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Estimating the costs of nuclear power: benchmarks and uncertainties

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Introduction

The debate on this topic is fairly confusing. Some present electricity production using nuclear power as an affordable solution, others maintain it is too expensive. These widely divergent views prompt fears among consumers and voters that they are being manipulated: each side is just defending its own interests and the true cost of nuclear power is being concealed.

Companies and non-government organizations certainly adopt whatever position suits them best. But at the same time, the notion of just one 'true' cost is misleading. As we shall see in this paper there is no such thing as *the* cost of nuclear power: we must reason in terms of costs and draw a distinction between a private cost and a social cost. The private cost is what an operator examines before deciding whether it is opportune to build a new nuclear power station. This cost varies between different investors, particularly as a function of their attitude to risks. On the other hand the social cost weighs on society, which may take into account the risk of proliferation, or the benefits of avoiding carbon-dioxide emissions, among others. The cost of actually building new plant differs from one country to the next. So deciding whether nuclear power is profitable or not, a benefit for society or not, does not involve determining the real cost, but rather compiling data, developing methods and formulating hypotheses. It is not as easy as inundating the general public with contradictory figures, but it is a more effective way of casting light on economic decisions by industry and government.

Without evaluating the costs it is impossible to establish the cost price, required to compare electricity production using nuclear power and rival technologies. Would it be preferable to build a gas-powered plant, a nuclear reactor or a wind farm? Which technology yields the lowest cost per KWh? Under what conditions – financial terms, regulatory framework, carbon pricing – will private investors see an adequate return on nuclear power? In terms of the general interest, how does taking account of the cost of decommissioning and storing waste affect the competitiveness of nuclear power?

This paperanswers these questions in three stages. We shall start by taking a close look at the various items of cost associated with nuclear power. We shall look at how sensitive they are to various factors (among others the discount rate and price of fuel) in order to understand the substantial variations they display. We shall then review changes in the cost dynamic. From a historical perspective nuclear technology has been characterized by rising costs and it seems most likely that this trend will continue, being largely related to concerns about safety. Finally we shall analyse the poor cost-competitiveness of nuclear power, which provides critics of this technology with a compelling argument.

Adding up costs

Is the cost per MWh generated by existing French nuclear power stations €32 or €49? Does building a next-generation EPR reactor represent an investment of about €2,000 per kW, or twice that amount?

The controversy about the cost price borne by EDF resurfaced when a new law on electricity was passed in 2010[1], requiring France's incumbent operator to sell part of the output from its nuclear power plants to downstream competitors. Under this law the sale price is set by the authorities and must reflect the production costs of existing facilities. GDF Suez, EDF's main competitor, put these costs at about €32 per MWh, whereas the operator reckoned its costs were almost €20 higher. How can such a large difference be justified? Is it just a matter of a buyer and a seller tossing numbers in the air, their sole concern being to influence the government in order to obtain the most favourable terms? Or is one of the figures right, the other wrong?

As for investments in new nuclear power plants, the figures are just as contradictory. Take for example the European Pressurized Reactor, the third-generation reactor built by the French company Areva. It was sold in Finland on the basis of a construction cost of €3 billion, equivalent to about €2,000 per kW of installed capacity. Ultimately the real cost is likely to be twice that amount. At Taishan, in China, where two EPRs are being built, the bill should amount to about €4 billion, or roughly €2,400 per kW of installed capacity. How is it possible for the cost of building the same plant to vary such much, simply by changing its geographical location or timeframe?

The notion of cost

The disparity between these figures upsets the idea, firmly rooted in our minds, that cost corresponds to a single, somehow objective value. Surely if one asks an economist to value a good, he or she will pinpoint its cost like any good land surveyor. Unfortunately it does not work like that. Unlike physical magnitudes, cost is not an objective given. It is not a distance which can be assessed with a certain margin of error due to the poor accuracy of measuring instruments, however sophisticated they may be; nor is it comparable to the invariant and intrinsic mass of a body. Cost is more like weight. Any object, subject to the force of gravity, will weigh less at a certain elevation than at sea level, and more at either Pole than at the Equator. In the same way cost depends on where you stand. It will differ depending on whether you adopt the position of a private investor or a public authority, on whether the operator is subject to local competition or enjoys a monopoly; again it will vary depending on a given country's hydrocarbon resources, and so on. Change the frame of reference and the cost will vary.

In economics opportunity plays the same role as gravity in physics. Faced with two mutually exclusive options, an economic agent loses the opportunity to carry out one if he or she chooses the other. If I go to the movies this evening I shall miss a concert or dinner with friends. The cost of forgoing one of the options is known as the opportunity cost. As economic agents must generally cope with non-binary options, the opportunity cost refers more exactly to the value of the next-best (second-best) option forgone. As preferences are variable (Peter would rather see a movie than spend the evening with friends; for John it is the opposite), the opportunity cost depends on which economic agent is being considered. As a result it is eminently variable. Ultimately there may be as many costs are there are consumers or producers. Regarding our present concern, the cost of building nuclear power plants in Russia, which exports gas, will be different from the cost borne by another state. Investing in nuclear plants to generate electricity, rather than combined-cycle gas turbines, enables locally produced gas to be directed to a more profitable outlet. The economic concept of opportunity cost puts an end, once and for all, to any idea that cost might be an objective, invariant magnitude.

Moreover, it should be borne in mind that cost relates, not to a good or service, but to a decision or action. The opportunity cost is not the cost of something, rather the cost of *doing* something. This of course applies to the cost of production, which is defined by economists using an equation, the production function. This function expresses the relation, for a

[1] French law dated 7 December 2010 on re-organization of the electricity market.

particular technology, between the quantity produced – a kWh for instance – and the minimum production factors required to achieve such output: labour, capital, natural resources. The production function enables us to determine the cost of an additional unit of the good, or the marginal cost- the opportunity of this additional production being measured against the decision not to produce-. The production function also allows us to determine the fixed cost of production, this time compared with the alternative option of producing nothing at all. Its cost is not zero, because before producing the first unit, it was necessary to invest in buildings and machines. So, even if the infrastructure is not used, it must be paid for.

To assess officially the cost of a good or service, it is advisable to ask an accountant, using the appropriate methods. An accountant will calculate direct costs, in other words the costs directly related to the product (steel purchases in car manufacturing) and indirect costs (R&D expenditure, overheads) depending on the prevailing rules on cost allocation. Accountants will distinguish between operating and maintenance costs, capital expenditure drawing on shareholders' equity or on borrowing in order to make investments. For 2010 France's Court of Auditors[2] estimated that the accounting cost, not including decommissioning, of electricity production by EDF's nuclear fleet amounted to €32.30 per MWh. This figure corresponds to annual operating and maintenance expenditure of nearly €12 billion, to produce 408 TWh, and €1.3 billion annual capital costs, restricted to provision for depreciation. Obviously the production cost found by an accountant depends on the method used. Using the full cost accounting method for production the Court of Auditors found a total cost of €39.80 per MWh. This figure is higher than the previous one, because the first method, cited above, only includes depreciation in the capital costs, but does not allow for the fact that the fleet would cost more, in constant euros, to build now than it did in the past. With the full cost accounting method for production, assets not yet depreciated are remunerated and the initial investment is paid back in constant currency.

In the another paper we shall take a detailed look at calculating the cost per kWh of generating nuclear electricity with France's existing capacity. For the time being we may simply observe that neither an approach based on accountancy nor on economics yields a single cost. For one kWh of nuclear electricity, much as for any other good or action, the idea of a true or intrinsic cost for which accountants or economists can suggest an approximate solution is misleading. On the other hand, as we shall see, their methods do help to understand variations in costs, identify the factors which determine costs, compare such costs for different technologies, and also observe the efficiency of operators. All these data are valuable, indeed necessary to decide whether or not to invest in one or other electricity generating technology.

Social, external and private costs

So cost is not invariant. Sometimes it is quite simply impossible to put a figure on it. This additional complication concerns the external effects of using nuclear power generation, be they negative – such as the unavoidable production of radioactive waste and damage in the event of accident – or positive – avoiding CO_2 emissions and reducing energy dependency. Such external effects (or externalities in the jargon of economics) explain the disparity between the private cost, borne by producers or consumers, and the social cost, borne by society as a whole.

Economic theory requires us to fill the gap. Because of this disparity, the decisions taken by households and businesses are no longer optimal in terms of the general interest; their decisions no longer maximize wealth for the whole of society. For example, if it costs €10 less per MWh to generate electricity using coal rather than gas, but the cost of the damage caused by emissions from coal is €11 higher, it would be better to replace coal with gas. Otherwise society loses €1 for every MWh generated. But in the absence of a tax or some

[2] Cour des Comptes, Les Coûts de la Filière Nucléaire, topical public report, January 2012.

other instrument charging for carbon emissions, private investors will opt to build coal-fired power stations. Hence the economic precept of internalizing external effects.

How, then, are externalities to be valued in order to determine the social cost of nuclear power? How much does it cost to decommission reactors and store long-term waste? What price should be set for releasing one tonne of carbon into the atmosphere? How can the cost of a major nuclear accident be estimated? What method should be used to calculate the external effects of nuclear power generation on security with respect to energy independence or the risk of proliferation?

We shall see that the answers to these question raise not so much theoretical or conceptual issues, as practical difficulties posed by the lack of data and information. As a result, the positive and negative external effects of nuclear power are only partly internalized. But then the same is true of other sources of energy.

External effects relating to independence and security

We shall start with the trickiest question: putting a figure on the effects of national independence. This is such a complicated task that no one has ever attempted it. Analysis so far has only been qualitative. We often hear that nuclear electricity production contributes to the energy independence of the country developing it. It purportedly yields greater energy security. Many political initiatives are justified by such allegations, but the terms of the debate are muddled. Conventionally energy dependence refers to the supply of oil products. The latter weigh down the balance of trade of importing countries and subject them to price shocks and the risk of shortages in the event of international conflict. Nuclear electricity production only replaces oil and its derivatives in a marginal way. Only 5% of the electricity generated worldwide is produced using oil derivatives.

In fact it would make more sense to look at gas, in order to justify the claim that nuclear power contributes to energy independence and security. In this respect Europe, for example, is dependent on a small number of exporting countries. The European Union imports two-thirds of the gas it requires and the Russian Federation is its main supplier. Everyone remembers the disruption of Russian gas transit through Ukraine in the winter of 2008-9. As a knock-on effect gas deliveries in Europe were held up for almost three weeks. Millions of Poles, Hungarians and Bulgarians were deprived of heating and hundreds of factories ground to a halt. There is no doubt that Poland's determination sooner or later to start nuclear electricity production is partly due to the need to reduce its dependence on Russia. On the other hand we have heard no mention of calculations putting a figure on the expected benefit: a calculation resulting in acceptance, for instance, of nuclear power costing €5 or €10 per MWh more than that of electricity generated using imported gas. The concepts of energy independence and security are too fuzzy to measure. The best one can do is estimate the cost of the shortfall for the Polish economy per day of disrupted supply. But to calculate the gain in independence, this cost would have to be multiplied by the probability of such disruption. However in 41 years Russia has only failed to honour its commitments twice, with one interruption lasting two days, and the other 20. It would be difficult, on the basis of such a small number of events, to extrapolate a probability for the future.

To take full account of security issues, allowance must be made for the risk of military or terrorist attacks, and the risk of proliferation. In this case the externality is negative and could counterbalance nuclear power's advantage in terms of energy independence. A nuclear power station is vulnerable to hostile action. For example, during the Iran-Iraq war in 1980-88 the nuclear plant being built at Busheir in Iran was bombed several times by Iraqi forces. All other things being equal, the higher the number of nuclear plants in a country, the larger the number of targets available to enemy action.

The development of civilian applications for the atom may entail the additional risk of facilitating proliferation of nuclear weapons. Nuclear weapons can be manufactured using plutonium or highly enriched uranium. The latter may be obtained by using and stepping up enrichment capacity that already exists for producing fuel for nuclear reactors. Such fuel must contain about 5% of uranium-235, whereas the concentration of this fissile isotope must exceed 80% in order to produce a bomb. Plutonium is obtained from reprocessing spent fuel.

No country has so far used fissile material from commercial reactors to produce weapons. Reactors used – purportedly at least – for civilian research have however been used to produce plutonium which can be used in weapons. India and North Korea are two instances of this diversion. Iran's nuclear programme also substantiates the claim that civilian nuclear materials may be diverted toward military purposes. According to many observers the development of commercial nuclear power is a cover for the production of fissile material to make weapons.

One way of reducing the risk of proliferation would be to guarantee countries launching programmes to develop nuclear power a supply of fuel for their reactors. In this way they would no longer need their own enrichment capacity. This measure would restrict the spread of enrichment technology, which can be diverted from its original civilian purpose. The United Arab Emirates has, for example, made a commitment not to produce its own fuel. The UAE will import it from South Korea, which is supplying turnkey reactors. Similarly the Russians will guarantee a supply of fuel for the nuclear plants they are due to build in Turkey. However agreements of this sort are contrary to the goal of reducing energy dependence often associated with the decision to resort to nuclear power, there being only a limited number of potential fuel suppliers. In the long run some countries will want to have their own enrichment units, at least once they have a sufficient number of reactors.

There are no firm figures for the external effects of nuclear power on national and international security, no more than there are for energy independence. Any attempt to calculate such figures is thwarted by the scope of these concepts, both too broad and too fuzzy. It would probably be wiser to leave it up to the diplomats and military strategists to persuade their governments – using qualitative arguments – to revise, upwards or downwards, the cost of resorting to nuclear power in their country.

The price of carbon

How are we to assess nuclear power's contribution to combating global warming? Stated in these terms the question is too general to allow an economist to provide an accurate answer. There are too many uncertainties regarding the goal being sought and the consequences if no action is taken. How is global warming to be defined? How large a share should be attributed to human activity? Which greenhouse gases should be taken into account? We are to back to the previous problem. On the other hand, values may be suggested for the benefit of nuclear power in relation to reducing CO_2 emissions to the atmosphere. To calculate this benefit we need to know the price per (metric) tonne of carbon emissions, which can then be combined with the emissions avoided for each MWh generated. At first sight this seems straightforward. At a theoretical level, all the textbooks on environmental economics explain how to determine the optimal price of a pollutant. In practical terms trade in CO_2 emissions credits provides an indication of the price of carbon. But in fact, the problem is still a thorny one: we lack the data to apply the theory and the carbon markets produce the wrong price signals.

