

LARGE-SCALE DEPLOYMENT OF RENEWABLES FOR ELECTRICITY GENERATION

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Comparisons of resource assessments suggest that sufficient renewable energy resources are available to allow for large-scale deployment of renewable energy technologies. Economic analysis identifies barriers to the adoption of renewable energy sources resulting from (i) market structure, (ii) competition in an uneven playing field, and (iii) various non-marketplace barriers. However, even if these barriers are removed, the problem of 'technology lock-out' remains. The key policy response is strategic deployment coupled with increased R&D support to accelerate the pace of improvement through market experience. This paper suggests significant contributions from various technologies are possible, but does not assess their optimal or maximal market share.

I. INTRODUCTION

Using renewables on a large scale to replace fossil-fuel electricity generation offers two principal advantages. Environmentally, renewables offer a means to reduce significantly greenhouse-gas emissions. This is a priority, given the need to minimize

the risks of climate change resulting from rising concentrations of greenhouse gases, caused in large part by the burning of fossil fuels. Renewable energy sources can also help to diversify energy supplies in most countries. Reducing dependence on energy imports reduces the exposure of economies to international fuel-price fluctuations and potential

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interruptions caused by political instability and resource constraints. In addition, most renewables are cleaner, thereby providing ancillary benefits to the environment and to human health.

A variety of studies show that renewables have a large technical potential. Yet, currently they only supply 13.5 per cent of global energy demand, and nearly all of this is from established sources of hydropower and small-scale wood fuel and other biomass combustion, which are limited in their potential expansion. The reason why renewable energy technologies contribute so little to global energy demand differs between three groups of technologies. The mature generation includes hydropower, biomass combustion, solar thermal hot water, and geothermal technologies. These technologies are already cost-competitive with conventional forms, provided the renewables plant is located in a high-quality resource area, and where there is low-cost access to the grid. The challenge to expanding these markets relates to high up-front costs and to local site issues. The emerging generation of technologies includes wind, several advanced forms of bioenergy, and solar photovoltaic (PV). These technologies are proven technologically, but still need substantial cost reduction through market experience. The third group are the technologies still in the R&D phase, including concentrating solar power, ocean energy, and even more advanced forms of bioenergy, such as lignocellulose processing. These technologies will require substantial public research, development, and demonstration (RD&D) support in order to prove them on a market scale, and to begin entry into commercial markets.

This paper does not address the optimal mix of different renewable and conventional generation technologies to supply future energy demand. It only asks whether individual renewable technologies are capable of supplying more than a small percentage of our energy demand. After renewable technologies are developed and society is accustomed to their use, markets can then determine what fraction of energy to supply from individual technologies. This paper discusses the potential for new renewables and addresses the economic issues associated with their deployment in three main parts.

- Section II summarizes the resource potential for renewables, concluding that fundamental

technological and resource constraints are *not* the major obstacle to large-scale deployment (section III).

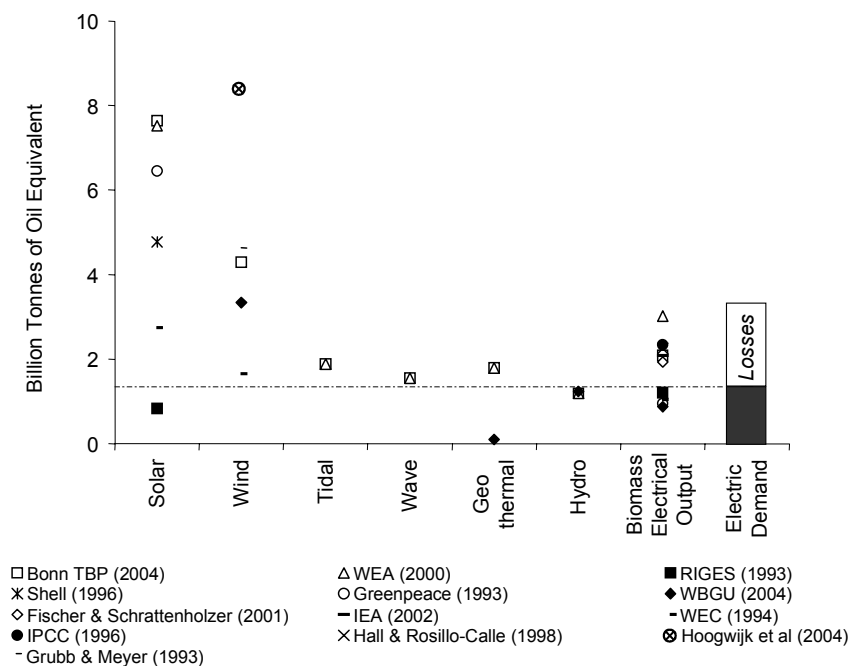
- The core of the paper looks in depth at the economic barriers to renewable energy: the impact of competition in an uneven playing field (section IV) and the specific obstacles associated with market structure (section V) and non-market (section VI) barriers. The main argument for active technology policy is presented in section VII. The nature of the product and markets structure requires government intervention to overcome technology lock-out in the energy sector.
- Finally, the paper considers the potential policy responses. It is argued that the key is for programmes of strategic deployment (section VIII) to accelerate the pace of improvement through market experience (learning). Given the strong feedback loops between research and market experience, R&D as a supporting, but not unique, element of renewable energy technology policy is discussed (section IX). The specific instruments available are then reviewed (section X), and the paper takes a brief look at the international dimension of renewable technology policy (section XI).

II. RENEWABLE MARKET SHARE AND POTENTIAL

Currently, only bioenergy and hydropower make significant contributions to meeting energy demand (IEA, 2003*b*), followed by geothermal energy and wind power. Africa and Asia are the biggest users of bioenergy, but this will only be sustainable if active replanting complements the collection of firewood. Renewables supply only 19.6 per cent of global electricity and 13.5 per cent of global energy demand (IEA, 2004*b*).

Several studies show that this is only a small part of their technical resource potential. These estimations take account of a range of constraints; for example, WBGU (2004) assumes that only 4 per cent of land with significant wind resources or 1 per cent of all land will be used for electricity production. Figure 1 shows the estimated energy that can be

Figure 1
Achievable Electric Energy from Renewable Sources



Note: Detailed references in Neuhoff (2004).

produced per year with solar, wind, tidal, wave, geothermal, hydro, and biomass resources, translated to a common tonnes-of-oil unit. This potential is compared to current global electricity demand. Current energy systems require 2.5 units of primary energy to produce 1 unit of electricity—renewable energy in the form of electricity would, therefore, not only replace the electric energy but also eliminate the corresponding transformation losses.

The figure assumes that all renewable-resource potential is allocated to electricity generation. If biomass is used for heating or cooking, then transformation losses (assumed to be 65 per cent) can be reduced. In the medium term, the highest value application of biomass will be through bio-fuels. Storage and safety requirements for fuels in the transport sector can be better and more cheaply addressed by bio-fuel than by hydrogen. Space and water heating can be provided by solar and geothermal energy. In this case, the transformation losses to electricity are avoided and local resources can be used up to five times more efficiently.

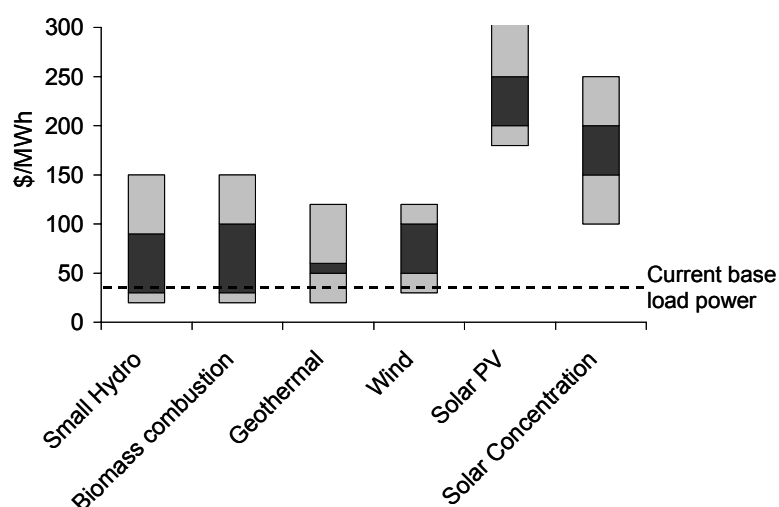
Figure 1 also demonstrates the large range of estimated global resource potentials of wind and solar power, and underlines the need for discussions

about an appropriate level of land-use restrictions. For tidal, wave, and geothermal energy, technological uncertainty is high. It is difficult to predict what fraction of the theoretical potential can be tapped. Therefore, the resource assessment is less certain.

Figure 2 presents estimates for costs of electricity produced with current renewables technologies. Costs are above costs for conventional technologies—one reason why they contribute so little to satisfy current energy demand, despite the large resource potential identified in Figure 1. Small hydro, bio-power, geothermal, and, recently, wind generators are only competitive with current power prices of conventional generation capacity if local resource potentials are exceptionally good. Solar PV and solar concentration generators are not competitive in the wholesale markets. If intermittent renewables contribute large shares of electricity, then their value might be reduced as they require additional storage or demand management.

Finally it should be noted that renewable energy sources are not the only means of tackling the problems associated with current fossil-fuel dependency. The single most promising approach is improvement of energy efficiency in all sectors. The

Figure 2
Estimated Power Generation Costs in 2002
 (dark area is central estimation)



Note: Based on NET Ltd. Switzerland. Assumes a discount rate of 6 per cent for all technologies, amortization periods of 15–25 years and technology specific operation and maintenance costs.
Source: IEA (2003b).

European Commission estimates that demand reductions of up to 18 per cent are currently cost effective, and reductions over 40 per cent are typical in the field (EU Commission, 2000). Taking into account economic and population growth, promoting energy efficiency, without further development of renewable energy sources, is unlikely to address adequately the need for energy security and carbon dioxide (CO₂) emission reductions (Hoffert *et al.*, 2002). Equally, the reverse is true, and the ideal approach would comprise both policies.

