The Full Costs of Electricity Provision

Executive Summary

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NUCLEAR ENERGY AGENCY
ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

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The OECD is a unique forum where the governments of 35 democracies work together to address the economic, social and environmental challenges of globalisation. The OECD is also at the forefront of efforts to understand and to help governments respond to new developments and concerns, such as corporate governance, the information economy and the challenges of an ageing population. The Organisation provides a setting where governments can compare policy experiences, seek answers to common problems, identify good practice and work to co-ordinate domestic and international policies.

The OECD member countries are: Australia, Austria, Belgium, Canada, Chile, the Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Israel, Italy, Japan, Korea, Latvia, Luxembourg, Mexico, the Netherlands, New Zealand, Norway, Poland, Portugal, the Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The European Commission takes part in the work of the OECD.

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NUCLEAR ENERGY AGENCY

The OECD Nuclear Energy Agency (NEA) was established on 1 February 1958. Current NEA membership consists of 33 countries: Argentina, Australia, Austria, Belgium, Canada, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Korea, Luxembourg, Mexico, the Netherlands, Norway, Poland, Portugal, Romania, Russia, the Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The European Commission and the International Atomic Energy Agency also take part in the work of the Agency.

The mission of the NEA is:

– to assist its member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally sound and economical use of nuclear energy for peaceful purposes;

– to provide authoritative assessments and to forge common understandings on key issues as input to government decisions on nuclear energy policy and to broader OECD analyses in areas such as energy and the sustainable development of low-carbon economies.

Specific areas of competence of the NEA include the safety and regulation of nuclear activities, radioactive waste management, radiological protection, nuclear science, economic and technical analyses of the nuclear fuel cycle, nuclear law and liability, and public information. The NEA Data Bank provides nuclear data and computer program services for participating countries.

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Executive summary

Electricity production, transport and consumption affect every facet of life in the advanced market economies of countries such as those which are members of the Organisation of Economic Co-operation and Development (OECD) and the Nuclear Energy Agency (NEA). Market prices and production costs are important measures of the economics of electricity. However, over at least the past two decades, there has been a growing recognition that these values do not represent the whole story; the social and environmental impacts of electricity provision affect individuals, economies and countries in ways that are not captured in market prices, but yet are too important to be neglected.

Despite their importance, full accounting for these costs remains difficult. From researching biophysical dose-response function, calibrating dispersion models and probabilistic assessments to the contentious issue of monetary valuation, different groups of experts need to be co-ordinated in large-scale multi-year efforts to arrive at robust results. Such a large, systematic effort is, however, beyond the scope of this report.

Nevertheless, the issue is too important to be disregarded. The NEA has therefore decided to produce the present study on *The Full Costs of Electricity Provision* in order to summarise and synthesise the most recent research in this area. Research on the full costs of energy and electricity is an ongoing effort. The report highlights the importance of full cost accounting, in particular in the context of the energy transitions under way in several countries. Ideally, it will contribute to spawning new and more comprehensive research in the area of the full costs of electricity to allow policy makers and the public to take better informed decisions along the path towards fully sustainable electricity systems.

For a number of years, the NEA has been analysing and researching different aspects of the full costs of electricity. The results of this work have found their expression in a number of publications that have already appeared or are forthcoming. While most of these publications centred on nuclear energy, others included different sources of power generation. They include:

- *Risks and Benefits of Nuclear Energy* (2007).
- *Comparing Nuclear Accident Risks with Those from Other Energy Sources* (2010).
- *The Security of Energy Supply and the Contribution of Nuclear Energy* (2010).
- *Projected Costs of Generating Electricity: 2010 Update* (2010), with the International Energy Agency (IEA).
- *Economics of Long-term Operations of Nuclear Power Plants* (2012).
- *Nuclear Energy and Renewables: System Effects in Low-carbon Electricity Systems* (2012).
- *The Economics of the Back End of the Nuclear Fuel Cycle* (2013).
- *Projected Costs of Generating Electricity: 2015 Update* (2015), with the IEA.
- *Nuclear Energy: Combating Climate Change* (2015).
- *Costs of Decommissioning Nuclear Power Plants* (2016).

The NEA is also currently working on a number of publications with relevance to the discussion on full costs and that will be forthcoming in the coming months. These include *Climate Change: Assessment of the Vulnerability of Nuclear Power Plants and Adaptation Costs*, *Estimation of Potential Losses Due to Nuclear Accidents*, *Measuring Employment Generated by the Nuclear Power Sector* and *System Costs in Deep Decarbonisation Scenarios: The Contributions of Nuclear Energy and Renewables*.

A significant number of studies have also been published by other institutions, including the OECD Environment Directorate (see, for instance, *The Economic Consequences of Outdoor Air Pollution*, *The Cost of Air Pollution: Health Impacts of Road Transport* or *Mortality Risk Evaluation in Environment, Health and Transport Policies*) and the IEA (see, for instance, *World Energy Outlook Special Report 2016: Energy and Air Pollution* or *Harnessing Variable Renewables: A Guide to the Balancing Challenge*) alongside a rich academic literature on the full costs of energy, some of which is summarised in the different chapters of this report.

