Climate Change, Energy Security, and Nuclear Power

Milan Ilnyckyj

Two factors have resuscitated interest in nuclear power throughout the developed world: high hydrocarbon prices and concerns about climate change. This paper considers the advantages and disadvantages of nuclear power as a mechanism for achieving climate change mitigation and energy security objectives. It also highlights some of the methodological problems faced by governments trying to decide which energy technologies to support in the future, including uncertainties about the comparative economics of nuclear power and other low-carbon options, particularly renewables. Special consideration is given to issues including lifecycle emissions, radioactive wastes, the proliferation of nuclear weapons, water and fuel availability issues, and the relationship between forms of electrical generation and the character and functioning of the electrical grid.

This paper does not seek to provide a final qualitative judgement of the relative merits of nuclear power and renewables, nor the relative validities of some of the most contested arguments for and against them. Rather, it seeks to summarize the state of the debate and some of the key contested elements within it.

Nuclear power is a more divisive issue than any other amongst those who are concerned with climate change and with driving the push towards a low-carbon global society. Advocates of a nuclear revival consider support for nuclear energy to be a badge proving genuine concern about climate change.[1] Those who disagree assert both that nuclear power has unacceptable problems associated with it and that climate change can be managed without the need to build more nuclear capacity. Adjudicating between the two positions is extremely difficult. Doing so requires assessing both the advantages and difficulties associated with nuclear power and those associated with the best available alternatives; it requires projections about what kind of technology will scale up in what ways, as well as controversial economic arguments about subsidies. The debate about nuclear energy and energy security is similar in many ways - although the areas in which they differ will be discussed below. In both cases, the kind of unbiased empirical data necessary to make an informed choice does not seem to be available. While this examination

Milan Ilnyckyj, 'Climate Change, Energy Security, and Nuclear Power,' *STAIR* 4:2 (2009): 92-112.

will largely focus on the intersection between climate change and nuclear power, energy security issues are raised throughout.

Arguably, the problem of climate change is dramatically more important than that of energy security, although that may not be the case for politicians who must face voters with an increasingly acute concern about energy prices and availability. The worst possible outcome for states that fail to secure energy supplies concurrent with their domestic needs is a contraction in the quantity of energy-intensive work that can be done. By contrast, the worst possible outcome from climate change is a situation in which natural carbon sinks become self-amplifying net sources of carbon, producing a runaway climate change effect ultimately leading to a world very hostile to human life. The prior existence of such inhospitable climates, as documented in paleoclimatic records, demonstrates that climatic forcings of a certain type and magnitude can be amplified into massive shifts in the climate system.[2] Even non-runaway climate change outcomes could prove devastating for the global economy as well as international peace and security, particularly if large-scale reductions in water availability or major agricultural impacts emerge on regional or continental scales.

Thankfully, it seems plausible that energy security and climate change objectives can be met simultaneously. Various options for producing energy from non-hydrocarbon sources offer up that possibility. The most probable clash between these objectives relates to coal: an amply available hydrocarbon towards which states — including China and the United States — might be driven to turn more sharply in response to greater uncertainty about energy imports. Coal for electricity, and liquefied coal for transport, holds the promise of reduced hydrocarbon imports. At the same time, continued use of coal threatens to seriously worsen climatic outcomes. Whether nuclear power or some other option proves to be the preferred mechanism for reconciling society's energy needs with the planet's limited capacity to absorb human impacts, avoiding the consequences associated with releasing the carbon in the world's coal reserves into the atmosphere must be a crucial objective for humanity. Because coal reserves are much larger than oil reserves, and because more carbon DIOxide is produced for each unit of energy when burning coal, the climatic consequences of burning all of the world's coal would be far greater than those of burning all of the world's oil. That carbon must be kept in the ground or – if it proves effective and economically viable – temporarily extracted and then permanently re-buried, using Carbon Capture and Storage (CCS) technology.

This paper will concentrate on nuclear fission and renewables as possible sources of future electricity production. The latter category includes hydroelectric, wind, concentrating solar and solar photovoltaic, biomass, tidal, wave, and geothermal energy: all forms of energy with unlimited fuel supplies and no emissions aside from those required for construction. The possibility of continuing to use hydrocarbon fuels in conjunction with carbon capture and storage technology will not be considered extensively. While many governments and firms have expressed their confidence in CCS technology, it has not been demonstrated in a commercial power plant. Furthermore, the difficulties associated with the development and deployment of global CCS infrastructure are likely to be considerable. Former Assistant Secretary of the US Department of Energy Joseph Romm has estimated the physical requirements of producing one 'stabilization wedge' of emisisons reductions using CCS. The concept of such wedges for climate change mitigation originated with the work of Stephen Pacala and Robert Socolow.[3] Each wedge represents a policy or technology that reduces emissions below business-as-usual levels, reaching a rate of one gigatonne of annual reductions by 2050. Due to that process of ramping up, each wedge represents twenty-five gigatonnes of avoided emissions before 2050. Romm estimates that producing one wedge of emissions reductions using CCS would require physical infrastructure equivalent to all that being presently employed globally to extract oil from the ground.[4] Given the enormous expense and the decades of construction that have gone into that infrastructure, physical limitations seem to be a realistic reason to limit estimates for the medium-term contribution of CCS, although others dispute this position. This is not to say that CCS will play no role in the energy mix of the future, but rather to somewhat temper expectations of how quickly and comprehensively it could be deployed, and identify it as not being a major subject of this analysis.