The theory for determining the optimal price of a pollutant emission is simple enough in principle. The optimal price is found at the point where the curve plotting the marginal cost of pollution abatement intersects the curve for the marginal benefit of the avoided damage. The general idea is that the level of pollution which is economically satisfactory for society is the point beyond which further abatement costs more than the benefit from avoiding additional damage. Or put the other way round, it is the point below which the situation would not serve the public interest, the cost of additional abatement being lower than the benefit it would yield; abatement is consequently worth carrying out. This coincides with a basic economic principle according to which all actions for which the social cost is lower than the social benefit should be carried out. As is the case with any equilibrium, the optimal price corresponds to the optimal amount of pollution. Normative economics does not prescribe zero pollution. The economically optimal amount of waste or effluents is only equal to zero in the rare event of it being less expensive to eliminate pollution, down to the last gram, rather than suffering the damage it entails.

Applying this theory is another matter. The data required to plot curves for CO_2 emissions abatement and avoided damages does not exist. Obviously there are estimates of the cost of various actions such as insulating homes or recycling waste, which in turn limit carbon emissions to the atmosphere. But economists need future costs, not just current costs. The former are unknown, because technological innovation – such as carbon capture and storage – has yet to yield conclusive results. It would also be necessary to know the cost of measures to adapt to global warming. It may be more economical, at least for part of the temperature increase, to adapt to the situation rather than combating it. But it is future generations which will have to adapt. How can we know how much it will cost them? We cannot ask them. The same applies to the damages suffered by our descendants. How could they be calculated without an exact idea of their extent and without questioning those who might be exposed to them? For example the cost of migration to escape changing geographical conditions depends on the individuals concerned, in particular how much value they attach to the loss of their land. The last, but no means the smallest, obstacle to assessing damages is the lack of a robust formula for converting the concentration of CO_2 in the atmosphere into temperature increase. It is not the amount of carbon which causes the economic loss but the climate change it may bring about. In this situation economists are dependent on the scientific knowledge of climatologists. Unfortunately analysis of the exact consequences for climate change of a rise in the amount of greenhouse gas stored in the atmosphere is still tentative.

But does looking at the markets makes it any easier to find the price of carbon?

At first sight, yes. Since 2005 Europe has had a market for tradable emissions permits. On this market the price of a tonne of CO_2 fluctuated on either side of €15 in 2009-10 (equivalent to €55 a tonne of carbon, a tonne of CO_2 containing 272 kilograms of this element). Given that generating one MWh using coal releases roughly a tonne of CO_2, the operators of coal-fired plants had to pay an average of €11 per MWh for their emissions in 2009-10. In other words, all other things being equal, if in the course of this period, 1 MWh generated by a coal-fired power station had been replaced by 1 MWh generated by a nuclear plant, €11 would have been saved. Projecting ourselves into the future and anticipating that the market price of carbon will double, switching electricity production from coal-fired to nuclear power stations would save €22 per MWh.

So far, so good. On the basis of the market price we can obtain the opportunity cost we sought, be it past or future. In addition the private and social costs seem to have been reconciled: private operators are forced to make allowance for the price of carbon emissions when choosing to invest in coal-fired or nuclear plants. Thanks to the market, the external effect has been internalized.

In fact, nothing has been settled. For two reasons. Firstly, the European Emissions Trading Scheme is not a market for polluters and polluteds, but an exchange for companies at the source of emissions. It reflects the abatement performance of the various players, but in no way the damage done. Secondly the market was badly calibrated. The prices it reveals are not sufficient to achieve the targets set by the EU for reducing CO_2 emissions. We shall now take a closer look at these two reasons.

Economic theory explains that externalities occur in the absence of a market, so the answer is to design one. With no market, there is no price, hence no purchasing cost and no accountable expenditure. When manufacturers discharge harmful emissions into the atmosphere, they are using the latter as a huge tip, access to which is free of charge. Some polluters are not against the principle of a toll system, particularly for the sake of their image. Similarly, to improve the market value of their home, some residents would be prepared to pay polluters to restrict their emissions. But there being no marketplace where polluters and polluteds can meet, pollution is free; it appears in no accounting system and remains an external cost.

The European market for tradable emissions permits is not a place of exchange between polluters and polluted. On the contrary it brings together companies to which individual CO_2 emissions quotas have been distributed, but for a total amount capped below the level of industry's overall emissions. Let us suppose that, for example, 100,000 permits, each for a tonne of CO_2, are allocated whereas emissions from polluting companies amount to 120,000 tonnes. In this fictitious case, the companies would have to reduce emissions by 20,000 tonnes. In some companies the cost of cutting CO_2 emissions is low, for others it is higher. The first group will become sellers and carry out more abatement, the second group will buy permits and abate less. At equilibrium, the price will be equal to the marginal cost of eliminating the last tonne required to meet the limit. The advantage of this market is that expenditure by industry on cutting emissions is minimized. Economic theory demonstrates that a tax yields a similar benefit. With a tax on each unit of pollution, companies with low costs for cutting emissions will abate more to reduce their liability for taxation; on the other hand companies with high abatement costs will pay proportionately more tax and do less to cut emissions. The main difference between a permit and a tax is the initial variable selected by the competent authority. In the case of a tax, the price is set in advance and deploying the instrument will show ex post the corresponding cut in emissions. For example a tax pegged at €20 a tonne will lead to a 20,000 tonnes drop in emissions. For a permit, the amount is decided first and the market then reveals the price per tonne of emissions avoided. If an upper limit of 100,000 tonnes is set to reduce emissions by 20,000 tonnes the market will balance out at a price of €20 a tonne.

The decision to base the system on price or quantity is closely related to the political consensus underpinning the action. In the first instance agreement was reached on the level of the acceptable surcharge per unit, in particular for consumers and business. Here the unknown factor was the amount of abatement; it might be too low, but in any case the economic conditions were such that a higher surcharge could not be applied. In the second instance agreement was reached on the level of a significant reduction that needed to be achieved, in particular according to scientific experts. The unknown was the price to be paid for such a reduction, but in any case setting a lower target for pollution abatement would certainly not have achieved the desired environmental effect. This is obviously an oversimplification. In the absence of accurate data on the cost of abatement, orders of magnitude may sometimes be posited. When the initial level of taxation is announced, business and government may be able to estimate how much pollution will be abated within a certain range. In the other case, when the initial abatement target is published, the various players can estimate an approximate price. Once the first variable has been set, the second is not usually completely unpredictable.

However, as the European example (see box) shows, the initial calibration may be faulty.

The failures of the EU Emissions Trading Scheme

By mid 2013 the price of CO_2 had dropped to less than €5 a tonne. Five years ago the European Commission predicted that by this point in time it would be worth €30. The financial crisis and the drop in industrial output obviously explain part of the difference. But in 2006 the price had already fallen below €15 a tonne. The main structural reason behind the persistently low price of CO_2 is the failure to create scarcity, too many permits having been distributed. The resulting downward pressure on prices has been exacerbated by lower than expected emission-abatement costs. The European CO_2 trading system does not fulfil its purpose: it does not send a reliable signal enabling industry to curtail long-term investments, in particular enabling electricity utilities to choose between various generating technologies according to their CO_2 emissions performance.

The case of the United Kingdom is a perfect illustration of this failure. The UK has undertaken to halve CO_2 emissions by 2030. To achieve this target it plans to set a carbon-price floor at €20 a tonne in April 2013, slated to double by 2020, ultimately reaching €87 a tonne by 2030. The price in the EU Emissions Trading Scheme will only exert an influence if it exceeds these price-floors, which is unlikely to happen very often unless the ETS is reformed in the meantime. France offers another example. In 2009 the government was planning to introduce a carbon tax as an incentive to reduce the use of oil products. The rates recommended to achieve a fourfold cut in emissions by 2050 were €32 a tonne in 2010, rising to €100 a tonne in 2030, and twice that amount by mid-century[3]. The ETS price for carbon is far below the value recommended by experts to achieve long-term targets for reducing emissions.

The preceding discussion of the price of carbon is important, as we shall see, for it is one of the determining factors in the competitiveness of nuclear power: without taxes on CO_2 emissions or in the absence of an emissions trading scheme, nuclear power cannot compete with coal or even gas. Furthermore, a consideration of how the cost of carbon is assessed highlights the dual role played by economic analysis. In the world of perfect information posited by economic theory, such analysis would enable us to set the optimal level of abatement, at the intersection between the cost of the damage done by an additional tonne of emissions and the cost of reducing pollution by an additional tonne. The role of government would be simply to plot curves and enforce the resulting target price or quantity. The economic analysis would dictate its prescriptions to policy-makers. In the real world of limited information, in which we live, economics occupies a humbler position and the roles are reversed. Political decisions, through voting, debate or consultation lead to the definition of an acceptable level of either damages or expenditure. Economic analysis only intervenes to minimize the cost of achieving the degree of damage decided by government or to maximize the quantity produced corresponding to the level of expenditure set by government.

Decommissioning and waste: setting the right discount rate

Nuclear electricity generators are responsible for the waste and by-products they produce. In this field, much as elsewhere, the polluter-pays principle applies. Nor is this principle disputed by the operators of nuclear plants, nor yet by opponents of nuclear power. So the controversy does not centre on the need to internalize the costs of decommissioning reactors and storing waste (spent fuel, decommissioning debris), but on the amount to be set aside now to cover these costs, in order to ensure that these back-end activities can be carried out tomorrow.

Worldwide we have almost no experience of dismantling power stations and burying radioactive waste. Nowhere in the world has anyone so far built a permanent storage facility for burying long-term waste. In France not a single nuclear power station has been completely decommissioned. Work decommissioning the Chooz A reactor, in the Ardennes, is only scheduled to end in 2019. The reactor was commissioned in 1967 and shut down 24 years later. Worldwide less than 20 commercial reactors have been completely dismantled.

The lack of references makes appraisal very uncertain. We cannot rule out the possibility that the technical costs of dismantling and the costs of waste-management may prove very high. However, even if this were the case, it would have little effect on the return on investment from a new nuclear power station. The return is not very sensitive to this parameter because the costs at the end of a nuclear plant's service life are very remote in time, and a euro tomorrow is worth less than a euro today, and even less the day after tomorrow. Future costs or benefits are wiped out by the rate of exchange used to convert present funds into future funds (or vice versa). For example, at an annual rate of 8%, €1 million would only be worth €455 in a century. This amount drops to €0.20 after two

[3] Centre d'Analyse Stratégique, La Valeur Tutélaire du Carbone. Report by the committee chaired by Alain Quinet, La Documentation Française, n° 16, 2009.

centuries and in 500 years it would have dwindled to almost nothing. If the plant had to be decommissioned now, taking the same rate and supposing that decommissioning would cost 15% of the total cost of a new reactor, this share would only represent 0.7% of the total cost if work was carried out 40 years later. This rate, known as the discount rate, plays a decisive part in assessing the costs of decommissioning plant and managing waste. To avoid wiping out such costs, a discount rate close to zero would need to be used. Certain environmental conservation groups advocate this position, but there is little support among economists. We shall now look in greater detail at how the discount rate works.

To avoid confusion, we should start by explaining what this rate is not. Firstly the discount rate bears no relation to inflation. The latter, whether its origin is monetary or results from indexing wages, is a phenomenon which raises prices. Consumers will buy less tomorrow because the same shopping basket will cost more. Secondly the discount rate does not reflect the risks associated with the investment project being assessed. Such risks cast doubt on income and expenditure and change the way they are estimated, but not due to the discount rate.

To convert current euros into future euros we must start from existing knowledge. Despite the limited experience mentioned above, we do have preliminary orders of magnitude. In 2010 France's Court of Auditors used the EDF estimate of how much it would cost to decommission its 58 reactors. The cost entered in the company's accounts amounts to €18 billion, equivalent to €300 per kW of installed capacity. In comparison with assessments in other countries, and consequently relating to reactors and conditions which may be very different, this figure is near the lower end of the range. The management consultants Arthur D. Little estimated that the upper value in Germany would be close to €1,000 per kW. In the United States estimates of the cost of decommissioning the Maine Yankee plant, completed in 2005, are in the region of €500 per kW. As for waste destined to be buried in deep geological repositories, only very preliminary estimates have been made. Work is still focusing on pilot schemes or has barely started. The only site currently operating stores radioactive waste of military origin at Carlsbad, New Mexico. This waste is easier to manage because it does not release any heat. To store the amount of long-term waste produced by a reactor in one year the order of magnitude currently cited is €20 million. This figure is based on various British, Japanese and French estimates[4]. The amount is likely to change with progress by research and technical know-how. In 2005 France's Nuclear Waste Authority (Andra) estimated that it would cost a little under €20 billion to build and operate a deep geological repository. Five years later adjusted new assessment was made up to €35 billion. The second amount makes allowance for additional parameters, integrating return-on-experience from excavating underground galleries, requirements for greater capacity and tougher safety constraints, among others.

The timescales we are dealing with here are very long. Some categories of nuclear waste will go on emitting radiation for several hundreds of thousands of years. For example plutonium-239 has a half-life – the time required for half the radioactive atoms to disintegrate – of 24,000 years. For technetium-99 it rises to 211,000 years and for iodine-129 it is 15,7 million. Such time spans are stupendous when compared to the scale of human life. Our most distant ancestors, *Australopithecus*, appeared on Earth 4 million years ago and modern humans (*homo sapiens*) only emerged about 200,000 years ago. Of course there are no plans for the storage facilities to operate for such long periods. For example the deep geological repository projected by Andra is expected to last for 120 years, from the start of construction to final closure. If a decision was taken now to invest in a new reactor, the plant would be commissioned in 2020 and operate for 60 years. Only in 2100 would decommissioning be complete, with the last tonnes of waste finally being buried in 2200. These economic deadlines are short compared with the half-life of certain waste products, but nevertheless dizzying. A century is a very long time, in the life of an economy, with its

[4] Cour des Comptes, op cit, p150.

multiple crises. Government bonds, the investments with the longest time span, spread over periods of 20 or sometimes 30 years, stretching to 50 in exceptional cases.

With such long timeframes, how can we account for this expenditure now? Utilities must make provision for such liability in their accounts, integrating the cost in calculations of the social rate of return on generating nuclear electricity.

The reference to government bonds suggests a preliminary approach to the discount rate and its basis. If someone offers to give you €100 today or in 20 years time, there is no need to think twice. If you take the €100 now you can make a very sound investment in US Treasury bonds. Thanks to the interest you will have more than €100 in 20 years. You will thus be able to consume more than if you had agreed to wait before receiving the funds. The decision, based on a simple trade-off, justifies the use of discounting and the long-term interest rate may be used to find the future value of today's euros. With 4% interest, €100 today will be worth €220 in 20 years or, inversely, €100 from 20 years ahead would be worth only €45.60 at present. However using this interest rate to discount the value does not solve the problem, if the aim is to determine the value of a euro in a century. As the business weekly The Economist amusingly observed[5], "At a modest 2% rate [...] a single cent rendered unto Caesar in Jesus' time is equivalent to [...] 30 times the value of the entire world economy today".

