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Energy Policy 34 (2006) 2048–2059

ENERGY POLICY

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Counting the cost of water use in hydroelectric generation in Scotland

Michael MacLeod[a,*], Dominic Moran[a], Ian Spencer[b]

[a]*Land Economy Group, Scottish Agricultural College, West Mains Road, Edinburgh EH9 3JG, UK*
[b]*Entec UK Ltd, 17 Angel Gate, City Road, London*

Abstract

Increasing the proportion of renewable capacity in the national energy mix may give rise to a range of economic costs. This paper considers the nature of water use in hydroelectric generation in Scotland. Hydroelectric generation is currently the highest volumetric use of water in Scotland. After calculating this volume, the paper considers the nature of some of the non-priced costs associated with this use.

The paper is set in the context of the transposed EU Water Framework Directive (WFD), which states that users of water should face the full costs. This article of the Directive has yet to be fully implemented, and may have consequences for hydroelectricity that have not yet been fully explored. For example, the low value of water use in hydro schemes compared to competing uses, implies an opportunity cost, which is a signal of potential resource misallocation that the WFD aims to address. In practice however, there are likely to be limited circumstances where economic misallocation can be practically redressed.

Keywords: Hydroelectricity; Water use; Valuation

1. Introduction

The likelihood of fundamental short to medium term changes in Scotland's electricity generation mix raises a number of questions about the economic feasibility of renewable energy supplies. One irony is that in addressing a global external cost, that of global warming, the development of renewables can give rise to other resource costs that are predominantly domestic. Considering the full economic costs, it has also been pointed out that some technologies (e.g. onshore wind power) are less favored since they give rise to visual disamenity that some communities feel disproportionately affected by Simpson (2004). In contrast there is less apparent public concern about the environmental and economic costs of hydropower, perhaps because there has been a relatively small number of new hydro developments in the UK in recent years. Yet the impoundment of large volumes of water for generation purposes is technically a form of water use, and the sheer volume of flows involved can impose environmental costs and (economic) opportunity costs. These resource costs are important as Article 9 of the EU Water Framework Directive (WFD) (Directive 2000/60/EC) states that:

> "Member States shall take account of the principle of recovery of the costs of water services, including environmental and resource costs, having regard to the economic analysis conducted according to Annex III, and in accordance in particular with the polluter pays principle." In order that "water-pricing policies provide adequate incentives for users to use water resources efficiently, and thereby contribute to the environmental objectives of this Directive" (European Parliament, 2000).

Potential inconsistencies exist between the aims of the WFD and the Scottish Executive's energy policy, which aims to increase the amount of electricity coming from renewable sources. Accordingly it is of some interest to

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*Corresponding author. Tel.: +44 131 535 6452; fax: +44 131 667 2601.
E-mail address: michael.macleod@sac.ac.uk (M. MacLeod).

0301-4215/$ - see front matter © 2005 Elsevier Ltd. All rights reserved.
doi:10.1016/j.enpol.2005.02.015

consider how full economic pricing may alter the economics of the energy mix if (or when) users must internalize them.

This paper considers the nature of water use by hydroelectric generators in Scotland. In the context of likely medium-term electricity mix scenarios, water use is quantified and the value of that use relative to competing uses is assessed. The paper is structured as follows. First we provide some background to the energy strategy in Scotland: a country relatively well endowed with hydro capacity and currently undergoing change in its electricity mix. Next, the nature of water use in hydroelectricity is reviewed and we attempt to quantify the volume of use. The nature of the full economic costs of use is then considered and an attempt made to place a monetary value on hydroelectric use. This makes the value of water use in this sector comparable to the returns to alternative uses. The final section offers conclusions on the value of water to hydroelectric generation.

2. The changing patterns of electricity generation in Scotland

The electricity industry in Scotland is set to undergo a period of rapid transformation over the next 10–20 years. This change is being driven by a range of factors, including:

- the decommissioning of major plants (Cockenzie, Longannet, Chapelcross);
- Government policy (UK Energy White Paper; Scottish Executive's renewable energy strategy; Renewables Obligation; the Climate Change Levy; BETTA; introduction of the EU Emissions Trading Scheme in 2005);
- development of the electricity supply infrastructure;
- fuel prices and supply (e.g. the viability of gas as a fuel may be affected by price and supply issues);
- technological development (efficiency increases in existing technologies (e.g. coal and wind), proof of concept of emerging technologies).

One of the likely outcomes of this period of change is a transition towards a mix in which there is little or no coal-fired generation and a significant reduction in nuclear capacity. The shortfall arising from the reduction in nuclear and coal capacity is predicted to be met with combined cycle gas turbines and renewable generation technologies, particularly wind turbines. The Scottish Executive has set two challenging targets for use of renewable power sources. By 2010, 18% of electricity consumed should come from renewable generation, rising to 40% by 2020 (Scottish Executive, 2003). Currently only 10% of the electricity produced in Scotland comes from renewable sources (see Table 1 and Fig. 1). The new commitment entails a range of economic impacts in Scotland.