The Case for Nuclear

Some of the most outspoken advocates for rapid and comprehensive action on climate change are also big supporters of nuclear power. They see it as a low-carbon way to provide large amounts of electricity to national grids, as well as an important 'wedge' in the drive towards stabilizing global concentrations of greenhouse gasses. Examples of such supporters include climatic scientist James Hanson and biologist James Lovelock. Political support for nuclear energy exists for several reasons: among them, concerns about maintaining secure access to energy and with low-carbon energy production. Views on nuclear energy as a long-term option differ among supporters. Whereas some see nuclear power as a desirable option indefinitely, others see it as a temporary bridge serving as a deeply flawed stop-gap until superior energy options are more fully developed and deployed. Given the long timelines associated with power plant planning, construction, and deployment, errors made in the choice of generating options will have an impact for many decades.

Nuclear energy is a low-carbon way to produce electricity. Even when lifecycle emissions are considered – including energy use in locating, mining, milling, enriching, and disposing of spent uranium – nuclear energy has strong potential as a climate-friendly option. The Canadian experience provides a good example. The Pembina Institute estimates that the total emissions for Canada's nuclear sector (including twenty-three reactors at seven power stations) are between 468,000 and 594,000 tonnes of carbon dioxide per year.[5] That is about 0.07 per cent of Canada's total emissions for the year in which the estimate was made (2006). In 2005, Canada's nuclear industry produced eighty-five terawatt hours of electricity, approximately eleven per cent of Canada's total energy use.[6] By comparison, one five-hundred megawatt coal-fired power plant produces about three million tonnes of carbon dioxide. That is equivalent to about 0.4 per cent of Canada's installed electrical capacity, and about 0.4 per cent of Canada's 2006 emissions. The Pembina Institute estimates consider the greenhouse gas emissions associated with the construction and decommissioning of nuclear power stations, as well as those associated with fuel production and disposal. The Intergovernmental Panel on Climate Change (IPCC) estimates that if all the world's existing nuclear generating stations were coal plants, 2.2 billion tonnes of additional CO_2 per year would be entering the atmosphere. When lifetime emissions are taken into account, arguments that nuclear energy is nearly as bad as energy from fossil fuel are thus not credible. Nuclear energy has a genuine capability to produce low-carbon electricity.

The power output from nuclear plants is large and relatively consistent. Barring maintenance shutdowns, they are capable of maintaining large and steady flows into the electrical grid.[7] This stands in particular contrast to individual renewable generating sites, where power output varies with wind intensity, incoming solar radiation, and so forth. A relatively predictable output means that nuclear stations do not require as much 'peak' generation capacity on standby. That being said, inevitable shutdowns for refuelling and maintenance mean that nuclear energy cannot claim to be entirely consistent, or wholly without the need for backup capacity that can serve the grid during times of disruption. These disruptions are, however, more rare and often more predictable than those associated with intermittent renewable technologies, such as wind power. Nuclear power also has an advantage in terms of the amount of land required to produce a certain amount of electricity. Compared to renewable options like solar, a nuclear plant can produce more than one hundred times as much power on the same plot of land.

The economically viable supply of nuclear fuel in the medium-term seems adequate for present purposes. Furthermore, the most significant uranium producers globally are Canada and Australia: states likely to be stable suppliers, in contrast with some of the volatile regimes exporting hydrocarbon fuels. Certainly, states such as the US, France, and Japan would prefer to be able to secure long-term contracts for access to fuel from rich and stable democracies, as opposed to facing the need to buy fuel at volatile prices from states facing both significant internal and regional security challenges. Theoretically, it may become commercially viable in the future to use thorium for fuel in fission reactors,[8] or to extract uranium from novel sources such as phosphates or seawater. Another possibility is that fuel reprocessing or so-called 'breeder' reactors will be developed to the point of commercial viability. If so, fuel availability for nuclear reactors might be extended quite considerably.[9] While it would still not be accurate to refer to nuclear fission as a renewable source of energy, the provision of additional fuel and extension of its viability would generate a greater span of time in which technological progress could occur on other fronts. In so doing, nuclear energy could act as a significant bridge between an economy largely powered on carbon-intensive, increasingly costly and depleted fossil fuels, and one that relies upon energy extracted from inexhaustible sources.

Part of the case for nuclear also lies in the rebuttals of some of the charges against it. For instance, when it comes to the emission of toxic and radioactive substances into the environment, coal-fired electrical generation seems to be worse than nuclear power.[10] Additionally, while nuclear accidents are far more sensational than those associated with other forms of electrical generation, they have been arguably less severe in reality than in the popular imagination. Even Chernobyl, a name that has become synonymous with all the dangers of nuclear energy, is estimated by the World Health Organization to have killed fifty-six people directly with four thousand expected extra cancer deaths among the six-hundred thousand most exposed people. Three-hundred thousand people were also permanently relocated.[11] By comparison, the WHO estimates that 2.4 million people per year die as the result of air pollution. By reducing deaths associated with toxic smokestack emissions (not to mention those associated with climate change), nuclear power might actually save lives, even when inevitable small and medium-scale accidents are taken into account. While challenging methodological and ethical questions accompany any such comparisons, it must be acknowledged that there are serious risks and health consequences associated with the conventional alternatives to nuclear energy, as well as with nuclear power itself.