Furthermore interest rates only partly justify discounting. According to economic theory discounting is necessary for two reasons: people are impatient and future generations will be better off. The economic agents featuring in the models display a pure time preference for the present. Instead of taking an interchangeable value, let us suppose that the choice concerns the possibility of attending the performance of an opera in the course of the coming year, or the same performance in five years' time. Which ticket would you choose? The interest rate argument does not hold because you can neither loan nor resell the ticket. If you do not use it, it will be wasted. It is highly likely that you will opt for the performance in the coming year, rather than waiting five years. This impatience is reflected in a pure time preference for the present, which crushes future consumption to give it less weight.

It is more difficult to illustrate the notion that future generations will be better off. The discount rate depends on the growth rate of the economy and a barbaric term, the elasticity of inter-temporal substitution in consumption. The overall idea is that the richer you are, the less satisfaction an additional euro will yield. If you give €100 to someone with a low income, you will be making him a present worth much more than if you give the same amount to a millionaire. Marginal utility decreases with income. Consequently if society is €1 billion richer tomorrow, it will respond less to this gain than now. With an ordinary utility function, society 10 times better off than at present, and elasticity equal to 1, contemporary society would see its well-being increase 10 times more for each marginal unit of consumption (€1 billion) than tomorrow's society. So it would be advisable to limit our efforts to provide benefits for future generations.

Economists thus provide the following key, forged by Ramsey in 1928[6], for calculating the discount rate: the discount rate (d) is equal to the sum of the pure preference rate for the present (p) and the product of the elasticity of the marginal utility due to consumption (e) multiplied by the growth rate of per capita GDP (g), in other words $d=p+eg$. With the three values often used [2,2,2], the discount rate is 6%.

Interpretation of the three variables merits closer attention.

The pure preference rate for the present may be seen as an equity parameter, its value depending on how fairly we wish to treat future generations. Let us suppose that the output from a new nuclear plant entails a waste-management cost of 100 in a century, but yields a present gain because nuclear technology is cheaper. If we want to treat future generations even-handedly, we should only commit ourselves to the investment if its present benefit for

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[5] The Economist, Is it worth it, 3 December 2009

[6] F.P. Ramsey, 1928, A Mathematical Theory of Saving, Economic Journal, 38, p543-559.

us is greater than 100. In this case we would apply a pure preference rate equal to zero. This position in favour of equality between generations is defended by some economists, including Ramsey. It rejects the idea of discrimination depending on the date of birth and involves treating all generations on the same footing, even if they are more prosperous. If we want to treat our descendants slightly less favourably (if, for example, we are convinced they will find smarter means of storage or recycling), we need to use a slightly positive preference rate. A gain of 14 today will suffice (equal to 100 discounted at 2% over 100 years). If on the other hand we are feeling selfish and have no concern for what comes after, the rate will be very high: even if nuclear power only yields today a unit gain, it is worth taking, its value exceeding 100 in the future (discounted at 8% a year, it will be worth €0.40 in a century). We may also interpret the pure preference rate in terms of our chances of survival. With a one in ten chance of mankind not surviving for 100 years (following, for example, collision with a meteorite), the value of the preference rate is 0.1; it rises to 1 if we assume the likelihood of survival is 0.6 (a 4 in 10 chance of the end of the world).

The elasticity of the marginal utility due to consumption also measures equity. The greater the difference in utility for a marginal unit of consumption between low and high-income households, the more justification there is for high levels of transfer, through taxation for instance, from rich to poor. Such transfers raise the utility of the whole of society. In other words, this parameter reflects our attitude to unequal levels of consumption, between different people in the present day, or between them and their descendants. Unlike the previous variable, the difference in treatment is not related to time. The more egalitarian we are the more we favour redistribution from rich to poor and the higher the value we need to use for elasticity when calculating the discount rate. If we assume that future generations will be richer than today, it is legitimate to limit our efforts to improve their welfare. On the other hand, elasticity equal to 1 is unfair. Given a constant population it would justify spending 1% of today's GDP to give future generations the benefit of an additional 1% of GDP, even if they are incomparably more prosperous. Per capita fractions of GDP can therefore be traded between generations on equal terms. The elasticity of marginal utility may also be linked to risk. According to economic theory risk aversion is proportional to elasticity. The higher the elasticity, the more a person is prepared to pay for the certainty of consuming 100, rather than a random outcome (for example, a one-in-two chance of consuming 200, or zero). Taking a higher value for this parameter, which is then multiplied by the growth rate of per capita GDP is tantamount to assuming that the present generation is averse to risk.

Setting the three values which make up the discount rate is no easy matter; but they will play a decisive role in how we act now. An instance of this point is the controversy prompted by the publication in 2006 of the Stern Review[7]. This report caused quite a stir because it concluded that substantial, immediate expenditure (about 1% of GDP) was needed to reduce greenhouse gas emissions. This recommendation contradicted the conclusions of most climate-change economists which suggested a more gradual increase in expenditure. The work of the US economist William D. Nordhaus[8], for example, recommends a carbon tax of $13 a tonne over an initial period in order to internalize the damage done by global warming. Nicholas Stern prescribed $310 a tonne. Half of this difference is simply due to the discount rate used by the two parties: 4% for the former, 1.4% for the latter.

In his estimate Stern uses a preference rate for the present of 0.1 and elasticity of 1. These two values represent the lower limits of the ranges economists generally accept. His choice is open to criticism because it raises a logical contradiction. A low preference rate for the present should go hand-in-hand with high elasticity or, on the other hand, low elasticity should match a high preference for the present. It would be mistaken to suppose that one of these two parameters reflects equity between generations, the other solidarity within a single generation. A low value for the elasticity of the marginal utility due to consumption

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[7] The Stern Review of the Economics of Climate Change, October 2006.

[8] [note manquante ?]

can be justified on the grounds of reducing inequality between rich and poor, regardless of when they were born. This choice coincides with a high preference rate for the present, which endorses the idea that the present generation should only make limited sacrifices for future generations (given that the latter will be better off, as Stern posits with a positive growth rate for per capita GDP). Using a simplified economic model the Cambridge economist, Partha Dasgupta[9], has demonstrated that the parameters used by Stern would lead to inconceivably high saving ratios. With a preference rate for the present of 0.1, elasticity of 1, and a world with neither technological progress nor population growth, we should be investing 97.5% of our current output in boosting the standard of living of future generations. The Stern Review asks whether it makes economic sense to spend 1% of today's GDP to prevent damage amounting to 5% of GDP in a century. The three values it uses, [0.1; 1; 3], would lead to a discounted benefit five times *greater* than the cost. But if we use [2; 2; 2] the discounted benefit would be 10 times *smaller* than the cost! In other words, with a 1.4% discount rate it is entirely justifiable to spend 1% of GDP on reducing greenhouse gas emissions, whereas with a 6% discount rate it would be quite out of the question.

We have so far set aside the question of the third parameter, the future growth rate of per capita GDP. Its value is just as uncertain as the others, but setting it does not raise equity-related issues. Looking back in time, the annual growth rate of per capita GDP was 1.4% in the UK from 1870 to 2000, and 1.9% in France. However these averages conceal significant variations. In the UK the growth rate was 1% in 1870-1913, 0.9% in 1913-50, 2.4% in 1950-73, and 1.8% from 1973 to 2000. Over a very long period of time – 1500 to 1820 – it is estimated to have been 0.6%. Which of these different rates should we use? The growth rates for the next century or two may be very different. Nor can we rule out a negative growth rate, though it is not very likely. However global warming in excess of 6°C in 200 years could have precisely that effect.

The discount rate cuts both ways, exerting a decisive influence on decisions regarding public and private investment, but it is impaired by numerous unknowns. One recent attempt to reduce this tension has involved using a rate that varies over time – rather than being constant – declining as it advances into the future. The per capita growth rate can be used to illustrate the intuition behind this idea: the more remote the future, the greater the uncertainty regarding economic and technological progress; and consequently the greater our caution regarding action that might jeopardize the well-being of future generations, the lower the discount rate should be. The French economist Christian Gollier[10] recommends using a 5% annual discount rate for costs borne over the next 30 years, dropping to 2% for subsequent costs. It is also possible to set the discount rate on a downward path, with either several steps or a steady decline. In a report submitted to the British government in 2002[11], Oxera Consulting Ltd suggested adopting a 3.5% rate from 0 to 30 years, 3% from 31 to 75 years, 2.5% from 76 to 125 years, and so on, with the rate ultimately bottoming out at 1% after 300 years. In France the Lebègue report[12], on a review of discount rates in public investment, recommended a 4% rate for the first 30 years, then a rate that would steadily decrease to reach 3% after 100 years, tending towards 2% for a time horizon of over 300 years.

A varying rate also seems to represent a compromise between two demands: on the one hand taking account of our preference for the present and our contribution through technical progress to the prosperity of future generations; and on the other hand allowing for the

[9] P. Dasgupta, Comments on the Stern Review's Economics of Climate Change, November 2006, memo.

[10] C. Gollier, Discounting an Uncertain Future", Journal of Public Economics, 85, 2002, p149-166.

[11] A Social Time Preference Rate for Use in Long-Term Discounting, Oxera, December 2002.

[12] Report by the group of experts led by Daniel Lebègue, Révision du Taux d'Actualisation des Investissements Publics, Commissariat Général du Plan, January 2005.

potentially very negative consequences of our action, or inaction, with regard to future generations[13].

It is obviously up to the relevant authorities to ensure that adequate provision is made for the projected costs of decommissioning and waste management, in accordance with the discount rate they have decided. In both the United States and France the government took such measures long ago. Left to themselves utilities would stand to gain by underestimating future expenditure on this work and by opting for high discount rates in order to minimize projected costs. In the US and France – but also in many other countries – today's consumers are paying for tomorrow's expenditure. There are no hidden costs for decommissioning and waste which once internalized would make the cost of nuclear electricity production prohibitive (see box).

Taking into account the costs of decommissioning and waste

In France regulation is based on special discounted provisions imposed on EDF. They appear on its balance sheet and the utility is required to secure them with specific cover assets. The law sets an upper limit for the discount rate pegged to 30-year government bonds, currently close to 3%. With this rate EDF's provisions for decommissioning and waste amount to €28 billion. They would increase by 21% with a 2% discount rate, adding 0.8% to the overall cost of a MWh. Furthermore, if just the cost of decommissioning was to rise by 50% (amounting to €30 billion as opposed to €20 billion), the cost of electricity would increase by 2.5%[14]. If the cost of deep geological repositories was to double, it would result in a 1% increase. In the US a special fund has been set up to cope with the future expense of deep repositories for spent fuel. Utilities pay a fee into the fund equal to $1 per MWh they generate. The Department of Energy checks at regular intervals that the fee is sufficient. For this purpose it has developed about 30 cashflow models designed to balance out by 2133[15]. These scenarios depend on a large number of parameters, including the discount rate. The lowest rate considered is 2.24% per year. Two out of the four scenarios based on this rate result in a deficit, whereas the proportion is only one in four for the scenarios using a higher rate. The figures above are valid for existing reactors in the US and France.

For new nuclear plants, the time horizon for expenditure would be longer, so decommissioning and waste-management costs would have even less impact on the present value of projects. A Massachusetts Institute of Technology study[16] on the future of nuclear power puts the overnight cost of building a reactor at $4,000 per kW, and the cost of decommissioning it at $700 per kW, or 17.5%. Spreading decommissioning expenditure out between the 41st and 110th year after the reactor is commissioned, and assuming a 6% discount rate, would bring the present value of decommissioning down to $11 per kW. This value would be five times higher ($52) if the rate was almost halved (3.5%). But as before, this cost is negligible compared with construction costs. With the above discount rates, the 17.5% shrinks to 1.3% or 0.2%, respectively.

So back-end activities have no significant impact on the cost competitiveness of existing or new nuclear power. Unless of course one adopts a very low, or even zero, discount rate for very distant time horizons – as is the case in the Stern Review's calculations for climate change. In our opinion, this stance – which its advocates justify by the hazardous nature of nuclear waste and its very long life – boils down to using inconsistent economic reasoning to endorse a legitimate argument. In this paper we have not allowed for the possibility that such waste might represent a risk for future generations. The only waste-related costs taken

[13] The intuitive, common sense solution of a declining, variable discount rate now has a solid base in economic theory, see the book by C. Gollier, Pricing the Planet's Future, The Economics of Discounting in an Uncertain World, Princeton University Press, 2013.

[14] Cour des Comptes, op cit, p282.

[15] DoE, Civilian Radioactive Waste Management Fee Adequacy Assessment Report, July 2008. RW-0593.

[16] Update of the MIT 2003 Future of Nuclear Power, 2009.

into account are the preventive costs built into the quality of repositories and their supervision. These costs vary depending on the safety standards set by government for decommissioning and storage. To take a trivial example, the cost of a repository increases in relation to the length and depth of its tunnels. On the other hand, this calculation makes no allowance for the cost of possible accidents, despite the fact the risk does exist.

At Fukushima Daiichi there could have been a loss of water from the cooling ponds containing spent fuel, or even their collapse, leading to massive radioactive emissions. Securing future generations against a disaster of this sort poses the problem of assessing the uncertain damages associated with events with a very low probability and a very high cost. The release of radioactive substances into the atmosphere following the meltdown of a reactor core raises the same question: how is one to estimate the costs without knowing how the risks are distributed. We shall address this key question in a companion paper. The discount rate is of only limited value for finding an answer. A wrong way out would be to give the matter no further thought and select a very low, or zero, value to allow for the hazards of wasteMaking allowance for a possible disaster caused by downstream activities may mean opposing the construction of new nuclear reactors without it being necessary to hide behind a very low or zero discount rate.

Liability in the event of accident

Another paper devoted to risks and regulation deal in detail with the cost of major accidents and the legal framework for the civil liability of nuclear power. But we need to mention the matter briefly here, many authors having suggested that estimates of the cost of nuclear power fail to make allowance for the risk of disaster.

