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Nuclear Power and CO_2 Emission Reductions
Comments on Radioactive Waste Management and Relative Costs of Options[1]

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A. Introduction

The objective of this report is to examine whether nuclear power should be pursued as a means of reducing CO_2 emissions from the energy sector. Specifically, it is focused on the problems of radioactive waste, notably spent fuel, and of the cost and timeliness of nuclear in reducing CO_2 emissions compared to available low-or zero-CO_2 alternatives to coal-fired generation. Both European and U.S. experience have been used to exemplify the waste and cost issues.

Like Spain, the United States gets about 20 percent of its electricity from nuclear power. But, unlike Spain, which gets 11 percent of its electricity from wind energy alone, the United States gets only about 3 percent of its electricity from renewables (excluding large-scale hydro), about half of which is wind-generated electricity; the rest is geothermal and biomass. While solar energy is growing rapidly, it is still well under the one percent mark in the United States. About half of U.S. electricity comes from coal-fired power plants. About 20 percent of U.S. electricity

[1]This paper was published on May 20, 2009, as "Section 2.2 El coste de la energía nuclear y el problema de los residues" (pages 55-76) in Fundación Ideas para el Progreso, *Un nuevo modelo energético para España: Recomendaciones para un futuro sostenible*, Informe, Fundación Ideas, Madrid, 20 de Mayo 2009, online at http://www.fundacionideas.es/noticias/pdf/20090520NuevoModeloEnergetico.pdf. The author would like to thank Professor Stephen Thomas of Greenwich University in the UK for his suggestions and many really useful review comments on drafts of this report. He would also like to thank Marcel Coderch for sending Spanish fuel cost and electricity data and for his suggestions. And finally, he would like to thank Peter Bradford for his review as well. Of course, the author alone is responsible for the contents and analysis in this report and any deficiencies that may remain.

[2] Arjun Makhijani is president of the Institute for Energy and Environmental Research. He holds a Ph.D. from the University of California at Berkeley, where he specialized in controlled nuclear fusion. He has been involved in analyzing energy issues since 1970 and is the principal author of the first ever assessment of the energy efficiency potential of the U.S. economy (1971). He is the author of *Carbon-Free and Nuclear-Free: A Roadmap for U.S. Energy Policy* (2008).

generation comes from natural gas, most of it from combined cycle power plants. Spain gets about one-third of its electricity from combined cycle power plants.

There are three broad issues to consider in assessing whether to make a push for new nuclear power plants to address the problem of greatly reducing CO_2 emissions from the electricity sector:

1. Radioactive waste, and specially spent fuel, management. If the CO_2 problem is reduced but only at the expense of creating a different and intractable environmental problem, radioactive waste disposal, it will be a poor solution.
2. Factors in estimating the cost of nuclear power plants, including financial risk compared to alternatives that can be built faster and with lower risks.
3. Cost of reducing CO_2 emissions using nuclear compared to alternative approaches for reducing carbon emissions – natural gas combined cycle and wind power plants.

So far as the economic analysis is concerned, it is important to note that this report is focused on comparative cost of reducing CO_2 emissions by replacing fully depreciated coal-fired power plants with alternative low or zero-CO_2 sources of electricity. In other words, it is intended to be an analysis of the *relative* costs of the various approaches in reducing CO_2 emissions and should be used primarily for that purpose.

B. Spent fuel management considerations

In the early days it was an article of faith almost, based on scant calculations and technical considerations, that high-level nuclear waste could be disposed of in deep geologic formations without much difficulty. At the time it was assumed that uranium was a very scarce resource. A corollary was that spent fuel would be reprocessed and that essentially all the fissile and fertile materials (U-235, U-238) in reactor fuel would be used up in the production of nuclear energy, increasing the life of the natural uranium resources by a factor of about 100.

These assumptions did not hold up well during the first half century of nuclear power production. Sodium-cooled breeder reactors proved not only to be very expensive, but turned out to be very difficult to master technically. Some prototype and demonstration plants worked well (such as EBR II in the United States for instance), while others had early failures (EBR I, Fermi I, Monju[3]) and yet others proved too difficult to operate consistently Superphénix.[4] Monju is not definitively closed yet, it is in long-term shutdown. Another demonstration breeder, the Dounreay Prototype Fast Reactor (250 MWe) built in Scotland which went on line in the mid-1970s was in the difficult-to-operate category, with a lifetime capacity factor was 23%.[5] The cost of decommissioning is estimated to be $6 billion, amounting to $2,400 per kW for decommissioning alone!

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[3] The Monju reactor went critical in 1994 and had a sodium fire in the secondary loop in 1995. It was restarted in 2009.

[4] For a history see Arjun Makhijani, *Plutonium End Game: Managing Global Stocks of Separated Weapons-Usable Commercial and Surplus Nuclear Weapons Plutonium*, Institute for Energy and Environmental Research, Takoma Park, January 2001.

[5] PFR data are from Professor Steve Thomas, personal communication, 6 May 2009.

The result of the failure of breeder reactor technology to come to technical and economic maturity is that almost the entire waste stream remains to be managed even in the country that has the most extensive plutonium (mixed oxide) fuel use – France. Only about one percent of the recovered materials at the reprocessing plant at La Hague have actually been reused as fuel. And France has generated added radioactive wastes contaminated with plutonium and other transuranic radionuclides to concentrations high enough to require them to be disposed of in a deep geologic repository along with vitrified high-level waste. The U.S. Department of Energy (DOE) estimates that the volume of high-level and transuranic radioactive wastes to be disposed of in a repository as a result of the use of a reprocessing cycle in thermal reactors would be about six times the volume of direct disposal of spent fuel.[6]

It has also turned out to be more complex than imagined to dispose of spent fuel in salt, the geologic medium originally considered the best for disposal of radioactive waste. A recent draft rule published by the U.S. Nuclear Regulatory Commission states as follows:

> Salt formations currently are being considered as hosts only for reprocessed nuclear materials because heat-generating waste, like spent nuclear fuel, exacerbates a process by which salt can rapidly deform. This process could potentially cause problems for keeping drifts stable and open during the operating period of a repository.[7]

In other words, the operational period of a salt formation could be problematic, a consideration that has been borne out by some of the troubles experienced by the Gorleben site in Germany.[8]

Second, reprocessing has turned out to be more-proliferation prone and expensive than acknowledged during the days of greater enthusiasm for that technology. The *surplus* plutonium in the commercial sector today rivals that of all the weapons plutonium in the nuclear warheads of all nuclear weapon states combined.

Third, reprocessing is polluting the oceans with radioactivity; France and Britain discharge large amounts of radioactively contaminated liquids into the English Channel and Irish Sea (respectively), contrary to the wishes of most parties to the Oslo-Paris Accord.[9]

Largely as a result of the problems that emerged with reprocessing and breeder reactors and the fact that uranium turned out to be more plentiful than imagined in the 1950s, most countries turned to direct disposal of spent fuel in deep geologic repositories as their main waste management

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[6] U.S. Department of Energy, Office of Nuclear Energy, *Draft Global Nuclear Energy Partnership Programmatic Environmental Impact Statement*, GNEP PEIS; DOE/EIS-0396, October 2008, links at http://nuclear.gov/peis.html; hereafter PEIS 2008, Table 4.8-6, p. 4-189. See thermal reactor recycle, Option 1. Comparable French data that separate reprocessing and reactor wastes are not readily available.

[7] U.S. Nuclear Regulatory Commission, "Waste Confidence Decision Update," *Federal Register* v. 73, no. 197, October 9, 2008, pp. 59551 to 59570. On the Web at http://edocket.access.gpo.gov/2008/pdf/E8-23381.pdf. Hereafter referred to as NRC 2008.

