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Evaluating the Costs and Benefits of Renewable Energy Technologies

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1. Introduction

Despite the apparent environmental attractiveness of renewable energy, with the exception of hydropower its market penetration has been limited to date relative to past projections. This failure has not, however, been due to any failure in its anticipated reduction in cost. For all major renewable technologies, future cost projections for successive generations have either agreed with previous projections or have been even more optimistic. Their lack of commercial success has in large part been due to declining fossil fuel prices for conventional technologies, combined with energy market reforms that have tended (at least in the short run) to return substantial cost savings for utilities utilising these technologies. However, global environmental concerns over emissions of carbon dioxide (CO_2), and other so-called greenhouse gases, are likely to exert significant pressure on governments in industrialised countries to encourage power generation by means of more environmentally benign technologies and micro-power supply sources.

This article commences with a summary of the methodology of life cycle analysis and its application to the energy sector to derive estimates of environmental externalities. The implicit costs of externalities attributable to power generation (from both commercial and potentially commercial technologies) are then compared with the private costs that are generally passed on to the consumer. The focus is on the stationary power sector, since renewable technologies in the transportation sector are relatively underdeveloped.

2. Externalities

2.1 Definition

Externalities are defined as benefits or costs generated as an unintended by-product of an economic activity that do not accrue to the parties involved in the activity. Environmental externalities are benefits or costs that manifest themselves through changes in the physical–biological environment.

Pollution emitted by road vehicles and by fossil fuel power plants during power generation is known to result in harm to both people and the environment. In addition, upstream and downstream externalities, associated with securing fuel and waste disposal respectively, are generally not included in power or fuel costs. To the extent that the ultimate consumers of these products do not pay these environmental costs, or do not compensate people for harm done to them, they do not face the full cost of the services they purchase (that is, implicitly their energy use is being subsidised) and thus energy resources will not be allocated efficiently.

Estimation of damage costs involves assessment of four stages in the environmental 'impact pathway': emission quantities, emission concentrations at receptor points or areas, the physical effect of those concentrations on that point, and the economic value of those effects in terms of willingness to pay to avoid damage arising from the emissions. This is the approach adopted in this article and, as we will see, all four factors are subject to significant degrees of uncertainty.

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2.2 Externality Adders

An 'externality adder' is simply the unit externality cost added to the standard resource cost of energy to reflect the social cost of its use. For power generation, the externality adder would generally be specified in terms of milli-dollars (1000th of a dollar) per kilowatt-hour (m$/kWh). For the transport sector the corresponding units would be m$/vkm (that is, 1000th of a dollar per vehicle kilometre) for passenger vehicles and m$/tkm (that is, 1000th of a dollar per tonne kilometre) for goods vehicles.

Pearce (2001) lists five uses for externality adders:

(i) For public or quasi-public ownership of sources of electric power generation, the full social cost of alternative technologies could be used to plan future capacity with preference being given to that with the lowest social cost. Where electric power generation is privately owned, then regulators could use the full social cost to influence new investment, perhaps through an effective environmental tax.

(ii) Environmental adders can be used to estimate the appropriate level of environmental taxes. Although estimates of environmental adders have been derived for a number of applications, examples of their actual implementation are few.

(iii) Environmental adders could be used to adjust national accounts data to reflect depreciation of natural resources and damage to the environment arising from economic activity, yielding so-called 'green' national accounts.

(iv) Environmental adders could be used for 'awareness raising' (that is, to inform the public of the degree to which alternative energy sources have externalities that give rise to economically inefficient allocation of resources).

(v) Environmental adders might assist in determining environmental policy priorities.

The task of estimating the value of an externality adder involves a substantial commitment of resources and expertise in order to ensure credible information for policy purposes. In the context of the energy sector, a life cycle approach must be adopted in order to identify and quantify environmental adders associated with energy use. The approach also provides a conceptual framework for a detailed and comprehensive comparative evaluation of energy supply options (based upon both conventional and renewable sources). The methodology employed is the subject of the next section.