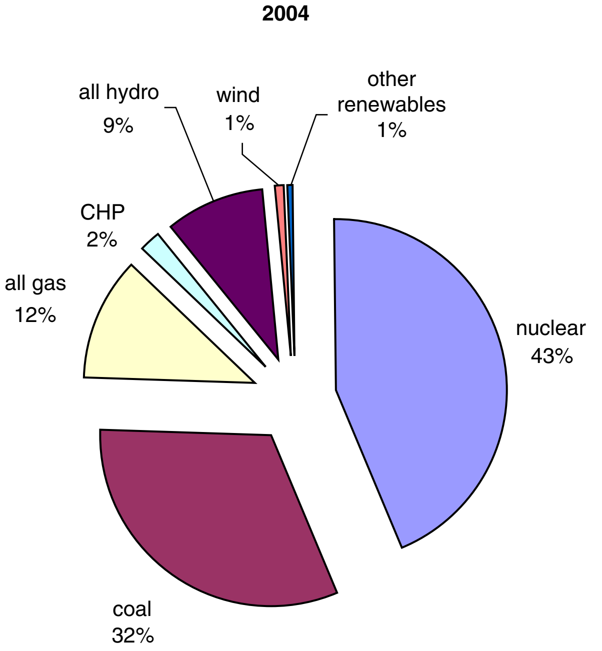

Fig. 1. Proportion of total electricity generated in Scotland in 2004 by source.

The major political and legal reasons for promoting renewable energy are external to Scotland. The United Kingdom has accepted a legally binding target of reducing emissions of a group of greenhouse gases (GHGs) by 12.5% below 1990 emission levels by 2008–2012, as its share of the European Union negotiated target of an 8% reduction in GHGs under the Kyoto Protocol. The UK Energy White Paper "Our energy future—creating a low carbon economy", published in February 2003, sets an even greater ambition by declaring that the nation should pursue a path of reducing CO_2 emissions by some 60% of current levels by 2060.

At present, there is considerable uncertainty regarding the likely electricity mix in the medium term. This is due to the lack of any clear decision as to how to fill the gap created by the decommissioning of the ageing power stations at Cockenzie, Longannet and Chapelcross. In order to derive a likely scenario for 2015, this study reviewed key policies and predictions, including: The Scottish Executive's Renewable Energy Strategy (Scottish Executive, 2003); The UK Energy White Paper (DTI, 2003b); DTI Energy Projections for the UK (DTI, 2000; Watson, 2003). Discussions were held with key energy industry stakeholders (Scottish and Southern Energy; BNFL; The Scottish Renewables Forum) and the patterns of generating plant "in the pipeline" (i.e. consented, or planned and formally notified) were analysed (using the data in the Scottish Executive's

Table 1
Percent of total electricity generated in Scotland

	Category	2004[a]	2015
Non-renewable	Nuclear	43.7	36
	Coal	31.7	0
	Gas (Peterhead)	11.8	11
	Combined Heat and Power (CHP)	2.0	5
	Combined Cycle Gas Turbines (CCGT)	0.0	18
Renewable	Hydro	8.2	10
	Pumped storage	1.2	1
	Wind	1.0	15
	Biofuels and wastes	0.5	4
	Other renewables	0.0	1

[a] *Source:* Scottish Executive (2004).

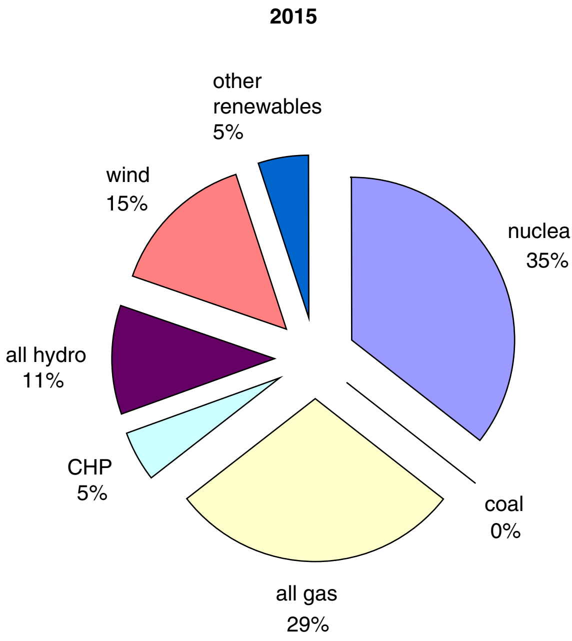

Fig. 2. Forecast proportion of total electricity generated in Scotland in 2015 by source.

Renewable Energy Database (Scottish Executive, 2004). Present day to 2015 was chosen as it covers a period in which there will be considerable change in the electricity mix, and implementation of the WFD. The resulting scenario is outlined in Table 1 and Fig. 2).

The scenario for 2015 is based on the following assumptions:

1. Electricity generated increases by 1% per annum (pa).
2. We are on course to meet our 2020 renewables target of 40%.
3. Hunterston, Torness and Peterhead are still generating.
4. Cockenzie, Longannet and Chapelcross have been decommissioned.
5. At least one new large hydro scheme is generating (Glendoe). None of the present capacity is decommissioned.
6. No new nuclear, coal or oil stations are generating.
7. Combined cycle gas turbines (CCGTs) will be used to make up the balance.
8. Fuel sources for biomass become available.
9. Barriers to the development of CHP are removed.

2.1. *Electricity generation and water use*

In volumetric terms, electricity generation is one of the major water uses in Scotland (Moran et al., 2004), therefore changes in the way in which electricity is generated have significant implications for water use. To identify the implications of these changes for water use, this study employed previously derived water use coefficients outlined in Table 2.

