Nuclear Development
2012

Nuclear Energy and Renewables

System Effects in Low-carbon Electricity Systems

Executive Summary

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NUCLEAR ENERGY AGENCY
ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

Executive summary

What are system effects?

Electricity generating power plants do not exist in isolation. They interact with each other and their customers through the electricity grid as well as with the wider natural, economic and social environment. This means that electricity production generates costs beyond the perimeter of the individual plant. Such external effects or system effects can take the form of intermittency, network congestion or greater instability but can also affect the quality of the natural environment or pose risks in terms of security of supply. Accounting for such system costs can make significant differences to the social and private investor costs of different power generation technologies.

This study focuses on the system effects of nuclear power and variable renewables, such as wind and solar, as their interaction is becoming increasingly important in the decarbonising electricity systems of OECD countries. In particular, the integration of variable renewables is a complex issue that profoundly affects the structure, financing and operational mode of electricity systems in general and nuclear in particular. The present study, overseen by the Working Party on Nuclear Energy Economics (WPNE) of the OECD Nuclear Energy Agency (NEA), presents an overview of the most important system effects, proposes methodologies to assess them and provides systematic empirical cost estimates.

The introduction of significant amounts of variable renewables generates a number of hitherto unaccounted for impacts that are composed *inter alia* of the increased costs for transport and distribution grids, short-term balancing and long-term adequacy. The deployment of electricity from variable renewables is also significantly affecting the economics of dispatchable power generation technologies, in particular those of nuclear power, both in the short and the long run.

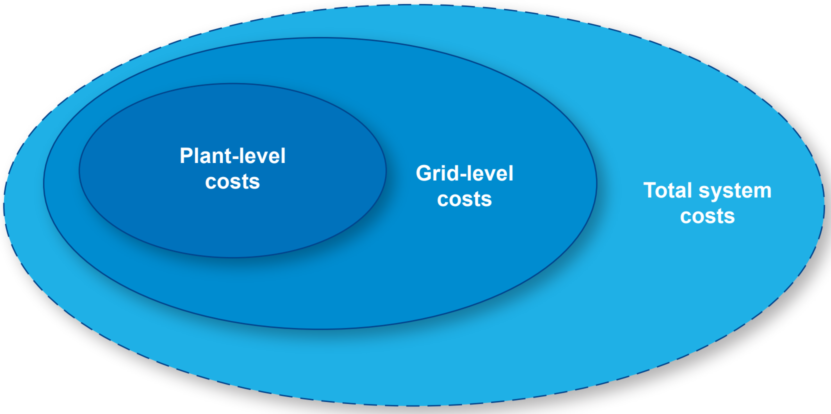
In the short run, with the current structure of the power generation mix remaining in place, all dispatchable technologies, nuclear, coal and gas, will suffer due to lower average electricity prices and reduced load factors. Due to its relatively low variable costs, existing nuclear power plants will do better than gas and coal plants, which are already substantially affected in some countries. In the long run, however, high-fixed cost technologies such as nuclear will be affected disproportionately by the increased difficulties in financing further investments in volatile low-price environments.

The outcome of these competing factors will depend on the amount of variable renewables being introduced, local conditions and the level of carbon prices. The latter are particularly important. While nuclear power has some system costs of its own, it remains the only major dispatchable low-carbon source of electricity, other than hydropower which is in limited supply. Carbon prices will thus be an increasingly important tool to differentiate between low-carbon and high-carbon dispatchable technologies.

All power generation technologies cause system effects. By virtue of being connected to the same physical grid and delivering into the same market, they exert impacts on each other as well as on the total load available to satisfy demand at any given time. The interdependencies are heightened by the fact that only small amounts of cost-efficient electricity storage are available. Variable renewables such as wind and solar, however, generate system effects that are, according to the results of this study, at least an order of magnitude greater than those caused by dispatchable technologies.

System costs in this study are defined as the total costs above plant-level costs to supply electricity at a given load and given level of security of supply. In principle, this definition would include costs external to the electricity market such as environmental costs or impacts on the security of supply. However, this study focuses primarily on the costs that accrue inside the electricity system to producers, consumers and transport system operators. This subset of system costs that are mediated by the electricity grid are referred to in the following as "grid-level system costs" or "grid costs" (see Figure ES.1).

Figure ES.1: Plant-level, grid-level and total system costs



Grid-level system costs already constitute real monetary costs. They are incurred as present or future liabilities by producers, consumers, taxpayers or transport grid operators. Such grid-level system costs can be divided broadly into two categories: (1) the costs for additional investments to extend and reinforce transport and distribution grids as well as to connect new capacity to the grid; and (2) the costs for increased short-term balancing and for maintaining the long-term adequacy of electricity supply in the face of the intermittency of variable renewables.