The Seriousness of Climate Change

The need to massively reduce global greenhouse gas emissions is clear and urgent. According to the Fourth Assessment Report of the IPCC, stabilizing the atmospheric concentration of greenhouse gasses at a level consistent with the European Union's target of less than 2°C of global temperature change requires massive reductions. Even at 2°C of change, the IPCC predicts wide-ranging and serious impacts.[12] Stabilizing concentrations means cutting emissions of all greenhouse gasses to a level where net absorption by sinks equals net global production. The level at which stabilization occurs determines what level of warming will occur. Two different stabilization scenarios offer a glimpse of the relationship between stabilization concentration, temperature change, and difficulty of implementation:

Stabilization at 450 Parts Per Million (PPM) of Carbon Dioxide Equivalent:

According to the IPCC, stabilization between 445 and 490 PPM would likely produce temperature increases of between 2.0°C and 2.4°C by 2100. Stabilizing at 450 PPM would require that global emissions peak by 2010 and fall by seven per cent per year thereafter, falling to seventy per cent below 2005 va--lues by 2050. A study by Malte Meinshausen uses IPCC estimates about the relationship between stabilization and temperature change to estimate that there is a risk of between twenty-six per cent and seventy-eight per cent (mean forty-eight per cent) that mean global temperature change will exceed two degrees under this scenario.[13]

Stabilization at 550 PPM:

According to the IPCC, stabilization between 535 and 590 PPM would likely produce temperature increases of between 2.8°C and 3.2°C by 2100. This would require emissions to peak between 2016 and 2026, then fall at a rate of one to three per cent per year, reaching levels twenty-five per cent below 2006 levels by 2050. The Meinshausen study projects a risk of between sixty-eight per cent and ninety-nine per cent that the two degree target will be exceeded, with a mean estimate of eighty-five per cent.

Another way to consider the problem is to decide upon a maximum level of acceptable temperature rise. By using that figure and estimates of the sensitivity of the climate to carbon dioxide, it is possible to determine how many carbon emissions humanity can produce while not exceeding the temperature threshold. Taking the 2.0°C target for temperature change adopted by the European Union, and using the climatic sensitivities at the upper and lower bound of the probable range determined by the IPCC, the total quantity of carbon dioxide that humanity can emit between the present day and the point where global society is carbon neutral is estimated between 484 and 661 billion tonnes of carbon – a figure that includes all emissions from both developed and developing states.[14] Annual emissions of carbon are already ten billion tonnes per year (thirty-six billion tonnes of carbon dioxide) and increasing at around 3.5 per cent per year, despite the significant increase in fossil fuel prices. Given the definition of probability used by the IPCC, the 661 billion tonne figure only corresponds to a sixty-six per cent chance of avoiding a temperature increase of over 2.0°C, and it must be recalled that the emergence of strong positive feedback loops could boost climatic sensitivity well outside this range. Indeed, scientists including James Hansen have argued that stabilization below 350PPM is necessary to avoid dangerous anthropogenic climate change.

According to the *The Economics of Climate Change: The Stern Review*, a business-as-usual scenario in which emissions continue to increase at the present rate would likely result in 2.0°C to 3.0°C degrees of warming by 2050 and concentrations well over 1000 PPM by 2100, with probable temperature increases of more than 5.0°C.[15] To put this in context, the temperature difference between the world at present and that prevailing during prior ice ages was between 3.5°C and 5.0°C.[16] The higher the stabilization concentration, the greater the risk of runaway climate change, in which positive feedback loops such as losing reflective sea ice and the release of methane from melting permafrost reinforce the anthropogenic warming trend. Positive feedback loops of sufficient magnitude would overwhelm the capacity of carbon sinks, turning the planet into a net emitter of greenhouse gasses, even in the absence of human activity. In such a situation, humanity would be left with two options: waiting for the climate to reach a new equilibrium (which could be very hostile) through the combination of biological and geological effects, or actively trying to manipulate the climate system. Such 'geoengineering' possibilities carry the grave risk of unintended consequences, even if they did prove effective at helping to stabilize temperatures.

All of this strengthens the case for re-examining nuclear energy: a technology that was essentially rejected as too risky and expensive in the period before climate change was a serious and well-understood concern. Stabilizing atmospheric concentrations of greenhouse gasses at a level that avoids dangerous interference in the climate system requires the rapid deployment of known low-carbon energy technologies. Aside from large-scale hydroelectricity, nuclear energy is the most significant such technology widely deployed today. That said, appropriately evaluating nuclear energy in a warming world requires objective and comprehensive consideration of its disadvantages, as well as alternative means for achieving the same outcomes. All this requires the balancing of many different kinds of risks: those directly associated with different forms of energy production, as well as those associated with health, environmental, economic, and geopolitical consequences arising from energy choices.

The Problems with Nuclear

Most of the major problems of nuclear energy are well known. They include the danger of accidents or the intentional targeting of nuclear stations by malicious actors. There are also issues of uranium mining and enrichment and the disposal of waste. Other arguments against nuclear energy include expense, the disputed need for major public subsidies, water usage, and deployment timelines. Geopolitical concerns include the dangers of nuclear proliferation. Finally, there is the reality that nuclear power plants do use a non-renewable resource as fuel, raising questions about how long reliance upon them can successfully delay the need for truly renewable options. Not all the problems associated with nuclear power differentiate it from all other options – for instance, fossil fuel power plants also require water for cooling. That said, each of these issues needs to be considered when assessing the costs and benefits of nuclear power.

One concerning aspect of using nuclear power is the possibility of catastrophic accidents. As etched into the public consciousness by the accidents at Chernobyl and Three Mile Island, it is possible for nuclear generating stations to go from billion dollar assets to major liabilities in minutes. The reality of this danger is underscored by the liability guarantees extended to nuclear firms in Canada and the United States. In Canada, the Nuclear Liability Act requires that nuclear generators purchase insurance for damages up to seventy-five million dollars. The responsibility to pay claims exceeding seventy-five million dollars then rests with the federal government. There is no legal limit on the size of such claims. Suppliers of equipment for nuclear power generation are exempt from liability in the event of an accident. Given the possibility that a nuclear accident could cause far more than seventy-five million dollars in damages, significant financial risk is being transferred from private operators to taxpayers. In the United States, the Price-Anderson Nuclear Industries Indemnity Act limits the liability of private operators to ten billion, beyond which responsibility transfers to the federal government. Private firms are apparently unwilling to tolerate the full potential costs involved in an accident at their facilities, and the willingness of national governments to accept the transfer of risk must be seen as a significant implicit subsidy to the industry. The political risks associated with an accident are also substantial. A major shift towards new nuclear construction could be derailed in response to a major accident somewhere in the world. Wherever the probable rate of failure is non-zero and wherever some possible failure outcomes are catastrophic, the danger of such an outcome will continue to haunt the nuclear industry.

