Published as Chapter 2.17 in *Comprehensive Renewable Energy*
edited by A. Sayigh. Vol 2, pp.541-568. Oxford, GB: Elsevier.

Wind Energy Policy

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Key Words: renewable energy, economics of wind energy, reducing carbon dioxide emissions, energy security

ABSTRACT

The role of renewable energy is examined within the context of global energy markets. As an alternative to fossil fuels in generating electricity, wind energy turns out to be the most viable of renewable energy options because of its lower costs. But there remain two obstacles to wider penetration of wind energy: (1) Without large subsidies or mandates, there is little incentive for private firms to invest in wind generating capacity, which results primarily from government programs. (2) Wind's intermittency militates against its use in lieu of coal or nuclear energy for base-load power generation. Overcoming these remains the challenge.

Author Biography

G. Cornelis van Kooten received his Ph.D. in Agricultural and Resource Economics from Oregon State University in 1982. He has been associate professor in the Department of Agricultural Economics at the University of Saskatchewan and the School of Management at Groningen University, Netherlands; professor in the Departments of Agricultural Economics and Forest Resources Management at the University of British Columbia; and professor and Chair of the Department of Applied Economics and Statistics at the University of Nevada. Currently, he is professor of Economics and the Canada Research Chair in Environmental Studies and Climate at the University of Victoria; and adjunct professor at Wageningen University and a Research Fellow at the Agricultural Economics Institute in The Hague, both in the Netherlands.

Dr. van Kooten has over 25 years experience with interests that range from agricultural and forest economics to development and computational economics and energy economics. He has published more than 170 peer-reviewed journal articles and more than 35 book chapters; he is the author or co-author of five books on land and forest economics, and co-editor of three books.

Dr. van Kooten has been a consultant to various governments and government agencies, the United Nations, the World Bank, and a variety of non-governmental organizations, including the International Fund for Animal Welfare and the WWF. His numerous graduate students have gone on to work in the private sector, academic institutions and government. More information can be found at http://www.vkooten.net.

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In an effort to get serious about climate change, the leaders of the largest eight countries (G8) meeting in L'Aquila, Italy, agreed on July 8, 2009 to limit the increase in global average temperature to no more than 2°C above pre-industrial levels. To attain this, they set "the goal of achieving at least a 50% reduction of global emissions by 2050, [with] ... developed countries reducing emissions of greenhouse gases in aggregate by 80% or more by 2050 compared to 1990 or more recent years."[1] The U.S. House of Representatives passed the *American Clean Energy and Security Act* (also known as the Waxman-Markey Bill) by a vote of 219 to 212 on June 26, 2009. The Act identifies certain large emitters of greenhouse gases and these emitters must reduce their aggregate CO_2 and equivalent emissions by 3% below 2005 levels in 2012, 17% below 2005 levels in 2020, 42% in 2030, and 83% in 2050. The Waxman-Markey initiative subsequently stalled in the Senate because of looming mid-term elections in November 2010. Nonetheless, the agenda for developing countries is quickly to de-carbonize their economies.

To achieve these targets, it is necessary radically to transform the fundamental driver of global economies – the energy system. The main obstacle is the abundance and ubiquity of fossil fuels, which can be expected to power the industrialized nations and the economies of aspiring industrial economies into the foreseeable future. Realistically, global fossil fuel use will continue to grow and remain the primary energy source for much of the next century (Bryce 2010; International Energy Agency 2009; Duderstadt et al. 2009; Smil 2003).

The extent to which this prognosis will change depends on factors that are impossible to predict in advance. These include primarily the willingness of countries to spend vast sums on programs to reduce reliance on fossil fuels – to forgo cheap fossil fuel energy that emits CO_2 for much more expensive non-carbon energy sources, such as wind, solar, hydro, wave and tidal power, and, of course, nuclear power. They depend on the ability of governments to convince their citizens to accept large increases in energy prices and thereby reduced standards of living. They depend on the prices of fossil fuels relative to other energy options, and on very iffy and uncertain technological breakthroughs. Economists cannot predict technical advances, nor can others, because they depend on the minds and resourcefulness of citizens, and on the educational, cultural and governance settings of society.