The study does not neglect "total system costs" but does not attempt to systematically assess them in monetised form. Total system costs would include those effects that are difficult to monetise and that could affect a country's wider economy and well-being beyond the power sector itself. This broader set of system costs would include environmental externalities other than CO_2 emissions, impacts on the security of energy supply and a country's strategic position as well as other positive or negative spillover effects relating to technological innovation, economic development, accidents, waste, competitiveness or exports.

This study also examines the pecuniary and dynamic effects of variable renewables. These are difficult to conceptualise clearly, may not constitute externalities in the traditional sense of the term and are difficult to quantify fully at the current stage of debate. However, they may well constitute the impacts that are most acutely felt by electricity producers and may in the long run have the most profound effect on the operations and structure of electricity markets. The three principal effects falling into this category are:

- Lower and more volatile electricity prices in wholesale markets due to the influx of variable renewables with low marginal costs.
- The reduction of the load factors of dispatchable power generators (the compression effect) as low-marginal cost renewables have priority over dispatchable supply.
- The de-optimisation of the current production structure coupled with the influx of renewables implies an increasing wedge between the costs of producing electricity and prices on electricity wholesale markets.

In assessing grid-level costs, total system costs and financial impacts of different power generation technologies, this study clearly recognises that it is participating in an ongoing, sometimes highly technical, discussion that has yet to deliver generally accepted results in an area – the structure of a country's electricity supply – that has strong advocates for differing viewpoints. Present conclusions and to some extent even methodologies are likely to be refined or further developed in the future.

Nevertheless, the study has the objective to draw attention to the fact that system costs are an increasingly important portion of the total costs of electricity and must be recognised and internalised in order to avoid serious challenges to the security of electricity supply in the coming years. It also provides the first systematic assessment of the grid-level system costs for different technologies in six OECD countries. The study thus advances the discussion on this important issue that is likely to shape the future of the electricity supply in OECD countries and, in particular, that of nuclear energy over the coming years.

Nuclear power and system effects

This report addresses the system effects of power generation technologies in general, while focusing on the effects stemming from variable renewables and nuclear energy. It also considers the ability of nuclear energy to contribute to the internalisation of the system costs generated by intermittency in low-carbon electricity systems.

The most important system effects of nuclear power relate to its specific siting requirements, the conditions that it poses for the outlay and technical characteristics of the surrounding grid, as well as specific balancing requirements due to the size of nuclear power plants. Siting constraints may also affect the overall economics of the nuclear power plant, via a longer time for site selection, additional investment costs for upgrades or reduced overall efficiency of the plant. However, those costs are mainly borne by the nuclear power plant developer and only impose limited additional costs on the electricity system as a whole. The specific arrangements in place in OECD countries may be different with regard to the special conditions that nuclear power plants impose on the electrical system in terms of higher requirements for grid stability and security, specific conditions for the grid layout, as well as the interaction between the overall generation system and nuclear plants due to the latter's operational characteristics.

Nuclear power may cause additional balancing costs if the transport system operators have to maintain a larger amount of spinning reserves to ensure the stability and reliability of the electricity supply. In fact, the large size of a nuclear power plant may require increasing the amount of available reserves to offset, according to the N-1 criterion, the risk of a frequency drop in the case that a nuclear power plant trips. All these system costs are real, but are overall in the range of USD 2-3 per MWh, slightly above those of other dispatchable technologies but well below those of variable renewables (see Table ES.2 below).

At least as important as the system effects of nuclear power plants themselves is their ability to deal with the system effects generated by other technologies, in particular variable renewables. The short-term intermittency of wind and solar plants puts great demands on the dispatchable providers of residual demand to vary substantial portions of their load in very short time frames. The ability to follow load will become an increasingly important criterion to choose between different back-up technologies. In this context, only nuclear and hydro do not emit any greenhouse gases during electricity generation.

Most nuclear power plants operate at stable levels close to full capacity in order to supply baseload electricity. This is not only the simplest operational mode but also economically the most advantageous as long as prices are stable, and it is thus the operational mode that is preferred in most OECD countries. For different reasons, there exists considerable experience with load following by nuclear power plants in France and Germany. In France, nuclear capacity exceeds baseload needs during certain periods during which it is necessary to reduce nuclear load. In Germany, the introduction of large amounts of variable renewables has repeatedly led to prices below the marginal costs of nuclear, including several instances of negative prices.