As with the extraction and processing of fossil fuels, the front end of the nuclear fuel cycle involves significant environmental impacts, including the toxic products of mining and the greenhouse gas emissions associated with exploration, mining, milling, enrichment, and transport. Many sites around the world have become seriously contaminated as the result of nuclear materials being handled there. The Hanford Site, used in the early period of nuclear technology in the United States, is probably the most contaminated site in the entire country, with millions of gallons of high-level waste present and large but uncertain associated future cleanup costs. While higher standards now exist in developed states, radioactive contamination of land and water must continue be borne in mind as costs associated with the use of nuclear energy. So too must the energy costs associated with fuel processing be counted against the total energy output of the nuclear industry. That is particularly important in circumstances where high-carbon power sources are used to power extraction and enrichment equipment. While the enrichment of fuel certainly generates net energy, energy use associated with producing uranium fuel can diminish the low-carbon qualifications of nuclear power.[17]

At present, the great majority of nuclear waste from commercial reactors is stored in either cooling ponds or dry storage casks. From both an environmental and a public support standpoint, the generation of nuclear waste is one of the largest drawbacks of nuclear fission as a power source. Just as the emission of greenhouse gasses threatens future generations with harmful ecological outcomes, the production of nuclear wastes at all stages in the fuel cycle presents risks to those alive in the present and to those who will be alive in the future, across a span of time not generally considered by human beings. Wastes like Plutonium-239 remain highly dangerous for tens of millennia: a span roughly equivalent to the total historical record of human civilizations.[18] Furthermore, while most states using nuclear power have declared an intention of creating geological repositories for wastes, no state has such a facility in operation.[19] The decades-long story of the planned Yucca Mountain repository in the United States demonstrates some of the practical, political, and legal challenges to establishing such facilities in democratic societies. Dry cask storage is not an acceptable long-term option, as suggested by its Canada Nuclear Safety Commission categorization as 'a short-term management technique.'[20] When dealing with wastes dangerous for millennia, it cannot be assumed that regular maintenance and inspection will continue. Storage systems must be 'passively safe': able to contain the wastes they store for the full duration of their dangerous lives, without the need for active intervention from human beings. To date, no such facilities exist. Their successful development and commercial operation is a pre-requisite of the responsible expanded use of nuclear power. In an ideal world, passively safe storage facilities for waste would be established before, not after, the reactors that will eventually fill them.

Nuclear power has also been widely criticized for receiving high levels of governmental subsidies, both implicit (as with liability legislation) and explicit (as with direct support for new facilities). Estimates of the total subsidies provided to the nuclear industry in the United States alone range up to one-hundred billion dollars, though the early conflation of nuclear energy and nuclear weapons programmes makes precise estimation challenging.[21] This leads to two major questions: firstly, why is it that the nuclear industry has been in subsidized operation for over fifty years but has not yet overcome the need for public support? Secondly, what proportion of the costs associated with new facilities will actually be borne by taxpayers, rather than the firms hoping to profit from them? The purpose of government subsidy is to correct for externalities in the market – situations where individually rational profit-maximizing actors will not make socially optimal choices. Given the negative externalities associated with nuclear power (waste, risks, etc.), justification for ongoing subsidy requires very strong evidence that nuclear energy produces substantially fewer externalities than alternatives, and that the absence of subsidy would lead to outcomes that are more adverse to a degree larger than the cost of the subsidies themselves. The effective comparison of costs per unit of energy between nuclear power and other options requires a clearer understanding of all the subsidies and externalities involved with each.[22]

Nuclear proliferation is a major geopolitical concern in several regions. States with hostile neighbours watch nervously whenever nuclear facilities of any kind are constructed. Furthermore, there can never be a complete separation between equipment, personnel, materials, and knowledge used for civilian nuclear power generation and the same things used for weapons development. All else being equal, a state in possession of reactors, fuel, and scientists will be able to produce an atomic bomb significantly more easily than one lacking these ingredients; this is especially true given the consensus that the most difficult aspect of acquiring a crude but functional fission device is the acquisition of bomb-grade uranium or plutonium. States that have either developed or sought to develop nuclear weapons using expertise (and possibly materials or equipment) diverted from civilian programs include Israel, South Africa, Pakistan, North Korea, Iraq, and possibly Iran. While the construction of new nuclear reactors in states that already have nuclear weapons probably does not contribute to proliferation risks, their more widespread dissemination in states with few or no bombs may well encourage regional rivals to consider moving towards nuclearization. The more volatile a particular region becomes – and the more acute the security concerns different states develop about one another become – the more likely various actors will seek to convert civilian into military nuclear capability.

One somewhat less obvious consequence that arises from the military connections of nuclear power is the degree to which secrecy impedes public scrutiny above and beyond the opacity of the figures available for other industries. Given that nuclear operators will always be presented with serious questions of security – as will the governments that license them – the nuclear industry has a unique opportunity to evade public and journalistic scrutiny through the assertion that secrets must be kept for security purposes. In Israel, for example, publicly available information about the storage of radioactive wastes is extremely limited. Such limitations frustrate attempts to discover the actual fiscal and environmental costs associated with the nuclear industry. This, along with the unwillingness of governments to provide too much public information on an issue as controversial and unpopular as nuclear energy, reduces the depth and meaningfulness of debates about nuclear energy. This makes it especially challenging to answer questions about the total levels of subsidy directed to the nuclear industry, as well as to determine what proportion of those subsidies supported civilian electricity generation technologies and facilities.