Switching fuel sources from coal to gas would reduce CO₂ emissions if gas resources remain adequate. Carbon sequestration could capture CO₂ from coal and gas power plants. This would require new technologies for sequestering and storing CO₂, storage facilities with low leakage rates, and deployment both of new power plants and of CO₂ transport networks.² Nuclear energy could provide for up to

40 per cent of global electricity demand. Assuming that proliferation risks continue to necessitate open fuel-cycles, the global uranium resources would at this level only last for 50 years and therefore the demand for renewable energy technologies would not be affected.³

III. TECHNOLOGICAL BARRIERS

Research to date does not point to fundamental technological barriers to renewable energy technologies. This assessment is robust for technologies such as on-shore wind, geothermal, and solar PV (Alsema, 2000), where deployment experience is significant. The assessment is also valid for technologies that have been applied in demonstration projects, such as offshore wind (Neumann *et al.*, 2002; EWEA, 2004; Musial and Butterfield, 2004) and solar concentration. Demonstration projects for

² Carbon sequestration involves the capture of CO₂ produced during the use of fossil fuels, and its storage. For example, CO₂ from the oil and gas production process is reinserted into wells and enhances oil recovery. For large-scale application, new infrastructure must be built to generate electricity with sequestration, to transport and store CO₂ underground. Cost-effectiveness and leakage of stored CO₂ back into the atmosphere are still widely debated.

³ An interdisciplinary research group at MIT concluded: 'over at least the next 50 years, the best choice to meet [cost, safety, proliferation and waste management] challenges of nuclear generation is the open, once-through fuel cycle' (Ansolabehere *et al.*, 2003). At twice the current uranium price, the known uranium resources suffice to fuel a global fleet of 3,000 reactors of 1 GW for 50 years. Apart from nuclear operational and transport risks in this large-scale scenario, nuclear will provide less than 40 per cent of global electricity demand.

wave and tidal energy are needed to assess potential technical barriers.

Typical concerns about renewable energy relate to their intermittency. It can be assessed on the following three time frames.

First, 3–4 hours before production, average regional output can be predicted with a high degree of accuracy. Remaining uncertainty is mainly due to sudden wind bursts shutting down turbines or cloud fronts covering solar panels. Transmission networks are already designed to cope with larger output changes caused by sudden shutdowns of large fossil or nuclear power stations (Grubb and Vigotti, 1997). Currently, the heavy and fast-rotating conventional generators provide the inertia to drive the system through the critical first moment after a failure. If wind and solar replace most or all conventional generation, their power electronics will have to be improved so they can drive the system through the critical moment. Network tariffs do not (yet) reward such capabilities. At the distribution level, sudden output changes from large shares of renewable generation capacity can result in voltage swings. Recent developments of power electronics or active management of distributed generation offer solutions.⁴

Second, during the 24 hours prior to production, the accuracy of output predictions for wind, solar, and wave generation increases. With improving predictions, the operation schedule for power plants and the transmission network must be adjusted to make efficient use of all resources. Current electricity market designs do not provide the flexibility or trading liquidity for such adjustments. For example, in Germany deviations from the rather inaccurate 24-hour predictions of wind output are compensated for with last-minute balancing activities. This requires flexible and, therefore, expensive plant operation. Germany's system operators have an incentive to retain this scheme, because they own most of the generation assets and benefit from selling balancing services. Furthermore, they can reduce political support for further wind deployment by pointing to (artificially) high balancing costs⁵ and

thereby reduce competition for their existing fossil and nuclear generation.

Third, for system-planning purposes no power plant can be assumed to produce with 100 per cent availability. Repair, maintenance, constraints on fuel and cooling water, and availability of wind and solar energy can reduce or inhibit production from all technologies. Statistical models are used to calculate the risk that multiple plants are not available simultaneously. This determines how much back-up capacity is required to ensure reliable electricity supply. Availability of output from wind, solar, wave, and tidal generators is far lower than that of conventional power stations. If they contribute only a small share of total electricity generation (<5 per cent), the system benefits from the increased diversity and renewable output is of similar value to conventional generation output.

With increasing market shares, the lower availability implies that individual renewable technologies contribute less towards peak demand and, therefore, that wholesale value of their output is reduced (by approximately 10 per cent, with market shares below 20 per cent, according to Smith *et al.* (2004); see also Strbac (2002)). If individual intermittent renewables contribute large shares of electricity, then they require significantly more back-up and storage capacity than conventional power stations. Retaining old power plants was historically the cheapest option for provision of back-up capacity for periods of peak demand or power-station outages. This could also prove a low-cost way for initial support of larger market shares of intermittent renewables. In the long term, if intermittent renewable resources dominate electricity generation, new back-up capacity or storage technologies must play an important part.

The 20 per cent quoted above is not a fixed number; it is subject to current research and a function of at least four system characteristics. (i) Spatial diversity reduces the correlation of output of renewable generation and therefore increases the value. This provides a strong argument for integrated networks rather than micro-grids and closely coordinated

⁴ See recent EU research projects: www.sustelnet.net, www.dispower.org, www.clusterintegration.org and <http://www.ecn.nl/docs/library/report/2004/rx04078.pdf>

⁵ E.ON Netz *Wind Report 2004*, at www.eon-netz.com

operation of these networks. (ii) Mixing different renewable technologies provides uncorrelated output—once again increasing the value.⁶ (iii) PV output is, in many regions, correlated with peak demand from air conditioning and can, therefore, significantly reduce system costs (Herig, 2000). (iv) Demand-side response and demand shifting reduce the need for peak capacity and increase the value of intermittent generation.

The discussion shows that individual renewable energy technologies can contribute a significant share of electricity production. This makes them valuable for our electricity systems. The uncertainty about availability and costs of generation, network, storage, and control technologies makes it difficult to predict the maximum market share or optimal future mix of individual renewable energy technologies.

IV. UNEVEN PLAYING FIELD

In liberalized energy markets, investors, operators, and consumers should, in theory, face the full costs of their decisions. This applies to access to resources and capital, and the social and environmental impacts of energy consumption. However, current practice falls short of this ideal. In the first place, impacts may be hard to quantify. Second, even if potential impacts can be quantified, any decision on the extent to which they should be internalized will be a highly politicized judgement. This can be difficult enough with new technologies (for instance, opposition to the detrimental impact on landscapes by windfarms). But where impacts have previously been tolerated, seeking to change what are perceived to be existing rights is even more difficult. The same holds for those energy producers whose commercial viability has relied on a variety of financial and social subsidies. Not surprisingly, operators want to protect any benefits they have been granted and avoid any new constraints that would limit environmental impacts. Levelling the playing field to enable renewable energy to compete on a more equal footing involves tackling these unpriced ‘advantages’ for conventional technologies.

The most obvious influences on markets are direct and indirect subsidies (see Pershing and Mackenzie (2004) for a recent survey). It is estimated that OECD countries alone still spent US\$20–30 billion on energy subsidies in 2002 (OECD *et al.*, 2002; see also de Moor, 2001). The level of subsidies in developing and transition economies is much higher. These subsidies often include cheap domestic rates, which are intended to benefit people on low incomes, but usually benefit well-off households that tend to consume much more energy. The effect of such energy subsidies is increased consumption by 13 per cent (IEA, 1999) and delayed investment in energy efficiency and renewable energy provision.

In many developing countries, traditional energy technologies also benefit from export credit guarantees extended by OECD government agencies. In the late 1990s, export credit guarantees facilitated US\$17 billion annual investment in fossil energy and only US\$0.8 billion investment in renewables (G8, 2001). In 2003, the World Bank allocated only 13 per cent of its energy loan portfolio to renewable projects. The nuclear-energy sector illustrates a more subtle type of subsidy, rooted in the role governments played in the development of the industry. A government underwriting of accidents means that private insurance cover for only €700m is required for nuclear power plants.

The failure adequately to ‘internalize’ environmental impacts in prices is the other obvious source of ‘subsidy’ that makes it difficult for clean energy technologies to make headway. Traditional environmental regulation sets emission limits and requires firms to invest in improved combustion or exhaust-clearing technology. Emissions below the emission limits also cause environmental damage, but firms are not exposed to these costs and will not include them in the energy price. Estimates for these damages, excluding the costs of global warming, range from an additional €8.7–25/MWh for modern coal power plants.⁷ Most of this damage relates to human health problems. These unpriced externalities will obviously rise if some account is taken of CO₂ emissions and their contribution to climate

⁶ See <http://www.eci.ox.ac.uk/lowercf/intermittency/summary.html>

⁷ Source: Externalities of Energy, A Project of the European Commission, <http://externe.jrc.es>. Roth and Ambs (2004) estimated externality costs of modern coal plants in \$/MWh as NO_x 12.96, SO₂ 1.68, PM (particulate matter) 0.24, N₂O 0.15, upstream 2.57, land use 5.26, water related 1.3 (best estimates quoted). All externalities are based on coal power plants. They have the highest emissions levels (apart from peaking oil plants) and are, therefore, most likely to set the marginal electricity price if externalities are priced.

change. Averaging over a large set of studies for the cost of climate change suggests that the CO₂ impact of electricity produced by coal can be conservatively estimated at €10–23/MWh (Tol, 2003).⁸ The true costs are likely to be higher, as current studies compare snap-shots of future outcomes and ignore extreme weather events and the costs of changing infrastructure, agricultural practices, and living patterns (Tol, 2003).

Cap-and-trade programmes aim to internalize the costs of SO₂, NO_x, and, most prominently, CO₂, and might in the long run ensure that electricity prices reflect the true environmental costs. The experience gained in using emission-trading schemes is less promising. In political negotiations, emission-reduction targets, and therefore scarcity price of emission certificates, are frequently set below the levels suggested by scientific evidence. To ensure the support of the power sector, a large fraction of the allowances are usually handed out for free. As a one-off windfall payment, based on historic output, this would not affect prices and investment decisions. The national allocation plans for CO₂ allowances in Europe, however, show that politicians are reluctant to grant such large one-off payments. They insisted that free allocation is conditional on future output or availability. This reduces the opportunity costs of allowances and the resulting electricity prices. Some national allocation plans also grant free allowances to new power plants. This distorts technology choices (Keats-Martinez and Neuhoff, 2004). As a result of these political processes, electricity prices will only gradually come to reflect environmental externalities.