Based on the French and the German experiences, nuclear power has the technical capabilities to engage in load following. While more precise results would depend on the specific reactor technologies employed, the results below were reported for currently operating reactors in France and Germany. They are also consistent with the current European Utility Requirements (EUR). The short-term load following capabilities of nuclear power plants are thus comparable to those of coal-fired power plants but somewhat below plants with combined cycle gas turbines (CCGT). They clearly remain inferior to those of open cycle gas turbines (OCGT); however, the latter's very high variable costs limit their use except for covering the most extreme demand peaks (see Table ES.1). During load following, different technologies must also operate in certain ranges of total capacity, in particular nuclear power. While new nuclear power plants can operate at a power level as low as 25% of their rated capacity, most of the older designs cannot be operated for a prolonged period below 50% of their rated capacity.

Table ES.1: The load following ability of dispatchable power plants in comparison

	Start-up time	Maximal change in 30 sec	Maximum ramp rate (%/min)
Open cycle gas turbine (OCGT)	10-20 min	20-30%	20%/min
Combined cycle gas turbine (CCGT)	30-60 min	10-20%	5-10%/min
Coal plant	1-10 hours	5-10%	1-5%/min
Nuclear power plant	2 hours - 2 days	up to 5%	1-5%/min

Source: EC JRC, 2010 and NEA, 2011.

The study also provides estimates of the economic value generated by load following, which depends on the volatility of electricity prices, marginal costs and the minimum load requirements of a plant. While the benefits to the nuclear utility of around USD 1 per MWh or less are quite limited, the contribution to the stabilisation of overall dispatchable load and prices is certainly higher, but impossible to assess in the context of the current study.

Residual demand can be further stabilised through seasonal nuclear fleet management, as exemplified in France. Fleet management thus reduces the potential imbalances introduced by the regular outages for refuelling and maintenance by 6.4 GW which corresponds to a benefit that lies, depending on assumptions, around USD 1 per MWh or slightly below. While such considerations would primarily apply to countries with a large share of nuclear in the generation mix, the total gains at the level of the electricity system can be significant.

Measuring system effects

The central contribution of this study is the detailed qualitative assessment of total system costs and the explicit quantitative assessment of grid-level system costs. As previously noted, the assessment of total system costs should include not only the costs for grid connection, extension and reinforcement, the technical and financial costs of intermittency but also security of supply impacts, local and global environmental impacts, siting and safety (both in its objective and subjective dimensions). The comparative performance of nuclear power in most dimensions is quite good. A thorough comparison of environmental impacts, both local and global, in the recent NEEDS project,[1] as well as a comparison of the impacts of major accidents on the basis of data from the Paul Scherrer Institute and the World Health Organisation (WHO), both show that the performance of nuclear power in these crucial dimensions of public attention is better than that of its competitors, but still remains a sensitive issue.

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[1] Recently, the web-based NEEDS project, which stands for New Energy Externalities Development for Sustainability and is sponsored by the European Commission, has established life-cycle inventories for different scenarios of future electricity supply (www.needs-project.org) and has updated many previous externality estimates.

The most innovative contribution of the study, however, is certainly the systematic quantitative assessment of grid-level system costs in a number of selected OECD countries. On the basis of a common methodology and a large number of country-specific studies for the underlying data, the costs for short-term balancing[2] and long-term adequacy,[3] as well as the costs for grid connection, extension and reinforcement required for different technologies were calculated for Finland, France, Germany, the Republic of Korea, the United Kingdom and the United States. Technologies included were nuclear, coal, gas, onshore wind, offshore wind and solar PV. System costs were calculated at 10% and 30% penetration levels of the main generating sources.

The results show that system costs for the dispatchable technologies are relatively modest and usually below USD 3 per MWh. They are considerably higher for variable technologies and can reach up to USD 40 per MWh for onshore wind, up to USD 45 per MWh for offshore wind and up to USD 80 per MWh for solar, with the high costs for adequacy and grid connection weighing heaviest. The costs for variable renewables would be lower by roughly USD 10 to USD 20 (USD 26 in the case of UK solar) per MWh if the costs for back-up were not included, under the assumption that current electricity systems of OECD countries already have sufficient dispatchable capacity to cover demand at all times. While this may be an admissible assumption in the short run, it would not be a correct assumption for the long run when existing capacity needs to be replaced.[4]

Table ES.2: Grid-level system costs in selected OECD countries (USD/MWh)

Finland

Technology	Nuclear		Coal		Gas		Onshore wind		Offshore wind		Solar	
Penetration level	**10%**	**30%**	**10%**	**30%**	**10%**	**30%**	**10%**	**30%**	**10%**	**30%**	**10%**	**30%**
Back-up costs (adequacy)	0.00	0.00	0.06	0.06	0.00	0.00	8.05	9.70	9.68	10.67	21.40	22.04
Balancing costs	0.47	0.30	0.00	0.00	0.00	0.00	2.70	5.30	2.70	5.30	2.70	5.30
Grid connection	1.90	1.90	1.04	1.04	0.56	0.56	6.84	6.84	18.86	18.86	22.02	22.02
Grid reinforcement and extension	0.00	0.00	0.00	0.00	0.00	0.00	0.20	1.72	0.12	1.04	0.56	4.87
Total grid-level system costs	**2.37**	**2.20**	**1.10**	**1.10**	**0.56**	**0.56**	**17.79**	**23.56**	**31.36**	**35.87**	**46.67**	**54.22**

