Introduction

Is nuclear power a thing of the past or a technology for the future? Has it become too expensive and dangerous, or is it still competitive and sufficiently safe? Should emerging countries develop nuclear power or look elsewhere? Can we trust calculations of the risk of a major nuclear accident, given that their results diverge? Is international cooperation on safety and non-proliferation bound to fail or is it in fact gathering strength? The views on all these subjects are contradictory. Often the only common ground between them is their uncompromising, categorical nature. A quick look at the facts certainly fails to yield any obvious answers. The construction projects for new nuclear plants in Europe are behind schedule and well over their original budgets; meanwhile similar projects in China are on target, both for their deadline and budget. Japan, a country renowned for its excellent technology, failed to prevent a major accident at Fukushima Daiichi. The United States, surfing on a shale gas boom, is turning its back on nuclear power. In Europe, the United Kingdom is planning to build several new reactors, whereas Germany is stepping up plans to retire existing plants. Depending on which source you accept, the disaster at Chernobyl caused several hundred fatalities, or several tens of thousands. The number of major accidents observed since the start of nuclear power is greater than the figure forecast by the experts' probabilistic studies. Similarly the perception of nuclear risk is very different from the value calculated by cool-headed scientists. After lengthy debate, the European Union

has adopted a common framework for nuclear safety, but the safety authorities are still national agencies and civil liability regimes form a contrasting patchwork. Lastly, with regard to the non-proliferation of nuclear weapons, Iran has signed the international treaty designed to limit the use of civilian nuclear facilities for military ends, but at the same time it has launched a uranium-enrichment programme which bears no relation to its energy requirements.

Faced with so many divergent claims and apparently contradictory facts, we obviously need to take a closer look at what is going on. It is time for in-depth analysis of costs, hazards, risks, safety measures, decisions by specific countries to invest in nuclear power or pull out, and the rules for international governance of the atom. In short, it is time to study and understand the global economics of nuclear power. Such is the purpose of this book.

It is rooted in two convictions.

Firstly, that analysis which does not take sides, for or against nuclear power, can interest readers.

I hope to show that it is possible not to adopt a normative stance on this issue without handing out platitudes. The economic approach adopted here is deliberately positive, the aim being to understand particular situations, explain phenomena and foresee certain developments. In a word, to focus on consequences: the political consequences for a country which decides to invest in nuclear power or retire its existing plants; the effect of a carbon tax on the competitive position of nuclear power; the impact of observed accidents and public opinion's biased perception of risk; the effect of liberalizing electricity markets on nuclear investments; the consequences of industrial nationalism on reactor exports. My aim is to use economics to analyse effects, not to dictate the decisions that public and private-sector policy-makers should make, less still teaching people the *right* way to think and behave.

Secondly, I believe much the best way to throw light on the individual and collective decisions before us is to gain an understanding

of the many uncertainties weighing on the cost, risks, regulation and politics of nuclear power. A possible sub-heading for this book might be 'In the Light of Uncertainty'. It is vital to set aside a whole series of categorical claims such as the notion that there is a single *true* cost of nuclear power, be it high or low; that a major nuclear accident will certainly occur somewhere in the world over the next twenty years, or alternatively that a disaster is impossible in Europe; that safety regulation in the US is above reproach, or on the contrary in the hands of the nuclear lobby; that a national nuclear industry is a sure-fire asset for France's future balance of payments, or a complete waste of resources. Such assertions only serve to rubber-stamp decisions that have already been taken. Any attempt to settle the many questions raised by nuclear power must allow for such uncertainties, and to do so they need to be circumscribed. The present work shows how the theory of decision under uncertainty can throw light on nuclear debate, how probabilistic assessment can prompt a reappraisal of beliefs, and how the median voter theorem and the theory of political marketing can explain some public decisions.

The book is in four parts, addressing costs, risks, regulation and politics. Each one provides a wealth of detail on its subject, providing the facts of the matter and their theoretical basis, backed by references to academic literature. I am convinced that a degree of immersion gives the reader proportionately many more insights than a brief summary of ideas and arguments.