The recent debate on security of supply has highlighted a different way in which traditional energy pricing does not accurately reflect the social and economic risks many societies run. The dependence of many economies on imported fossil fuels means that they are vulnerable to serious disruption if geo-political events disrupt supply. The same risk applies to the disruptions of fossil-fuel use in the case of future stringent action to slow global warming. Macroeconomic and technology models show that it is socially rational to diversify technology

options when confronted with such supply uncertainties (Gruebler *et al.*, 1999). For example, a study of the UK electricity system showed that wind power reduced the risk of power shortages during gas supply interruption, thus increasing the value of small shares of wind power by €7.60/MWh (OXERA, 2003). Further studies are required to put a price tag on the value of energy and technology diversity.

If the political influence of incumbent energy companies is likely to hold back moves to eliminate subsidies and internalize environmental impacts, there is a strong case for subsidizing renewable energy, to prevent an on-going distortion in the choice of technologies that figure in future investment decisions.

V. MARKETPLACE BARRIERS

The electricity sector has been liberalized gradually to ensure that security of supply will be maintained. As a result, the electricity market has been designed to replicate the historic operation of centralized power plants and favours their operation. For example, solar PV can reduce peak loads on the distribution network in summer peaking systems, and combined heat and power—whether gas or bioenergy—can do likewise in winter peaking systems (Hoff and Cheney, 2000). Frequently, however, network tariffs do not reward this kind of system service (Alderfer *et al.*, 2000). Another example of inherited market design is provided by mechanisms that accommodate the inflexible operation of some fossil and nuclear power plants, while few markets are optimized to provide flexibility for intermittent generation.

The main market concern for renewable energy technologies is that wind, solar, and wave output cannot be predicted with sufficient accuracy at the time of the liquid day-ahead market. By the time the prediction accuracy improves (about 4 hours before final production), most international electricity transmissions have been allocated and liquidity in energy markets is low. This is despite the fact that transmis-

⁸ Roth and Ambs (2004) estimated global warming externality costs of \$26.38/MWh. ExternE (<http://externe.jrc.es>) calculated a range of €3–111/MWh. Increasing the implied rate of time preference from 2 to 3 per cent will reduce the weight on people in 100 years from 37 to 5 per cent of today's population and thereby reduce the marginal cost of CO₂ emission. Equity weighing of global population leads to a higher estimate of the marginal costs (Yohe, 2003).

sion flows can be adjusted within seconds, most power plants can be started and stopped, and all power plants can change their output within this time frame.⁹ As a result, the electricity system is operated inefficiently and wind, solar, and wave generators selling their output in the general energy market receive lower than justified prices.

In most countries, electricity generation companies have high market shares in their regional markets and can influence prices in day-ahead and intra-day markets. Currently, they sell most output on longer-term contracts and therefore profit little and will typically refrain from influencing short-term prices. With higher penetration by renewables, trade in the short-term market will increase. At times of low renewable output, it is profitable for conventional generation to sell additional output in the short-term market above cost. At times of high renewable output, it is profitable for conventional generation to buy back energy sold on longer-term contracts, but below cost. This market power will reduce the revenue of intermittent renewables below their fair value and can result in production inefficiencies.

Vertically integrated companies face additional incentives to obstruct the entry of renewable energies, if this takes market share from their conventional generation assets, or if it results in changes to the transmission system, which reduce the value of some of their existing assets (Alderfer *et al.*, 2000). However, inexperienced or inert companies can also increase project costs for decentralized generation and cause unnecessary delays, if they have not established procedures for interconnections, or if they request technical assessments and insurance cover that are only appropriate for large central power plants. If the market share of a technology is at or below 1 per cent, niche applications or specific regulatory provisions dominate its economies, even when they are economically competitive in a technology-to-technology comparison (Kammen, 2004). Regulatory intervention can reduce this effect or compensate initial investors for these costs.

Most renewable energy sources are small relative to the expansion scale of transmission and most

distribution capacity. If a project developer has to pay large fractions of the lumpy network expansion costs required for its turbines (deep connection charging), then these costs are likely to inhibit the project. Coordination among project developers to build in the same area and to share the cost would resolve the issue. Such coordination is difficult as each project hinges on funding, planning permits, and energy contracts. Conventional technologies do not require coordination as they are of the same scale as network expansion projects. To avoid delays, countries have shifted towards charging shallow connection charges. Only the cable from the last distribution point to the turbine is paid directly by the project. Of the lumpy investment costs within the network, only the fraction used by the individual generator is allocated to the specific generator (e.g. the British energy regulator, Ofgem, is discussing locational differentiated access tariffs to the distribution network). The remaining costs are socialized among all users until additional generators pick up the tab. This obviously creates the risk of stranded assets, but is a common approach on the demand side: costs of excess network capacity to accommodate for potential demand growth have always been socialized.

A different set of questions relates to the regulatory and market risk of investment in electricity generation capacity. It is currently widely debated whether the risk might prevent timely investment in new generation capacity. This risk could be eliminated by long-term contracts between final consumers or consumer franchises and electricity generation companies. However, current regulators prevent such long-term contracts in an attempt to foster retail competition. This exposes investors to electricity price risk and induces them to charge a risk premium on their capital. The risk premium, created by artificial regulatory constraints, affects capital-intensive technologies more than technologies with high fuel costs and therefore biases against nuclear and renewables (Neuhoff and De Vries, 2004).

Regulators are concerned about the implications of investment risk, because it could postpone invest-

⁹ This effect is enhanced if, in systems like the English and Welsh NETA, renewables generators balance their output if they want to avoid high imbalance prices. As individual output is relatively more volatile than aggregate output, this results in higher levels of flexible plant that must be kept running, creating energy and capital costs.

ment, causing unpopular power shortages. But instead of reducing market and regulatory risk, they typically implement financial payments for available capacity. Regulators not only retain the bias against capital-intensive technologies but might reinforce that bias, if the (small) contribution which intermittent generation offers towards supply during peak demand is not rewarded. Furthermore, short-term contracting in electricity markets can reinforce cyclical investment patterns. This can hinder development of small industries with less scaling opportunity and restrict their opportunities for continuous research and production improvements.

Financial markets face difficulties in providing risk-management instruments for new renewable technologies (United Nations Environment Programme, 2004). First, historical actuarial data are not available to assess risk (Sonntag-O'Brien and Usher, 2004). Conventional technologies have never faced these difficulties, because they were already deployed before liberalization. Historic records from these times have allowed risk assessment since liberalization. A second disadvantage faced by renewable energy projects is their small scale, which results in disproportionately high transaction costs for risk management tools, complex financing arrangements, or export credit guarantees. Large institutions such as the World Bank have little track record with efficient administration of small-scale projects (below \$15m).

VI. NON-MARKETPLACE BARRIERS

The complex interactions between the public, administration, private sector, and electricity system operators can create non-marketplace barriers for new energy technologies.

Administrative frameworks were developed for existing technologies and are not yet tailored to the needs of renewables. While spatial planning traditionally envisages specific zones for industrial development, local plans must frequently be revised to allow for the location of wind or bioenergy plants. This creates uncertainty and costly delays for project

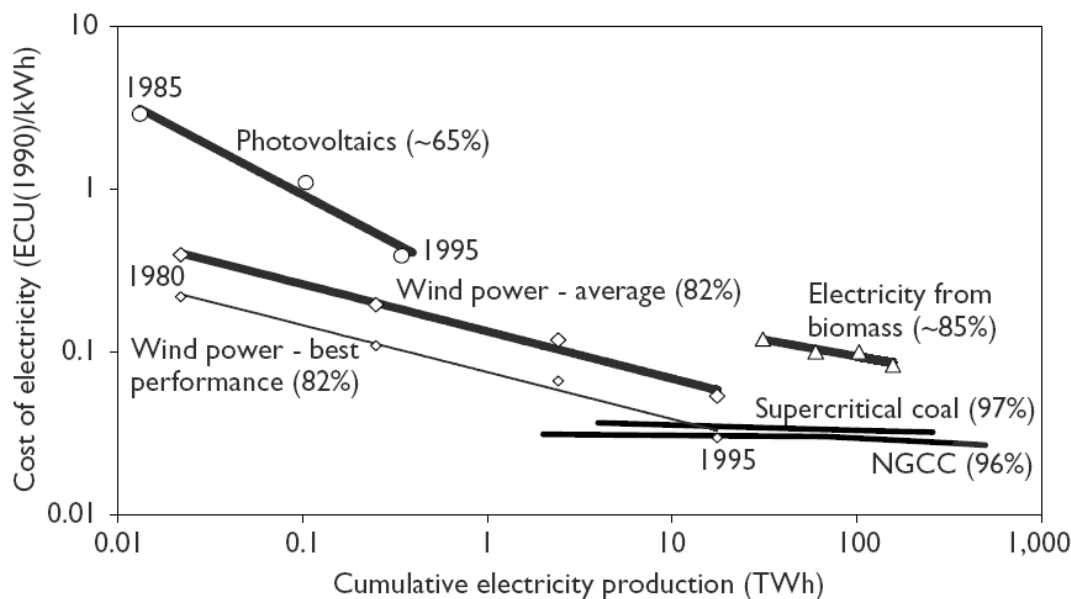
developers, for European wind projects between 1.5 and 4.5 years (Admire Rebus, 2003). The small scale of renewable energy projects multiplies the relative costs incurred through multiple administrative processes. For example, biogas plants in Germany required several parallel permit processes designed to address issues such as EU regulations to prevent the spread of bovine spongiform encephalopathy (BSE), while large power plants only require a single general permit process (Klinski, 2004).

Reliable and comprehensive information about the motivation and benefits, as well as the costs and externalities, of renewable technologies must be shared with involved and affected citizens. While early investors in renewable energy technologies require technical and economic information upon which to base their decisions, subsequent groups of adaptors might have to familiarize themselves with the technology through trial and error and learning through experience (Kaplan, 1999). Citizen support has been seriously affected by concerns about wind turbines killing birds, that since seem to have been addressed by the design and siting of new turbines, or by unease about the excessive energy-intensity of solar PV production, based on prototype figures (Alsema, 2000). In contrast, German project developers report that if they involve citizens and local councils in the early planning stages, they are more likely to obtain planning consent. In addition, polling in Europe shows that support for wind energy tends to strengthen after plants have been installed and in operation for some time.¹⁰ This illustrates that some time is required to allow stakeholders to adjust to and accept new technologies.

