The Full Costs of Electricity Provision

Extended Summary

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NUCLEAR ENERGY AGENCY

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ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

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The OECD is a unique forum where the governments of 36 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.

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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.

Cover photos: A city showing the effect of climate change (Shutterstock, De kwest); Coal power station and cement plant at night (Shutterstock, Cozyta); Antarctic melting glacier in a global warming environment (Shutterstock, Bernhard Staehli).

Why calculating the full costs of electricity matters

Accounting for and internalising the full costs of electricity provision is decisive if full advantage of the energy transitions under way in many countries is to be realised. If properly done, internalising the full costs will allow policy makers and the public to make better informed decisions along the path towards better policies and more sustainable electricity mixes.

Market prices and production costs account for an important share of the overall economic impacts of electricity. However, this "private value" of electricity is not the whole story as the social and environmental impacts of electricity provision are affecting individuals, economies and societies in ways that are not presently captured by these market prices. The consequences of not internalising the full costs of electricity provision are too important to be neglected any longer. Concerns about anthropogenic climate change strongly reinforce this. In addition, such considerations as the impact of local pollution from electricity generation on health and longevity, the fear of a major accident, and the prospects for employment and technological developments have all troubled policy makers and the public for many years.

Such impacts are variously called external effects, externalities or social costs. While not reflected in market prices, researchers can nevertheless fairly well identify the external impacts of electricity generation and provision, often measuring them and sometimes even monetising them. To improve welfare, decision makers must integrate such costs into their policies. The full costs of the electricity generated by a given technology are thus the sum of the technology's private (market) costs plus its social costs. Since at least the early 1990s, when a raft of major studies on energy externalities was launched, accounting for the full costs has become part of the work of a large constituency of researchers.

Recently, public attention moved away from the full costs of electricity, partly because of concerns about climate change with its particular processes and methodological conventions. However, the issues associated with externalities did not go away. One particularly stark example is provided by the World Health Organization (WHO), whose research indicates that globally, three million deaths every year are caused by ambient air pollution and by particulate matter released mainly through the burning of coal or biomass. Add to this the impact of household air pollution, much of which could be avoided by the provision of clean electricity, and the number of deaths per year rises to over seven million. All sources of electricity have advantages and drawbacks. However, it would be wrong to think that no distinctions should be made in terms of social costs. *The Full Costs of Electricity Provision*, on which this summary is based, highlights the most important facts in order to assist countries in formulating their sovereign policies that determine their electricity mix.

Three things policy makers should do now

1) ***Recognise*** that air pollution, climate change and system costs constitute the largest currently uninternalised costs of electricity production.

2) ***Ensure*** that these social costs are fully internalised, so that all technologies bear the full cost of connecting to the grid.

3) ***Apply*** practical policy instruments:

   - Price- and market-based measures such as taxes, prices, subsidies, the allocation of property rights and market creation;
   - Norms, standards and regulations;
   - Information-based measures, including support for R&D.

Despite the evident importance of full costs, accounting for them systematically in monetary terms 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 has yet to be undertaken.

Nevertheless, the issue is too important to be disregarded any longer. *The Full Costs of Electricity Provision* summarises and synthesises the most recent research in the field. That an agency dedicated to nuclear technology would publish a report on the full costs of electricity provision, including all major generation technologies, may easily invite questions about even-handedness. However, the authors have synthesised well-documented information from a wide range of sources. The report is another step towards understanding the full costs of electricity provision and should, more importantly, be a starting point for more comprehensive research supported by a broad range of stakeholders in the electricity sector.

Research on the full costs of energy and electricity is an ongoing effort. *The Full Costs of Electricity Provision* highlights the importance of full cost accounting, in particular in the multifaceted context of the energy transitions under way in many countries. Consistent with its mission, the NEA's aim is to forge a common understanding on a key issue that is a vital input to government policy-making to allow policy makers and the public to make better informed decisions about their electricity systems. The well-being of their citizens and the welfare generated by their economies depend on those decisions.

LAUNCH WEBINAR

The Full Costs of Electricity Provision

oe.cd/nea-electricity-costs-webinar-2018

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The full costs of electricity provision:

Extended summary

Electricity production, transport and consumption affect every facet of life in many countries. 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 this "private value" of electricity is not the whole story and that the social and environmental impacts of electricity provision affect individuals, economies and societies in ways that are not captured in market prices, but yet are too important to be neglected. While estimates of social costs inevitably display large uncertainties, studies converge on the identification of key problem areas. However, decision makers have 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 many countries around the world have been willing to contemplate so far.

Full costs: Key concepts, measurement and internalisation

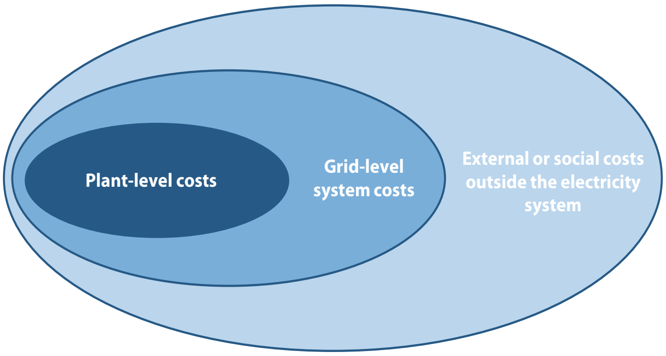
The costs of electricity provision fall into three different, comprehensible categories. The first category is constituted of plant-level costs, which include the concrete and steel used to build the plant, and the fuel and the human resources to run it. The NEA and the International Energy Agency (IEA) publish a survey of the plant-level costs in OECD countries every five years in the *Projected Costs of Generating Electricity* series (the 2020 edition 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 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 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.