The operators of nuclear power stations are liable in the event of accident, but it is true that in most cases an upper limit is placed on such liability. The amount of compensation they must pay in the event of massive radioactive emissions is less than the value of the damages. In France, for instance, the limit is €91.5 million. It will soon be raised to €700 million. Such caps on liability raise the question of whether the costs of major accidents are sufficiently internalized. According to the opponents of nuclear power, limited liability is equivalent to a hidden subsidy. After all a Swedish study[17] estimated that the Chernobyl disaster cost nearly $400 billion. There is no way of settling the matter without a detailed review of the expected and observed frequencies of accidents and the uncertainty surrounding the level of damages. Here we shall make with a much simplified examination of the risk involved, in order to determine, within this framework, how much impact it has on the full cost of existing nuclear plants and new reactors.

Risk is classically defined as the result of multiplying the probability of an accident by the severity of the outcome. For the sake of argument, we shall take the highest values cited in the literature for these parameters. We shall suppose that there is one chance in 100,000 that a disaster may occur during one year of a reactor's service life, a probability 100 times higher than the figure cited by Areva for the EPR. We shall then suppose that the massive release of radioactivity causes damage to public health and the environment worth €1 trillion, 10 times higher than the provisional estimates for Fukushima. So the risk is equal to 0.00001 x 1,000,000,000,000, or €10 million a year. Supposing that the reactor's annual production amounts to 10 million MWh, the risk would be equivalent to €1 per MWh, or 40 times less than the cost estimated by the regulatory authorities for nuclear electricity generated by EDF, or indeed between 50 and 100 times less than the estimates of the average cost of new nuclear. This scratch calculation shows that, under much simplified conditions – in particular no allowance for uncertainty or aversion to risk – internalizing the full cost of an accident has only a very slight impact on the cost of nuclear electricity.

[17] Economic losses estimated at $148 billion for Ukraine and $235 billion for Belarus. Figures cited by Z. Javorowski, The Chernobyl Disaster and How it has been Understood, 2010.

We should however point out that, on the basis of these hypothetical data, the upper limits on liability currently in force mean that only a relatively small share of costs is internalized. If we take the case of the €91.5 million limit in France, it only amounts to 0.4% of the full cost of an accident[18]. Raising the limit to €700 million would still leave 97% unaccounted for. In other words internalization is indeed partial, but internalizing the full cost would only result in a slight increase in the cost of nuclear electricity.

Technical and financial production costs

Here at last we may venture onto more solid ground. Engineering economists do not base their decisions on externalities which are so difficult to grasp and estimate. On the contrary they work on data, relating in particular to the costs of reactors built in the past and current operating costs. They can use proven, widely accepted methods for calculating costs, in particular for project funding. They juggle with concrete, steel, enriched uranium, man-months, assets and deadlines.

To come to grips with the subject we shall start with construction. This involves an overnight cost and a capital cost. The overnight cost refers to a hypothetical construction project completed in an instant, or 'overnight'. Spending on material, machines and wages is entered into the accounts at the prices in force when construction starts. This does not overlook financial costs; they are simply processed separately. It takes from five to 10 years to build a power station, from initial preparation of the site to the moment it is connected to the grid. During this time there is no return on investment. On the contrary, it represents a cost. If the operator borrows half the amount it needs from banks, at a 4% real interest rate (allowing for inflation), and funds the rest out its own resources at 6%, for instance, the average cost of capital is 5%. This cost must be added to the overnight cost to obtain the cost of investment, or installed cost.

The overnight cost is useful if we want to make an abstraction of the variability of construction lead-times. It makes comparisons easier, because construction times vary depending on the reactor model and size, but also due to non-technical causes, particularly changes in the prevailing regulatory framework or local opposition. In the US for example, the shortest construction project lasted less than four years, but the longest one took 25 years.

Although it overlooks such factors the overnight cost can vary a great deal. Firstly, over time. On a per kW basis the first reactors were much cheaper than at present. We shall examine this dynamic in the following section. The overnight cost also varies in space. In its 2010 study of electricity production costs the OECD noted a difference of one to three between the overnight costs, expressed in $ per MW, for building a reactor in South Korea and Switzerland[19]. The size, model and country (cost of labour, regulatory framework, etc.) are not the same, but such a large difference may nevertheless come as a surprise. However it is not specific to nuclear power. The OECD observed a similar disparity for gas, with South Korea and Switzerland once again at the two extremes[20].

The overnight construction cost is one of the three main factors affecting the cost of generating nuclear electricity. The other two are the load factor and the capital cost (see box).

[18] A fleet of 58 reactors with a 40-year service life, or an expected number of accidents of 2320×10^{-5} = 0.0232 and damages of 0.023 x €1,000 billion, in other words €23.2 billion.

[19] Data compiled from 14 countries, of which three non-OECD, but not the US, p59 of the report.

[20] Table 3C p61. CCGT.

Load factor and cost of capital

Nuclear power plants are characterized by very long construction times and a very high fixed investment cost compared to a variable operating cost, particularly with respect to fuel expenses.

As a result, if a reactor does not operate at full capacity, once it has been built, the fixed cost must be paid off by a smaller amount of electricity production, which in turn means that each MWh is more expensive. Over the past decade the load factor of existing nuclear plants was about 95% in South Korea, 90% in the US and 70% in Japan. To illustrate the weight of this factor, we may use an example from the book by Bertel and Naudet[21]: improving the load factor from 75% to 85%, boosts output by 13% and cuts the cost of an MWh by 10%.

The cost of capital depends on how long it takes to build the plant, but also on the choice of discount rate. As the overnight construction cost is spread over several years, expenditure must be discounted. The calculation uses the date on which the plant was commissioned as its baseline and a discount rate decided by the operator. The difference between this discounted expenditure and the overnight cost is referred to as interim interest. It measures the cost of capital. For a private-sector operator the discount rate may range from 5% to 12%. With construction lasting six years, the overnight cost must be multiplied by 1.16 with a 5% discount rate, and by 1.31 with a 10% rate[22]. Obviously the sooner construction is complete, the sooner income will start to flow in, with interim interest reduced accordingly. In the example borrowed from Bertel and Naudet, shortening the construction time to five years reduces the cost of capital by 27%, with a 10% discount rate, and by 13% with a 5% discount.

Once construction of the plant is complete, expenditure concerns fuel and other operating and maintenance costs. Roughly speaking fuel costs represent between 5% and 10% of the cost of generating electricity, with the other costs totalling between 20% and 25%. The cost of fuel varies depending on the amount of electricity generated, because it is depleted as the chain reaction proceeds. It is this chain reaction which releases heat, used in turn to generate electricity. The level of production has little impact on the other operating costs, which may be treated as relatively fixed, at least as long as the reactor is in service. When the nuclear plant is finally shut down, most of these costs disappear.

Adding up the costs: the levelized cost method

The technical and financial costs of building and operating a nuclear power plant, the downstream costs of decommissioning and processing waste, and the external costs (avoided carbon emissions, accidents) must all be added up to obtain the full cost of nuclear power. It will then be possible to monitor variations in this cost over time and to compare it with the cost of electricity generated using other technologies. To do so, we need to convert the euros at different points in time into constant euros and MWs into MWhs. The discount rate is used for the first conversion. The second operation is required in order to add up fixed costs – expressed as value per unit of power, for example in € per MW – and variable costs – expressed as value per unit of energy, for example in € per MWh. By definition, one MWh is the amount of electricity generated by one MW of power in one hour. A 1,000 MW nuclear plant operating at full capacity round the clock will generate 8,760,000 MWh a year. To

[21] L'Economie du Nucléaire, by Evelyne Bertel and Gilbert Naudet, EDP Sciences, Paris, 2004, p57. Obtained using Direction du Gaz, de l'Electricité et du Charbon (Digec) assumptions and an 8% discount rate.

[22] Bertel and Naudet, op cit, p116.

allocate investment costs we need to know or anticipate the plant's load factor and its projected service life.

The full cost is worth knowing, but what is really important is whether it is greater or less than the revenues, in order to determine whether there is a net gain for the utility or any other company venturing into nuclear power. So far we seem to have disregarded revenues. Nor have we addressed the price of electricity and how it is sold. However, in conceptual terms, there is no difference between a cost and a benefit. One switches back and forth between them just by changing the sign. They are two sides of the same coin: a purchasing cost for a producer is a source of income for its supplier; an avoided carbon emission cost is a benefit for the environment.

Cost-benefit analysis, which compares discounted costs and benefits, is the canonical method used by economists to estimate the private or social merits of a project or decision. However a variant is used in the field of electricity, the levelized cost. It is used to determine the price of electricity required to balance income and outgoings all through a power station's service life. In a way it takes the opposite route to the economics canon: instead of calculating a project's rate of return as a function of assumptions on the future price of electricity, this variant sets a zero profit rate from which to deduce a price for electricity which balances discounted income and outgoings. For example, taking €75 per MWh as the levelized cost of the EPR plant at Flamanville, in western France, means it will break even if the average price recorded reaches this level during the plant's operational service life for the projected number of hours' operation. But bear in mind that zero profit does not mean that there is no return on capital. The outgoings accounted for by this method include the cost of bankers' loans and raising funds from investors.

The levelized cost method goes back to before liberalization of the electricity sector and the creation of wholesale electricity markets. It enabled a regulator to determine the sale price of a monopolistic operator on the basis of the latter's costs. It also allowed the two parties to identify, by comparison, the cheapest generating technology in which to invest in order to meet rising demand. For the economics of today's electricity markets, only the comparison is of any interest. In principle private operators, not government, take decisions on investment. Operators tend to base such decisions on forecasts of future electricity prices and consequently on the cost-benefit analysis. On the other hand, to decide whether it is preferable to add coal or gas-fired, or nuclear plant to existing capacity, they will use the levelized cost variant, because it makes it easier to compare technologies. In practice, even after liberalization of the electricity market, government has continued to have a say in the choice of generating technology. At the very least it plays a part in setting long-term targets for decarbonizing electricity generation in line with policy on emissions abatement. In this case the average discounted social cost will be used. Technical and financial costs, including back-end costs (site remediation and waste management), are added to estimates of external effects (such as accidents, pollutant emissions), unless they have already been fully integrated in private costs due to regulatory or legal constraints (liability, carbon tax, safety standards). Applying this method in the general interest also involves discounting future factors differently. The authorities' choice of discount rate is based on notions of equity discussed above, not on bank interest rates and investors' demands regarding the rate of return.

Predictably the disparities between levelized cost estimates are even greater than those observed between estimates of overnight construction costs, the latter being just one component of the former. According to the OECD the cost of construction varied by a factor of one to three between South Korea and Switzerland. In the case of the levelized cost these two countries still occupy the upper and lower extremities of the range, but with a one-to-five variation in estimates: $29 MWh for South Korea; $136.5 MWh for Switzerland[23].

[23] A small part of the difference is explained by different discounting values : 5% for South Korea and 10 for Switzerland.

The values taken into account for the overnight cost of construction and its duration, the load factor and discount rate explain much of the disparity between the various estimates of nuclear costs. The cost may be multiplied by four if only extreme, yet realistic, values are taken into account. Take for example the base case in the 2003 MIT study. The cost per kW of installed capacity is based on four parameters [$2,000 per kWe; 5 years; 85%; 11.5%]. Taking the extreme values [$2,000 per kWe; 4 years; 95%; 5%], on the one hand, and [$5,000 per kWe; 6 years; 85%; 12%] on the other, we obtain, respectively, a levelized cost of $34 per MWh and $161.5 per MWh. The operating costs, including the cost of fuel, weigh less heavily in the balance, decommissioning and waste-management costs more so. Of course we are referring here to the cost of next-generation nuclear plants. For aging reactors nearing the end of their service life, operation accounts for the lion's share of costs. Furthermore, decommissioning expenditure being imminent, it adds substantially to costs unless the operator has already made sufficient provision.

Allowing for external effects does not significantly change the ranking of cost determinants. According to the simplistic estimate discussed earlier, at the most the risk of an accident only adds one euro to the average cost per MWh. This is negligible compared with the cost of a new facility, and low even compared to the cost of operating existing plant. However it is still only partly internalized, the liability of operators being capped at low levels in the event of an accident. Nuclear power's advantage with regard to CO_2 emissions could certainly be taken into account as a social benefit. It could have a substantial impact on the levelized cost of nuclear power if the price for CO_2 emissions was in the upper range (€50 to €100 per tonne). However it makes more sense to integrate the price of carbon in the levelized cost of technologies responsible for emissions: indeed, it is integrated through taxes or emissions permits which directly affect these technologies. We shall consequently examine its impact when discussing the relative competitiveness of nuclear power.

The curse of rising costs

It is a well known phenomenon that the cost of a technology drops as it is deployed and becomes more widely used. We have all noticed that we pay less for using a telephone, computer or airplane than our parents did, simply because the cost of these goods has been substantially reduced since the first products rolled off factory production lines. Economic theory cites two causes to explain this phenomenon: the scale effect and the learning effect. The first one is both familiar and intuitive. The bigger the factory, the less each unit costs to produce. In other words, the unit cost of large production runs is lower than for smaller volumes. At the start of a technology cycle the capacity of each production unit is relatively small, in particular because demand is still limited. Subsequently the size of factories gradually increases, stabilizing when diseconomies of scale start to appear (due, for instance, to time spent moving from one workshop to another, or bureaucracy). The learning effect in manufacturing is linked to the know-how which accumulates over time. The most intuitive example to illustrate this point is the repetition of a single task. You may spend more than 10 minutes folding your first paper hen, but barely a minute after making a thousand or so. Manufacturing an airliner, steam turbine or solar panel is much the same. The learning effect is generally measured by the learning rate which corresponds to the reduction in cost when cumulative production doubles. The cost per kWh of wind power drops by about 10% each time installed capacity doubles[24].

[24] Asa Lindman and Patrick Söderholm, Wind power learning rates: a conceptual review and meta-analysis, Energy Economics 34, 2012, p754-761.

Nuclear technology displays the opposite trend. The per-kW construction cost of the most recent reactors, in constant (inflation-adjusted) euros or dollars, is higher than that of the first reactors. A technology with rising costs is a very strange beast, which requires closer study, particularly as this feature distinguishes it from several competing technologies, such as wind or solar. If nuclear engineering firms fail to find a solution in the near future, the cost of nuclear power will continue to rise, undermining its competitiveness.

The costs escalation of nuclear power

The rising cost of building nuclear reactors is a well established fact. In particular it has been studied in depth for installed capacity in the US. The overnight cost of the first reactors, built in the early 1970s was about $\$_{2008}$1,000 per kW. It has increased steadily ever since, reaching $\$_{2008}$5,000 per kW for the most recent reactors, built in the early 1990s. In other words a one-to-five difference in constant dollars. The increase in the installed cost is even more striking. The average construction time has increased with time, so interim interest has increased too. The time taken to build a nuclear power station has risen from between five and six years for the first plants to be connected to the grid, to more than twice as long for the most recent units. The average total cost per kWh displays the same upward trend. Maintenance and operating costs have dropped and the load factor has improved with time, but these two factors are not enough to counteract the very large increase in the fixed cost of construction[25].

