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External costs of nuclear: Greater or less than the alternatives?

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HIGHLIGHTS

- ▶ The external costs of nuclear electricity are compared with the alternatives.
- ▶ Frequency and cost of nuclear accidents based on Chernobyl and Fukushima.
- ▶ Detailed comparison with wind as alternative with the lowest external costs.
- ▶ High external cost of wind because of natural gas backup (storage too limited).
- ▶ External costs of wind higher than nuclear but uncertainty ranges overlap.

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ABSTRACT

Since Fukushima many are calling for a shutdown of nuclear power plants. To see whether such a shutdown would reduce the risks for health and environment, the external costs of nuclear electricity are compared with alternatives that could replace it. The frequency of catastrophic nuclear accidents is based on the historical record, about one in 25 years for the plants built to date, an order of magnitude higher than the safety goals of the U.S. Nuclear Regulatory Commission. Impacts similar to Chernobyl and Fukushima are assumed to estimate the cost. A detailed comparison is presented with wind as alternative with the lowest external cost. The variability of wind necessitates augmentation by other sources, primarily fossil fuels, because storage at the required scale is in most regions too expensive. The external costs of natural gas combined cycle are taken as 0.6 €cent/kWh due to health effects of air pollution and 1.25 €cent/kWh due to greenhouse gases (at 25€/t_{CO_2eq}) for the central estimate, but a wide range of different parameters is also considered, both for nuclear and for the alternatives. Although the central estimate of external costs of the wind-based alternative is higher than that of nuclear, the uncertainty ranges overlap.

1. Introduction

In the wake of the accident at the Fukushima power plants there has been a very understandable worldwide reaction against nuclear power. Germany has decided to phase out all their nuclear plants, Japan wants to reduce its reliance on nuclear and has currently shut down almost all of its nuclear plants, and in France the Socialists have written into their platform that they intend to close one third of the nuclear plants in France. But what are the alternatives?

It would not be wise to retire nuclear plants precipitously, if the alternatives entail total (private+external) costs that are even higher. This paper compares the external costs[1] of nuclear with those of the alternatives, considering only the use of nuclear power in countries that have a well established culture of safety and adequate safeguards against proliferation (EU, US, Canada, Japan, South Korea and Taiwan).

The opposition to nuclear power stems mainly from three aspects of the technology, namely radioactive waste, the links to proliferation and terrorism, and the risk of catastrophic accidents. As far as normal operation is concerned, its external costs have been evaluated by several major assessments, in the EU (ExternE,

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[1] Here the term external cost is used for the entire damage cost due to pollutants or other burdens, even if some of this cost may already be internalized by regulations such as pollution taxes. This is in fact how the term has been used in most studies, in particular those of the ExternE series.

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1995), the US (ORNL/RFF, 1994) and Canada (Ontario Hydro, 1993), with the conclusion that they are small, certainly much smaller than those of the fossil fuels. This conclusion has been reconfirmed via a literature review by the U.S. National Academy of Sciences (NRC, 2010).

Traditionally, probabilistic safety assessments (PSA) have been carried out to estimate the likelihood of a catastrophic nuclear accident, i.e., one involving a core meltdown accompanied with a large release of radionuclides into the environment. The resulting impacts and costs are estimated by means of detailed models, based on the distributions of populations, agriculture etc.

Since Three Mile Island and Chernobyl the safety of reactors has been greatly improved, and yet Fukushima happened. Cochran and McKinzie (2011) offer an instructive review of reactor accidents and compare the actual frequency of core damage accidents with the safety goals of the U.S. Nuclear Regulatory Commission, namely that the frequency of a core damage should not exceed 10^{-4}/year and the frequency of a core damage with large release should not exceed 10^{-5}/year. These safety goals are based on a PSA approach. Worldwide, there have been 593 nuclear power reactors and the cumulative operation amounts about 14,400 reactor-years. There have been 23 core damage events and their frequency has been one in 14,400/23 = 626 reactor years; even excluding the nine least severe cases the core damage frequency is still 10^{-3}/year. The frequency of a large release has been one in 14,400/2 = 7200 reactor years. Both frequencies are an order of magnitude higher than what has been estimated by PSAs for the majority of plants that have been built until now. Can a PSA-based approach really foresee all the site-specific design weaknesses or operator errors that led to Chernobyl and Fukushima?

For these reasons the present paper takes a different approach, which is based on the actual track record of nuclear power plants, in particular catastrophic accidents of which there have been two, Chernobyl and Fukushima. The frequency of such accidents is taken as one in every 25 years, the time between Chernobyl and Fukushima; that is also roughly the time from the first nuclear power plants until Chernobyl. This may well overstate the accident rate because after each large accident measures have been taken to improve the safety. For the central estimate impacts comparable to Chernobyl and Fukushima are assumed.

Of course, any assessment of the external costs of nuclear is controversial, in particular with regard to accidents, proliferation, terrorism and waste management. Subjective choices are inevitable and any specific assumption can and will be criticized. The present assessment is offered as a basis for discussion because it is better to base decisions on an explicit analysis rather than vague impressions. The calculations are simple and transparent, making it easy for the reader to modify the assumptions.

Many advocates of a nuclear shutdown propose renewables and load reduction through energy efficiency as clean and cost-effective substitutes. Among renewables the technologies with the greatest production potential are wind, solar, hydro and biomass. The issue to be addressed with wind and solar, quite apart from their cost, is the variability of wind or insolation, and the corresponding variability in the amount of electricity they supply. To achieve a reliable power supply, supplemental capacity must be available, especially if solar and wind provide a high fraction of the total electricity production. Of course, energy storage would be an attractive solution, but for most applications storage of the required magnitude and duration is still too expensive or the potential sites (for the most cost-effective option, pumped hydro) are too limited. Without sufficient storage the supplemental capacity requirement of wind and solar implies that part of the replaced electricity will come from natural gas, with the attendant costs for health and environment.

Section 2 discusses the external cost of nuclear power and presents an estimate of the cost of a nuclear accident. Section 3 examines the external costs of the principal non-nuclear technologies: coal, natural gas, wind, solar, hydropower, and energy efficiency, with special attention to the extent to which alternatives with the lowest external costs can serve as substitutes for the baseload power produced by nuclear. Section 4 discusses the results.

2. External costs of nuclear power

2.1. Normal operation

As mentioned in the Introduction, health impacts due to radiation from the normal operation of nuclear power plants are small compared to those of fossil power. For instance, ExternE (1995) found an external cost for nuclear of 0.0098 €cent/kWh at a discount rate of 3% and 0.25 €cent/kWh at a discount rate of 0%. The present paper uses the most recent estimate of the ExternE series by Markandya et al. (2010), which is 0.21 €cent/kWh at a discount rate of 5%. This cost is much higher than ExternE, 1995 at 5% discount rate because it is based on a more complete LCA inventory of upstream burdens, essentially all non-radiological. Lower and upper bounds are taken as 1/3 and 3× this value, based on Spadaro and Rabl (2008).