France

Technology	Nuclear		Coal		Gas		Onshore wind		Offshore wind		Solar	
Penetration level	**10%**	**30%**	**10%**	**30%**	**10%**	**30%**	**10%**	**30%**	**10%**	**30%**	**10%**	**30%**
Back-up costs (adequacy)	0.00	0.00	0.08	0.08	0.00	0.00	8.14	8.67	8.14	8.67	19.40	19.81
Balancing costs	0.28	0.27	0.00	0.00	0.00	0.00	1.90	5.01	1.90	5.01	1.90	5.01
Grid connection	1.78	1.78	0.93	0.93	0.54	0.54	6.93	6.93	18.64	18.64	15.97	15.97
Grid reinforcement and extension	0.00	0.00	0.00	0.00	0.00	0.00	3.50	3.50	2.15	2.15	5.77	5.77
Total grid-level system costs	**2.07**	**2.05**	**1.01**	**1.01**	**0.54**	**0.54**	**20.47**	**24.10**	**30.83**	**34.47**	**43.03**	**46.55**

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[2] Balancing refers to the ability to maintain the required system performance on a minute-by-minute basis, in the presence of uncertainty in supply and demand.

[3] Adequacy refers to the ability of the system to satisfy demand at all times, taking into account the fluctuations in supply and demand, reasonably expected outages of system components, the projected retirement of generating facilities, and so forth.

[4] The costs of dispatchable back-up for variable renewables are due only in the case that assumes that variable renewables are installed to cover genuinely new demand. In the case that the working assumption is that variable renewables are introduced into systems with dispatchable capacity that is already fully capable of satisfying demand at all times, the back-up costs can be dispensed with and thus the system costs will be lower. The study also presents an alternative methodology to calculate the costs of providing back-up capacity.

Germany

Technology	Nuclear		Coal		Gas		Onshore wind		Offshore wind		Solar	
Penetration level	**10%**	**30%**	**10%**	**30%**	**10%**	**30%**	**10%**	**30%**	**10%**	**30%**	**10%**	**30%**
Back-up costs (adequacy)	0.00	0.00	0.04	0.04	0.00	0.00	7.96	8.84	7.96	8.84	19.22	19.71
Balancing costs	0.52	0.35	0.00	0.00	0.00	0.00	3.30	6.41	3.30	6.41	3.30	6.41
Grid connection	1.90	1.90	0.93	0.93	0.54	0.54	6.37	6.37	15.71	15.71	9.44	9.44
Grid reinforcement and extension	0.00	0.00	0.00	0.00	0.00	0.00	1.73	22.23	0.92	11.89	3.69	47.40
Total grid-level system costs	**2.42**	**2.25**	**0.97**	**0.97**	**0.54**	**0.54**	**19.36**	**43.85**	**27.90**	**42.85**	**35.64**	**82.95**

Republic of Korea

Technology	Nuclear		Coal		Gas		Onshore wind		Offshore wind		Solar	
Penetration level	**10%**	**30%**	**10%**	**30%**	**10%**	**30%**	**10%**	**30%**	**10%**	**30%**	**10%**	**30%**
Back-up costs (adequacy)	0.00	0.00	0.03	0.03	0.00	0.00	2.36	4.04	2.36	4.04	9.21	9.40
Balancing costs	0.88	0.53	0.00	0.00	0.00	0.00	7.63	14.15	7.63	14.15	7.63	14.15
Grid connection	0.87	0.87	0.44	0.44	0.34	0.34	6.84	6.84	23.85	23.85	9.24	9.24
Grid reinforcement and extension	0.00	0.00	0.00	0.00	0.00	0.00	2.81	2.81	2.15	2.15	5.33	5.33
Total grid-level system costs	**1.74**	**1.40**	**0.46**	**0.46**	**0.34**	**0.34**	**19.64**	**27.84**	**35.99**	**44.19**	**31.42**	**38.12**