Figure 1: **Different cost categories that make up the full costs of electricity provision**



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. 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.

> ***The goal is not to establish rankings but to draw attention to understudied issues that should be better internalised into the policy process***

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-intended 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. 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 the full 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.

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

If this report has one single insight it is this: the external costs of the normal operations of electricity generation exceed the costs of other aspects 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 against the costs of air pollution. In terms of the back end of the life cycle, the decommissioning and the storage of waste constitute significant costs for nuclear power. 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 are so rare during the life cycle of all power generation technologies that they 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 emotional uproar 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 holistic perspective. The truly enormous impacts of air pollution and 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 three 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 measured in the trillions of 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 partial, if imperfect internalisation processes.

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 fatalities 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 benefit the latter.

Once the relevant subsets of full costs receive appropriate attention from the public, the media and policy makers, then the different manners to proceed towards internalisation are clear. Practical policy instruments that should then be considered fall into three broad categories:

- Price- and market-based measures such as taxes, prices, subsidies, the allocation of property rights and market creation.
- Norms, standards and regulations, which are the default measure of policy making.
- 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 and climate change.

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.

The external costs of the normal operations of electricity generation exceed the costs of all other phases of electricity generation

Plant-level production costs

Plant-level production costs limit themselves to the first of the three categories indicated in Figure 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 levelised cost of electricity (LCOE) indicates the discounted lifetime costs for different baseload technologies, averaged over the electricity generated. However, the LCOE is part of a much bigger picture and while a useful tool to compare the costs of baseload technologies in regulated systems, it leaves out many decisive aspects of the costs of electricity (see Figure 2 on page 9). Despite these limitations, it often remains an attractive first reference because of its simplicity and transparency.

Grid-level system costs

System costs have 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 as a result of the locational constraints 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.

> ***Grid-level system costs associated with renewables are large and increase over-proportionally with the share in electricity generated; system costs of dispatchable technologies are at least one order of magnitude lower***

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 technologies assessed and their share of 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 3 (page 10) 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 or hydro, are at least one order of magnitude lower.

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.

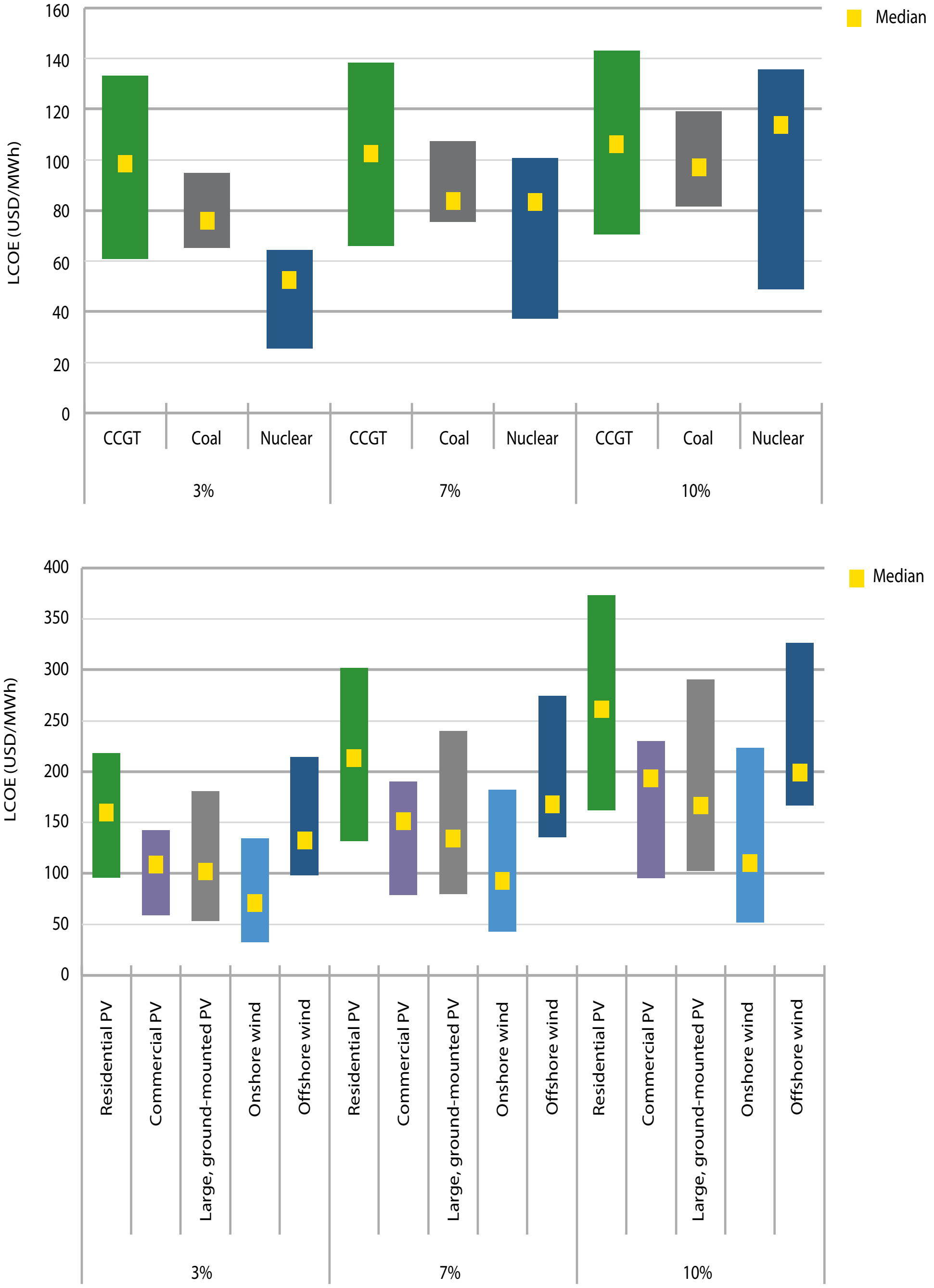
Climate change impacts

The desire to reduce greenhouse gas (GHG) emissions in order to prevent or mitigate the impacts of anthropogenic climate change has been a top 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 last two years have seen a stabilisation of annual emissions, albeit at a level still far too high to reduce atmospheric concentrations of GHGs. Climate change is also already under way and can be unequivocally measured in terms of rising global mean temperatures, increased numbers of tropical storms and changes in precipitation patterns (IPCC, 2014).

