices over time. Consumers will be paying for the development of technologies that benefit consumers in the future.

[54] http://www.dti.gov.uk/science/science-funding/eti/page34027.html
[55] Page 20 REN 21 Renewables global status report 2005 - See page 20 REN 21 (2005)
[56] Figures from 2005 - excluding large scale hydropower. Page 6 REN 21 (2006)

Box 16.6 Examples of existing deployment incentives

- **Fiscal incentives**: including reduced taxes on biofuels in the UK and the US; investment tax credits.
- **Capital grants** for demonstrator projects and programmes: clean coal programmes in the US; PV 'rooftop' programmes in the US, Germany and Japan; investments in marine renewables in the UK and Portugal; and numerous other technologies in their demonstration phase.
- **Feed-in tariffs** are a fixed price support mechanism that is usually combined with a regulatory incentive to purchase output: examples include wind and PVs in Germany; biofuels and wind in Austria; wind and solar schemes in Spain, supplemented by 'bonus prices'; wind in Holland.
- **Quota based schemes**: the Renewable Portfolio Standards in twenty three US States; the vehicle fleet efficiency standards in California
- **Tradable quotas**: the Renewables Obligation and Renewable Transport Fuels Obligation in the UK.
- **Tenders for tranches of output** (the former UK Non Fossil Fuel Obligation) with increased output prices subsidised out of the revenues from a general levy on electricity tariffs.
- **Subsidy** of the infrastructure costs of connecting new technologies to networks.
- **Procurement policies of public monopolies:** This was the approach historically of the public monopolies in electricity for purchase of nuclear power throughout the OECD; it is currently the approach in China. It is often combined with regulatory agreements to permit recovery of costs, soft loans by governments, and, in the case of nuclear waste, government assumption of liabilities.
- **Procurement policies of national and local governments**: these include demonstrator projects on public buildings; use of fuel cells and solar technologies by defence and aerospace industries; hydrogen fuel cell buses and taxis in cities; energy efficiency in buildings.

The deployment mechanisms described in Box 16.6 can be characterised as price or quantity support, with some tradable approaches containing elements of both. The costs of these policies are generally passed directly on to consumers though some are financed from general taxation. When quantity deployment instruments are not tradable, the policymaker should consider whether there are sufficient incentives to strive for cost reductions and whether the supplier can profit from passing an excessive cost burden onto the consumer. If the level of a price deployment instrument is too low no deployment will occur, while if it is too high large volumes of deployment will occur with financial rewards for participants which are essentially government created rents. With tradable quantity instruments, the market is left to determine the price, usually with tradable certificates between firms. This does lead to price uncertainty. If the quantity is too high, bottlenecks may lead to a high cost. If the quantity is too low, there may not be sufficient economies of scale to reduce the cost.

Both sets of instruments have proved effective but existing experience favours price-based support mechanisms. Comparisons between deployment support through tradable quotas and feed-in tariff price support suggest that feed-in mechanisms achieve larger deployment at lower costs[57]. Central to this is the assurance of long-term price guarantees. The German scheme, as described in Box 16.7 below, provides legally guaranteed revenue streams for up to twenty years if the technology remains functional. Whilst recognising the importance of planning regimes for both PV and wind, the levels of deployment are much greater in the German scheme and the prices are lower than comparable tradable support mechanisms (though greater deployment increases the total cost in terms of the premium paid by consumers). Contrary to criticisms of the feed-in tariff, analysis suggests that competition is greater than in the UK Renewable Obligation Certificate scheme. These benefits are logical as the technologies are already prone to considerable price uncertainties and the price uncertainty of tradable deployment support mechanisms amplifies this uncertainty. Uncertainty discourages investment and increases the cost of capital as the risks associated with the uncertain rewards require greater rewards.

[57] Butler and Neuhoff (2005); EC (2005); Ragwitz, and Huber (2005); Fouquet et al (2005)

Box 16.7 Deployment support in Germany

Feed-in tariffs have been introduced in Germany to encourage the deployment of onshore and offshore wind, biomass, hydropower, geothermal and solar PV[58]. The aim is to meet Germany's renewable energy goals of 12.5% of gross electricity consumption in 2010 and 20% in 2020. The policy also aims to encourage the development of renewable technologies, reduce external costs and increase the security of supply.