United Kingdom

Technology	Nuclear		Coal		Gas		Onshore wind		Offshore wind		Solar	
Penetration level	**10%**	**30%**	**10%**	**30%**	**10%**	**30%**	**10%**	**30%**	**10%**	**30%**	**10%**	**30%**
Back-up costs (adequacy)	0.00	0.00	0.06	0.06	0.00	0.00	4.05	6.92	4.05	6.92	26.08	26.82
Balancing costs	0.88	0.53	0.00	0.00	0.00	0.00	7.63	14.15	7.63	14.15	7.63	14.15
Grid connection	2.23	2.23	1.27	1.27	0.56	0.56	3.96	3.96	19.81	19.81	15.55	15.55
Grid reinforcement and extension	0.00	0.00	0.00	0.00	0.00	0.00	2.95	5.20	2.57	4.52	8.62	15.18
Total grid-level system costs	**3.10**	**2.76**	**1.34**	**1.34**	**0.56**	**0.56**	**18.60**	**30.23**	**34.05**	**45.39**	**57.89**	**71.71**

United States

Technology	Nuclear		Coal		Gas		Onshore wind		Offshore wind		Solar	
Penetration level	**10%**	**30%**	**10%**	**30%**	**10%**	**30%**	**10%**	**30%**	**10%**	**30%**	**10%**	**30%**
Back-up costs (adequacy)	0.00	0.00	0.04	0.04	0.00	0.00	5.61	6.14	2.10	6.85	0.00	10.45
Balancing costs	0.16	0.10	0.00	0.00	0.00	0.00	2.00	5.00	2.00	5.00	2.00	5.00
Grid connection	1.56	1.56	1.03	1.03	0.51	0.51	6.50	6.50	15.24	15.24	10.05	10.05
Grid reinforcement and extension	0.00	0.00	0.00	0.00	0.00	0.00	2.20	2.20	1.18	1.18	2.77	2.77
Total grid-level system costs	**1.72**	**1.67**	**1.07**	**1.07**	**0.51**	**0.51**	**16.30**	**19.84**	**20.51**	**28.26**	**14.82**	**28.27**

Establishing estimates for grid-level system costs also allows calculation of the total costs of electricity supply with and without variable renewables. Introducing variable renewables up to 10% of the total electricity supply will increase per MWh cost, depending on the country, between 5% and 50%, whereas satisfying 30% of demand might increase per MWh costs by anything between 16% and 180% (the latter relating to solar in Finland).

While the range of values for different countries and technologies is very large indeed, even in the most favourable cases system costs are too large to be ignored. While onshore wind is usually the variable technology with the lowest grid-level system costs and solar PV the one with the highest, country-by-country differences are more important than technology-by-technology differences. This means that natural endowments and circumstances matter enormously. It may also explain to some extent differing public and policy attitudes towards the large-scale deployment of variable renewables in different countries.

Finally, the study attempts to analyse the impacts of the deployment of variable renewables on the load factors and profitability of dispatchable technologies in the short run and on their optimal capacities in the long run. Table ES.3 below provides a first indication of the losses in load factors and profitability. It shows that those most heavily affected in the short run are indeed the technologies with the highest variable costs, which are hit hard by the unavoidable decline in electricity prices due to the influx of 10% or 30% of electricity with zero marginal cost.

Table ES.3: **Electrical load and profitability losses in the short term**[5]

Penetration level		10%		30%	
Technology		Wind	Solar	Wind	Solar
Load losses	Gas turbine (OCGT)	-54%	-40%	-87%	-51%
	Gas turbine (CCGT)	-34%	-26%	-71%	-43%
	Coal	-27%	-28%	-62%	-44%
	Nuclear	-4%	-5%	-20%	-23%
Profitability losses	Gas turbine (OCGT)	-54%	-40%	-87%	-51%
	Gas turbine (CCGT)	-42%	-31%	-79%	-46%
	Coal	-35%	-30%	-69%	-46%
	Nuclear	-24%	-23%	-55%	-39%
Electricity price variation		-14%	-13%	-33%	-23%

In the long run, the situation changes as high fixed cost technologies will leave the market due to reduced numbers of full load hours. While average electricity prices will tend to remain stable as low variable cost baseload providers leave the market, their volatility will increase strongly.

A country study of Germany based on the large, integrated energy market model of the IER Institute of the University of Stuttgart confirms at least the orders of magnitudes of the results derived in this study. This is encouraging as the two methodologies employed are entirely different.

Both the calculations in Chapter 4 of this study and the IER modelling effort, whose key results are reproduced in Chapter 7, show that the large increases in electricity supply costs as the share of variable renewables rises result from a combination of higher investment costs, balancing and adequacy costs as well as additional expenses for transmission and distribution. Both calculations also show a rapid decline in wholesale electricity prices as a function of the increasing share of low marginal cost renewables. Electricity systems with very high renewable shares will have electricity prices equal to or below zero during a high number of hours of a year. This remains a major challenge for dispatchable technologies which, unlike renewables, do not receive any subsidies.