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

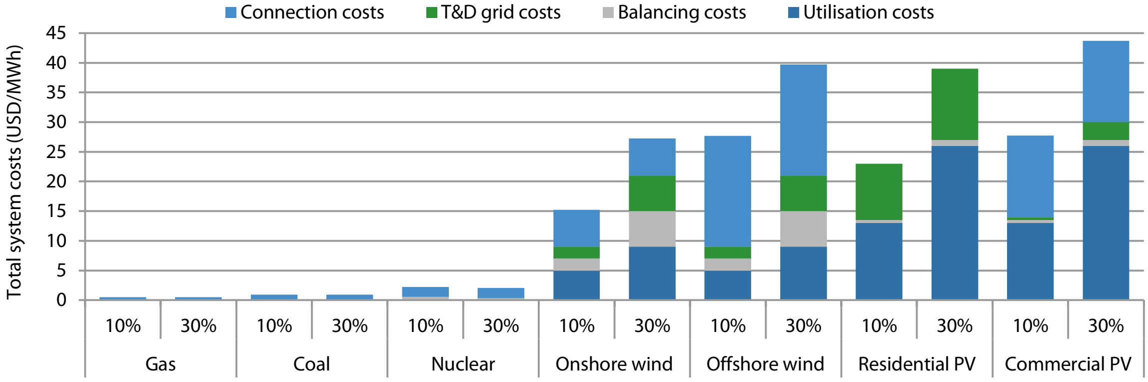
(USD per MWh)



Source: IEA/NEA, 2015.

Figure 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. 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.

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



Source: NEA, 2012b.

Given the difficulties of monetising climate change costs, the global policy-making process has thus chosen a different approach. Instead of estimating the marginal social costs, the amount of emissions that is considered socially optimal has been set as 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 the latter metric that best synthesised the range and probability of different climate change impacts for policy makers and the public. A general consensus, reflected in the 2016 Paris Agreement, has thus emerged that an increase of the global mean temperature of more than 2°C above pre-industrial levels should be prevented.

Air pollution is the world's largest single environmental health risk

On the basis of the temperature target, concentrations of CO_2 emissions in the atmosphere measured in parts per million (ppm), annual emissions and the costs of attaining them (abatements costs) can be defined and converted into USD or EUR per tonne of CO_2 (see Table 1 on page 11).

A comprehensive analysis of different models assessing the interaction between the economy and greenhouse gas emissions provides estimates of the marginal CO_2 abatement costs. The mean estimate of the marginal costs of attaining the Two-degree Celsius scenario (2DS) with 450 ppm in 2050 would thus amount to EUR 225 per tonne of CO_2. In principle, this would correspond to the level of the carbon tax required. More generally, the results 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 association between air pollutant concentrations and health damage can be divided into two categories, mortality (fatalities) and morbidity (disability and disease). Table 2 (page 11) summarises the number of deaths and cases of illness per TWh of different generating options based on a meta-analysis of different epidemiological studies by Markandya and Wilkinson (2007). It permits two undisputable conclusions. First, effects related to air pollution dwarf any effects related to accidents. Second, when it comes to air pollution, the impacts of lignite, coal and, to a somewhat lesser extent, oil are an order of magnitude higher than those of gas and biomass, which are two orders of magnitude higher than those of nuclear energy, hydroelectricity, wind or solar PV. The key public health issue is constituted by the emissions of particulate matter, SO_2, NO_x, and toxic metals, common throughout all carbon-based sources.

The only local air-polluting emissions from the generation stage of the nuclear fuel cycle are minor operational radionuclide emissions. These however must be put in perspective, as coal-fired generation releases 100 times more radioactivity per MWh than nuclear power generation, through fly-ash emissions. Even in the latter case, contributions to background radiation from these emissions during operations are numerically minute.

Converting these values into monetary damages gives gain rise to broad ranges. Sometimes, differences are due to objective factors such as location, population density, and wind speeds and directions. Sometimes, they are due to methodological differences or different estimations for the value of a statistical life. The 2012 meta-study by Burtraw et al. (2012) provides an overview in Table 3 (page 12) of the results of four important studies that have been undertaken in the past 20 years.

While characterised by large ranges, the monetary estimates confirm the relative severity of impacts. Burtraw, Krupnick and Sampson state, for example, that:

> In general, the results in Table 3 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 3 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 generally lowers air pollution.

Table 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

Source: Based on Kuik et al., 2009.

Table 2: **Health effects of electricity generation by primary energy source**

(Europe, deaths/cases per TWh)

	Deaths from accidents		Air pollution-related effects		
	Among the public	Occupational	Deaths*	Serious illness†	Minor illness‡
Lignite	0.02 (0.005-0.08)	0.10 (0.025-0.4)	32.6 (8.2-130)	298 (74.6-1 193)	17 676 (4 419-70 704)
Coal	0.02 (0.005-0.08)	0.10 (0.025-0.4)	24.5 (6.1-98.0)	225 (56.2-899)	13 288 (3 322-53 150)
Gas	0.02 (0.005-0.08)	0.001 (0.0003-0.004)	2.8 (0.70-11.2)	30 (7.48-120)	703 (176-2 813)
Oil	0.03 (0.008-0.12)	..	18.4 (4.6-73.6)	161 (40.4-645.6)	9 551 (2 388-38 204)
Biomass	..	..	4.63 (1.16-18.5)	43 (10.8-172.6)	2 276 (569-9 104)
Nuclear	0.003	0.019	0.052	0.22	..