Each generation technology is eligible for a different rate. Within technologies the rate varies depending on the size and type. Solar energy receives between €0.457 to 0.624 per kWh while wind receives €0.055 to 0.091per kWh. Once the technology is built the rate is guaranteed for 20 years. The level of support for deployment in subsequent years declines over time by 1% to 6.5% each year with the rate of decline derived from estimated learning curves[59].

In 2005 10.2% of electricity came from renewables (70% supported with feed-in tariffs) the Federal Environment Ministry (BMU) estimate that the current act will save 52 million tonnes on CO_2 in 2010. The average level of feed-in tariff was €0.0953 per kWh in 2005 (compared to an average cost of displaced energy of €0.047 kWh). The total level of subsidy was €2.4 billion Euro at a cost shared all consumers of €0.0056 per kWh (3% of household electricity costs)[60]. There are an estimated 170,000 people working in the renewable sector with an industry turnover of €8.7 billion.[61]

The 43.7 TWh of electricity covered by the feed in tariffs was split mostly between wind (61%), biomass (19%) and hydropower (18%). It has succeeded in supporting several technologies. Solar accounted for 2% (0.2% of total electricity) with an average growth rate of over 90% over the last four years. Despite photovoltaic's low share Germany has a significant proportion of the global market with 58% of the capacity installed globally in 2005 (39% of the total installed capacity) and 23% of global production.[62]

Regulation can also be used to encourage deployment, for example by reducing uncertainty and accelerating spillover effects, and may be preferable in certain markets (see Chapter 17 for details). Performance standards encourage uptake and innovation in efficient technologies by establishing efficiency requirements for particular goods, in particular encouraging incremental innovation Alternatively, technology specific design standards can be targeted directly at the cleanest technologies by mandating their application or banning alternatives.

There are already considerable sums of money spent on supporting technology deployment. It is estimated that $10 billion[63] was spent in 2004 on renewable deployment, around $16 billion is spent each year supporting existing nuclear energy and around $6.4billion[64] is spent each year supporting biofuels. The total support for these low-carbon energy sources is thus $33 billion each year. Such sums are dwarfed by the existing subsidies for fossil fuels worldwide that are estimated at $150 billion to 250 billion each year. All these costs are generally paid by the consumer.

Technology-neutral incentives should be complemented by focused incentives to bring forward a portfolio of technologies

Policy frameworks can be designed to treat support to all low-carbon technologies in a 'technology-neutral' way. The dangers of public officials 'picking winners' should point to this

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[58] Originally introduced in 1991 with the Electricity Feed Act this was replaced in 2000 with the broader Act on Granting Priority to Renewable Energy Sources (Renewable Energy Sources Act) and amended in 2004 http://www.ipf-renewables2004.de/en/dokumente/RES-Act-Germany_2004.pdf
[59] Small hydropower does not decline and is guaranteed for 30 years and large hydropower only 15 years.
[60] BMU (2006a)
[61] BMU (2006b)
[62] http://www.iea-pvps.org/isr/index.htm
[63] Deployment share of figure page 16 REN 21, 2005 grossed up to global figure based on IEA deployment figures. Nuclear figure from same source.
[64] Based on global production of 40 billion litres and on an average support of £0.1 per litre and a PPP exchange rate of $1.6 to £1

as the starting point in most sectors. Markets and profit orientated decisions, where the decision maker is forced to look carefully at cost and risk are better at finding the likely commercial successes. However, the externalities, uncertainties and capital market problems in some sectors combine with the urgency of results and specificity of some of the technological problems that need to be solved when tackling climate change, all point to the necessity to examine the issues around particular technologies and ensure that a portfolio develops.

The policy framework of deployment support could differentiate between technologies, offering greater support to those further from commercialisation, or having particular strategic or national importance. This differentiation can be achieved several ways, including technology-specific quotas, or increased levels of price support for certain technologies. Policies to correct the carbon externality (taxes / trading) are, and should continue to be, technology neutral. Technology neutrality is also desirable for deployment support if the aim is to deliver least cost reductions to meet short-term targets, since the market will deliver the least-cost technology.