Most of these estimates are based on the water use figures obtained directly from the power stations. The exceptions are Peterhead, Chapelcross and Hunterston, for which a mixture of published rates of water use and estimates were used, and hydroelectricity, where the rates were calculated from first principles. Key assumptions made during the calculation of the volumes and rates of water use are outlined below.

- Water use figures supplied by power stations are valid and reliable;
- The estimates made for Peterhead, Chapelcross and Hunsterston are accurate.
- Water use at Westfield, Fortum, Keadby and Little Barford are typical for power stations of their types.

Table 2
Estimated rates of present water use (m^3/MWh) (Moran et al., 2004)

	Mains	Freshwater	Seawater
Gas (Peterhead)	0.15	0.00	66.14
Coal (Cockenzie)	0.50	0.00	118.39
Coal (Longannet)	0.23	0.00	131.83
Nuclear (Torness)	0.04	0.00	85.78
Nuclear (Chapelcross)	0.04	4.06	0.00
Nuclear (Hunterston)	0.04	0.00	84.38
Hydro	0.00	6,109.69	0.00
Pumped Storage	0.00	1,941.18	0.00
Combined Heat and Power (CHP)	0.00	0.00	0.00
Wind	0.00	0.00	0.00
Wave	0.00	0.00	0.00
Biofuels and wastes	0.08	0.00	0.00
Combined Cycle Gas Turbines (CCGT)		0.94[a]	
	0.03	53.78[b]	0.00

[a] Assuming all CCGTs have recirculating cooling systems.

[b] Assuming 50% of CCGTs have recirculating cooling systems and 50% have once through systems using freshwater.

- The net water use in CHP is effectively zero. For example, Grangemouth CHP uses about 2,365,200 m^3 pa of mains water. However, almost all of this is converted into steam, which is then used for chemical processes. As this water would have been used by Grangemouth anyway, it could be argued that the net water use in electricity generation is effectively zero.
- Biomass plants are small scale and do not abstract water for cooling purposes.
- The water use of wind and wave power is effectively zero.

These rates were then used to examine the changing patterns of water use in electricity generation, which are outlined in Table 3.

It should be noted that the forecasts are based on the assumption that the overall rate of water use, i.e. the average amount of water used per unit of electricity generated per annum, remains constant for each type of generation. Whether or not this is a valid assumption is open to debate. Powergen (2001) have reported that overall, their net water use per MWh supplied decreased by approximately 40% between 1997 and 2001. However, most of this change is likely to be due to switching to types of generation that are more water efficient, rather than efficiency gains within types. However, the possibility of improving the efficiency of water use within a type, or even within an individual plant, should not be dismissed. Given the large volumes of water used in generation, it is possible that water pricing that more closely reflects its true cost, could make investment in water efficient technology and practices financially attractive.

Table 3
Predicted water use in 2015 ($m^3 \times 10^3$ pa) with a 1% annual increase in electricity generated

	Mains	Freshwater	Seawater
Gas (Peterhead)	790	0	353,203
Coal (Longannet)	0	0	0
Coal (Cockenzie)	0	0	0
Nuclear (Torness)	425	0	851,472
Nuclear (Chapelcross)	0	0	0
Nuclear (Hunterston)	365	0	719,021
Hydro	0	30,841,387	0
Pumped storage	0	1,078,951	0
CHP	0	0	0
Wind	0	0	0
Other renewables	0	0	0
Biofuels and wastes	167	0	0
CCGT	218	455,410	0
Total use in 2015 (m^3)	1,959	32,375,749	1,923,696
Change in water use 2003–2015 (m^3)	−3,797 (−66%)	8,615,753 (+36%)	−1,848,407 (−49%)

In the case of hydro generation, rates of water use vary in different ways depending on the rate in question. The rate of water use *per unit of output* for an individual scheme depends on the head of the scheme and the turbine efficiency; it is independent of load factor. The rate of water use *per unit of time* for the same scheme is directly dependent on load factor. The average rate of water use per annum for a group of turbines over the forecasting period will therefore depend on the overall head, turbine efficiency and load factor. It has been assumed that there is unlikely to be significant variation in turbine efficiency or average head during the forecasting period. However, if the average head of new hydro schemes turns out to be higher than the current average figure used in the forecasts, the water use will be lower than forecast. Given that the new Glendoe scheme will have a head of around 600 m, which is significantly higher than average, it may be that new schemes use less water than predicted. However, it has also been suggested by the British Hydropower Association that “most growth (in hydro capacity) will be run of river schemes” (Economic Advisory Stakeholder Group, 2004), implying less impoundment but greater flows of water through turbines than predicted.

While it is recognized that load factors are subject to considerable spatial and temporal variation, it is assumed that the average annual load factor for all hydro from 1996 to 2002 (see DTI 2003a, 5.9) can be used as a reasonable approximation for average annual load factor for all hydro in Scotland over the forecasting period. There are shortcomings of predicting future water use rates from historic data. The average load factors and average head of hydro in Scotland may well change as new schemes become operational. However, there is a great deal of uncertainty regarding what the characteristics of the new hydro capacity will be, which makes estimating the direction and magnitude of changes in load factor and average head in Scotland as a whole difficult. In theory, hydro sites should be selected for development in a way that minimizes generating costs (Bernard, 1989) and should therefore be predictable. In practice, factors such as anticipated public opposition to development influence decision-making and make prediction difficult. Despite these uncertainties, it is argued that these results illustrate the importance of hydroelectric generation in determining the overall volumes of water used in electricity generation. The next section examines water use in hydro schemes in more detail.