Data are mean estimates (95% confidence interval).

* Includes acute and chronic effects. Chronic effect deaths are between 88% and 99% of the total. For nuclear power, they include all cancer-related deaths, including accident and long-term effects.

† Includes respiratory and cerebrovascular hospital admissions, congestive heart failure and chronic bronchitis. For nuclear power, they include all non-fatal cancers and hereditary effects.

‡ Includes restricted activity days, bronchodilator use cases, cough and lower-respiratory symptom days in patients with asthma, and chronic cough episodes. TWh-1012 watt hours.

Source: Based on Markandya and Wilkinson, 2007.

Table 3: **Summary of external cost estimates from four 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.

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. If only human-made accidents were 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. 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 that are less extensively reported in the media, such as atmospheric pollution, but have indeed a higher mortality risk. Perceptions differ also with respect to different kinds of accidents in the energy sector. The risk of a nuclear accident thus plays a far bigger role in public discussions than the objectively much more likely accidents occurring in coal mines (see Table 4 on page 13 for a summary).

> *External costs associated with severe accidents are several orders of magnitude lower than those caused during normal operation from pollution and carbon emissions*

Partly, such differences in perception can be explained by the attention bias discussed earlier. Risk aversion, i.e. the preference for a constant level of standard risks over rare, high-impact events, also plays a role. A particular challenge arises when assessing the potential impacts, economic consequences and risks of a severe accident in nuclear energy. This is partly due to the specificity of nuclear accidents in terms of the temporal and geographic scale of their potential consequences and the complexity of the causal link between the consequences observed and the accident itself. Contrary to accidents, where most of the economic damages and health consequences are immediate and where effects are limited to a well-defined area, impacts of a nuclear accident may last for several years or decades, may affect a large region beyond the "contaminated" area and are dominated by indirect or induced effects on the economy. Also the response and decisions taken by governments and safety authorities in the aftermath of the event may have an important impact on the overall consequences of the accident. All these features add yet another layer of uncertainty and, inevitably, of subjective and context-dependent perceptions.

With respect to the impact on the population, most recent studies agree that it is extremely unlikely that a severe nuclear accident occurring in a modern plant could cause immediate fatalities. The vast majority of health effects are expected to occur several years after the exposure as, at most, a small increase of the cancer rate across the exposed population. Radiation-induced cancers may not be physically discernible from other unrelated pathologies, and the increase may not be statistically discernible from the mortality and morbidity rates normally occurring in a population. Moreover, the estimates of additional morbidity and mortality in the exposed population will be highly uncertain at low individual exposures. Such difficulties to relate radioactive emissions to a statistical increase in the frequency of cancers and mortality rates across large populations also help to explain the diverging estimates on future fatalities due to the Chernobyl accident, which often differ by more than an order of magnitude.

Land-use change

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: most land is in fact privately traded, and public land falls under strict regulations in OECD countries.

Table 4: **Summary of accidents with more than five fatalities***

(1970-2008)

Energy chain	**OECD**		**EU27**		**Non-OECD**	
	Accidents	Fatalities	Accidents	Fatalities	Accidents	Fatalities
Coal	87	2 259	45	989	2 394[a] 162 818 1 214	38 672 5 788 11 302 15 750
Oil	187	3 495	65	1 243	358	19 516
Natural gas	109	1 258	37	367	78	1 556
Liquefied petroleum gas	58	1 856	22	571	70	2 789
Hydroelectric	1	14	1	116	9[b] 12	3 961 26 108
Nuclear[c]	–	–	–	–	1	31
Biofuel	–	–	–	–	–	-
Biogas	–	–	–	–	2	18
Geothermal	–	–	–	–	1	21
Wind[d]	54	60	24	24	6	6

* From the Energy-related Severe Accident Database (ENSAD); a) Coal: first line non-OECD total; second line non-OECD without China; third line China 1994-1999; fourth line China 2000-2008; b) Hydro: first line non-OECD without China; second line China; c) Note: Fatalities from the Fukushima Daiichi NPP accident in 2011 are not included in this table, but it should be noted that the accident resulted in no immediate, radiation-related fatalities; d) Wind: only small accidents.

Source: Adapted from Burgherr and Hirschberg, 2014.

The most significant external cost of land-use changes are the effects on the ecosystems of natural areas. These ecosystems provide valuable ecological services such as water purification or protection against soil erosion. Land-use change is thus a proxy for the loss of such vital ecosystem services. Most electricity sources have significant land requirements when the whole fuel cycle is considered, including fuel extraction, generation and waste disposal. The fuel that by far has the highest land-use requirements is biomass (see Figure 4 on page 14).

Natural resource depletion

Natural resources used in energy and electricity provision not only include land but also water and energy resources. 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 included in the price 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.