2.2. Nuclear waste, proliferation and terrorism

Risks from storage of nuclear waste are extremely uncertain because they depend on the future management of the storage site. In the past the design goal of waste storage sites was to seal them when full, so one would never have to worry about them again. But detailed impact studies found that total safety could not be guaranteed for a sufficient duration. On the other hand, assessments of the impacts and damage costs that could result from a breach of confinement concluded that their contribution would be negligible, even compared to the low external cost of the normal operation of the nuclear fuel cycle (e.g., ExternE, 1995; ORNL/RFF, 1994). Such a result is plausible because the dispersion of pollutants in the ground is extremely slow and limited to the local range, unlike the dispersion of radionuclides emitted into the air or the ocean.

Risks from storage can be avoided almost entirely if the waste is stored in a retrievable manner and the site will be permanently maintained in safe condition. The means to do that are certainly available. In case of a leak, the waste can be taken out and repackaged. It can also be reprocessed and rendered less harmful once future technologies allow it. Many people argue that “we have no right to impose the burden of nuclear waste on future generations”; however, they should not overlook that the alternative implies fossil fuels, which impose the burden of greenhouse gases. Future generations can protect themselves from risks of our nuclear waste, but they cannot avoid the impacts of our greenhouse gases. The cost of permanently maintained storage sites is certainly not infinite, despite the practically infinite time horizon, because the appropriate discount rate is positive. Doing a cost–benefit analysis from the perspective of future generations (Rabl, 1996) shows that future generations would prefer us to use a discount rate equal to the long term average growth rate of real GDP per capita, for which historical data suggest a value of 1 to 2%. The reason is that future generations benefit from the growth stimulated by our economic activity. Even with such a low discount rate the total discounted cost of a permanently managed storage site is only 50 to 100 times the annual cost.

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It is difficult to estimate the true cost associated with the incremental waste from continued operation of the existing power plants because plans for the long term management are still evolving. In the US plans for the proposed storage site at Yucca Mountain have been abandoned and for the time being the waste is being stored on site at each power plant. To a large extent the cost is internalized because since 1983 plant operators have been paying 0.1 cent/kWh to a central waste management fund, and the $24 billion already in that fund could pay for a significant part of the cost of a permanent solution, estimated to cost between $23 billion and $81 billion by GAO (2009) and sufficient to store twice the current quantity of waste.

In France current plans call for final storage that is retrievable. The cost of such storage is estimated to amount to about 0.3 €cent/kWh (Cour des Comptes, 2012). Here, too, much of this cost is internalized by current payments by the nuclear industry. These numbers suggest that the cost of waste management is in the range of 0.1 to 0.3 €cent/kWh, and that a significant fraction of that is already internalized. The present analysis assumes 0.2 €cent/kWh as external cost of nuclear waste management, i.e., the cost that is not yet internalized.

As for the risks associated with proliferation, the relevant question is whether such risks are increased or decreased by a shutdown of nuclear power plants. Proliferation, in the sense of acquisition of nuclear weapons by countries that do not now have them, is indeed facilitated by the sale of nuclear power technology to non-weapon states. However, it is unclear how the operation of existing nuclear power plants in countries with adequate safeguards could have a significant effect on the transfer of nuclear technology to non-weapon states, except a transfer of expertise through migration of nuclear engineers. It is unlikely that such migration to non-weapon states would be decreased by a shutdown of existing plants. The risks due to terrorism are not considered in this paper.

2.3. The Impacts of Chernobyl and Fukushima

The first commercial nuclear power plants started operation in 1956 in the UK and in 1957 in the US. There have been only two catastrophic accidents, rated at the maximum value of 7 on International Nuclear and Radiological Event Scale of the IAEA, a scale intended to be approximately logarithmic: Chernobyl in 1986 and Fukushima in 2011. The third most severe accident of a power plant, Three Mile Island in 1979, is rated only 5. Of course, a sample of two is not a very reliable basis for making predictions for scale 7 accidents, but there are no alternatives that are much better in estimating the probability of an accident and its consequences.

Chernobyl was a reactor of the LWGR type (light water cooled graphite moderated reactor, also known as RBMK type), a design notorious for its lack of safety. The only reactors of this type still operating are in Russia (http://www.iaea.org/PRIS/CountryStatistics/CountryDetails.aspx?current=RU), and it is unlikely another one will be built. There was a general absence of a safety culture in the Soviet Union. The accident was initiated by a violation of operating procedures and its consequences were worsened by inadequate responses of the government. For instance, irradiated food was not taken off the market in time and no iodine pills were given to the population to reduce the risk of thyroid cancers.

After the accident some 350,000 persons were moved out of the areas with the highest radiation levels (IAEA, 2005). About 8000 km^2 were taken out of agricultural production. Apart from immediate deaths (less than a hundred) during the first weeks after the accident, the only health impacts of radiation are cancers. Measuring the total number of cancers due to an accident such as Chernobyl is impossible for several reasons: there is no tracer to identify a specific cancer as being due to radiation; most cancers develop slowly, typically one or two decades; and the increase is tiny compared to background rates. Instead the increase in the number of cancers is calculated by combining estimates of the exposure with a linear no-threshold dose–response function for fatal cancers due to radiation. The total number of fatal cancers worldwide (mostly in the former Soviet Union and in Europe) during the entire life of the exposed population has been estimated at about 16,000 (95% uncertainty interval 6700 to 38,000) by Cardis et al. (2006). The corresponding estimate by IAEA (2005) is much lower: 4000. Such estimates are uncertain because the population dose is difficult to determine, quite apart from uncertainties about the dose–response function.

Fukushima was caused by a tsunami due to a magnitude nine earthquake off the coast of Japan. There are six reactors at the Fukushima Daiichi plant and each reactor accident was rated separately; out of the six reactors, three were rated level 5, one was rated at a level 3, and the situation as a whole was rated level 7. Unlike Chernobyl, the reactors are boiling water reactors, designed by General Electric and built around 1970. Many plants of this type are still in operation (http://www.iaea.org/PRIS/WorldStatistics/OperationalReactorsByCountry.aspx).