The successful deployment of wind turbines in Denmark is a result of long-term thinking, local community involvement, benefits to incumbent energy companies, public and private R&D support, and government support (Ministry of Economic Affairs, 2004). Over time, Denmark has developed domestic industries to design, finance, insure, manufacture, install, and maintain renewables systems, using local equipment and labour (Sawin, 2004). Countries cannot simply rely on adopting an interna-

¹⁰ According to a 2003 survey in Scotland, among people living close to the ten largest wind farms, 82 per cent of respondents want an increase in electricity generated from wind, and 54 per cent support an increase in the number of turbines at their local wind farm (Braunholtz, 2003).

Figure 3
Learning Curve for Energy Technologies



Source: IEA (2000).

tionally developed technology. Even in the rapidly developing and uncontroversial field of the telecoms industry, some countries experienced significant delays in adopting new technologies (Dekimpe *et al.*, 2000). Active technology policy must give population, industry, and administration a chance to get used to a new technology and learn how to deal with its new characteristics (Duke *et al.*, 2002; Sonntag-O'Brien and Usher, 2004). Because of this 'institutional learning' process (Espejo *et al.*, 1996), countries benefit if they support the deployment of renewables before they are fully cost-competitive. This will remove non-marketplace barriers for subsequent use in competitive markets and accelerate their future growth.

VII. TECHNOLOGY LOCK-OUT

Technology 'lock-in' and 'lock-out' refer to processes which favour conventional, established technologies at the expense of innovative technologies. In this section it is discussed how learning-by-doing can result in a 'lock-out' of new technologies. The previous sections illustrated how an uneven playing field, marketplace, and non-market barriers and adoption costs can also deter new renewables

(Sanden and Azar, 2004). Because a combination of barriers causes the technology 'lock-out' it might not suffice to remove one barrier to resolve it. For example, a lack of full internalization of negative externalities on our climate from CO₂ emissions creates an uneven playing field for carbon-free energy sources. However, even if an effective CO₂ trading scheme would internalize externalities of CO₂ emissions, it will not remove the other barriers. Therefore it does not eliminate the need to assess and pursue active technology policy carefully (Jensen and Skytte, 2003).

Figure 3 shows how new renewable technologies have consistently reduced their costs with increasing market experience. The fact that the cost of new technologies falls with increasing deployment has been established in a large set of studies on energy technologies (Watanabe *et al.*, 2001) and in other industry sectors (Isoard and Soria, 1997; IEA, 2003a). Consequently, without large-scale applications, the cost of new technologies can stay high and investors will continue to use established technologies. As a result, new technologies can be 'locked out'. This is sometimes described as path dependency—what seems economic in the future depends on previous patterns of investment (Arthur, 1989; Kline, 2001; Unruh, 2002).

The strength of technology lock-out varies across industries. The energy sector exhibits three basic characteristics that result in a strong technology lock-out. First, new technologies produce the same basic product: electricity, in the case of most renewables. Hence, they have to compete mainly on price, making them immediately more vulnerable to lock-out. This is in sharp contrast to the IT, telecoms, and other sectors, where product differentiation is a prime instrument of marketing and innovation and the innovator can charge more for enhanced functionality or reduced size of a new device. This surpasses tendencies to lock out. Some high-value applications also exist for renewable energy technologies. But both the individual project size and the total market volume are probably too small to support significant learning by doing and research efforts. For example, PV cells are far more valuable in off-grid applications, but in 2002 this market segment contributed less than 10 per cent to global PV sales (PVPS, 2003).

Second, perhaps because they involve transformation and delivery of large quantities of energy, the technologies and systems tend to involve large-scale engineering products that last decades. This greatly increases the scale and time horizon of financial investment, and multiplies the risks associated with innovation; it also means that new energy technologies compete with incumbents that have gained market experience over several decades and large quantities of global investment, often drawing on prior public R&D.

Third, both the above factors make it far harder for individual private firms to appropriate the full benefits of learning and R&D in the energy sector than in other sectors. Dasgupta and Stiglitz (1988) show in a model that oligopolistic firms might be prepared to incur initial losses by expanding their production if learning effects would reduce their future costs, thereby allowing for larger future market shares and profit margins. However, technology ‘spillover’ allows other companies to copy the initial learning at

a fraction of the costs (Irwin and Klenow, 1994; Watanabe *et al.*, 2001). As more producers compete, the benefits of the invention are split among several producers who share the market and consumers who pay lower prices (Duke and Kammen, 1999). This problem has been resolved in the pharmaceutical sector by granting patents for inventions, and companies spend 15 per cent of revenue on drug development. But the monopoly position granted by patent rights also results in inefficient markets. Profits account for 30 per cent of sales volume in the pharmaceutical industry, with marketing and administration accounting for a further 30 per cent.¹¹

For at least two reasons it seems unlikely that patents will play a major role in promoting innovation and improvements of renewables. First, pharmaceutical patents protect a specific, distinct drug; it is far harder to define engineering patents in ways that cannot be circumvented over time.¹² There is even the risk that enhancing intellectual property rights protection impedes innovation and diffusion of new knowledge (Alic *et al.*, 2003). Second, renewable energy technologies consist of a large set of components and require the expertise of several companies to improve the system. A consortium will face difficulties in sharing the costs of ‘learning investment’, as it is difficult to negotiate and fix the allocation of future profits. Firms are, therefore, reluctant to invest for the benefits of consortium members (the hold-up problem). At the same time the scale, expertise, and time horizon of ‘learning-investment’ tends to exceed the funds of individual companies and the patience of the venture-capital markets.

Despite all these challenges to innovation in the energy sector, the oil extraction industry is relatively innovative. The example of deep-water oil drilling shows that government support was instrumental. Initially, costs were significantly higher than for on-shore or shallow water fields. Oil companies preferred to develop cheaper fields, as they had to sell output on a global oil market at a homogeneous

¹¹ Based on SEC filings, annual reports, Hoovers.com, and company presentations for Abbott Laboratories, Johnson & Johnson, Novartis, SmithKlineBeecham, Merck & Co, Bristol-Meyers Squibb, American Home Products, AstraZeneca, Pfizer, and GlaxoWellcome for the year 1999.

¹² First, successful drugs targeting is guided by scientific knowledge but requires a lot of luck. Therefore, it might take time for a competitor to find a substance with similar characteristics. Second, the new substance requires the same extensive clinical trials, which are the most expensive part of drug R&D. The substance will only be accredited if it has better features than the existing drug. Third, the follower must decide whether all these costs will be recovered with lower market share in a lower-margin duopoly market.

price. Governments reduced extraction taxes to compensate private oil companies for higher field development costs of deep-water oil fields. With improvements through market experience, costs for deep-water drilling fell and governments could reduce the scale of incentives. In the next section the economics of such strategic deployment are discussed.

VIII. THE ECONOMICS OF STRATEGIC DEPLOYMENT

These diverse barriers to deployment and impediments to innovation underpin the case for ‘strategic deployment’. Diverse policy options must be applied to foster large-scale investment in renewable energy technologies before they are commercially competitive in current energy markets. The existence of barriers obviously does not imply that a technology will be cost competitive if the barrier is removed; this suggests that both technology appraisal and some experimenting is required to guide policy decisions.

The experience with on-shore wind power is a good example of the success of strategic deployment. R&D-led attempts in Germany, the USA, and other countries to build multi-megawatt wind turbines in the early 1980s failed both on engineering and cost grounds (Norberg-Bohm, 2000; see also Bergek and Jacobsson, 2003). At the same time, private and subsequently public initiatives supported the deployment of small wind turbines in Denmark (Jensen, 2004). Through application experience, the turbine manufacturer learned how to address design challenges, and turbine size gradually increased (Grubb and Vigotti, 1997). Today’s commercial turbines have reached the size of the ambitious experimental turbines of the 1980s. A combination of public and private R&D, market feedback, operational experience, and incremental improvements achieved cost reductions and allowed an increase of turbine size. At windy locations, wind power is now as cheap as new conventional capacity, and it may approach competitiveness in other locations, depending on competing fuel cost and the extent to which policies reflect environmental costs. The wind power market is burgeoning, with growth sustained at 20–30 per cent/year since the early 1990s. Strategic deployment of wind energy cost Denmark an estimated US\$1.4 billion in subsidies over 1993–2001;

meanwhile, annual revenues of Danish wind companies by 2001 were \$2.7 billion, the vast majority from its dominant position in export markets (Carbon Trust, 2003).

Strategic deployment programmes must cover the difference between wholesale electricity price and the costs of new technologies. These costs of renewable technologies are initially high, as they have not experienced improvement through market experience. With increasing cumulative installation and market experience, costs of the new technology fall. Costs also fall for established technologies, but at a slower pace. This is because, for established technologies, doubling of global installed capacity takes much longer and further cost reductions are therefore slower. Strategic deployment must be continued until the cost of a new renewable technology becomes competitive with conventional technology. The grey area in Figure 4 illustrates this process, including the need for up-front subsidies at declining rates. As indicated, the time to break even and the longer-term gains will also depend upon the emergence of policies that reflect environmental costs, and in particular, CO₂ allowance prices.

After the break-even point is passed, new technologies produce electricity below the costs of established technologies and consumers will benefit from lower costs (striped area in Figure 4). In economic terms, the up-front subsidies seek to internalize the benefits of strategic learning, which to a large degree is an external, public good.

