Leveling the playing field - An economic assessment of electricity generation in Europe

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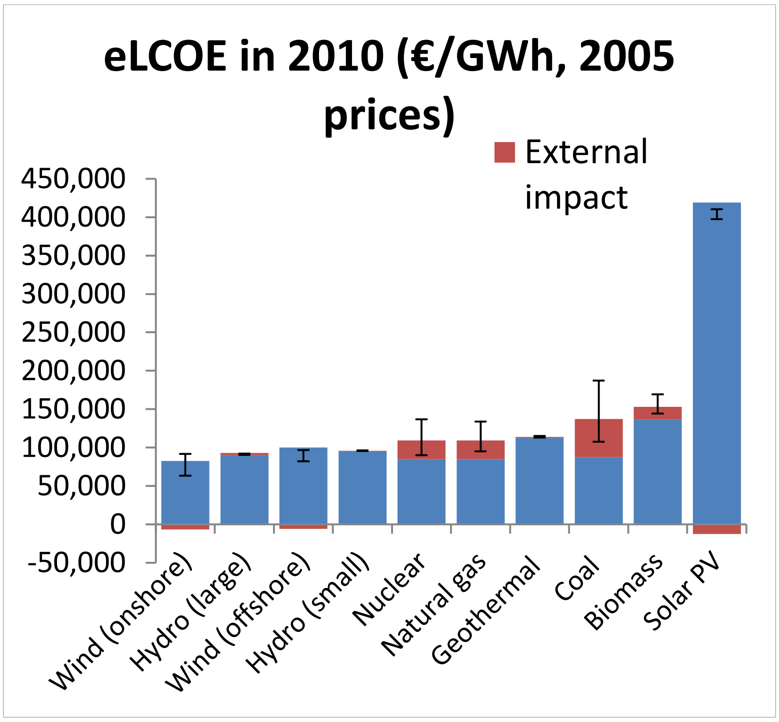
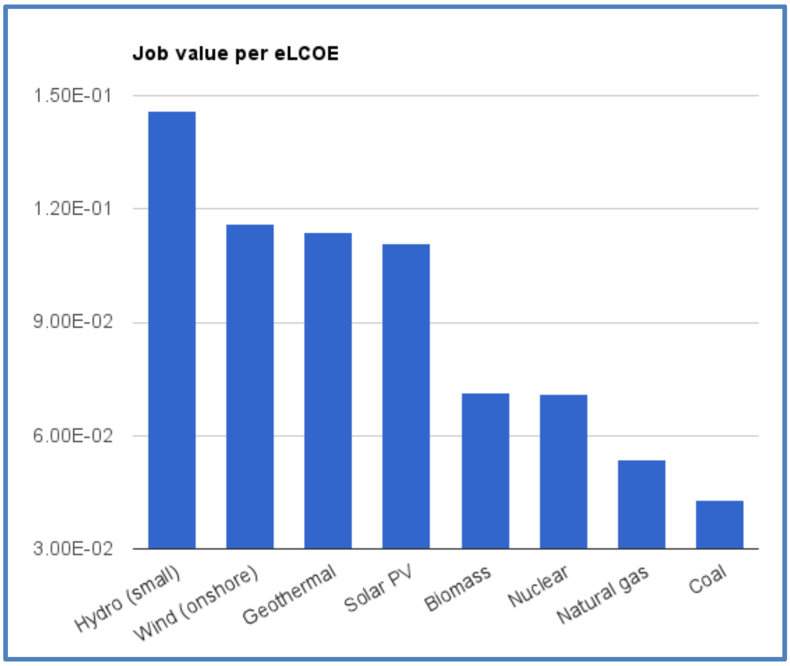
1. Abstract

The calculation of the externalities of electricity production is of great importance in shaping the views of businesses, policy-makers and the public in relation to the value of energy. This paper attempts to draw together a number of existing studies on aspects of electricity generation in the European Union in order to calculate an 'Extended Levelised Cost of Electricity' (eLCOE) which takes account of a wide range of externalities. I use benefit transfer to calculate a European average value for a number of generating technologies, both conventional and renewable. I find that the external costs are a significant component of overall electricity production costs, particularly for conventional generation, but also for biomass. I also estimate the employment value of various electricity generating technologies, and estimate overall costs of electricity in 2020 by technology.

The average European levelised cost of electricity by generating type, including externalities, is shown in the figure below. Onshore wind provides the least-cost electricity generation, and also rates highly in employment per unit electricity generation and cost.



Extended levelised cost of electricity (eLCOE), i.e. the LCOE plus externalities. Negative externalities indicate that there is an economic benefit above and beyond the production of electricity itself. The error bars indicate the range of costs arising from a sensitivity analysis. See full text for details.



Employment per unit electricity generation and cost. See full text for details

2. Introduction

Europe's energy system is entering a transition phase. The established mechanisms of centralised generation, and top-down transmission and distribution will see a shift unprecedented in the recent history of energy use. Distributed and intermittent renewable generation will become increasingly important components of the electricity mix, contributing to energy security and reducing the carbon content of electricity.

However, the field in which renewable energy operates is still not level with respect to its competitors. Conventional electricity generators benefit economically from an externalisation of impacts which are not perceived as direct costs to the generator. When costs are not properly allocated to generators, the economics of the electricity sector are skewed against renewable energy generators, which – by and large – have far lower external costs than traditional electricity generators.

Economic aspects are important, because decisions which are made on the basis of incomplete information can result in perverse outcomes. For example, the fact that environmental impacts are generally not included in the costs of coal extraction and combustion means that coal-fired power stations are more likely to be installed, because the final product – electricity at the point of use – contains an implicit subsidy which is not borne by the user or the generator. If better information is made available, then decisions are also likely to be improved.

This paper aims to help make the move towards more complete information on external costs by summing the outputs of existing studies, or ascribing a value to externalities which are not generally accounted for. It is a highly complex topic, and I am attempting no more than to draw together the most up to date literature in order to help inform current thinking.

3. Methodology

Units

The Levelised Cost of Electricity (LCOE) is the usual way to compare the cost of generating electricity from different sources. It represents the present value of the total cost of building and operating a generating plant over an assumed financial lifecycle, converted to equal annual payments and expressed in terms of Euros at a fixed point in time (herein 2005 unless otherwise stated). I adopt this standard, although I also derive an additional form – the Extended Levelised Cost of Electricity (eLCOE) – in order to compare different technologies. The eLCOE includes many of the calculable externalities which arise from electricity generation. I use GWh as the baseline energy unit, and derive all other outcomes from this. This approach allows maximum utility in extrapolating these figures for use in different Member States or geographical regions.

Geographic boundaries

I take the European Union Member States as the boundary in terms of data on impacts, although where justified I use benefit transfer from other regions such as the USA. The use of average figures for the EU is a necessary over-simplification, even where some impacts, such as employment, load factors of generating capacity, health impacts from air pollution, and water use, are highly location-specific. The methodology represents an approach which could be adopted at a local or regional level in order to derive more appropriate assessments, particularly considering the geographically-linked nature of many energy sources.

External impact and electricity generation types

The external impacts considered in this paper are Balancing Costs, CO$_2$ Cost, Damage to Materials, Fuel Cost Volatility, Merit Order Effect, Morbidity and Mortality, Risk Underwriting Cost, Security of Supply, Virtual Grid, and Water Use Cost.

Balance of Payments and Ecosystem Impacts were also considered. They have not been included, as the economic impact of a negative balance of payments is unclear, and the economic impacts of ecosystem damage from electricity generation is incalculable with present knowledge.

The technologies considered are Biomass, Coal (pulverized coal combustion), Geothermal, Natural Gas (combined cycle), Nuclear, Hydro (small and large), Solar PV and Wind (onshore and offshore). To simplify the operation, I take the 'best practice' within each sector where there are multiple technology types.

I do not consider Concentrating Solar Power, as it is largely predicted to be an 'import' technology (i.e. much of the electricity consumed within Europe will be imported from Turkey or further afield), and deployment will be low by 2020[1].

Cost of electricity

A number of organisations provide figures for the LCOE, both for the existing 'state of the art' and projecting costs to 2020. These costs are summarised in Figure 1 and Figure 2.

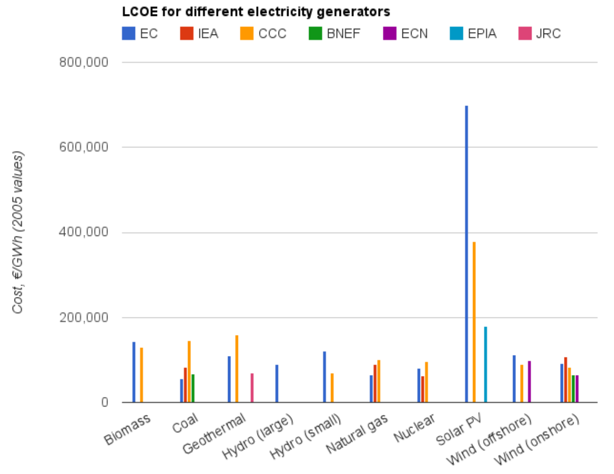


Figure 1: Comparison of LCOE calculated by different studies (EC[2], IEA[3], CCC[4], BNEF[5], ECN[6], EPIA[7], JRC[8])

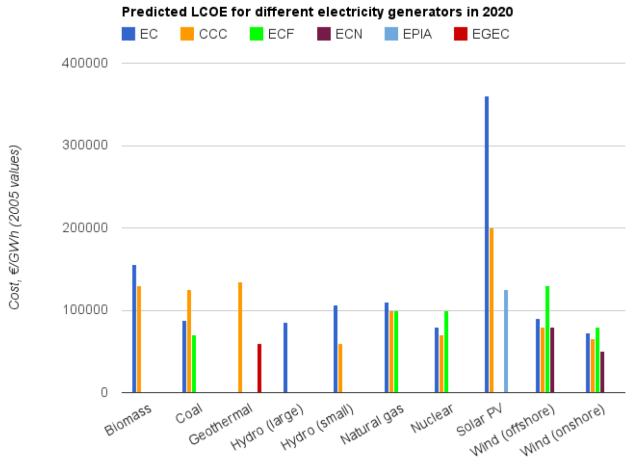


Figure 2: Predicted LCOE in 2020; sources as in Figure 1 except for ECF[9] and EGEC[10]

For the purposes of calculating the overall cost of electricity I take a numerical average for each technology (Table 1).

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[1] International Energy Agency, 'Technology Roadmap - Concentrating Solar Power', 2010.

[2] European Commission, 'Energy Sources, Production Costs and Performance of Technologies for Power Generation, Heating and Transport', 2008.

[3] International Energy Agency, 'Projected Costs of Generating Electricity', 2010.

[4] Committee on Climate Change, 'Costs of Low-carbon Generation Technologies', 2011.