Von Hippel (2011) cites a report by the Japanese Government to the IAEA of radioactive releases to the atmosphere, according to which the total is about one tenth of Chernobyl. Scaling in proportion to the Chernobyl cancers he estimates that the total number of cancer deaths due to Fukushima might be around 1000. Approximately 150,000 people were evacuated in response to the accident (National Diet of Japan, 2012). It is not clear how many will have abandoned their homes permanently. Detailed maps of land contamination have been prepared (Yasunari et al., 2011), and it is estimated that as much as 1800 square kilometers of land in Fukushima Prefecture has now been contaminated by a cumulative radiation dose of 5 mSv/year or higher (for comparison, typical natural background doses of the general population are around 2.5 mSv/year), but apparently no decision has yet been made about how much land will be taken out of agricultural production and for how long.

There have been other impacts in addition to cancers, displaced populations and contaminated agricultural land. There are six reactors at Fukushima and they will not be restarted, a significant financial loss. In the wake of the accident most of the remaining nuclear power plants of Japan were shut down and the loss of power imposed major (market and non-market) costs. The resulting loss of industrial production reduces the GDP, as does the loss of food. However, such effects are impossible to identify in the GDP data because they are swamped by the non-nuclear losses due to the tsunami as well as by the losses due to the worldwide economic crisis. Finally there is the cost of cleaning up and safeguarding the Fukushima reactors.

2.4. Cost of a nuclear accident

The above considerations lead to the following estimate of the costs of a future catastrophic nuclear accident. These cost categories are considered to be the most important:

i) Cost of lost reactors:
Assume a loss of 6 GW of nuclear capacity at 5 G€/GW.
ii) Cost of lost power:
The output of 6 GW of nuclear is assumed to be missing for 3000 h/year during 5 years, a total of 90 TWh, at an average cost of 0.2 €/kWh.
iii) Fatal cancers:
The number of fatal cancers is taken as 10,000 per accident (the mean of IAEA (2005) and Cardis et al. (2006) estimates for

Chernobyl), valued at 5 M€/cancer. Because the latency period for the development of most cancers is on the order of two decades after exposure, a discount factor $(1+0.05)^{-20}=0.38$ is applied to the cost of cancers.

iv) Lost agricultural production:
1000 km^2 are assumed to be out of production for 100 years. With typical productivity and market price of cereals they would have produced about 120,000 €/km^2 per year.

v) Displaced populations:
At Fukushima about 150,000 persons were moved, but the population density of the surrounding area was relatively low. Data for the geographic distribution of reactors in terms of the surrounding population densities can be found in Cochran and McKinzie (2011) who list 210 sites (with 508 reactors) worldwide together with the population within 30 km and within 75 km. Compared to Fukushima the worldwide average of the population within 30 km of a nuclear power plant is 2.9 times larger and the average within 75 km is 1.8 times larger. In the EU and in North America the largest population within 30 km is about ten times as high as for Fukushima. Hence permanent evacuation of 500,000 persons is assumed for the central and 2 million for the high estimate.
The cost is taken as 0.5 M€/person, corresponding to about 1 to 1.5 M€ for the loss of a home with all its belongings, and about 2 to 3 persons per home. Temporary evacuations cost far less per person and the estimate of permanent evacuations is high enough to cover that as well. The number of displaced persons is very uncertain. For a given release of radionuclides a government may respond in very different ways. For example, the US government advised evacuation for its own citizens living within 50 miles (~80 km) of Fukushima while the Japanese Government chose to evacuate only within 20 km. Wilson (2012) carried out a detailed analysis of radiation levels and cancer risks and concluded that people beyond 3 miles (~5 km) should not have been forced to evacuate. Wilson argues that the stress of being forced to evacuate should not be overlooked: excessive evacuation may induce more cancers due to stress than what would be caused by radiation. In any case, any long term or permanent evacuation would be based on measured exposures. The real exposures tend to be concentrated along dominant wind directions. For example, the high exposure region of Fukushima where long term evacuation may be necessary extends to about 50 km but its area is smaller than that of a circle of 20 km radius.

vi) Cost of clean up:
The cost of cleaning up and safeguarding the Fukushima power plants was estimated by the Japanese Government as about 15 billion € in October 2011; here 30 billion € is assumed in view of the universal tendency to underestimate costs before a project is started. This item is very uncertain because, like the evacuations, it depends on governmental choices for which there are no clear-cut criteria. The ensuing clean up may entail relatively limited costs or costs that could cripple the economy of a country. For instance in December 2011 a report commissioned by the Japanese government estimated that cleaning up the Fukushima disaster and compensating its victims could cost as much as 20 trillion yen ($257 billion) (http://www.reuters.com/article/2011/12/06/japan-nuclear-cost-idUSL3E7N60MR20111206), but that is not based on actual decontamination decisions which are still evolving. It is too early to know the real cost of the cleanup. An important consideration is the half life of the radionuclides. The most important of these are Iodine-131, with a half-life of 8 days, and cesium-137 with a half-life of about 30 years. Only cesium-137 is significant for decisions about long term evacuations and cleanup.

The resulting costs are for an accident occurring today. For an accident in the future the costs have to be discounted. Specifically, the time of the replacement of a nuclear plant by an alternative is taken as time zero, and an accident is assumed to occur with equal probability in each of the years thereafter. Since the scenarios consider an accident within the present generation, the conventional rather than an intergenerational rate is appropriate, here taken as 5%. Thus an accident in year t is discounted by a factor $(1+0.05)^{-t}$ and an average discount factor is obtained by averaging over the years between accidents, yielding a factor of 0.56 for the 25 years of the central estimate.

Table 1 shows what such assumptions imply for the central estimate of the accident cost. The cost per kWh is obtained by dividing the cost of an accident by the number of years between accidents and the annual electricity production of the countries considered here (EU, US, Canada, Japan, South Korea and Taiwan); in addition it is multiplied by a discount factor as explained above. The values listed in the Parameter column are used only for the central results. The last two columns indicate lower and upper bounds; they are rough estimates of plausible ranges about the central values. A proper calculation of the uncertainties would require a much more detailed discussion with Monte Carlo calculation to account for the combination of all the terms, beyond the scope of this paper. For comparison note that the accident database of Hirschberg et al. (2004) shows an estimate of G$ 339_{1996} (approx. 360 $G€_{2010}$) for the cost of Chernobyl; which is within the range shown in Table 1.

3. External costs of the alternatives

The alternatives involve a direct substitution for a nuclear plant, i.e., the alternative system must be capable of operating in a regime similar to that of the nuclear plant being replaced. Its capacity and electricity production is to be identical to that of the corresponding nuclear plant, effectively implying that there are no changes in the remainder of the system or the net load. For any specific system, a more complex assessment could be carried out, which would take into account the impact on and/or the contribution of the balance of the system.