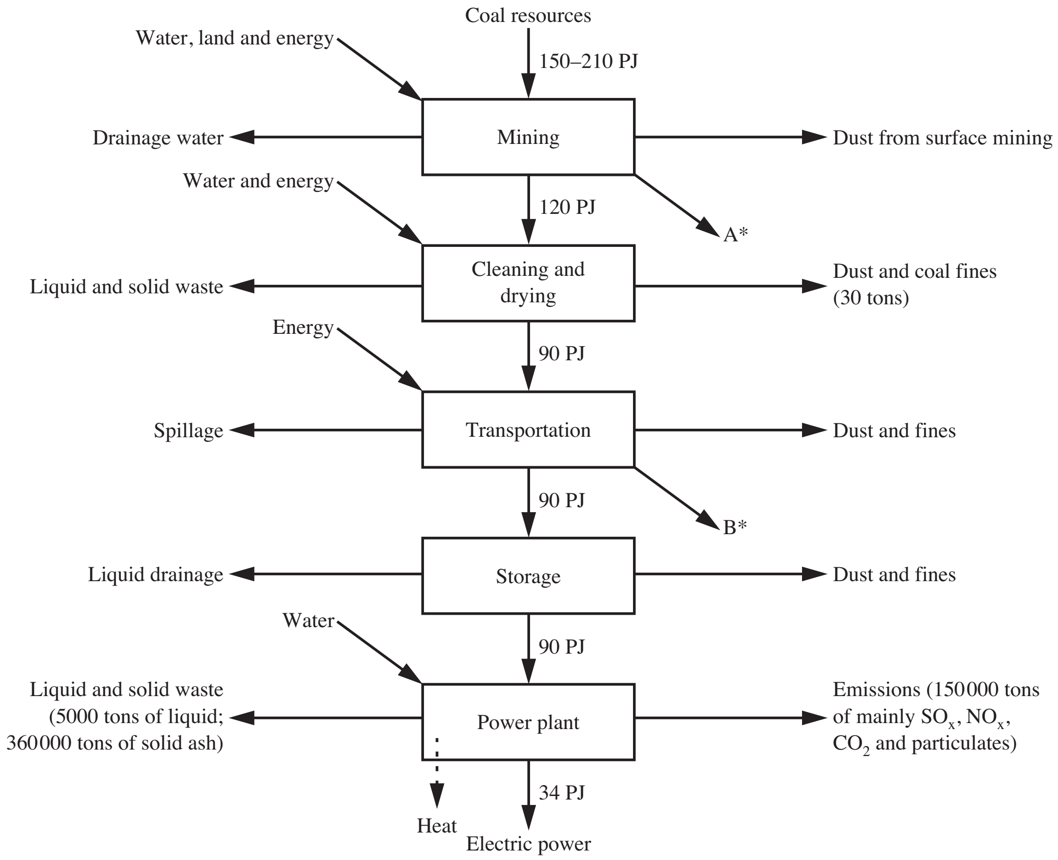
3. Life Cycle Analysis

Life cycle analysis (LCA) is based upon a comprehensive accounting of all energy and material flows, from 'cradle to grave', associated with a system or process. The approach has typically been used to compare the environmental impacts associated with different products that perform similar functions, such as plastic and glass bottles. In the context of an energy product, process or service, an LCA would analyse the environmental impact of fuel extraction, transportation and preparation of fuels and other inputs, plant construction, plant operation (power generation), waste disposal and plant decommissioning. Thus, it encompasses all segments including upstream and downstream processes and consequently permits an overall comparison (in a cost–benefit analysis framework) of short- and long-term environmental implications of alternative energy technologies. Central to this assessment is the valuation of environmental externalities of current and prospective fuel and energy technology cycles.

Undertaking an LCA requires the following steps:

- definition of the product cycle's boundaries;
- identification of the environmental emissions and their resulting physical impacts on receptor areas; and
- quantifying these physical impacts in terms of monetary values.