3. Water use in hydroelectric generation in Scotland

Hydroelectric power involves the use of significant volumes of freshwater to generate electricity. This process requires the establishment of predictable flow regimes, which entails the alteration of watercourses, the storage of large volumes of water in reservoirs and lochs and the controlled release of water through turbines. It therefore uses water as a means of storing potential energy, which is converted to mechanical energy and then to electrical energy.

At present, the installed capacity of hydroelectricity schemes in Scotland (excluding micro-hydro schemes, those <1 MW) is 1324 MW (Scottish Executive, 2004). In addition, there are 705 MW of pumped storage capacity at Foyers and Cruachan. Assuming load factors of 32% for hydroelectric stations and 9% for pumped storage, these generate 3777 and 556 GWh, respectively. This is approximately 9% of Scotlands electricity.

With the exception of the Galloway Hydro scheme, most of the capacity is located in the Highlands. The development of large-scale hydroelectric schemes has had an extensive impact on the water bodies of the Highlands, as Smout (2000, p. 108) noted:

> "By the time they (the North of Scotland Hydro-Electric Board) had finished, there was scarcely one really large natural water body left in Highland Scotland, apart from Loch Maree, which was untouched by water-impoundment or water extraction schemes, and hardly a Highland river whose flow was not affected."

3.1. Measuring the scale of water use in hydroelectric generation

Water is "used" in the hydroelectric generation in a variety of ways, for example; to fill reservoirs; to store potential energy; to drive turbines; to fill salmon ladders and provide freshets for migrating fish. It is therefore not possible to give a single figure that includes all water usage. In this paper the volume of water flowing through turbines per annum is employed to evaluate the changing patterns of water usage in the hydro industry.

3.1.1. Methodology for calculating the volume of water flowing through turbines per annum

The power output N (watts) of a hydroelectric turbine over a period of time t (seconds) is equal to the rate of loss of gravitational potential energy E_p of the water as it drops from the source through the turbine, multiplied by the overall efficiency of the generating system, K, at converting potential energy into electricity (see, for example, Brown and Wright, 1995):

$$N = E_p K/t. \tag{1}$$

The potential energy of a mass of water m (kg) dropping though a height h (metres) is given by $E_p = mgh$ (where g is the gravitational constant, $9.81\,\mathrm{m\,s^{-1}}$), so

$$N = mghK/t. \tag{2}$$

The mass of a volume of water V (m^3) is given by $m = \rho V$(where ρ is the density of water, $1000\,\mathrm{kg\,m^{-3}}$). Substituting this in (2) gives

$$N = \rho VghK/t. \tag{3}$$

The water flow rate Q ($\mathrm{m^3\,s^{-1}}$) is given by $Q = V/t$. Substituting this in (3) gives

$$N = \rho ghKQ. \tag{4}$$

Therefore the water flow rate is given by

$$Q = N/\rho ghK. \tag{5}$$

A sample calculation is outlined below.

The turbine at Rannoch in the Tummel system has a maximum power output, N, of 42 MW (Scottish Executive, 2004), and a head of 156.1 m (Payne 1988, p. 103). The flow rate, Q, at this output is given by:

$$\begin{aligned} Q &= N/(Kg\rho H) \\ &= 42{,}000{,}000/(0.75 \times 9.81 \times 1000 \times 156.1) \\ &= 36.6\,\mathrm{m^3\,s^{-1}} \text{ at maximum capacity.} \end{aligned}$$

The total volume of water flowing through the turbine in 1 year is obtained by multiplying the flow rate per second at maximum capacity by the average load factor over the year and the number of seconds in a year:

$$\begin{aligned} &= 36.6 \times 0.32 \times 31{,}536{,}000 \\ &= 369{,}350{,}000\,\mathrm{m}^3. \end{aligned}$$

This calculation was repeated for all the turbines for which head figures were available, representing 93% of the total capacity. An average flow per MW capacity was calculated for these turbines and used to estimate the flow in the remaining 7%.

The use of average load factors is a potential source of error in the estimates. Actual load factors vary considerably between turbines, and within individual turbines from year to year. However, the errors introduced should lead to approximately equivalent overestimates and underestimates of flows. In order to validate the methodology, the calculated flows at 3 turbines were compared with the actual flows using figures supplied by Scottish and Southern Energy (Donaldson, 2004), see Table 4. These results suggest that the calculated flows, although slightly higher, provide a reasonable approximation of the actual flows.

Key assumptions made during the calculations of hydro flows:

- Most of the water flowing though hydro-schemes passes through the turbines;
- The average efficiency of hydro schemes in converting the potential energy of reservoir water into electrical energy is 75%;

Table 4
Comparison of calculated and reported hydro flows

Station	A: Calculated annual flow ($m^3 \times 10^3$)	B: Reported annual flow ($m^3 \times 10^3$)	$((A-B)/B) \times 100\%$
Clunie	1,580,948	1,482,242	7%
Kilmerford	24,697	24,185	2%
Rannoch	368,718	351,790	5%

Table 5
Estimated total volumes of water flowing through hydroelectric turbines

Volume of water ($m^3 \times 10^3$) flowing per annum through		
Pumped storage hydro	Hydroelectric turbines (excluding pumped storage)	Total
1,078,950	22,675,744	23,754,695

- The average annual load factors for pumped storage and non-pumped storage hydro are 9% and 32%, respectively (these are the average of the annual load factors from 1996 to 2002 listed in DUKES 2003, see DTI, 2003a, 5.9);
- The water use in micro-hydro is negligible (It is assumed that the total capacity of micro-hydro schemes (those <1 MW capacity) is <50 MW (Leonard, 2004), or <2.5% of the total hydro capacity);
- The annual flows that were calculated using the head figures in Payne (1988) are a reasonable approximation of the actual flows.