However, as has already been discussed, the process of learning means that longer-established technologies will tend to have a price advantage over newer technologies, and untargeted support will favour these more developed technologies and bring them still further down the learning curve. This effect can be seen in markets using technology-neutral instruments: in the USA, onshore wind accounts for 92% of new capacity in green power markets[65].

This concentration on near-to-market technologies will tend to work to the exclusion of other promising technologies, which means that only a very narrow portfolio of technologies will be supported, rather than the broad range which Part III of this report shows are required. This means technology neutrality may be cost efficient in the short term, but not over time.

Most deployment support in the electricity generation sector has been targeted towards renewable and nuclear technologies. However, significant reductions are also expected from other sources. As highlighted in Box 9.2 carbon capture and storage (CCS) is a technology expected to deliver a significant portion of the emission reductions. The forecast growth in emissions from coal, especially in China and India, means CCS technology has particular importance. Failure to develop viable CCS technology, while traditional fossil fuel generation is deployed across the globe, risks locking-in a high emissions trajectory. The demonstration and deployment of CCS is discussed in more detail in Chapter 24. Stabilising emissions below 550ppm CO_2e will require reducing emissions from electricity generation by about 60%[66]. Without CCS that would require a dramatic shift away from existing fossil-fuel technologies.[67]

Policies should have a clear review process and exit strategies, and governments must accept that some technologies will fail.

Uncertainty over the economies of scale and learning-by-doing means that some technological failures are inevitable. Technological failures can still create valuable knowledge, and the closing of technological avenues narrows the investment options and increases confidence in other technologies (as they face less alternatives). The Arrow-Lind theorem[68] states that governments are generally large enough to be risk neutral as they are large enough to spread the risk and thus have a role to play in undertaking riskier investments. It is not a mistake per se to buy insurance or a hedge that later is not needed and that is in many ways a suitable analogy for fostering a wider portfolio of viable technologies than the market would do by itself[69].

Credibility is also important to policy design. Policies benefit from providing clear, bankable, signals to business. There is a role for monitoring and for a clear exit strategy to prevent excessive costs and signal the ultimate goal of these policies: competition on a level playing

[65] Bird and Swezey (2005)
[66] This is consistent with the IEA ACT scenarios see Box 9.7
[67] For more on CCS see Boxes 9.2 and 24.8 and Section 24.3
[68] Arrow and Lind (1970)
[69] Deutch (2005)

field. A good example has been the Japanese rebates in the 'Solar Roofs' programme, which have declined gradually over time, from 50% of installed cost in 1994 to 12% in 2002 when the scheme ended.

Alternative approaches can also help spur the deployment of new innovations. For example, extension services, the application of scientific research and new knowledge to agricultural practices through farmer education, had a significant impact on the deployment of new crop varieties during the Green Revolution. Also, organisations such as the Carbon Trust in the UK, Sustainable Development Technologies Canada, established by governments but independent of them to allow the application of business acumen, have proved successful in encouraging investment in the development and demonstration of clean technologies. They can play an important role at each stage of the technology process, from R&D to ensuring their widespread deployment once they have become cost effective. They have proved especially successful in acting as a "stamp of approval" that spurs further venture capital investment. Finding niche markets and building these into large-scale commercialisation opportunities is a key challenge for companies with promising low carbon technologies. These organisations are at the forefront of identifying niche markets for commercialisation of new technologies and promoting public-private investment in deployment.

16.7 Other supporting policies

***Other policies have an important impact on the viability of technologies*.**

There are many other policy options available to governments that can affect technology deployment and adoption. Governments set policies such as the planning regime and building standards. How these are set can have an important impact on the adoption of new technologies. They can constrain deployment either directly or indirectly by increasing costs. Regulations can stifle innovation, but if well designed they can drive innovation. Depending how these are set, they can act as a subsidy to low-emission alternative technologies or to traditional fossil fuels. Setting the balance is difficult, since their impacts are hard to value. But they must be considered since they can have an important effect on the outcome.

- The intellectual property regime can act as an incentive to the innovator, but the granting of the property right can also slow the dissemination of technological progress and prohibit others from building on this innovation. Managing this balance is an important challenge for policymakers.