Figure 1 Coal-Based Electricity Chain



Notes: The asterisks indicate that these impacts pass into another product's boundaries. PJ denotes petajoules.

Source: Sorensen (2000).

This 'chain' for coal-fired electricity generation is illustrated in Figure 1. Even from this simplified illustration, however, it is clear that the data requirements to undertake an LCA are formidable, particularly where sources in other countries have to be accessed. Data limitations and cost constraints will obviously combine to prevent a complete enumeration of the emissions of a given pollutant. It is essential, therefore, that when this situation is reached the proportion left unaccounted for should be clearly specified.

3.1 Quantifying these Physical Impacts in Terms of Monetary Values

The many receptors that may be affected by fuel chain activities are valued in a number of different ways. For example, forests are valued not just for the timber that they produce, but also for providing recreational resources, habitats for wildlife, their interaction (both direct and indirect) with climate, the hydrological cycle, protection from soil erosion, etc. All such aspects have to be valued in an externality analysis.

Commercial markets exist for a limited number of goods (for example, crops, timber and buildings), and consequently valuation data are easy to obtain. However, conventional markets do not exist for assessing damage from other impacts, such as human health, ecological systems, and non-timber benefits of forests. Alternative techniques have been developed for the valuation of such goods, predominantly hedonic pricing, travel cost methods, and contingent valuation.[1]

The temporal valuation of the cost of emissions also raises the issue of the appropriate rate for discounting over future generations.[2]

4. Assessing the Externalities of Power Generation

For simplicity, externalities of power generation (whether based upon fossil fuel combustion or renewable technologies) can be divided into two broad categories:

- costs of the damage caused to health and the environment by emissions other than those associated with climate change; and
- the net costs of climate change attributable to greenhouse gas (and particularly CO_2) emissions.

4.1 Pollution Damage from Emissions other than CO_2

This category refers to costs due to emissions that cause damage to the local (as opposed to global) environment.[3] These include a wide variety of effects, including damage from acid rain and health damage from oxides of sulphur and nitrogen from coal-fired power stations. Other costs in this category include such factors as power industry accidents (whether they occur in coal mines, on offshore oil or gas rigs,

Table 1 Damages of Air Pollutants

(per tonne of pollutant emitted)

EU country[a]	*SO_2 (ECU)*	*NO_X (ECU)*	*Particulates (ECU)*
Austria	9000	9000–16800	16800
Belgium	11388–12141	11536–12296	24536–24537
Denmark	2990–4216	3280–4728	3390–6666
Finland	1027–1486	852–1388	1340–2611
France	7500–15300	10800–18000	6100–57000
Germany	1800–13688	10945–15100	19500–23415
Greece	1978–7832	1240–7798	2014–8278
Ireland	2800–5300	2750–3000	2800–5415
Italy	5700–12000	4600–13567	5700–20700
The Netherlands	6025–7581	5480–6085	15006–16830
Portugal	4960–5424	5975–6562	5565–6955
Spain	4219–9583	4651–12056	4418–20250
Sweden	2357–2810	1957–2340	2732–3840
United Kingdom	6027–10025	5736–9612	8000–22917

US State[a]	*SO_2 (US$)*	*NO_X (US$)*	*Particulates (US$)*
California	4558	9266	4682
Massachusetts	1727	7316	4471
Minnesota	152	864	1294
Nevada	1744	7600	4672
New York	1460	1927	338
Oregon	0	3556	3048

Note: (a) EU data relate to 1995 and may be converted from ECU to US$ using the exchange rate applicable on 30 June 1995 (ECU 1.33 = US$1.00). US data relate to 1992 (and have been converted from tons to tonnes). No attempt has been made to devise an inflationary factor to update these estimates. In this context, therefore, these estimates could be viewed as ‘conservative’ for later years.

Sources: European Commission (1998) and Energy Information Administration (1995).

in nuclear plant, on wind farms or at hydro plants), visual pollution and noise.