Full costs: Key concepts, measurement and internalisation

The costs of electricity provision fall into three different, comprehensible categories. The first category is constituted of plant-level costs, which include the concrete and steel used to build the plant, and the fuel and the manpower to run it. The NEA and the IEA publish a survey of the plant-level costs in OECD countries every five years in the *Projected Costs of Generating Electricity* series (see IEA/NEA, 2010 and IEA/NEA, 2015; IEA/NEA, 2020 is currently in preparation).

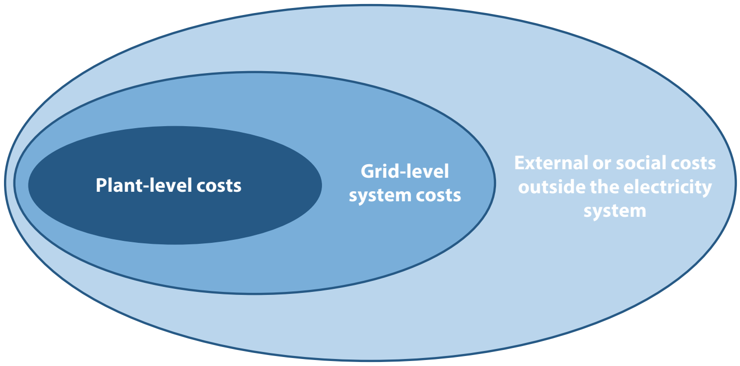
The second category concerns the costs at the level of the electricity system, linked through the transmission and distribution grid. It includes the costs that plants impose on the system in terms of extending, reinforcing or connecting to the grid, but also the costs for maintaining spinning reserves or additional dispatchable capacity when the output of some technologies – typically wind and solar photovoltaic (PV) – is uncertain or variable.

The third, even broader, category includes items that impact the well-being of individuals and communities outside the electricity sector. Known as external or social costs, such costs include the impacts of local and regional air pollution, climate change, the costs of major, frequently not fully insurable, accidents, and land use or resource depletion. Social costs also include the impacts of different power technology choices on the security of energy and electricity supply, employment and regional cohesion or on innovation and economic development. If these impacts are negative, they add to the full costs of a technology; if they are positive, in principle, they need to be deducted as a social benefit.

The full costs of energy provision now include the totality of the three categories: plant-level costs of generation, grid-level system costs and the external social and environmental costs (see Figure ES.1).

In the case of both grid-level system costs and external costs, the actors who cause them are not those who are primarily affected by them. Grid-level system costs thus have an "external" or "social" component as well. In essence, this means that an outside actor, the government, the regulator or the system operator, needs to step in to ensure that such external costs are not overproduced and are correctly internalised. Economic theory has devised a number of corresponding instruments, including standards and technical regulations, pollution taxes, new markets such as emissions trading, better information and research, as well as an overall strengthening of the legal system. Overcoming the knowledge gap is also part of moving towards sustainable electricity systems.

Figure ES.1: **Different cost categories composing the full costs of electricity provision**



Source: NEA, 2012b.

Concerns about higher electricity prices have regularly stunted internalisation efforts. However, it is the responsibility of experts and informed policy makers to insist on internalising social costs, since a reasonable degree of confidence exists that cost internalisation will improve the well-being of society as a whole, meaning that the pie will only become larger. Such internalisation will need to take place at the level of the individual technology in order to induce the relevant substitution effects that will lead to an overall system that minimises the full costs of electricity provision. Where necessary, appropriate compensation mechanisms can be devised to overcome unwelcome distributional consequences.

Accounting for full costs based on the measurement of external costs is not an uncontroversial topic. The monetisation of social costs outside a market framework can be misunderstood as an attempt to reduce human well-being to a question of dollars and cents. The large uncertainties involved, which can produce results that change considerably over time or between comparable projects, are also easy targets for detractors. Others have pointed to social factors as one of the impacts that will remain outside the scope of even very comprehensive efforts.

Most of these criticisms are based on a misunderstanding of what full cost accounting is trying to achieve. Estimates established for the social cost portion of the full costs of electricity provision will never be able to mimic the more reliable information about individual and social preferences conveyed by market prices. The objective is to provide order-of magnitude estimates that allow public discussion and policy making to integrate the most pressing issues in a meaningful way into the inevitable trade-offs that characterise all policy making. In doing so, full cost accounting will unavoidably mix hard market data, reasonably reliable estimates and less reliable estimates. The latter estimates may best be considered, even when undertaken by well-intentioned and experienced practitioners, as intelligent and informed guesswork.

A certain level of social costs due to air pollution, for example, or the impacts of a major accident, are often associated with a representative technology as they are in the present report. The presence or absence of specific pollution control equipment or certain physical barriers, could reduce or increase such impacts. In such cases, pragmatic good judgement needs to be applied to the decision on which reference technology to use. It is primarily for this reason that this report is organised according to subject area rather than according to technology. The goal is not to establish rankings but to draw attention to understudied issues that should be better internalised into the policy process.