[5] M Liebreich, 'Bloomberg New Energy Finance Summit; Keynote Speech', 2011.

[6] European Climate Foundation, 'A Zero-carbon European Power System in 2050: Proposals for a Policy Package', 2010.

[7] European Photovoltaic Industry Association, 'Solar Photovoltaics; Competing in the Energy Sector', 2011.

[8] R Arantegui, 'Current Costs of the Geothermal Power Technologies' (presented at the Geothermal electricity workshop, Brussels, 2011).

[9] European Climate Foundation, 'A Zero-carbon European Power System in 2050: Proposals for a Policy Package'.

[10] Jean-Philippe Gibaud, 'European Vision for Geothermal Electricity Development' (presented at the Geothermal electricity workshop, Brussels, 2011).

Table 1: LCOE values for different technologies (2005 prices)

Energy technology	LCOE/GWh (2007)	LCOE/GWh (2020)
Biomass	136 500	142 500
Coal	87 500	94 333
Geothermal	112 677	97 500
Hydro (large)	90 000	85 000
Hydro (small)	95 500	83 500
Natural gas	85 000	103 333
Nuclear	79 667	83 333
Solar PV	419 213	218 750
Wind (offshore)	100 000	95 000
Wind (onshore)	82 600	66 750

The fact that renewable technologies see such a high relative drop in their levelised cost by 2020 should not come as a surprise; the learning rates for these technologies are acknowledged to be much higher than their conventional counterparts[11], [12], [13]. The cost of biomass electricity is an exception, and this may reflect its sensitivity to fuel prices.

Sensitivity analysis

Each of the variables within the total cost has an uncertainty associated with it. The total external cost, and therefore eLCOE, has a value which is sensitive to each of the inputs. A sensitivity analysis studies how the variation of each of the variables affects the overall output.

To take an example, the cost of CO_2 has been calculated as anything from €0 to over €1 500 per metric tonne. A sensitivity analysis would recalculate the impacts of electricity generation using various possible values for each parameter, and demonstrate a range of outcomes.

A sensitivity analysis with two scenarios, 'renewable friendly' and 'conventional friendly', has been carried out on the data in this paper. The assumptions are provided in Table 2.

Table 2: Sensitivity analysis assumptions

Variable	Renewable scenario	Conventional scenario	Comment
Balancing costs	Half	Double	Balancing costs are not easily quantified; all generators need to be balanced against each other, including conventional fuels. This simple approach suggests two regimes which represent higher or lower costs than that selected from the literature.
CO_2 impact	€68/ tonne	€12/ tonne	Low value represents current CO_2 market values, which are likely to underestimate the full consequences of CO_2 emission. High value is the Euro equivalent of the value in the Stern Report ($85/ tonne)
Pollution	Double	Half	The renewable scenario assumes that the environmental damage arising from pollution doubles the human health impact; conventional scenario assumes that the health impacts are overstated
Hedging	Double	Half	The renewable scenario takes into account some aspect of the balance of payments impact (i.e. the additional cost of servicing imports); conventional value assumes a scenario of much more stable future fossil fuel prices
Occupational mortality	No change		Marginal impact to overall costs
Materials damage	No change		Marginal impact to overall costs

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[11] H. Winkler, A. Hughes, and M. Haw, 'Technology Learning for Renewable Energy: Implications for South Africa's Long-term Mitigation Scenarios', *Energy Policy*, 37 (2009).

[12] European Photovoltaic Industry Association, 'Solar Photovoltaic Electricity: A Mainstream Power Source in Europe by 2020', 2009.

[13] United Nations Environment Programme, 'Renewable Energy: Investing in Energy and Resource Efficiency', 2011.

Merit order	Double	Half	Renewable scenario takes a less conservative assessment, and broadens the value to all electricity rather than weighted by renewable installation level (see comment on page 9). Conventional scenario assumes that the benefits of the Merit Order effect are exaggerated
Risk underwriting	Double	Half	Renewable scenario assumes a higher level of risk for nuclear electricity than calculated, or could also be considered as a proxy for inclusion of some decommissioning costs. Conventional scenario assumes that risks are overstated
Virtual grid	No change		Marginal impact to overall costs
Water use	€1.2/ m^3	€0.05/ m^3	The renewable scenario uses the Italian 'water stress' scenario[14]; low value uses OECD average

Previous studies

Previous studies have considered electricity production externalities (see Table 3). However, they generally consider the situation in one Member State, or do not consider wider factors such as water use in the course of electricity generation.

Table 3: Summary of existing studies on electricity externalities

Report	Area	Comment
ExternE (2005)[15]	Europe	Calculates externalities for specific impacts (such as air pollution, nuclear accident, noise etc.), but does not provide an overall figure for different technologies
Umweltbundesamt (2007)[16]	Germany	Germany only; includes a summary of six previous externality reports; 3% discount rate (0-20 years), 1.5% discount rate (>20 years), 0% discount rate (inter-generational). Compares fossil fuel and renewable technologies
RECABS[17] (2007)	Europe	Online calculator which can be used to determine externalities according to different variables. Documentation provides reference scenario
National Research Council (2009)[18]	USA	USA-based study which cannot be compared with European figures due to very different environmental and economic factors
Danmarks Miljøundersøgelser (2010)[19]	Denmark	Denmark only; focus on airborne pollutants
Vlaamse Milieumaatschappij (2011)[20]	Flanders	Flanders only

4. Results

a. Balancing costs

A secure and reliable electricity grid requires that demand and supply match on an instantaneous basis. The traditional method of operation was straightforward, in that large generators were able to match the changing load on the network because they had well-defined outputs which could precisely match the predicted demand.

This system is changing as a result of the changing profile of electricity generators. Variable and intermittent generators, particularly wind and solar, are more difficult to fit to the demand because the difference between forecasted generation and actual supply is much more likely to be significant than for traditional generators. This gives rise to an additional need for balancing capacity. However, the potential gap between supply and demand

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[14] E.M. Jenicek et al., 'Army Overseas Water Sustainability Study', *US Army Corps of Engineers* (2011).

[15] ExternE, 'Externalities of Energy', 2005.

[16] Federal Environment Agency, Germany, 'Economic Valuation of Environmental Damage; Methodological Convention for Estimates of Environmental Externalities', 2007.

[17] RECABS, 'Interactive Renewable Energy Calculator - REcalculator - Renewable Energy Cost and Benefit to Society', n.d.

[18] National research council of the National Academies (USA), 'Hidden Costs of Energy: Unpriced Consequences of Energy Production and Use', 2009.

[19] Danish Environment Ministry, 'Environmental costs of emissions', 2010.

[20] Vlaamse Milieumaatschappij, 'Damage costs of current and future electricity production in Flanders', 2011.

is likely to be mitigated by an increasing sophistication in energy use, through consumer awareness coupled with smart metering systems. Improved prediction of output will also mitigate this impact.

The amount of balance capacity increases as the amount of renewable energy generation increases, although the relationship is not strictly linear. A simplified model of Europe with 100% renewable electricity, supplied by wind and solar power, suggests that the storage energy capacity required would be up to 15% of demand[21]. The storage (or balancing power) required depends on the energy mix, because some generation types are complementary, with a decrease in one generator often being compensated for by an increase in another (see *Figure 3*). It is also likely that demand-side management, including measures such as smart metering which allow real-time alteration of electricity use in response to price signals, will improve the ability of the electricity system to adjust to fluctuating input, and hence reduce the requirement to add balancing capacity.

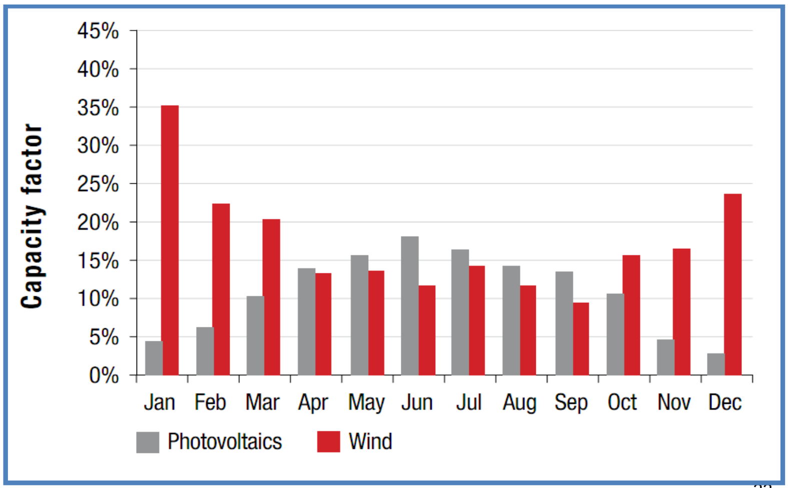

Figure 3: Monthly capacity factor for wind and solar in Germany[22]

The apportioning of fees for balancing capacity varies by Member State. In some countries the fees are passed on to all consumers by the TSO; in this case, there is an implicit subsidy to the generators which require the biggest balancing capacity. The method of apportioning costs varies greatly between Member States[23], which means that providing exact numbers for each technology is not possible.

I apply the cost of €4 000/GWh which is suggested by the upper end of estimates from the European Wind Energy Association (Figure 4), and a more modest value for solar PV estimated as €1 200/GWh[24].

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[21] D. Heide et al., 'Seasonal Optimal Mix of Wind and Solar Power in a Future, Highly Renewable Europe', *Renewable Energy*, 35 (2010).

[22] European Photovoltaic Industry Association, 'Set for 2020'.

[23] ENTSO-E, 'Overview of Transmission Tariffs in Europe: Synthesis 2010', 2010.

[24] Landesbank Baden-Wurttemberg, 'Photovoltaics Sector: Valuing the Invaluable', 2008.