[8] See for instance Bernd Franke and Arjun Makhijani, *Avoidable Death: A Review of the Selection and Characterization of a Radioactive Waste Repository in West Germany*, Washington, DC: Health & Energy Institute; Takoma Park, MD: Institute for Energy and Environmental Research, November 1987.

[9] Britain may shut its reprocessing operations in the next few years.

policy. Of course, as noted, reprocessing only increases the volume of waste to be disposed on in a deep geologic repository.

About two dozen countries have made declaratory statements that deep geologic disposal is a suitable means for disposing of spent fuel. But statements have turned out to be easier to make than providing a convincing demonstration that deep geologic disposal can occur while demonstrating with some confidence that it can be done safely – that is, according to some defined norms of radiation protection comparable to the present. In fact, decades of investigation and billions of dollars in expenditures have shown that such statements of safe are very difficult to prove, given long-term uncertainties. The U.S. and French repository programs are very important examples of the kinds of problems that have emerged in the course of investigations of geologic isolation of spent fuel and high-level radioactive waste.[10]

As a preliminary to the specifics in the United States and France, it is important to consider that three official terms are important:

- There should be a "reasonable assurance" that disposal can be safely done.
- There should be a definition of "safe disposal", and
- There should be a scientific demonstration that safe disposal with reasonable assurance is "technically feasible" for the lengths of time involved.

1. The United States Geologic Repository Program

Corrosion of the metal canisters has been a critical problem in assessing the suitability of Yucca Mountain as a deep geologic repository. While the DOE believes that certain corrosion problems are insignificant, other researchers have concluded that the problem is fatal to the DOE's design of an unsaturated repository – that is a repository above the water table that has water vapor and air in the rock pores.

DOE proposes disposal in the unsaturated zone in a configuration in which boiling of water is expected for "the first few hundred years after closure…in the drift vicinity."[11] The DOE expects the effects to be as follows:

> Thermal expansion of the rock matrix induces thermal stresses and associated changes in flow properties near emplacement drifts…. Thermally-driven effects also cause dissolution and precipitation of minerals, which may affect flow properties (thermal-hydrologic-chemical effects). [12]

[10] The following paragraphs are adapted from Arjun Makhijani, *Comments of the Institute for Energy and Environmental Research on the U.S. Nuclear Regulatory Commission's Proposed Waste Confidence Rule Update and Proposed Rule Regarding Environmental Impacts of Temporary Spent Fuel Storage*, Institute for Energy and Environmental Research, 6 February 2009. Hereafter referred to as Makhijani 2009.
[11] DOE 2008 p. 2.3.3-58 in Chapter 2
[12] DOE 2008 p. 2.3.3-58 in Chapter 2

While the DOE believes that these processes will not prevent satisfactory repository performance, Dr. Don Shettel, an expert geochemist and consultant for the State of Nevada, has concluded that a hot temperature design is "fatally flawed."[13] This was extensively discussed at the May 18, 2004, meeting of the U.S. Nuclear Waste Technical Review Board (NWTRB):

> We've talked about thermal concentration of brines and boiling point elevation. We can get fingering of concentrated solutions in fractures, thereby increasing the probability and percentage of thermal seepage waters that might reach the drift on the EBS [Engineered Barrier System]. We have mixed salt deliquescence [absorption of water vapor by solid salts so as to dissolve them], not so much from the dust that's on the canisters, but from the increased amount of thermal seepage water that we believe can reach the EBS. And, if these evaporated or concentrated solutions can reach the EBS before the thermal peak, then they can become, even after the thermal peak, get hydrated salts with thermal decomposition, with the evolution of acidic solutions and vapors. And, **one of the most important aspects of this model is the wet-dry cycling or intermittent seepage**. If you get some seepage on the canisters, and it evaporates to some extent, dries out, the addition of water to that can generate acid.
>
> ….We believe that the **high temperature design for the repository is fatally flawed** for the number of reasons that I've discussed, and that **emplacement in the saturated zone would be much better, because that's essentially where DOE has tested their metals at.** And, the saturated zone is also the much less complicated in terms of processes and modeling.[14]

There is experimental evidence that wet-dry cycling at Yucca Mountain could result in very rapid corrosion of the C-22 alloy containers. While the DOE believes the contrary, Dr. Roger Staehle, who worked as a consultant for the State of Nevada with a research team including other experts and Catholic University of America faculty, made a presentation to the NWTRB during which he went through the team's experimental findings for the NWTRB; he concluded with a set of stark "warnings"

> Warnings
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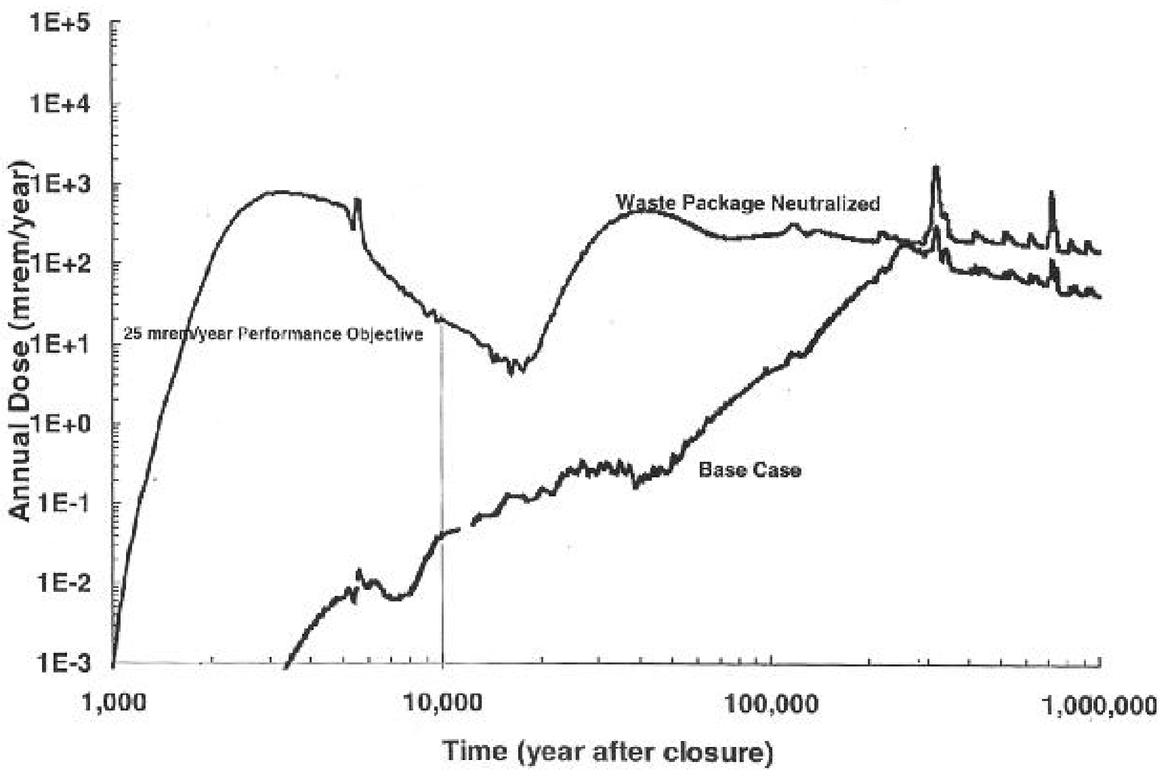
> 1. There is an abundance of warnings as well as solid quantitative data that demonstrate that corrosion of the C-22 alloy is *inevitable and rapid.*
>
> 2. A good paradigm for the warnings about C-22 can be found with Alloy 600 that was widely used in the nuclear industry as tubing in steam generators and as structural components. Alloy 600 has broadly failed in these applications, and present failures could easily have been predicted from past occurrences.
>
> 3. There are now *abundant warnings that that C-22 alloy is not adequate nor is the present design of the repository adequate*. Such warnings are founded on warnings, some of which are 15 years old.
>
> *4. Further, there is abundant evidence that the YM site itself is not adequate.*
>
> 5. The analogies of warnings from the present nuclear industry are abundant and apply directly to whether the present design at YM is adequate. *The answer is that it is not.*
>
> 6. Some of the warnings from experience of the water cooled nuclear reactor industry apply directly to the design and development of the Yucca Mountain facility. These should be carefully assessed, e.g. as they apply to heated surfaces.