The total volume of water flowing through hydroelectric turbines is given in Table 5. It should be noted that many hydro schemes are of a cascade design in which the same volume of water passes through different turbines as it travels down through the scheme. It could therefore be argued that the total annual flow figures, when used as a measure of water use, involve an element of double counting. Nevertheless, this volume of water usage gives rise to the question: what are the environmental and economic externalities of this usage? Gilvear et al. (2002) outline some of the impacts that flow regulation for hydroelectric schemes can have in terms of the hydrological regime, geomorphology, water quality and ecology of rivers in Scotland. Warren (2002, p. 120) summarizes the overall effects of flow regulation for hydroelectricity in Scotland with the comment "Wild rivers have been strait-jacketed". The second part of the question concerns the economic value of water relative to other possible uses. If the value of water use is below competing uses in the economy then low value uses impose a resource or opportunity cost on society in general. Put another way, even though energy generation is vital, there may be a higher value use for some water diverted for generation. Even in a water abundant country this notional cost is relevant. It is also relevant if the water "use" is non-consumptive and the water is eventually returned to the ecosystem—albeit in another location.

In addition to the financial costs of supply, these two extra cost considerations comprise the full economic cost of water use. As the WFD is transposed into national law in Europe there is currently debate about how to interpret the concept of full economic cost and measure these values. For the environmental external costs this debate draws on an existing body of environmental valuation studies that assess the monetary willingness to pay value of impacts. The opportunity cost calculation is more problematic. The strict economic interpretation suggests that water should be allocated to highest value uses. Anything else is inefficient and, by implication, imposes a social cost. But this is difficult to translate into practice, since in addition to environmental valuation, this reallocation probably requires institutional arrangements such that high value uses can buy out those of a lower value. Such arrangements do not currently exist in Scotland. Notwithstanding this, the relative values of water allocated to hydroelectricity relative to other uses in society are of interest, and an attempt to quantify them is made in the next section.

4. The value of water use in hydroelectricity

The physical productivity of water in hydroelectric generation is constant in that every m^3 dropped over a given head can make potentially the same amount of electricity. The average and marginal productivity of water are therefore equal. While the measurement of the physical productivity is straightforward, the same cannot be said for the economic value of water used as an input.

Electricity supply is not perfectly competitive and considerable distortions in pricing exist (thus marginal revenue does not equate to marginal cost). In the UK these distortions also include Government commitments to support renewable energy production through the Renewables Obligation. What this means is that it is not straightforward to value output using market prices. Instead a more general approach must be taken based on the alternative cost of generating power. Previous studies have employed approaches to valuing water based on a comparison of generation costs between hydropower and the cost of the next reasonable alternative generating capacity (Zucker and Jenkins, 1984; Gibbons, 1986). The difference in cost can be considered as a social value of water. But this comparison requires clarification of which hydropower costs we should be comparing and the identification of the costs associated with the most realistic alternative to hydro generation. The comparison can be made on different bases. Different facilities for generating hydroelectricity and conventional electricity can be defined in terms of fixed or variable costs elements. Thus there are different cost definitions (short run marginal, long run replacements capacity value, long run average value) on which to base the water valuation.

Gibbons (1986 op cit.) suggests the comparison could be based on the different scenarios under which a given country might use hydroelectricity production. These are summarized in Table 6. Valuation of use in hydroelectricity requires a comparison of the costs of generating electricity with hydropower and the costs of alternative generation technologies. The relevance of the value per kilowatt hour (kWh) produced using alternative technologies depends on the current situation insofar as it is important to define what the most likely alternative is to satisfy short- and long-term supply.

It has been suggested that where it may be necessary to mitigate impacts from hydroelectricity on water quality status, one potential way in which to achieve this could be through modifying the operation of its users (Scottish Executive, 2001). This implies that the most acceptable method of mitigation for existing facilities would be to alter the rate of flow regulation, perhaps on the basis of seasonal flow rates. Therefore a short run marginal value might most appropriately reflect the Scottish context of hydroelectricity water use under a situation where flow-based limits might be imposed, resulting in temporary restrictions on water impoundment and short-term displacement of generation requirements. It is unlikely that the WFD will lead to permanent closure of hydroelectricity facilities, even where impoundment of water for hydroelectricity generation is currently preventing achievement of WFD requirements.

In situations where new hydroelectricity development is under consideration, a long run average value approach might be employed to give a more realistic value comparison. As there are significant hydroelectric schemes being planned at present, the long run average value was calculated in order to provide the best measure of value.