- Planning and licensing regulations have proven a significant factor for nuclear, wind and micro-generation technologies. Planning can significantly increase costs or, in many cases, prevent investments taking place. Local considerations must be set against wider national or global concerns.

- It is important how governments treat risks and liabilities such as waste, safety or decommissioning costs for nuclear power or liabilities for CO_2 leakage from CCS schemes. Governments can bear some of these costs but, unless suppliers and ultimately consumers are charged for this insurance, it will be a subsidy.

- Network issues are particularly important for energy and transport technologies. The existing transport network and infrastructure, especially fuel stations, is tailored to fossil fuel technologies.

- Intermittent technologies such as wind and solar may be charged a premium if they require back-up sources. How this is treated can directly affect economic viability, depending on the extent of the back-up generation required and the premium charged.

- Micro-generation technologies can sell electricity back to the grid and do not incur the same distribution costs and transmission losses as traditional much larger sources. The terms under which such issues are resolved has an important impact on the economics of these technologies. Commercially proven low-carbon technologies require regulatory frameworks that recognise their value, in terms of flexibility and modularity[70], within a distributed energy system. Regulators should innovate in response to the challenge of integrating these technologies to exploit their potential, and unlock the resultant opportunities that arise from shifting the generation mix away from centralised sources.

- Capacity constraints may arise because of a shortage in a required resource. For example, there may be a shortage of skilled labour to install a new technology.
- There are other institutional and even cultural barriers that can be overcome. Public acceptability has proven an issue for both wind and nuclear and this may also be the case for hydrogen vehicles. Consumers may have problems in finding and installing new technologies. Providing information of the risks and justification of particular technologies can help overcome these barriers.

16.8 The scale of action required

Extending and expanding existing deployment incentives will be key

Deployment policies encourage the private sector to develop and deploy low-carbon technologies. The resulting cost reductions will help reduce the cost of mitigation in the future (as explained in Chapter 10). Consumers generally pay the cost of deployment support in the form of higher prices. Deployment support represents only a proportion of the cost of the technology as it leverages private funds that pay for the market price element of the final cost.

It is estimated that existing deployment support for renewables, biofuels and nuclear energy is $33 billion each year (see Section 16.6). The IEA's Energy Technology Perspectives[71] looks at the impact of policies to increase the rate of technological development. It assumes that $720billion of investment in deployment support occurs over the next two to three decades. This estimate is on top of an assumed carbon price (whether through tax, trading or implicitly in regulation) of $25 per tonne of CO_2. If the IEA figure is assumed to be additional to the existing effort, it suggests an increase of deployment incentives of between 73% and 109%, depending on whether this increase is spread over two or three decades.

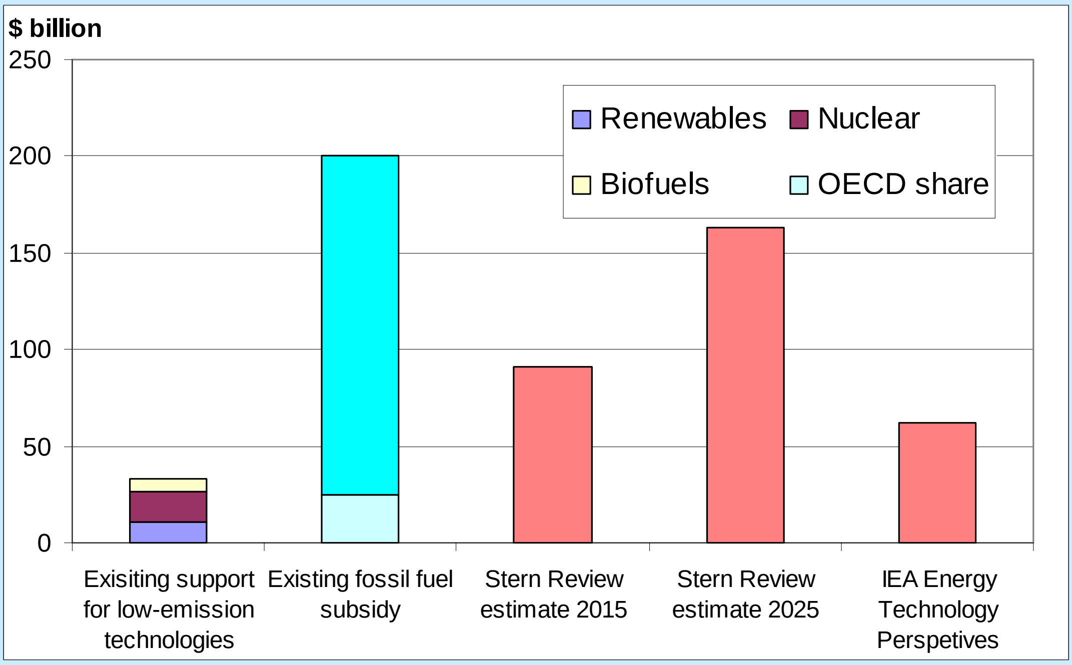
The calculations shown in Section 9.8 include estimates of the level of deployment incentives required to encourage sufficient deployment of new technologies (consistent with a 550ppm CO_2e stabilisation level). The central estimates from this work are that the level of support required will have to increase deployment incentives by 176% in 2015 and 393% in 2025[72]. These estimates are additional to an assumed a carbon price at a level of $25 per tonne of CO_2.