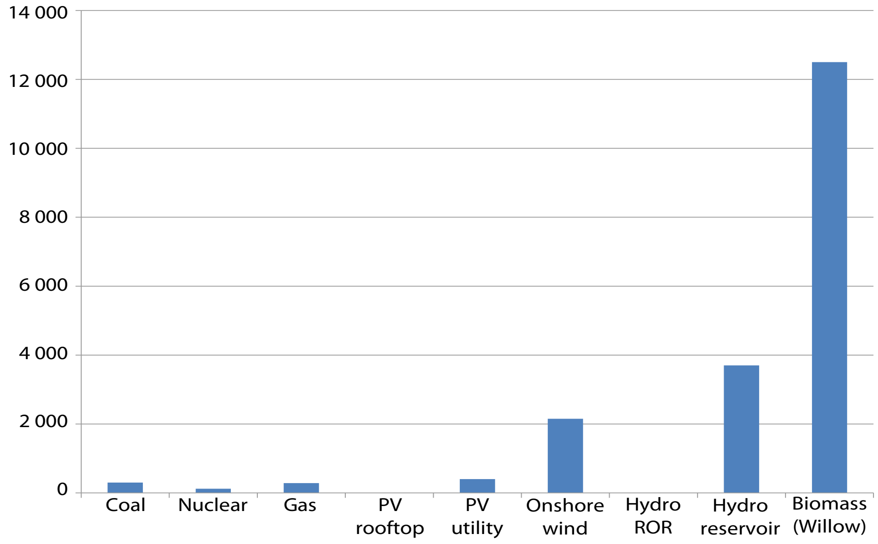
The best response to resource depletion concerns is to keep existing markets as open and competitive as possible

Concerns about resource exhaustion have an illustrious pedigree but have been confounded over and over again. Today, proved oil reserves, ready for extraction, are two-and-a-half times greater than they were only in 1980. The situation for other resources, such as coal, gas and uranium, is more favourable still. Available resources are, of course, finite in some abstract physical sense; however, they also far exceed what will ever be used for economic purposes. Economic recoverability instead is a function of technology, demand and difficulty of access. So far, progress in the technologies of prospection and extraction has outstripped resource use. If this process should ever come to an end, substitution will ensure that economic activity continues. Economic growth will not be limited by the scarcity of natural resources with commercial value.

This does not mean that there is no issue at all with resource depletion. However, it is limited to natural resources *without* commercial value. To the extent that impacts are external, i.e. not taken into account by market participants, natural resources can be quickly depleted with great losses to societies and individuals. Climate change is a case in point.

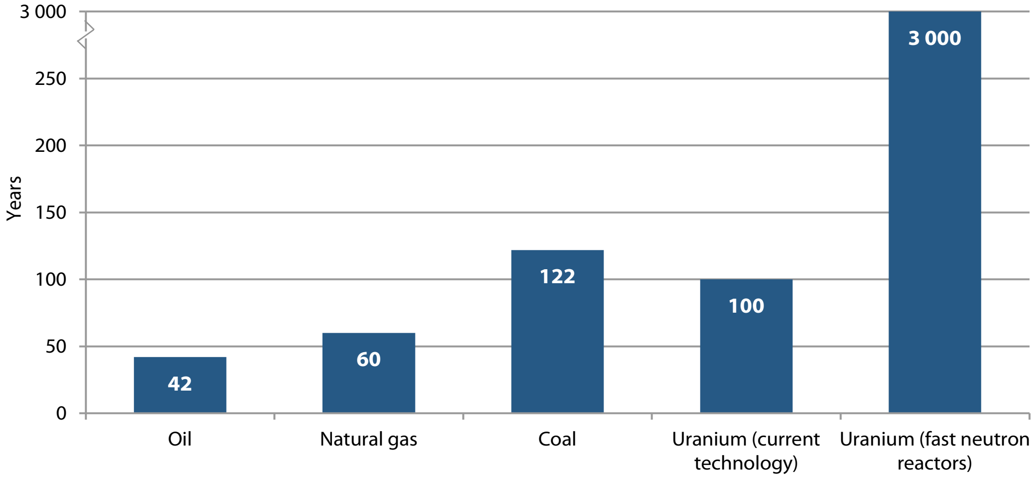
Figure 4: **Land-use requirements for different power generation technologies**

(Life-cycle assessment including mining and transport, m²/GWh)



Source: Based on Fthenakis and Kim, 2009.

Figure 5: **Reserve/production ratios for selected energy resources**



Source: NEA, 2010b.

The security of energy and electricity supply

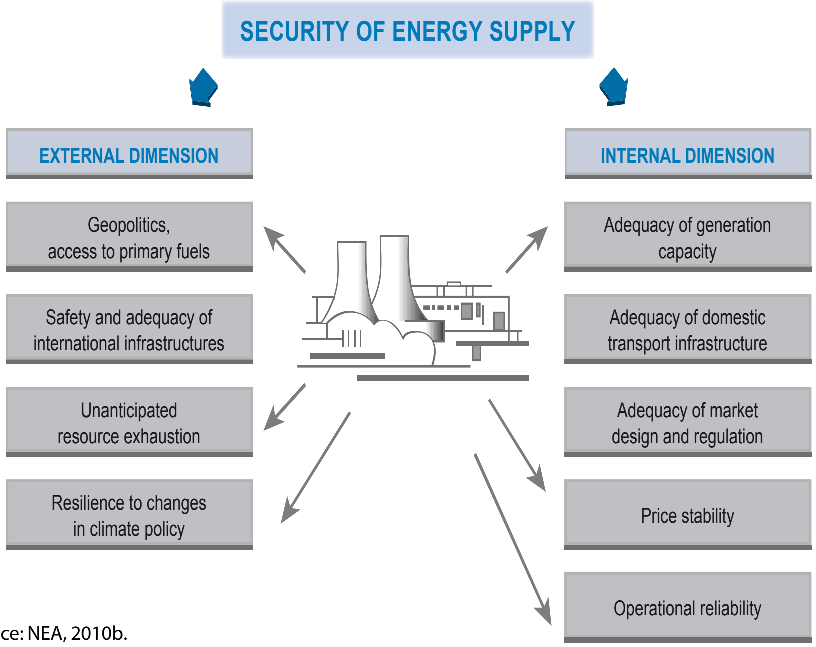
The continuous availability and affordability of energy and, in particular electricity, is an indispensable condition for modern societies. Security of energy supply does not necessarily equate with energy independence or self-sufficiency. Free and global energy trade through smoothly functioning competitive markets can ensure timely delivery of all necessary energy resources. Most countries rely at least partially on the international trade of energy and will continue to do so. It is also not a given that domestic energy resources necessarily outperform imported energy resources with respect to the security of energy supply. Strikes in the mining industry, regulatory initiatives or political expediency can affect the energy supply just as easily and as suddenly as geopolitical conflicts.