3.1. Fossil Fuels

Coal plants are most similar to nuclear power with regard to their use for baseload power, due to the high capital cost and relatively low fuel cost. However, concern about environmental impacts, especially greenhouse gas emissions, will severely limit recourse to conventional coal plants. Cleaner coal technologies, in particular IGCC (integrated gasification combined cycle) with pre-combustion carbon capture are still far too expensive. Post combustion carbon capture and sequestration is too immature and it is unlikely to make a significant contribution in the foreseeable future. Even though the efficiency of conventional coal plants continues to increase (see for example DOE-NETL, 2010), their greenhouse gas emission rates are about 1 kg_{CO_2eq}/kWh, substantially higher than those for gas-fired capacity. Because of this coal is not included among the alternatives considered here.

For natural gas the combined cycle (NGCC) has become the standard, except for peak load duty where simple-cycle gas turbines are used. The latter have much higher emissions of greenhouse gases and NO_x, but since they are used only a small portion of time, their contribution is neglected here by assuming for simplicity the emissions of NGCC for all natural gas plants;

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Table 1
Assumptions and results for the external costs of nuclear power.

Cost Elements	Parameter[a]	Units[e,f]	Central	Low	High
Fatal cancers	10,000				
Cost per cancer	5	M€/cancer			
Discount factor for cancers[b]	0.38				
Cost of cancers		**G€**	**18.8**	10	50
Lost reactors, 1 GW each	6				
Cost per reactor	5	G€/reactor			
Cost of reactors		**G€**	**30**	20	40
Cost of cleanup		**G€**	**30**	20	200
Displaced persons	500,000				
Cost per displaced person	0.5	M€/person			
Cost of displaced persons		**G€**	**250**	100	1000
Area lost for agricultural production	1,000	km^2			
Yield, cereals, 5 t/ha per year	500	t/km^2/year			
Price, cereals 150 €/t	150	€/t			
Loss €/km^2/year	75,000	€/km^2/year			
Loss duration	100	year			
Cost of lost agriculture		G€	**7.5**	5	50
Lost power production	90	TWh			
Value per kWh	0.2	€/kWh			
Cost of lost power		**G€**	**18**	10	50
Total cost of accident, if now		**G€**	**354**	**165**	**1390**
Years without accident			25	40	15
Discount rate	0.05				
Discount factor [c]			0.56	0.43	0.69
Nuclear production, 2008	2,100	TWh/year			
External cost of accident, per kWh[d]		**€cent/kWh**	**0.38**	**0.08**	**2.29**
External cost of current operation		**€cent/kWh**	**0.21**	**0.07**	**0.63**
External cost of waste management		**€cent/kWh**	**0.20**	**0.10**	**0.30**
External cost of normal operation		**€cent/kWh**	**0.41**	**0.17**	**0.93**
Total external cost of nuclear		**€cent/kWh**	**0.79**	**0.25**	**3.22**

[a] The parameter values are used only for the central estimate.
[b] To account for delay between accident and occurrence of cancer.
[c] To account for an accident occurring between now and 25 years from now.
[d] Cost if now × discount factor/(years without accident × TWh/year).
[e] T=tera, G=giga, M=mega, k=kilo.
[f] t=metric tonne.

that implies a slight underestimation for the calculation of the external cost of the alternatives. Greenhouse gas emission rates for NGCC are about 0.5 kg_{CO_2eq}/kWh. Oil is in-between coal and gas. Since oil is used less and less for power plants, it is not considered here.

The emissions of the classical air pollutants (NO_x, PM_{10}, SO_2, etc., also called "criteria pollutants") by fossil power plants in the EU have been greatly reduced by the Large Combustion Plant Directive of 2000 and no further reductions are on the horizon. The corresponding external costs have been calculated by the ExternE project series in the EU. Here the values in the most recent publication of that series (Markandya et al., 2010) are assumed, namely 1.2 €cent/kWh for coal and 0.6 €cent/kWh for NGCC.

The damage cost of greenhouse gases is uncertain and controversial; for a review see for example Tol (2005). Not only is it extremely difficult to quantify all the possible impacts, but their valuation hinges on choices of ethical nature, such as the intergenerational discount rate, the valuation of mortality in developing countries, and whether or not to apply equity weighting (i.e., whether an incremental dollar or euro should be weighted the same way in all countries). Values in the range of 15 to 30 €/t_{CO_2eq} are frequently mentioned by policy makers. The Government of the UK carried out a major review of the literature and found that the central estimate was 17.7 £/t_{CO_2eq} (22.4 €/t_{CO_2eq}) in 2010, increasing to 27.2 £/t_{CO_2eq} (34.5 €/t_{CO_2eq}) in 2030 (DEFRA, 2005). The widely publicized Stern review estimated a damage cost of $85/$t_{CO_2eq}$ (Stern et al., 2006). The present paper takes 25 €/t_{CO_2eq} as central value, with 8.3 and 75 as low and high values. At 25 €/t_{CO_2eq} the cost of GHG emissions is 2.5 €cent/kWh for coal and 1.25 €cent/kWh for NGCC.

3.2. Energy efficiency[2]

Energy efficiency is crucial for reducing the harmful impacts of energy use. Improvements in energy efficiency are an ongoing process, encouraged by governmental programs and regulations. Since the present paper concerns the external costs of the alternatives when an existing nuclear plant is shut down, the relevant question is how much of the electricity that would have been supplied by this plant will be replaced by reductions of electricity consumption.

Obviously, if the consumption drops by the amount that would have been supplied by the nuclear plant, no replacement is needed and the external cost of the alternative is zero. But if the consumption drops by less than that amount, the shortfall has to be provided by other power plants. Therefore energy efficiency can be counted as replacement for an existing nuclear power plant only if the consumption can be reduced by the output of that plant.

[2] Increase in energy efficiency is defined as the ability to perform a task using less energy.