One of the most probable and worrisome consequences of climate change is changes in regional water availability. Decreased water quantity and increased temperature both pose challenges for nuclear facilities, since they use very large quantities of water for cooling.[23] The IPCC projects that future precipitation is likely to be more sporadic, increasing in total quantity in high-latitude regions while subtropical zones dry out. Loss of winter snowpack leads to diminished summer river flow, while changes in precipitation patterns and evaporation will likewise alter the quantity and timing of water availability in different regions. Areas that have not faced significant water stress in the past may find themselves doing so, while areas that had previously faced moderate stress might find themselves in extreme conditions. Already, there are precedents of nuclear power plants that needed to be shut down due to high ambient water temperatures or low water flow. For example, in summer 2007, the generating station at Browns Ferry, Alabama had to be shut down because cooling water from the Tennessee River was too hot to use.[24] Particularly in areas like the Southern United States and Australia, uncertainty about future water availability could constrain the additional deployment of nuclear stations. Deployment in spite of such concerns could lead to additional shutdowns of the kind already seen, depriving the grid of power and the plants of usefulness.

At any point in time, the world's economically accessible supply of uranium depends upon several factors: the extent and quality of known reserves; available extraction and processing technologies; and the market price of uranium. In the medium-term, the last of these is arguably the most important, since higher costs should spur exploration and technological development. That said, it is possible that future supplies of uranium will prove insufficient to maintain low prices in the absence of commercial breeding of nuclear fuel; this is particularly true in the event that large amounts of new nuclear capacity is constructed. While nuclear supporters argue that future fuel constraints will be eliminated through technological advances, it is not currently clear whether such technologies will ever be viable and, if they are viable, when they will be available, at what cost, and with what level of government support. However, fuel costs are a comparatively small fraction of the total expense of building and operating nuclear plants. As such, the economics of doing so successfully is less dependent on fuel prices than for fossil-fuel fired thermal plants.

Enumerating the points against nuclear power does not, however, resolve the question of how to address climate change and energy security concerns. One prominent opponent of nuclear energy is the British journalist George Monbiot. Arguably, however, the approach he describes in his thought-provoking book *Heat: How to Stop the Planet from Burning* demonstrates the great difficulty of achieving climate change goals while discontinuing the use of nuclear power.[25] If restrictions as harsh as those he describes are necessary to achieve energy security and a stable climate, without using nuclear energy, the support of governments and private citizens for such an approach may be weak. While his plan also includes far more aggressive total emission reduction targets than have been seriously considered by any state thus far, the difficulty of reaching them and the extent of lifestyle changes required to meet them are partly indicative of extra cuts required elsewhere by virtue of foregoing nuclear.[26] Arguably, nuclear power could also provide a kind of safety net, in the event that other kinds of emission reductions do not emerge as rapidly or forcefully as expected. Of course, this would require that these other measures are implemented just as energetically alongside nuclear construction as they would have been in its absence.

The Positive Case Against Nuclear

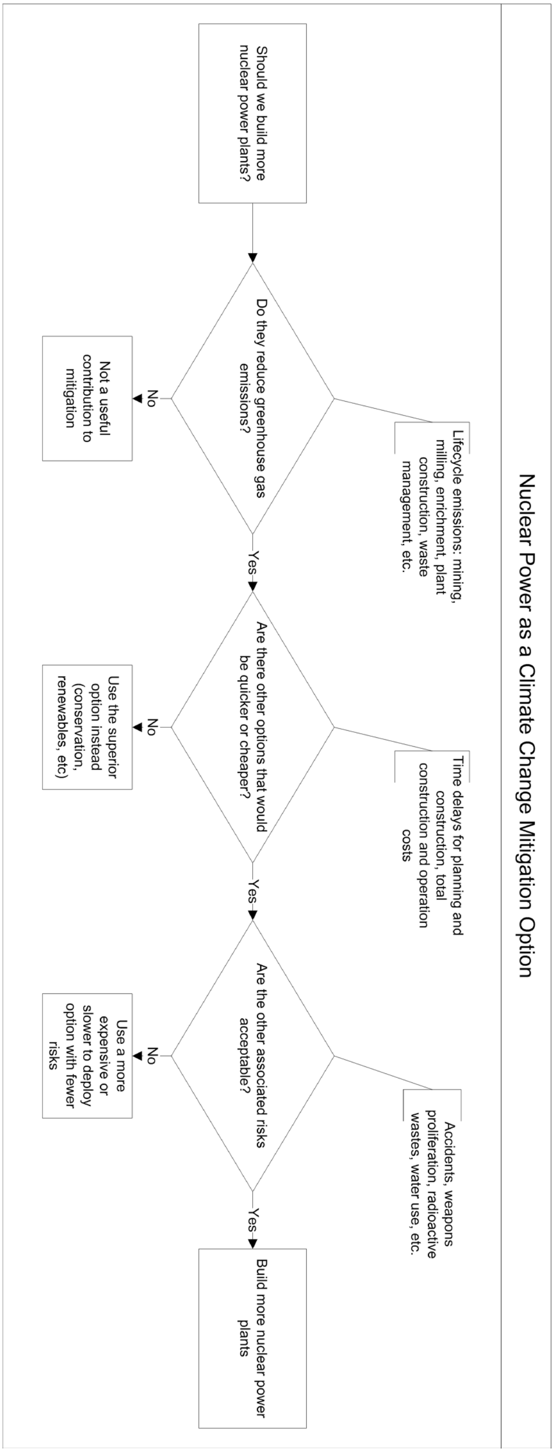
There are those who argue emphatically that the goals sought by nuclear advocates can be achieved more rapidly and at a lower cost through other means. Conservation can reduce total energy usage, efficiency can be improved, and funds that would have been used to subsidize nuclear power can be directed toward more rapidly-deployable renewable generating options such as wind and concentrating solar power. A prominent advocate of this view is Joseph Romm, whose analysis of carbon capture and storage (CCS) is mentioned above. He argues that not only can renewable sources of energy be used to mitigate climate change and bolster energy security, but that they can do this in ways that fundamentally and beneficially alter the energy basis of the world economy.