[13] Don Shettel is Chairman and Geochemist, Geoscience Management Institute, Inc.
[14] Shettel 2004. Emphasis added.

7. Finally, the incapacity to inspect the YM containers requires assurances of reliable performance that are higher than those of normal industrial expectations.[15]

The NWTRB urged the DOE to include consideration of deliquescence-induced corrosion in its license application to the Nuclear Regulatory Commission. [16] The DOE rejected this advice, saying that such corrosion would be “insignificant”.[17]



Source: U.S. DOE Office of Civilian Radioactive Waste Management, “NWTRB Repository Panel meeting: Postclosure Defense in Depth in the Design Selection Process,” presentation for the Nuclear Waste Technical Review Board Panel for the Repository, January 25, 1999. Presented by Dennis C. Richardson. Online at http://www.nwtrb.gov/meetings/1999/jan/richardson.pdf.

The controversies surrounding Yucca Mountain have been so serious that President Obama declared the site unsuitable during his campaign and he has been supported in this by Energy Secretary Chu, who is a Nobel-Prize-winning physicist. The above graph, produced by the DOE itself, shows that the only element of the isolation system that would contribute substantially to

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[15] Staehle 2004. Italics added.

[16] U.S. Nuclear Waste Technical Review Board. *Report to The U.S. Congress and The Secretary of Energy: March 1, 2006-December 31, 2007*. Arlington, VA: NWTRB, [2008]. On the Web at http://www.nwtrb.gov/reports/nwtrb_2007_web_508.pdf, pp. 27-28.

[17] U.S. Department of Energy, Office of Civilian Radioactive Waste Management, *Safety Analysis Report: Yucca Mountain Repository License Application*, DOE/RW-0573, Rev. 0, Las Vegas, NV: OCRWM, June 2008. Links on the Web at http://www.nrc.gov/reading-rm/adams/web-based.html, searching for ML081560400, p. 2.3.5-12

waste isolation is the metal container – and that is the very element that some researchers believe is the fatal flaw in the entire repository design! The Figure shows that if the waste package is removed, the containment of the waste is projected to be very poor and doses are expected to be high.

I support the development of a geologic repository program in the United, but my opinion, Yucca Mountain is the worst site that has been investigated there. As a result of a number of technical, scientific, design, institutional, and political problems, the Yucca Mountain program is on the brink of failure. A new inquiry commission on nuclear waste is to be formed and it appears likely that the whole process will have to begin from "square one" again though about ten billion dollars of ratepayer money has been spent already and over a quarter of a century ahs gone by since the Nuclear Waste Policy Act was passed in 1982. That law led to the investigation of a number of sites between 1982 and 1986. The search was narrowed to a single site by a revision of the law in 1987, rather than by the process of screening and site characterization that was envisioned in the 1982 Act. In the meantime, the U.S. government is in breach of its contracts with nuclear utilities to begin taking charge of the wastes as of January 31, 1998. Court-ordered damage payments against the government are mounting by the year. The poor, politicized process that was supposed to hasten the development of the repository has, instead, turned into a much more prolonged and costly process due to its underlying scientific deficiencies and the greater political turmoil that bypassing sound science, among other things, has caused.

It is to be noted that the other top sites investigated in the United States have also had their problems. One was a salt site, which is the type of formation not now being considered by the NRC for spent fuel, as noted above. The third top site selected in the 1980s before research was confined to the single location of Yucca Mountain was the basalt formation at the Hanford, Washington site. Many serious defects of the site, including very serious problems in safety, were noted by one of the leading geologist in the United States, Donald E. White, who was a member of the National Research Council panel that wrote a report for the DOE on geologic isolation. In regard to safety Dr. White noted three "threatening effects" including "rock bursting," "costly and troublesome drainage problems" and the following:

> Construction of the repository at very high in-site temperatures, estimated by Rockwell to be 57^{o}C but possibly considerably higher. Refrigeration on a scale seldom if ever attempted in world mining may be necessary. **The costs in time, money, energy, and lives of men are likely to be very high.**
>
> **Even if each of the above [threatening effects] is individually tractable, all in combination may be intolerable.** More satisfactory alternatives probably can be found elsewhere.[18]

Yet, the DOE ignored this 1983 analysis and went ahead and selected basalt at Hanford as one of the top three sites it would characterize.

A large part of the problem in the United States is that political expediency has tended to dominate the process of site selection and characterization. Once that occurs, the temptation to overlook or

[18] White 1983, p. 25, reprinted as an appendix to Makhijani and Tucker 1984, emphasis added.

downplay critical problems to the point of failing to fully investigate them is great. Political pressures to ignore problems have been so strong that when it was found that Yucca Mountain may not meet environmental standards, Congress simply ordered the development of new standards that would be specific for Yucca Mountain. Similarly, when the NRC found that Yucca Mountain may not meet its technical performance criteria for repositories, it simply revised its technical criteria.[19]

2. The Bure repository project in France

The results of the French repository investigation also illustrate some of the same problems, such as failure to include experiments that are suitable for demonstrating performance. For instance, an expert team of geologists put together by IEER concluded that both the thermal and mechanical aspects of the research designed to study the suitability of the French repository location were deficient in essential respects, despite the fact that the program had many strong points:

> A crucial problem for research is that the model must estimate performance not of the natural setting but of a geologic system that has been considerably disturbed by a large excavation, which may induce fractures not originally present, by the introduction of (thermally) hot wastes, and by the addition of various backfill materials and seals. *Hence, the system being modeled is no longer the original geologic system, but a profoundly perturbed system.* …. Estimation of performance of a system under these conditions with some confidence poses challenges that are, in many ways, unparalleled in scientific research.
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> In the specific case of the Bure site, the host rock is argillite, a hard rock consisting of clayey minerals, carbonates (mainly calcites), and quartz. The in-tact rock is not very porous, leading to expectation of diffusive flow in the absence of fractures and in the absence of disturbance by mining. Such flow would be very slow and the expected travel time of radionuclides released from waste packages could be very long.
>
> However, the IEER team's evaluation of (i) the documents, (ii) argillite rock properties under conditions of heat and humidity, and (iii) the research done to model the site performance indicated that the actual conditions prevailing in an actual repository could be very different from diffusive flow. Failure of certain components, notably repository seals, could result in rapid (in geological terms) transport of radionuclides to the human environment.
>
> ANDRA's own estimate of dose under conditions of seal failure was higher than the allowable limit of 0.25 millisieverts (25 millirem) per year. In this context, IEER concluded that ANDRA's scenario for human exposure was not necessarily conservative, in that doses to an autarchic farmer family (also called "subsistence farmer family") using groundwater in certain locations could be even higher than the dose at the surface water outcrop estimated by ANDRA.[20]

[19] Makhijani 2009, pages 11 to 13.
[20] Makhijani and Makhijani 2006. Italics in the original. This article is based on the full report, which is in French: *Examen critique du programme de recherche de l'ANDRA pour déterminer l'aptitude du site de Bure au confinement géologique des déchets à haute activité et à vie longue : Rapport Final*. Hereafter cited as IEER 2005. The qualifications of the team members are found in Attachment C.