4.1. Calculating the long run average value of hydro

Electricity generation costs for a range of technologies are generally available. Those calculated in Royal Academy of Engineering (2004) provide estimates for

Table 6
Potential methods for valuing water use for hydroelectricity (adapted from Gibbons, 1986)

Method	Assumptions	Measurement of value	Interpretation for Scottish hydropower
Short run marginal value	All capital investment is fixed, and reduced water availability for hydropower generation displaces generation to an alternative source. Therefore, a temporary increase in alternative generation occurs with no necessary capacity increase.	Alternative source production less hydropower production costs (per kWh), not including capital outlay, depreciation or other longer-run costs.	Suited to measuring value in a context where abstraction for hydropower may be limited based on river flow rates, in order to preserve habitats or ecological health.
Long run replacement capacity value	Water availability restrictions create a need for augmentation of alternative capacity, hence the 'replacement' value.	The cost (per kWh) of new non-hydro capacity, less the foregone hydropower production costs.	Most suited to a situation where overall reductions in hydropower capacity are expected, for environmental or economic reasons, e.g. habitat replenishment, or avoidance of opportunity costs.
Long run average value	This represents the long-run value of water relative to alternative sources. It reflects the efficiency of hydropower generation's dependence on water itself and available feet of head.	Difference between total costs of the non-hydropower generation, less the total costs of hydropower generation.	Relevant to long term consideration of the value of water in hydropower, relative to long term alternatives for power generation. Most relevant to situations where hydropower capacity expansion is environmentally feasible.

electricity "delivered at the boundary of the power station site" (Royal Academy of Engineering, 2004, p. 7). Hydroelectric plants were omitted from this as it was believed that most suitable sites had been exploited and that new schemes would be deemed unacceptable due to their environmental impact (despite the fact that there are 8 schemes totaling 130 MW under consideration in Scotland at present (Scottish Executive, 2004)). To compare hydro with other technologies, the cost of hydro had to be calculated from first principles using the following data taken from IPA/Brodies (2003):

Construction costs:
  Small hydro (3.5 MW) = £1450/kW
  Large hydro (80 MW) = £1063/kW
Annual operating costs = 2.2% of construction costs
Annual non-domestic rates[1] = installed capacity (MW) × 10,000 (£/MW) × 0.478
(Based on a rateable value for hydro of £10,000 per MW and a non-domestic rate of 47.8p in the pound.)

4.2. Method

1. Assuming a linear relationship between the installed capacity, I, of a hydro scheme and its construction costs, C_c, (£/kW), the following expression can be derived from the construction costs given in IPA/Brodies (2003):

   $$C_c = -4.8 \times I + 1447.$$

   This expression was used to calculate the construction costs for a 10 and a 100 MW scheme. The construction costs were then annualized, using a discount rate of 7.5% and assuming an economic life span of 40 years.
2. Annual operation and maintenance costs were assumed to be 2.2% of construction costs (IPA/Brodies 2003, p. A6).
3. Annual Non-Domestic Rates, R, (£) were given by:

   $$R = I \times 10,000 \times 0.478$$

4. The total annual costs (i.e. the annualized construction costs + annual operating costs + annual domestic rates) for a 10 MW and a 100 MW scheme were calculated using the results from 1 to 3. The cost of generating electricity, C_e, (p/kWh) was then calculated by dividing the total annual costs by the amount of electricity generated by each scheme in 1 year at a load factor of 0.32 (see Table 7).
5. Assuming that, for the range of installed capacities in Scotland (2–160 MW), there is a linear relationship between installed capacity, I, and the cost of generating electricity for hydro schemes, C_e, the following expression can be derived from the figures in Table 7:

   $$C_e = -0.00822 \times I + 2.66.$$

Table 7
The estimated cost of generating at a 10 MW and a 100 MW hydro scheme

Installed capacity (MW)	10	100
Cost of electricity (p/kWh)	2.58	1.84

This expression was used to calculate the cost of electricity generated at each hydro power station in Scotland for which head figures were available (representing 93% of the total capacity). This enabled the value of water use at each station to be calculated by comparing the cost (p/kWh) at the hydro station with the costs for other technologies given in Royal Academy of Engineering (2004). This was then converted in p/m^3 and the weighted average value for Scotland calculated (see Table 8 and Fig. 3).

The value of water to hydro varies considerably, depending on which technology it is compared with. When compared to gas or coal with no CO_2 emission charges the value ranges from 0.00 to 0.05 p/m^3. However, once CO_2 charges of £10/tonne are added the value of water increases to 0.07 and 0.18 p/m^3 for gas and coal, respectively. The most likely alternative to a particular hydro scheme will depend on the specific circumstances of the scheme in question. However, the alternative that is generally best suited to performing hydro's role of meeting peak load demands at short notice, is likely to be combined cycle gas turbines. Assuming a level of CO_2 charging set at £10/tonne, this implies a value of water to hydro of 0.07 p/m^3.

The value of water to hydro is significantly higher when compared to wind technologies, due mainly to the greater capital costs involved in constructing wind farms. While these costs are predicted to fall over the next 15–20 years (Royal Academy of Engineering, 2004, p. 44) they are likely to remain high relative to other technologies. Overall, changes in the electricity market, i.e. increasing gas prices, the introduction of CO_2 charges and the increasing use of renewable technologies imply that the value of water to hydroelectricity is likely to increase. It should be noted that one of the major limitations of this analysis is the lack of data on the actual capital and operating costs of new large hydro schemes as none have been constructed in Scotland in recent years. While the figures in IPA/Brodies (2003) are the best data currently available, it is possible that these may be significant underestimates of the actual costs. The construction of new hydro capacity in the near

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[1] A local tax (also known as "business rates") paid by all businesses and non-domestic properties.