At this price the abatement options are forecast to become cost effective by 2075 so the level of support tails off to zero by this time. If policies lead to a price much higher than this before the technologies are cost effective then less support will be required. Conversely if no carbon price exists the level of support required will have to increase (by a limited amount initially but by much larger amounts in the longer term). While most of this cost is expected to be passed on to consumers, firms may be prepared to incur a proportion of this learning cost in order to gain a competitive advantage.

Such levels of support do represent significant sums but are modest when compared with overall levels of investment in energy supply infrastructure ($20 trillion up to 2030[73]) or even estimates of current levels of fossil-fuel subsidy as shown in the graph below.[74]

[70] Small-scale permits incremental additions in capacity unlike large technologies such as nuclear generation.
[71] Page 58, IEA (2006)
[72] See papers by Dennis Anderson available at www.sternreview.org.uk
[73] IEA (in press)
[74] In this graph mid points in the fossil fuel subsidy range is used in and the IEA increase made over a 20 year period.

Figure 16.7 Estimated scale of current and necessary global deployment support



The level of support required to develop abatement technologies depends on the carbon price and the rate of technological progress, which are both uncertain. It is clear from these numbers that the level of support should increase in the decades to come, especially in the absence of carbon pricing. Based on the numbers above, an increase of 2-5 times current levels over the next 20 years should help encourage the requisite levels of deployment though this level should be evaluated as these uncertainties are resolved.

The scale is, however, not the only issue. It is important that this support is well structured to encourage innovation at low cost. A diverse portfolio of investments is required as it is uncertain which technologies will prove cheapest and constraints on individual technologies will ensure that a mix is necessary. Those technologies that are likely to be the cheapest warrant more investment and these may not be those that are the currently the lowest cost. This requires a reorientation of public support towards technologies that are further from widespread diffusion.

Some countries are already offering significant support for new technologies but globally this support is patchy. Issues on coordinating deployment support internationally to achieve the required diversity and scale are examined in Chapter 24.