Note that as of the date of the IEER report on the Bure site in France, ANDRA's own estimate of dose exceeded its regulations in the event of seal failure. In this context, research on characterizing the long-term integrity of seals becomes critically important. And IEER found ANDRA's research program in this very area to be deficient. One of its principal conclusions about the research on seals was that it seemed to of "marginal value" and was far from adequate to enable a sound determination of repository performance:

> One crucial problem is that the simulated slot sealing test in the underground laboratory may be of marginal value and utility. The test is planned to be done very early on after excavation and only over a very short period of time relative to the duration of performance requirements and even relative to the time lapse over which the actual EDZ [Excavated Damaged Zone] will develop, prior to seal installation. This is neither convincing nor satisfactory. It is difficult to see how and why increasing the stress component parallel to the gallery walls will reduce the permeability in that direction or how a flatjack can simulate a bentonite seal, except in the most crude of approaches.[21]

Here again we found that critical tests required to properly assess the performance of the seals were not part of the repository characterization program. A related issue that came to light during the evaluation of the repository research program in France was that in case of a failure of the seals, ANDRA, the agency responsible for repository development, estimated that the radiological protection standards would be greatly exceeded. Calculated peak doses in that scenario due to chlorine-36 in Class B waste (the approximate equivalent of U.S. Greater Than Class C waste) would be 300 millirem per year and those due to iodine-129 in spent fuel would be 1,500 millirem per year.[22] Both of these are greatly in excess of the French limit of 25 millirem per year and even of the more lax U.S. final EPA standard for Yucca Mountain of 100 millirem per year beyond 10,000 years.

3. Potential lessons for Spain – new reactors and relicensing existing reactors

One of the problems that has emerged as a result of the difficulties of actually characterizing and completing a repository development program is that nuclear waste has to be stored on site for many decades longer than originally anticipated. In its proposed draft rule on "waste confidence", the NRC has suggested that a repository may not be available until 50 to 60 years after the expiry of the license of the last reactor, without even specifying which generation of reactors it was talking about.[23] Hence, after having previously stated that a repository would be available by 2020, the NRC now proposes no fixed date for commencing disposal. This means that waste would have to be stored at reactor sites for a 100 to 150 years and perhaps much longer than that. Further, if reactors continue to be re-licensed, as they are being currently in the Untied States, spent fuel pools cannot be emptied. Fresh spent fuel must be stored in such pools for five to seven years before it can be moved to dry storage. Spent fuel pools are the most vulnerable to accident and terrorist attack compared to dry storage and much more vulnerable compared to dry

[21] IEER 2005, p. 59, in Chapter 2. Retranslated from the final French report by Annie Makhijani.
[22] ANDRA 2001, p. 139.
[23] NRC 2008, Proposed Finding 2.

hardened storage of spent fuel. Despite this, the NRC has not required the emptying of the pools to the extent possible, but instead allows re-racking – that is more dense packing of the pools – increasing the risks and consequences of problems or attacks. Finally, the NRC has not ordered hardened on site storage, which would decrease the consequences of a terrorist attack by making dry storage canisters and storage more resistant to damage in case of such an attack.

Spain is fortunate in that it so far has only eight operating power reactors accounting for only about 8.5 percent of its installed capacity. It has combined cycle power plants that operated at less than fifty percent capacity factor in 2008. This capacity could be used more intensively to replace nuclear generated electricity for part of the year during the period when renewables are ramped up more rapidly. Spain has a large renewable energy industry in both the wind and solar sectors. By phasing out nuclear power, Spain can plan hardened on-site storage to make its population as safe as possible from the risks of extended on site storage. So long as spent fuel pools exist – that is so long as reactors are operating, risks to surrounding populations and to future generations who might live in those areas will remain significantly higher than they need be.

Further, if Spain keeps the total amount of its spent fuel to a modest amount and embarks on a policy of phase out of its reactors a strategy of joining with countries, such as Germany, that have also decided to phase out nuclear power may become viable for repository development. If Spain relicenses existing reactors and builds new ones, the need for a domestic repository program will grow; along with it the social controversy and conflict are almost certain to grow as well. One of the most important problems that has not received due attention in this regard is the loss of focus on the problem of actually getting rid of fossil fuels from the energy system. Nuclear requires not only a disproportionate amount of financial resources to develop, it also requires a hugely disproportionate amount of a society's political resources to manage the social conflicts that go with it.

Finally, a decision not to re-license the Garona reactor, and old, smallish plant of less than 500 MW that has operated for 40 years, will not greatly affect the CO_2 emissions situation, since no other operating license is due to expire in Spain in the near future. Simply continuing the recent shut down of the reactor would allow room for the kind of debate on Spain's energy system to occur without the distraction of a short-term issue. In other words, Spain is in the fortunate situation of being able to decide its energy future and its global role in a twenty-first century energy system without being encumbered by pressing short-term issues that would be a distraction from the larger economic, security, environmental, and industrial questions that need to be decided in all major countries.

In sum, there are substantial reasons, connected to

- immediate waste issues,
- security,
- planning and implementing the safest possible on-site storage, and
- holding a clear-eyed debate about the future of Spain's energy system without short-term distractions

that argue for not extending the operating license of Garona and focusing the debate on creating a fully renewable and efficient electricity sector in Spain.

C. Economics of nuclear power plants based on current U.S. data[24]

This section provides an assessment of the costs of nuclear power plants and discusses the financial risks, costs of delay and other uncertainties and cost factors that have been associated with much of the nuclear development in the past. Present experience in the West appears to be reproducing these old patters. We will refer both to U.S. and European examples. The U.S. experience, where private investment dominates the electricity sector, may be especially relevant for Spain, where the electricity market is also largely liberalized.

1. The United States

At the present time, some privately owned utilities have made estimates of nuclear power costs in the process of applying for permits to build the plants. While they have also made applications for government subsidies, the utility assessment of costs prior to subsidies provides a suitable basis for estimating nuclear power costs in a way that can be compared with unsubsidized costs of renewable electricity.[25]

A number of estimates have been made since late 2007, when applications began to be filed with Public Utility Commissions and some companies started to make public announcements about expected costs. These estimates vary widely. Moreover recent estimates (late 2007 to present) are much higher than earlier estimates due to rapid cost escalation in the construction sphere and especially in large scale power plants, including coal and nuclear plants but also wind and natural gas fired power plants. Only solar electricity costs have been declining.

Rapid cost escalations have made it difficult to make precise cost forecasts. The most reliable estimates come from regulated utilities, which must make declarations to regulatory bodies so as to be able to recover their costs from ratepayers. Such estimates have been made by updating and converting experience in Japan and South Korea in the early part of this decade and the last decade to U.S. conditions, with appropriate cost escalations.

The most detailed estimate of the capital costs of nuclear power were presented in a late-2007 filing with the Florida Public Service Commission by Florida Power and Light.[26] This filing contains a detailed breakdown of the overnight costs of a commercial nuclear reactor as well as estimates for cost escalation during construction and interest costs incurred during construction. The cost estimated for a 2,200 megawatt project with two reactors of 1,100 MW each ranged from $12.1 billion to $17.8 billion, yielding a per kilowatt cost range of $5,492 to $8,071. A larger two-reactor project (3,040 MW) was estimated to cost $5,426 to $8,005 per kW. These include transmission $300 costs of about per kW (including interest and inflation during construction of

[24] This section is adapted from Arjun Makhijani and the Sustainable Energy and Economic Development (SEED) Coalition, *Nuclear Costs and Alternatives*, April 2009.
[25] Renewable electricity costs for Spain are not estimated in this section.
[26] FPL 2007.

the transmission lines), which should be deducted to yield a comparison based on busbar costs. The FPL estimates indicate that a reasonable middle figure to use (in the absence of delays) for capital cost would be about $6,400 per kilowatt.

