# A REVIEW OF ELECTRICITY UNIT COST ESTIMATES

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# Contents

# Introduction

## Approach and methodology

As part of the Investment Decisions project the team undertook a systematic review of the literature on electricity generation levelised unit cost estimates (hereafter referred to as unit costs). The principal aims of this paper are to examine the range of reported unit costs for major generating technologies, show the range of estimates, explain where possible the reasons for the range, and show to what extent there is any clustering around central values. In addition, the paper explains the components of unit cost calculations and discussed what is, and is not, included in these calculations.

Using the agreed set of search terms and databases (see the annex to this working paper for the full list), a total of 145 relevant documents were revealed that either presented data on unit costs for one or more technologies or discussed the issues surrounding unit cost estimates. The project team categorised each reference by:

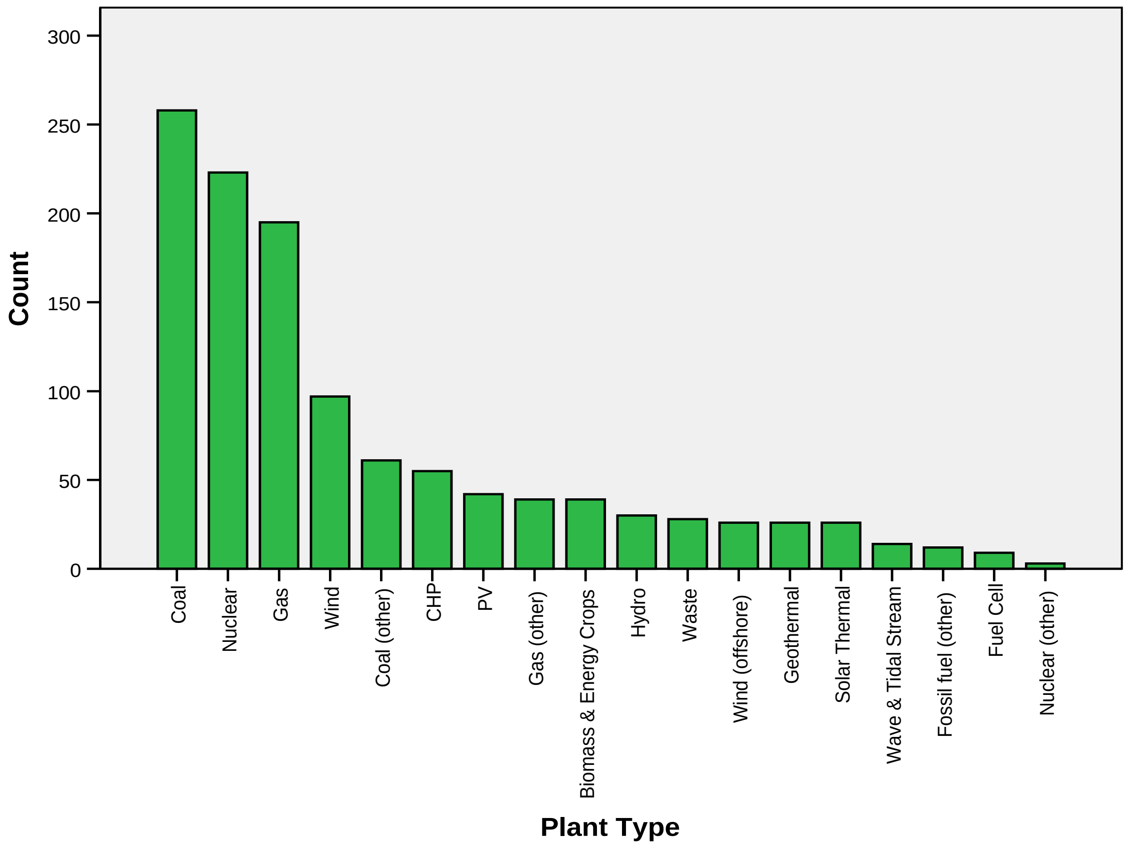
- The generating technology or technologies covered.
- The country or region that findings were relevant to.
- The approach – determining for example whether numbers presented were the results of modelling.
- The funding source, establishing whether the research was initiated by industry participants, international agencies, academic, or other bodies.
- Whether (and in what format) electricity generation unit costs are presented.

To allow the project team to focus on material which most closely matched the research requirements, documents were also allocated a 'relevance rating' where:

- A rating of 1 indicates that the paper dealt very clearly with one or more aspects of the research questions. Approximately 44% of references were assigned this rating.
- A rating of 2 indicates that although the paper is relevant, it's findings are presented in a way which could preclude direct comparison with other results. Approximately 28% of references were assigned this rating.
- A rating of 3 indicates limited relevance and/or clarity. 20% of references were assigned this rating.
- A rating of 4 denotes papers that are duplicative or, on closer inspection, were deemed not relevant. Approximately 8% of references were assigned this rating.

There is a complete list of documents in the Annex to this paper. The detailed findings presented in this working paper are drawn from the unit cost estimates found in the 64 documents with the highest relevance rating. From these 64 sources, almost 1,200 data points were extracted. This represents the total for all generating technologies – the breakdown by technology is provided in figure 1. This illustrates the predominance within the statistics of coal, gas, nuclear, and to a lesser extent wind, and the wide range of other technologies covered.

Figure 1.1 – Number of estimates by plant type




## Limitations

It is recognised that it may be appealing to compare ex-ante estimates with actual ex-post costs. However in practice the availability of 'real numbers' appears to be very poor. In liberalised markets this information resides with generating companies who may have a commercial incentive to keep the data out of the public domain. It is also important to recognise that any such numbers which are available may be subject to a range of imbedded assumptions within the generating companies operating and accounting systems e.g. what approach has been adopted to allocating corporate level costs to individual power plants? Unless answers to these types of questions are available then analysis of ex-post costs face many of the challenges (discussed later in this paper) which surround ex-ante estimates.

Unit costs presented in this paper are converted to Sterling using exchange rates as at the year of publication of each reference (or the 'as at' date defined within the reference where it is explicit) and inflated to 2006 values using Producer Price Index. It is recognised that this may introduce a degree of variation between the findings which is not reflected in the original data, but data cannot be compared at all unless they are converted to a common base – and any method of conversion and inflation to one currency and year has the potential to introduce unwarranted variation.