Does this mean that any number is no better than the absence of a number as is sometimes advanced? For policy-making purposes, a number advanced by a responsible researcher on the basis of the best available information with the appropriate sources, uncertainties and *caveats* would certainly be better than no number, despite the uncertainties and the *caveats*. The purpose of full cost accounting is not to engage in economic imperialism, nor is it to establish futile oppositions between market prices and social costs. Its sole purpose is to allow for better policy making in the electricity sector.

Overall, this study takes a pragmatic, partial equilibrium approach. The externalities of energy provision in different policy areas such as grid-level system costs, atmospheric pollution or climate change are thus considered one by one. The alternative of considering them together, with the help of a computable general equilibrium (CGE) model, economy-wide input-output models or a macro-econometric model, would have diminished the transparency and readability of findings which are first and foremost addressed to policy makers. Facilitating a more comprehensive and structured discussion of such issues at the policy-making level, rather than at the research level, is the primary purpose of this report.

Plant-level production costs

Plant-level production costs limit themselves to the first and the smallest of the three categories indicated above in Figure ES.1. The NEA began reporting plant-level costs in the *Projected Costs of Generating Electricity* series in 1983, comparing nuclear power plant (NPP) and coal-fired power plant costs. The IEA joined the NEA in publishing this report in 1989. Together, the two agencies updated the study in 1992, 1998, 2005, 2010 and 2015 to evaluate the levelised cost of electricity (LCOE) for a variety of technologies.

The LCOE indicates the discounted lifetime costs for different baseload technologies, averaged over the electricity generated. It has its purpose for informing the investment choices of electric utilities in regulated electricity systems, but it is less pertinent in deregulated electricity systems where revenues vary from period to period over an electricity generator's lifetime. LCOE is also unable to capture the system costs of certain technologies (see Figure ES.2 below). Despite these limitations, it often remains an attractive first reference because of its simplicity and transparency.

Figure ES.2: **Plant-level costs for different power generation technologies**

(USD per MWh)

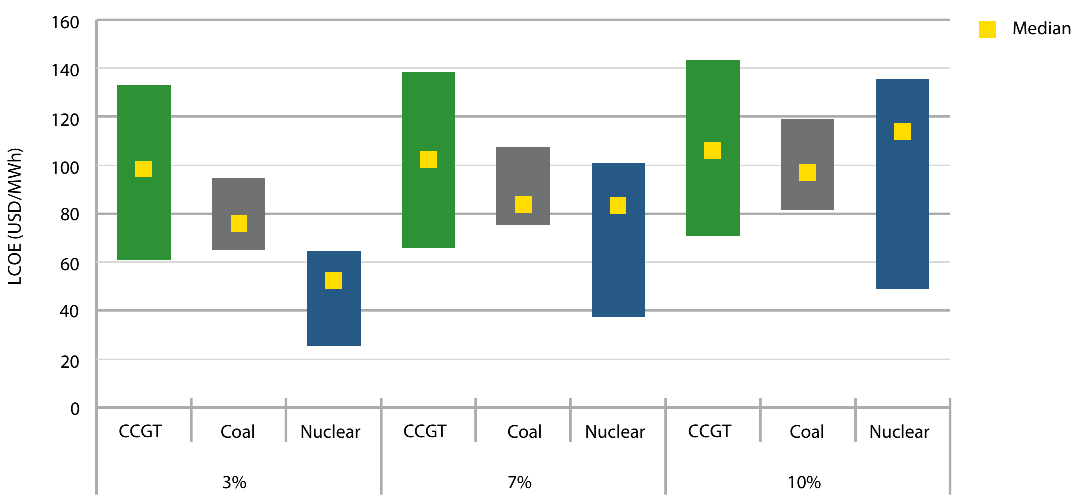
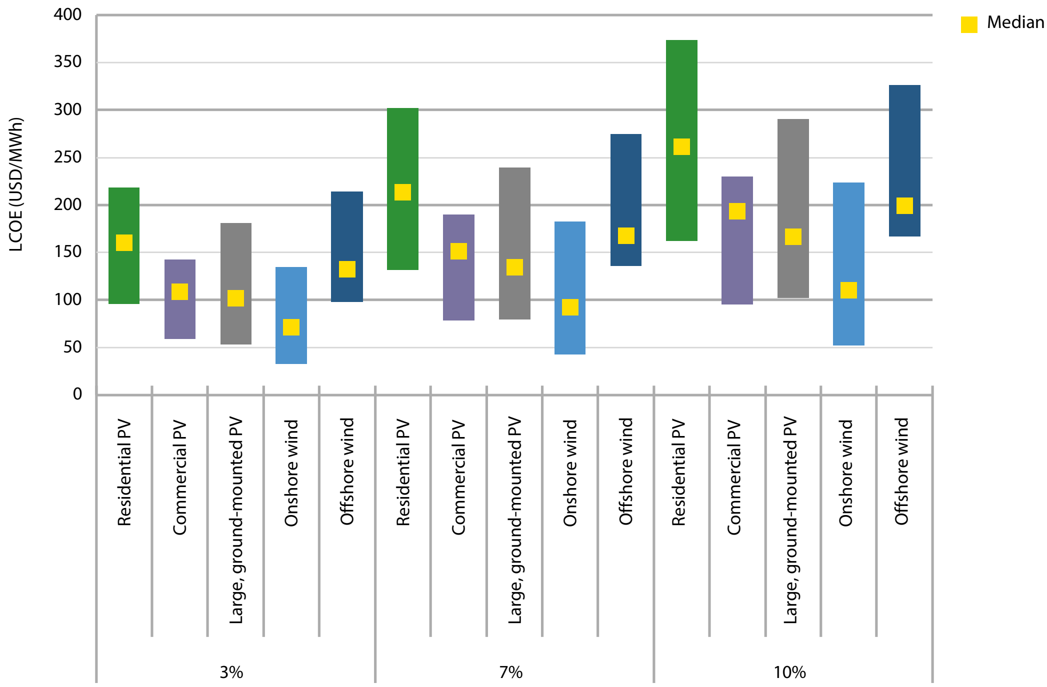