For technologies with some market experience, such as wind and solar PV, historic data can be used to estimate costs and benefits of such an active technology policy (IEA, 2000; McDonald and Schrattenholzer, 2001). Cost predictions for offshore wind, solar concentration, and marine technologies rely on engineering assessments, which are more detailed but also more subjective as a specific technology evolution has to be assumed. Table 1 shows the public ‘learning investment’ that may be required to create sufficient market experience for PV to make it cost competitive with existing technologies. Neuhoff (2004) provides more details and comparison with the similar calculations of IEA (2000) and Duke (2002). In the base case, €20 billion of public subsidies are required, spread over the period 2005–23. The calculations assume that PV is

Figure 4
Learning Investment and Future Benefits of a New Technology

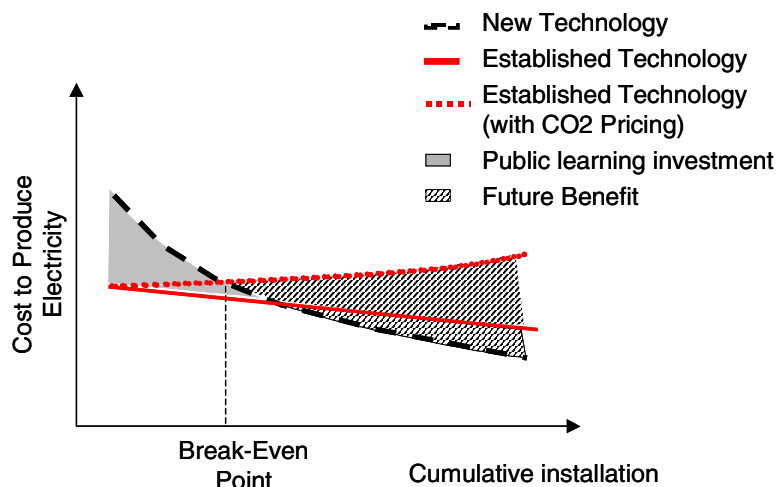


Table 1
Public Learning Investment (Billion Euro) Required to Make PV Cost Competitive at Wholesale Level

Rate at which technology improves with market experience	Future wholesale electricity price level		
	€40/MWh	€50/MWh	€60/MWh
Slow	110	55	29
Historic	38	20	12
Rapid	17	10	6

Table 2
Ratio between Net Present Value (NPV) and Learning Investment

Rate at which technology improves with market experience	Future wholesale electricity price level		
	€40/MWh	€50/MWh	€60/MWh
Slow	0	2	9
Historic	4	15	38
Rapid	17	44	92

applied both in markets for high-value off-grid and distributed PV and in centralized installations to gain sufficient scale.

Two uncertainties drive the prediction. The first uncertainty is the future costs of conventional generation, including the extent to which environmental and security externalities are internalized; this determines the wholesale price against which PV

needs to compete. Second is the rate at which PV costs decline with increasing market experience. Slow improvements through market experience correspond to cost reductions of 17 per cent with each doubling of cumulative installed capacity, ‘historic’ to 20 per cent and ‘rapid’ to 23 per cent. IEA (2000) assumes learning rates between 18 and 22 per cent. A survey by McDonald and Schratzenholzer (2001) suggest 20 per cent.

These uncertainties influence the benefits that society will obtain from strategic deployment. Table 2 shows the global ‘strategic benefit–cost’ ratio. In the base case the benefits until 2040, at a 5 per cent discount rate, would be 15 times the costs of learning investment. However, if both learning rates and the reference electricity price were at the lower end of the assumed distribution, the ‘learning investment’ would not be recovered by 2040. This type of technology risk is unavoidable (Alic *et al.*, 2003). It requires continuous evaluation of technology progress in order to stop unsuccessful programmes. It also requires support of several technology options to ensure that future energy security is not jeopardized if one technology does not satisfy expectations.

Of course, the real picture is complicated by the diversity of resources and potential applications. For example, PV electricity in very sunny regions is obviously cheaper than in others. In addition, there are issues of international competition: learning is likely to be partly domestic and partly generic, and many different actors and countries could contribute to learning, and in turn, recoup benefits of component or machine exports (as with Danish wind energy). But the fundamental point is that there is a clear economic case for government action to build markets for advanced deployment of emerging clean-energy technologies.

In such strategic deployment, policy determines the subsidy volume and therefore the growth rate. The previous calculations assumed a growth rate of 35 per cent, slightly above recent development of 32 per cent (PVPS, 2003) and slightly below the growth rates of the semi-conductor industry.¹³ If the growth rate is reduced, more learning takes place in high-value off-grid and distributed markets. This reduces the cost of strategic deployment, but also postpones the benefits which society will obtain from larger-scale application of competitive PV.

The anticipated cost improvements can only materialize if producers invest and experiment with new production processes and technology options. For this to happen, industry must be confident that the global market growth will be sustained. While it is not difficult to give guarantees around individual

projects, it is far more difficult to guarantee that strategic deployment policies will be maintained; indeed, they are bound to be reviewed periodically. However, the more countries that are engaged, the less exposed producers will be to interruptions of policy processes in individual countries (Wilson, 1989; Grubb and Vigotti, 1997).

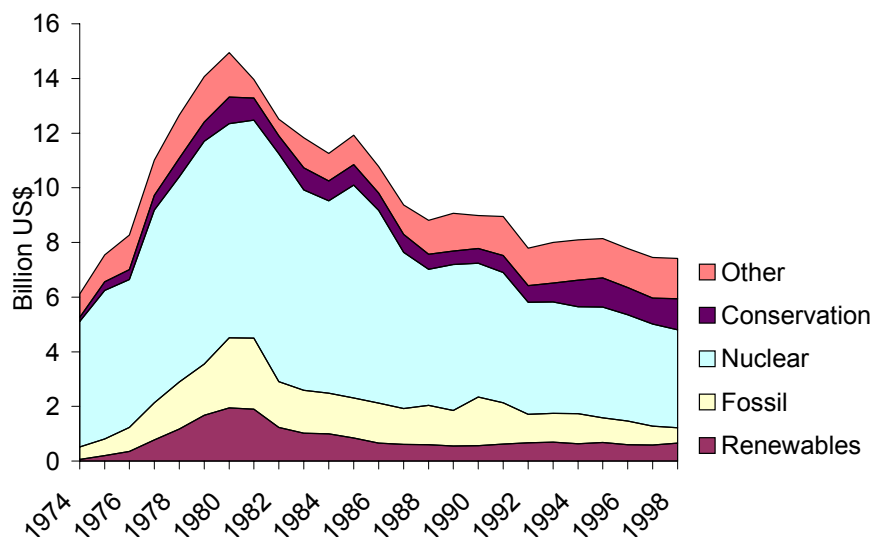
IX. RESEARCH, DEVELOPMENT, AND DEMONSTRATION

Innovation is frequently pictured as a linear process, taking a new technology from R&D to demonstration and strategic deployment until the technology can finally compete in mass markets (Foxon and Kemp, 2004). Tidal, wave, and solar concentration technologies are at an early stage of the innovation process and require extensive demonstration projects to explore options and improve solutions. More advanced technologies, such as wind and solar PV, also need R&D to improve their performance. Market experience from strategic deployment programmes then refines the research results and at the same time helps to identify new research needs.

Margolis and Kammen (1999b) estimate that private returns on R&D across various sectors are between 20 and 30 per cent, while social rates of return are around 50 per cent. This shows that private investors only appropriate a fraction of social returns because technology ‘spillover’ in the energy sector is large. Investors also face difficulties in evaluating intangible R&D output (Alic *et al.*, 2003) and therefore under-invest in R&D (Azar and Dowlatabadi, 1999). As a result, R&D-intensive companies are systematically under-priced by the market. This is likely to reduce the incentive to perform basic research. Lev (2004) observed among companies that are members of the industrial research institute that they reduced the allocation of R&D funds to basic research every year from 1993 to 2003, in favour of modifications and extensions of current products. Furthermore, energy technologies are usually sold to markets that are closely regulated. A path-breaking research success might induce a change in the market design or regulation, such that the public appropriates the profits, not the

¹³ D-Ram semiconductor sales show an average annual growth rate of 33 per cent, in units shipped of 43 per cent and in shipped memory density of 98 per cent for the period 1974–98 (Source: Firsthand, Understanding Semi Conductor Cycles, http://advisors.firsthandfunds.com/documents/investor_ed/semiconductors.pdf).

Figure 5
IEA Country Public R&D Expenditure on Energy Technologies



Source: IEA database of R&D.

private innovator. This would further reduce the incentive to fund R&D privately. Therefore it is generally accepted that public support is required to achieve the optimal R&D level.

The importance of R&D is also supported by macroeconomic analysis. Jorgenson and Wilcoxon (1990) attribute about 50 per cent of economic growth to technology change. Goulder and Schneider (1999) argue that increasing R&D expenditures in carbon-free technologies could crowd out R&D in the rest of the economy and therefore reduce overall growth rates. However, Azar and Dowlatbadi (1999) refer to Mansfield's (1968) counter-argument: radical technological change will trigger more research overall and therefore increase economy-wide productivity rates.

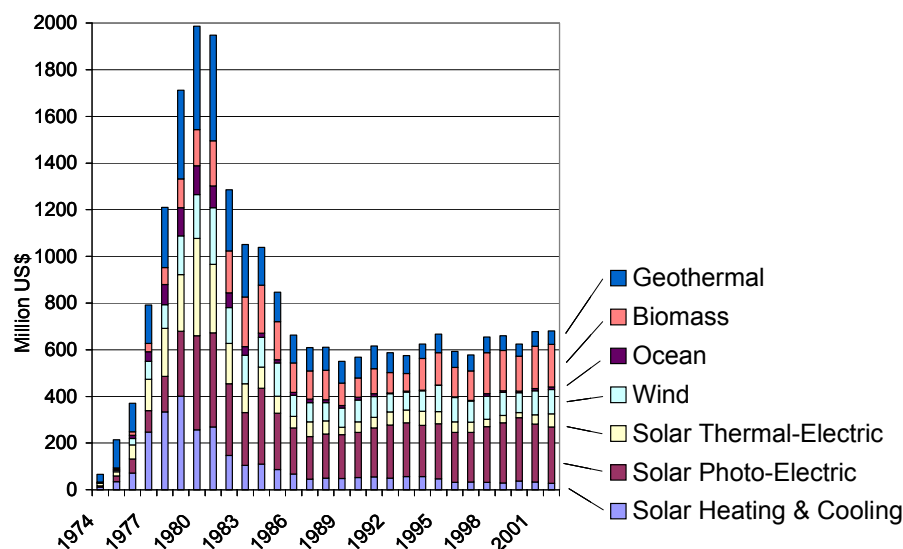
Industry-funded R&D focuses on the areas of existing activity of the firm. Jelen and Black (1983) observed that companies fund internal R&D in rough proportion to sales revenues. The market volume of renewable energy technologies is still small and therefore industry R&D is likely to be small. Furthermore, even forward-looking companies do not plan for more than a decade and are therefore likely to focus on improvements that can be leveraged in the short term (Anderson and Bird, 1992).