In France the overnight construction cost reported by EDF for its various plants was made public for the first time in a 2010 report by France's Court of Auditors[26]. It amounted to $€_{2010}$860 per kW for the first four reactors at Fessenheim and Bugey, commissioned in the late 1970s, and $€_{2010}$1,440 per kW for the last four reactors, at Chooz and Civaux, which came online in the early 2000s[27]. Although it is less than twice the initial amount, the increase is nevertheless substantial.

Nuclear power consequently has a record of rising costs. But what is the explanation for this anomaly? A great many factors may have come into play, such as the rising cost of materials and machinery, or the lack of economies of scale. The figures cited above are the result of several forces, invisible to the naked eye, which may conceal causes exerting an opposite force, with varying degrees of influence. To highlight all these factors we need to use a statistical method known as econometrics. This tool enables us to isolate each of the factors determining a phenomenon and to measure their respective influence. As early as 1975[28] econometrics was used to scrutinize the costs of nuclear power in the US. Other work using the same method has been done since, yielding very interesting results.

Firstly, these works show the absence of any significant economies of scale. The cost per MW of installed capacity is no lower for the construction of the largest reactors. Why? Because they are not just scaled up replicas of their predecessors. They are more complex, fitted with more parts and components, often of a different design. Some research even shows diseconomies of scale. For instance Robin Cantor and James Hewlett calculated that a 1% increase in the size of a reactor resulted in a 0.13% hike in the overnight cost per kW. They demonstrated that initially, other things being equal – in other words maintaining the other factors they examined at a constant level – the construction cost was significantly less with lower reactor power (a 1% increase in capacity cuts the cost by 0.65%). However another

[25] See the article by Koomey et al on busbar costs.

[26] The overnight construction cost for the French fleet, cited in the Cour des Comptes report, amounted to about $€_{2010}$83 billion. The report also published the construction cost of each pair of reactors, but these detailed figures do not correspond to the overnight cost, strictly speaking, as they omit engineering expenses and pre-operating costs.

[27] Averages based on Cour des Comptes figures. The difference between Chooz 1 and 2 (€1,635 per kW), and Civaux (€1,250 per kW) vanishes. The high figure for Chooz is due to the fact that these were the first units of the N4 series, a new reactor model.

key factor, construction time, also varies with size. Increasing the size by 1% adds 0.6% to construction time, entailing in turn a 0.78% increase in cost. The net effect is therefore 0.78 - 0.65, making a 0.13% increase in cost. Large reactors would have been more economical had they been built as quickly as their smaller counterparts.

Secondly, there were few if any learning effects. This result concerns possible savings for the nuclear engineering firm. For example, according to Roy Zimmerman[29], if the experience accumulated by a firm rises from four to eight units, it reduces the overnight cost by 4%. Taking the US nuclear industry as a whole it is difficult to isolate the learning effect specifically. The figures show that the cost increases with the overall volume of installed capacity in the US. However this correlation is not due to diseconomies of learning but rather, as we shall see below, to regulation, which, with passing time, has increased the construction cost of all reactors. It is important to remember that a correlation does not necessarily mean there is a relation of cause and effect. There is a correlation between sales of ice cream and suntan lotion, but one does not drive the other. The correlation is due to a single hidden variable, the weather, which affects sales of both products.

Thirdly, learning effects appear or are simply greater when utilities act as the prime contractors on projects, rather than simply purchasing a turnkey plant. There is less incentive for engineering firms to cut costs. But diminished economies of learning may also be due to their market power and a better understanding of costs. Firms may take advantage of their experience to boost profits, to the detriment of their customers. This conceals learning effects.

Lastly the rising costs are not the result of the accident in 1979 at Three Mile Island, though it did speed up the process[30]. The partial reactor meltdown which occurred there delayed some ongoing construction projects, but the rising costs also concern the overnight cost, which is not directly impacted by the duration of the project. Furthermore the slowdown in the US nuclear programme started before the accident. In 1977 the volume of capacity ordered but subsequently cancelled exceeded built and commissioned capacity. The two curves crossed over[31]. The already visible rise in costs partly explains the slowdown in the US programme.

One variable is missing yet omnipresent: safety regulation. But this variable is hard to measure, unlike reactor capacity or construction time. The number of texts and their length is not much use as an indicator, making no distinction between major and minor regulations. As a result safety regulation is rarely taken into account as a variable in econometric equations. In 1979 two authors, Paik and Schriver, invented an *ad hoc* index in an attempt to integrate regulation. They listed all the regulations issued by the US Nuclear Regulatory Commission and sorted them into four categories, depending on their supposed importance. They were thus able to calculate that between 1967 and 1974 regulation had caused a 70% increase in the investment cost per kW, equivalent to a 16% annual increase. In most other publications economists have used a temporal milestone (start or end of construction, issue of building permit) as an approximation for regulation. The work of the NRC continued at a steady rate all the way through the period during which nuclear plants were being built in the US; every year it published new standards, rules and measures. The regulation variable may thus be correlated with time. Any simple variable representing the passing of time, such as the year when a nuclear plant is connected to the grid, is just as useful as a complex indicator based on compiling and analysing NRC publications. Using temporal milestones to inform the regulation variable, US economists estimate that it is responsible for a 10% to 25% increase in construction costs.

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[28] Bupp IC, Derian J-C, Donsimoni MP, Treitel R, The Economics of Nuclear Power, Technology Review, p14-25, quoted by Koomey and Hultman.

[29] Zimmerman, M. (1982), 'Learning effects and the commercialization of new technologies: The case of nuclear power', The Bell Journal of Economics 13, 297–310.

[30] Lucas W Davis, Prospects for Nuclear Power, Journal of Economic Perspectives, vol 26 n°1, 2012.

[31] Mark Cooper.

The inflation in safety regulation is by far the largest factor in the escalating costs observed in the US. Stricter regulations require larger numbers of safety devices and systems, thicker containment walls, and completely isolated control rooms. In response to these tougher requirements engineers design increasingly complex facilities and systems. Only at the end of the 1990s did it occur to anyone that a possible solution might be to make things simpler, leading to the Westinghouse's AP1000, which is based on a passive safety system. Rather than increasing the number of backup pumps, for instance, a gravity-fed flow would be maintained if the cooling system failed. In the meantime safety was reflected in higher construction inputs and overall a more cumbersome framework for coordinating the construction of plants. The frequent changes in regulations also had a direct impact on the duration of construction projects. Work on a large number of US power stations had to be stopped in order to make allowance for new rules introduced since the start of work. Longer lead times meant higher financial costs, which of course added to the cost of investment. When new rules required additional inputs, this also impacted indirectly on the overnight cost. And, despite it being based on the assumption that plant was built in one night, longer lead times pushed up overnight costs in the US.

At first sight analysis of the escalating costs of nuclear power in the US might suggest that stricter safety requirements imposed by the regulator are to blame. But several factors contradict such a simplistic conclusion. It is not so much the severity of regulation as its own defects that cost US nuclear power so dearly. Fluctuating rules and shifting priorities, excessive delays in decision-making and an inadequate understanding of the fundamental technical issues may generate excess costs for utilities, which far outstrip the impact of rising safety requirements. It seems more probable that, up to the end of the 1970s, the regulations did not so much attempt to raise the initial safety level as simply to achieve it. It is far from easy to assess the safety level of a nuclear power station, particularly before the fact, simply on the basis of drawings. Building and operating a plant may ultimately reveal that it does not meet the safety targets set by the regulator, and the operator, at the design stage. So the regulator intervenes to ensure that the original safety targets are fulfilled. This may remedy defective quality but does not raise its level. Some authors, such as Mark Cooper, assert that early US reactors were quite simply defective in safety terms and that regulation imposed a form of making good. Lastly, if we read between the lines of escalating US costs we may detect serious shortcomings in terms of industrial organization. Divided into a large number of utilities, often small and limited in territorial reach, and a host of engineering firms, the industrial organization failed to achieve sufficient standardization of procedures, reactor models and construction practices. Apart from Bechtel, which built 24 reactors, the experience of engineering firms and operators was limited to building just a few nuclear plants. In short, unlike many other fields of technology in which the US led the way, the development of nuclear power on an industrial scale was not a great success.

The picture in France was very different, whatever its critics may have maintained (see box). It has now been firmly established[32] that the escalation in costs was far less spectacular, with overnight costs rising by 1.7% a year, compared with 9.2% in the US.

A dizzy rise in costs based on mistaken analysis

In 2010 an academic journal published an article[33], which attracted considerable attention. For the first time the construction costs of French reactors were detailed and tracked over time. But contrary to what everyone imagined, the figures showed that France, despite its assets, had also suffered a steep escalation in costs: the cost of building France's last four reactors was allegedly 4.4 times higher than that of the first four. Worse still, the last reactor to completed (Civaux 2) purportedly cost 7.5 times more than its cheapest counterpart

[32] See Lina Rangel Escobar and François Lévêque, 2013.

[33] The Costs of the French Nuclear Scale-up: a Case of Negative Learning by Doing, Arnulf Grubler, Energy Policy 38, 2010.

(Bugey 4). It seemed that through some intrinsic fault nuclear technology was incapable of controlling costs and impervious to learning effects. The large scale of the construction projects, the limited unit count, the need to adapt to different sites, and the task of managing such a complex undertaking all contributed to cancel out the cost-cutting mechanisms observed elsewhere: standardization, production runs comprising several thousand units, and the repetition of almost identical processes.

This diagnostic would have been justified, had it not been founded on a mistaken estimate. In the absence of publicly available data on the construction costs of each French reactor, the author of the article, Arnulf Grubler, extrapolated the cost of plants from EDF's annual report on investments. Work had been carried out on several reactors – often of different sizes – in the course of the same year, so Grubler had broken down annual investment, using a theoretical model of expenditure to estimate the cost of each plant. Unfortunately this extrapolation yielded figures which subsequently proved to be at odds with reality. Far from a more than fourfold increase in the construction cost of reactors, from start to finish, the data later published by the Court of Auditors revealed a slightly less than twofold increase, in no way comparable to what had happened in the US.

So why was there such a big difference between the United States and France?

Econometrics is unfortunately not much help here. On the one hand, only a small amount of work has focused on France's nuclear reactors; on the other, the sample itself is small. In all we only have 29 records of costs. France has a total of 58 reactors, but they were built in pairs and the EDF accounting system did not itemize them separately. With such a small sample, fewer variables can be tested. With respect to economies of scale, there is no sign of a positive effect, quite the opposite. The nameplate capacity of French reactors increased in three steps, rising from 900 MW for the first reactors, through 1,300 MW for the majority of them, culminating at 1,450 MW for the last four. It is immediately apparent that the cost per kW went up with each step or *palier*, with a particularly spectacular leap at the end. The overnight cost reached €$_{2010}$1,442 per kW, compared with an average of €$_{2010}$1,242 per kW for the 20 second-step reactors, or €$_{2010}$1,121 per kW for the first 54 overall. Econometric analysis yields no further information on this point; the diseconomies of scale persist. Here again the explanation is to be found in the relation between size and complexity. Not only did the reactors on each step differ in size, they varied in other ways. Each step brought technological advances. For example the second-step plants were equipped with a completely updated control room and system. The design of the last four was almost completely different. When it comes to learning effects, econometric analysis is more helpful, revealing that the overnight cost of a reactor fell depending on the number of reactors already built on a given *palier*. Each additional reactor brought a 0.5% drop in cost. On the other hand the effect is no longer visible if we look at the total number of reactors previously built. Apparently the experience gained building one model of reactor did not benefit a different model.

It is essential to grasp the step-related learning effect, because it throws light on a recent controversy. The French nuclear programme offered the best possible conditions for powerful learning effects. The power stations were built by a single operator, EDF, which was able to appropriate all the experience accumulated with each new project. The plants were built in a steady stream over a short period of time. In the space of just 13 years, from late 1971 to the end of 1984, work started on construction of the first 55 reactors. The programme as a whole only slowed down at the end, with work on the last three units starting between late 1985 and mid-1991. The average construction time was consistent, only increasing slightly over time. Unlike what happened in the US, the regulatory framework did not upset construction of nuclear plants. The fleet expanded gradually thanks to dialogue and cooperation between all the players (EDF, Atomic Energy Commission [CEA], Framatome, Ministry of Industry), well out of sight of non-specialist outsiders.

So, despite the fact that France enjoyed the most favourable conditions for a gradual drop in the cost of building nuclear power plants, this did not materialize. What went wrong? We may suggest a series of specific explanations: the easiest sites were chosen first; quality assurance was gradually tightened up; the rising price of energy impacted on the price of machinery; project ownership expenses increased[34]. At a more fundamental level, the French nuclear programme was over-ambitious and focused too much on just one country. The standardization and learning effects it made possible were cancelled out by changes in reactor models. The two capacity increases, from 900 MW to 1,300 MW, and then from 1,300 MW to 1,450 MW, coincided with substantial, expensive changes in technology. Some were adopted to make the technology French. In an effort to achieve greater independence and improve its chances of exporting its own reactors, France was determined to break free from the US technology used in the first pressurized-water reactors built there. The first stage in this process involved the design of the P'4 variant of the first-step 900 MW reactor. This dispensed with the need to pay licence fees to Westinghouse. The second stage brought the original design of a 1,450 MW reactor, but ultimately only four units were built. This model proved more expensive than its predecessor, due to its greater technological complexity and the exclusive use of components and machinery made in France[35]. In addition construction times grew longer, reaching an average of 126 months for the last four plants, half as much again as for the plants built during the previous step. The French nuclear programme was nearing its end, indeed rather sooner than expected, because growth in demand for electricity, with a corresponding increase in capacity, had been overestimated. Completion of the last reactors was deliberately spread out in time, to adjust to demand and cope with the gradual winding down of the workforce [caused by the end of the construction programme]. Things are always clearer with the benefit of hindsight, but it does look as though France could have done without the last four reactors, yielding a substantial saving.