Other estimates are higher. Puget Sound Energy has made a cost estimate of $10,000 per kW.[27] Progress Energy, which has proposed a two-reactor (AP 1000) project in Florida, Progress Energy's project cost estimate in 2008 was $17 billion, including $3 billion for transmission. Excluding the transmission investment, the cost per kW works out to about $6,360 as initially estimated.[28]

The cost of some of these projects are so high that the CEO of General Electric, who supports nuclear energy since his company is trying to get a new reactor design certified, told the *Financial Times* in November 2007 that if he were the CEO of an electric utility, he would not order a nuclear plant:

> If you were a utility CEO and looked at your world today, you would just do gas and wind…You would say [they are] easier to site, digestible today [and] I don't have to bet my company on any of this stuff. *You would never do nuclear. The economics are overwhelming*.[29]

The main point of the comment, of course, is that natural gas and wind are much less risky. Moreover, both can be built more rapidly in smaller increments, making them less vulnerable mis-estimation of future electricity demand.

Wall Street has made similar estimates of the cost of new nuclear power plants. For instance, Moody's estimated the cost of new plants at $5,000 to $6,000 per kW.[30]

In sum, a reasonable range for U.S. estimates of new nuclear plants, based on company filings with regulators as well as Wall Street estimates is $5,000 to $8,000 per kW, excluding the cost of delays, defaults on loans, and other risks associated with long-lead time capital intensive projects at a time of economic uncertainty. It should be noted that since no reactors have actually been built or have even been licensed to be built for a long time (all reactors ordered after October 1973 were cancelled and the last completed reactor was brought on line in 1996), there is a large uncertainty in these costs simply form lack of recent U.S. experience. This has also been noted on Wall Street, which is reluctant to finance these plants without federal loan guarantees. Indeed companies are reluctant to build them without those guarantees.

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[27] As cited in Jim Harding. "Nuclear Power 2008" Harding Consulting. Power Point Presentation presented at the *Bulletin of Atomic Scientists' Conference on the Future of Nuclear Power*, including supplemental slides, Chicago, Illinois, September 25, 2008. Hereafter referred to as Harding 2008. Jim Harding was part of the 2007 Keystone study and did much of the economic work for that study. The Keystone study was cited in TVA 2008. Mr. Harding is also a consultant on nuclear energy costs to the National Research Council.

[28] John Murawski, "Nuclear reactors' cost: $17 Billion: Progress Energy plans to file its estimate for two new reactors with Florida regulators today", *News and Observer*, 11 March 2008.

[29] Jeffrey Immelt, as quoted by Sheila McNulty and Ed Crooks, "U.S. Utilities Sceptical over Nuclear Plants," *Financial Times*, November 18, 2007. Italics added; bracketed information supplied by FT authors.

[30] New Nuclear Generation in the United States: Keeping Options Open Vs Addressing and Inevitable Necessity, October 2007, p. 11.

A range of $5,000 to $8,000 per kW corresponds to 4,300 to 6,300 euros per kW (rounded at 1.17 dollars per euro).[31]

2. Europe

There are two reactors under construction in Europe. Both are EPRs. The one in the more advanced stage of construction is the Olkiluoto reactor in Finland. The original cost was estimated at 3.2 billion euros, or 2,000 euros per kW. There have been repeated delays and cost escalations. The delay at present is estimated at 3 years and the cost escalation is over 50 percent. The present cost therefore stands at about 3,000 euros per kW.

It is unlikely that the delays and cost escalations are over (see below).

3. The Costs of Delay

Delays have been and continue to be typical of relevant nuclear reactor construction experience in the West. The longest instance in the United States was the TVA Watts Bar project. Construction of TVA's Watts Bar reactor project started in 1973; the completion date was 23 years later in 1996.[32] As another example, the Comanche Peak Unit One, in Texas, had a planned construction period of 5 years, but took over 11½ years to build, a 6½ year slippage.[33] Comanche Peak holds the dubious distinction of being the most expensive completed nuclear power project built in the United States.[34] The 1975 definitive cost estimate (DCE) was $978 million, but the actual cost was $7.8 billion, a 690 percent cost overrun.[35] The total project cost, including capitalized financing charges, Allowance for Funds Used During Construction, was 140 percent above the average total for multi-unit nuclear power plants build during the 1980's.[36]

The Dungeness B reactor in the UK took a comparable amount of time.[37] The Olkiluoto reactor's turnkey cost has been obsolete for some time. But recent days portend a new and more difficult phase, since fundamental safety issues have arisen about the reactor that portend higher costs and more delays:

The brief present experience in Europe and the United States appears to be repeating this unfortunate pattern. The most ominous note has perhaps been sounded regarding the AREVA project in Finland. On December 9, 2008, the head of the Finnish regulatory agency, STUK,

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[31] An exchange rate of 1.17 dollars per euro is used throughout this report. It is the original issuing rate of the euro and also corresponds approximately to purchasing power parity. Exchange rate volatility is one of the uncertainties in nuclear power costs.
[32] TVA website at http://www.tva.gov/sites/wattsbarnuc.htm
[33] Clarence Johnson, *Costs of Current and Planned Nuclear Power Plants in Texas, A Consumer Perspective*, CJEnergyConsulting, Austin, Texas, [March 2009]. Page 19. Hereafter Johnson 2009.
[34] *Ibid*. Page 14
[35] *Ibid*. Page 16
[36] *Ibid*. Page 14
[37] Steve Thomas, personal communication, 6 May 2009.

wrote to the CEO of AREVA, the reactor vendor, that basic safety issues were not being addressed:

> Dear Mrs. Lauvergeon,
>
> With this letter I want to express my great concern on the lack of progress in the design of Olkiluoto 3 NPP automation.
>
> The construction of Olkiluoto 3 plant seems to proceed generally well but I cannot see real progress being made in the design of the control and protection systems. Without a proper design that meets the basic principles of nuclear safety, and is consistently and transparently derived from the concept presented as an annex to the construction license application, I see no possibility to approve these important systems for installation. This would mean that the construction will come to a halt and it is not possible to start commissioning tests.[38]

Changes in or updates to the design, delays in testing and commissioning will all lead to higher costs. Moreover, the delay means that the Finnish utility, TVO, will have to purchase electricity from sources that emit carbon dioxide. As a result it faces substantial costs related to power purchases and CO_2 permits under its Kyoto Protocol commitments. An even more important problem may be that the energy-intensive industries that had been counting on cheap power based on 2,000 euros per kW will now have to purchase power on the open market, which may be far more costly to them and to the Finnish economy. TVO has filed a lawsuit claiming 2.4 billion euros in compensation from AREVA and Siemens.[39]

In the United States delays are occurring even before reactor construction has begun. Progress Energy had been counting on pouring concrete before securing a construction license. The NRC has denied permission to do this. A 20-month delay has been announced.[40]

According to the Florida Power and Light study cited above, a delay of a year could add between \$800 million and \$1.2 billion to the capital cost in a 2,700 MW project due an increase in the Allowance for Funds Used During Construction.[41] Reactor projects in the United States have experienced delays ranging from a short period to decades. A several-year delay could therefore increase the cost by billions of dollars.