Figure ES.2: **Plant-level costs for different power generation technologies** *(cont'd)*

(USD per MWh)



Source: IEA/NEA, 2015.

Figure ES.2 provides estimates of plant-level costs for dispatchable and renewable power generation technologies at capital costs of 3%, 7% and 10%, assuming region-specific fuel prices, an 85% load factor for nuclear, coal and gas, as well as a carbon price of USD 30 per tonne of CO_2. The latter assumes that the social costs of climate change due to carbon emissions are at least partially internalised in the policy provisions of OECD countries (IEA/NEA, 2015, Figure ES.1, p. 14 and Figure ES.2, p. 15). With the direct carbon emissions of coal being around one tonne per MWh and those of gas around 400 kg per MWh, their respective median values would be around USD 30 and USD 12 lower, if strictly no efforts to reduce CO_2 emissions were made.

Grid-level system costs

While system costs have always existed in unbundled electricity systems, the topic has moved into focus over the last few years with the deployment of significant amounts of variable renewable energy (VRE) sources in many OECD countries. Such system effects are often divided into the following three broad categories:

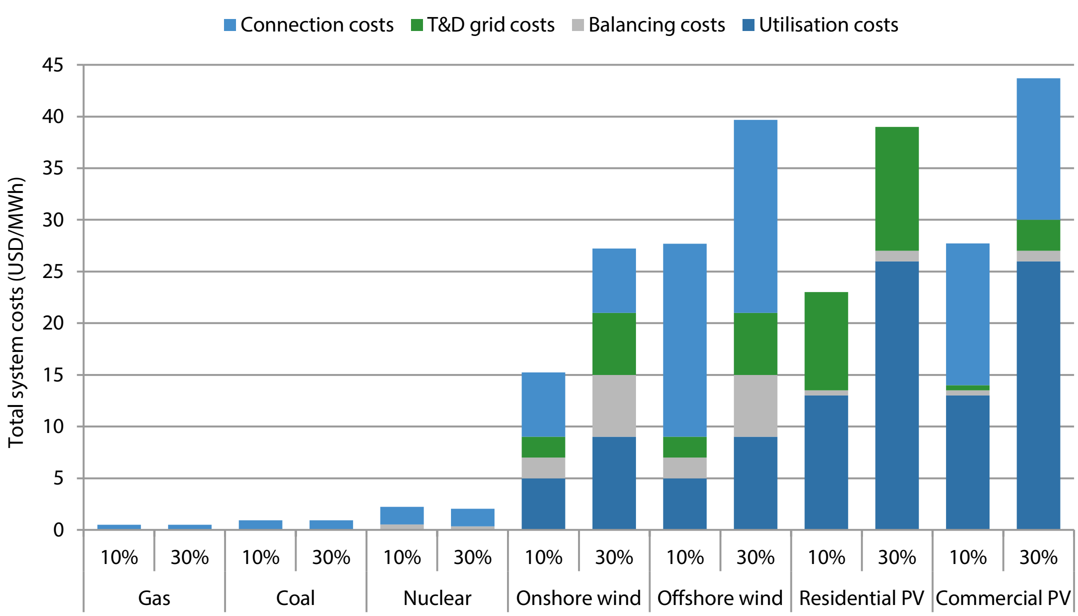
- *Profile costs* are related to the variability of VRE output, and they are able to demonstrate that in the presence of VRE generation it is generally more expensive to provide the residual load. The overall system thus becomes more expensive even if the plant-level costs of VRE are comparable to those of dispatchable technologies.
- *Balancing costs* are related to the uncertainty of power production due to unforeseen plant outages or to forecasting errors in relation to production. Unforeseen plant outages or forecasting errors related to electricity generation require that a higher amount of spinning reserves be carried out. Uncertainties in VRE power production may also lead to an increase in ramping and cycling of conventional power plants, to inefficiencies in plant scheduling and, overall, to higher costs for the system.
- *Grid and connection costs* reflect the effects on the transmission and distribution grid infrastructure due to the locational constraint of generation plants. While all generation plants may have some siting restrictions, the impacts are more significant for VRE. Because of their geographic location constraint, it could be