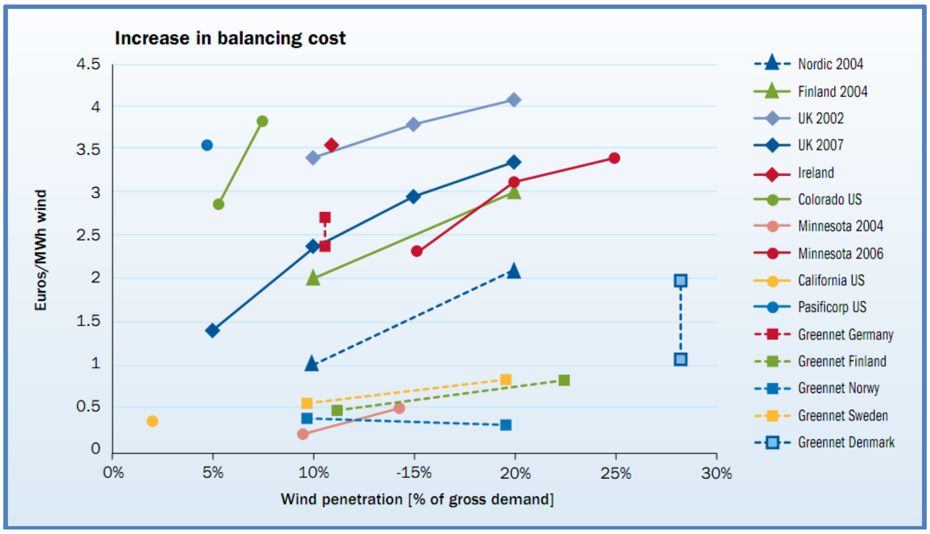

Figure 4: Result of meta-study on balancing costs for a number of wind regimes[25]

b. CO_2

The economic impact of anthropogenic CO_2 emissions has been placed within a wide spectrum, from zero to many hundreds of US dollars per tonne. Discussions surrounding the impact are likewise characterised by wide variety and I do not intend to reproduce them here. I follow the approach adopted in the EEA publication “Costs of Air Pollution from Industrial Facilities in Europe”[26] which uses the short term traded price of carbon in the UK in 2020, set at €33.6/tonne.

The EU Emission Trading Scheme (ETS) is currently operating in its second Trading Period, which runs from 2008 until the end of 2012. The vast majority of permits in this Trading Period were freely allocated to participants in the ETS, so although there is a ‘price’ for carbon, it is not currently borne by the producer, and can be considered as an externality. I therefore make no distinction between the monetised costs of CO_2 produced by ETS participants (generally coal, natural gas and co-fired biomass) and that from lifetime emissions from renewable electricity generators.

Knowing the Life Cycle Emissions (LCE) of different electricity generating technologies, I can calculate the cost of CO_2 emissions for each type of generator (Table 4).

Table 4: LCE of different generating technologies; from average values within Kenny et al[27], except where otherwise stated

Energy technology	Biomass[28]	Coal	Geothermal	Hydro (large)[29]	Hydro (small)	Natural gas	Nuclear	Solar PV[30]	Wind[31] (offshore)	Wind[32] (onshore)
LCE (tCO_2/GWh)	32	925	15	32	11	437	82	40	30	11
CO_2 emission cost (€/GWh)	1 075	31 080	504	1 075	370	14 683	2 755	1 344	1 008	370

c. Damage to materials

In 2008, AEA Technology carried out a modeling exercise to evaluate the impacts of $PM_{2.5}$, SO_2, NO_x, VOC and NH_3 on human health and materials[33]. These are the pollutants covered by the Thematic Strategy on Air

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[25] European Wind Energy Association, ‘Powering Europe: Wind Energy and the Electricity Grid’, 2010.

[26] European Environment Agency, ‘Revealing the Costs of Air Pollution from Industrial Facilities in Europe’, 2011.

[27] R. Kenny, C. Law, and J.M. Pearce, ‘Towards Real Energy Economics: Energy Policy Driven by Life-cycle Carbon Emission’, *Energy Policy*, 38 (2010).

[28] Does not include Indirect Land Use Change emissions

[29] Hanne Lerche Raadal et al., ‘Life Cycle Greenhouse Gas (GHG) Emissions from the Generation of Wind and Hydro Power’, *Renewable and Sustainable Energy Reviews*, 15 (2011).

[30] Compatible with A.F. Sherwani, J.A. Usmani, and Varun, ‘Life Cycle Assessment of Solar PV Based Electricity Generation Systems: A Review’, Renewable and Sustainable Energy Reviews, 14 (2010).

[31] Hermann-Josef Wagner et al., ‘Life Cycle Assessment of the Offshore Wind Farm Alpha Ventus’, *Energy*, 36 (2011).

[32] Raadal et al., ‘Life Cycle Greenhouse Gas (GHG) Emissions from the Generation of Wind and Hydro Power’.

[33] S Pye et al., ‘Analysis of the Costs and Benefits of Proposed Revisions to the National Emission Ceilings Directive. NEC

Pollution[34](TSAP), and the power sector is responsible for a significant proportion of them. Damage to crops is already considered under the CAFE modeling programme, and is therefore included within the 'Morbidity and Mortality' section (Page 9).

The estimated annual damage to materials from SO_2 is €1.1 bn in 2000, and €0.7 bn in 2020[35]. I assume a linear change in the SO_2 emissions giving an annual cost of €0.94 bn for 2008. The sectoral emissions for the same year totalled 3 144 000 tonnes[36], which means that each emitted tonne of SO_2 had an economic cost on materials, due to the secondary impacts of acid damage, of €299.

Biomass, coal and gas-fired electricity account for the electricity sector SO_2 emissions, with emission coefficients of 11, 310 and 0.3g/GJ respectively[37].

The 2009 EU-27 output of heat from combustible fuels was 405 166 GWh, and from electricity was 456 873 GWh. It is not possible to disaggregate the inputs to the heat and electricity sectors, so I make a simple apportion of damage according to the output. I therefore calculate that 53% of the damage from total SO_2 emissions comes from the electricity generation sector, which underestimates its contribution, as efficiency in combustion to generate electricity is generally lower than efficiency of heat production.

This provides the final damage costs of €6/GWh for biomass, and €157/GWh for coal.

d. Fuel cost volatility

A 10% increase in the price of oil is calculated to decrease European GDP by 0.5%[38]; given a number of recent oil price shocks, there are clear economic benefits to be obtained from diversifying from those energy sources which are most heavily dependent on this sector. In the context of this study, the impact acts predominantly on natural gas-fired electricity, the value of which is strongly coupled to the price of oil. To a lesser extent it impacts on the other 'fuel-using' technologies which use significant quantities of petroleum products in the fuel supply chain, namely biomass, coal and nuclear.

The hedging value of renewables is more subtle than just lessening exposure to volatility or high fuel prices. High oil prices are linked with a significant economic impact in most oil-importing countries[39], and the performance of renewable electricity generation can therefore be seen as having a strongly counter-cyclical impact which further augments its benefits. The hedging benefits may have been first described by Lind[40], who described renewable energy investments as a form of 'national insurance'. Wider macro-economic benefits from a diversification from fossil fuel include mitigating inflation and interest rate increases, and reducing shock impacts to stock markets. The economic impact of oil price changes is discussed in detail by Awerbuch and Sauter[41].

The same authors calculate that the offsetting of oil-induced macro-economic losses are worth $250-$450/kWh for renewable electricity, which is subdivided into wind and solar ($200/kWh), and geothermal and biomass ($800/kWh) on the basis of capacity factors (23% and 92% respectively). Nuclear electricity is included within the $800/kWh 'offset' section.

The RECABS assessment[42] converts this 'installed capacity' value to a kWh rate assuming a 5% discount rate and 20 year life-span, and incorporates it as an additional externality to the cost of gas and coal-fired electricity generation, at rates of €7 000/GWh and €2 300/GWh respectively.

e. Merit order effect

Several European studies have concluded that renewable energy installations with no fuel costs, such as wind energy, act to suppress prices for the consumer[43,44]. This is because they are used preferentially to supply

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CBA Report 3' (DG Environment, 2008).

[34] European Commission, 'Thematic Strategy on Air Pollution', 2005.

[35] P. Watkiss, S. Pye, and M. Holland, 'CAFE CBA: Baseline Analysis 2000 to 2020' (CAFE programme, 2005).

[36] European Environment Agency (Copenhagen)., 'Air Pollutant Emissions Data Viewer (NEC Directive)', 2010.

[37] European Environment Agency (Copenhagen)., *Combustion in Energy Transformation Industries; Guidebook*, 2009.

[38] International Energy Agency, 'Analysis of the Impact of High Oil Prices on the Global Economy', 2004.

[39] R. Jiménez-Rodríguez, M. Sánchez, and European Central Bank, *Oil Price Shocks and Real GDP Growth; Empirical Evidence for Some OECD Countries* (European Central Bank, 2004).

[40] R Lind, *Discounting for Time and Risks in Energy Policy* (Washington D.C.: Resources for the future, 1982).

[41] S Awerbuch and R Sauter, *Exploiting the Oil-GDP Effect to Support Renewables Deployment* (University of Sussex, SPRU - Science and Technology Policy Research, 2005).

[42] International Energy Agency, 'Renewable Energy Costs and Benefits for Society - RECABS', 2008.

[43] W. Steggals, R. Gross, and P. Heptonstall, 'Winds of Change: How High Wind Penetrations Will Affect Investment

electricity when they are generating, which tends to reduce the exposure of consumers to the marginal generators, such as open-cycle gas turbines, which are very costly. This effect is known as the 'merit order effect', because it describes the way in which the merit (or cost) of a generator is used to define the stage in the load profile when it should become operational. An example of this is seen in Figure 5. Wind and hydro, which have near-zero marginal costs, come first in the merit order. Nuclear electricity is generally used as baseload, due to its inability to significantly modulate its output (both for economic and practical reasons) and because the fuel cost is a very small proportion of the overall energy price. Thus, nuclear electricity also comes early in the merit order.

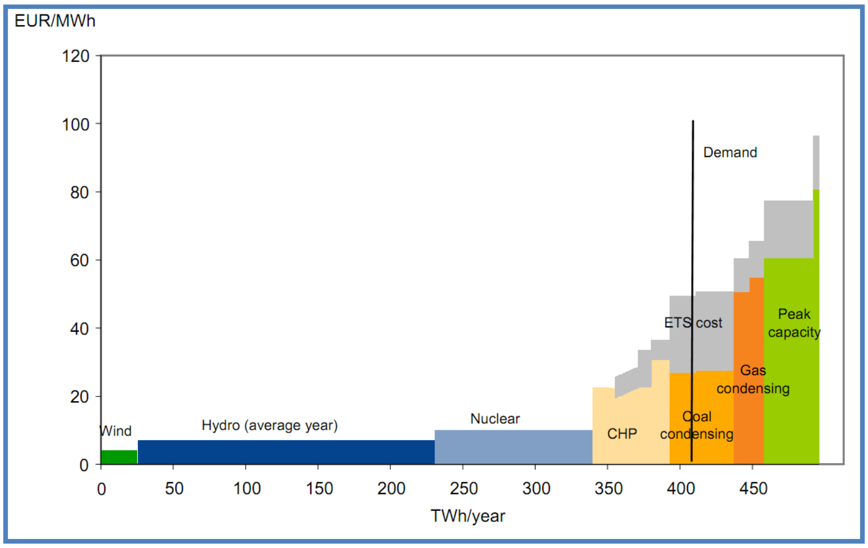

Figure 5: Merit order of marginal production at the Nordic Nord Pool Market[45]

The case of wind energy has been studied far more than any other generator. In this case, the magnitude of the benefit is about 1% of the spot value of electricity for each percentage point of installed wind capacity (wind is generally the subject of these studies as it has significant penetration in several Member States). The example of the effect of wind on electricity prices in West Denmark can be seen in Figure 6. Similar conclusions can be drawn about the case of wind power in Ireland; a 2011 paper[46] shows that the reduction in wholesale market price of electricity produces a benefit to the consumer greater than the balancing costs; in other words, the additional benefits of reduced CO_2 emissions and improved energy security come at no cost[47].