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It is instructive to review predictions for electricity consumption. Eurelectric (2011), the association of the electricity industry in Europe, estimates the consumption in Europe to increase between 2009 and 2020 by about 10%. The corresponding estimate by IEA (2008) is a 15% increase. For the average of all OECD countries IEA foresees growth rates of at least 1% per year until 2030. Eurelectric (2010) expects an increase by a factor of about 1.5 by 2040, corresponding to an average growth rate of 1.4% per year. In the USA the Energy Information Administration (EIA, 2012a) forecasts a 0.72% per year growth rate for retail electricity sales between 2010 and 2025. All these predictions take into account the expected effects of energy efficiency. Continued growth in electricity use is likely, for several reasons:

i) Much energy conservation, especially in industry, involves replacing fossil fired technologies by electricity, for example switching from drying by hot air (heated by burning fuel) to drying by microwaves. Such changes reduce the consumption of primary energy but increase the consumption of electricity; they also reduce costs and/or improve the product quality—otherwise industry would not make such changes. The pressure for such changes increases with the cost of CO_2 tax or permits.
ii) A similar development can be expected in the transport sector with a shift to electric vehicles, as one of the avenues to increase transportation efficiency and reduce greenhouse gas emissions. Typical scenarios for the transport sector predict that much if not most of road transport will be electric in a few decades.
iii) Heating by heat pump can be very cost-effective for sufficiently moderate climate zones; in the USA, for example, heat pumps are popular even as far north as New York and Chicago, where winters are quite severe. Except for very cold climates the life cycle greenhouse gas emission of heat pumps for space heating tend to be lower than space heating by natural gas. Such an option is particularly attractive if the heat pump is reversible, i.e., provides also air conditioning in summer—an important consideration in view of global warming.
iv) Historically electricity consumption per capita has been increasing (except during some deep recessions) despite major improvements in overall energy efficiency. At the same time the U.S. energy intensity (amount of energy needed per $ of GDP) has been decreasing, while the fraction of energy used for electricity has been increasing; the greater the electrification of energy uses and industrial processes, the more efficient the U.S. economy became. All forecasts indicate that this electrification trend will continue and it is unlikely that there will be any appreciable decline in electricity use in the foreseeable future.

On the other hand the impact of energy efficiency improvements may be larger than the above forecasts. Barbose et al. (2013) carry out a detailed analysis of energy efficiency programs funded by utility customers in the United States and conclude that these programs may reduce the growth foreseen by EIA (2012a) to such an extent that the total retail sales of electricity in 2025 may be essentially the same as the present level. York et al. (2013) go even further and argue that an aggressive energy efficiency program could reduce the electricity consumption in 2030 by 27% below the EIA forecast—implying a potential decrease of about 15% compared to the present.

However, in many countries with nuclear power plants the fraction of electricity supplied by nuclear is so high (e.g., USA ~20%, Spain ~20%, UK ~15%, Germany ~18%, Switzerland ~40%, Japan before Fukushima ~30%) that in the foreseeable future total replacement by energy efficiency is unlikely and alternative power sources will be needed. This paper compares the external costs of continued operation with such alternatives—an assessment that would still be appropriate for the balance of the nuclear generation fleet.

3.3. Substituting renewables for nuclear capacity

In order to analyze renewable substitutes for nuclear generation, it is important to understand the role of nuclear in the power system. In most modern systems nuclear and coal plants provide baseload capacity (capacity which is exceeded by the system load most of the time) and operate at full power virtually all the time. The measure of the "utilization" of the power plant is the capacity factor, defined as the actual annual output divided by the output the plant could provide if it operated at rated capacity for the entire year. Capacity factors for typical U.S. nuclear plants are in excess of 90%.

Hydro would be an excellent alternative because it can be dispatched according to need and the external costs would be low at most sites. However, the potential for additional hydro in most of Europe and North America is too limited for replacing most of the nuclear plants.

As for wind and solar, capacity factors in the U.S. are in the range of 25–35% for on-shore wind (see e.g., LBL, 2012) and in the range from 15 to 20% for photovoltaics, depending on location (see e.g., DOE, 2011). The on-shore wind capacity factors in Europe range from about 15% in France to about 27% in the U.K. (Lightbucket, 2008), averaging slightly over 20% (Boccard, 2009). The State of Victoria, Australia, reports over 30% for wind (Sustainability Victoria, 2011). The present analysis uses the range of 25 to 35% with 30% as the central value for wind, even though this may be too optimistic for European conditions.

The large difference between capacity factors of nuclear and renewables is one of the drivers of the need to augment renewable resources by other options to provide the balance of the nuclear electricity supply to be replaced. The other major driver is the need to maintain reliability similar to that provided by the nuclear plant.

To come close to the nuclear capacity factor, wind and solar would have to be augmented by large-scale, long-term storage and/or fossil plants. Excess electricity generated by renewables could be stored and later used to compensate for the variations in supply from renewable resources—the sun does not shine all the time, wind does not blow all the time, and the output fluctuates with cloud patterns or wind speed. At the present time and in the foreseeable future pumped hydro is the most promising option for grid-level storage and at the same time an excellent complement to renewables. Several plants have recently come on line or are under construction in the U.S. and Europe and new design concepts are being pursued. The round-trip efficiency is 75–80% (MWH, 2009), but at current costs it is expensive to dedicate the entire storage system to a complete replacement of nuclear by renewables. Thus gas-fired plants would currently be the most likely alternative to fill some or all of the gap in electricity supply created when attempting to replace a nuclear plant with renewables.

The discussion below illustrates the issues that arise while attempting to substitute wind for a nuclear plant. As stated above, the objective is to create a wind-based system which behaves as a nuclear plant operating at 90% capacity factor. Here the nominal capacity of the wind fleet is assumed equal to the nuclear capacity to be replaced. This is the simplest assumption in absence of a specific wind duration curve (frequency distribution of wind electricity output). In practice, somewhat higher penetrations of

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wind supply can be achieved if wind capacity is sized larger and some of the output is curtailed (or stored).

Since wind operates at a capacity factor ranging from 25 to 35%, the balance of electricity needs (75 to 65%) has to be provided by fossil generation. Much of the time these fossil plants will operate at part load, causing a decline in efficiency and increase in greenhouse gas emissions per kWh. However, to keep the analysis simple, this effect is ignored here, resulting in a potential underestimate of the external costs of the alternative.

In addition to the plants needed to provide all of electricity that would have been generated by the nuclear plants, fast-response capacity (see e.g., ICF, 2011) may be needed to compensate for any unexpected rapid changes in wind output. This could be met by demand response or fossil generation, which would be the least efficient part of the system. However, the energy contribution is relatively small and will be ignored for this analysis.

The specific assumptions are summarized in Table 2. It is not necessary to provide similar data for the fossil plant; with the simplifying assumptions discussed above, externalities depend only on the amount of energy supplied by fossil and that in turn is the difference between the baseline nuclear generation and the useful output of the wind plant. In the context of this paper "useful" is the amount generated at less than the capacity of the nuclear plant. However, in the simple example discussed here, the nominal wind capacity is equal to the nuclear capacity; therefore all wind production is useful.

Like the private costs, the external costs have two components: a capacity cost (due to burdens from the construction of the plant) and an energy cost (due to burdens from the production of electricity). For nuclear and fossil plants the capacity cost component is orders of magnitude smaller than the energy component and can be neglected. For wind, solar and hydro only the capacity component of the external costs is significant. It can be expressed as an equivalent cost per kWh by making appropriate assumptions about lifetime, discount rate and capacity factor. Not surprisingly, the external costs of wind, solar and hydro are so low that they can be neglected in view of the uncertainties of the much larger cost elements; for example Markandya et al. (2010) cite costs less than 0.1 €cent/kWh. The resulting assessment of emissions and damage costs of the alternatives is shown in Table 3. The health damage costs of NGCC, 0.6 €cent/kWh, are also based on Markandya et al. (2010).