necessary to build new transmission lines or to increase the capacity of existing infrastructure (grid reinforcement) in order to transport the electricity from centres of production to load. Also, high shares of distributed PV resources may require sizeable investment into the distribution network, in particular to allow the inflow of electricity from the producer to the grid when the electricity generated exceeds demand. Connection costs (i.e. the costs of connecting the power plant to the nearest connecting point of the transmission grid) can also be significant, especially if distant resources have to be connected, as is sometimes the case for offshore wind.

Any quantification of system effects is challenging, not only because of the intrinsic complexity of the phenomena involved, but also because system costs depend strongly on the individual characteristics of the system analysed, on the time frame considered, as well as on the characteristics of the technology assessed and its share in the generation mix. In addition, the composition of the generation mix and the assumptions on the availability and costs of future technologies play a key role in system cost assessments. Innovation and technological progress can further change the system over time. Any estimate of system costs is therefore bound by significant uncertainty and cannot be easily extrapolated to a different system or to a different context.

Figure ES.3 provides an example of the reconstruction of grid-level system costs for different dispatchable and renewable technologies, based on a survey of the literature and the NEA study *Nuclear Energy and Renewables: System Effects in Low-carbon Electricity Systems* (NEA, 2012), whose results continue to hold up well despite the evidence provided by the growth of variable renewables since then. The purpose of this illustrative figure is not to provide an estimate of system costs for a specific system, but rather to help visualise these effects and give an order of magnitude to their value. While uncertainties are considerable, most estimates recognise that the grid-level system costs associated with VRE integration are large and increase over-proportionally with the share in electricity generated (i.e. the penetration level). In comparison, system costs of dispatchable technologies, such as coal, gas, nuclear power or hydro, are at least one order of magnitude lower.

Figure ES.3: **Grid-level system costs of selected generation technologies for shares of 10% and 30% of VRE generation**



Given the extent of system effects and the impacts on electricity markets, governments and policy makers should introduce policies aimed as much as possible at their internalisation. More specifically, it is urgent that all technologies be exposed to the market price and bear the full cost of connecting the plant to the transmission and distribution (T&D) infrastructure.

Climate change impacts

The desire to reduce greenhouse gas (GHG) emissions in order to prevent or mitigate the impacts of anthropogenic climate change has been a high priority for policy makers in many countries for the past two decades. However, this priority has not translated into an ability to quantify and monetise the impacts of fossil fuel combustion. There are three major issues in this context: i) different dimensions of uncertainty; ii) discounting future impacts and; iii) equity issues between different stakeholders.

The multilateral process has thus chosen a different approach because of the factors mentioned above. Rather than estimating the marginal social costs, the amount of emissions considered socially optimal has been the target. Such quantitative targets can be formulated in terms of annual GHG emissions, their resulting concentration in the earth's atmosphere or in terms of the global temperature increase that the latter would cause. In the end, it was this metric that best synthesised the range and probability of different climate change impacts for policy makers and the public – the increase of the global mean temperature compared to the global mean temperature prevailing before the industrial revolution. A consensus has emerged in international fora that a temperature rise of more than 2°C should be avoided.

Table ES.1: **Marginal abatement costs for scenarios with 500 ppm and 450 ppm**

(2005 euros per tCO_2)

	2025		2050	
	Range	Mean	Range	Mean
500 ppm	37-119	60	79-226	130
450 ppm (2DS)	69-241	129	128-396	225

The marginal cost of attaining the 2DS with 450 ppm in 2050 would thus amount to EUR 225 per tCO_2-equivalent. In principle, this would correspond to the level of the carbon tax required. Ppm: parts per million.

Source: Based on Kuik et al., 2009.

A comprehensive analysis of the marginal costs corresponding to the 2DS established in a large number of different climate and energy models have obtained values for marginal abatement costs (MAC) for concentration targets of 450 and 500 ppm in 2025 and 2050 (see Table ES.1). These values imply a cost per tonne of CO_2 of at least USD 100 by 2025 and of at least USD 200 by 2050.

Air pollution

Air pollution constitutes the biggest uninternalised cost of electricity generation. According to the World Health Organization (WHO), it is the world's largest single environmental health risk. WHO studies from 2014 and 2016 find that in 2012 more than 7 million deaths were caused by air pollution (WHO, 2014a, 2014b and 2016). About 3 million deaths are due to outdoor air pollution, to which electricity is a significant contributor, and 4.3 million deaths are due to household air pollution. Even if air pollution is mainly an issue in developing countries, OECD countries are also affected. A recent study estimated the social welfare loss in OECD countries due to air pollution is far above one trillion USD, corresponding to about 3% of the gross domestic product (GDP) (OECD, 2016).