A significant proportion of the studies have costs estimates that project well into the future, some as far as 2050 e.g. (Delene et al 1999). Such studies rely on assumptions about cost reductions, such as through the application of learning curves. It is at least debatable whether these studies are directly comparable with other estimates based on current engineering assessments. Results for these types of long term projections have been included in the findings – partly because of the practical difficulties in excluding them, but primarily because it was considered more appropriate to show the full range of estimates.

There is no intention to draw any conclusions about the what the ‘right’ answer may be – indeed one of the points which this analysis illustrates is that there is a whole range of answers, all of which could be ‘right’, given a particular set of circumstances and assumptions.

Every effort has been made to avoid duplication of data – for example where a paper restates estimates from other work which is captured elsewhere, then those numbers are excluded from the analysis.

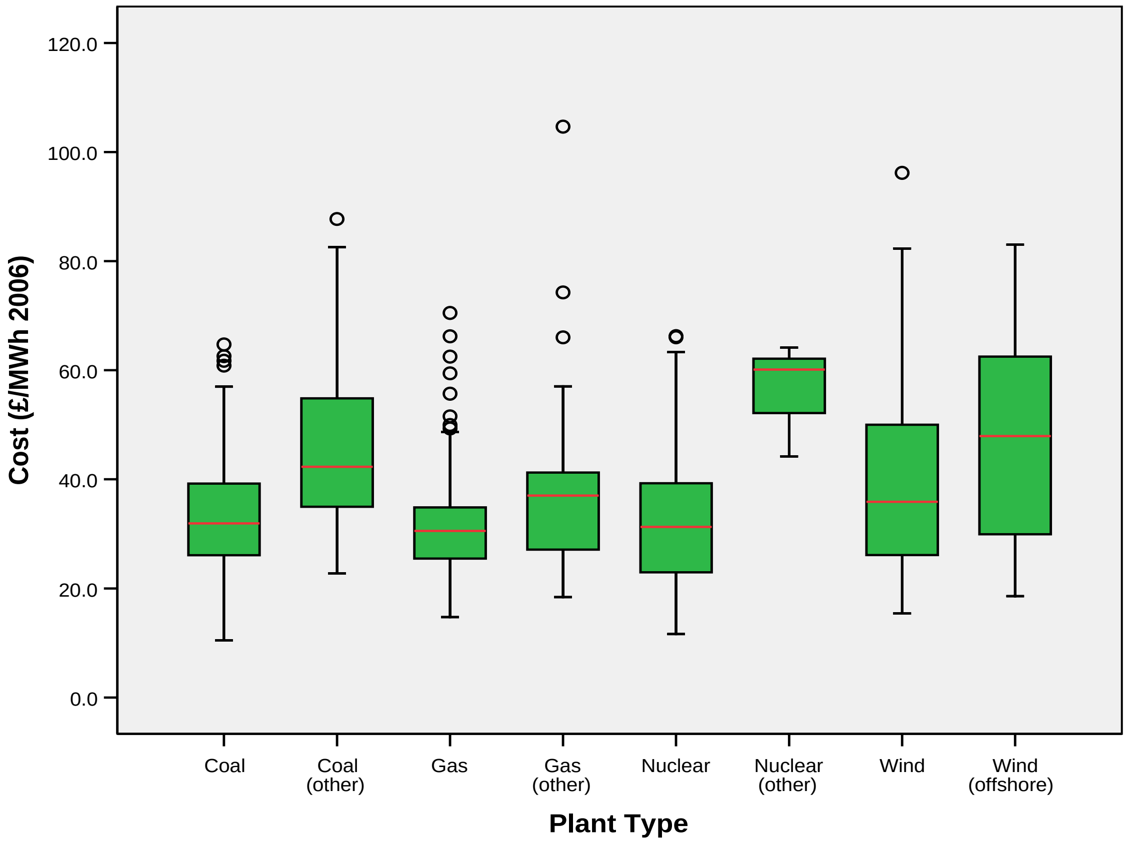
# The range of levelised cost estimates

It is important to note that no attempt has been made to normalise the data sets described below (e.g. to one consistent discount rate or plant load factor). The ranges therefore represent the impact of the full variation of input assumptions. They are not intended to show the sensitivity of estimates to any particular input assumption (see the worked examples shown in section 4 for an illustration of the effects of using various plausible values for discount rate, fuel costs and electrical output).

## Cost ranges by technology

As can be seen from figure 1, cost estimates were captured for 18 technology categories. For the sake of clarity and brevity the cost ranges presented in the remainder of this paper focus on coal, gas, nuclear and wind generation technologies. Figure 2.1 below shows the ranges of estimates for this subset of categories. The green box for each technology represents the inter quartile range (i.e. the central 50% of values), and the median value is denote by the red line. The lines from each box extend as far as the highest and lowest values, excluding outliers which are represented with individual circles. Outliers are those values which are further than 1.5 times the inter-quartile range from the box boundaries.

Figure 2.1 – Cost ranges for predominant technologies




The 'Coal (other)' and Gas (other)'groups include a range of technologies which are either at less advanced stage of commercial development (such as Integrated Gasification Combined Cycle, Oxycombustion, and CO2 capture), or have performance characteristics that make them suitable for specific roles in the electricity generation mix (such as Open Cycle Gas Turbine). They have been grouped separately from the standard coal and gas technologies to avoid skewing the results. The ‘Nuclear (other)’ group has a very small sample size (see figure 1), which would suggest that drawing conclusions for this category would have little value.

It is worth noting how close the measures of central tendency for each of the main technologies are to each other. The mean values for coal, gas and nuclear are within approximately 5% of each other, with wind significantly higher, and offshore wind higher still. Respective values for the coal and gas ‘other’ categories show a wider range of approximately 12%, possibly reflecting the more disparate technologies in each group. As was explained above, the ‘other’ category for nuclear has a very small sample size and two of the three data points are estimates for nuclear fusion plant so cannot really be regarded as firm estimates, given the status of this technology. Statistics on the predominant technologies are shown in table 2.1 below.