This suggests that public funding will be the main driver for longer-term developments in new technology and production processes for existing renewables, exploration of untried renewable technologies, superconductivity to provide the option for efficient long-distance electricity transport, and non-hydro storage technologies. The innovation process is not linear but entails various feedback loops between market experience and research activities. Cost and efficiency improvements in existing renewable technologies (Luther, 2004) therefore require a parallel increase in strategic deployment efforts and public research funding. The optimal mix between R&D support and support for strategic deployment is unclear. Twenty-two per cent of the Japanese PV programme was spent on R&D in the period 1973–95 (Gruebler *et al.*, 1999). The Japanese, German, and US PV programmes devoted 31 per cent of support in 2002 to R&D (PVPS, 2003).

Figure 5 shows that, in recent decades, only a small fraction of public energy R&D funds of IEA countries have been allocated to renewable energy technologies, less than 8 per cent in the period 1987–2002.¹⁴ Given public expectations and policy commitments, it is surprising that renewable energy technologies continue to be funded at a low level relative to nuclear and fossil energy. This picture is

¹⁴ Margolis and Kammen (1999a) show that total investment in R&D in the USA increased from US\$100 billion in 1976 to US\$200 billion in 1996, while US energy R&D decreased from US\$7.6 billion to US\$4.3 billion. Renewable fuels make up 4 per cent of the United States' energy supply, yet receive only 1 per cent of federal tax expenditures and direct fiscal spending, excluding revenue outlays for the Alcohol Fuels Excise Tax (Herzog *et al.*, 2001).

Figure 6
Public R&D Expenditure on Renewable Energy Technologies in IEA Countries



Source: IEA, USD of 2000.

even more disturbing if we consider that private R&D expenditure in the energy sector is extremely low. In the USA, as a typical example, 0.5 per cent of sales revenue in the electricity sector is devoted to R&D, compared to 3.3 per cent in the car industry, 8 per cent in electronics, and 15 per cent in pharmaceuticals (based on Alic *et al.*, 2003).

Figure 6 shows the allocation of public R&D funds to different renewable technologies over time. Total funding has dropped after the initial interest created through the oil shock in the 1970s, and has stayed constant since.

However, the aggregate picture hides the large uncertainty to which individual research streams are exposed. Funding levels for individual technologies in individual countries have changed by more than 30 per cent in about half the observation years.¹⁵ This ‘roller-coaster’ of research funding limits the ability of laboratories to attract, develop, and maintain human capital for successful R&D.

X. POLICY INSTRUMENTS

This paper has surveyed five key features of energy-technology systems: an uneven playing field;

specific barriers in the market; non-market structures; lock-out phenomena; and the overall economics of strategic deployment for technology learning. They provide economic arguments for government policies to unlock new technologies, if the expectation is that the unlocked technologies offer a valuable option for future energy supply. In the absence of such policies, new renewable technologies will be introduced, if at all, with large delays. Carbon constraints alone will not do the trick. With further reductions in CO₂ quotas, it is likely that renewable technologies are necessary to satisfy energy demand. Without strategic deployment, the carbon price will rise until it is high enough to finance new renewable technologies. With the application of these technologies, their costs, and therefore also the carbon price, will fall again. Such a peak in the carbon price is likely to result in distortions in other economic sectors and to increase the total costs of climate policy to society.

Governments have successfully supported technology improvements through market experience in other sectors, as the example of deep-water oil drilling showed (section III). Governments reduced extraction taxes to compensate private oil companies for higher field-development costs of deep-water oil fields. Tax levels in the electricity sector

¹⁵ Based on own analysis of R&D data provided by IEA. Kammen (2004) concludes that national R&D programmes have frequently exhibited ‘roller-coaster funding cycles’.

are lower than in oil extraction, and a tax reduction would not suffice to make new renewable technologies cost competitive. A financial premium is needed, either funded from the general budget or through electricity consumers. General taxation creates economic distortions (Duke, 2002). It is economically preferable and also more commonplace to incorporate 'learning investment' costs for energy technologies into the price of electricity. As environmental externalities are not fully included in electricity prices, the modest addition to electricity prices makes consumption decisions more efficient.

A variety of policy instruments are used to deliver financial support to renewable energy projects.

Up-front capital subsidies or investment tax deductions provide public financial support for the initial investment. The Japanese PV programme has successfully combined direct investment aid and capital grants with stable energy prices guaranteed at the level of retail tariffs (net-metering). This is a simple way to support distributed small-scale projects and creates few transaction costs. However, if too much of the project funding is based on up-front payments or tax deductions, India's experience with 100 per cent depreciation from corporate taxes shows that investors might pay insufficient attention to turbine siting, durability, and maintenance (Jagadeesh, 2000). As technologies improve and the scale of deployment increases, experience shows that it is increasingly important for incentives to support the value of power produced, rather than just the investment: to reward performance, not merely the fact of installing equipment.

Labelling of electricity and relying on consumer choice has been proposed as an alternative to obligatory schemes. While this option might be attractive in certain respects, it seems to have little impact on the deployment of renewable energy technologies (EWEA, 2004). Most consumers prefer renewable energy but are happy to free-ride, if their neighbours incur the costs (Rader and Norgaard, 1996; Swezey and Bird, 2001). With few consumers opting to buy renewable energy at higher tariffs, they are supplied by existing rather than new capacity.

Weitzman (1974) analysed the basic options for governments to set either price or quantity targets.

Both approaches are currently applied in different countries to support new technologies. In the quantity approach, electricity suppliers are obliged to provide a certain percentage of power from renewables—'renewable portfolio standards' either through own production or purchases—generally implemented with some form of tradable 'renewable energy credits'. The major benefit attributed to trading of renewable energy certificates is price reductions from competition. This argument ignores the multi-layer market structure. Producers, installers, and planners compete to supply to project developers or investors, irrespective of the funding regime to which project developers are exposed. A drawback of renewable portfolio standards is that, so far, no mechanism has been found to isolate markets for renewable energy certificates from future policy decisions. The setting of the overall quota involves trade-offs between investment security and inherent uncertainties about rates of installation and qualifying technologies. As a result, the quota value may be quite unstable and difficult to predict and revenue streams of renewable energy projects are exposed to uncertainties from both the market and future government decisions. With such regulatory risk, investors apply higher discount rates when evaluating future revenues, and require higher total payments for projects to break even (see also Moore and Ihle, 1999).

Regulatory risk can be reduced if policies provide legally enforceable long-term guarantees. The German feed-in tariff and the British auctions for long-term renewable contracts under the Non Fossil Fuel Obligation (NFFO) in the 1990s defined electricity prices for most of the project lifespan. Although the tariff is fixed for the lifespan of a project, it can be adjusted year by year to represent technology advances for new projects coming online. Fixed prices have the additional benefit of insulating investors from the regulatory risk caused by future changes to electricity market design. For renewable energy plants, other than bio energy, fixed off-take prices do not distort the efficient operation of the plant, because the system operator does not require marginal prices to give priority to technologies with zero fuel costs. The increased investment security associated with long-term guarantees reduces the cost of financing (Butler and Neuhoff, 2004). Danish and German experience shows that it is still possible to

find arrangements within the fixed-price feed-in mechanism to allow the system operator to reduce short-term output from wind turbines if required for system purposes (spill wind). Mechanisms, such as the feed-in tariff, offer two more levers to optimize technology policy. First, the tariff can be technology specific—enabling the parallel advancement of various renewable technologies in the market. Second, the tariff can be conditioned on the local wind resources. This adjustment minimizes the subsidy paid for a specific site, as it reduces the tariff below the level paid to the marginal unit in the system. It can also be used to develop a large range of sites, thereby increasing public acceptance and retaining high-wind sites for larger future turbine sizes.

As an alternative support mechanism in the USA, production tax-credits are used to offer investors tax benefits during the project's life. However, tax schemes are frequently modified; investors face risk, and discount the benefits, meaning higher payments are needed to ensure projects break even (Crooks, 1997).

Overall, the experience of different policy instruments is mixed. There is some indication that mechanisms that expose investors to regulatory risk or uncertainty about future market designs are either more expensive for the ratepayers, or do not result in significant investment. Mechanisms that do not provide technology-specific support premiums inevitably focus investment on the most cost effective technology available and do not encourage improvements, through market experience, in other renewable energy technologies. For example, Bird and Swezey (2004) report that wind accounts for 94 per cent of new renewables installed under green marketing programmes. The optimal policy instrument or mix of instruments might depend on the local and technology circumstances. A harmonization of instruments does not seem to be required, as the mechanisms predominantly affect local project developers and investors. These local actors then contract out technology and construction services

and negotiate the best possible price. Therefore, a global market for renewable technologies is compatible with a mix of support mechanisms, as we can already see today.

XI. INTERNATIONAL

Cost reductions in renewable technologies or their production process occur on an international scale.¹⁶ Therefore, strategic deployment not only reduces technology costs for users in one country, it also has a positive impact in other countries. Global welfare increases with the number and scale of strategic deployment programmes.¹⁷ Such joint learning experience can be facilitated if standards are harmonized. Standardization in the telecoms sector has allowed transfer of mobile equipment between most markets. Currently, wind-turbine producers face difficulties, as their power electronic equipment has to satisfy different requirements in many markets.

The objective is, therefore, to achieve coherence in energy and technology policy. This is not the same as convergence of policy instruments (Rowlands, 2004), which is perhaps not even desirable. Alic *et al.* (2003) argue that policy-makers should channel funds for technology development and diffusion through multiple agencies and programmes to promote competition and support a diversity of options rather than particular technological choices. Proponents of tradable renewable energy certificates argue that international trading of certificates allows developers to access the best wind and solar resources. This might reduce short-term costs, which are easily quantifiable and therefore typically emphasized. It ignores the fact that one objective of strategic deployment is to foster local industry, and institutional and stakeholder learning.

Renewable technologies are traded in competitive markets, which already successfully interface with a variety of support mechanisms in different countries. Costs of strategic deployment programmes

¹⁶ Bottazzi and Peri (2004) use a panel data analysis over all industries to show that internationally generated ideas have a very significant impact in helping innovation in a country. As a consequence, a positive shock to innovation in a large country has, both in the short and in the long run, a significant positive effect on the innovation of all other countries.