Together the US and France have a total of 162 reactors, equivalent to just under a third of global capacity. What is known about the costs of other reactors? Nothing! There is no public source of data for all the nuclear capacity deployed in the former Soviet Union, Japan, India, South Korea or the People's Republic of China. No figures are available to say whether costs escalated there too, less still at what rate. We can only resort to qualitative reasoning. Apart from South Korea, no doubt, and perhaps China more recently, it is hard to imagine costs rising less than in France. South Korea enjoys similar conditions, which should have enabled costs to be contained: swift pace of construction; reasonably similar reactor design and layout; well integrated industry and a single operator; nationalist fervour. In fact it may have done better than France. The picture in China is much more disparate, featuring all types of technology – boiling water, pressurized water, heavy water – and many sources – Canada, Russia, France and even the US. Less than 10 years ago China decided to give priority to building large numbers of its own CPR-1000 reactor, derived from the French 900 MW model. The speed of construction has been stupendous, great efforts have been made to standardize processes and the industry is very well organized. The cost of building this reactor has probably dropped with each new unit.

On the other hand the former Soviet Union and India would be plausible candidates for notching up escalating costs even worse than in the US. In the first case because costs under the socialist system were never a key issue when deciding to invest in infrastructure. Politics had more say than economics in the siting of plants, in the choice of model and the speed of construction. India is well placed too, no country having witnessed such a chaotic civil nuclear programme.

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[34] Bertel and Naudet, 2004 and (quoted in the work of) Moynet,1984.

[35] Grubler 2010.

Is there no limit to escalating costs?

Will what happened yesterday hold true tomorrow? We are confronted with a classic case of inductive reasoning. We have seen that the second reactor costs more than the first one, the third one more than the second ... and that reactor n costs more than n-1. So can we conclude that the same progression will hold true for n+1 and n+2. The immediate answer is affirmative. If you have only seen black cats in the past, you will be quite ready to bet they are all black. In the past nuclear power has reported rising costs, so nuclear technology is synonymous with rising costs. It is tempting to generalize. Particularly as new next-generation reactors – the ones following the nth reactor such as the EPR – are again more expensive than their predecessors. However, we shall see that it is possible to upset this progression, even if it is much less likely than the continuation of the previous trend. Research would also need to explore new routes, with industry finding ways of standardizing models and developing modular machinery. If no spell is found to lift the curse of escalating costs, nuclear power will be gradually sidelined.

At the beginning of the 2000s costs seemed to have stopped escalating. Next-generation reactors were expected to bring improved safety, but they would also be cheaper than their forebears (see box). On paper the outlook for nuclear costs was rosy, on both sides of the Atlantic.

Costs at renaissance

After a long, sluggish period in western countries, nuclear power woke up again in the early 2000s. New construction projects were tabled in the US and Europe. Many countries with no previous experience of nuclear power were also eager to enter the technological fray. This, it seemed, marked the so-called renaissance of nuclear power. The International Energy Agency forecast the construction of several hundred new plants by 2030. The outlook on costs was naturally just as upbeat. In 2003 the MIT published a study estimating the cost of building a plant with a next-generation reactor. In its base case it assumed an overnight cost of about $2,000 per kW, which yielded a levelized cost of $67 per MWh (with an 11.5% discount rate). To situate the latter cost in relation to the past[36], let us imagine a scale of 1 to 100 ranking existing US plants by rising cost (calculated in constant dollars, adjusted for inflation and with a uniform 6% interest rate[37]). The MIT's projected plant would be ranked 19th, in the top 25% least expensive plants ever built, reaching back to the 1970s. In an even rosier scenario, positing a swifter, more flexible response by administrative bodies for the issue of construction permits, the cost would be lower than any plant previously built in the US. A year later the University of Chicago carried out a similar study, drawing comparable conclusions. On the supply side Westinghouse announced an overnight cost for its AP1000 of $1,400 per kW[38] and a levelized cost of $27 per kWh[39]. Predictably this estimate was more optimistic than the ones produced by university research laboratories.

In France the baseline costs were published by the Ministry of Energy. In 2003 the costs for third-generation nuclear plants were estimated at €1,300 per kW for the overnight cost[40] and €28.4 per MWh for the levelized cost (with an 8% discount rate). With these values the EPR bettered, in terms of cost, the reactors on the last step built in France. Industry was slightly less optimistic, with EDF suggesting an overnight cost of between €1,540 and €1,740 per kW and a levelized cost of €33 per MWh[41].

[36] Koomey and Hultman, 2007.

[37] With a 6% discount rate, the levelized cost in the MIT study is $42 per MWh.

[38] Zaleski, p3, first of a kind, Chine, p. 3, http://nuclearinfo.net/Nuclearpower/WebHomeCostOfNuclearPower

[39] Koomey.

[40] Glachant and Lévêque (ed), Electricity Reform in Europe. Towards a Single Energy Market, Edward Edgar, London, 2009.

[41] Dupras, Joudon, Revue Générale Nucléaire, VI-2004, and Zaleski.

Barely 10 years later, the first construction projects soon showed that the de-escalation everyone hoped to see had not yet started. The next-generation reactors were even more expensive. Present trends are after all entirely consistent with those of the past.

In 2009 the MIT published a second report[42], updating the findings of the initial study six years earlier. The increase in the overnight cost was spectacular: expressed in current dollars it doubled, rising from $2,000 to $4,000 per kW[43]. In particular this figure took into account the estimated costs of 11 projected plants in the US, for which the relevant utilities had applied to the regulatory bodies for reactor licensing. Meanwhile the University of Chicago investigated applications for construction licences for the Westinghouse AP1000. On average, the overnight cost quoted in applications was $\$_{2010}$4,210 per kW, multiplied by a factor of 2.3, in constant dollars, compared with a study seven years earlier[44].

Unlike what occurred in the US, where next-generation reactors went no further than the drawing board, construction projects in Europe got off the ground. Work started on two EPRs, one at Olkiluoto, Finland, the other at Flamanville, France. Here the increase in costs has been even more spectacular. In Finland the initial cost of the project when work started was €3 billion[45], or €1,850 per kW. It has since been revised upwards on several occasions; delays have accumulated too. The final cost is now estimated at €6.6 billion, or €4,125 per kW. The job was supposed to last four and a half years, with grid connection in mid-2009. In the end, production will not start before 2014, at best. Say 10 years to be on the safe side. Work at Flamanville started two years later and took the same unhappy route as its elder sister. The initial cost of €3.3 billion[46] has soared to €8.5 billion[47] and the original construction time of under five years will probably stretch to nine years. So the first EPRs cost much more than the preceding 1,450 MW reactor model, on which they are based.

The changes in academic studies and industrial quotes are so large that it would be easy to make fun of them, or even to suspect deception. But it would be a mistake. It is only natural that the initial estimates of experts and vendors should be a little optimistic. But for new nuclear there were neither experience nor facts to temper initial optimism. After a long period without any new plant being built, a large share of American and French expertise had vanished. Most of the engineers and senior executives who had taken part in the golden age of nuclear power had either moved to another sector or retired. Furthermore the first cost estimates were drafted when design of the next-generation reactors was still in its early stages. Millions of man hours were still needed to finalize detailed plans[48], which inevitably revealed additional costs. Then it was time to obtain quotes from suppliers and to sign contracts for parts and machinery, a process which moved the true understanding of costs one step further. The last set of estimates generally focuses on indexed values, in particular the price of raw materials and building materials. This brought additional price increases, the first decade of the 2000s having seen substantial upward pressure on these commodities. The overnight cost of gas and coal-fired power stations also increased steeply over this period[49]. The difference with nuclear power was that the initial estimates for the fossil-fuel

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[42] Update of the MIT 2003 Future of Nuclear Power, MIT, 2009.

[43] Expressed in $\$_{2007}$, with a 25% increase in the levelized cost.

[44] The lower end of the overnight cost for the 2004 study was $\$_{2010}$1,413-2,120 with a mean value of 1,765, hence the increase by a factor of 2.3. Focussing just on the AP 1000, the 2004 range was $\$_{2010}$1,554-2,331 with a mid-point at $\$_{2010}$1,943. So the study took $2,000 per kW and compared this to $4,210 per kW, in other words an increase by a factor of 2.1.

[45] According to French Member of Parliament Marc Goua, tasked with reviewing the accounts of Areva and EDF, http://www.enerzine.com/2/12796+lepr-finlandais-couterait-au-final-6-6-mds-deuros+.html, 14 October 2011.

[46] Le Monde, http://www.lemonde.fr/planete/article/2011/11/10/sur-le-chantier-de-l-epr-a-flamanville-edf-est-a-la-moitie-du-chemin_1602181_3244.html.

[47] EDF communiqué cited in the Cour des Comptes report.

[48] See second study by the University of Chicago.

[49] For example, in its updated study the MIT revalues the overnight cost per kW of a gas plant, resulting in a 70% increase, and a 130% increase for a coal-fired thermal plant.

plants were more accurate. They were based on a building process which had never stopped, nor yet slowed down, all over the world, with hundreds of examples on which to draw.

Optimism may also be dictated by self-interest. Utilities in favour of nuclear power and reactor engineering firms stand to gain by reporting low costs in their initial estimates, by only publishing values at the lower end of their spread estimates. But on the other hand, much as any trader selling goods to a small number of buyers, on whose custom the business depends, it is not in the interest of reactor vendors and turnkey plant integrators to announce miraculous figures. Making promises, which they know they cannot keep, permanently saps their credibility in the eyes of customers, bankers and governments. If there was any deceit regarding costs at the renaissance of nuclear power, it was the industry which fooled itself.

To put an end to any notion of cross-the-board deceit, it should also be borne in mind that the baseline academic studies did not only work on a set of assumptions favourable to nuclear power. The reason why the first MIT study caused such a stir in 2003 was that it made the iconoclastic choice of a high discount rate, which was unfavourable to nuclear power. The MIT highlighted the high financial risk associated with this investment in liberalized electricity markets. As a result, the assumptions regarding the structure and cost of nuclear capital were less attractive than for gas or coal. Nuclear power involved higher capital outlay, less debt and a 15% return on assets, rather than 12%. Without these assumptions the MIT study would have concluded that the excess cost of nuclear power, compared to gas, was only half as large[50].

There is no escaping the facts and they are particularly stubborn: nuclear power now is much more expensive than before. For the time being third-generation reactors are still plagued by rising costs, and new reactor models bring additional costs. What does the future hold?

With the same design, costs should certainly drop, but by how much? It is impossible to say whether there will be a slight reduction or a huge one. Take the EPR. Its cost is bound to drop, but how far? First of a kind costs are known to be higher, generally by about 20% to 30%[51], but it is not known how the excess cost is amortized. Does the full burden fall on the first unit, or is it spread over the first five or 10 reactors? For obvious reasons – the first customers do not like teething problems – data of this sort is confidential. Furthermore there has been a loss of experience on the construction side, following a long period without any new projects. Lastly, the first two EPRs are not being built by the same company. Seen from abroad, the French nuclear industry may look like a homogenous block; EDF and Areva, both publicly owned companies, seem barely distinguishable. But in fact they have been keen rivals in recent years. Areva went it alone in Finland, operating as a turnkey plant vendor, rather than just selling a reactor, which is its core business. EDF has longstanding experience as both the prime contractor and project owner of nuclear plants. It sees Areva as an original equipment manufacturer, or even – rather disparagingly – as a boiler manufacturer. So there is no sign of any learning effects between Olkiluoto and Flamanville. The two firms have been at loggerheads, rather than pooling their experience. The opposite seems to have happened at Taishan, in China, were two EPR-powered plants are being built. EDF and Areva are working together with the prime owner, the China Guangdong Nuclear Power Group, the utility in Guangdong province. For the time being Taishan-1 is on target for both construction time (five years) and cost (€3 billion). Areva management[52] say this is thanks to the return on experience from the Finnish and French jobs. Certainly, between Olkiluoto and Taishan, the supply deadlines have improved by 65%, engineering man hours for the nuclear steam-

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[50] The levelized cost for the base case was $67 per MWh for nuclear, $43 per MWh for coal and $41 per MWh for gas. With the same financial conditions the cost of nuclear power drops to $51 per MWh. See Table 1, Yangbo Due and John E Parsons, Update on the Cost of Nuclear Power, MIT, May 2009.

[51] The 2004 University of Chicago study suggests that First Of A Kind costs may be as much as 35% of the overnight cost. For their part Dupraz and Joudon, cited by Zaleski, estimate that FOAK costs add 20% to the levelized cost of the first of a kind, for a series of 10 units ($€_{2004}$41 per MWh, instead of $€_{2004}$33 per MWh).

[52] Luc Oursel

supply system are down by 60%, and the time taken to build the main components has been cut by 25% to 40%. So the third reactor seems poised to finish first. Work on Taishan-1 started in 2009, after the other two, but it should be connected to the grid by the end of 2013, several years ahead of Olkiluoto and Flamanville. But return on experience is not the only reason for the impressive performance in China regarding costs and deadlines. The Public Republic of China boasts top-notch civil engineering contractors, can count on a seasoned nuclear industry, is deploying a massive programme (with 26 reactors under construction in 2011), and has the advantage of a cheap, well qualified workforce and a well organized site where work continues round the clock, even at weekends.

The last unknown regarding the scale of the drop in the cost of the EPR relates to the number of units ultimately built worldwide. Four, 10, 20 or more? All other things being equal, the more reactors sold, the lower the cost and vice versa. The serpent eats its tail. Potential buyers are price-sensitive – though we do not know whether this effect is very slight or substantial – and learning effects cut costs, though here again we cannot say by how much.

From a technical point of view the key to lower costs is to be found in standardization and modularity. Standardization requires every unit of a particular reactor model to be identical, which is not always the case, due to specific changes demanded by customers or safety authorities. As mentioned above, standardization allows learning effects; we may add that it also facilitates competition between suppliers, another powerful mechanism pushing costs down. Modularity means construction in modules, in other words component parts which are relatively independent one from another, making it easy to separate them and simply assemble them on-site (structural elements, but also cable ducts, reinforced concrete mats, etc.[53]). A good example of modular building is factory-assembly of the roof timbers of a detached house, rather than erecting them piece by piece on-site. Pre-assembly is advantageous because a factory is a sheltered environment and such operations lend themselves to automation, yielding productivity gains. Pre-assembly also reduces the amount of clutter on a building site, streamlining its organization. So modularity has the potential for substantial gains[54].

So far our reasoning has been based on an unchanging technological framework. What happens to the costs entailed by nuclear power if we take into account innovation, and the design and development of new reactors? Past form is far from encouraging. We have seen that in France, where conditions were most favourable, each new model led to an increase in the construction cost per kW of installed capacity. Two insurmountable obstacles seem to be preventing a reduction in the cost of new models. The first relates to the increasingly strict rules on safety. It is hard to imagine the authorities certifying a new model with lower safety performance than its predecessors. As time passes experience gained from building and operating plants reveals defects; progress in science and technology provides solutions to correct them. Furthermore, with time, new political risks may emerge (terrorist hijacking of an aircraft to target a power station, for instance) and in general public opinion is increasingly averse to technological risks. The above is true for countries already equipped with nuclear power. For new players safety requirements may be less stringent and they may not require the latest generation of reactors. But keen to develop their science and technology, such countries are unlike to resist the appeal of modernity for long.