The internal dimension of the security of energy supply is also increasingly coming into focus as policy-makers are concerned about the security of electricity supply. In particular, the deployment of significant shares of variable renewables questions whether infrastructures for transport and distribution are adequate and whether dispatchable capacity is sufficient to deal with demand peaks. Figure 6 draws together the different dimensions of energy security.

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 (SSDI). Inputs of the SSDI are the degree of diversification, the level of energy and carbon efficiency, the adequacy of infrastructures and scalable weights reflecting the perceived vulnerability of different fuels. 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 (see Figure 7 on page 16).

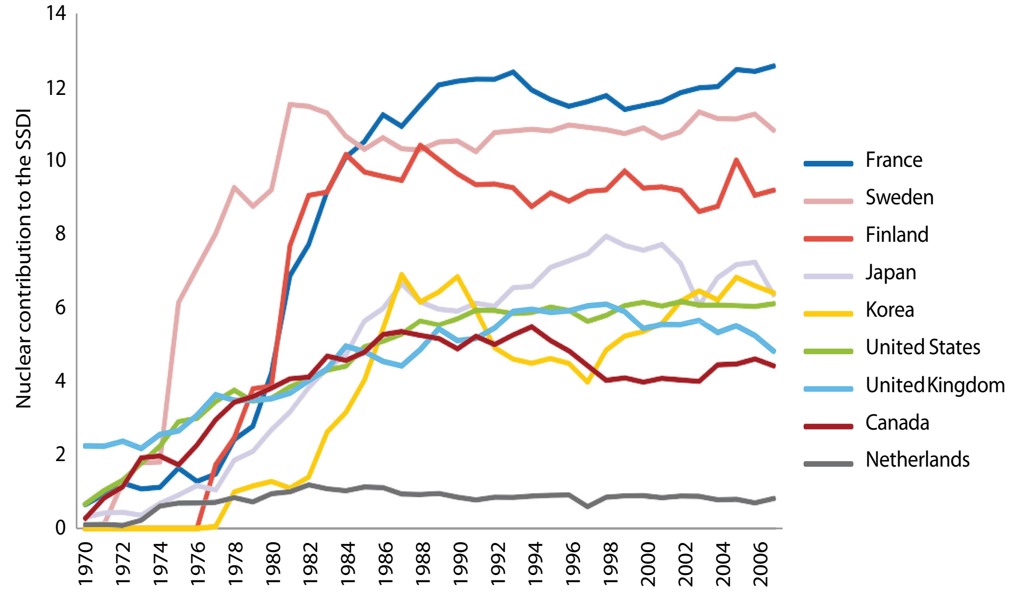
The value of the SSDI significantly increased between 1970 and 2007 in most economies in the study: Australia, Canada, Finland, France, Japan, the Netherlands, Sweden, the United Kingdom and the United States. This improvement resulted from the introduction of nuclear power for electricity generation, decreasing energy intensity and increased diversification of imported fuels such as coal, oil and gas. In general, all low-carbon technologies such as nuclear, 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.

Figure 6: **Dimensions of energy security**



Source: NEA, 2010b.

Figure 7: **Evolution of the SSDI in selected OECD countries**



Source: NEA, 2010b.

Employment generated in the electricity sector

The employment required for different generating technologies in the electricity sector is the result of cost minimisation by competitive firms. So why should employment be considered a positive externality? While the political argument for employment studies in the electricity sector is obvious, the economic argument is far less so. High labour intensity may be of interest to local policy makers, but it could also constitute a disadvantage in economic competition. There exists nevertheless one economic argument that can justify the study of employment effects. This consists of the fact that the quantitative and qualitative characteristics of employment in different power generation technologies can generate positive externalities beyond sheer labour productivity. Under this hypothesis, high employment rates generate positive spillovers by contributing to social and regional cohesion and to greater levels of well-being. In this perspective, the quality of the labour required is of particular interest. The higher the qualification of the workforce and the longer the duration of the employment contract, the higher is the likelihood that long-term positive externalities would accrue to 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. 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). In particular, the sector provides a comparatively high number of local jobs per MW during operations (see Table 5 on page 17). The concentrated nature of large facilities tends to contribute further to the generation of positive spillovers on the local and regional economy. Employment is one policy issue, however, where a careful disentanglement of financial, economic and social aspects is needed.

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 as firms and households are dependent on cheap and reliable energy supply, iii) the waves of innovation and positive spillovers that are generated on both the supply and the demand side. These are the principal reasons why governments fund research and development (R&D) in the energy field. Over time, 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 largest part (see Figure 8).

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, of course, 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. Policy makers should therefore 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.