The most carefully studied sources of air pollution are particulate matter (PM) of different sizes, ground-level ozone (O_3), sulphur oxides (SO_x), nitrogen oxides (NO_x) and lead. These emissions arise during the combustion of fossil fuels, coal, oil, gas or biomass, and impact primarily the respiratory system leading to bad health (morbidity) or premature death (mortality). In both cases, large uncertainties remain. The 2012 meta-study by Burtraw, Krupnick and Sampson (2012) provides an overview of the results of four important studies that have been undertaken in the past 20 years (see Table ES.2).

Table ES.2: **Summary of estimates from four external cost studies**

(Mills* per kWh or USD per MWh)

	Coal	Peat	Oil	Gas	Nuclear	Biomass	Hydro	PV	Wind
ORNL/RFF	2.3	–	0.35-2.11	0.35	0.53	3	–	–	–
Rowe et al.	1.3-4.1	–	2.2	0.33	0.18	4.8	–	–	0.02
EC ExternE	27-202	27-67	40.3-148	13.4-53.8	3.4-9.4	0-67	0-13	8.1	0-3.4
NRC	2-126	–	–	0.01-5.78	–	–	–	–	–

* A mill is one-tenth of a cent or one-thousandth of a dollar; PV is photovoltaic.

Source: Burtraw et al., 2012.

While much remains to be said about uncertainties, population densities and wind dispersion modelling, existing work has led to some preliminary conclusions. Burtraw, Krupnick and Sampson have stated, for example, that:

> In general, the results in Table 1 [here Table ES.2] and from the literature support a rank order of fossil fuels wherein the coal fuel cycle is more damaging than the oil fuel cycle, which is more damaging than the natural gas fuel cycle. This difference would be magnified with consideration of climate change impacts… The nuclear fuel cycle has low external costs in general, although the remote probability of accidents adds a very high consequence factor into the estimates. Photovoltaics and wind are essentially emission-free energy sources at the use stage, but impacts over the life cycle occur. (Burtraw et al., 2012: pp. 13-14)

Table ES.2 does not include climate change impacts. Since fossil fuel combustion is the primary source of both GHG, and local and regional air pollution, there are obvious synergies between these two areas. While policies mitigating air pollution *can*, but do not necessarily, reduce GHG emissions, reducing GHG emissions always lowers air pollution.

The costs of major accidents

The reported number of damages – not necessarily the number of fatalities – caused by both natural catastrophes and human-made accidents has continuously increased in the last three decades. Many factors have contributed to this trend and have increased the vulnerability of societies to accidents and catastrophe hazards: growth of the population and the global economy, industrialisation, urbanisation and development of coastal and other risk-prone areas, as well as the growth of more complex and interrelated infrastructures. Better reporting may also have contributed to such vulnerability. Natural catastrophes impose the largest toll in terms of human fatalities and economic consequences. If only human-made accidents are considered, the energy sector is the second-largest contributor, with transportation causing about 60% of all mortalities (EC, 1995).

For all energy technologies, however, the external costs associated with severe accidents are several orders of magnitude lower than those caused during normal operation from pollution and carbon emissions. Risks of severe accidents in all energy chains should not be neglected, however, as they have the potential to cause large-scale and long-term impacts to human health, to the environment and to the whole of society. Severe accidents also tend to have broad media coverage and to attract the attention of the population and different stakeholders. Many studies have pointed out that such extensive media coverage may lead to an overestimation of the probability and of the perceived risk of severe accidents. The likelihood of deaths from widely reported disasters is thus perceived to be higher than that from events, which are less extensively reported in the media but have a higher mortality rate. Risk aversion also plays a role. Overall, additional scientific and economic research and more factual information on the impact of severe accidents should be undertaken and brought to the attention of the public and policy makers.

Land-use change and natural resource depletion

Different forms of electricity generation can have large and lasting impacts on the land they use, the availability of the resources they consume and the ecosystems they affect. While such impacts can be dramatic, the exact nature of land-use change is largely site- and technology-specific. Studying impacts on land-use change also poses a fundamental methodological challenge for full cost accounting: since most land is in fact privately traded, and public land falls under strict regulations in OECD countries.

The most significant external cost of land-use changes are the effects on the ecosystems of natural areas. Most electricity sources have significant land requirements when the whole fuel cycle is considered, including fuel extraction, generation and waste disposal. The fuel that has the highest land-use requirements is by far biomass.

Land use is part of the larger category of natural resource use, which includes water pollution and natural resource depletion. While the impact of power generation on water quality is limited outside mining, the depletion of non-renewable energy resources is frequently mentioned as an issue that deserves policy attention. Despite these concerns, the depletion of non-renewable resources, such as fossil fuels and uranium, should not be a major issue of consideration in policy making. As commodities with high private and little additional social value, oil, coal, gas and uranium are traded on large and liquid international markets, where information about long-term scarcity is widely known and would be priced in immediately if it ever became a genuine cause for concern. From a policy-making point of view, the best response to resource depletion concerns is to ensure that existing markets remain as open and competitive as possible and that information about resource availability is shared widely.