As mentioned earlier, it would be possible to increase the fraction replaced by renewables by increasing the nominal capacity of the wind system. This, of course would increase the cost of the system and, unless the excess can be stored for later use, it would also result in some wind curtailment.

3.4. Comparison of external costs

Fig. 1 compares the external costs of nuclear (Table 1) with the alternative (Table 3). For the central estimate, with a social discount rate of 5%, the external cost of the alternative is about 50% higher than that of nuclear. If NGCC without wind is used as alternative, the external cost of the alternative would be a factor of 1.5 (1/0.66) higher—more than twice the cost of nuclear.

The calculations help identify the most important assumptions for the analysis. Clearly the amount of electricity produced from natural gas, the cost of greenhouse gases and the accident frequency are crucial. Among nuclear costs the number of permanently displaced people is the most important factor, highlighting the need to take a close look at plants in regions with high population density or old plants with insufficient safety measures; in such cases a shutdown may indeed be justified. On the other hand, for plants that meet the safety goals of the U.S. Nuclear Regulatory Commission the accident frequency and hence the external costs would be an order of magnitude lower. Perhaps surprisingly, the cost of cancers makes a relatively minor contribution, even though the value is based on Chernobyl, which was much higher than Fukushima. The cost of lost agricultural production is also relatively unimportant.

In addition to the parameters for which we show a range of possible values in Tables 1 and 3, the comparison is also affected by the choice of the discount rate and the capacity factor of the nuclear plants. Within our simple model the discount rate affects only the cost of nuclear since we take the cost of greenhouse gases as given (even though in reality it increases if the discount rate is lowered). Reducing the capacity factor of nuclear reduces the amount of energy to be supplied by NGCC and hence the corresponding emissions. The influence of these parameters is rather weak. Reducing the discount rate from 5 to 3% would lower the ratio of alternative/nuclear from 1.54 to 1.37 (and the ratio of alternative, low/nuclear, high from 0.12 to 0.11), not a significant change. Reducing the capacity factor of nuclear plants from 90 to 80% would reduce the external costs ratio of alternative/nuclear from 1.54 to 1.45 (and the ratio of alternative, low/nuclear, high from 0.12 to 0.11), also not a significant change. In fact, the nuclear capacity factor would have to be close to 50% for the

Table 2
Assumptions for performance of nuclear and wind plants.

	Central (%)	Low (%)	High (%)
Nuclear Plant			
Capacity factor	90	90	90
Wind			
Capacity factor	30	25	35

Table 3
Assumptions and results for the external costs of alternative generation mix. ("Fraction of energy replaced by…" refers to the fraction of the kWh that would have been produced by nuclear. GHG = greenhouse gases).

Cost elements	Units	Central	Low	High
Cost of GHG	€/t_{CO_2eq}	25	8.3	75
Fraction of energy replaced by wind[a]		0.34	0.38	0.27
Damage cost of wind	**€cent/kWh**	**0**	**0**	**0**
GHG emissions from NGCC	kg/kWh	0.5	0.5	0.5
Cost of GHG emissions from NGCC	€cent/kWh	1.25	0.42	3.75
Health damage costs from NGCC	€cent/kWh	0.6	0.2	1.8
Fraction of energy replaced by gas (NGCC)		0.66	0.62	0.73
NGCC contribution due to GHG costs	**€cent/kWh**	**0.83**	**0.26**	**2.74**
NGCC contribution due to health damage costs	**€cent/kWh**	**0.40**	**0.12**	**1.31**
Total external cost of alternative	**€cent/kWh**	**1.22**	**0.38**	**4.05**

[a] These fractions are higher than the wind capacity factors provided in Table 2 because of the 90% capacity factor assumed for nuclear.

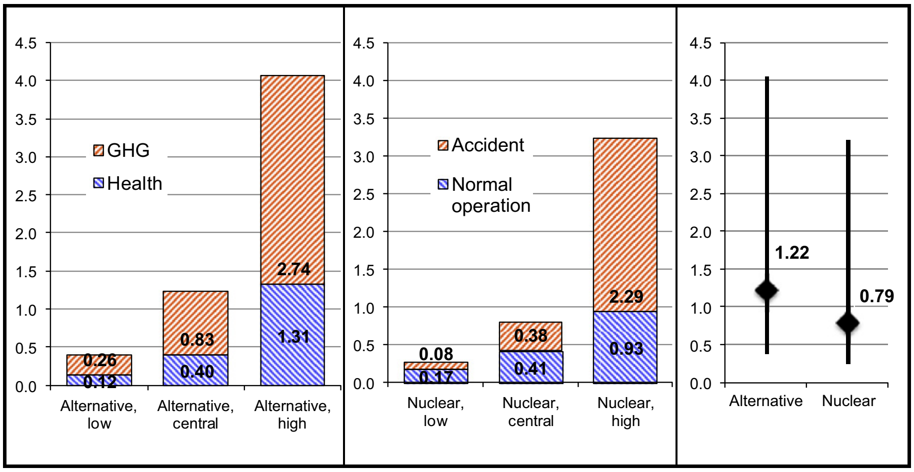

Fig. 1. Comparison of external costs (€cent/kWh). The right panel shows the total external cost, with error bars corresponding to the high and low estimates.

external cost of the alternative to be less than that of nuclear. Thus the effect of these parameters is small compared to the largest sources of uncertainty discussed above.

4. Discussion and conclusions

Since the uncertainty ranges in Fig. 1 overlap, one cannot exclude the possibility that the alternative could have lower external costs. However, since decisions about energy choices should take into account the total social cost, i.e., the sum of external and private costs, it is instructive to take a look at the latter. An early retirement of nuclear power plants would certainly increase the private (non-external) cost of electricity and it can be justified only if the reduction of the external cost more than compensates for the cost increase.

4.1. How do external costs compare to private cost

A rigorous comparison of private costs would be a complex undertaking, far beyond the scope of this paper, hence the rough estimates presented here are based on EIA (2012b) levelized cost data for new power plants. This data includes many simplifying assumptions and, as emphasized by the explanations in the full EIA report, should be treated with caution.

As with external costs, the private costs are estimated for two options:

A) Continue operating an existing nuclear plant
B) Replace it by the alternative based on NGCC and wind.