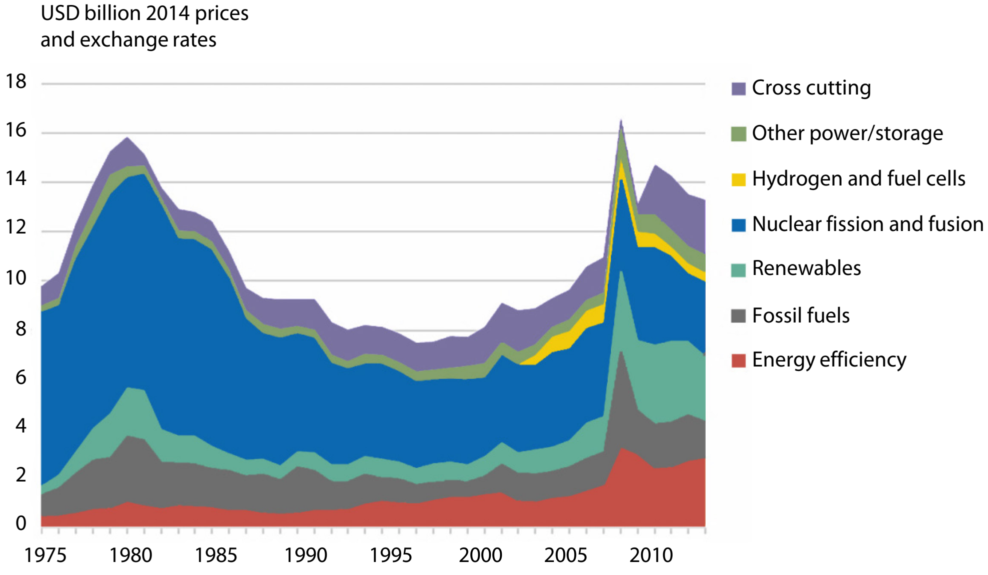
Table 5: **Local jobs in the O&M of various electricity generating technologies, ordered by average size of the electricity generating facility**

Technology	Jobs/MW	Average size (MW)	Direct local jobs
Nuclear	0.50	1 000	504
Coal	0.19	1 000	187
Hydro > 500 MW	0.11	1 375	156
Hydro pumped storage	0.10	890	85
Hydro > 20 MW	0.19	450	86
Concentrating solar power	0.47	100	47
Gas combined-cycle (CCGT)	0.05	630	34
Photovoltaic (PV)	1.06	10	11
Micro hydro < 20 MW	0.45	10	5
Wind	0.05	75	4

Source: Harker and Hirschboeck, 2010.

Figure 8: **Energy R&D public expenditures over time in Europe**

(Prices and exchange rates in 2014 billion US dollars)



Source: EC, 2016.

The policy implications of full costs accounting in the electricity sector

Policy makers have never properly implemented the recommendations of experts to fully internalise social costs into private decisions. It may have been optimistic to presume that the frank imposition of fiscal measures, based on precisely monetisable social costs and the resulting tax adjustments that would bring social and private costs in line, could be routinely implemented in all circumstances. Yet, converging results from a number of broad-based and well-balanced studies have all implied that much stronger action than countries have been willing to contemplate – at the very least on air pollution and climate change – is required to move towards economic optimality. The widespread lack of a meaningful carbon tax in many countries is a case in point. Stronger technical regulations, market creations, subsidies, improved transparency and reduced legal and institutional transaction costs, however, are all available as part of an arsenal of measures that can be used where the straightforward imposition of Pigouvian taxes remains elusive because of political roadblocks resulting from distributional concerns.

The Full Costs of Electricity Provision is part of the growing series of NEA studies on the costs of nuclear energy and other power generation options. Several of these studies, including those on plant-level costs, system costs and security of supply, are summarised in the full report. They reflect a desire to arrive at robust and meaningful cost measures for electricity provision that go beyond the traditional LCOE-measure for the costs of plant-level baseload provision in regulated power systems. Given its simplicity, transparency and easy comparability, the LCOE will continue to one of the metrics used by experts, researchers and policy makers. However, even the next edition of the NEA/IEA flagship publication on *The Projected Costs of Generating Electricity*, which is foreseen for 2020, acknowledges that broader, complementary measures are now required, since the per MWh cost of a generating technology can no longer be assessed independently of the surrounding electricity system. The role of day-ahead dispatch, which was the prevailing paradigm for both regulated and, initially, liberalised markets, is declining, while the role of payments for capacity, flexibility, stability and system services is increasing. Even at the level of the grid-connected system, an MWh of electricity is no longer a homogeneous good.

It is even less a homogeneous good at the level of the surrounding environment, the citizens who live in it, the security of supply they aspire to, or their existing social and technological dynamics. It is why the notion of full costs is so important. Moving towards improved welfare requires differentiating technologies according to a number of relevant metrics that reflect their full impact on society and on the economy.

The challenges that this implies are evident, both at the level of assessing full costs and of determining widely acceptable ranges of valuation, as well as at the level of overcoming the entrenched interests and the resistance to being held accountable. Full costs are plant-level and system costs, plus uninternalised externalities. If the latter are negative, they need to be added as extra costs; if the latter are positive, in principle, they need to be subtracted. The term "in principle" is used here because positive externalities such as the spillovers of employment in certain technologies or the impact of innovation on economic performance and growth are, usually, of an even more uncertain nature than the negative impacts on human health, longevity and the environment. The internalisation of positive externalities is thus usually best handled in an implicit manner through general policy rather than through the imposition of monetary incentive measures that would adjust market costs.

How to internalise?

Once the different subsets of full costs receive the appropriate attention they deserve, well-understood instruments for internalisation can be applied. The full report presents the applied economics behind practical policy decisions, which continue to fall into three broad categories:

- *Price- and market-based measures:* in many circumstances, the simple application of a Pigouvian tax to any externality that can be identified is neither practicable or desirable. Nevertheless, taxes, prices, subsidies, the allocation of property rights and the reduction of transaction costs are key measures in the policy makers' arsenal to reflect the full costs of electricity provision. Such instruments should be used in a qualitative and predictable manner to steer electricity provision into the desired direction over the long term.
- *Norms, standards and regulations*: these are the default measures of policy making and have already been widely adopted. They have the added advantage of leaving the pollution rent to the polluter. However, in the area of air pollution and greenhouse gas emissions in particular, a review and eventual tightening of emission standards seem warranted.
- *Information-based measures*: contrary to a frequent misconception, these measures are not minor add-ons to "real" measures but are at the heart of modern internalisation. Support for research and innovation belongs

here, as does taking part in the policy-making and rule-setting processes. *The Full Costs of Electricity Provision* is a small but focused effort to overcome some of the informational transaction costs that stand in the way of better policy making in the electricity sector.