President Obama announced on various occasions that the United States would embark on new research programs that would enable America to retain its technological advantage over other countries, including a research and development program to de-

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[1] Paragraph 65, 'Responsible Leadership for a Sustainable Future' Declaration, G8 Summit, July 2009. Available at www.g8italia2009.it/static/G8.../G8_Declaration_08_07_09_final,0.pdf (viewed July 22, 2009).

carbonize the U.S. economy, especially the electricity sector.[2] The President is counting on spinoff benefits of the kind that have characterized the U.S. industrial-military complex for the past fifty years and perhaps longer if research related to World War II is taken into account. Government funded military and space research under the Defense Advanced Research Projects Agency (DARPA),[3] originally created in 1958 as the Advanced Research Projects Agency (ARPA) in response to the Russian launch of Sputnik, led to technologies – the internet, micro chips, food processing and fast-food technologies currently in use, spandex, cell phones, et cetera – that are now ubiquitous (Nowak 2010).

This impetus to rid the economy of fossil fuels might indeed change the playing field against fossil fuels. It is a 'put-a-man-on-the-moon' type of R&D program for finding a technological solution that will enable humankind to control the climate. In this Chapter, we address questions related to the role of wind power in achieving the desired objective of de-carbonizing the energy sector. In order to do so, however, we must briefly consider other energy options. Therefore, we begin our examination with a discussion of the global challenges facing the energy sector in converting global economies from a fossil fuel basis to a non-fossil fuel basis? What are the prospects and the potential costs? Will the new technologies and energy sources reduce the anthropogenic component of global warming?

The chapter is structured as follows. In the next section, we consider the link between energy and economic development, and examine production and trade of various energy resources. In section 2, the focus shifts to the important role of fossil fuels and nuclear energy. We argue that fossil fuels are likely to remain important throughout the 21st Century, although countries will move away from them to greatest extent possible because of the problem of associated CO_2 emissions. Part of this will lead to greater reliance on natural gas, which emits less CO_2 per unit of energy. Then, in section 3, we examine the case for renewable sources of energy besides wind. We argue that, while there is a role for all types of renewable energy, economic feasibility remains a major if not the obstacle. In this regard, wind likely offers the best prospects. Section 4 is devoted to the economics of wind energy, and we assume that wind will be used solely to generate electricity. Hence, we first discuss the economic structure of electricity grids, and how wind fits into the so-called merit order. Then we examine the costs that wind imposes on the rest of the grid as wind penetration rates increase. We provide some notion as to the potential costs of integrating wind into various generation mixes, both in terms of costs per kilowatt hour and costs per unit of CO_2 emissions saved. The chapter ends with some concluding observations.

1. Energy and the Economy

While good governance (low corruption, effective rule of law, etc.) is crucial to

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[2] See "Energy and Environment," White House, posted April 11, 2010 (http://www.whitehouse.gov/issues/energy-and-environment, viewed April 21, 2010).

[3] See http://www.darpa.mil/. "DARPA defines its mission as preventing technological surprise for the United States and to create technological surprise for adversaries" (DARPA: developing the wild, the wacky and wicked cool for 50 years, by M. Cooney at http://www.networkworld.com/community/node/24814, viewed April 20, 2010).

economic growth, economic development cannot occur without expanding energy use – rich countries are rich because they used and continue to use large amounts of energy to create wealth and satisfy consumption (Smil 2003). By 2030, global energy use is expected to increase by nearly 50% over what is was in 2005; this will require the equivalent of one new 1,000 megawatt (MW) power generating plant coming on stream every day for the next twenty years just to satisfy growth in electricity demand (Duderstadt et al. 2009, p.9). Likewise, the International Energy Agency (IEA 2010a) projects that, unless governments implement major policies to reduce carbon dioxide emissions, energy consumption will increase by 40% between 2007 and 2030, with three-quarters of this growth coming from fossil fuels. The 40% as opposed to 50% projection is the result of taking into account the impact of the 2008 financial crisis and subsequent recession in North America and Europe.