Since the capital costs of the nuclear plant are the same, whether it operates or not, only the O&M costs need to be taken into account when comparing the two options. Table 4 lists the private costs; Table 5 compares the total social costs. The headings Central, Low, and High in Table 5 reflect only the uncertainty range of the external costs. As indicated above, full estimation of private costs is outside the scope of this paper and is presented here only to provide order-of-magnitude comparisons.

As seen in the table, external costs can be significant compared to private costs and should not be neglected in the decision making.

Table 4
Comparison of private costs.

Option	$/MWh	€cent/kWh[a]
(A) Nuclear plant, O&M only	22.9[b]	1.76
NGCC, total private	63.1[c]	4.85
Wind, total private	96.0[c]	7.38
(B) Alternative, total private		5.71[d]

[a] Assuming exchange rate of 1.3 €/$.
[b] From EIA (2012b): private cost of continuing operation of existing nuclear plants (only the costs for O&M).
[c] From EIA (2012b): total private costs of advanced NGCC and of wind.
[d] Costs of NGCC and wind, weighted by their contributions (Table 3, lines 3 and 8, central) to the total cost of the alternative: $4.85 \times 0.66 + 7.38 \times 0.34 = 5.71$.

4.2. Discussion of selected alternative

The alternative considered here is wind augmented by NGCC because it is the most likely choice. For example EURELECTRIC (2010) foresees that most of the expected growth of electricity demand will be supplied by wind. Of course, the need for backup by NGCC could be reduced if more biomass and hydro were available. But the potential for biomass and hydro is too limited, as shown for example by EURELECTRIC (2010) for Europe. The forecasts of IEA (2008) for OECD countries are similar, with little increase in hydro.

For an alternative perspective on the external cost comparison it may be instructive to estimate the break-even requirements. To break even with external costs of nuclear (.79 vs. 1.22) would require that almost 60% of energy be provided by wind. In principle this could be accomplished by increasing the nominal capacity of the wind plant to about twice the capacity of the nuclear plant and storing, rather than curtailing, all excess wind output. To calculate the required size of the storage system one would need a complete time-series of wind output data. The storage would then be sized so as to assure that the entire stored amount of electricity can be used at some time. As an example, assume that 10 hours of storage would meet this requirement (see e.g., Sørensen, 1976 and Esteban et al., 2012). The power rating of the system would be equal to the added nominal wind capacity, 1 GW. Currently the cost of such a storage system would be comparable to that of a 1 GW wind turbine. So in order for the external cost of the wind system to break even with the external costs of nuclear would require a system whose private

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Table 5
Comparison of total social costs (€cent/kWh).

Option	Central	Low	High
Continued operation of nuclear plant, private[a]	1.76	1.76	1.76
Continued operation of nuclear plant, external[b]	0.79	0.25	3.22
A) Existing nuclear plant, total social cost	**2.55**	**2.01**	**4.98**
Alternative, private[a]	5.71	5.71	5.71
Alternative, external[c]	1.22	0.38	4.05
B) Alternative, total social cost (€cent/kWh)	**6.93**	**6.09**	**9.76**

[a] For this simple comparison uncertainty ranges for the private costs are not considered.
[b] See Table 1.
[c] See Table 3.

cost is roughly three-times as large as the alternative system considered in this paper.

4.3. Summary and conclusions

This paper presents an estimate of real risks and real damages, not perceived risks. Of course, in order to implement a policy, it is necessary to deal with perceptions by educating the population about the consequences of the various alternatives. Also, energy policy has to take into account the possibility or even likelihood of inappropriate actions after an accident, for instance evacuating far more people than necessary. Such costs are real.

Besides risk perception, in practice decisions about the continuation of nuclear power involve additional considerations that are difficult or impossible to quantify in monetary terms, for example, stability of the electric grid, energy independence and the risk of fuel price shocks.

This analysis should not be interpreted as an argument against renewables; quite the contrary—renewables and energy efficiency are crucial for the reduction of air pollution and greenhouse gases, not to mention the benefits of supply security by reducing the dependence on depletable resources. Renewables should be used as much as can be justified by full consideration of the total social costs. The conclusions represent merely a caution against the premature shutdown of existing nuclear plants because that entails very high private costs, costs that are most probably not compensated by a reduction of the external costs.

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References

Barbose, G.L., Goldman, C.A., Hoffman, I.M., Billingsley, M. 2013. The Future of Utility Customer-Funded Energy Efficiency Programs in the United States: Projected Spending and Savings to 2025. Environmental Energy Technologies Division, Lawrence Berkeley National Laboratory Report LBNL-5803E.

Boccard, N., 2009. Capacity factor of wind power realized values vs. estimates. Energy Policy 37 (2009), 2679–2688.

Cardis, E., Krewski, D., Boniol, M., et al. (2006). The Cancer Burden from Chernobyl in Europe. World Health Organization, International Agency for Research on Cancer Briefing Document, April 20. 〈http://www.iarc.fr/en/media-centre/pr/2006/IARCBriefingChernobyl.pdf〉.

Cochran, T.B., McKinzie, M.G. 2011. Global Implications of the Fukushima Disaster for Nuclear Power. Natural Resources Defense Council, Inc, and World Federation of Scientists' International Seminars on Planetary Emergencies, Ettore Majorana Centre, Erice, Sicily, August 19–25, 2011. 〈http://docs.nrdc.org/nuclear/nuc_11102801.asp〉.

Cour des Comptes 2012. "Les coûts de la filière électronucléaire" (The costs of nuclear power). Rapport public thématique. January 2012. Cour des Comptes, 13 rue Cambon 75100 PARIS.

DEFRA 2005, The Social Costs of Carbon (SCC) Review—Methodological Approaches for Using SCC Estimates in Policy Assessment, Department for Environment, Food and Rural Affairs, London. 〈http://www.decc.gov.uk/assets/decc/what%20we%20do/a%20low%20carbon%20uk/carbon%20valuation/social_cost/aeat-scc-report.pdf〉.

DOE 2011. 2010 Solar Technology Market Report, US Department of Energy report DOE/GO-102011-3318, November 2011; 〈http://www.nrel.gov/docs/fy12osti/51847.pdf〉.

DOE-NETL 2010. Improving the Efficiency of Coal-Fired Power Plants for Near Term Greenhouse Gas Emissions Reductions, DOE/NETL-2010/1411, April 2010.

EIA 2012a. Annual Energy Outlook, 2012. Energy Information Administration. 〈http://www.eia.gov/forecasts/aeo/pdf/0383(2012).pdf〉.

EIA 2012b. Levelized Cost of New Generation Resources in the Annual Energy Outlook 2012. US Energy Information Administration. 〈http://www.eia.gov/forecasts/aeo/electricity_generation.cfm〉.