Another aspect of delays that is likely to become more costly in the future is that utilities that have CO_2 -emitting generating plants will have to pay to acquire the CO_2 permits to keep them in operation during the period of delay. At 40 euros per metric ton of CO_2, operating a coal-fired

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[38] This letter, which was recently leaked to the press, has been posted on the Greenpeace website at http://weblog.greenpeace.org/nuclear-reaction/2009/05/problems_with_olkiluoto_reacto.html

[39] *Helsingin Sanomat*, "TVO seeks EUR 2.4 billion in damages for Olkiluoto nuclear reactor delays," April 4, 2009, at www.hs.fi/english/article/TVO+seeks+EUR+24+billion+in+damages+for+Olkiluoto+nuclear+reactor+delays+/1135243097398

[40] "Progress Energy Delays Nuclear Power Plant," 1 May 2009, Power Group Online Article at http://pepei.pennnet.com/display_article/360918/6/ARTCL/none/none/1/Progress-Energy-delays-nuclear-power-plant/

[41] FPL 2007, p. 52.

power plant for an additional year would impose an added cost of 300 euros per kW. For an EPR, this would amount to 480 million euros per year.

4. Financial risks associated with nuclear power

High capital costs are only one part of the financial risk of nuclear power. The long lead times, even in the absence of delays, is a major risk factor, and delays, which are often likely, add to this problem. Successful investing in high capital costs projects requires reliable demand forecasts for electricity. Yet, long lead times mean that a forecast must be reliable about 10 years or more from the date of significant expenditures on planning and half a dozen years from the start of construction, even in the absence of delays. This is one of the risk factors associated with long lead times.

As another example of greater financial risk associated with long lead times, there could be cost escalations during the planning and construction periods, with the latter being particularly problematic. According to estimates by Jim Harding, a former utility executive, cost escalation between zero and 14 percent per year increases the costs from 10.7 cents per kWh to 23 cents per kWh, when variation in the overnight costs is also taken into account.[42]

As another risk factor, forecasts of demand in a rapidly changing economic environment are very difficult. Since new power plants, whether nuclear or solar and wind with storage are likely to result in electricity that is more expensive on average than current generation costs, there will likely be a demand response. This occurred in the mid- to late-1970's in the United States, when the rate of electricity growth relative to the rate of economic growth declined sharply from the period prior to the onset of the energy crisis in 1973. As a result many reactor projects were cancelled during that energy crisis. In fact, all reactors ordered in the Untied States after October 1973, the date of the onset of the first energy crisis, were cancelled, in large measure due to the failure of utilities to anticipate the consistent long-term reduction in growth rate of electricity per unit of GDP growth.

The present situation is quite similar. Commodity prices have recently been even more volatile than in the crisis from 1973 to the mid-1980's. The risks of cancellation of new nuclear power plants, which have very long lead times compared to combined cycle natural gas plants, wind, and solar (of any type) are serious. Costing of nuclear power plants needs to include both the cost of delays and the risk that the plant may not be completed for a variety of reasons, including the possibility that demand may be lower than projected.

The combined risks of large capital costs, long lead times, and possible increases in costs due to delays is reflected in the reluctance of utilities to go to banks or to equity markets to raise the capital to finance new nuclear plants and the reluctance of Wall Street in turn to provide that financing. In fact, no new nuclear plant that has been proposed in the United States is planned to be financed by any traditional combination of equity and bond financing. But an estimate of the costs can be made if we compare nuclear financing to high risk bonds (popularly known as "junk bonds" also called "high yield" bonds). In recent months, the premium over long term U.S.

[42] Harding 2008

Treasury bonds in a turbulent economic time can be 15 to 20 percent. For instance, according to *Fortune*, the rates on junk bonds soared to 20 percentage points above those on Treasurys" towards the end of 2008 before easing off by a few points.[43] Hence, financing nuclear power plants in the absence of federal loan guarantees could mean interest rates of 20 to 25 percent.

If we use the high risk rates to approximate the real-world inability to obtain free market financing (even prior to this crisis), then the risk-informed capital cost per kWh of nuclear power would be much higher than that estimated by a calculation that ignores that risk. It is likely that no power plant could be financed on the open market with such high prospective interest rates; nor would any prudent company seek such financing. And the facts on the ground support this view, since all proposals to build nuclear power plants in the United States involve federal government loan guarantees of advance payments from ratepayers towards capital costs during construction ("Construction Work in Progress" or CWIP), or both. In other countries where nuclear is making more inroads, such as China and India, this is occurring only because of very strong state support. It is also interesting to note that France's nuclear transformation occurred entirely when its utility, EdF was 100 percent government-owned; it is still 84% owned by the French government.

While there are no CO_2-emission-related risks associated with new nuclear power plants (or renewable energy sources), there are two other risks of high CO_2 costs associated with nuclear power plants.

First, since nuclear power plants take much longer to build than solar or wind power plants, or combined heat and power systems or projects to increase efficiency, using nuclear power involves additional CO_2 emissions during the period of construction compared to incrementally increasing zero- or low- CO_2 capacity (including efficiency). Delays in nuclear power plants would also increase CO_2 costs in terms of added costs of acquiring CO_2 emissions allowances of payment of added taxes. A $50 per metric ton of CO_2 cost could add hundreds of millions of dollars to the annual operating cost of a utility, depending on the mix of generating sources from which the make-up power is purchased during the delay.

Overall, it is reasonable to assume that the charge per kWh for new nuclear plants could range anywhere from about 7 U.S. cents per kWh to 15 cents or more per kWh (about 6 to 13 euro-cents per kWh, rounded), though the low end of this range may be unrealistically optimistic. This would reflect the potential range of costs, except in the case of cancellation, delays of many years, or severe real cost escalations during construction, all of which have occurred with some frequency in the past.

5. Cost escalation during construction

We have briefly illustrated the problem of cost escalation during construction arising from delays. But cost escalation can also arise without delays – due to real costs increases in materials and labor above the rate of inflation. Adverse exchange rate movements can also cause cost increases, just as favorable ones can cause decreases. Jim Harding, a former utility executive and consultant

[43] Mina Kimes, "There's Still Juice in Junk Bonds, *Fortune*, February 18, 2009, at http://money.cnn.com/2009/02/17/magazines/fortune/kimes_junkbonds.fortune/index.htm

on economic issues estimates that a range of cost escalation assumptions from zero to 14 percent per year and overnight costs leads to a cost range of electricity of 10.7 to 23 cents per kWh.[44]

6. Estimating total busbar costs of electricity from new nuclear power plants

The total busbar costs of nuclear power should include:

- Capital costs per kWh
- Non-fuel Operating and Maintenance (O&M) costs
- Fuel costs
- Decommissioning costs
- Waste management and disposal costs, including spent fuel as well as other wastes.

At present, non-fuel O&M and fuel costs combined average about under 1.88 cents per kWh in the United States (1.6 euro-cents, rounded). However, these do not reflect higher uranium prices, higher prices for enrichment services that may result from new plants being built, the costs of disposal of depleted uranium, for which there is as yet no suitable disposal path, and potentially higher security costs.

In addition, the problem of spent fuel disposal has not been addressed. If we take the U.S. direct disposal charges currently paid by nuclear electricity consumers, this yields a rather modest cost of 0.1 cent per kWh fixed by the U.S. government in the Nuclear Waste Policy Act. But now the Yucca Mountain program is essentially on its last legs. Since there is no operating repository for spent fuel or high-level waste, there is no really good guide for estimating the costs of a satisfactory repository that will meet the licensing test of reasonable assurance of safe disposal with strict environmental and health standards. It is likely that the 0.1 cent per kWh hour fee will turn out to be quite inadequate. Further, if reprocessing becomes part of the waste management policy, the costs would likely increase to 2 cents per kWh,[45] possibly more. Decommissioning costs are likely to be much smaller than this on a per kWh basis.

In sum, the costs, other than capital costs, per kWh may be in the 2 cents to 5 cents per kWh (rounded) range, possibly more.[46] For the purposes of this study, we have assumed a range of 1.6 to 2.4 euro-cents, corresponding to recent U.S. costs at the lower end and 50 percent higher than present U.S. costs at the higher end representing the potential for higher waste and fuel costs and other O&M costs.