The majority of the growth in energy consumption will come in developing countries, especially China and India, which together account for about one-third of the world's population. In 2010, Chinese emissions of greenhouse gases surpassed those of the U.S., although per capita emissions remain glaringly lower. Attempts by rich countries to reign in economic growth in developing countries for the purpose of mitigating climate change are strongly resisted, as indicated by the failure to reach agreement on emissions reduction at the 15th Conference of the Parties (COP15) to the 1992 United Nations' Framework Convention on Climate Change (UNFCCC), which was held in Copenhagen in late 2009. Energy policies that lower rates of economic growth in developing countries will simply perpetuate the misery of millions of people who live in poverty. While clean and renewable energy sources can contribute to the energy needs of developing nations, economic growth will depend primarily on traditional sources of energy, such as coal, oil and natural gas, because they are relatively cheap and ubiquitous, and are a great improvement over heating with wood biomass, agricultural wastes, dung, et cetera, especially from a health standpoint. In this section, we consider global energy markets and trade in more detail so that we can better understand the challenges and limitations facing wind energy.

Global Energy Markets

Fossil fuels are the most important source of energy in the world. This is clear when we look at the sources of energy used in the global generation of electricity (Figure 1) and the world's final consumption of energy (Figure 2). Approximately two-thirds of electricity is produced from fossil fuels, while the remainder comes primarily from hydro and nuclear sources. Geothermal, biomass, solar, wind and other sources contribute a meager 2.6% of the energy required to produce electricity.

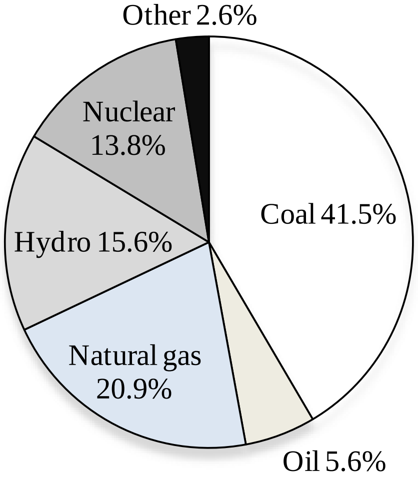

Figure 1: Global Electricity Production by Energy Source, 2007, Percent, Total = 19,771 TWh

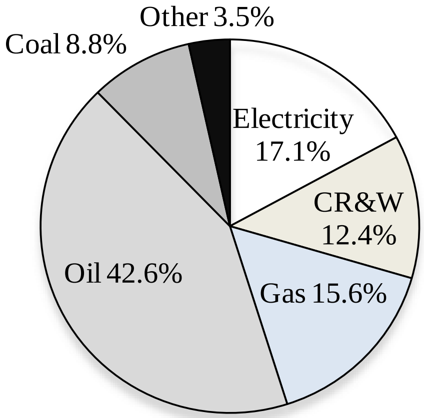

Figure 2: Global Energy Consumption by Source, 2007, Percent, Total = 8286 Mtoe[4]

To obtain some notion regarding which countries generate the most electricity and the importance of coal in the global electricity generating mix, consider Table 1. Nearly 20,000 terawatt hours (TWh), or 20 petawatt hours (PWh),[5] of electricity were generated in 2007, the latest year for which statistics are available from the International Energy Agency (IEA 2010a, 2010b). Notice that the U.S. and China are the largest producers of electricity and also the largest producers of coal-fired power. Other large industrial nations generate large amounts of electricity, with many relying on coal (Figure 1). Canada is the

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[4] CR&W refers to combustible renewables and wastes.

[5] A watt (W) equals 1 joule (J) per second. A kilowatt (kW) equals 1000 W; megawatt (MW) = 10^6 W; gigawatt (GW) = 10^9 W; terawatt (TW) = 10^{12} W; petawatt (PW) = 10^{15} W. Kilo is abbreviated with k and equals 10^3; Mega (M, 10^6); Giga (G, 10^9); Tera (T, 10^{12}).

sixth largest producer, but much of it comes from hydro sources and a significant amount (≈ 25 TWh annually) is exported to the U.S. Clearly, rich countries are rich because they consume large amounts of energy, especially electricity.