Table 2.1 – Statistics for predominant technologies

| | Coal | Gas | Nuclear | Wind | Wind (offshore) |
|---|---|---|---|---|---|
| Mean | £32.9/MWh | £31.2/MWh | £32.2/MWh | £39.3/MWh | £48.0/MWh |
| Median | £31.9/MWh | £30.5/MWh | £31.3/MWh | £35.9/MWh | £47.9/MWh |
| Inter-quartile range | £13.1/MWh | £9.5/MWh | £16.5/MWh | £24.2/MWh | £33.6/MWh |
| Standard deviation | £9.7/MWh | £8.9/MWh | £10.5/MWh | £16.6/MWh | £20/MWh |

The outlying values shown on figure 2 for coal, gas, nuclear and wind are from just five original references. In the case of coal they are from (IEA and NEA 1989) and (Alpert and Gluckman 1986). For gas they are also from (IEA and NEA 1989), and from (IEA and NEA 1998). For nuclear they are from (Cousins and Hepburn 2005). For wind they are from (IEA 2005).

### Cost ranges by country for the major technologies

This section presents the cost ranges for coal, gas, nuclear, wind and offshore wind on a per country basis. The charts are arranged so that the country with the highest mean value for each technology is on the left, with the lowest on the right. The intention is to show the extent of any variation in estimated costs between countries for each technology, and also to illustrate whether the size of the range differs between countries.