Overall, a range of 9 or 10 U.S. cents per kWh at the optimistic low end to 20 U.S. cents or more per kWh at the high end represents the range of nuclear electricity costs from new plants about as well as might be anticipated at present. The high end represents a high overnight costs and a high risk premium to represent a variety of cost increases of the sort that have been experienced in the

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[44] Harding 2008, slide 6.

[45] This is the estimated added cost of electricity from mixed oxide fuel made with reprocessed fuel in France. See Arjun Makhijani, *Plutonium End Game*, Institute for Energy and Environmental Research, January 2001.

[46] The Joint Keystone Fact Finding which included both nuclear industry and nuclear skeptic experts estimated the range of fuel and non-fuel O&M costs as being much higher: 3.7 cents to 4.9 cents (U.S.) per kWh or 3.2 to 4.2 euro-cents per kWh at 1.17 dollar = 1 euro. Nuclear Power Joint Fact-Finding, The Keystone Center, June 2007, p. 11.

past. The uncertainty in costs of mature renewable energy technologies, notably wind-generated electricity, is far lower. In the case of concentrating solar power and solar PV, the costs are coming down as the technologies mature. Among major electricity generation technologies, solar electricity generation technologies are the only ones where the costs have declined in the past few years.

6. Combining uncertainties

We adopt an approach of using a range of construction costs that reflect present day estimates in the U.S. and Europe of 3,500 to 6,600 euros per kW ($4,100 to $7,700 per kW). The lower end of the range is lower than the detailed Florida Power and Light estimate and is very optimistic; the higher end of the range is about equal to the high estimate made by FPL.

To reflect all the other risk factors, such as long lead times, higher cost of capital due to risk of default (assuming no government backing or loan guarantees, much higher costs of spent fuel disposal at some later, undetermined time, lower electricity growth leading to lower sales or even cancellation of some reactors, we have used a risk premium of 5% over short lead time projects, such as wind or combined cycle natural gas plants. For the latter, we use a range of fuel costs to reflect uncertainty (see below). We note that the high end of the range used for these comparisons does not reflect the full range of risks faced by nuclear plants; a five percent risk premium is too low to do so. A much higher risk premium, such as 8 or 10 percent, is needed to do so.

D. The comparative economics of reducing CO_2 emissions[47]

Much of the debate on reducing and eventually eliminating fossil fuels from the electricity sector has centered on comparing renewable energy systems like wind and solar to nuclear power plants. This is an important exercise. However, a comparison that is restricted to zero- CO_2 electricity sources[48] is far too narrow. The main issue is what will replace coal fired power plants, which account for about 55 percent of Spain's electricity sector emissions.

Consider then the following investment question: how does an investment in nuclear energy compare with an investment in natural gas or wind in reducing CO_2 emissions. In other words, for a given expenditure of money, can more CO_2 be reduced, for instance by investing in combined cycle power plants or wind than by investing in nuclear. The question is evident in the case of wind – it is a straight comparison between two sources of electricity that have no direct CO_2 emissions at the power plant. But combined cycle natural gas power plants do have CO_2 emissions. Yet, it may be that it CO_2 emissions could be reduced more cost effectively by replacing coal-fired power plants with natural gas-fired power plants. Ultimately the gas-fired generation might have to be replaced by zero- CO_2 sources, but the use of natural gas in a transitional role might allow new options to be developed and the cost of existing zero- CO_2

[47] All economic calculations in this paper are on an unsubsidized basis. No government loan guarantees, tax credits, etc. are considered for any electricity source. This enables direct and valid comparisons to be made between different sources of electricity. We do not address the problem of government-subsidized insurance and government mandated limits on liability far below potential accident damages in this paper.
[48] Direct emissions only.

renewable sources to be reduced. Wind generated electricity is equally or more advantageous than natural gas in many cases, depending on the circumstances, the price of gas, the specific wind site and whether storage is involved or not.

We consider the following parameters (costs are in euros and euro-cents unless otherwise mentioned):

- Variable costs of coal-fired generation: 2.4 euro-cents, including fuel and non-fuel costs.[49]
- Emission factors: coal = 950 grams of CO_2 per kWh, combined cycle: 380 grams per kWh, nuclear = zero, wind = zero.[50]
- Fuel cost of natural gas combined cycle power plants: 2.25 euro-cents per kWh, which is the current cost in Spain. Additional non-fuel operating costs of 0.75 euro-cents per kWh are assumed for a total of 3.0 euro cents per kWh in fuel and non-fuel operating and maintenance costs. We also use a high case for natural gas fuel cost assuming a 50 percent increase in the cost of gas to illustrate the effect of a potential rise in gas prices. We stress that his is not an estimate that natural gas prices will increase in a sustained way. The high gas price case is used just as an illustration of a contingency, which shows the relative CO2 reduction cost in case natural gas prices rise.
- Fuel and operating costs for nuclear = 1.6 euro-cents per kWh in the low nuclear cost case and 2.4 euro-cents per kWh in the high nuclear cost case.
- Capital costs; Nuclear – low: 3,500 case and high: 6,600 euros per kW installed as noted above, 40 year operating life, 90 percent capacity factor.
- Capital costs natural gas combined cycle = 1,000 euros per kW (rounded). Capacity factor = 90 percent. Based on U.S. costs of about $1,150 per kW.[51]
- Capital costs: onshore wind: low case = 1,500 euros per kW (based on $1,800 per kW) and capacity factor = 35%.; high case: 1900 euros per kW (based on $2,200 per kW) and capacity factor = 25%.
- Interest and depreciation: 8% for wind and combined cycle and 13% for nuclear, reflecting a modest risk premium of 5% (compared to potential high-yield bond ("junk bond") premium that could be much higher, given the various risks involved..

As noted at the outset, these are simplified calculations intended only to compare the approximate cost of CO_2 reductions in the case of replacing existing depreciated coal-fired power plants by new power plants of three types – combined cycle natural gas, nuclear, or wind. If a sensitivity analysis is done, the above parameters yield the values shown in Table 1. Note that while the capital costs for combined cycle and wind are realistic figures, the range for nuclear is very large

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[49] This is based on July 2008 average U.S. costs converted to euros at 1.17 dollars per euro, which was the issue rate of the euro and corresponds roughly to the purchasing power parity exchange rate. The exact value is not essential as it is used only to estimate the cost differential for replacing a fully depreciated coal-fired power plant with a new power plant. This enables the cost per metric ton of CO2 to be established for various power plants. *Note that* all *U.S. dollar data are converted to euros at the rate of 1.17 dollars per euro.*

[50] Based on 1.3 MJ natural gas to heat compressed air for a 90 percent load factor. See below.

[51] *CONE Combined Cycle Revenue Requirements Update PJM Interconnection, LLC. Cost of New Entry Combined Cycle Power Plant Updated Revenue Requirements*, for PJM Interconnection, LLC, August 26, 2008. An escalation corresponding to an inflation rate of 2.5 percent for three years has been taken into account to make the constant 2008 dollar estimates comparable to the FPL nuclear cost estimates. AN average of three values of capital cost cited in this report has been used. Converted to euros at 1.17 dollars = 1 euro.

due to uncertainties and the wide range of experience with nuclear. The low end of the cost range may be unrealistically low to represent the cost of a completed plant.[52] It has been used here as a lower bound to compare whether there is any case for using nuclear to reduce CO_2 emissions compared to natural gas combined cycle power plants. As it turns out, there is not.