Oil dominates total global consumption of energy, primarily because it is used for transportation and, to a much lesser degree, generation of electricity – primarily in diesel generators in remote communities (as well as much of sub-Sahara Africa), although there are a few large generation facilities that rely on oil. The major producers, exporters and importers of crude oil are indicated in Table 2, as are the amounts involved. Although Canada is not indicated as a major exporter, because the data on exports are for 2007, it is expected to move up the table in the future because of large oil sands development. Notice that both the United States and China are major oil producers, but they are also major importers because of the size of their economies.

Table 1: Largest Electricity Producers, Total and by Selected Fossil Fuel Energy Source, 2007, TWh

TOTAL		Coal/Peat		Gas	
U.S.	4323	China	2656	U.S.	915
China	3279	U.S.	2118	Russia	487
Japan	1123	India	549	Japan	290
Russia	1013	Japan	311	Rest of World	2435
India	803	Germany	311	**Total**	**4127**
Canada	640	South Africa	247		
Germany	630	Australia	194	Oil	
Rest of World	7960	Korea	171	**Total**	**1114**
Total	**19,771**	Russia	170		
		Poland	148		
		Rest of World	1353		
		Total	**8228**		

Source: International Energy Agency (2010b)

Table 2: Major Global Producers, Exporters and Importers of Crude Oil, 2007/2008[a]

Producers	Mt	Net exporters	Mt	Net importers	Mt
Saudi Arabia	509	Saudi Arabia	339	U.S.	573
Russian	485	Russia	256	Japan	206
U.S.	300	Iran	130	China	159
Iran	214	Nigeria	112	India	122
China	190	UAE	105	Korea	118
Mexico	159	Norway	97	Germany	106
Canada	155	Mexico	89	Italy	94
Rest of the World	1829	Rest of the World	829	France	81
Total	**3841**			Spain	59
				Netherlands	58
				Rest of the World	515

[a] Production statistics for 2008; exports and imports for 2007.

Source: International Energy Agency (2010b)

Together fossil fuels (coal, oil and natural gas) account for about 78.5% of total global energy consumption if account is taken of electricity generated from fossil fuels (Figure 1). Upon including combustibles, renewables and waste (CR&W),[6] more than 90% of all energy used globally comes from sources that emit CO_2. Of the remainder, 5% comes from hydro and nuclear sources, leaving less than four percent from solar, geothermal, wind, tidal, and biofeedstock sources. Clearly, reducing reliance on fossil fuels in a big way presents a tremendous challenge for the renewable energy sector.

Fossil fuels are ubiquitous and cheap. Therefore, policies to replace them will likely require a combination of large subsidies (e.g., to producers of alternative fuels), regulations forcing firms and individuals to rely more on non-fossil fuel sources (such as renewable energy standards), publicly-funded R&D, and taxes or cap-and-trade schemes that drive up fossil fuel prices to the point where it makes economic sense for consumers to switch to alternative energy sources or adopt smaller more fuel-efficient vehicles and smaller houses. However, there are limits to the amounts governments will pay to subsidize development of non-carbon sources of energy and to citizens' willingness to accept huge increases in the price of energy when cheaper fossil fuel alternatives are available. As the French intellectual, Christian Gerondeau (2010), argues, it is unlikely that cheap fossil fuels

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[6] CR&W includes primarily wood biomass, crop residues, dung, et cetera, that are burned in stoves and used for space heating by those living in developing countries; this is a major source of black carbon (soot) that contributes to global warming. CR&W also includes wastes from sawmilling and pulp making for space heating and generation of electricity.

will go wanting – someone or some country will use them. But it is morally objectionable to raise energy costs when poor people already need to pay too much for energy (Prins et al. 2010).