The falling price per watt of solar capacity suggests that renewable power could become cost-competitive with traditional generation options in the near-to-medium term, even when externalities like greenhouse gas emissions are not considered. According to *The Economist*, the price of solar cells has fallen from nearly twenty dollars per watt during the early 1980s to under five-dollars per watt in 2005.[27] Organizations including Google's RE < C initiative are seeking explicitly to produce renewable generation options that are economically as well as environmentally superior to coal power.[28] So long as one of the most major objections to renewable power is the high capital costs, the extended and ongoing trends towards commercial viability are evidence that renewable power can rise to the challenge, potentially while receiving far less substantial subsidies than the nuclear and fossil fuel industries. States that implement carbon pricing policies, thus internalizing the climatic externalities associated with fossil fuel use, will further improve the relative economic appeal of renewable power, while generating more socially optimal outcomes (since externalities previously imposed upon powerless third parties will be constrained).

The arguably more transparent economics of renewables is a significant advantage over nuclear, at least from the perspective of those evaluating the two options. While there have certainly been subsidies granted for the development and deployment of renewable generation technologies, these are relatively transparent and well quantified. Because of secondary impacts and risks, the subsidies for renewables can be considered more justified than those granted to the nuclear industry. Whereas nuclear power plants produce significant externalities in the form of waste and accident risk, neither is a significant factor in relation to renewables. Of course, other issues exist with renewable options, such as land use, harm to birds and bats, and the disruption of river flow by dams. The use of renewables for electricity generation does have a stronger claim to 'infant industry' status than nuclear power, which is no newcomer to the business of large-scale electrical generation. Electricity has been commercially generated using nuclear fission since 1956. Nuclear fission also provides eleven per cent of Canada's electricity, nineteen per cent in the United Kingdom, thirty per cent in Japan, and eighty-eight per cent in France. It is neither a newcomer nor a small player, unlike many renewable options, such as wave, tidal, and ocean thermal power systems.

Arguably, renewable technologies have the capacity to be more rapidly deployed than nuclear technologies. Whereas a small number of firms have the heavy manufacturing equipment and expertise required to build nuclear reactors, the technology and capital required to produce various types of renewable power systems is more widely distributed. Whereas nuclear generating stations are massive, capital intensive, and slow to construct, renewable generation options have the potential to be more nimble and responsive to local conditions. This may prove especially advantageous in rapidly developing states like India and China. Renewable sources of energy also have the potential to form the backbone of a genuinely sustainable society: that is, one that would be capable of perpetuating itself indefinitely, given the limitations imposed by the finite nature of the planet.

Whereas nuclear plants would basically serve the same role as coal plants in the grid – single, large producers – renewable generation op-



Nuclear Power as a Climate Change Mitigation Option tions have a varying level of output. Indeed, balancing the variable input from renewables would require far more energy storage and integrated energy transmission capacity than a nuclear-based alternative. The potential of renewables to provide the equivalent of baseload electrical capacity is therefore coupled with the development of a more efficient and intelligent electrical grid. Using high voltage direct current (HVDC) power lines makes it feasible to transport electricity long distances: connecting solar facilities in the American southwest to major cities, or others in North Africa to Europe. The more effective integration of electrical grids holds the promise of more closely equalizing energy prices: removing price differentials and situations where electricity is used wastefully in areas rich in generating capacity but poor in export capacity. An enhanced grid would also allow for more effective load balancing. Wind and solar power plants with outputs that peak at different times could be integrated to smooth output. They could also be combined with renewable options like hydroelectric and biomass plants capable of altering their output in real time. This approach – already being implemented in Germany's pilot Kombikraftwerk project – could lead to a grid where most capacity comes from renewables, with energy storage systems and perhaps some hydrocarbon-powered 'peaker' plants to deal with demand surges.

Demand management could also enhance the relative appeal of renewable sources of power. For instance, the transition towards a large number of electric battery vehicles operating in urban environments could create an enormous new reserve pool of energy. At times when renewable output exceeded demand, vehicles could be selectively charged. Likewise, at times when demand exceeded production, vehicle batteries could be partially drained to compensate. A smart electrical grid capable of managing such operations could also time and scale the operation of heating and cooling, energy intensive industrial processes, and other sources of demand so as to shift energy consumption from times of peak usage to those of peak availability. A renewably-backed smart grid could also improve efficiency in some areas through decentralization.

A transition to an electricity generation system based on renewable sources would both facilitate and require the development of significant new capacity in energy storage and transmission. While these would not be required in a scenario where coal and gas generation are simply supplanted by nuclear, their development may nonetheless be justified by the avoidance of many of the problems associated with nuclear fission, as well as the new opportunities a more flexible and distributed electricity generation system could provide.