Figure 2.3 – Cost ranges for coal by country

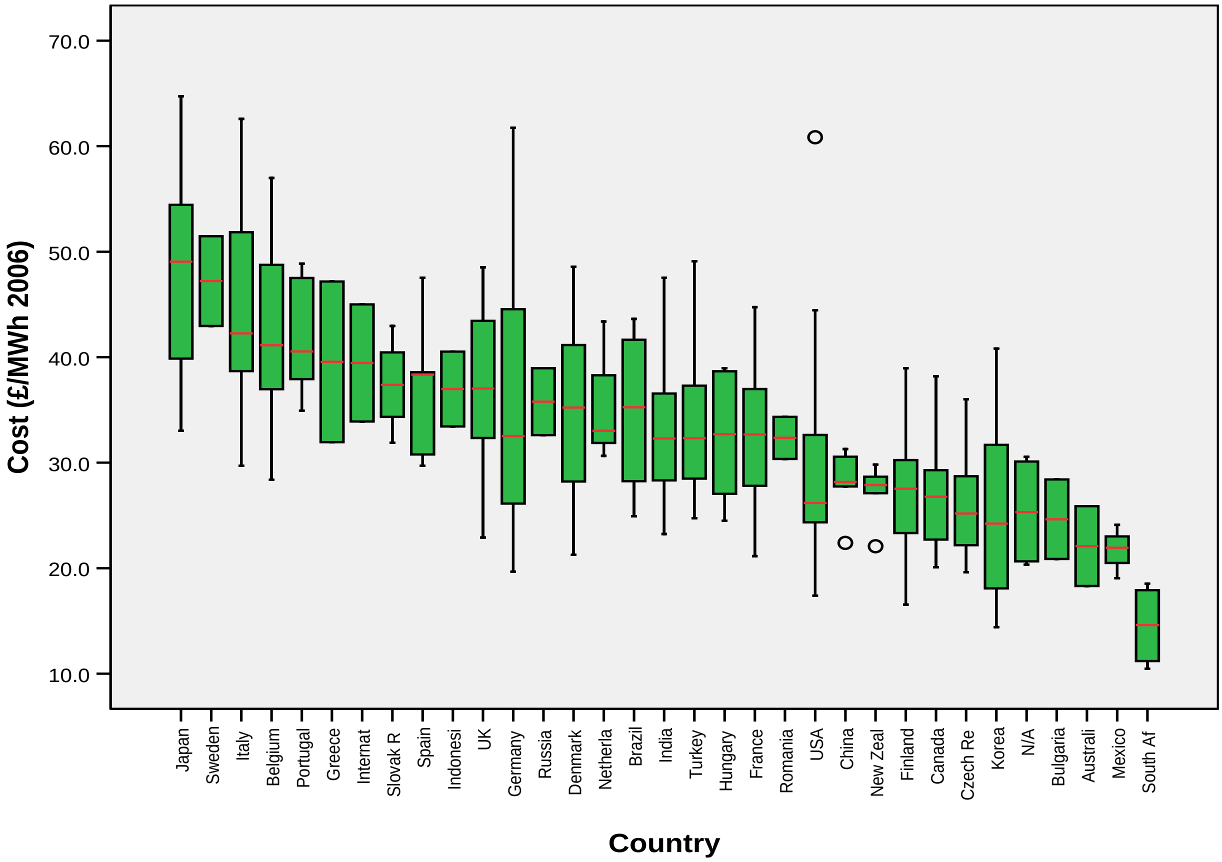



Figure 2.4 – Cost ranges for gas by country

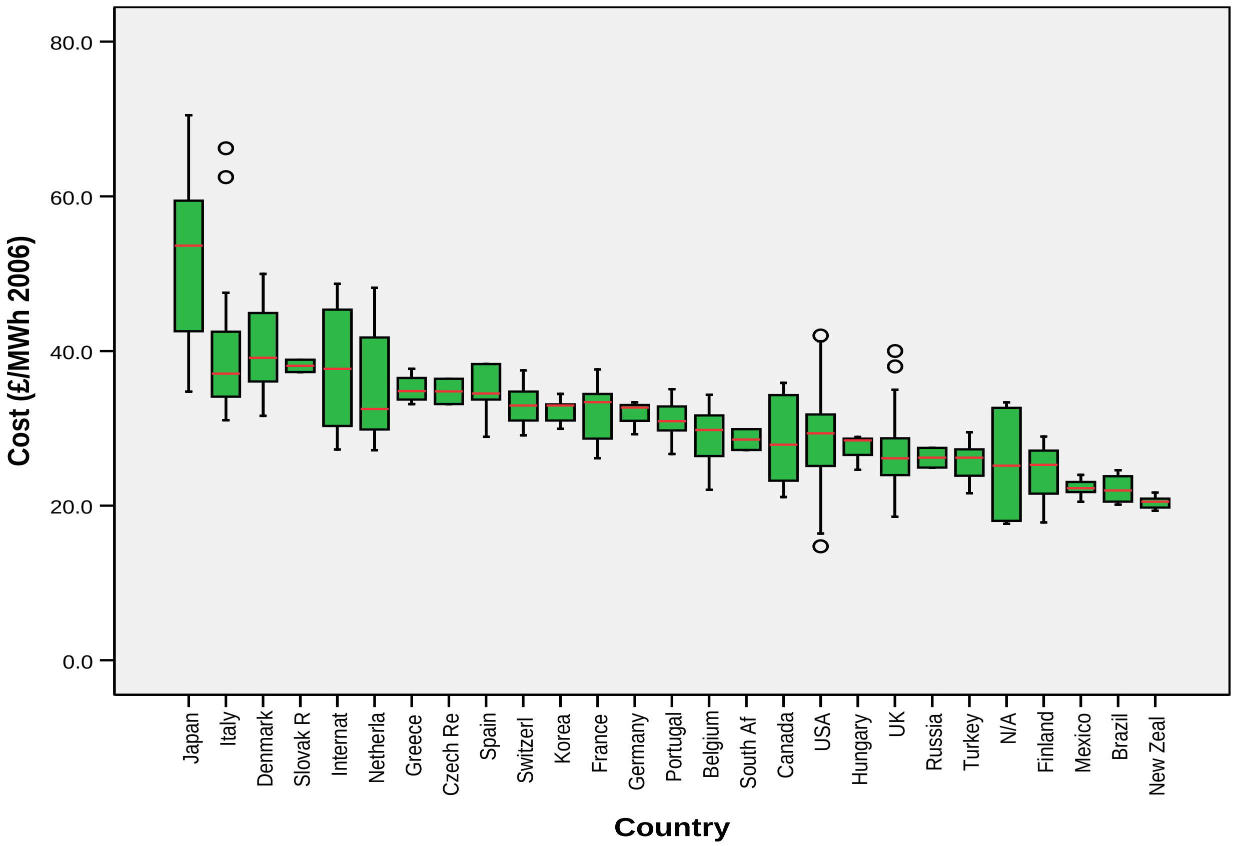



Figure 2.5 – Cost ranges for nuclear by country

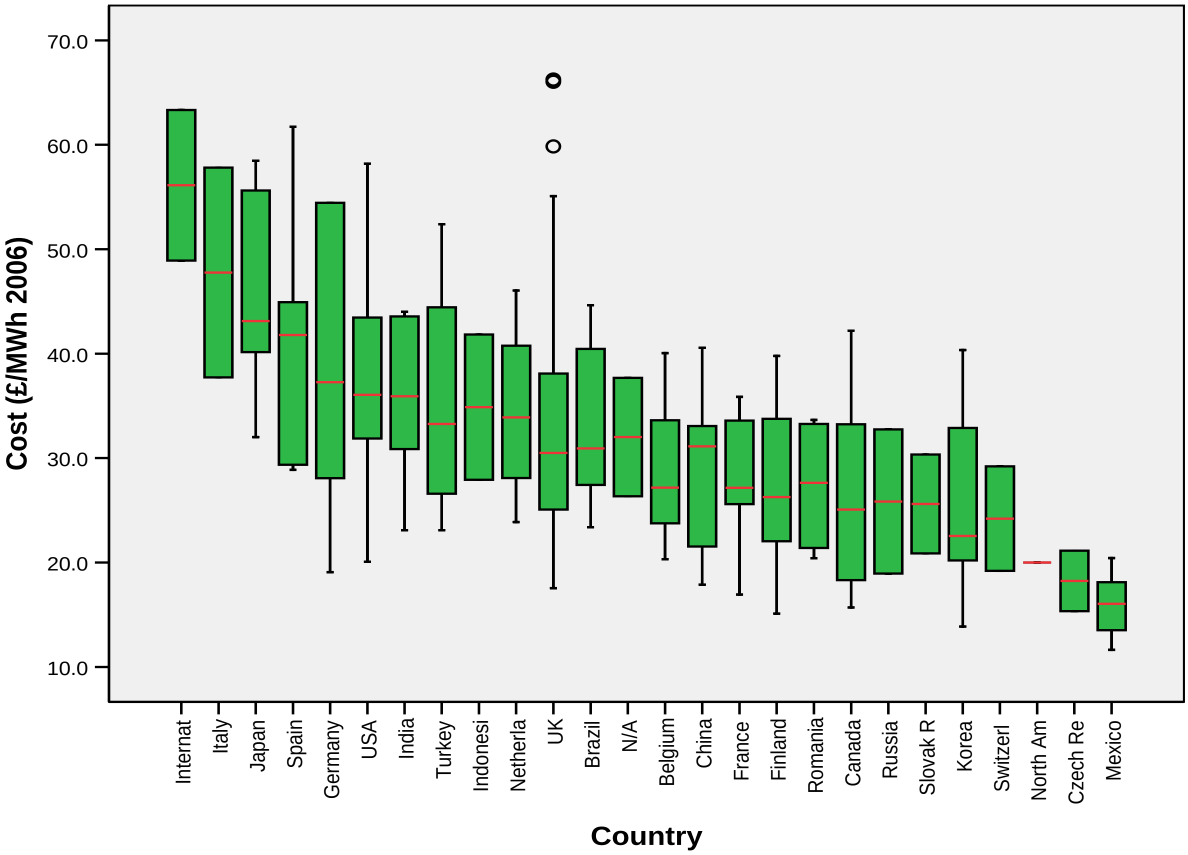



Figure 2.6 – Cost ranges for wind by country

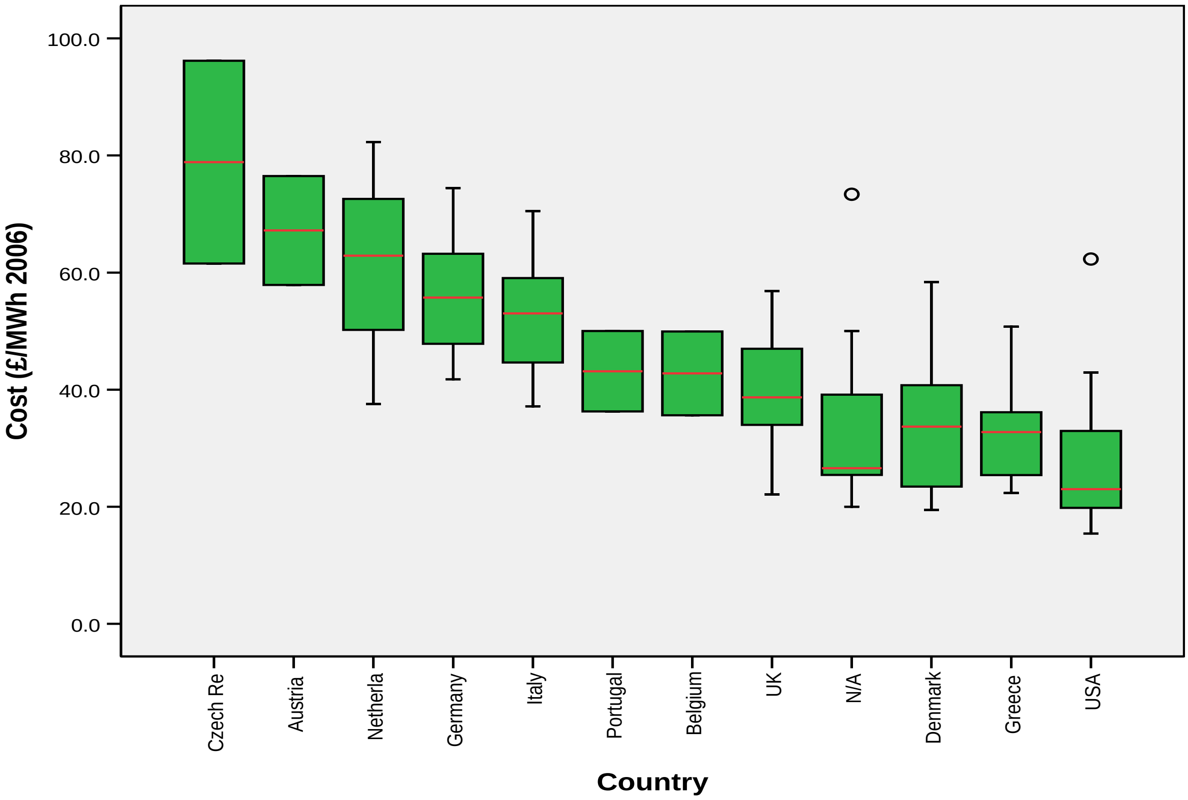
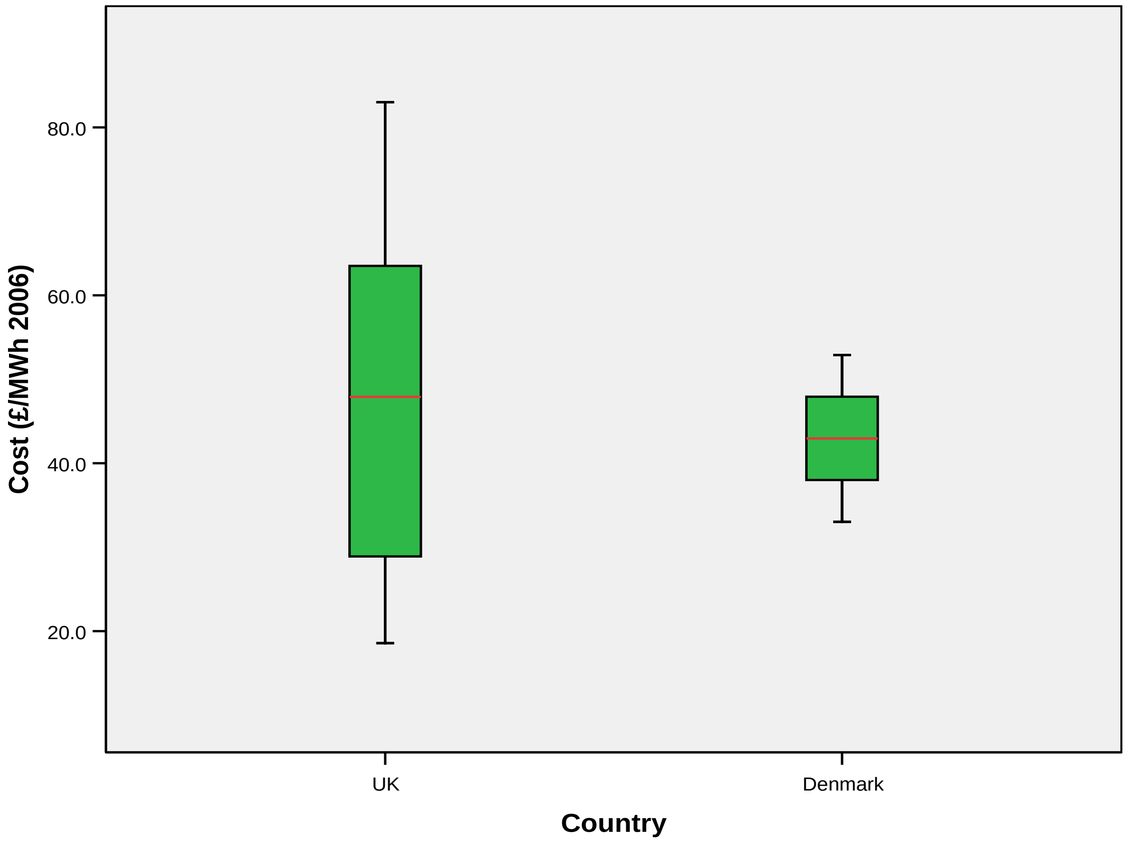



Figure 2.7 – Cost ranges for offshore wind by country


80.0
60.0
40.0
20.0
Cost (£/MWh 2006)
UK
Denmark
Country

# Components of levelised unit cost estimates

One of the most succinct definitions of levelised unit cost is from (IEA 2005), where it is defined as:

'the ratio of total lifetime expenses versus total expected outputs, expressed in terms of the present value equivalent'

The actual calculation for levelised unit costs is in some respects deceptively simple, requiring values for:

- Investment expenditures in each year
- Operational and maintenance expenditures in each year
- Fuel expenditure in each year
- Electricity generated in each year
- The discount rate to be applied to future year's expenditures and plant output

It is, therefore, an attempt to capture the full lifetime costs of an electricity generating installation, and allocate these costs over the lifetime electrical output, with both future costs and outputs discounted to present values.