One argument used to justify public spending on alternative energy is that the globe will run out of fossil fuels and that we need to prepare for that eventuality. For example, there are predictions that the world's oil production will soon attain 'Hubbert's peak' and begin to decline (Deffeyes 2003). Hubbert's peak is predicated on the notion that prices and technology remain unchanged, because it will shift outwards with improvements in technology and higher prices. Indeed, from an economic standpoint, the idea that we will run out of oil (or gas or coal) is simply nonsense. We will never run out of oil, gas or coal. As these resources become increasingly scarcer, supply and demand intersect at increasingly higher prices; the market will always clear – there is always enough of the resource to meet demand. However, the higher prices will, in turn, signal scarcity and thereby induce technological innovations that will increase supply, reduce demand and/or lead to new sources of energy. Reliance on wind energy will expand without government intervention if it is able to compete as an energy source as prices of fossil fuels rise.

Recent increases in the supply of oil have come from the Alberta oil sands and deep-water drilling.[7] As discussed in section 2 below, new natural gas drilling technologies have recently been developed in Texas, which enable gas to be extracted from various types of rocks, most notably shale. This has resulted in massive upgrades in reserves and a surfeit of gas. Shale is globally ubiquitous and the drilling methods developed in Texas can easily be repeated elsewhere. Indeed, recoverable reserves of shale or unconventional gas are now estimated to be about five times as large as recoverable conventional reserves of natural gas.[8] In terms of reducing CO_2 output, these developments position natural gas as the most likely alternative to coal for generating electricity because it releases much less CO_2 per heat unit than coal.

At the same time, there have been advances in transportation and other technologies that reduce the amounts of energy to produce the same levels of economic services. Vehicles can travel farther on the same amount of fuel, new public transportation infrastructure has been built to reduce demand for fuel, and hybrid and electric vehicles are being brought to market.[9] Costs of space heating have fallen as buildings have become

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[7] Deep-water drilling will continue despite the massive oil spill resulting from the British Petroleum disaster in the Gulf of Mexico in 2010. If drilling is prevented in the U.S., this does not mean it will not be pursued by other countries. In Alberta, environmental concerns related to oil sands development are increasingly addressed by new investments in technology and methods for restoring the environment.

[8] See (viewed July 15, 2010) http://www.dawn.com/wps/wcm/connect/dawn-content-library/dawn/the-newspaper/letters-to-the-editor/breakthrough-in-gas-technology-240.

[9] Automobiles in the United States require an average of 10 liters to drive 100 km, with those in Germany only slightly lower. Automobiles now coming onto the French market have a fuel economy of 5 liters per 100 km, despite relying on internal combustion engines, while economy might get down to 3 liters/100km as a result of better engines, lighter vehicles, etc. (Gerondeau 2010, pp.100-106).

‘greener.’

Costs of producing electricity from alternative wind and solar sources have fallen dramatically as well, while new geothermal, tidal, wave and other renewable energy technologies are in various stages of development. Advances in nuclear power generation technology and experience also continue, particularly with regards to performance and safety (Ansolabehere et al. 2003; Deutch et al. 2009). However, most of the renewable portfolio standards (RPS) programs implemented by many countries to address concerns about climate change tend to exclude important low-carbon technologies, particularly the substitution of natural gas for coal and greater reliance on nuclear energy. In essence, the objective of reducing carbon emissions is confused with encouraging renewable energy in electricity generation (Deutch et al. 2009, p.9).

What has driven these developments? First and foremost, market signals have played an important role. In real terms, oil prices reached an all time high in 1980, peaking again in 2008, but at a slightly lower level; natural gas prices peaked in 2005 and again in 2008, but at a slightly lower level the second time, before plunging as a result of recession and new developments in drilling technology. While oil and gas prices are historically above their levels in the period before the first ‘oil crisis’ in 1973, which was brought on by the exercise of monopoly power on the part of the Organization of Petroleum Exporting Countries (OPEC) followed by price controls that reduced incentives for bringing new sources of petroleum to market, they have exhibited more erratic movement since then (Figure 3).[10] More recently, environmental concerns and political factors (much like price controls) have prevented the expansion of drilling activities, while economic growth in developing countries, primarily China, has expanded demand, together resulting in higher real prices of oil. The same was true for natural gas, although rates of increase in natural gas prices are now limited as a result of the new reserves. Anticipation of continued higher oil prices in the future has spurred on technological changes, greater conservation and a switch to alternative fuels, including natural gas. The other incentive has been government policies, particularly subsidies.