Among the major external impacts attributed to electricity generation are those caused by atmospheric emissions of pollutants, such as particulates, sulphur dioxide (SO_2) and nitrogen oxide (NO_x), and their impacts on public health, materials and crops. The impact of these atmospheric pollutants on forests, fisheries and unmanaged ecosystems are also important but have not yet been quantified. Emissions of SO_2 and NO_x have long-range transboundary effects, which makes calculation of damages an imprecise exercise. Such calculations require measurement to be based upon the unique link between fuel composition, characteristics of the power unit, and features of the receptor areas. Thus, estimated damage costs vary widely across countries (see Table 1). For example, for member countries of the European Union (EU), damage costs arising from power plant emissions of SO_2 range from ECU[4] 1027–1486 per tonne for Finland[5] to ECU 11388–12141 per tonne for Belgium. Comparable US data, where they exist, also exhibit substantial variability across states.

The results are dominated by damages arising from human health effects, which are largely determined by the population affected (and hence the comparatively high damage values quoted in Table 1 for the more densely populated EU nations). Estimation of health impacts is generally based upon exposure-response epidemiological studies and methodologies for placing a valuation on human life remain controversial. Furthermore, countries that are sparsely populated, or populated in largely non-receptor areas, will have relatively low health damage costs.

4.2 The External Damage Costs of Emissions of CO_2

This category refers to external costs due to greenhouse gas emissions from electricity-generating facilities that contribute towards climate change with all its associated effects. This is a very contentious area, and the range of estimates for the possible economic ramifications of global climate change is vast. Costs associated with climate change, flooding, changes in agriculture patterns and other effects all need to be taken into account. However, there is a lot of uncertainty about the magnitude of such costs, since the ultimate physical impact of climate change has yet to be determined with precision. Thus, deriving monetary values on this basis of limited knowledge is, at present, an imprecise exercise.

Table 2 gives life-cycle CO_2 emissions (in tonnes per gigawatt-hour (GWh)) of the major forms of electric power generation. From this table it is evident that CO_2 emissions from coal and oil-based technologies far exceed those of the 'renewables' and are twice those of gas.

Tol (2005) has reviewed 88 estimates, from 22 published studies, of the marginal cost of CO_2 emissions and combined them to form a probability density function. He found that the function is strongly skewed to the right, with a mode of US\$1.40 per tonne of CO_2 (tCO_2), a mean of US\$28.30/tCO_2, and a 95th percentile of US\$121.50/tCO_2.[6] If only peer-reviewed studies were included in the analysis, then corresponding estimates would be US\$1.40, US\$15.50 and US\$83.70 respectively. Thus, not only would the mean estimate be substantially reduced, but so would be the degree of uncertainty. Equity weighting[7] and declining discount rates were also shown to have significant effects on these estimates. Overall, Tol concluded that, for all practical purposes, it is unlikely that the marginal costs of CO_2 emissions would exceed US\$13.60/tCO_2 and are likely to be substantially lower.

Taking this 'maximum' marginal damage figure, and combining it with CO_2 emissions data from Table 2, gives damage for coal- and gas-fired electricity generation technologies of about US¢1.3/kWh and US¢0.65/kWh respectively. Although relatively small when compared with the cost of renewables-based power, nevertheless these damage estimates are very significant when comparing coal and gas costs.

5. The Costs of Electricity-Generating Technologies

Table 3 gives (indicative) levelised electricity costs (in US\$/kWh) for electricity generation

Table 2 CO_2 Emissions from Different Electricity Generation Technologies
(tonnes per GWh)

Technology	*Fuel extraction*	*Construction*	*Operation*	*Total*
Coal-fired (conventional)	1	1	962	964
Atmospheric fluidised bed combustion	1	1	961	963
Integrated gasification combined cycle	1	1	748	751
Oil-fired	–	–	726	726
Gas-fired	–	–	484	484
Ocean thermal energy conversion	na	4	300	304
Geothermal	< 1	1	56	57
Small hydro	na	10	na	10
Nuclear	~ 2	1	5	8
Wind	na	7	na	7
Photovoltaics	na	5	na	5
Large hydro	na	4	na	4
Solar thermal	na	3	na	3
Wood (sustainable harvest)	–1509	3	1346	–160

Note: na denotes not applicable.