Four general points apply in this context:

1) Successful measures often combine aspects of different categories. An important example in this context is emissions trading, which combines the setting of a quantitative standard with the creation of a market that allows a price for the externality to emerge. Information and education can further improve the effectiveness of such economic incentive measures.
2) Any measure can be tailored so as to be adapted to different normative frameworks concerning distributional arrangements. From the point of view of welfare optimisation, whether a carbon price in the area of climate change comes in the form of a tax, a quota that has been allocated through an auction, a quota that was given for free or a zero-emission credit (i.e. subsidy for low-carbon production) is secondary. The decisive point is that a price needs to be set that differentiates incentives for low-carbon and for high-carbon power generation.
3) Synergies exist between measures addressing different social costs of electricity generation. An obvious example is the fact that any measure that will reduce air pollution from fossil fuels will also reduce carbon emissions, and vice versa. In addition, such action will produce beneficial side effects on resource depletion and the security of energy supplies.
4) The distributional impacts of different measures of internalisation are frequently the most significant barrier to the internalisation of external costs. These impacts are real and must be addressed. Appropriate measures of compensation are relatively simple to put in place and are, if well done, fully compatible with efficient internalisation. They can be permanent or temporary, aiming at full or partial compensation. They require, however, that the logic of confrontation be abandoned and that the different actors commit to working in a framework of overall welfare maximisation.

Finally, when discussing full costs, one must underline the role, importance and responsibility of governments in this area. The gap between full costs and private costs is related to the inability of private actors to take into account all relevant information about welfare effects, as feedback mechanisms between private parties and appropriate incentive structures are lacking. "Transaction costs" is the catch-all term that economists have coined to refer to barriers to arrangements that, in principle, would be mutually advantageous since the gains of winners would be larger than the costs of losers. These transaction costs are not an unavoidable factor of economic life but can be dramatically reduced over time through both information and incentives.

More information on the full costs of energy is required. The European *New Energy Externalities Developments for Sustainability* (NEEDS) project that was completed in 2008 is a fundamental building block for this work, but it is, alas, also an example of how an enormous amount of good work is suboptimally used when managers are incapable of limiting the perimeter and scope of externality accounting. Future research must prioritise key areas of research and focus on intelligent metrics with relevance for policy making. It also needs to freely acknowledge when topics are not yet ripe for quantification and monetisation, and thus require qualitative approaches. The old adage that any number is better than no number is simply wrong in this case, and it has diminished the role of full cost accounting in policy making.

Further reading and ongoing work

Research on the full costs of energy and electricity is an ongoing effort. The full report highlights the importance of full cost accounting, in particular in the multifaceted context of the energy transitions under way in several countries. Ideally, this will contribute to two separate effects. First, it will contribute to spawning new and more comprehensive research in the area of the full costs of electricity, the kind of which has not been undertaken in recent years. Second, it will already on the basis of existing knowledge 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 following, 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 centre on putting nuclear energy into perspective alongside other energy sources, 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 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* 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 the full report.

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About the publication

This *Extended Summary* is based on the NEA report *The Full Costs of Electricity Provision* published in April 2018, a collaborative effort by the Division of Nuclear Technology Development and Economics of the Nuclear Energy Agency (NEA), under the oversight of the Working Party of Nuclear Energy Economics (WPNE) chaired by Matt Crozat and Professor Dr Alfred Voss. The study has been overseen and approved by member countries in the parent committee of the WPNE, the NEA Nuclear Development Committee (NDC).

Dr Jan Horst Keppler, Senior Economic Advisor at the NEA, co-ordinated the original report and contributed Chapter 1 (Full costs: Key concepts, measurement and internalisation), Chapter 4 (Climate change impacts), Chapter 5 (Air pollution, together with Karl Aspelund, Harvard University), Chapter 7 (Land-use change and natural resource depletion, together with Karl Aspelund), Chapter 8 (The security of energy and electricity supply) as well as the policy conclusions (The policy implications of full costs accounting in the electricity sector). Dr Geoffrey Rothwell, Principal Economist at the NEA, contributed Chapter 2 (Plant-level production costs) and Chapter 9 (Employment generated in the electricity sector). Dr Marco Cometto, Nuclear Energy Analyst from the NEA, contributed Chapter 3 (Grid-level system costs) and Chapter 6 (The costs of major accidents). Dr Marc Deffrennes contributed Chapter 10 (The impact of energy innovation on economic performance and growth). Managerial oversight was provided by Dr Daniel Iracane, Deputy Director-General and Chief Nuclear Officer; Dr Jaejoo Ha and Dr Henri Paillère, the former and Acting Head of the NEA Division of Nuclear Technology Development and Economics respectively.

Participants in the International WPNE Workshop on The Full Costs of Electricity Provision on 20 January 2016 helped frame the structure and content of this report. The Secretariat also received a large number of detailed comments from NEA member countries, including Austria, Canada, France, Germany, Japan, Poland, Russia, and Switzerland, as well as from WPNE delegates. Experts at the International Energy Agency (IEA) also provided valuable comments. These knowledgeable and highly technical comments very much improved the final version. They speak to the policy relevance of the full costs of electricity provision, as well as to the need for further study, which is carefully targeted on the most significant aspects of this important subject.

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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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