Esteban, M., Zhang, Q.I., Utama, A., 2012. Estimation of the energy storage requirement of a future 100% renewable energy system in Japan. Energy Policy 47 (2012), 22–31.

EURELECTRIC 2010. Power Choices: Pathways to Carbon-Neutral Electricity in Europe by 2050, Full Report. The Union of the Electricity Industry, Brussels. Downloaded 3 May 2012 from 〈http://www.eurelectric.org/media/45274/power__choices_finalcorrection_page70_feb2011-2010-402-0001-01-e.pdf〉.

EURELECTRIC 2011. Power Statistics & Trends 2011—Synopsis. The Union of the Electricity Industry, Brussels. Downloaded 3 May 2012 from 〈http://www.eurelectric.org/PowerStats2011/PowerStats2011.asp〉.

ExternE 1995. ExternE: Externalities of Energy. ISBN 92-827-5210-0. Vol.5: Nuclear (EUR 16524). Published by European Commission, Directorate-General XII, Science Research and Development. Office for Official Publications of the European Communities, L-2920 Luxembourg.

GAO 2009. NUCLEAR WASTE MANAGEMENT: Key Attributes, Challenges, and Costs of the Yucca Mountain Repository and Two Potential Alternatives. Highlights of GAO-10-48, a Report to Congressional Requesters. United States Government Accountability Office, Nov. 2009.

Hirschberg, S., Burgherr, P., Spiekerman, G., Dones, R., 2004. Severe accidents in the energy sector: comparative perspective. Journal of Hazardous Materials 111, 57–65.

IAEA 2005. Chernobyl: The True Scale of the Accident. International Atomic Energy Agency, World Health Organization, and United Nations Development Programme. 2005. 〈http://www.who.int/mediacentre/news/releases/2005/pr38/en/index.html〉 (accessed 07 Jan. 2012).

ICF 2011. Integrating Variable Renewable Electric Power Generators and the Natural Gas Infrastructure, ICF, Nov. 2011, 〈http://www.icfi.com/insights/white-papers/2011/integrating-variable-renewable-electric-power-generators-natural-gas-infrastructure〉.

IEA 2008. World Energy Outlook 2008. International Energy Agency, 9 rue de la Fédération, 75739 Paris Cedex 15, France. Available at 〈http://www.iea.org/Textbase/about/copyright.asp〉.

LBL 2012. "Recent Development in the Levelized Cost of Energy from U.S. Wind Power Projects," presentation by Ryan Wiser et al., Lawrence Berkeley National Laboratory, February 2012; 〈http://www.awea.org/_cs_upload/blog/14816_1.pdf〉.

Lightbucket 2008. The capacity factor of wind power. Wordpress 2008; 〈http://lightbucket.wordpress.com/2008/03/13/the-capacity-factor-of-wind-power/〉.

Markandya, A., Bigano, A., Roberto Porchia, R., 2010. The Social Cost of Electricity: Scenarios and Policy Implications. Fondazione Eni Enrico Mattei. Edward Elgar Publishing Ltd, Cheltenham, UK.

MWH 2009. Montgomery, Watson, Harza, Technical Analysis of Pumped Storage Integration with Wind Power in the Pacific Northwest Prepared by MWH Americas for the U.S. Army Corps of Engineers Northwest Division Hydro-electric Design Center, August 2009.

National Diet of Japan 2012. The Official Report of The Fukushima Nuclear Accident Independent Investigation Commission. Submitted 5 July 2012 to The National Diet of Japan. 〈http://naiic.go.jp/en/〉.

NRC 2010. "Hidden Costs of Energy: Unpriced Consequences of Energy Production and Use". National Research Council of the National Academies, Washington, DC. Available from National Academies Press. 〈http://www.nap.edu/catalog.php?record_id=12794〉.

Ontario Hydro. 1993. Full Cost Accounting for Decision Making. Toronto: Ontario Hydro, 700 University Ave. H18 J18 Toronto, Ontario. December 1993.

ORNL/RFF 1994. Estimating Externalities of Nuclear Fuel Cycles. Vol.8 of External Costs and Benefits of Fuel Cycles. Prepared by Oak Ridge National Laboratory and Resources for the Future. Edited by Russell Lee, Oak Ridge National Laboratory, Oak Ridge, TN 37831. 〈http://www.ornl.gov/info/reports/1995/3445604259148.pdf〉.

Rabl, A., 1996. Discounting of long term costs: what would future generations prefer us to do? Ecological Economics 17, 137–145 1996.

Sørensen, B., 1976. Dependability of wind energy generators with short-term energy storage. Science 26, 935–937, Nov. 1976.

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Spadaro, J.V., Rabl, A., 2008. Estimating the uncertainty of damage costs of pollution: a simple transparent method and typical results. Environmental Impact Assessment Review 28 (2), 166–183.

Stern, N., et al., 2006. The Economics of Climate Change: The Stern Review. Cambridge University Press, Cambridge, UK, Available at.

Sustainability Victoria 2011.Victorian Wind Update: Quarter 4, 2011, Sustainability Victoria, 〈http://www.sustainability.vic.gov.au/resources/documents/2011_Q4_Quarterly_Wind_Update.pdf〉.

Tol, R.S.J., 2005. The marginal damage costs of carbon dioxide emissions: an assessment of the uncertainties. Energy Policy 33, 2064–2074.

von Hippel, F.N., 2011. The radiological and psychological consequences of the Fukushima Daiichi accident. Bulletin of the Atomic Scientists 67 (5), 27–36.

Wilson, R., 2012. Evacuation criteria after a nuclear accident: a personal perspective. Dose–Response, March 12.

Yasunari, T.J., Stohl, A., Hayano, R.S., Burkhart, J.F., Eckhardt, S., Yasunari, T. 2011. Cesium-137 deposition and contamination of Japanese soils due to the Fukushima nuclear accident. Proceedings of the National Academy of Sciences. PNAS 2011 108 (49) 19530-19534; published ahead of print November 14, 2011, doi:10.1073/pnas.1112058108; 〈http://www.pnas.org/content/108/49/19530〉 (accessed 07 Jan. 2012).

York, D., Molina, M., Neubauer, M., Nowak, S., Nadel, S., Chittum, A., Elliott, N., Farley, K., Foster, B., Sachs, H., Witte, P. 2013. Frontiers of Energy Efficiency: Next Generation Programs Reach for High Energy Savings. American Council for and Energy-Efficient Economy. Report U131, 〈http://www.aceee.org/research-report/u131〉.

Please cite this article as: Rabl, A., Rabl, V.A., External costs of nuclear: Greater or less than the alternatives? Energy Policy (2013), http://dx.doi.org/10.1016/j.enpol.2013.02.028