¹⁷ Barreto and Klaassen (2004) use the ERIS model to show that, with global learning, optimal investment in renewable technologies is increased.

can be added to the tariff bills of national consumers without significant distortions.¹⁸

How many countries will autonomously develop or expand strategic deployment programmes for renewable energy technologies? Results from R&D not only ‘spill over’ between companies but also between countries. This might induce national governments to free-ride on foreign R&D and deployment efforts, undermining the objective of large-scale deployment of renewable energy technologies (Barreto and Klaassen, 2004). However, the benefits from unlocking renewable technologies are a multiple of the costs of the learning investment. Therefore, it can be advantageous for individual countries to finance learning investment, even if they only capture a fraction of the global benefits. Furthermore, national industry policy and national institutional learning provide additional arguments to pursue or expand a strategic deployment programme.

National politicians or administrations will be more successful in pursuing strategic deployment programmes, if these programmes are coherent with similar initiatives in other countries (Barreto and Klaassen, 2004). A joint public declaration or non-committing statement made by the Johannesburg Renewable Energy Coalition, the G8 (2001), or similar institutions (Johansson *et al.*, 2004), could express support for stretching targets for increases in R&D budgets or strategic deployment funding. This could provide a reference point for national policy debate and focus the attention of national administrations on energy technology policy.

An international agreement that supports the strategic deployment of several renewable energy technologies would have the advantage that the nationally championed technology of each country could be included. This is likely to increase the number of participating countries. However, it would require a lengthy international process to foster such an agreement, as demonstrated by negotiations of the Kyoto Protocol and the difficulties experienced with the

EU policy-making process in defining a renewable quota (Rowlands, 2004).

It might be easier to foster agreements for individual technologies. For example, the Concentrating Solar Power Global Market Initiative of several European, North American, and North African countries aims at deploying 5 GW of solar concentration in the next 10 years. The resulting learning-by-doing is expected to reduce costs and allow competition with mid-range generation capacity.¹⁹

In the past, Implementing Agreements of the International Energy Agency focused on R&D and particularly on information provision and exchange. These exist not only in fields such as bioenergy, climate technology initiative, PV power systems, solar heating and cooling, and wind turbine systems, but also in fossil technologies, energy efficiency, and other topics (in all, 41 Agreements). Total spending under the collaborative programme is only \$120–150m per year, of which renewables get a minor share. In principle, there are no objections to using the credibility provided by the IEA to support internationally coordinated deployment programmes.

Partnerships with developing countries could provide mutual benefits. OECD countries would benefit from larger markets and lower production costs; developing countries would obtain access to new technologies, new employment opportunities, and reduced fossil fuel costs. All participants would benefit from reduced emissions. One step towards facilitating such cooperation would be the expansion of export credit guarantees for renewable energy technologies.

XII. CONCLUSION

Resource assessments suggest that renewables could satisfy a much larger share of global energy demand. This would enhance our security and environment. However, the market share of renewables will not increase unless new energy

¹⁸ In 2003, the average EU retail tariff based on class Da and Dd for Italy was 181.2 €/MWh with standard deviation of 47.0 €/MWh. The average tariff for large industrial customers was 58.8 €/MWh with standard deviation of 12.36 €/MWh (Eurostat, *Statistics in Focus*, Theme 8, 21/2003). This compares to a less than 4 €/MWh price increase to cover costs of the current German deployment programme. In 2003, 6.1 per cent of electricity was produced from renewables with average remuneration of 91.3 €/MWh. The costs above wholesale price level (~30€/MWh) are shared among all consumers with the exception of exempt industrial customers (6 per cent in 2003) (http://www.vdn-berlin.de/aktuelledaten_eeg.asp).

¹⁹ See <http://www.solarpaces.org>

and technology policies address the following barriers.

- (i) Traditional energy technologies are not exposed to full security and environmental costs, and they offer energy below the level of total social costs. Levelling the playing field implies re-allocation of rent between stakeholders and is, therefore, a slow process. In the meantime, subsidies for renewable technologies might be required to ensure efficient investment decisions, while subsidies for conventional technologies should be reduced.
- (ii) Markets and tariff structures are designed and optimized for fossil generation technologies. They do not address the specific requirements of renewables: flexible operation, long-term contractual arrangements to reduce financing costs, particularly in an environment with high regulatory risk, and simple procedures with low-transaction costs for their small-scale nature.
- (iii) Renewables are at different stages of development, and fit into different markets. Therefore,

policy support must address the specific stage and market of each renewable. For emerging and innovative technologies, this means increasing substantially the collective investment in RD&D and, for those entering the market, increasing the level of deployment incentives. Several countries applying strategic deployment in parallel will create industry confidence in continuous market growth.

The discovery of a new energy technology that suddenly resolves all energy challenges is a frequently cited dream, but has not happened in the past and is unlikely to occur in the future. In contrast, we have consistently observed that technologies become more cost effective with improvements through market experience. However, this does not happen autonomously. Most renewable energy technologies are locked out from large-scale market experience because the playing field is uneven and various barriers and technology spillover prevent industry from financing the learning investment. It is in the power of governments to unlock these technologies.

REFERENCES

- Admire Rebus (2003), 'Renewable Electricity Market Development in the European Union', final report, www.admire-rebus.net
- Alderfer, R. B., Eldridge, M. M., and Starrs, T. J. (2000), 'Making Connections, Case Studies of Interconnection Barriers and their Impacts on Distributed Power Projects', NREL/SR-200-28053.
- Alic, J. A., Mowery, D. C., and Rubin, E. S. (2003), 'US Technology and Innovation Policies: Lessons for Climate Change', prepared for the Pew Center on Global Climate Change.
- Alsema, E. A. (2000), 'Energy Pay-back Time and CO₂ Emissions of PV Systems', *Progress in Photovoltaics: Research and Applications*, **8**, 17–25.
- Anderson, D., and Bird, C. D. (1992), 'Carbon Accumulations and Technical Progress—A Simulation Study of Costs', *Oxford Bulletin of Economics and Statistics*, **54**(1), 1–27.
- Ansolabehere, S., Deutch, J., Driscoll, M., Gray, P. E., Holdren, J. P., Joskow, P. L., Lester, R. K., Moniz, E. J., Todreas, N. E. (2003), *The Future of Nuclear Power*, an interdisciplinary MIT study, Boston, MA, MIT.
- Arthur, W. B. (1989), 'Competing Technologies, Increasing Returns, and Lock-in by Historical Events', *The Economic Journal*, **99**(394), 116–31.
- Azar, C., and Dowlatabadi, H. (1999), 'A Review of Technical Change in Assessment of Climate Policy', *Annual Review of Energy Economics*, **24**, 513–44.
- Barreto, L., and Klaassen, G. (2004), 'Emission Trading and the Role of Learning-by-Doing Spillovers in the "Bottom-up" Energy-system ERIS Model', *International Journal of Energy Technology and Policy*, **2**(1/2), 70–95.
- Bergek, A., and Jacobsson, S. (2003), 'The Emergence of a Growth Industry: A Comparative Analysis of the German, Dutch and Swedish Wind Turbine Industries', in S. Metcalfe and U. Cantner (eds), *Change, Transformation and Development*, Heidelberg, Physica-Verlag, 197–228.

- Bird, L., and Swezey, B. (2004), 'Capacity Estimates of Renewable Energy Developed to Serve Green Power Markets', National Renewable Energy Laboratory.
- Bottazzi, L., and Peri, G. (2004), 'The Dynamics of R&D and Innovation in the Short Run and in the Long Run', Centre for Economic Policy Research, DP4479.
- Braunholtz, S. (2003), *Public Attitudes towards Wind Farms*, Mori Scotland and Scottish Executive, www.scotland.gov.uk
- Butler, L., and Neuhoﬀ, K. (2004), 'Comparison of Feed in Tariff, Quota and Auction Mechanisms to Support Wind Power Development', CMI Working Paper 70.
- Carbon Trust (2003), 'Building Options for UK Renewable Energy', www.thecarbontrust.co.uk
- Crooks, A. C. (1997), 'Cooperatives and New Uses for Agricultural Products: An Assessment of the Fuel Ethanol Industry, USDA Rural Business-Cooperative Service', RBS Research Report 148.
- Dasgupta, P., and Stiglitz, J. (1988), 'Learning-by-doing, Market Structure and Industrial and Trade Policies', *Oxford Economic Papers*, **40**, 256–68.
- Dekimpe, M. G., Parker, P. M., and Sarvary, M. (2000), 'Globalization': Modeling Technology Adoption Timing Across Countries', *Technology Forecasting and Social Change*, **63**, 25–42.
- de Moor, A. (2001), 'Towards a Grand Deal on Subsidies and Climate Change', *Natural Resources Forum*, JNRF, **25**.
- Duke, R. (2002), 'Clean Energy Technology Buydowns: Economic Theory, Analytic Tools, and the Photovoltaics Case', Ph.D. Dissertation, Princeton University.
- Kammen, D. M. (1999), 'The Economics of Energy Market Transformation Programs', *The Energy Journal*, **20**(4), 15–64.
- Jacobson, A., and Kammen, D. M. (2002), 'Photovoltaic Module Quality in the Kenyan Solar Home Systems Market', *Energy Policy*, **30**, 477–99.
- Espejo, R., Schuhmann, W., Schwaninger, M., and Bilello, U. (1996), *Organizational Transformation and Learning—A Cybernetic Approach to Management*, Chichester, John Wiley & Sons.
- EU Commission (2000), *Towards a European Strategy for Security of Energy Supply*, Green Paper.
- EWEA (2004), *Wind Energy, The Facts, An Analysis of Wind Energy in the EU-25*, European Wind Energy Association, funded by EU Commission, DGTREN.
- Foxon, T., and Kemp, R. (2004), 'Innovation Impacts of Environmental Policies', in *International Handbook on Environment and Technology Management*, forthcoming.
- G8 (2001), 'Renewable Energy: Development that Lasts', G8 Renewable Energy Task Force Chairman Report.
- Goulder, L. H., and Schneider, S. H. (1999), 'Induced Technological Change and the Attractiveness of CO₂ Emissions Abatement Policies', *Resource and Energy Economics*, **21**, 211–53.
- Grubb, M., and Vigotti, R., (1997), *Renewable Energy Strategies for Europe—Electricity Systems and Primary Electricity Sources*, vol. II, London, Earthscan.
- Gruebler, A., Nakicenovic, N., and Voctor, D. G. (1999), 'Modelling Technological Change: Implications for the Global Environment', *Annual Review of Energy and the Environment*, **24**, 545–69.
- Herig, C. (2000), 'PV is On When the Power is Out', National Association of Regulatory Utility Commissioners Committee on Energy Resources and the Environment, 2000 Annual Convention, San Diego.
- Herzog, A. V., Lipman, T. E., Edwards, J. L., Kammen, D. M. (2001), 'Renewable Energy: A Viable Choice', *Environment*, **43**(10).
- Hoff, T., and Cheney, M. (2000), 'The Potential for Photovoltaics and Other Distributed Resources in Rural Electric Cooperatives', *The Energy Journal*, **21**(3), 113–27.
- Hoffert, M., Caldeira, K., Benford, G., Criswell, D. R., Green, C., Herzog, H., Jain, A. T., Kheshgi, H. S., Lackner, K. S., Lewis, J. S., Lightfoot, H. D., Manheimer, W., Mankins, J. C., Mauel, M. E., Perkins, L. J., Schlesinger, M. E., Volk, T., and Wigley, T. M. L. (2002), 'Advanced Technology Paths to Global Climate Stability: Energy for a Greenhouse Planet', *Science*, **298**, 981–7.
- IEA (1999), *World Energy Outlook, Looking at Energy Subsidies: Getting the Price Right*, Paris, OECD/International Energy Agency.
- (2000), *Experience Curves for Technology Policy*, Paris, International Energy Agency.
- (2003a), *Creating Markets for Energy Technologies*, Paris, International Energy Agency.
- (2003b), *Renewables for Power Generation, Status and Prospects*, Paris, International Energy Agency.
- (2004b), *World Energy Outlook*, Paris, International Energy Agency.
- Irwin, D., and Klenow, P. (1994), 'Learning-by-Doing Spillovers in the Semiconductor Industry', *Journal of Political Economy*, **102**, 1200–27.