Compelling arguments exist in favour of nuclear power, as well as against it and in favour of alternative options. The challenge presented to those wishing to select the best option is to weigh these arguments against one another, under conditions of uncertainty about what some key elements of the situation in the future will be. A number of possible outcomes could arise from the nuclear debate and subsequent choices. It is not clear at this point whether nuclear power or renewables would actually be the more expensive option in the long term. It is unlikely that a clear-cut answer to this question is possible, given the different weightings that could be given to factors like land and water use, the risk of accidents, and so on. Furthermore, given the path dependencies involved, it may not beg knowable after the fact either. Regardless of which option is actually more costly, a number of possible outcomes could arise from the policy debate about nuclear energy and renewables:

- The expensive option is chosen and it works - achieving the desired outcomes for climate change and energy security.
- The cheaper option is chosen and it works.
- The cheaper option is chosen and it fails to adequately reduce emissions or enhance energy security.
- The expensive option is chosen and it fails.

The possible negative outcomes are therefore either (a) having spent too much money to achieve an outcome or (b) having chosen an unsuccessful strategy. (a) is not entirely separate from (b), since costs will likely influence the rate of deployment. It is also theoretically possible to succeed in either climate change or energy security, but not both. For instance, a strategy could be adopted that eventually requires severe cuts in energy usage, because the technology to provide the energy in a low-carbon manner does not emerge viably.[29] Alternatively, the failure to produce effective low-carbon technologies may drive states towards the continued heavy use of climatically unacceptable options like coal for energy generation, and possibly even transport fuels. Another interpretation is to consider ‘try both approaches’ to be the expensive option and ‘choose one or the other’ to be the less costly alternative. In this scenario, the same tradeoffs apply, although there is a higher overall possibility of finding at least one viable option, as well as a higher overall possibility of wasting money on unsuccessful or unacceptable approaches. Compounding the problem of absent knowledge is the problem of impossible knowledge. When a major choice is made (implicitly or explicitly) about the direction to be taken, opportunities to learn about the outcomes of alternative choices are constrained. For instance, humanity might act aggressively to prevent dangerous climate change, achieve stabilization, and later doubt whether so aggressive an approach was actually required. Conversely, rejecting opportunities to create a low-carbon global economy might lead to very harmful climatic outcomes, but still leave uncertainty about whether any feasible action could have made a difference. Given the singular nature of the planet, genuine experimentation is impossible. As a result of that, and of the wide-reaching and potentially catastrophic character of climate change, policymakers must choose under conditions of considerable risk and uncertainty.

Perhaps the mechanism through which the best balance between risk management and cost optimization can be struck is a combination of experimentation and scrutiny. Differing political outcomes in various jurisdictions are likely to produce experiments of both kinds in the medium-term, with some states opting for a nuclear strategy and others seeking to achieve similar goals by other means.[30] The independent and rigorous evaluation of the costs, successes, and failures of each approach could provide invaluable guidance for the next round of decision-making. While security concerns must obviously be borne in mind, they must be addressed in a way that does not obscure the success or failure of new nuclear stations as commercial, civilian endeavours. By adopting both approaches, it may be possible to avoid prematurely closing off promising routes to emission reductions, while also not following blind alleys for too long. This is an approach that necessarily carries risks – most significantly, of wasting time in which a more effective strategy could have been deployed, as well as creating additional nuclear waste and proliferation problems. At the same time, it is arguably the approach that produces the best possibility of successfully shifting to a low-carbon society rapidly enough to avoid catastrophic climatic impacts. Given that no global coordination exists on energy choices, it seems inevitable that the experiment will be carried out. It will be incumbent upon those with the intention of tackling climate change to effectively assess the strength of arguments for and against nuclear energy on the basis of progressively accumulating data and experience. ■

Notes

[1] For example see Mark Lynas, 'Why greens must learn to love nuclear power,' *New Statesman*, September 18, 2008, http://www.newstatesman.com/environment/2008/09/nuclear-power-lynas-reactors (accessed December 31, 2008).

[2] The IPCC glossary defines external forcing as 'a forcing agent outside the climate system causing a change in the climate system. Volcanic eruptions, solar variations and anthropogenic changes in the composition of the atmosphere and land use change are external forcings.' Intergovernmental Panel on Climate Change, 'Glossary of Terms used in the IPCC Fourth Assessment Report,' http://www.ipcc.ch/glossary/index.htm (accessed January 5, 2009).

[3] Stephen Pacala and Robert Socolow, 'Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies,' *Science* 305:5686 (2004): 968-972. Available online at http://www.sciencemag.org/cgi/content/full/305/5686/968?ijkey=Y58LIjdWjMPsw&keytype=ref&siteid=sci (accessed December 31, 2008).

[4] Joseph Romm, *Hell and High Water: Global Warming - the Solution and the Politics and What We Should Do* (New York: William Morrow, 2007).

[5] Mark Winfield, Alison Jamison, Rich Wong and Paulina Czajkowski, 'Nuclear Power in Canada: An Examination of Risks, Impacts, and Sustainability,' December 2006, http://pubs.pembina.org/reports/Nuclear—web.pdf (accessed December 31, 2008).

[6] See International Atomic Energy Agency, 'Nuclear Energy Country Profiles: Canada,' http://www.nea.fr/html/general/profiles/canada.html (accessed September 11, 2008).

[7] Next generation reactor designs are intended to further increase both output and reliability. For a discussion of next generation design possibilities, see Declan Butler, 'Nuclear power's new dawn,' *Nature* 429 (2004): 238-240. Available online at http://www.nature.com/nature/journal/v429/n6989/full/429238a.html (accessed December 31, 2008).

[8] Experimental usage of thorium fuel has been undertaken in the Molten-Salt Reactor Experiment at the Oak Ridge National Laboratory in the United States. Though the project was discontinued in 1976, many sources identify thorium as a possible alternative fuel for nuclear fission reactors in a situation where uranium becomes scarce and expensive.

[9] For a discussion of the potential longevity of the Earth's uranium supplies, see David MacKay, 'Nuclear?', *Sustainable Energy – Without the Hot Air*, 2008. http://www.withouthotair.com (accessed December 31, 2008).