The merit order effect can only provide some net economic benefit in relation to an average annual electricity value. In Figure 5 the average demand is signified by the line at 410TWh/year so anything below that line provides a net benefit. This includes all renewables which operate with near-zero marginal cost, such as solar photovoltaic.

Incentives in the GB Electricity Sector', *Energy Policy* (2010).

[44] European Wind Energy Association, 'Wind Energy and Electricity Prices; Exploring the "Merit Order Effect"', 2010.

[45] H. Lund et al., *Danish Wind Power-Export and Cost* (Institut for samfundsudvikling og planl\aegning, Aalborg Universitet, 2010).

[46] E Clifford and M Clancy, 'Impact of Wind Generation on Wholesale Electricity Costs in 2011' (Sustainable Energy Authority of Ireland, EirGrid, 2011).

[47] International Energy Agency, 'Climate and Electricity Annual', 2011.

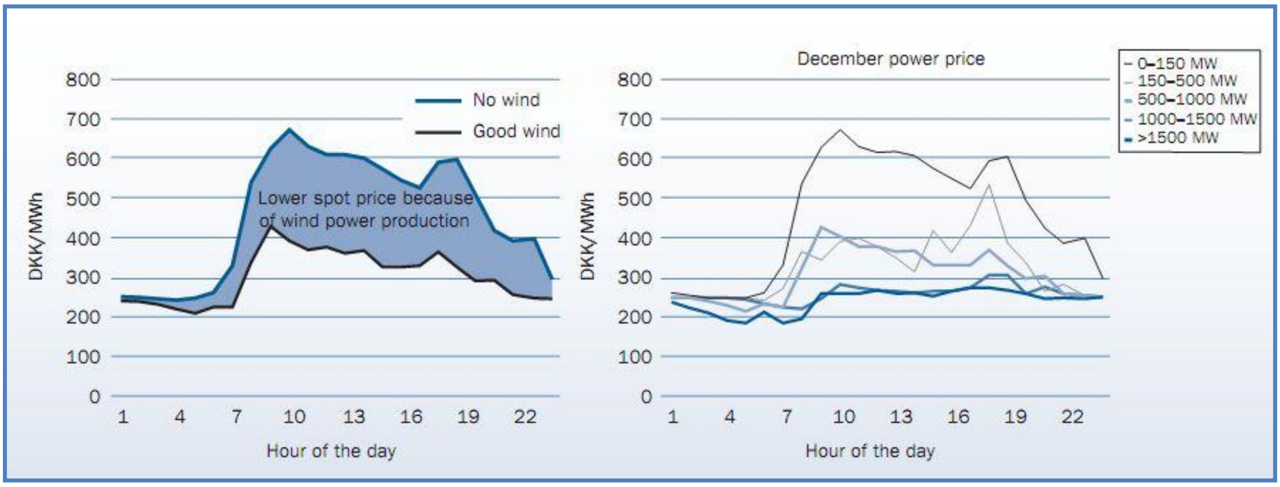

Figure 6: Impact of wind power on spot electricity prices in West Denmark, December 2005[48]

I take this opportunity to clarify that, although the merit order effect applies to all electricity prices, rather than just those associated with each technology, I cannot logically extrapolate this value across the whole of Europe, as the installed capacity of each generator type is different in each Member State. Thus I calculate the benefit for each generator due to its installed capacity (i.e. on a 'per GWh' basis). This has the effect of significantly underestimating the actual benefit.

Table 5: Economic impact of the Merit Order Effect

	Biomass	Coal	Geothermal	Hydro (large)	Hydro (small)	Natural gas	Nuclear	Solar PV[49]	Wind[50]
€/GWh	n/a	n/a	n/a	Unknown	Unknown	n/a	Unknown	10,000	11,000

It seems reasonable to assume that there is also a merit order effect for nuclear and large hydro; however, there is no mention of this in the literature, and they have therefore not been included in the overall total.

Note that as the renewable proportion of Europe's electricity increases, the merit order effect lessens. This is because additional renewable capacity decreases the 'full load hours' (a measure of the annual usage of generators) of the plants towards the right of the merit order (Figure 5) which decreases the incentive to install conventional plant.

As the proportion of low-margin production increases, the electricity price will start to track variable costs less, and fixed costs more. This will be beneficial to consumers as price stability is locked into the system, but the relative advantage of low marginal-cost generators due to the merit order will be lost.

An additional and significant impact of the growing penetration of renewable electricity will be to increase the amortisation risk for fuel-consuming generators which will escalate investment costs for new generating plant.

f. Morbidity and mortality

The choice of the value of a statistical life (VSL) significantly influences the economic impacts of mortality and health-related factors. The most recent OECD meta-study[51] suggested a median value of $2,814,000 (equivalent to €2,181,412[52]). Although different studies demonstrate some variation in the value ascribed to human life, this does not significantly affect the relative order of the electricity generators in the economic impact assessment.

The ExternE project states that pollution deaths need to use the Value of a Life Year (VOLY), because "the loss per air pollution death tends to be small".[53] The value of €40 000 for the EU-25 was obtained in a survey carried out in nine European countries on 'contingent valuation'. This method asks how much people would be willing to

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[48] European Wind Energy Association, 'Wind Energy and Electricity Prices; Exploring the "Merit Order Effect"'.

[49] International Energy Agency, 'Renewable Energy Costs and Benefits for Society - RECABS', p. 40.

[50] European Wind Energy Association, 'Wind Energy and Electricity Prices; Exploring the "Merit Order Effect"'.

[51] H Lindhjem, S Navrud, and Nils Braathen, 'Valuing Lives Saved from Environmental, Transport and Health Policies; a Meta-analysis of Stated Preference Studies', 2010.

[52] Assuming 2% inflation 2010-2011, and an exchange rate of 0.76 in 2010

[53] ExternE, 'Externalities of Energy - Frequently Asked Questions', n.d.

pay to reduce health risks associated with air pollution.

In this study I use VSL where there are immediate economic impacts from lives lost (CO_2, occupational mortality), and VOLY for the economic impacts from pollution which causes long-term reduction in life expectancy.

Occupational hazard

The renewable energy fuel supply chain is short or non-existent compared with fossil fuel and nuclear electricity. The expansion of the renewable energy sector thus has potentially significant occupational health benefits. The obvious exception to this is the biomass sector, which potentially includes the occupations of farming, forestry and combustion. This accounts for its relatively high mortality rate, second only to the coal supply chain.

There are cogent arguments within the literature that there is some degree of internalisation of the economic impact of morbidity in the energy sector, through wage values, education and training. In other words, participants within this sector receive high wages (which are a recognition of the increased risk of their profession), and there is an additional training burden on those businesses to properly prepare their employees for work within a relatively hazardous environment. In line with the literature, I therefore calculate the cost of occupational morbidity as 20% of the VSOL value[54].

Table 6: Economic impact of mortality and morbidity via the fuel supply chain; biomass, coal, natural gas, nuclear figures taken from ExternE[55], and geothermal, large hydro, solar PV and wind figures taken from the SECURE project[56]

	Biomass	Coal	Geothermal	Hydro (large)	Hydro (small)	Natural gas	Nuclear	Solar PV	Wind
Mortality /GWh	1.6×10^{-4}	3.1×10^{-4}	2.0×10^{-7}	9.7×10^{-6}	Unknown	4.6×10^{-5}	1.7×10^{-5}	2.8×10^{-8}	3.4×10^{-7}
Cost €/GWh	74	142	0	4	0	21	8	0	0

Although the occupational benefits are small for some sectors compared with a reduction in by-products associated with combustion, in terms of directly perceived benefits the fuel supply chain is highly important:

> *"Whereas many health benefits associated with a reduction in high carbon dioxide emission energy production may be perceived by some as distant or uncertain, prevention of deaths of energy workers as a result of an improved occupational safety profile of renewable technologies has the potential to be immediate, obvious, and sizable".*[57]

Societal costs

The by-products of electricity production take various forms, but they are generally detrimental to the environment. Therefore, human health is also affected; the pathways by which this occurs are well summarised in [58].

Those pollution impacts which can be quantified are summarised in .

Table 7: Mortality and morbidity levels, and economic impacts, of electricity generation (excluding supply chain). Economic impact taken from [59]

		Economic damage, €/GWh							
Pollutant	Damage cost (€/t)	Biomass	Coal	Geothermal	Hydro (both)	Natural gas	Nuclear	Solar PV	Wind (both)
SO_x	6 381	253	7 121	neg.	neg.	7	neg.	neg.	neg.
NO_x	6 263	4 757	3 382	neg.	neg.	2 007	neg.	neg.	neg.
NMVOC	513	13	1 514	neg.	neg.	3	neg.	neg.	neg.
PM_{10}	13 851	1 895	997	neg.	neg.	45	neg.	neg.	neg.
$PM_{2.5}$	21 331	2 534	691	neg.	neg.	69	neg.	neg.	neg.
Pb	965 000	73	28	neg.	neg.	1	neg.	neg.	neg.

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[54] ExternE, 'Externalities of Energy', p. 210.

[55] ExternE, 'Externalities of Energy'.

[56] P Burgherr, P Eckle, and S Hirschberg, 'Final Report on Severe Accident Risks Including Key Indicators' (Secure project, 2011).

[57] Steven Sumner and Peter Layde, 'Expansion of Renewable Energy Industries and Implications for Occupational Health', *Journal of the American Medical Association*, 302 (2009).

[58] D. Pudjianto et al., 'Costs and Benefits of DG Connections to Grid - Studies on UK and Finnish Systems', 2006.

[59] M Holland, 'Costs of Air Pollution from Industrial Facilities in Europe' (European Environment Agency, 2011).

Cd	29 000	0	0	neg.	neg.	0	neg.	neg.	neg.
Hg	910 000	5	5	1	neg.	0	neg.	neg.	neg.
As	349 000	12	10	neg.	neg.	0	neg.	neg.	neg.
Cr	38 000	1	1	neg.	neg.	0	neg.	neg.	neg.
PCDD/F	27 000 000 000	4 860	972	neg.	neg.	49	neg.	neg.	neg.
Benzo(a)yprene	1 279 000	5	3	neg.	neg.	3	neg.	neg.	neg.
Indenopyrene	1 279 000	2	6	neg.	neg.	4	neg.	neg.	neg.
Radioactive waste cost		0	0	0	0	0	6 000	0	0
Total		**14 411**	**14 731**	**1**	**0**	**2 187**	**6 000**	**0**	**0**

Although combustion technologies are currently responsible for the majority of pollution from electricity generation, the trend for harmful by-products is continuing to decrease[60], and the future economic impact from these sources will follow that trend.