Comparing the low natural gas cost case to the low nuclear cost case, we can see that the nuclear plant has a 80 percent greater cost for CO_2 reduction. The high nuclear case is nearly four times the CO_2 reduction cost compared to the low nuclear case. The result is the same when the low nuclear cost case is compared to the low wind cost case. At the high end of nuclear costs, nuclear is also more expensive than the high end of wind energy costs. There is only a marginal advantage for nuclear when the high wind cost case is compared to the low nuclear cost case. This is in my view the result of using a low end value that, at least in the United States, appears unrealistically low. It should also be noted that a proper comparison for policy choices should compare the high cost with the high cost cases and the low cost with the low cost cases.

It is useful to make a "best estimate" or central estimate comparison of these various values. It is also useful to add a storage element to wind to check how that changes the cost relative to nuclear. We chose a natural gas cost of 3.0 euro-cents per kWh for combined cycle power plants, considerably in excess of the present price, but well within the range of spot prices in the last few years. We use a capital cost of nuclear of 5,000 euros per kW (rounded) and of 1,700 euros per kW for wind; these are approximately the averages of the ranges used in Table 1. A 30 percent capacity factor is used for wind, which is in between the low and high cases.

In order to make the wind-nuclear comparison in a situation of advanced penetration of renewables, we added a compressed energy storage (CAES) component so that wind would be dispatchable rather than intermittent. The estimates of CAES cost are drawn from a detailed assessment done for a Texas wind farm by Ridge Energy Storage & Grid Services.[53] Two large-scale compressed air energy storage systems have been operating in conjunction with coal-fired power plants in Huntdorf, Germany (290 MW) and McIntosh, Alabama (110 MW). The latter has been operating since 1991. Hence ample operational and cost data are available for CAES at operational scales for central station generation. The baseload wind concept using CAES, including fuel consumption, is described by the National Renewable Energy Laboratory in a 2007 paper with estimates of fuel use at various capacity factors.[54]

The results of the comparison are shown in Table 2. This shows that the central estimate of nuclear costs in reducing CO_2 is about double that of combined cycle or wind power plants. Even when compressed air energy storage is added at an added cost of just over 3 U.S. cents per kWh (2.6 euro-cents per kWh), dispatchable wind-generated electricity is still somewhat lower in cost than nuclear. The costs of capital and operating costs (modest natural gas costs) are derived from the Ridge Energy study. The capital costs of CAES have been adjusted upward by 50 percent to

[52] This is the view of Peter Bradford, Former Commissioner of the U.S. Nuclear Regulatory Commission. Peter Bradford, personal communication, 8 May 2009.
[53] Ridge Energy Storage & Grid Services, *The Economic Impact of CAES on Wind in TX, OK, and NM, Final Report,* June 27, 2005, p. 82. Hereafeter Ridge Energy 2005.
[54] Derived from National Renewable Energy Laboratory, *Creating Baseload Wind Power Systems Using Advanced Compressed Air Energy Storage Concepts*, 2007, online at http://www.nrel.gov/docs/fy07osti/40674.pdf. Hereafter NREL 2007.

account for cost escalation between the time of publication of the study (2005) and 2008. Capital cost represents about two-thirds of the total annual cost of CAES in 2005 and about three-fourths of the cost in the 2008 calculation shown in Table 2.

E. Conclusions

This analysis shows that the common assumption in many circles that nuclear is essential for reducing CO_2 emissions is incorrect. On the contrary, emissions can be more effectively reduced at much lower risk if existing coal-fired power plants are replaced by wind and combined cycle power plants. In the long run, natural gas can be replaced by biogas derived from biomass for instance to eliminate the CO2 emissions associated with it and also to eliminate the risk of natural gas price increases over the long-term. Even when compressed air energy storage is added to wind to make it dispatchable, the costs of CO2 reduction are slightly higher for the central estimate of nuclear than for wind with storage.

It does not appear desirable to take the risks associated with nuclear power both in regard to waste and money in order to reduce CO2 emissions. Moreover, given that the lead time for building nuclear power plants is 8 to 10 years (perhaps more in case of long delays), CO2 reductions can be carried out much more rapidly if renewable energy is deployed, since renewable projects typically take two to three years or less. Therefore, there could be a substantial CO2 cost penalty associated with using nuclear power due to its long lead time. The nuclear industry will also take time to ramp up. In the United States, it is anticipated that less than ten plants and possibly less than half that will be built in the next ten years. The amount of equivalent renewable capacity, in terms of generation and hence CO_2 reductions, that can be brought on line in that time could be many times that. When combined with large efficiency investments and investments in storage, the overall share of the cost of electricity in the Gross Domestic Product can be maintained even if renewable electricity remains somewhat more expensive than conventional fossil fuel generation (in the absence of CO_2 charges).

Nuclear power is a distraction from the real task at hand – transitioning to an efficient, smart-grid electricity system based entirely on renewables. John Wellinghof, the Chairman of the U.S. Federal Energy Regulatory Commission, has recently noted that there may be no need for new nuclear or coal plants ever.[55] My research indicates that he is right. Policies in regard to existing nuclear plants can safely be based on the assumption that we will be able to phase them out and that we will not need new nuclear power plants to address climate change concerns.

[55] Noelle Straub and Peter Behr, "Energy Chief Says New Coal, Nuclear Plants May Be Unnecessary, *New York Times*, April 22, 2009, on the Internet at http://www.nytimes.com/gwire/2009/04/22/22greenwire-no-need-to-build-new-us-coal-or-nuclear-plants-10630.html

Table 1: Comparison of CO_2 reduction costs: combined cycle, nuclear wind

Power System	Capital Cost euros/kW	Interest + Depreciation euro-¢/kWhe	Fuel and non-fuel O&M cost euro-¢/kWhe	Total cost euro-¢/kWhe	Coal, variable costs only	Added cost over coal euro-¢/kWhe	CO_2 displaced per kWh, grams	euros per mt CO_2 displaced	Ratio CO_2 reduction cost: low nuclear to alternative	Ratio CO_2 reduction cost: high nuclear to alternative
CC – present gas cost	1000	1.2	3.0	4.2	2.4	1.8	570	31	180%	389%
CC – high gas cost	1000	1.2	4.1	5.3	2.4	2.9	570	51	110%	239%
Wind low case	1500	4.6	0.8	5.4	2.4	3.0	950	31	180%	389%
Wind high case	1900	8.1	0.8	8.9	2.4	6.5	950	69	82%	178%
Nuclear Low	3500	6.2	1.6	7.8	2.4	5.4	950	56	100%	217%
Nuclear High	6600	11.6	2.4	14.0	2.4	11.6	950	122	46%	100%

Table 2: Central estimate values for combined cycle, wind, wind with storage, and nuclear in for CO_2 reduction

Power System	Capital Cost euros/kW	Interest + Depreciation euro-¢/kWhe	Fuel Cost euro-¢/kWhe	Non-fuel O&M ¢/kWhe[3]	Total cost euro-¢/kWhe	Coal variable costs only	Added cost over coal euro-¢/kWhe	CO_2 displaced per kWh, grams	euros per mt CO_2 displaced	Ratio CO_2 reduction cost: nuclear to alternative
Combined Cycle	1000	1.2	3.00	0.8	4.9	2.4	2.5	570	45	198%
Wind	1700	6.1	0.0	0.8	6.9	2.4	4.5	950	47	188%
Wind with storage	1700	6.1	2.6 (Note 1)	0.8	9.5	2.4	7.1	850 (Note 2)	83	106%
Nuclear	5000	8.8	1.0	1.0	10.8	2.4	8.4	950	88	100%

Note 1: Fuel, non-fuel, and capital cost for Compressed air energy storage (CAES); see discussion above.

Note 2: About 100 grams of CO_2 per kWh would be emitted in using wind with CAES in a baseload mode. See NREL 2007