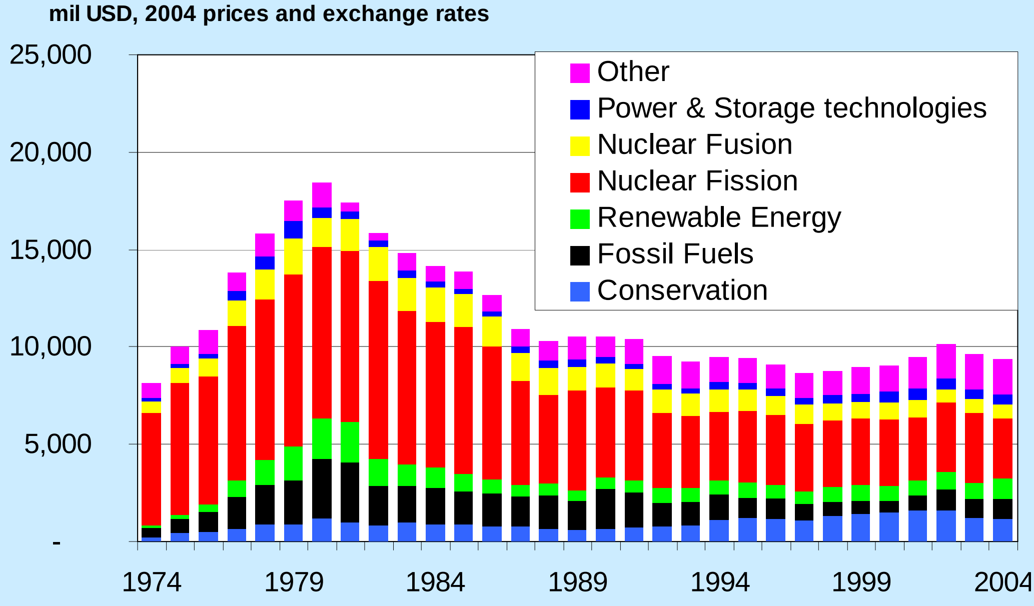
Global energy R&D funding is at a low level and should rise

Though benefits of R&D are difficult to evaluate accurately a diverse range of indicators illustrate the benefits of R&D investments. Global public energy R&D support has declined significantly since the 1980s and this trend should reverse to encourage cost reductions in existing low-carbon technologies and the development of new low-carbon technological options. The IEA R&D database shows a decline of 50% in low-emission R&D[75] between 1980 and 2004. This decline has occurred while overall government R&D has increased significantly[76]. A recent IEA publication on RD&D priorities[77] strongly recommends that governments consider restoring their energy RD&D budgets at least to the levels seen, in the early 1980s. This would involve doubling the budget from the current level of around $10

[75] For countries available includes renewables, conservation and nuclear. The decline is 36% excluding nuclear.
[76] OECD R&D database shows total public R&D increasing by nearly 50% between 1988 and 2004 whilst public energy R&D declined by nearly 20% over the same period.
[77] Page 19 OECD (2006)

billion[78]. This is an appropriate first step that would equate to global levels of public energy R&D around **$20 billion** each year.

Figure 16.8 Public energy R&D in IEA countries[79]



The directions of the effort should also change. A generation ago, the focus was on nuclear power and fossil fuels, including synthetic oil fuels from gas and coal, with comparatively few resources expended on conservation and renewable energy. Now the R&D efforts going into carbon capture and storage, conservation, the full range of renewable energy technologies, hydrogen production and use, fuel cells, and energy storage technologies and systems should all be much larger.

A phased increase in funding, within established frameworks for research priorities, would allow for the expansion in institutional capacity and increased expertise required to use the funding effectively. A proportion of this public money should target be designed to encourage private funds, as is proposed for the UK's Energy Technology Institute (see Box 16.5).

Private R&D should rise in response to market signals. Private energy R&D in OECD countries fell in recent times from around $8.5bn at the end of the 1980s to around $4.5bn in 2003[80]. Significant increases in public energy R&D and deployment support combined with carbon pricing should all help reverse this trend and encourage an upswing in private R&D levels.

This is not just about the total level of support. How this money is spent is crucial. It is important that the funding is spread across a wide range of ideas. It is also important that it is structured to provide stability to researchers while still providing healthy competition. There should be rigorous assessment of these expenditures to ensure that they maintained at an appropriate level. Approaches to encourage international co-operation to achieve these goals are explored in Chapter 24.

16.9 Conclusions

This chapter explores the process of innovation and discovers that externality from the environmental impact of greenhouse gas emissions exacerbates existing market imperfections, limiting the incentive to develop low-carbon technologies. This provides a

[78] 2005 figure Source: IEA R&D database http://www.iea.org/Textbase/stats/rd.asp
[79] Source: IEA Energy R&D Statistics
[80] Page 35, OECD (2006)

strong case for supporting the development of new and existing low-carbon technologies, particularly in a number of key climate change sectors. The power of market forces is the key driver of innovation and technical change but this role should be supplemented with direct public support for R&D and, in some sectors, policies designed to create new markets. Such policies are required to deliver an effective portfolio of low-carbon technologies in the future.

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