Source: International Energy Agency (1989).

Table 3 Cost of Traditional and Renewable Energy Technologies, Current and Expected Trends
(US$, 1998)

Energy source	*Technology*	*Current cost of delivered energy (US$/kWh)*	*Expected cost trend*
Coal	Coal-fired steam with flue gas desulphurisation	0.03–0.05	Stable
Gas	Combined cycle	0.03–0.05	Small decrease
Nuclear		0.03–0.06	Stable
Solar	High temperature solar thermal	0.10–0.25	Decrease 25+ per cent by 2010
Solar	Photovoltaics	0.50–1.50	Decrease 50+ per cent by 2010
Solar	Water heating	0.03–0.20	Decrease 30–50 per cent by 2010
Wind	Land-based wind	0.04–0.10	Decrease 20–35 per cent by 2010
Biomass	Combustion of solid wastes	0.02–0.14	Slight increase
Biomass	Anaerobic digestion of wastes	0.02–0.14	Slight decrease
Biomass	Landfill gas from wastes	0.04–0.06	Slight increase
Biomass	Energy forestry and energy crops	0.05–0.08	Decrease 30–50 per cent by 2010
Biofuels	Ethanol	0.24–0.37 per litre	Decrease 25–50 per cent by 2010
	Biodiesel	0.40–0.52 per litre	Decrease 20–25 per cent by 2010
Hydro	Grid connected	0.02–0.10	Slight increase as most attractive sites are used

Sources: Adapted from International Energy Agency (1997) and Nuclear Energy Agency and International Energy Agency (1998).

by the major renewable and non-renewable technologies. Both coal and gas exhibit an absolute cost advantage over the bulk of renewable technologies, although electricity generated by 'best performance' wind power has recently approached similar cost levels. It should be noted, however, that costs associated with renewables that are, by their nature, intermittent in their production of electricity, do not include essential back-up costs to ensure reliability of supply. Thus on purely financial grounds (inclusive of all forms of subsidy), renewable technologies are, in general, non-competitive.

Over the past two decades, unit generating costs of renewable technologies such as wind, solar photovoltaics and biomass have declined at a significantly faster rate than those of advanced fossil fuel technologies, such as natural gas combined cycle, largely as a result of a learning curve effect as the level of their installed capacity has increased. This may give the impression that their costs could ultimately be lower per kWh. However, without significant policy actions to encourage enhanced levels of investment in research and development of renewable energy technologies, and purchasing incentives designed to deliver economies of scale in production, the cost gap is unlikely to be closed quickly enough to assist governments to meet their Kyoto (or other) commitments on global climate change initiatives in any major way. Perhaps the most important step in this regard is to internalise as many of the environmental externalities of power generation as possible through the market place, and thus allow energy producers and consumers to respond to such price signals in the most efficient and cost-effective manner.

6. Internalising the Externalities of Electricity Production

Once monetary values have been derived to reflect the external costs of differing technologies, the next step is to devise a mechanism for 'internalising' them into market prices. In theory, an energy tax would represent a relatively straightforward solution, although the practicalities of its imposition would be fairly complicated. The tax would be required to be imposed at differential rates, depending upon the total estimated damages resulting from the fuel in question. A simple carbon tax alone, for example, would not impose any cost on the nuclear power industry. The tax would also have to be imposed by all nations, to ensure that the competitiveness of their industries in global markets was not compromised. The resulting tax revenue would also have to be distributed in such a way that implicit energy subsidies were not reintroduced. Finally, the worst of any social impact of energy taxes on poorer sections of society would have to be offset to ensure that the tax burden was not disproportionate in its incidence.