Estimating the costs of nuclear power: points of reference, sources of uncertainty

Predictably the first part of a book by an economist is given over entirely to the competitiveness of nuclear power. Does it cost less or more than electricity generated using coal, gas or wind? Does it make financial sense for electricity utilities to invest in nuclear technology? The cost of nuclear power has escalated since the first plants

were built. How could it break out of this vicious circle and prevent a further drop in its relative competitive advantage? Financial and economic factors now furnish anti-nuclear campaigners with compelling arguments.

The risk of a major nuclear accident: calculation and perception of probabilities

Measures to enhance safety are among the factors which are making nuclear power increasingly expensive. The second part focuses on the risks of an accident and efforts to limit them. On the one hand, although it is still difficult to assess nuclear risk precisely, it can be analysed dispassionately using a whole series of instruments and methods. As an overall trend, nuclear risk is declining. On the other hand, risk as perceived by the general public, in the wake of major disasters such as Chernobyl or Fukushima Daiichi, is on the rise. So is the public attitude to such hazards irrational? Should government decisions be based on risk as assessed by experts or the general public? Is it possible to narrow the gap between calculated and perceived risk? This part explores in detail the biased perception of probabilities brought to light by experimental psychology, a discipline which now significantly influences economic analysis. It shows how modern probabilistic analysis enables us to reconcile our prior perception of a hazard with input from material knowledge.

Safety regulation: an analysis of the American, French and Japanese cases

The more effective nuclear-safety regulation is, the fewer accidents there will be. How can this technology be expected to inspire confidence among the general public if reactor-safety standards are badly designed by the authorities or improperly applied by operators? But how is effective regulation to be achieved? This is not a simple

matter, safety regulation being dogged by imperfections and uncertainty. The third part of the book analyses several examples closely. The Fukushima Daiichi accident has shown that regulation as practised in Japan is an example to be avoided. Regulation operates along very different lines in France and the US, yet both are exemplary on account of the transparency, independence and competence of their respective nuclear safety authorities. If the same criteria were enforced worldwide the risk of an accident would be much lower.

National policies and international governance

The fourth and last part deals with politics, to which decision-making under uncertainty devolves. This process plays a considerable part in nuclear power: witness the diversity of choices made by individual nations. Some countries have embraced the atom for military and economic reasons, whereas others – the majority – have only developed civil nuclear applications. Some countries are now phasing out their nuclear power plants, others are keen to adopt the technology. Why? Over and above national policies, mechanisms of international governance are trying to contain the risk of proliferation, and improve the safety of reactors and their operation, for the good reason that both safety and security have a planetary dimension. But these efforts to institute supranational governance must come to terms with the sovereignty of states. The economic and commercial interests of countries which export nuclear technology are also at stake here. Clearly, political and strategic considerations still weigh heavily on the world market for reactors.

This book aims to adopt a non-partisan stance, neither pro- nor anti-nuclear. But it does not claim to be objective. As in any essay, the choice of issues, facts and perspective reflects the author's personality and situation. I teach at Mines ParisTech, Paris, one of France's top engineering schools. Many of those who have gone on to build and operate France's nuclear industry were educated here.

Many of my former students still work in the industry. Furthermore, the research carried out by my laboratory is funded by EDF, which also numbers among the clients of my consultancy company, alongside other electricity-generating companies elsewhere in the world. This record may prompt some readers to query the independence of the views expressed in the book, perhaps even suspecting the author of having 'sold out' to the international nuclear lobby. Others, familiar with the intellectual freedom which prevails in the academic world and the open minds of energy engineers, will soon set aside such suspicions. Others still will conclude that the author's links with the 'nucleocrats' are after all a guarantee of the validity of the information contained in these pages.

PART I

Estimating the costs of nuclear power

Points of reference, sources of uncertainty

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-governmental 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 section 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 plant. 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 made 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 part answers these questions in three chapters. We shall start in Chapter 1 by taking a close look at the various items of cost associated with nuclear power.[1] 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. Chapter 2 reviews 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 in Chapter 3 we shall analyse the poor cost-competitiveness of nuclear power, which provides critics of this technology with a compelling argument.

ONE

Adding up costs

Is the cost per MWh generated by existing French nuclear power plants €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 largest 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?

The figures for investments in new nuclear power plants 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 can

the cost of building the same plant vary so much, simply due to a change in 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, 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 precisely to the value of 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 as there are consumers