Internalising system effects through capacity mechanisms and technological change

The introduction of large amounts of variable renewables creates, in many ways, a radically new situation in electricity wholesale markets, which will require rapid adaptation from all actors. Currently, dispatchable producers ensuring the public good of security of electricity supply are exposed to increasing commercial pressures due to the lower wholesale electricity prices and reduced load factors resulting from the influx of large amounts of electricity from subsidised renewables. This requires the creation of

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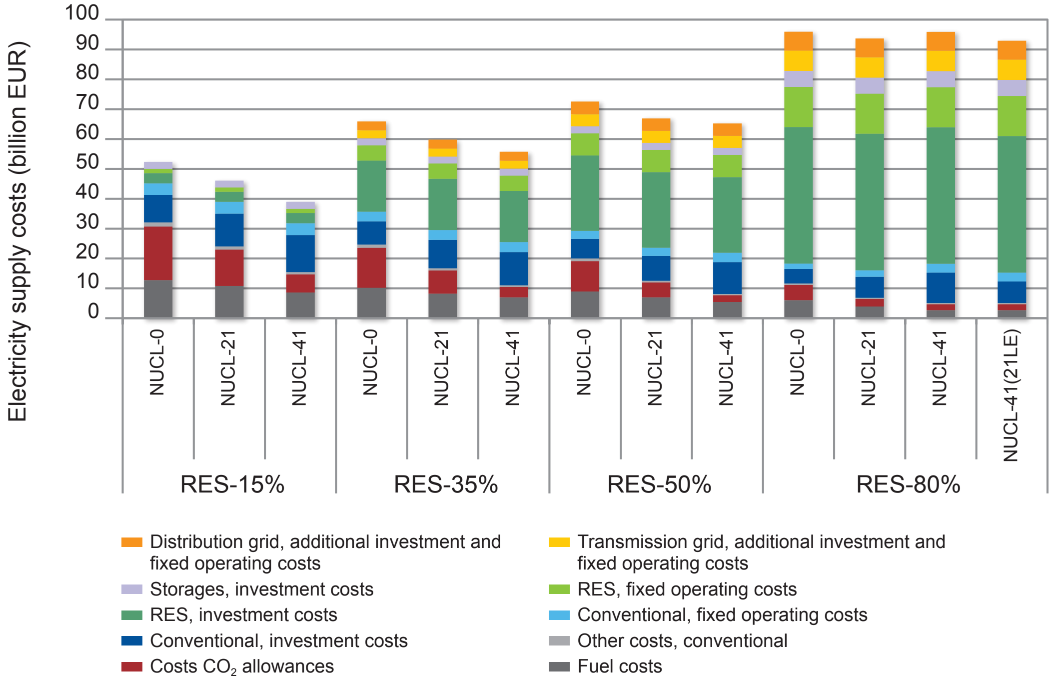
[5] The data presented in this table have been obtained for an optimal (least-cost) dispatchable generation mix, comprising nuclear, coal and gas. Electricity price is assumed to be the cost of the marginal technology plus a mark-up of USD 10 per MWh.

new and innovative institutional, regulatory and financial frameworks that would allow the emergence of markets that remunerate so-called “flexibility services”, which includes the provision of short-term balancing services and, in particular, sufficient amounts of dispatchable long-term capacity.

It also requires rethinking the mechanisms through which subsidies are administered. While member countries are free to choose the energy mix they prefer, the combination of fixed feed-in tariffs (FITs) and grid priority for renewables, means that the latter have no incentive to adjust their load to overall market conditions. Utilities already make an increasing share of their profits in the balancing and adjustment markets for primary, secondary and tertiary reserves to adjust load to the variable production of renewables. While this may alleviate short-term commercial pressures, it is an inefficient manner in which to run an electricity system, creating additional costs that ultimately have to be absorbed by consumers through higher tariffs for transport and distribution. More efficient mechanisms would be feed-in premiums (FIPs) or an obligation for all providers, including producers based on variable renewables, to feed stable hourly bands into the system, even if this means subsequently remunerating the latter for the added costs.

Figure ES.2: **Annual electricity supply costs in Germany as a function of different shares of variable renewables and nuclear**



Note: The acronyms on the horizontal axis correspond to scenarios without nuclear (NUCL-0) and with installed nuclear capacity of 21 GW (NUCL-21) and 41 GW (NUCL-41); RES indicates the share of renewable energy sources in electricity production.

On the supply side for flexibility services, the study shows that there are essentially four dimensions in which one may consider providing the necessary balancing and capacity services to ensure the balance between demand and supply in electricity systems with a significant share of variable renewables:

- Short-term spinning reserves and long-term capacity provided by dispatchable power generators such as nuclear, coal or gas.
- The extension of existing market interconnections to spread demand and supply imbalances over larger areas.