The security of energy and electricity supply

The continuous availability and affordability of energy and, in particular, electricity is an indispensable condition for modern societies. Unsurprisingly, governments of many countries are concerned with understanding the factors influencing the security of energy and electricity supplies and are seeking to develop policy frameworks and strategies to enhance them.

Discussions about energy supply security have for a long time lacked meaningful quantification. An indicator of the security of supply for OECD countries over 40 years was thus developed by the NEA – the simplified supply and demand index or SSDI (see Chapter 8 for further details). The SSDI shows a remarkable improvement of the security of energy supplies for the great majority of OECD countries over the 40-year time frame of the study.

The value of the SSDI significantly increased between 1970 and 2007 in most economies in the study: Australia, Canada, Finland, France, Japan, the Netherlands, Sweden, the United Kingdom and the United States. This improvement resulted from the introduction of nuclear power for electricity generation, decreasing energy intensity and increased diversification of imported fuels such as coal, oil and gas. In general, all low-carbon technologies such as nuclear energy, hydro, wind and solar possess a number of attractive characteristics in terms of external energy supply security. They differ, however, with respect to the contribution to the internal or technical security of supply, in particular in electricity systems. Governments should thus create frameworks that allow all low-carbon technologies to make their contribution to the security of energy supplies and work towards the full internalisation of system costs to further differentiate between dispatchable and non-dispatchable sources of low-carbon power.

Employment generated in the electricity sector

Since the employment required for different technologies in competitive labour markets is the result of competitive, firm cost minimisation, one might ask why employment should be considered as a positive externality. In addition to constituting an economic cost, it is because high employment rates can contribute to social cohesion and general well-being at the societal level. From this perspective, not only the quantity but also the quality of the labour that is required by different technologies should be taken into consideration. Other things being equal, the higher the qualifications of the workforce and the longer the duration of the employment contract, the greater are the positive externalities to social cohesion at the level of local, regional and national economies.

If operations and manufacturing are included, indications are that nuclear power is more labour-intensive than other forms of electricity generation. It also has higher education requirements than renewable electricity generators, which may relate positively to spillovers in terms of social cohesion and regional development. From available evidence, educational requirements (as well as salaries) appear to be higher in the NPP construction and operating sectors (although not as high as in the decommissioning and waste management sectors) than in onshore wind, and in both PV and concentrated solar power (CSP).

The impact of energy innovation on economic performance and growth

Technological change in the energy sector contributes to the macroeconomy in terms of i) value added, income and employment, ii) the functioning of the economy, firms and households that are dependent on cheap and reliable energy supply, iii) the waves of innovation and the spillovers that are generated on both the supply and demand sides, which constitute the principal reason why governments fund basic research and development (R&D) in energy. Trends in R&D funding have changed remarkably. Since 2000, the public budget for R&D on renewables has been multiplied by five, and for energy efficiency by two. For nuclear energy, there has been a sharp decrease from about USD 8 billion per year in 1980, largely for fission, to less than 3 billion today, with fusion now taking the bigger part (EC, 2016a).

R&D funding is often most successful if combined with other instruments. In climate change policy, for instance, pollution pricing should be complemented with specific support for clean innovation (e.g. through additional R&D subsidies). Promising new clean technologies deserve the highest possible attention in terms of policy support, even if this would mean reducing R&D support targeted on improving existing dirty technologies. Policies should thus support a wide range of low-carbon technologies, as no one, single silver bullet exists. Innovation policies also need to be consistent over time by using a portfolio approach with a long-term perspective.

The policy implications of full cost accounting in the electricity sector

Production and consumption of electricity are not only a major economic issue but also a large contributor to adverse impacts on human health, longevity and the natural environment. Driven by this insight, applied economic research on external effects, externalities or social costs have frequently taken the electricity sector as a starting point. In the 1990s and early 2000s, a series of broad, well-funded studies with dozens of high-level experts from different fields took on the full costs of electricity. Many of the results produced from these studies remain relevant today. While estimates of social costs inevitably display large uncertainties, the studies converged in the identification of key problem areas. However, decision makers never properly implemented the policy conclusions from these studies. It appeared that converging results from several unbiased studies would have implied, at least in qualitative terms, much stronger action on air pollution and climate change than countries around the world were willing to contemplate.

Air pollution, climate change and system costs constitute the largest uninternalised costs

The different chapters in this report converge on one single insight: the external costs of the normal operations of electricity generation exceed the costs of other phases of the life cycle of electricity generation – upstream or downstream of operations – as well as the costs of major accidents by at least one order of magnitude. Mining and transport for the primary fuels of electricity generation (e.g. coal, oil, gas or uranium) do have social costs, but the latter are locally well circumscribed and pale when compared, for example, against the costs of air pollution. In terms of the back end of the life cycle, decommissioning and the storage of waste constitute significant costs for nuclear power indeed. However, these are economic costs, for which provisions exist to be internalised through the funds that are constituted by electricity producers and that are passed on in customer prices and tariffs.