So the question is whether it is possible to build reactors which are similar to the current generation, but safer and cheaper. Very probably not, but as it is still too soon to pass judgement on the AP1000, we should allow for a positive outcome. Westinghouse designed this reactor with two aims: to provide a mechanical solution to some of the safety problems; and to simplify the overall design. For example, water tanks are positioned on the roof in order to cool the reactor vessel should the need arise, fed by gravity and the pressure inside

[53] Reduction of Capital Costs of Nuclear Power Plants, OECD, February 2000.

[54] Occasional, initial and old experience of construction in Sweden and Canada estimated at between 1.4% and 4%. See OECD study, 2000, p10.

the system. This more or less halves the need for pumps, valves and pipework. Four AP1000s are currently under constructionin China. It will be interesting to see, in a few years' time, whether they cost substantially less to build than the EPR. If the concept is a success, it could lead to the development of improved versions, using the new design rules, but at even lower cost. Nuclear power may finally cast off the curse of rising costs.

The second, apparently insurmountable obstacle concerns on-site construction and short production runs. Much as other large civil engineering projects – bridges, airports or dams – nuclear power stations are mainly built on-site. Progress may be made towards greater modularity, but there is little hope of a 1,000-MW plant one day being put together like a flat-pack kitchen. Civil nuclear power differs from other electricity-generation technologies in that only a small number of units are built. Whereas hundreds or thousands of wind-farms, or coal or gas-fired plants are ordered worldwide every year, there are just a few dozen new construction nuclear construction projects. One of the reasons is the trend towards building increasingly large reactors. The scale of fixed costs justifies this option, because they can be recouped on a larger volume of electricity output. But there is nevertheless a downside. All other things being equal, the more powerful the reactor, the smaller the number of identical units built. So production runs are short and only a few similar parts and components are manufactured. The trade-off between economies of scale per unit and manufacturing economies of scale[55] has so far tipped in favour of the former. Giving fresh impetus to small-reactor projects would break with this approach.

The example of small reactors is worth looking at, because it demonstrates the scope for radical innovation, which in our opinion offers the only lasting antidote to the curse of rising costs. People have been developing low-power nuclear reactors for many years. They are used to drive nuclear submarines, drawing on work and trials going back to the 1950s. What is new though is the sudden emergence of futurist projects. Take for instance the best known example, funded by Microsoft-founder Bill Gates. The project is being developed by TerraPower, in which he is the prime shareholder. The aim is to produce a mini-reactor several metres high, running on natural uranium and cooled by liquid sodium. It is based on the travelling-wave principle, with the reaction slowly spreading outwards from the core of a block of uranium. Picture a candle with a flame inside gradually advancing as it consumes the surrounding wax. For the reactor itself, imagine a cylinder less than one metre high, which requires no outside intervention once the reaction has started and which shuts down on its own after several tens of years. We may also cite the project for an underwater nuclear power station being developed by France's naval defence firm DCNS. In this case the cylinder is 100 metres long and 15 metres in diameter, containing a reactor and remote-controlled electricity generating plant. With several tens of MWs capacity, it would be located out to sea, several kilometres from the coastline, anchored to the seabed. The cylinders would be modular units, several of which could be placed side by side, in the case of higher output requirements. The units would be taken back to a shipyard for maintenance and replaced by other units, much as bottles with a refundable deposit. These projects, which sound even more fantastic when described in such brief terms, will very probably never see the light of day. Either they will founder completely or change so much that the final application bears no resemblance to the initial concept. It matters little to our current concerns. That is how radical innovation works: projects pursuing a large number of original ideas are launched; very few give rise to pilot schemes; an even smaller number lead to commercial projects; and in each case the ongoing redefinition process will shift pilot schemes and commercial goods further and further away from the original idea. Obviously there is no way of knowing in advance whether, out of the hundreds of current and future projects to develop modular small or mini-reactors similar to those discussed above, at least one could reach fruition and enter industrial production. But unless nuclear research moves away from the present model of large, non-modular plants and gigantic construction

[55] Nemet, 2007, quoted by Koomey.

projects, the costs of nuclear technology will continue to rise, which is a serious drawback in the competition between nuclear power and other electricity-generating technologies.

Nuclear power and its alternatives

We cannot do without oil but we may, on the other hand, stop using the atom. We should never lose sight of the fact that there are several means of generating electricity, using among others coal, gas, oil, biomass, solar radiation and wind. At the scale of a whole country these generating technologies are generally combined to form an energy mix, which may or may not include nuclear power, much as it may or may not include thermal coal or gas, wind or solar.

The various technologies are both competitors and complementary. Conventionally a distinction is made between base load generating technologies, coal or gas-fired powered stations for example, which operate round the clock all year long, and peaking generating technologies, such as oil-fired power stations, which only operate at times of peak demand. With a finer mesh, a distinction may sometimes be made between semi-base load and extreme-peak generation. The overall idea is to classify production resources in such a way that the ones with high fixed costs and low variable costs are used for as many hours a year as possible, while on the other hand those with low fixed costs and high variable costs are only used for a few hours a year. We shall analyse this rationale in detail in another paper. However it is immediately apparent that two categories of base load technology – coal and nuclear – are in competition, whereas oil-fired technology is complementary. However, in situations where they overlap this ranking may change. For example gas, which tends to be seen as a semi-base load resource, may play a primary role as a base load resource; nuclear power may lend itself to load-balancing and is consequently suitable as a semi-base load resource. Renewable energy sources also upset the ranking. Hydro-electric power from dams is generally seen as a peaking resource, despite its extremely high fixed cost and variable operating cost close to zero, the explanation being that its variable cost should in fact be treated as a marginal opportunity cost. It is preferable to hold back a cubic metre of water for peak hours with correspondingly high prices, rather than wasting it by generating electricity at times when demand drops and the price is low. Regarding wind and solar, production is intermittent when it depends on the force of the wind or the amount of sunlight, which vary in the course of a day, and from one day to the next, quite beyond our control. Here again variable technical costs are close to zero, but the irregular nature of output makes it impossible to classify these technologies among base load resources. At the same time, the lack of any way of controlling them means they cannot be treated as peaking resources. If intermittent renewable energy sources play a significant part in the energy mix, backup capacity must be available – generally gas-fired plants – to take over in the absence of sunlight and wind. Under these circumstances gas and the renewable energy are complementary. On the other hand the growth of intermittent energy sources pushes the market price of electricity down and base load and semi-base load sources operate for shorter periods. This creates competition between nuclear power and gas, on the one hand, and renewable energy sources, on the other. Lastly nuclear power and renewables have one characteristic in common: they produce no CO_2 emissions. They may consequently be seen as rivals for achieving the targets set for reducing greenhouse gas emissions, or alternatively, as it seems difficult to rely exclusively on just one of these sources, they may be seen as complementary, with a view to completely carbon-free electricity generation. To simplify matters, any comparison of nuclear electricity should make allowance for two factors: on the one hand its competitive or complementary position in relation to coal or gas, for base load electricity production; and on the other hand its competitive or complementary position in relation to other carbon-free energy sources.

The relative competitive advantage of nuclear power over gas or coal

The levelized cost enables us to classify the various generating technologies. Which one, out of coal, gas or nuclear power, offers the lowest cost? How do these forms of energy rate in the overall cost ranking? Our obsession with rank prompts us to ask the wrong questions, which only yield contingent answers.

There is no single ranking system because the costs depend on different locations and hypotheses on future outcomes. With regard to nuclear power we have seen that the cost varies from one site to another, from one country to the next, and that it above all depends on the discount rate. The cost of fuel is the key parameter for coal and gas. But the price of energy resources depends on geography. The cost of transporting coal or gas being high, building a fossil-fuel power station in one place or another yields different results. Furthermore market prices fluctuate a great deal, particularly for gas, often indexed on the price of oil. The rate of return on an investment in a new fossil-fuel plant depends on assumptions as to how fuel prices will behave over the next 10 or 20 years. Consequently it is only possible to use the levelized cost to rank coal, gas or nuclear power on the basis of a very specific set of conditions, valid at the geographical scale of a country and in line with the expectations of specific operators. For example, taking a broad-brush approach to the current position in the US, gas enjoys a comfortable lead, followed by coal, with nuclear power in third place. This ranking may vary between US states depending on the proximity of coal-mining resources and unconventional gas reserves.

We should nevertheless bear in mind a few, almost universal trends and shifts, which also happen to explain to a large extent the current US ranking of base load generating technologies: before and after climate-change policy; before and after shale gas; before and after deregulation of the electricity market.

In a world with no pollution-abatement measures, coal would lead the pack with the cheapest MWh almost all over the world. But using it to generate electricity causes local pollution (release of dust, soot, sulphur and nitrogen oxides) and CO_2 emissions. The first group is by far the most costly, unless a very high price is set for CO_2 (in excess of $100 per tonne)[56]. In ExternE, the major European study of the externalities of generating electricity, the damage caused by coal, setting aside that linked to CO_2 emissions, was estimated to range between $\$_{2010}27$ and $\$_{2010}202$ per MWh. The lower value in this range is the same as the one reported by William Nordhaus and other authors in a conservative assessment dating from 2011[57]. As for the upper value, it can be found in a maximalist study by Professor Paul Epstein, at Harvard, published the same year[58]. Taking the values which the experts consider to be the 'best estimates', we may note that the cost of a coal-generated MWh doubles when we include its externalities. The large divergence between the upper and lower values in the estimates can be partly explained by the different types of plant under consideration and the prevailing environmental standards. In OECD countries the regulatory framework for local emissions from coal is very strict. Part of the externalities is internalized by emissions standards, which raises the overnight cost of coal-fired thermal plants, and consequently the levelized cost of energy for the utility. Similarly some OECD countries have introduced a carbon price, or are planning to do so. Depending on their level, such taxes and tradable emissions permits internalize, to a greater or lesser extent, a share of CO_2 externalities and add to the variable cost borne by the utility. On the other hand, in most developing or emerging countries, the cost of a coal-generated MWh is still low because neither investors nor utilities pay for any part of the environmental damage entailed, in the absence of both regulations on local pollution and a carbon price. This lack of symmetry explains why it is now almost out of the question to build coal-fired power stations in the US, the UK or Japan,

[56] [note manquante ?]

[57] Value reported as $28.3 per MWh. Article co-authored with Nicholas Muller and Robert Mendelsohn, American Economic Review.

[58] Full cost accounting for the life cycle of coal. Here the value was $269 per MWh, of which $44 per MWh corresponds to the impact on public health.

whereas such facilities are springing up in China, Malaysia, Senegal and South Africa. In terms of new electricity-generating capacity being installed, coal is by far the technology which has enjoyed the strongest growth worldwide since 2000. In the long term, the cost of a coal-generated MWh in non-OECD countries is expected to rise, reducing the gap. The localized pollution and damage this technology entails for public health exert pressure which encourages a shift towards other more expensive technologies which cause less pollution. In OECD countries it is more difficult to predict future developments. The application of R&D work on clean coal, particularly for carbon capture and storage technology, is uncertain. Future trends for the price of CO_2 emissions are equally uncertain.

Gas has a very different environmental profile from coal, with little or no local pollution, and half the volume of CO_2 emissions. This explains its spread in OECD countries, at the expense of coal. The price of gas delivered to the generating plant is generally higher than for coal, but this competitive disadvantage is counterbalanced by incomparably lower environmental costs[59]. There is certainly a before and after unconventional gas here, because this advantage is now being enhanced by lower costs due to new gas-exploitation techniques (horizontal drilling and hydraulic fracturing), and the resulting extension of reserves. In the US, where shale gas was first exploited (alongside Canada), this change means that nuclear power is durably losing its status as a base load generating technology. Gas is now in first place and is likely to stay there for a long while. However it should be borne in mind that unconventional gas currently enjoys a novelty effect, which underestimates its social cost. It took decades to work out the economic estimates of the externalities of coal, conventional natural gas and nuclear power. They took shape as science advanced in its understanding of the effects of pollution and on-site measurements. The dissemination of scientific advances and the results of metrology, beyond the confines of laboratories and a small number of experts, works on a specific time scale. None of this applies to shale gas, yet. The measurements and studies have barely started, particularly to estimate greenhouse gas emissions and possible damage to aquifers. It is plausible to suppose that what has so far been gained through lower exploitation costs may tomorrow be lost to rising environmental costs. Lastly it is worth noting that the decision by some markets to delink oil and gas prices gives the latter an advantage which is likely to last. Until now, in many countries gas prices were driven up by the rising price of oil. Oil-indexed gas supply contracts were encouraged by various factors: comparable extraction conditions; joint production in some cases; and markets offering imperfect competition, due to the dominant position of monopsonists. In places where the exploitation of conventional gases has developed, this arrangement has been permanently destroyed.

Liberalization of the gas and electricity markets is the third key shift which changes the relative competitiveness of base load generating technologies. Here too nuclear power has lost ground on the whole. For many years the gas and electricity markets were organized as municipal, regional or national monopolies subject to regulated tariff schemes. Regardless of whether generating companies belonged to the public or private sector, the investments they made were exposed to little risk, being paid back by captive consumers. Dependent on the authorities, these companies often acted as cogs in the implementation of energy policies based on factors related to cost, but also to national independence, scientific prestige, job creation and such. Instigated by some US states and the UK, privatization and the opening up of the gas and electricity markets to competition upset this model. In its place, or alongside it, another model was established in which the link between production and captive consumption was broken, and in which investment was decided by shareholders and bankers. From being utilities – public service providers – the electricity generating companies became operators at the head of merchant plants, power stations selling electricity to the wholesale market. The risks here were not of the same order. Much as football teams which

[59] The ExternE study estimates the external costs of electricity generated using natural gas (excluding carbon emissions) at between $\$_{2010}$13.4 and $\$_{2010}$53.8 per MWh, as against $\$_{2010}$27 to $\$_{2010}$202 for coal (reported in The Social Cost of Coal, Samuel Grausz, October 2011, Climate Advisers). Natural gas produces half as much carbon emissions as coal.

compete on the same playing field, be it muddy or too hard, one might suppose that liberalization would affect all the electricity generating technologies in the same way. Accordingly the new deal should not alter their competitive positions in relation to one another. In practice this did not prove to be the case for nuclear power, which, as far as the financiers were concerned involved greater, more serious risks[60]: higher risks of budget overruns and missed deadlines, in the course of construction and during operation (e.g. safety defects leading to unpredictable reactor shutdowns and consequently lost output); a long period over which to recover investment, increasing the risk due to uncertainty in wholesale electricity markets; higher regulatory and political risks due to the opposition of part of public opinion and some political parties to atomic energy. In the face of these additional risks, the MIT study cited above set a weighted average capital cost 25% higher than for gas and coal, which pushed up the cost per MWh of nuclear power by 33%[61].