In general, lifetime emissions for renewables except geothermal (secondary emissions) and biomass are negligible. The most significant pollutant during production of geothermal electricity is H_2S, but no value could be found in the literature to calculate its economic impact.

Many additional health effects are outwith the scope of this paper, due to the complexity of the systems. They include:

- Ozone production (local) and depletion (global)
- Secondary effects which may also indirectly affect human health, such as:
    - Climate change-related issues such as temperature change, extreme weather events, sea-level rise
    - Ecological issues, such as deforestation, desertification, biodiversity, disease and changes in agriculture practice

Nuclear pollution

Nuclear plants are a special case in terms of pollution, as the quantity and impact of radioactivity is more difficult to quantify and monetise. There is, however, a significant body of literature which has been produced looking at exactly this issue.

The issue of waste was considered by the CE Delft paper[61], which attempted to create an average value for the implicit subsidy to managing and storing high-level waste. The paper considered the fact that funding of current radioactive waste management is partially or fully accounted for by the operators of nuclear facilities in some countries, whilst final waste management costs are not. It is undeniable that nuclear waste will continue to need handling, storage and management, and the fact that this is not being funded through current electricity generation costs mean that there is an implicit subsidy being levied on future storage costs. This subsidy is calculated as €3 000/GWh.

The subsidy for future waste management is exclusive of the impact of radioactive emissions from the mill tailings, which have a very small impact but last for an extremely long time. These have been calculated at €3 000/GWh[62]. These costs may just be the tip of the iceberg; the Nuclear Energy Agency of the OECD reproduced a table in its 2003 paper on nuclear externalities demonstrating that the tailings account for a very small component of overall radioactive emissions; 97% of which arise from electricity generation and fuel reprocessing[63].

Decommissioning costs, which are partly paid for under an operating tax in some countries, are not quantifiable, but almost certainly represent another subsidy by the State to nuclear power operators. The case of the Department for Energy and Climate Change in the UK is an illustrative one. In 2009/10, it saw 56% of its net operating costs allocated to the Nuclear Decommissioning Authority[64]. In other words, the UK taxpayer is still paying large amounts for the legacy of activities in the civil nuclear sector more than 50 years ago; the total

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[60] European Environment Agency, ‘European Union Emission Inventory Report 1990 — 2008 Under the UNECE Convention on Long-range Transboundary Air Pollution (LRTAP)’, 2010.

[61] B. A. Leurs et al., *Environmentally Harmful Support Measures in EU Members States* (CE, Solutions for environment, economy and technology, 2003), p. 145.

[62] International Energy Agency, ‘Renewable Energy Costs and Benefits for Society - RECABS’, p. 33.

[63] Nuclear Energy Agency, ‘Nuclear Electricity Generation: What Are the External Costs?’, 2003.

[64] Department for Energy and Climate Change, ‘DECC Resource Accounts 2009-2010’ (UK Government, 2010).

liability for UK nuclear sites is estimated as €51bn[65]. This is an example of mortgaging the wealth of future generations against the lower cost of electricity to present consumers.

g. Risk underwriting

The operators of fossil fuel and nuclear plants need to insure against far higher risks than their renewable energy counterparts. Whilst fossil fuel and renewable energy plant operators must accept the full liability, this is not generally the case for nuclear plant operators.

Nuclear operators are bound by national policy, which in turn is generally defined by an international agreement. The international legal framework is a complex patchwork of different conventions, which makes it difficult to understand the liabilities of each party. However, it is clear that the variety of liability between Member States means that the amount of risk underwriting likewise varies by Member State.

This variation in liability has been highlighted as a matter of concern by the European Economic and Social Committee:

> *"A harmonised liability scheme, including a mechanism to ensure the availability of funds in the event of damage caused by a nuclear accident without calling on public funds, is in the view of the EESC also essential for greater acceptability of nuclear power. The current system (liability insurance of $700 million) is inadequate for this purpose"*[66]

A study carried out for the European Commission in 2003[67] reported a premium of €190/GWh to cover the limited national and international liabilities of €1 500m[68] for France. This is equivalent to €197/GWh in 2005 values. Assuming a 'liability gap' for France of €1 409m I calculate that a premium of €0.14/GWh is required per €m of liability gap.

However, this liability level – €1.5bn – is not grounded on realistic evaluations of the impact of a severe nuclear accident, as has been amply demonstrated by the events following the Fukushima disaster in March 2011. A more relevant calculation assumes levels of financial cover such as have been reserved by TEPCO for compensation related to the Japanese nuclear incident at Fukushima. The total issued in special bonds to cover the liability could reach €83bn[69] (2005 value). These figures are supported by more recent figures from the Japan Centre for Economic Research, which posit a value within the range €48-168bn[70] (2005 value).

I calculate the publicly subsidised risk as the liability difference between the existing levels of private coverage, and the damage caused by the nuclear disaster at Fukushima. The steps in the calculation are:

- Establish the gap between a realistic economic impact of major nuclear incident and the average insured amount for EU nuclear electricity producers
- Calculate the insurance premium which would be required to cover this gap (€0.154/GWh per €m of liability gap, 2010 values)

Table 8: Nuclear liability, liability gap compared with €1,500m, and generation capacity per Member State

Member state	Covered liability (€m)[71,72]	Liability gap (€m)[73]	Liability premium (€m/GWh)
Belgium	550	86 450	13 313
Czech Republic	296	86 704	13 352

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[65] Nuclear Decommissioning Authority, 'NDA Annual Report and Accounts, 2009/10', 2010, p. 21.

[66] Official Journal of the European Union, 'Opinion of the EESC on the Nuclear Illustrative Programme', 2007.

[67] Leurs et al., *Environmentally Harmful Support Measures in EU Members States*, p. 137; Scenario 'A' selected for comparison.

[68] Total compensation available under Brussels Convention (2004)

[69] The Guardian, 'Japan Cabinet Approves Fukushima Nuclear Compensation', 2011.

[70] http://www.jcer.or.jp/eng/research/policy.html

[71] S Carroll and A Froggatt, 'Nuclear Third Party Insurance - the "Silent" Subsidy. State of Play and Opportunities in Europe', 2007, p. 36.

[72] World Nuclear Association, 'Civil Liability for Nuclear Damage', n.d.

[73] Defined as the gap between current liability levels, and the reported economic liabilities of the Fukushima disaster of €83bn

Finland	300	86 700	13 352
France	91	86 909	13 384
Germany	2 500	84 500	13 013
Hungary	183	86 817	13 370
Lithuania	50	86 950	13 390
Netherlands	522	86 478	13 318
Romania	550	86 450	13 313
Slovakia	75	86 925	13 386
Slovenia	275	86 725	13 356
Spain	275	86 725	13 356
Sweden	345	86 655	13 345
UK	275	86 725	13 356
Average	449	86 450	13 313

The figures are summarised in Table 8. They demonstrate the average public subsidy value for nuclear electricity liability in Europe is €13 329/GWh (€11 796/GWh in 2005 values).

This compares rather conservatively with other studies. The Germany Renewable Energy Foundation has calculated the cost of insuring against real liability for nuclear power in Germany as between €14 000/GWh and €230 000/GWh[74]. The ‘Scenario B’ (upper estimate of damages) insurance cost estimated by Leurs and Wit[75] was €50 000/GWh.

h. Security of supply

Security of supply encompasses a range of aspects, some of which (e.g. hedging, balance of payments) have already been considered. Here I focus on the aspect of systematic risk related to the mix of electricity generators.

There are clear benefits to the stability of an electricity system if it distributes energy from a number of different sources. This reduces the likelihood of systematic collapse, because outages from a particular sector have proportionally smaller impact as the number of generating sources increases. The increasing resilience of the system is well-described by Mean-Variance Portfolio (MVP), which is a tool widely used in financial services to manage risk within a complex and unpredictable economic landscape. Transferring the concept to the power sector, MVP states that considering generating assets in combination rather than individually lowers the overall risk. Efficient generating portfolios therefore maximise the expected return on investment for a given risk; or conversely, they minimise risk for a given return[76]. This concept is outlined in Figure 7.

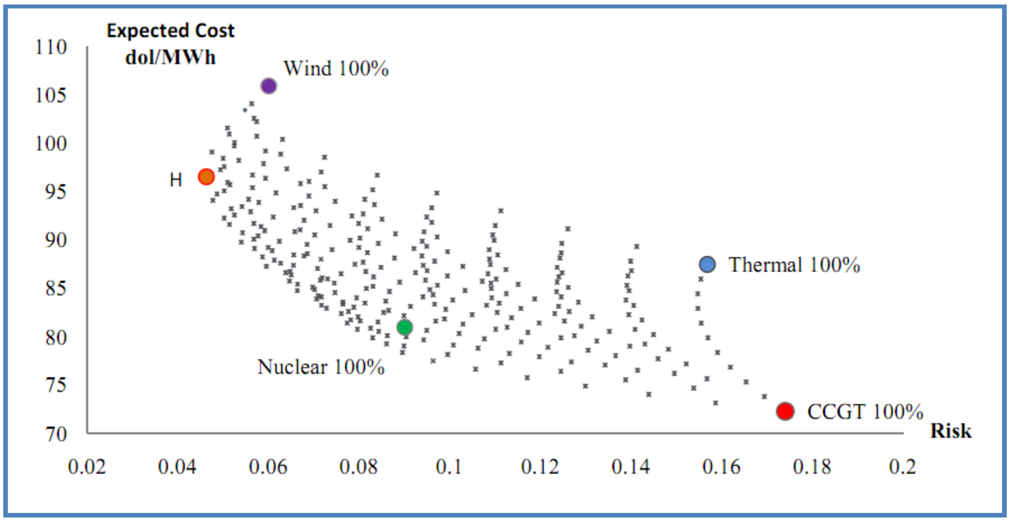

Figure 7: Risk-cost combinations for a modelled electricity supply[77]*. The most efficient balance of cost/risk is described by the frontier of the points; in this case the point ‘H’ represents the minimum risk portfolio between the choices of four assets; wind, nuclear, CCGT and oil combustion.*

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[74] B Gunther et al., ‘Nuclear power plant liability in Germany’ (Bundesverband Erneuerbare Energie, 2011).

[75] Leurs et al., *Environmentally Harmful Support Measures in EU Members States*, p. 137.

[76] H. A Beltran, ‘Modern Portfolio Theory Applied to Electricity Resource Planning; MSc Thesis’ (University of Illinois, 2009).

[77] Beltran, ‘Modern Portfolio Theory Applied to Electricity Resource Planning; MSc Thesis’.