Major accidents of energy structures, be they oil spills, gas pipeline explosions, dam breaks, mining disasters or nuclear accidents, dreadful as these may be for those concerned, are fortunately rare during the life cycle of all power generation technologies and thus do not figure heavily in the accounting of full costs. The problem for policy making is, of course, that such accidents receive an extraordinary amount of attention from the media and the general public. The greatest number of fatalities is recorded in coal mining and hydroelectricity, two technologies which do not generate widespread public concerns. Oil spills and nuclear accidents, in particular, receive an amount of media and policy attention that is extraordinary compared to the damages and human casualties for which they are responsible.

Individual human suffering induced by any sort of accident or external effect, whether it captures public attention or not, cannot be reduced to statistics. Policy makers have the difficult task to balance both aspects, the legitimate public concern of the moment and the need for a longer-term structure of an energy system constituting the best available option to minimise accidents and hardship in a 360° perspective. The enormous impacts of air pollution and the greenhouse gas emissions associated with climate change, or even the multi-billion system costs of the variability of certain renewable technologies, have thus been unable to make an impact on public perceptions. Air pollution constitutes the biggest uninternalised cost of electricity generation. It is also an intensively studied area with stable research protocols, consistent methodologies and converging results. Worldwide, the deaths of 3 million people per year are attributed to ambient air pollution, of which power generation contributes a significant share.

The full costs of climate change come with high uncertainties but are routinely characterised by analysts to be in the trillions of US dollars or euros. Climate change action has a unique role in this context. Public awareness, media focus and political attention are intense, but have failed thus far to translate into effective GHG emission reductions. The under-reported subset of full costs constituted by system costs are also bound to increase further. Yet outside the circle of electricity market experts, the issue is virtually unknown.

Security of supply, employment effects and the impacts of technology innovation are rather technical issues. Contrary to system costs, however, they do possess their own, if rather limited, constituencies that ensure that they are taken into account at least in a partial, if imperfect internalisation process.

Policy makers must internalise full costs where it matters most

Public attention does not focus extensively on an issue such as air pollution, where a steady stress builds up over years to combine with genetic and other factors to cause respiratory illness and heart failure. The complexity and duration of the process makes covering, reporting, disseminating and absorbing the relevant information much more difficult.

In such cases, the public, the media and policy makers are prone to *attention bias*. An accident with 50 fatalities once every ten years will get infinitely more media and policy attention than 1 000 premature deaths coupled with increased morbidity in a large population because of a constant level of pollution over the same time span. While individual human suffering cannot be calculated and compared, dispassionate reflection with an aim to improve general welfare would suggest that the far larger number of casualties due to air pollution would demand at least as much attention as rare accidents. However, public opinion, social forces and political pressures have ensured that policy attention and resources disproportionately favour the latter.

It is the role of publications such as the present report to mitigate or to reverse attention bias. Once the relevant subsets of full costs receive appropriate attention from the public, the media and policy makers, the different manners to proceed towards internalisation can be better understood. Practical policy instruments that should be considered fall into three broad categories:

1. Price- and market-based measures such as taxes, prices, subsidies, the allocation of property rights and market creation.
2. Norms, standards and regulations, which are the default measure of policy making.
3. Information-based measures, including R&D support, are not minor add-ons but are at the heart of internalisation.

Whatever the chosen instrument, governments must be the primary driver behind implementation. When the lives of millions of people are at stake, governments have an obligation to put into place incentive structures that reduce transaction costs and enable new allocations that allow for large welfare improvements so as to address key issues such as air pollution.

In parallel, work on better information should be ongoing. It is vital that governments resuscitate the important debate and large-scale work on external effects in the energy sectors of the 1980s and 1990s. Measured against the scale of the externalities discussed, the required funds for research are negligible. At the same time, such work needs to be managed tightly and focus on key issues with a view to contributing to better policy making in the context of the energy transitions under way. Disseminating and synthesising knowledge on some of the most salient features of the full costs of electricity provision is key to arriving, through the progressive internalisation of social costs, at better policies and more sustainable electricity mixes.

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The Full Costs of Electricity Provision

Electricity provision touches upon every facet of life in OECD and non-OECD countries alike, and choosing how this electricity is generated – whether from fossil fuels, nuclear energy or renewables – affects not only economic outcomes but individual and social well-being in the broader sense. Research on the overall costs of electricity is an ongoing effort, as only certain costs of electricity provision are perceived directly by producers and consumers. Other costs, such as the health impacts of air pollution, damage from climate change or the effects on the electricity system of small-scale variable production are not reflected in market prices and thus diminish well-being in unaccounted for ways.

Accounting for these social costs in order to establish the full costs of electricity provision is difficult, yet such costs are too important to be disregarded in the context of the energy transitions currently under way in OECD and NEA countries. This report draws on evidence from a large number of studies concerning the social costs of electricity and identifies proven instruments for internalising them so as to improve overall welfare.

The results outlined in the report should lead to new and more comprehensive research on the full costs of electricity, which in turn would allow policy makers and the public to make better informed decisions along the path towards fully sustainable electricity systems.

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