- Isoard, S., and Soria, A. (1997), 'Learning Curves and Returns to Scale Dynamics: Evidence from the Emerging Renewable Energy Technologies', IPTS Working Paper Series WP 97/05.
- Jagadeesh, A. (2000), 'Wind Energy Development in Tamil Nadu and Andhra Pradesh, India: Institutional Dynamics and Barriers—A Case Study', *Energy Policy*, **28**, 157–68.
- Jelen, F. C., and Black, L. (1983), *Cost and Optimization Engineering*, New York, McGraw Hill.
- Jensen, S. G. (2004), 'Reducing Costs of Emerging Renewable Energy Technologies—An Analysis of the Dynamic Development with Wind Power as Case Study', *International Journal of Energy Technology and Policy*, **2**(1/2), 179–202.
- Skytte, K. (2003), 'Simultaneous Attainment of Energy Goals by Means of Green Certificates and Emission Permits', *Energy Policy*, **31**, 63–71.
- Johansson, T. B., Fritsche, U. R., Flavin, C., Sawin, J., Assmann, D., and Herberg, T. C. (2004), 'Policy Recommendations for Renewable Energies', International Conference for Renewables, Bonn.
- Jorgenson, D. W., and Wilcoxon, P. K. (1990), 'Environmental Regulation and US Economic Growth', *RAND Journal of Economics*, **21**(2), 314–40.
- Kammen, D. M. (2004), 'Renewable Energy Options for the Emerging Economy: Advances, Opportunities and Obstacles', Background Paper for 'The 10–50 Solution: Technologies and Policies for a Low-Carbon Future', Pew Center & NECP Conference, Washington, DC.
- Kaplan, A. (1999), 'Generating Interest, Generating Power: Commercializing Photovoltaics in the Utility Sector', *Energy Policy*, **27**, 317–29.
- Keats-Martinez, K., and Neuhoff, K. (2004), 'Allocation of Carbon Emission Certificates in the Power Sector, How Generators Profit from Grandfathered Rights', Cambridge Working Papers in Economics 0444.
- Kline, D. (2001), 'Positive Feedback, Lock-in, and Environmental Policy', *Policy Science*, **34**, 95–107.
- Klinski, S. (2004), 'Rechtliche und administrative Hemmnisse des Ausbaus erneuerbare Energien in Deutschland', Ergebnisse des 1. Teilberichts (Results of the Interim Report), March.
- Lev, B. (2004), 'Sharpening the Intangibles' Edge', *Harvard Business Review*, June, 109–16.
- Luther, J. (2004), 'Research and Development, The Basis for Wide-spread Employment of Renewable Energy', Thematic Background Paper, International Conference for Renewable Energies, Bonn.
- McDonald, A., and Schrattenholzer, L. (2001), 'Learning Rates for Energy Technologies', *Energy Policy*, **29**, 255–61.
- Mansfield, E. (1968), *Industrial Research and Technological Innovation*, New York, Norton.
- Margolis, R. M., and Kammen, D. M. (1999a), 'Underinvestment: The Energy Technology and R&D Policy Challenge', *Science*, **285**, 690–2.
- — (1999b), 'Evidence of Under-investment in Energy R&D in the United States and the Impact of Federal Policy', *Energy Policy*, **27**, 575–84.
- Ministry of Economic Affairs, Netherlands (2004), *Innovation in Energy Policy, Energy Transition: State of Affairs and the Way Ahead*.
- Moore, C., and Ihle, J. (1999), 'Renewable Energy Policy outside the United States', *Renewable Energy Policy Project*, No. 14, October.
- Musial, W., and Butterfield, S. (2004), 'Future for Offshore Wind Energy in the United States', National Renewable Energy Laboratory, CP-500-36313.
- Neuhoff, K. (2004), 'Large Scale Deployment of Renewables for Electricity Generation', Cambridge Working Papers in Economics, 0460.
- De Vries, L. (2004), 'Insufficient Incentives for Investment in Electricity Generation', *Utilities Policy*, **12**, 253–67.
- Neumann, T., Ender, C., Molly, J. P., Neddermann, B., Winkler, W., and Strack, M. (2002), 'Weiterer Ausbau der Windenergienutzung im Hinblick auf den Klimaschutz —Teil 2', Deutsches Windenergie-Institut.
- Norberg-Bohm, V. (2000), 'Creating Incentives for Environmentally Enhancing Technological Change: Lessons from 30 years of US Energy Technology Policy', *Technological Forecasting and Social Change*, **65**, 125–48.
- OECD, IEA, and UNEP (2002), *Reforming Energy Subsidies*, Paris, Organization for Economic Cooperation and Development, International Energy Agency, and United Nations Environment Programme.
- OXERA (2003), 'The Non-market Value of Generation Technologies', funded by British Nuclear Fuels, available at [www.oxera.co.uk/oxera/public.nsf/images/DKIG-5NCERA/\\$file/OXERAReport.pdf](http://www.oxera.co.uk/oxera/public.nsf/images/DKIG-5NCERA/$file/OXERAReport.pdf).
- Pershing, J., and Mackenzie, J. (2004), 'Removing Subsidies, Leveling the Playing Field for Renewable Energy Technologies', Thematic Background Paper, International Conference for Renewable Energies, Bonn.
- PVPS—Photovoltaic Power System Program (2003), 'Trends in Photovoltaic Applications, Survey Report of Selected IEA Countries between 1992 and 2002', Report IEA-PVPS T1-12.

- Rader, N., and Norgaard, R. (1996), 'Efficiency and Sustainability in Restructured Electricity Markets: The Renewables Portfolio Standard', *The Electricity Journal*, **9**(6), 37–49.
- Roth, F. I., and Ambs, L. L. (2004), 'Incorporating Externalities into a Full Cost Approach to Electric Power Generation Life-cycle Costing', *Energy*, in press.
- Rowlands, I. H. (2004), 'The European Directive on Renewable Electricity: Conflicts and Compromises', *Energy Policy*, in press.
- Sanden, B., and Azar, C. (2004), 'Near-term Technologies for Long-term Climate Targets—Economy-wide versus Technology-specific Approaches', *Energy Policy*, in press.
- Sawin, J. L. (2004), 'Mainstreaming Renewable Energy in the 21st Century', Worldwatch Paper 169.
- Smith, J. C., DeMeo, E. A., Parson, B., and Milligan, M. (2004), 'Wind Power Impacts on Electric Power System Operating Costs: A Summary and Perspective on Work to Date', National Renewable Energy Laboratory, CP-500-35946.
- Sonntag-O'Brien, V., and Usher, E. (2004), 'Mobilising Finance For Renewable Energies', International Conference for Renewable Energies, Bonn.
- Strbac, G. (2002), 'Quantifying the System Costs of Additional Renewables in 2020', Report to UK Department of Trade and Industry.
- Swezey, B., and Bird, L. (2001), 'Utility Green Pricing Programs: What Defines Success?', National Renewable Energy Laboratory, TP-620-29831.
- Tol, R. (2003), 'The Marginal Cost of Carbon Dioxide Emissions: An Assessment of the Uncertainties', Working Paper FNU 19.
- United Nations Environment Programme (2004), 'Financial Risk Management Tools for Renewable Energy Projects', study available at www.uneptie.org/energy/act/fin/index.htm
- Unruh, G. C. (2002), 'Escaping Carbon lock-in', *Energy Policy*, **30**, 317–25
- Watanabe, C., Zhu, B., Griffy-Brown, C., and Asgari, B. (2001), 'Global Technology Spillover and its Impact on Industry's R&D Strategies', *Technovation*, **21**, 281–91.
- WBGU (2004), *World in Transition: Towards Sustainable Energy Systems*, London, Earthscan
- Weitzman, M. L. (1974), 'Prices vs Quantities', *Review of Economic Studies*, **41**(4), 477–91.
- Wilson, J. Q. (1989), *Bureaucracy: What Government Agencies Do and Why They Do It*, Library of Congress, Basic Books.
- Yohe, G. W. (2003), 'More Trouble for Cost–Benefit Analysis', *Climatic Change*, **56**(3), 235–44.

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