A more complete calculation was carried out in 2003 on the existing electricity generating stock in Europe (Figure 8). This indicates that system security (measured through risk) can be correlated to both cost and generating mix. Although there is no quantifiable output which can be derived from the literature to ascribe a cost to 'generic' security of supply issues, this approach may suggest an avenue of further research in order to assist policy-makers with making such an informed decision. For example, I could calculate the difference between the current energy mix, and a set of possible European scenarios to determine the marginal impact of a change in each electricity generating type on the portfolio return.

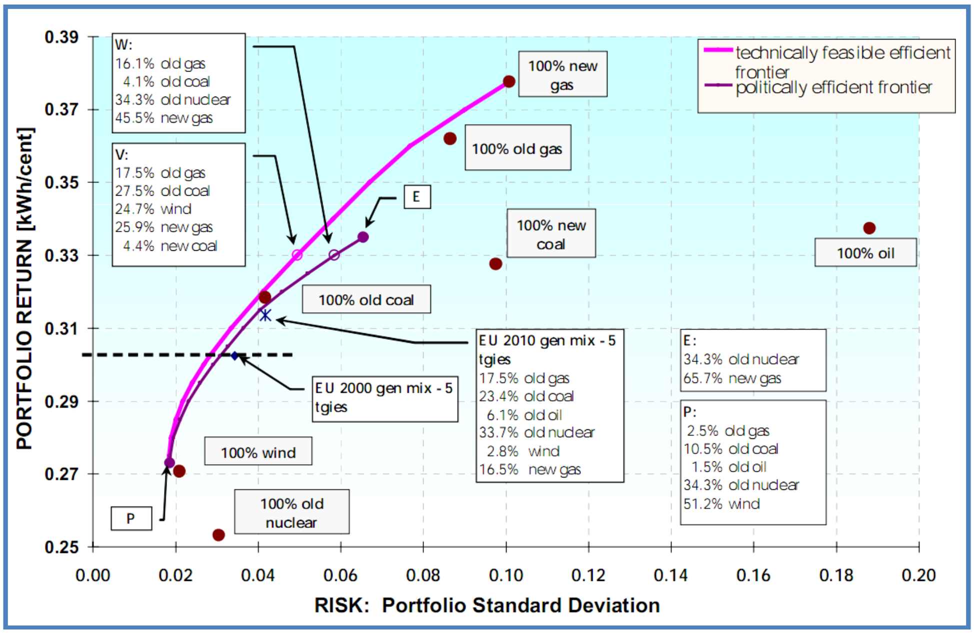

Figure 8: EU energy portfolio, including fuel, O&M and construction period risk for new and existing capacity. Note that a less risky portfolio can be obtained for the same return by moving horizontally leftwards from the point of existing electricity generating infrastructure, indicated by the 'EU 2000 gen mix' box[78]

Note that merely having a diversified energy mix does not of itself reduce overall risk unless price, technology and correlation are properly considered; in this regard academic studies demonstrate what is suggested by common sense[79] and are an extremely useful tool in analysing the system make-up.

It is interesting to consider what impact the outputs of this paper, particularly the eLCOE, would have upon the MVP approach for electricity generation. The cost of each generating technology in the eLCOE is different to its LCOE. This would presumably lead to a greater proportion of renewable energy along the minimum cost frontier, and support the argument for a greater spread of technology types (i.e. greater proportion of renewable energy) within the energy mix.

i. Virtual grid

Theory suggests that the installation of decentralised generators, such as renewable energy generators will influence the costs to the Distribution Network Operator (DNO) in a number of ways. A full description of these impacts is available in the literature[80]; a brief summary of the main points follows.

Network reinforcement, which is unnecessary at low levels of distributed generation (DG) penetration, increases progressively with the amount and density of DG. In rural areas this takes the place of upgraded circuits and substations to cope with voltage rise; urban areas require an upgrade of switchboards to provide additional protection.

Energy losses will initially decrease as DG is introduced to the network, due to reduced power flows across it. Losses will also tend to be reduced through the use of any decentralized generator which is embedded near the end user, as losses in transmission are avoided. Solar PV is the principal contributor to this virtual grid benefit

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[78] S Awerbuch and M Berger, 'Applying Portfolio Theory to EU Electricity Planning and Policy-making' (International Energy Agency, 2003).

[79] M. Sunderkötter and C. Weber, 'Valuing Fuel Diversification in Optimal Investment Policies for Electricity Generation Portfolios' (2009).

[80] Pudjianto et al., 'Costs and Benefits of DG Connections to Grid - Studies on UK and Finnish Systems'.

because the energy is largely used onsite or close to the generator. I use European Photovoltaic Industry Association (EPIA) figures showing a net economic benefit of €5 000/GWh[81], noting that this is substantially lower than the suggested average benefit of €14 000/GWh[82] made by RECABS.

The increased electricity input from DG can be handled either actively or passively by a DNO. Active management requires lesser capital cost but increases the system losses, as components are used to their maximum potential. Passive management relies on upgrading infrastructure to cope with ‘worst-case scenarios’ from the point of view of large loads being produced by the DG.

There is an additional economic benefit from the ‘capacity replacement value’ which mitigates the requirement to reinforce the system due to load growth, which arises from the reduced power flows across the network. The general view of the literature is that distributed generation at a small-scale (which generally refers to solar photovoltaic, but could also apply to small-scale wind or CHP systems) has a positive economic impact; a quantitative assessment for all technologies is not possible at this stage.

It is likely that electricity storage will start to play a more significant role in grid operation in the future, and will help define the content and concept of ‘virtual grids’. Recent work suggests that storage can obviate the need for regulating combustion technology, at a rate of at least 2:1[83].

j. Water use

Providing clean drinking water requires energy, and water is needed for most energy generation types. This energy-water relationship is sometimes referred to as the water-energy ‘nexus’.

Water is a crucial component in Europe’s ecosystems and society. It is also a stressed resource, which is likely to come under further strain as climate change alters the flow patterns in the future (see Figure 9).

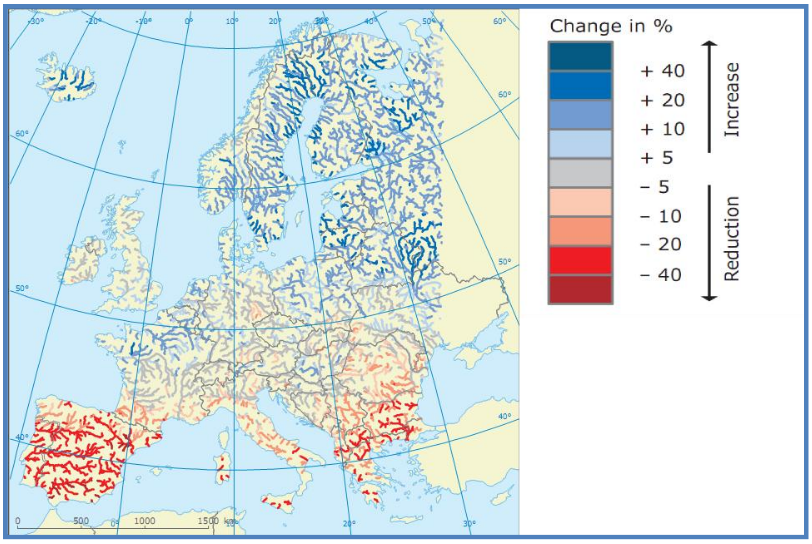

Figure 9: Relative change in annual river flow between reference (1961-1990) and scenario (2071-2100)[84]

In order to fully understand the interplay between water and electricity generation, I must delineate two concepts which are used to describe water use by the sector, namely water withdrawal and water consumption. I define water withdrawal as the amount which is removed from a water body, regardless of whether it is returned to the water body or totally consumed. Water consumption is defined as the net loss to the water body as a result of electricity generating chains; this can happen due to physical loss (such as through evaporation, inclusion in crops) or because it has become unsuitable for return due to contamination or pollution. I use the figures for consumption by the electricity generators to calculate economic impact.

Water is used in different ways by the energy sector. Thermal plants (such as biomass, coal, natural gas and

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[81] European Photovoltaic Industry Association, Greenpeace, ‘Solar Photovoltaic Electricity Empowering the World’, 2011.

[82] International Energy Agency, ‘Renewable Energy Costs and Benefits for Society - RECABS’, p. 37.

[83] Inc Kema, ‘Research Evaluation of Wind and Solar Generation, and Storage on the California Grid’ (California Energy Commission, 2010).

[84] European Environment Agency, ‘Water Resources: Quantity and Flows — SOER 2010 Thematic Assessment - Thematic Assessments — EEA’, 2010.

nuclear) require large amounts of cooling water to cool and condense the steam which drives the turbines. The amount of water required depends on the overall plant thermal efficiency, fuel type, power plant technology and the type of cooling. Hydropower operators use water as the ‘fuel input’ to turn the turbines. All generators use water in their fabrication.

In this study, the thermal efficiency and power plant technology is averaged amongst OECD or European plant. Regarding the type of cooling, there are two main ways for thermal plant to use cooling water; ‘once-through’ and ‘recirculating’.

As the name suggests, once-through systems extract water, typically from a river or the sea, and then discharge it (with its thermal energy greatly increased) back to the water body. Leaving aside the ecological effects of this thermal shock, there are practical implications to the electricity generation system which result from this mechanism. Any significant impediment to the water intake can cause disruption to the activity of the thermal plant. This has been amply demonstrated on a number of occasions, most recently in Germany in 2010 when the Unterweser nuclear power plant had to reduce its output by 60% due to high temperatures of the cooling water[85]. Recirculating or closed-loop cooling systems reuse the cooling water. These technologies withdraw less water than once-through systems but evaporative water consumption is about 80% higher.

The principal consumption of water in hydropower occurs in evaporative losses from reservoirs. This is clearly a geographically-sensitive variable, which underlines the need for the information herein to be interpreted with caution.