The apparent simplicity of the calculation makes it attractive for use as a comparator between generating technology options, as evidenced by the large number of estimates discussed above. However, implicit in these variables are a whole range of detailed estimates and assumptions (described in more detail below), each of which is open to analysis, critique and debate. The purpose of this section is to explain what is, and is not, included in levelised cost estimates, and to illustrate some of the potential limitations of unit cost calculations.

### Included in levelised cost calculations

Components that are captured by, or factored into, the calculation:

- Capital costs
- Fuel cost (including projected cost inflation) and fuel taxes
- Operating and maintenance costs
- Waste management costs
- Decommissioning costs
- Site-specific R&D and insurance costs
- Costs of meeting emissions regulations (including possibly the cost of carbon)
- Plant lifetime (economic)
- Plant load factor
- Discount rate
- Build schedule
- Shape of the learning curve and it's impact on future cost reductions

### Excluded from levelised cost calculations

Components that are potentially not captured by levelised costs are shown below. The word 'potentially' is used because it may be argued that it is possible to incorporate some of these factors by adjusting one or more of the elements described above, so that they act as a proxy for the 'missing' elements.

Externalities

- Value of government funded research programmes
- Residual insurance responsibilities that fall to government
- External costs of pollution damage
- External benefits e.g. the value of learning to future generations
- Inter-temporal and inter-generational cost issues

System factors

- Transmission costs and other network costs such as impact on system balancing and system security requirements
- Impact on state/system level energy security
- Flexibility/controllability of power station output, suitability for different operating modes e.g. baseload or balancing services, and relative impact of demand variation

Business impacts

- Option value that investment in a particular technology may give a utility (Awerbuch et al 1996).
- Impact of project size/scale/modularity
- The cost of the irrevocability of investments
- The costs of information gathering (i.e. the information required to inform an investment decision)
- Plant lifetime (actual) – may well be longer than 'economic' life
- Fuel price volatility (distinct from expected cost inflation)
- Future revenue volatility (electricity volume and prices)
- Future changes to: tax regimes, environmental legislation, government support mechanisms
- Corporate level taxes – both the absolute level and the details of the tax regime e.g. some tax rules allow the accelerated depreciation of assets – which may affect choices between capital intensive and less capital intensive technologies (IEA and NEA 1989).
- Portfolio value, whereby investment in generating technologies whose costs do not co-vary with other technologies can reduce overall costs at any given level of risk (Awerbuch 2000)

### Observations

Looking at the list of what is potentially not captured by levelised cost estimates, there are two striking points. Firstly the sheer number of factors that this approach either struggles to incorporate or ignores completely, and secondly, the importance of these excluded factors in the investment decision process. Given this, it is not surprising that levelised costs are only one of the indicators that companies may consider when assessing their investment options.

In defence of levelised costs, there appears to be a clear understanding (at least in some quarters) that they are not intended to be a definitive guide to actual electricity generation investment decisions e.g. (IEA 2005), (DTI 2006). Some studies suggest that the role of levelised costs is to give a 'first order assessment' (EERE/DoE 2004) of project viability. Others recognise that focusing exclusively on 'least cost' technologies is not a good basis for investment decisions (Corey 1981).

The danger comes when such estimates are incorrectly interpreted as being a reliable indicator of how commercial generators will act, or are used somewhat disingenuously to show that a particular generation technology is 'cheaper' or 'more expensive' than another.

One illustration of the dangers of lending more weight to levelised cost estimates than they might warrant concerns the discount rate. This is an absolutely critical component of the levelised cost calculation yet decades of debate over the 'correct' value has not produced a conclusive answer.

The impact of the discount rate on levelised cost calculation depends on the characteristics of the technology. Capital intensive technologies will be more sensitive to discount rates, and some technologies may be associated with higher discount rates because they are perceived to be riskier. If a technology is perceived by investors to be higher risk as a result of relatively high capital intensity, then it will suffer doubly under levelised cost estimates because it will be burdened with a relatively high discount rate, and the effect of the discount rate (irrespective of the actual value) will be relatively higher than for a low capital intensity technology.

(IEA 2005) make the distinction between discount rate values used to reflect:

1. Differences in the cost of capital, essentially debt finance versus equity finance – all other things being equal, a greater share of equity finance in a project will imply a higher discount rate. Equity is riskier than debt (White 2006).
2. Differences in the perceived risk of the generating technology – high risk technologies will require higher discount rates.

Another component of the discount rate issue is that the appropriate value depends on the context e.g. the market characteristics, with some arguing that values that have been used in the past have not accurately reflected the risk factors described above (Roques et al 2004). Some are even more disparaging about discount rate choices: 'all the effort in estimating investment and operational costs is rendered worthless by a deviation in the choice of discount rates' (Khatib 2003).
Assumptions for the plant load factor have a direct effect on levelised costs because it will affect how many units of electricity a plant's costs are allocated over. What is particularly important though when using levelised costs as a comparator between technologies is that capacity factor assumptions will affect different technologies in different ways, depending on the fixed/variable cost split. For technologies with high fixed costs, load factor assumptions are of critical importance (Tarjanne and Rissanen 2000) (IEA 2006).

The insulation of levelised costs (in that they are independent of the effects of the market) may help to explain why such cost estimates were very useful to monopoly electricity generators, but are a potentially a lot less useful in liberalised markets. (White 2006) illustrates this by showing that new nuclear plant would be competitive in the UK on a levelised cost basis in a monopolistic market – but that the investment proposition is not feasible in a liberalised market.

(Awerbuch 2000) also argues that ‘ground-up’ engineering cost estimates don’t differentiate for risk, and that although, for example, fuel price risk hedging strategies do exist, they are not 100% effective and in any case impose a cost. Awerbuch suggests that if generating companies were to correctly value risk then seemingly high cost but zero fuel price risk technologies would actually be competitive. However, there is a danger that this approach could potentially disadvantage a generator who correctly values the contribution that an alternative (higher unit cost but no fuel price risk) technology can make and invests in it – their short run costs will be higher than a generator who doesn’t invest in the technology (assuming that the fuel price risk does not materialise), so they will be at a short run competitive disadvantage. See box 3.1 for a summary of Awerbuch’s critique of levelised cost calculation methods.