- Storage in order to have short-term power reserves available in time of need.
- Demand-side management (DSM) to curb demand in case of supply shortfalls.

Given the current market environment, a particular role in this context could be played by capacity mechanisms to remunerate dispatchable capacity purely for its availability in time of need. The technical and pecuniary system effects of variable renewables are already putting considerable stress on the long-term adequacy of the electricity systems of OECD countries. The clear implication is that dispatchable technologies, including nuclear, will require that a portion of their revenues be derived from other sources if they are to stay in the market and provide the necessary back-up services. There are currently three major perspectives in which such additional revenue generation can be envisaged:

- Capacity payments or markets with capacity obligations, in which variable producers need to acquire the adequacy services from dispatchable providers, which would thus earn additional revenue.
- Long-term, fixed-price contracts subscribed by governments for guaranteed portions of the output of dispatchable plants whether in the form of contracts for differences or feed-in tariffs.
- The gradual phase-out of subsidies to variable renewables and the discontinuation of grid priority and a "shallow" allocation of additional grid costs; this would slow down the latter's deployment, which is currently bought at considerable economic cost, but would also force the internalisation of grid and balancing costs.

Governments and regulators in OECD countries will need to swiftly start the necessary processes of education, consultation and consistent policy formulation that will allow for such additional mechanisms. This is not an easy task. Given that all such mechanisms will inevitably increase electricity prices but will also be seen as support for technologies such as nuclear, coal or gas that may raise safety, environmental or security of supply concerns, such necessary reforms will not be easy unless their underlying rationale, the protection of electricity supply security, which is a highly valued good in its own right, is convincingly explained and communicated. The alternative, repeated challenges to and occasional breakdowns of electricity supply, is far worse.

The need for structural change in electricity markets will also drive technological change. Therefore, the study discusses two technologies that have potential transformative power for the way electricity is produced and consumed – smart grids and small modular reactors. "Smart" or "intelligent" electricity grids have recently received a high degree of attention due to progress in information technology, heightened regulatory focus and better informed consumers as well as an increasing need for flexibility due to the arrival of significant amounts of variable renewables. In parallel, a number of improvements have taken place in network infrastructure, operations and regulation, which together are likely to have a significant impact on the operation of the different parts of the electricity system (generation, trading, transmission and consumption).

With respect to nuclear energy, a pervasive deployment of smart electricity grids might lead to two very different outcomes. On the one hand, smart grids favour nuclear energy by smoothing load curves and providing added opportunities for large baseload providers such as nuclear. As the latter are faced with the risk that a high share of variable renewables such as wind and solar reduces the number of hours during which a given demand is guaranteed (compression effect), the role of smart grids in this case is to reshape the residual demand curve. Through demand response, load shifting and integration of storage applications, smart grids might change the load curve and re-establish a stable, continuous demand for longer periods of time. This way, a minimum demand over a sufficiently high number of hours could be achieved, resulting in a role for nuclear baseload even in systems with a strong penetration of renewable energy sources.

On the other hand, smart grids may enable decentralised production from smaller units where demand-supply balancing is performed on a more local scale and thus restrict the demand for large baseload units such as nuclear. A more decentralised electricity system based on local energy sources could under certain conditions, such as the local matching of supply and demand, allow for shorter electricity transport distances and thus reduce electricity transmission losses. In such a setting, nuclear power plants could only be used in economically less attractive load following modes as part of so-called local virtual power plants (VPP). This is clearly an issue to be followed closely in the years to come.

As far as nuclear technology is concerned, the deployment of small modular reactors (SMRs) may offer greater flexibility to investors and reduce the balancing costs by reducing the size of the reactor. Their smaller size eases their siting and integration into the electrical grid and guarantees stronger operational flexibility, thus reducing the system costs. From an economic viewpoint, SMRs currently still have higher per unit investment costs and, consequently, higher levelised costs of electricity (LCOE) than larger nuclear units.

However, the smaller size of SMRs offers a broader range of opportunities for choosing the generating portfolio and provides higher flexibility in making investment decisions. The shorter construction time and the possibility of fractioning the total investment in several subsequent units allows utilities to defer or suspend a nuclear project if market conditions are unfavourable. This reduces the overall financial risk. Such investment flexibility is particularly valuable in deregulated electricity markets with variable renewables, where electricity market prices are particularly volatile.