[10] See Mara Hvistendahl, 'Coal Ash Is More Radioactive than Nuclear Waste,' *Scientific American*, December 13, 2007. Available online at http://www.sciam.com/article.cfm?id=coal-ash-is-more-radioactive-than-nuclear-waste (accessed December 31, 2008).

[11] World Health Organization, 'Estimated deaths & DALYs attributable to selected environmental risk factors,' 2002, http://www.who.int/entity/quantifying—ehimpacts/countryprofilesebd.xls (accessed December 31, 2008). See also Mark Peplow, 'Counting the dead,' *Nature* 440 (2006): 982-983. Available online at http://www.nature.com/nature/journal/v440/n7087/full/440982a.html (accessed December 31, 2008).

[12] Intergovernmental Panel on Climate Change, 'Fourth Assessment Report: Climate Change 2007,' http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4—syr.pdf (accessed December 31, 2008).

[13] Malte Meinshausen, 'On the Risk of Overshooting 2°C,' Scientific Symposium 'Avoiding Dangerous Climate Change,' 2005, http://www.stabilisation2005.com/14—Malte—Meinshausen.pdf (accessed December 31, 2008).

[14] Weaver, *Keeping Our Cool: Canada in a Warming World* (London: Penguin Books, 2008), 250.

[15] Nicholas Stern, *The Economics of Climate Change: The Stern Review*, October 2006. http://www.hm-treasury.gov.uk/sternreview—index.htm (accessed December 31, 2008).

[16] Andrew Weaver, *Keeping Our Cool: Canada in a Warming World*, 208.

[17] See: Nate Hagens, 'The Energy Return of Nuclear Power,' *The Oil Drum*, April 22, 2008. http://www.theoildrum.com/node/3877 (accessed December 31, 2008).

[18] That said, Andrew Weaver and others have pointed out that the long-lived character of carbon dioxide in the atmosphere, combined with the lags in the climate system, make greenhouse gasses a comparable kind of long-term threat. See also Nature Reports Climate Change, 'Carbon is forever,' November 20, 2008, http://www.nature.com/climate/2008/0812/full/climate.2008.122.html (accessed December 31, 2008).

[19] Facilities for the storage of low-level wastes do exist, such as the Waste Isolation Pilot Plant in the United States. See Geoff Brumfiel, 'Nuclear waste: Chernobyl and the future: Forward planning,' *Nature* 440 (2006): 987-989. Available online at http://www.nature.com/nature/journal/v440/n7087/full/440987a.html (accessed January 2, 2008).

[20] Atomic Energy of Canada Limited, *The concept for disposal of Canada's nuclear fuel waste: proposed for long-term protection of human health and the natural environment* (Manitoba: AECL Research, 1994).

[21] Some argue that public support for the nuclear industry has not been out of line with support for other forms of electrical generation. For instance, in a 2008 report for The Nuclear Energy Institute, it was estimated that total subsidies to the American nuclear industry were $65 billion, when regulation, research and development,

government services, and disbursements were taken into account. The same document concludes that total subsidies to renewable sources were $45 billion exclusive of hydroelectric and geothermal power, and $132 billion with those included. See Management Information Services, Inc., 'Analysis of Federal Expenditures for Energy Development,' September 2008, http://www.nei.org/filefolder/Bezdek—Report.pdf (accessed December 31, 2008). For another discussion of subsidies, see Jim Giles, 'Nuclear power: Chernobyl and the future: when the price is right,' *Nature* 440 (2006): 984-986. Available online at http://www.nature.com/nature/journal/v440/n7087/full/440984a.html (accessed December 31, 2008).

[22] For a more detailed discussion of some of the economic issues associated with nuclear power, see 'The shape of things to come?', *The Economist*, July 7, 2005. Available online at http://www.economist.com/displaystory.cfm?story—id=4149623 (accessed December 31, 2008).

[23] The Palo Verde Nuclear Generating Station in the United States is the only nuclear power plant not located beside a large body of water used for cooling. Instead, it uses treated sewage from nearby residential areas to disperse surplus heat. For more information on potential water availability limitations for nuclear power plants, see Joseph Romm, 'The Self Limiting Future of Nuclear Power,' June 2008. http://www.americanprogressaction.org/issues/2008/pdf/nuclear—report.pdf (accessed December 31, 2008).

[24] Kent Faulk, 'Reactor shut down at Browns Ferry Nuclear Plant,' *The Birmingham News*, August 9, 2008. Available online at http://www.al.com/news/birminghamnews/index.ssf?/base/news/1218269761142400.xml&coll=2 (accessed December 31, 2008).

[25] George Monbiot, *Heat: How to Stop the Planet from Burning* (New York: Random House, 2006).

[26] Like many others, Monbiot also assumes that carbon capture and storage (CCS) will emerge as an effective and economically viable option. It remains to be seen whether CCS can be deployed as cheaply, effectively, and rapidly as proponents suggest.

[27] 'Another Silicon Valley?,' *The Economist*, June 19, 2008. Available online at http://www.economist.com/specialreports/displaystory.cfm?story—id=11565636 (accessed December 31, 2008).

[28] See 'Google's Goal: Renewable Energy Cheaper than Coal,' November 27, 2008. http://www.google.com/intl/en/press/pressrel/20071127—green.html (accessed December 31, 2008).

[29] For instance, if nuclear power is rejected but the land and materials for renewable generation do not prove to be sufficiently available to provide the level of electrical power that would sustain or expand current levels of global prosperity.

[30] Still others are likely to deploy carbon capture and storage in combination with fossil-fuel fired plants, allowing the evaluation of both optimistic and skeptic claims about the viability of that technology.