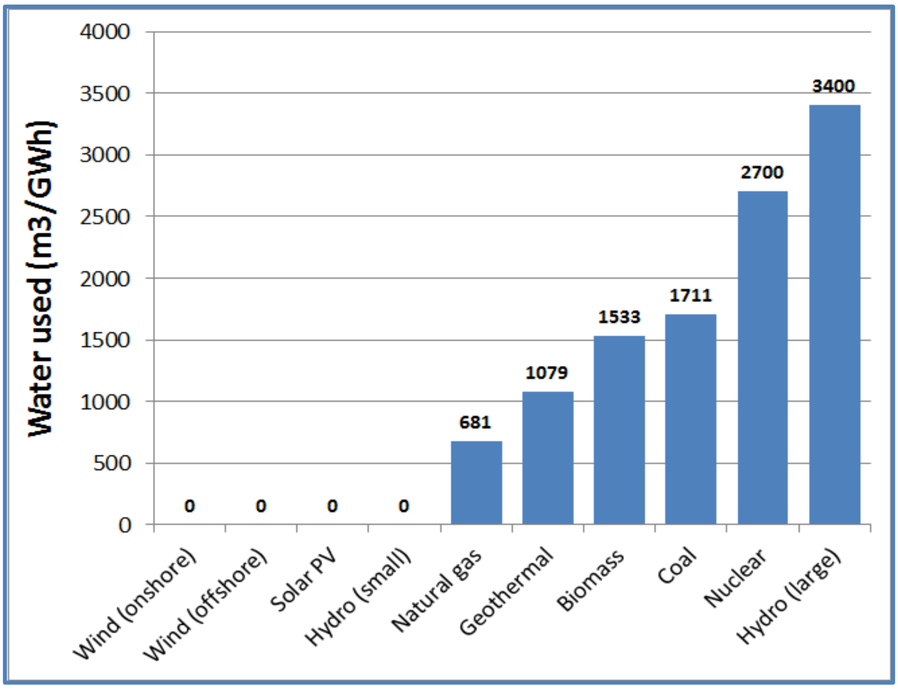

Figure 10: Water use of different electricity generators. Water use for the growth of biomass feedstock is excluded, as is the water temporarily extracted from the flow of the main water body from small hydro (Sources: [86,87,88,89,90,91,92])

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[85] www.tagesspiegel.de/politik/auch-atomkraftwerke-machen-bei-hitze-schlapp/1886228.html

[86] Kenneth Mulder, Nathan Hagens, and Brendan Fisher, ‘Burning Water: A Comparative Analysis of the Energy Return on Water Invested’, *AMBIO*, 39 (2010).

[87] B Sovacool, ‘Critically Weighing the Costs and Benefits of a Nuclear Renaissance’, *Journal of Integrative Environmental Sciences*, 7 (2010).

[88] Annette Evans, Vladimir Strezov, and Tim J. Evans, ‘Assessment of Sustainability Indicators for Renewable Energy Technologies’, *Renewable and Sustainable Energy Reviews*, 13 (2009).

[89] K Gerdes and C Nichols, ‘Water Requirements for Existing and Emerging Thermoelectric Plant Technologies’ (National Energy Technology Laboratory, 2009).

[90] C Clark et al., ‘Water Use in the Development and Operation of Geothermal Power Plants’ (US Department of Energy, 2010).

[91] Alexandre Stamford da Silva and Fernando Menezes Campello de Souza, ‘The Economics of Water Resources for the Generation of Electricity and Other Uses’, *Annals of Operations Research*, 164 (2008).

[92] Vasilis Fthenakis and Hyung Chul Kim, ‘Life-cycle Uses of Water in U.S. Electricity Generation’, *Renewable and*

There are many studies on the water use of electricity generating plant. I analysed the outputs of seven different studies or meta-studies. There is some variation in values, which is frequently a result of methodological choices or technology types; however, most studies produce values which are roughly aligned, and I take an average of these and discard the outliers. The results of this analysis are shown in Figure 10. Note that I do not include in the biomass figures the water used to grow the feedstock

In order to determine the economic impact for each generator type due to water usage, I need to establish the value of water. Methodologies for this calculation exist (e.g.[93]), but are generally complex and site-specific. I need to take a broader approach which uses an acceptable average for Europe as a whole.

According to the OECD[94], the cost to the household user in Europe is approximately \$1.75/m^3. The cost to industry of abstracting groundwater or surfacewater is lower, and ranges from zero to something approaching Full Cost Recovery (FCR), such as the Netherlands (€1/m^3) and Denmark (€0.55/m^3)[95]. Countries where the charge is low generally do not include FCR which is the guiding principle behind water pricing according to the Water Framework Directive. Recent research has suggested a price increase of between 20% and 400% on current charges to reach FCR. In order for FCR to be met in Cyprus[96] in 2010, predicted irrigation charges will need to be raised from €0.17/m^3 to €0.53/m^3.

With a wide spread of values for water, I select something of an average value of €0.5/m^3 . The influence this has on the cost of electricity is further explored in the sensitivity analysis; Table 9 summarises the costs of water use for each technology. Most of Europe will experience increasing water scarcity in the coming decades[97], so it is almost certain that the societal costs of water consumption due to electricity generation will also rise.

Table 9: Cost of water consumption by electricity generation technology (2005 values)

	Biomass	Coal	Geothermal	Hydro (small)	Hydro (large)	Natural gas	Nuclear	Solar PV	Wind
Water use (m^3/GWh)	1 533	1 711	1 079	0	3 400	681	2 700	0	0
Cost (€/GWh)	678	757	477	1,504	0	301	1,195	0	0

5. Discussion

a. Cost of electricity

My findings are clear. The economic impacts of electricity generation, above and beyond the market cost, are positive for wind and solar PV, and negative for the other generators considered in this paper. Coal-fired electricity emerges as the technology with the largest negative external impact (Figure 11).

Sustainable Energy Reviews, 14 (2010).

[93] Stamford da Silva and Campello de Souza, ‘The Economics of Water Resources for the Generation of Electricity and Other Uses’.

[94] Organisation for Economic Cooperation and Development, ‘Pricing Water Resources and Water and Sanitation Services’, 2010.

[95] J. Berbel, J. Calatrava, and A. Garrido, ‘Water Pricing and Irrigation: a Review of the European Experience’, *Irrigation Water Pricing Policy: The Gap Between Theory and Practice. CABI, IWMI* (2007).

[96] C. Zoumides and T. Zachariadis, ‘Irrigation Water Pricing in Southern Europe and Cyprus: The Effects of the EU Common Agricultural Policy and the Water Framework Directive’, *Cyprus Economic Policy Review*, 3 (2009).

[97] European Environment Agency, ‘Adapting to Climate Change - SOER Thematic Assessment’, 2010, p. 15.

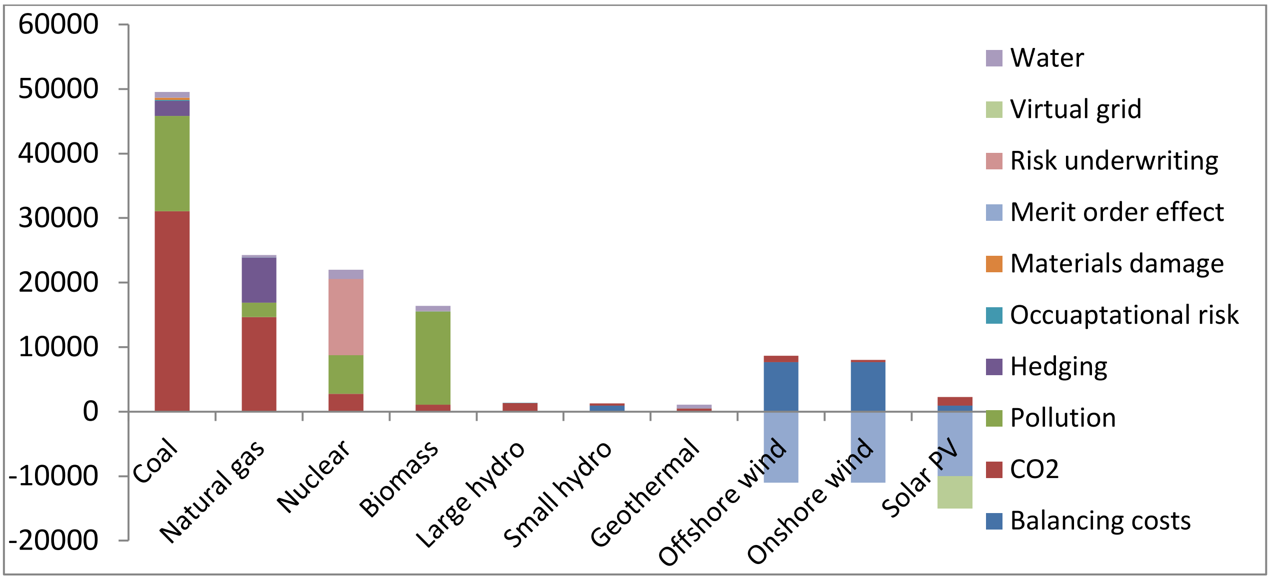

Figure 11: External costs of electricity generation, € /GWh

However, the externalities alone do not provide the most appropriate way to consider the cost of electricity. In order to gain a true understanding of the picture, I need to add the externalities to the LCOE. In doing so I obtain a new 'Extended' Levelised Cost of Electricity (eLCOE) which is presented in Figure 12.

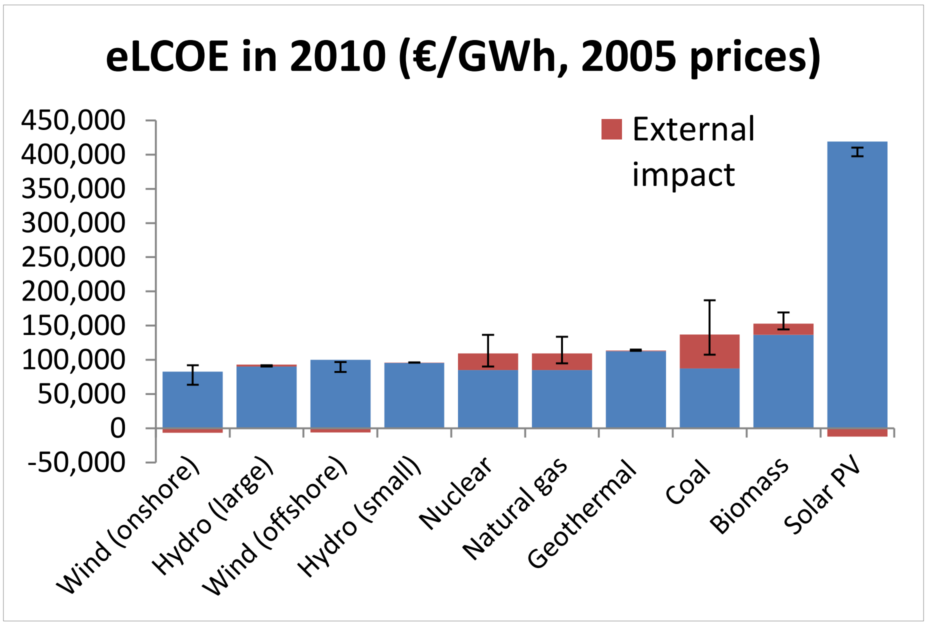

Figure 12: Extended levelised cost of electricity (eLCOE), i.e. the LCOE plus externalities. Negative externalities indicate that there is an economic benefit above and beyond the production of electricity itself. The error bars indicate the range of costs arising from a sensitivity analysis.

The result of including a wide range of externalities into the costs of electricity production demonstrate that 'business as usual' burdens human health and the environment with large costs, and that a transition to a low-carbon energy system will have multiple benefits beyond simple CO_2 reduction.