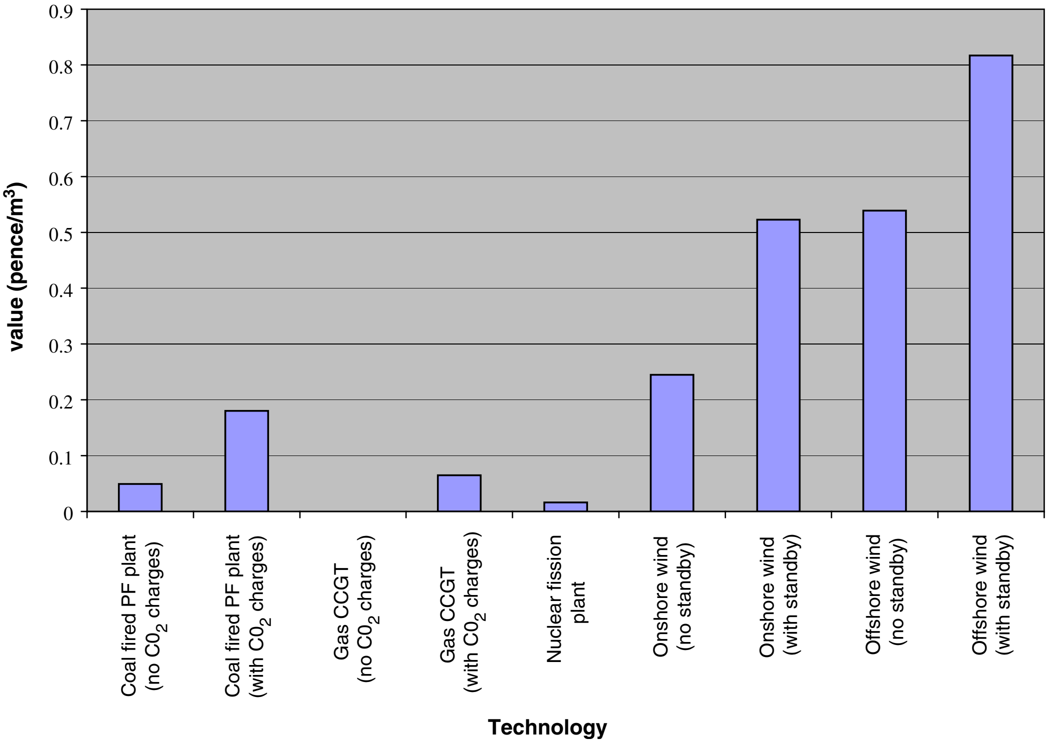

Fig. 3. The values of water to hydroelectric generation across Scotland.

Table 8
The values of water to hydroelectric generation across Scotland

Technology	Cost of electricity (p/kWh)[a]	Total value of water to hydro across Scotland (£)	Weighted average value of water to hydro across Scotland (p/m^3)
Coal fired PF plant (no CO_2 charges)	2.5	9,908,000	0.05
Coal fired PF plant (CO_2 charges of £10/tonne)	3.3	36,403,000	0.18
Gas CCGT (no CO_2 charges)	2.2	−28,000	0.00
Gas CCGT (CO_2 charges of £10/tonne)	2.6	13,220,000	0.07
Nuclear fission plant	2.3	3,284,000	0.02
Onshore wind (no standby)	3.7	49,650,000	0.25
Onshore wind (with standby)	5.4	105,951,00	0.52
Offshore wind (no standby)	5.5	109,263,000	0.54
Offshore wind (with standby)	7.2	165,564,000	0.82

[a] Royal Academy of Engineering (2004).

future will provide a means of testing the validity of these figures.

4.3. Effects of the WFD on the cost of hydroelectricity

The WFD requires that, with certain exceptions, water bodies meet "good ecological status" (GES). Achieving this status will, in many instances, involve work to mitigate the impacts of water use, which may have significant financial costs. While most of the water uses associated with hydroelectric generation are derogated, there are still likely to be costs associated with mitigation. Black et al. (2002) have calculated the costs of a range of options for restoring good ecological status to the Garry/Errochty system. In order to evaluate the scale of these mitigation costs, the total annual costs for the Garry/Errochty system were calculated and are outlined in Table 9.

4.4. Description of the mitigation options (see Black et al. (2002) for details)

Option 1

- Restoring means of fish passage at Struan Weir;
- Restoring means of fish passage at Garry Intake;

- Restoring means of fish passage at Loch Garry Weir;
- Providing a more natural flow regime, particularly during low flow periods;
- Channel bed restoration downstream of Garry Intake.

Option 2 is a subset of *Option* 1, looking at the section between Garry Intake and Struan Weir. *Option* 3 looks at additional measures to make more likely the restoration of good ecological status between Garry Intake and Struan Weir. *Option* 4 consists of measures to restore GES to the Errochty system and involves revised compensation flows and water level restrictions.

These results show that mitigation could lead to significant increases in the cost of hydroelectricity with a consequent decrease in the value of water. With the exception of option 1, most of the mitigation costs arise from lost water, which suggests that the costs of mitigation are likely to be long term.

5. Comparing the value of water to hydroelectric generation with other uses

In order to put the values outlined in Table 8 in context, it is necessary to compare them with other water uses. Two other large volume uses, which, like hydroelectricity, have a particular importance for rural Scotland, are crop irrigation and aquaculture. While not immediately implicated as competing uses, values from these sectors can be used for the purpose of an illustrative comparison. Clarke et al. (2004) estimated the value of water to aquaculture and potato irrigation, and these are compared with the value to hydroelectricity in Table 10.