It may be the case that calculation of an accurate levelised is more straightforward for some technologies than for others. Certain technologies have costs that are very location specific e.g. hydro power and other renewables (IEA 2003) or the cost of fitting carbon capture and storage (CCS) equipment to fossil fuel plant. Costs for these technologies cannot easily be compared from one location to another, and the in case of CCS requires very careful examination of what components are and are not included in any estimates. Other technologies present very specific problems – for example calculating the cost of electricity produced by a Combined Heat and Power (CHP) plant requires the allocation of total plant costs between heat and electricity outputs (McMasters 2002). Even if this can be done it may not be clear whether the heat output is actually used productively or that the electricity produced is not displacing other generating options (which may perhaps have lower costs). Some studies suggest that the performance characteristics of non- dispatchable generating plant mean that comparing costs between these and dispatchable plant is inappropriate (EERE/DoE 2004).

Unit cost estimates are typically (in practice, almost always) quoted at the power station boundary – the point of connection to the transmission grid. Some argue that this makes cost comparisons of limited value unless the transmission and distribution costs are also included because the comparison should be on a ‘delivered KWh’ basis (WADE 2005). The contention is that estimates that fail to include transmission costs unfairly disadvantage those technologies which lend themselves to being located closer to the demand (and so reduce transmission costs).

**Box 3.1 Critique of levelised costs (Awerbuch 2006)**

Awerbuch's argument is that the levelised cost calculation fails to differentiate between cost streams which have different risks – the result of which is to underestimate the costs of generating technologies with relatively risky future cost streams (e.g. fossil fuel plants) and to overestimate the costs of technologies with lower risk future cost streams (e.g. wind turbines). The argument is as follows:

- Renewable electricity generation technologies such as wind have variable future costs with a low systematic risk.
- Investors should place a higher value on less risky costs/income streams so different discount rates should be used, depending on the risk of the future stream. Risky/unpredictable costs should be discounted at a lower rate than more predictable cost streams. Using a single discount rate ignores these risk differentials.
- For a levelised cost to be accurate then the calculation should use a discount rate that is appropriate to each cost stream. E.g. future Operation and Maintenance (O&M) costs are more predictable than future fuel costs so fuel costs should be discounted at a lower rate than O&M costs. A high risk/unpredictable cost stream is a worse proposition than a lower risk cost stream so should have a larger present value – so must have a lower discount rate.
- The Capital Asset Pricing Model (CAPM) should be used to derive the appropriate discount rate for cost streams. Applying this model to future fuel costs suggests that the discount rate used should be 1-3 %, which is much lower than the discount rates typically used in levelised cost estimates e.g. IEA (IEA 2005) use 5% and 10%, applied uniformly to all cost streams (and electricity output) for all technologies.
- Fuel costs are the major component of total costs in the case of CCGT generation, and are incurred throughout the lifetime of the plant, so applying a lower discount rate to this cost stream will significantly increase total costs in present value terms. As an illustration, reducing the discount rate of the fuel cost stream from 7.5% to 2% increases the present value of the costs for CCGT by over 75% (using a version of the worked examples in section 4). In principle this is arguably just a more focussed perspective on the discount rate sensitivity illustrations in section 4 – but see the penultimate point below for a qualification of this.
- The IEA levelised cost method involves discounting the future cost stream and future output stream and dividing the present value of lifetime costs by the present value of lifetime output. The 'annuity' method involves calculating the present value of the cost stream (giving a lump sum value), which is then converted to an Equivalent Annual Cost (EAC) using a standard annuity formula. Dividing the EAC by the average annual electrical output (not the discounted present value of the output) results in a levelised cost. If the discount rate (used in calculating the present value of the total costs) and 'levelisation' rate (used in the annuity formula) are the same then the results will be the same as the IEA method.
- It is possible to apply different discount rates to the various components of the costs e.g. one for O&M and one for fuel, and get a present value of the cost streams that more accurately reflects the risk differentials of each component. This stage is the same for both the IEA and annuity methods. The second stage of the calculations (to derive the per MWh cost) will also produce the same results for both methods provided that the future electricity output in the IEA method is discounted at the same rate as that used in the annuity formula, because in the IEA method the discount rate is used to derive the denominator (the present value of the electrical output) and in the annuity method the discount rate is used to derive the numerator (the annuity amount).
- Others (e.g. Anderson) would argue that this is the wrong approach, and that 'the proper way to treat uncertainties in any component of costs, such as capital or fuel costs, is to address them explicitly by feeding their means, ranges and variations directly into the analysis…...The discount rate should be varied for only one reason, which is that the discount rate is uncertain……It is true that companies may raise the threshold rate of return for risky projects, but the right thing to do as a point of principle is to combine the variances of all quantities that are uncertain.'[1]

[1] Pers Comm. With Dennis Anderson February 2007

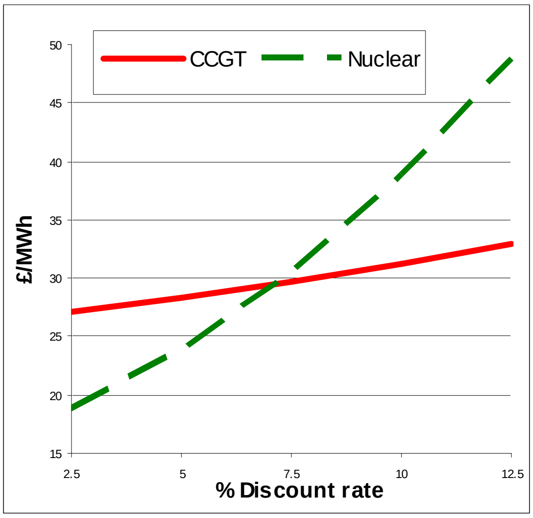
# The effect of varying the input assumptions

This section seeks to illustrate the sensitivity of levelised cost calculations to input assumptions. As was described previously, levelised costs are calculated using capital costs, operational costs, fuel costs, electricity generated, and a discount rate. This section will focus on the effect of varying the discount rate, fuel costs and electricity generated (i.e. the plant load factor). This is because the intention is to show the impact of these largely exogenous factors on the result, and to separate these factors from any debate over estimated capital and running costs of specific plant technologies (which are essentially dependant on the accuracy of engineering assessments). The influence of the three exogenous variables is analysed through  worked examples and the results illustrated in figures 4.1, 4.2 and 4.3 below.