I exclude from this analysis those factors which are already incorporated into pricing mechanisms, such as costs for forecast error in variable generators. In other words, I assume that these are already incorporated into the LCOE. I am also unable to calculate the impact for a number of external factors, including ecosystem impacts, second-order climate change impacts of combustion such as increased sanitation and parasite-related health problems, desertification, deforestation etc; and the health impacts from a number of combustion by-products such as PCBs, Cu, Se and Zn.

Using existing references to provide an average value for LCOE in 2020, I can also generate an eLCOE for 2020 (. I assume that external impacts remain the same with the exception of pollution costs, which are reduced by 50% due to improved technology and efficiency. The significant change is the overall cost of solar PV, and the improved position of geothermal with respect to conventional generation.

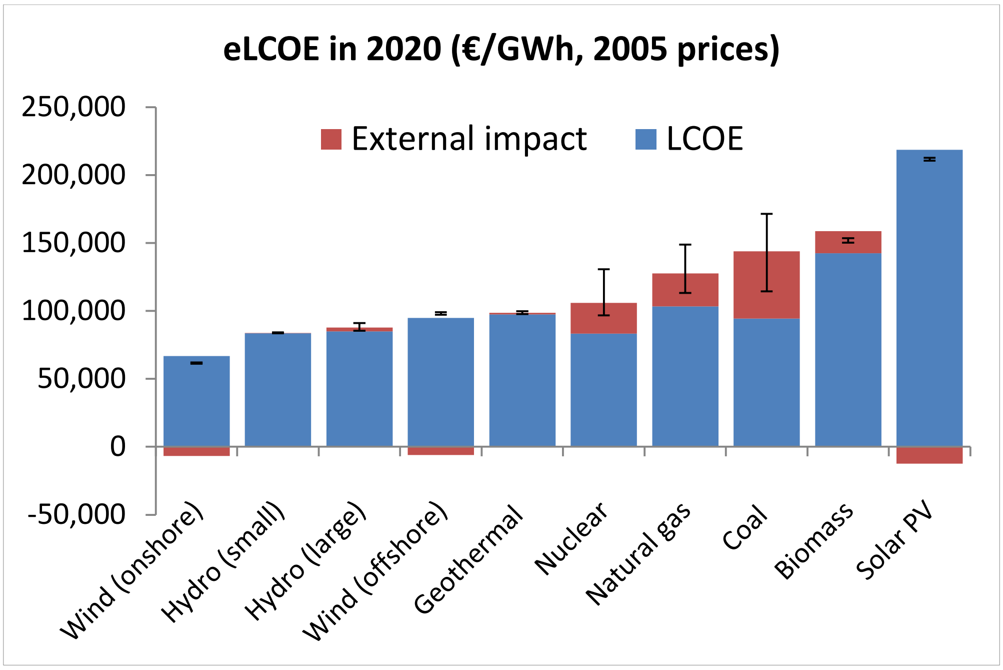

Figure 13: Extended levelised cost of electricity (eLCOE), i.e. the LCOE plus externalities. Negative externalities indicate that there is an economic benefit above and beyond the production of electricity itself. The error bars indicate the range of costs arising from a sensitivity analysis.

b. Employment

The creation of new jobs is increasingly being seen as a positive 'externality' of activity in different sectors[98], and there is considerable enthusiasm in the renewable energy sector for being able to demonstrate a high employment factor for the sector.

The value of employment to an economy is defined through the internationally agreed System of National Accounts[99]. Within this framework, individuals supply labour that generates 'compensation'. This compensation is a monetary unit which is the component of the 'generation of income' account directly attributable to employment. Simply put, the income derived from a paid activity can be considered a direct economic benefit equivalent to the value of the income. However, there is sufficient uncertainty in the accuracy of the estimates of job creation to lead me to exclude this component from the overall value, and instead to use it as an external indicator of additional value.

To determine this value, I need to calculate the number of jobs created through the construction and operation of electricity generating plant (levelised over its lifetime), and the value of the employment to the individual.

I use the outputs of a meta-study aggregating many different individual assessments on employment per GWh[100] over the lifetime of the generating technology. This paper calculates direct and indirect jobs only; induced employment (which is that created by economic activity carried out by direct and indirect employment) is not included. Jobs within the offshore wind and large hydro sectors are also not provided.

I assume a sector average salary for renewable energy employees of €58 601[101]. Although the salary for the renewable energy sector is US-based (rather than European), it represents a relatively up-to-date figure, and is probably broadly representative of the European figures. I also assume that this salary is representative of wages in the 'conventional' energy sector.

I multiply the average job-years/GWh by the average energy sector salary to obtain an employment value for

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[98] C. Tourkolias and S. Mirasgedis, 'Quantification and Monetization of Employment Benefits Associated with Renewable Energy Technologies in Greece', *Renewable and Sustainable Energy Reviews*, 15 (2011).
[99] EC, IMF, OECD, UN, WB, 'System of National Accounts 2008' (EC, IMF, OECD, UN, WB, 2009), p. 22,33.
[100] Adapted from Max Wei, Shana Patadia, and Daniel M. Kammen, 'Putting Renewables and Energy Efficiency to Work: How Many Jobs Can the Clean Energy Industry Generate in the US?', *Energy Policy*, 38 (2010).
[101] Simply Hired, 'Renewable Energy Salaries', 2011.

each electricity generating technology, which is then levelised by the electricity output (Table 10).

Table 10: Employment value/GWh of different electricity generators		
Energy technology	Average job years/ GWh	Annual value (€)
Biomass	0.21	12 306
Coal	0.11	6 446
Geothermal	0.25	14 650
Natural gas	0.11	6 446
Nuclear	0.14	8 204
Small hydro	0.27	15 822
Solar PV	0.87	50 982
Wind	0.17	9 962

This demonstrates that labour-intensive operations (particular solar PV) generate significant employment benefits. However, this is a rather simplistic way of considering the issue. More relevant to most policymakers will be the economic benefit from employment, levelised by both the electricity output and the cost of that electricity.

This additional step is calculated by dividing the economic benefit for each technology by the LCOE. This provides me with an 'Electricity Employment Factor' (EEF) presented in Figure 14. This factor is dimensionless, as I am dividing a value of employment in €/GWh by the LCOE, which has the same units.

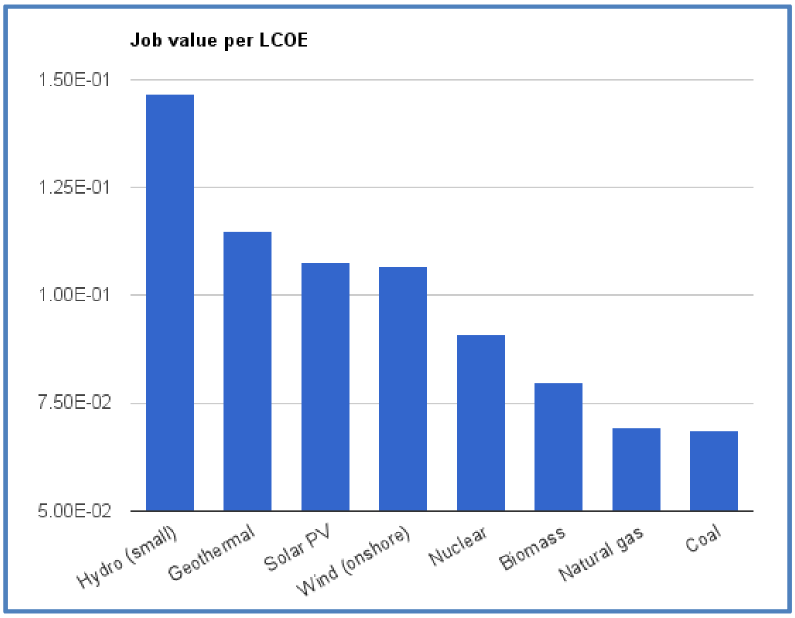

Figure 14: EEF (levelised by electricity generation and LCOE)

However, this picture is, once again, too simplistic, because the use of LCOE does not include the externalities which accrue from using each electricity generating technology. The most relevant metric is therefore the employment value, divided by eLCOE (*Figure 15*). The main difference between the LCOE and eLCOE figures for employment is the improved position of biomass compared with nuclear.

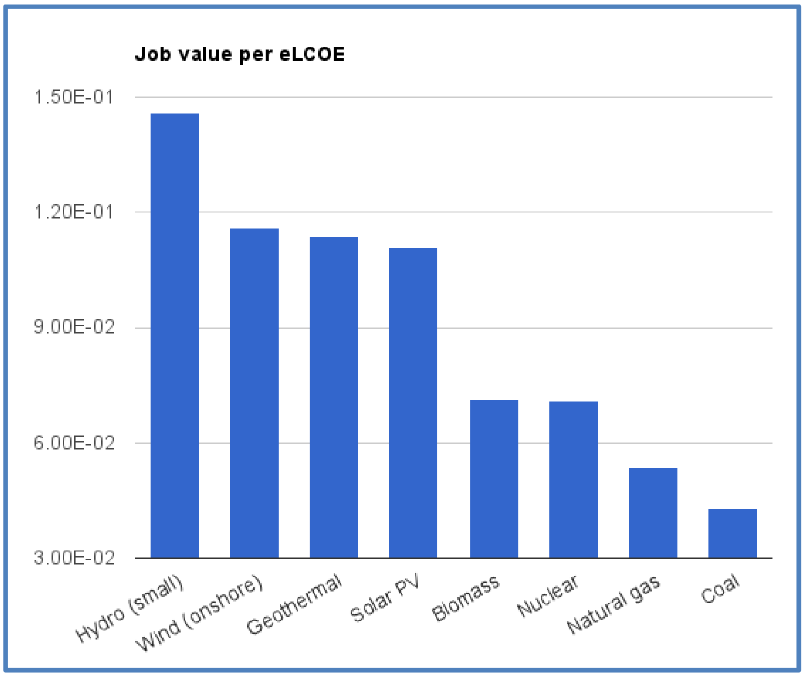

Figure 15:EEF (levelised by electricity generation and ELCOE)

Questions have been raised about whether net jobs are created by the renewable energy sector, or whether they are merely displaced from other sectors. The results of four studies in Germany are clear; that the sector creates significant additional employment above and beyond any displacement effect[102]. My calculations validate this result. All these developments take place within the same sector, and so the comparison demonstrated by Figure 15 is valid; in other words, employment on a hydropower project creates jobs additional to those that would have been created from producing the same amount of electricity in a coal-fired generator. The marginal benefit is the difference between the EEF of the different generating types.

I can therefore conclude that when externalities are taken into account, renewable electricity generators demonstrate a very strong economic benefit related to employment, compared with conventional generators.

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[102] Federal Environment Agency, Germany, ‘Report on the Environmental Economy 2009’, 2009, p. 32.