The low value of water to hydroelectricity compared to aquaculture and irrigation suggests that there is a significant opportunity cost associated with the use of water to generate hydroelectricity. This differential underlines our point about an implicit resource cost in current water use patterns. However, this conclusion has limited applicability and the following points need to be taken into account when assessing the value of water.

First, one needs to ask how valid it is to assign an opportunity cost based on a comparison between hydroelectric generation and aquaculture or irrigation. To do so implies that they are always genuinely competing uses, an assumption that is open to question. In reality only a small proportion of the water presently used in hydroelectric schemes could readily used instead to irrigate potatoes or treat waste in aquaculture. Ideally we would like to advance values for uses that compete directly with hydropower, as a basis for an opportunity cost comparison. Anecdotal evidence suggests that direct competition is increasing in terms of displaced recreational uses such as kayaking and recreational angling. However, convincing use values for these activities has yet to be derived on a directly comparable site basis. Transfer of existing values from alternative sites may not be appropriate. While this raises some doubt regarding the usefulness of the

Table 9
The effects of mitigation on the annual costs for the Garry/Errochty scheme

Option	Annual cost (£k), without mitigation	Annual cost of mitigation (£k)[a]			Total annual cost (£k)	% change
		Capital and running costs	Lost water costs	Total		
BAU	7,921	0	0	0	7,921	0
1	7,921	1097	513	1,610	9,531	+20.3
2	7,921	49	329	378	8,299	+4.8
3	7,921	49	342	391	8,312	+4.9
4	7,921	0	2176	2,176	10,097	+27.5

[a] Black et al. (2002, p. 92).

Table 10
Comparison of the value of different uses of water

Water use	Value (p/m^3)	Basis
Waste assimilation in aquaculture	1.86–13.89 0.67	Willingness to pay (avoided costs) Net back analysis
Potato irrigation	23–138 496	Analysis of yield changes in Cambridgeshire potato crops Net back analysis of the West Pfeffer catchment, East Lothian
Hydroelectricity	0.07	Comparison with CCGT, assuming CO_2 charges of £10/tonne (see Table 8)

opportunity cost concept in this context, there are still likely to be specific circumstances and locations where hydroelectric water use does impose significant opportunity costs.

Secondly, the values in Table 10 do not take into account the externalities (positive and negative, socio-economic and environmental) of different water uses. For example, it could be argued that hydroelectricity is of strategic economic importance to Scotland in terms of maintaining security of electricity supply and achieving renewable energy policy objectives. It also has an important role to play in flood control. In order to make a truer comparison of the values of competing water uses, the externalities need to be taken into consideration within a cost-benefit framework.

6. Conclusions

By 2015, the amount of freshwater used per annum in electricity generation is likely to increase by 21–49% driven primarily by the commissioning of a small number of new hydro schemes. Measured by volume, the greatest water usage by far is associated with hydroelectric generation. However, it should be noted that the way in which water is used in hydro schemes is fundamentally different to other forms of generation and, simple comparisons by volume do not provide a meaningful measure of relative usage.

Furthermore, while the volumes of water used in electricity generation are very large, most of the uses are non-consumptive—i.e. water is used to drive turbines in hydroelectric schemes, or passes through cooling circuits in thermal power stations, and is then returned to the water body, largely unchanged. This contrasts with other sectors such as agriculture where more than half the water abstracted for irrigation can be consumed, i.e. it "evaporates, transpires or becomes part of a product or crop" (Mancino and Berger, 2002) and is permanently removed from the water body. However, despite the non-consumptive nature of water use in hydroelectric generation, the scale of water use in this sector demands that any discussion of the full economic cost should take into account the associated external environmental and economic costs.

The general environmental impacts of flow regulation in hydro schemes have been well documented. However, it is difficult to make specific predictions about the environmental impacts that changing levels of water use will have without detailed spatial and temporal information about the changes. This requires, for example, information regarding which water bodies will be affected, their present status, the nature of the flow regulation and its timing. Most of the water use figures in this paper are at a national or regional level and do not, in most cases, allow robust predictions of environmental impacts to be made. Detailed biophysical and economic modelling at the water body or catchment level is required to predict the impacts with certainty. Other work being undertaken at present, such as SEPAs Pressures and Impacts study, should enable predictions to be made with a higher degree of certainty. However, further economic analysis is required to predict the detailed spatial and temporal patterns of changing water usage within the electricity industry.

The comparison of the value of water to hydroelectricity with the returns to other uses suggests that there may be a significant opportunity cost associated with hydroelectric generation. Despite this, it is unlikely that this cost can be systematically addressed due to the scale and location of hydro schemes and the absence of institutional arrangements to move water between low and high value uses. There may still be locations where, due to competition for water, hydroelectricity does impose a significant opportunity cost, however determining this requires detailed local or regional data. Given the predicted increase in water use by electricity generators, identifying areas where generation is likely to impose opportunity costs could be an important step towards achieving the WFD aim of efficient use of water resources through pricing policies.

Acknowledgements

The authors would like to acknowledge the support of the Scottish Environment Protection Agency and the Scottish Executive Environment and Rural Affairs Department who funded the research from which this paper was developed.

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