Policy recommendations

System costs in electricity markets are a major issue. While all technologies have system costs, those generated by variable renewables are of at least an order of magnitude larger than those of dispatchable technologies. In addition, they are creating a market environment in which dispatchable technologies are no longer able to finance themselves through revenues in "energy only" electricity wholesale markets. In addition, system costs tend to increase over-proportionally with the amount of variable electricity injected into the system. This has serious implications for the security of electricity supplies. It is only due to the weakened demand for electricity in the current low-growth environment of OECD economies and the considerable excess capacity constructed during more favourable periods in the past that more serious stresses have so far been avoided.

The magnitude of both technical and pecuniary system costs implies that they can no longer be borne in a diffuse and unacknowledged manner by operators of dispatchable technologies as an unspecific system service. Currently, dispatchable technologies are expected to provide the back-up for intermittent renewables to cover demand when the latter are unavailable. This service is costly, but currently not remunerated. Economically speaking, dispatchable technologies are expected to provide the unremunerated positive externality of long-term flexible capacity for back-up. System costs require (a) fair and transparent allocation mechanisms to maintain economically sustainable electricity markets and (b) new regulatory frameworks to ensure that balancing and long-term capacity provision can be provided at least cost.

While future studies will undoubtedly refine the results of this study, in particular with respect to the empirical estimates, current research already allows the identification of four main policy recommendations:

Recommendation 1

It is important to ensure the transparency of power generation costs at the system level: when making policy decisions affecting their electricity markets, OECD countries need to consider the full system costs of different technologies. Failure to do so will rebound in terms of unanticipated cost increases in overall power supply for many years to come.

Recommendation 2

Regulatory frameworks to minimise system costs and favour their internalisation should be prepared: OECD countries with major shares of intermittent renewables need to plan and implement coherent strategies for the long-term adequacy of their energy systems. Four points have particular importance for rendering future electricity market frameworks sustainable:

- The decrease in revenues for the operators of dispatchable capacity due to the compression effect needs to be recognised and adequately compensated through capacity payments or markets with capacity obligations.

- To internalise the system costs for balancing and adequacy effectively, one option may be to feed stable hourly bands of electricity into the grid rather than random amounts of intermittent electricity. If the introduction of variable renewables remains the overriding policy objective, additional non-proportional compensation can be offered.
- While costs for grid reinforcement and interconnection are difficult to allocate to any one technology, the costs for grid extension and connection should be allocated as far as possible to the respective operators.
- The implications for carbon emissions of different strategies for back-up provision need to be closely monitored and should be internalised through a robust carbon tax.

Recommendation 3

The value of dispatchable low-carbon technologies in complementing the introduction of variable renewables should be more effectively recognised. Nuclear energy, as a low-carbon provider of flexible back-up capacity in systems with significant shares of intermittent renewables, plays an important role in meeting policy goals and should be recognised. A combination of capacity markets, long-term supply contracts and carbon taxes would provide a market-based framework to ensure that nuclear energy and other dispatchable low-carbon technologies remain economically sustainable.

Recommendation 4

Flexibility resources for future low-carbon systems must be developed. At the current stage of technological development, low-carbon electricity systems will inevitably be based on high shares of variable renewables and nuclear energy. Hence it is recommended that flexibility resources should be developed based on a systems approach where full costs and interdependencies are recognised. This will require increasing the load-following abilities of dispatchable low-carbon back-up including nuclear, expanding storage, rendering demand more responsive and increasing international interconnections.

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Nuclear Energy and Renewables: System Effects in Low-carbon Electricity Systems
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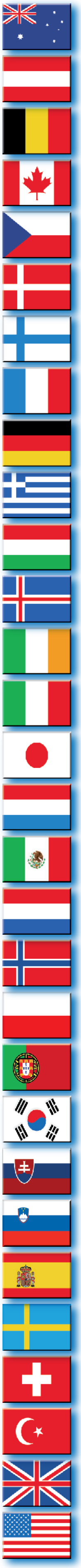

Nuclear Energy and Renewables: System Effects in Low-carbon Electricity Systems

This report addresses the increasingly important interactions of variable renewables and dispatchable energy technologies, such as nuclear power, in terms of their effects on electricity systems. These effects add costs to the production of electricity, which are not usually transparent. The report recommends that decision-makers should take into account such system costs and internalise them according to a "generator pays" principle, which is currently not the case. Analysing data from six OECD/NEA countries, the study finds that including the system costs of variable renewables at the level of the electricity grid increases the total costs of electricity supply by up to one-third, depending on technology, country and penetration levels. In addition, it concludes that, unless the current market subsidies for renewables are altered, dispatchable technologies will increasingly not be replaced as they reach their end of life and consequently security of supply will suffer. This implies that significant changes in management and cost allocation will be needed to generate the flexibility required for an economically viable coexistence of nuclear energy and renewables in increasingly decarbonised electricity systems.

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The full publication
ISBN 978-92-64-18851-8
is available at:
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