We may observe that it is inconsistent to rely on the levelized cost method in an economy with liberalized energy markets. The rationale used to establish the price of electricity, which balances income and expenditure, including the remuneration of capital, is more in keeping with regulated electricity tariffs set by the authorities. In a market economy, electricity prices fluctuate; they are uncertain, just like the price of fuel consumed by generating plants, or the price of tradable emissions permits. The solution is to use the conventional method for calculating the return on a project in terms of net present value, while taking into account the uncertainties. The price of electricity can thus be treated as a variable, which is associated with a distribution function (e.g. a bell curve, on which the peak represents the most probable expected value, and the extremities the lowest and highest values, of low probability). Similarly various values with a range of probabilities are allocated to the other variables affecting income or outgoings. Then we shake up all these data, carrying out repeated random sampling, thousands of times – using the Monte Carlo method, in reference to roulette. We thus obtain the risk profile for the investment, in other words a curve showing the losses and gains it may produce, each level of loss and gain being associated with a probability. If the curve is relatively flat the risk is high, because the probability is more or less the same for low or high rates of return, both positive and negative. If the curve rises sharply, the risk is low, with a substantial probability that the rate of return will be centred near the peak, be it positive or negative. The merit of this probabilistic approach is that it yields a mean value (obviously essential to know whether the return will be positive or negative, low or high), but also an indication of the possible variances on either side of the mean. Assisted by other authors[62], Fabien Roques has used this approach to obtain a better comparison of base load electricity generating technologies. With a whole series of possible hypotheses – in particular a 10% discount rate – their research shows that gas yields higher profits than nuclear power, at a lower risk, the latter point being due to the gains achieved by more flexible plant operation. The load factor, instead of being constant throughout the service life of plants, varies according to the market price of electricity. If the price results in a loss, production stops, starting again when the net present value is once again positive. A second interesting outcome of this work is that it puts figures on the complementary relation between gas and electricity. A portfolio of assets, with gas-fired plants making up 80% of capacity and nuclear power the remainder, yields a lower average return than an exclusively gas-fired portfolio, but entails less risk. Investors may prefer this combination which offers better protection, particularly from high, but unlikely losses incurred if gas and carbon prices are high, a situation which has no effect on nuclear power.

[60] See The Financing of Nuclear Power Plants, OECD Nuclear Energy Agency, 2009.

[61] See footnote 18 [??] at the bottom of page 26.

[62] Fuel mix diversification incentives in liberalized electricity markets: A Mean-Variance Portfolio theory approach, Energy economics, 30, July 2008.

The competitive advantages of nuclear power and renewable energies

In suitable locations onshore wind farms display levelized costs comparable to those of nuclear plants. Neither technology releases CO_2 emissions and both are characterized by high fixed costs. However, although nuclear power has a low marginal cost (about €6 per MWh for fuel[63]), for wind the cost is zero. (The same is true of solar but, except under extremely favourable conditions, its levelized cost is way above that of nuclear.) From an economic point of view this difference is of fundamental importance, because in an electricity market the optimal price is equal to the marginal cost of the marginal unit, in other words the unit that needs to be generated to meet instantaneous demand. When instantaneous demand is at its lowest point, generally in the middle of the night, only base load plants are used (nuclear plants in France). If massive wind capacity were to be installed, the night breeze would blow away gas and coal (perhaps even nuclear) during off-peak hours, reducing their load factor and raising their respective costs per MWh. In fact the loss would be even greater. Coal-fired or nuclear power stations do not ramp up to full capacity or shut down instantaneously. So slowing down or stopping output at night would reduce the power available in the early morning. To sell more electricity at times when prices are higher, it may be in the interest of base load plant operators to bid negative prices in order to keep their plants running all night. So at certain times of the day, large scale wind capacity would result in a market price equal to its marginal cost, in other words zero, and even, at other times, in a lower market price, equal to the opportunity cost of base load operators foregoing a reduction in output.

Not taking into account variations in demand distorts the results when calculating the levelized cost. Paul Joskow, at the MIT, has shown that this method is unsuitable for intermittent renewables[64]. Only exceptionally are intermittent energies in synch with demand. The wind does not blow harder at the beginning or end of the day, nor yet during the five working days of the week, which is when power demand is highest. To simplify matters we shall suppose that peak and off-peak hours are evenly distributed throughout the year. We shall then suppose that an intermittent renewable plant produces two-thirds of its output at off-peak hours, the remaining third at peak hours, and that its levelized cost per MWh is the same as a base load plant. If the country as a whole needs one additional MWh of power, the levelized cost method tells us that it makes no difference whether we invest in wind power or a base load technology. Yet the second option is more useful because it will produce proportionately more at peak hours: with all-year round output it operates half of the time at peak hours, the other half off-peak. So the levelized cost method is biased against investment in base load technology. It is also worth noting that it distorts the ranking of intermittent renewable energies. As the sun does not shine at night, a solar plant generally responds in a larger proportion to peak demand in summer than a wind farm. To compare investment projects in various generating technologies, it is consequently wiser to use the net present value method to estimate income on the basis of the hourly generation profiles of plants and the electricity prices expected at different times of the day.

A third form of distortion which handicaps nuclear power is specific to Europe. The EU has set targets for renewable energies. By 2020 renewables are slated to account for 20% of final energy consumption. As applied to electricity this target means that renewables should supply 35% of all electricity. Measures of this sort requiring a share of renewables in the overall energy mix are commonplace. Most US states apply similar measures. But the EU is unusual in that the measure operates in parallel with a carbon price. The EU system of tradable emissions permits already adds to the cost of fossil-fuel generated electricity, compared to nuclear power or renewables, changing their relative competitiveness in the same way as a carbon tax. For example, with a permit costing €30 per tonne of CO_2, it costs

[63] Cour des Comptes report, p51.

[64] Paul L. Joskow, Comparing the Costs of Intermittent and Dispatchable Electricity Generating Technologies, American Economic Review, American Economic Association, vol. 101(3), May 2011, p238-41.

about €30 per MWh more to generate 1 MWh using coal. Adding a target for renewables to this scheme pushes the price of carbon down. The 20% target for 2020 was set without adjusting the cap on CO_2 emissions decided when the Emissions Trading Scheme was originally set up. As a result the cut in emissions, made compulsory by the renewables quota, restricts demand for permits. So their price drops. David Newbery has estimated that the price of permits will be driven down by €10 per tonne by 2020, from €60 to €50[65]. To avoid this downward pressure, the cap on emissions should have been lowered to allow for the volume of CO_2 recently avoided, in such a way as to achieve the target of 35% electricity from renewable sources. In conclusion, the quota for renewable energies in the EU energy mix has a dual effect. It deprives nuclear power of part of its potential market, despite it also being carbon-free, and makes it less competitive by doing less to increase the price of competing base load technologies, due to a lower carbon price.

We need to see the electricity system as a whole in order to grasp the relative competitive advantages of nuclear power and renewables. As wind, solar and wave are intermittent energy sources, and storing electricity is very expensive, large-scale development of renewables involves building backup capacity to make up for the lack of wind, sunlight or tide at certain times. Such capacity is far from negligible. For Ireland to meet its target for the 2020 renewables quota, it will have to install 30 GW more renewable capacity, while providing a further 15 to 20 GW of non-intermittent capacity as a backup[66]. To enable such supplementary capacity to be built, the country must either agree to stupendous electricity prices (several thousands of euros per MWh) at certain times of day, or set up capacity markets to pay utilities even when they are not producing anything. Otherwise the plant will simply not be built, because investors will anticipate difficulties covering fixed costs due to the insufficient load factor. Nuclear power, dogged by higher fixed costs than gas and less flexible production, is ill suited to catering for this new demand. All other things being equal, the more intermittent energies develop, the more the competitiveness of nuclear power with regard to gas will be undermined.

Looking beyond 2020 we see no sign of a possible improvement in the competitiveness of nuclear power compared with renewables: quite the opposite. The development of storage technologies and ongoing learning effects for wind and solar represent serious threats. Using batteries to store electricity is still outrageously expensive. So far the only alternative solution to have been developed is pumped-storage hydroelectricity. This involves using electrical pumps to raise water from one reservoir to another at a higher elevation. Meanwhile research is focusing on countless other possibilities. What results and applications will research yield over the next 20 years? Without an answer it is hard to see whether electricity storage will one day be sufficiently affordable to be deployed on a very large scale. Realizing such a possibility would remedy the main shortcoming of intermittent renewable energy and substantially increase its economic value, at least for renewables for which the cost is currently close to that of more traditional technologies. This is the case for onshore wind, setting aside the sources of distortion cited above. In the future it might also be the case for offshore wind, and photovoltaic or concentrated solar. The costs of these technologies have dropped substantially, with scope for powerful learning effects. But we shall once again concentrate on terrestrial wind power. Its levelized cost per MWh was divided by three, allowing for inflation, between the early 1980s and the late 2000s[67]. Estimates indicate learning effects between 10% and 20%[68]. However a closer look reveals that the reduction in the levelized cost in constant dollars stopped in 2005, and that the levelized cost has actually risen since. Is this a sign that the technology has reached

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[65] Reforming Competitive Electricity Markets to Meet Environmental Targets, EPRG Working Paper, 1126, Cambridge Working Paper in Economics, 1154

[66] Quoted by Ambec and Crampes, 2010

[67] See NREL 2012, IEA Wind Task 26, The Past and Future Cost of Wind Energy, WP2, May 2012

[68] In a meta-study carried out for the International Panel on Climate Change, bearing on 18 estimates, Wiser et al, 2011 (cited in the NREL study) suggest a 4% to 32% range. But the gap narrows to a 9% to 19% range, if only post-2004 estimates are considered.

maturity, with an end to diminishing costs? Very probably not, as shown by the report by the US National Renewable Energy Laboratory. The rise in costs towards the end of the 2000s is due to the increase in the price of materials and machinery, and a flattening out of performance gains. But since then performance gains have started to improve and the cost per MW of installed capacity is steady. The levelized cost across all wind speeds started dropping again in 2012, down on 2009. The NREL has also done a comparison of 12 prospective studies looking ahead to 2030, covering 18 scenarios in all. Most of them predict a 20% to 30% reduction in the levelized cost. Only one forecasts that it will remain steady. These results obviously concern specific wind classes. The average performance of wind capacity in a country or region may decline over time, due to the less favourable characteristics of more recent locations, the first wind farms having occupied the spots with the best conditions. The issue of siting is the only factor driving costs upwards. However in the future it would be more than offset by the gains derived from mass production and higher performance fed by R&D.

So nuclear has been caught in a pincer movement, so to speak. In OECD countries its high cost, particularly regarding capital, is a handicap compared to gas. It is only competitive if a carbon price is introduced. A fairly high one at that. In a drive to decarbonize its electricity, playing on growth in renewables and replacement of its old nuclear power stations, the UK has set a floor price for carbon in order to attract investors to its nuclear projects. Without a carbon price, underpinned by a long-term commitment on its level, nuclear power no longer makes the grade as a base load technology. On the other hand, setting aside onshore wind power, it is still more cost-effective than intermittent renewables. So in principle there is every reason why it should feature in a mix of carbon-free generating technologies. But only in principle, because in practice it is sidelined and hampered by quotas for renewable energies. In other countries nuclear power is at a disadvantage when compared to cheap, polluting coal, but at least the prospects are a little better. Demand for energy is often so great that all technologies are considered. Large countries such as China and India can plausibly hope to reduce costs through large-scale production and learning effects. Smaller nations may count on the advantage derived from keen competition between vendors of turnkey solutions.

On reaching the end of the first part of this book, readers may feel slightly bereft, having lost any sense of certainty regarding costs. There is no such thing as a 'true' cost for nuclear power, which economists may discover after much trial and error. Nor yet are there any hidden external costs, such as those related to managing waste or the risk of serious accidents, which might completely change the picture if they were taken into account. Far from reducing the cost of nuclear power, technical progress has actually contributed to its increase. It makes no sense to assert that it is currently more or less expensive, in terms of euros per MWh, to build a wind farm or a nuclear power station. There can be no universally valid ranking order for coal, gas and the atom based on the cost of generating electricity.

But the loss of such illusions should not leave readers in a vacuum. The first part has also provided a firm basis for assessing the costs of electricity, which depend on location and various hypotheses on future developments. Consequently such costs can only be properly calculated with a clear understanding of both factors. The construction cost of a nuclear power station is not the same in Finland, China or the United States. Overall expenditure may vary a great deal depending on the influence of the safety regulator, scale effects and the cost of capital. Regarding wagers, the future prices of gas, coal and carbon dioxide will be largely decisive in the ranking of coal, gas and nuclear power. These same prices will also affect the profit margins of nuclear plants, their revenue depending on the number of hours per year during which they operate, and whether the prices per kWh during those hours are decided by a marginal generating plant burning coal or gas, or one powered by sunlight or wind. Confronted by the risky long-term wagers which investors must make to calculate costs and take decisions, even the most *laissez-faire* public authority will feel obliged to intervene. Concerned by the general interest, it must set a discount rate, yet this is the parameter with the greatest impact on the cost of nuclear power. This particular wager hinges on how prosperous future generations may be: the richer they are, the lower the discount rate will be, making nuclear power that much cheaper. Furthermore there is a political choice to be made, in order to maintain a certain degree of equity between rich and poor, and between generations, a choice which influences the rate set for converting present euros into future euros.

What is more, analysing trends for past costs throws light on their future behaviour. Historically nuclear technology has been characterized by rising costs. Today's third-generation reactors are no exception to this iron rule. They are safer than earlier counterparts, but also more expensive. The escalation of costs may stop, but only on two conditions: through a massive scale effect – if China chooses one type of reactor and sticks to it, it may achieve this effect – or through a fundamental change in direction of innovation – giving priority to modular design and small reactors, for instance. Failing this, nuclear technology seems doomed to suffer a steady decline in its competitiveness compared with any thermal technologies spared by taxes and renewable energies boosted by high learning effects.

Setting aside any consideration of possible accidents, it would be an economically risky choice for an operator to invest in building new nuclear power stations or for a State to facilitate such projects. A daring bet indeed!