Examples are provided for two technologies – low capital cost, high fuel cost (e.g.. CCGT), and high capital cost, low fuel cost (e.g. nuclear). Estimates for capital and running costs, plant efficiency, and plant life are taken from (DTI 2006). Base case values for discount rate, plant load factor and fuel costs are taken from (DTI 2006) and (Holt 2005) .The base case results are within 3% of the median values reporting in table 2.1 above.

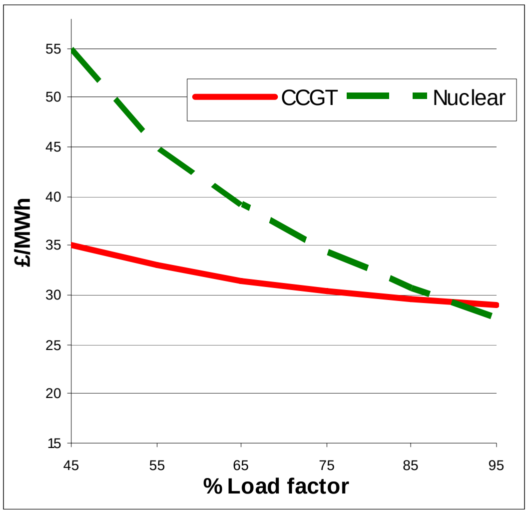
### Discount rate

Figure 4.1 – sensitivity of levelised costs to discount rate variation



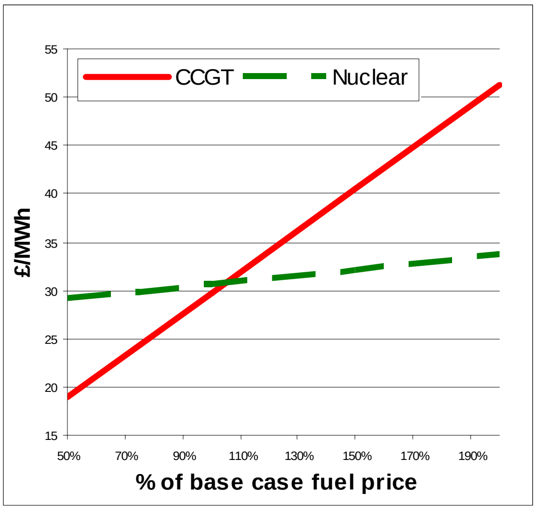
## Plant load factor

Figure 4.2 – sensitivity of levelised costs to plant load factor variation




## Fuel costs

Figure 4.3 – sensitivity of levelised costs to fuel price variation




Figures 4.1 to 4.3 clearly illustrate that a relatively high capital cost, low fuel cost technology is particularly sensitive to variation in discount rates and plant load factors, and very insensitive to fuel price variation. The opposite is true for a low capital cost, high fuel cost technology. The key message however, is that even if there is some agreement over the physical construction and operating costs of particular technologies, wide variations in levelised cost estimates can result from the other factors – and that these factors will affect cost estimates in different ways depending on the characteristics of the technologies.

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Tarjanne and Rissanen, 2000, Nuclear Power: Least-Cost Option for Baseload Electricity in Finland

WADE, 2005, Projected costs of electricity generation (2005 update) WADE response

White, 2006, Financing New Nuclear Generation, Climate Change Capital, London

# Annex

**Databases and other research sources**

Annual Reviews
Elsevier 'Science Direct'
'ESTAR' (British Library)
IEEE Explore
IEE Inspec
ETDA (Energy Technology Data Exchange)
IEA documents and publications
DTI documents and publications
EU documents and publications
US DoE documents and publications
Industry associations (e.g. World Nuclear Association, World Coal Institute)
Research groups (e.g. SPRU, ICEPT, UMIST, Environmental Change Institute, Strathclyde University)
Energy consultancies (e.g. Future Energy Solutions, Oxera, Ilex)
Specific recommendations from UKERC members
Google

**Search terms**

Unit costs + electricity generation
Unit costs + power generation
Unit costs + electricity
Unit costs + electricity prices
Unit costs + electricity generation mix

Levelised costs + electricity generation
Levelised costs + power generation
Levelised costs + electricity
Levelised costs + electricity prices
Levelised costs + electricity generation mix

Future costs + electricity generation
Future costs + power generation
Future costs + electricity
Future costs + electricity prices
Future costs + electricity generation mix

Modelling future costs + electricity generation
Modelling future costs + power generation
Modelling future costs + electricity
Modelling future costs + electricity prices
Modelling future costs + electricity generation mix

Risk + electricity generation
Risk + power generation
Risk + electricity
Risk + electricity prices
Risk + electricity generation mix

Cost projections + electricity generation
Cost projections + power generation
Cost projections s + electricity
Cost projections + electricity prices
Cost projections + electricity generation mix

Learning curves + electricity generation
Learning curves + power generation
Learning curves s + electricity
Learning curves + electricity prices
Learning curves + electricity generation mix

Projected costs + electricity generation
Projected costs + power generation
Projected costs + electricity
Projected costs + electricity prices
Projected costs + electricity generation mix

Portfolio effects + electricity generation
Portfolio effects + power generation
Portfolio effects + electricity
Portfolio effects + electricity prices
Portfolio effects + electricity generation mix

## Full list of documents

(Grouped by relevance rating, then sorted by author and year)

| Relevance rating | Author | Year | Title | Ref |
|---|---|---|---|---|
| 1 | Alpert SB;Gluckman MJ; | 1986 | Coal Gasification Systems for Power Generation | 51 |
| 1 | Awerbuch S; | 2000 | Investing in photovoltaics: risk, accounting and the value of new technology | 4 |
| 1 | Awerbuch S; | 2003 | The True Cost of Fossil-Fired Electricity in the EU: A CAPM-based Approach | 148 |
| 1 | Awerbuch S; | 2004 | Portfolio-Based Electricity Generation Planning: Policy Implications for Renewables and Energy Security | 7 |
| 1 | Awerbuch S;Berger M; | 2003 | Applying Portfolio theory to EU electricity planning and policy-making | 63 |
| 1 | Awerbuch S;Dillard J;Mouck T;Preston A; | 1996 | Capital budgeting, technological innovation and the emerging competitive environment of the electric power industry | 3 |
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