An alternative approach to the problem of reflecting external costs, and one that would possibly cause less economic disturbance, would be to introduce 'environmental credits' for the uptake of renewable energy technologies. Examples are currently commonplace. However, such credits do not 'internalise' the social costs of energy production but rather subsidise renewables. In addition, the taxpayer pays the subsidy and not the electricity consumer, thus rejecting the 'polluter pays principle'.

The leading renewable energy technologies are characterised by relatively high initial capital costs per megawatt of installed capacity, but very low running costs. As we have already seen, this structure can make renewable technologies financially unattractive compared with traditional fossil fuel derived power using traditional project evaluation techniques based upon the anticipated life of the electricity-generating facility (say, 30 years). However, in terms of an economic or environmental evaluation, the relevant time-frame should be set by the date at which all of the consequences attributable to the project had ceased to exist. In the context of CO_2 emissions from fossil fuel power stations this period could exceed 100 years, and in the case of spent-fuel storage for nuclear plants it could exceed many thousands of years. Further, it is likely that the value of emission reduction will continue to rise into the future given projected world population growth, economic growth, and the subsequent difficulties in meeting global climate change agreements. In this context, the rate of discount is crucial in assessing the relative cost and benefit streams of alternative energy technologies in the context of intergenerational equity.

7. Conclusions

This article has considered the economics of renewable energy technologies through the quantification in financial terms of the externalities of electric power generation, according to a range of alternative commercial and almost-commercial technologies.

On the basis of CO_2-imposed externalities alone, it has been shown that estimates of damage costs resulting from combustion of fossil fuels, if internalised into the price of the resulting output of electricity, could make a number of renewable technologies (specifically wind and some applications of biomass) financially competitive with coal-fired generation. However, combined cycle natural gas technology would clearly have a marked financial advantage over both coal and renewables under current technology options and market conditions. The internalisation of other environmental externalities has not been addressed in this article, but it is evident from Table 1 that including costs associated with power station emissions of SO_2 and NO_x would further strengthen the competitive position of renewable technologies. In addition, over the next couple of decades, the cost of renewable technologies (particularly those that are 'directly' solar-based) is likely to decline markedly as technical progress and economies of scale combine to reduce unit generating costs.

The principle of internalising the environmental externalities of CO_2 emissions (and other pollutants) resulting from power generation is of global validation. Whether this is achieved directly through the imposition of a universal carbon tax and emission charges, or indirectly as a result of ensuring compliance with Kyoto targets and other environmental standards, a similar result is likely to be achieved (that is, a rise in the cost of power generation based upon fossil fuel combustion and a relative improvement in the competitive position of an increasing range of renewable energy technologies).[8]

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Endnotes

1. See, for example, Perman et al. (2003) for an introduction to these techniques.

2. Philibert (1999) summarises the options available for discount rate determination in the context of intergenerational environmental damages.

3. Global pollutants refer to emissions of the uniform-mixing so-called greenhouse gases whose damage is independent of the source of the emissions. Local pollutants are those exhaust gases whose damage is dependent upon the geographic location of source and receptor points.

4. The European Currency Unit (ECU) was conceived in 1979 as an artificial 'weighted' European currency. It was replaced by the Euro, the single European currency, on 1 January 1999.

5. The data for Finland reflect the sparsely populated nature of the country, the fact that significant levels of pollutants fall into the sea, and an underestimate of damages due to the lack of data from Eastern European receptor points.

6. Original estimates were quoted in tonnes of carbon. To retain consistency of units in this article, they have been changed to tCO_2. To return to the original values, multiply by 3.67.

7. Equity weighting gives a higher weight to damages that occur in poor countries relative to the same cost of damage in a rich country. It requires the specification of a social welfare function in order to derive the weights.

8. It is important here to distinguish between damage and control costs. This article has focused on damage costs, since these reflect economic efficiency in a cost–benefit analysis context. Control costs are the costs of controlling emissions of pollutants to levels which are socially optimal (that is, where the marginal cost of abatement is equivalent to the marginal damage caused by the pollutant). Environmental policy is generally based upon the latter.

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