Renewable Energy Policy

Various countries are hoping to wean their economies off fossil fuels and thereby reduce CO_2 emissions. These countries have established renewable energy targets (renewable portfolio standards) and are in the process of implementing policies to meet targets – subsidizing the production of electricity from renewable sources or production of biofuels for transportation, or mandating levels of renewable energy so they can pass costs on to consumers. For example, a jurisdiction can require renewable standards for gasoline and diesel fuel, which will ensure that 20% or 40% (or some other proportion) of the fuel sold at the pump consists of biofuels. Electrical system operators may be required to purchase some minimum proportion of their power from renewable generating sources, or a country may mandate that a minimum proportion of the generating capacity of a

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[10] In Figure 3, oil prices are from (viewed July 15, 2010) http://inflationdata.com/inflation/inflation_rate/historical_oil_prices_table.asp; gas prices from http://www.eia.doe.gov/oil_gas/natural_gas/data_publications/natural_gas_monthly/ngm.html.

particular electricity system must come from renewable sources.

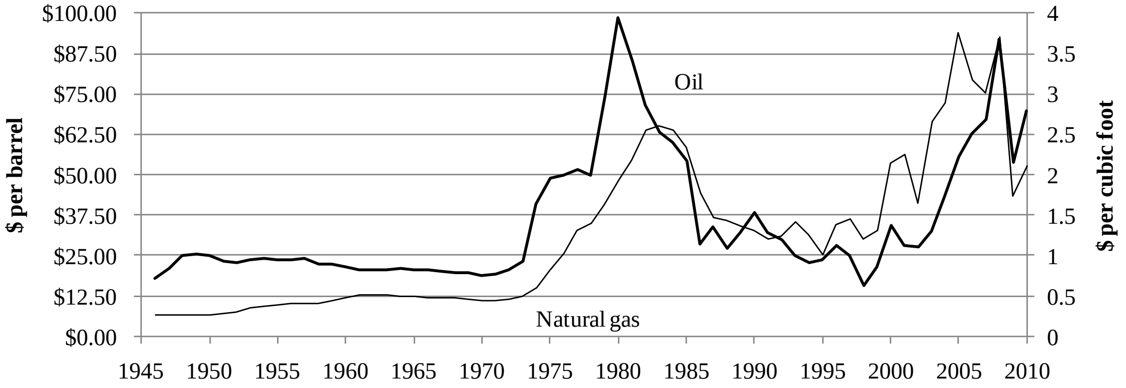

Figure 3: Inflation-adjusted U.S. Oil and Natural Gas Prices, 1946-2010

Scrambling to reduce CO_2 emissions: The renewable target game

Many jurisdictions have now passed laws requiring that renewable targets be met. Countries comprising the European Union have agreed that 20% of total energy will be derived from renewable energy sources by 2020, although only some 7% of energy was derived from renewable sources in 2009. To meet these targets, many countries will rely primarily on wind and energy from biomass. However, a wood deficit of 200 to 260 million m^3 is consequently forecast for the EU by 2020, while, globally, an ECE/FAO report estimates that there will be a wood deficit of 320 to 450 million m^3 annually simply to satisfy planned demand for wood for energy plus a growing wood-based industry.[11] This will certainly cause global wood fiber prices to increase, resulting in potentially detrimental changes in land use. The EU is also targeting vehicular use of renewables. By 2020, ten percent of the fuel used for transportation is to come from biofuels.

As an EU member, the United Kingdom's climate change mitigation plan also requires an increase in the share of renewable energy to 20% by 2020 (although 15% was originally targeted) from approximately 1% in 2006. The target requires that 35% of electricity generated in the UK is to be from renewable sources by 2020, compared to about 5% in 2007. Germany, on the other hand, has more ambitious climate goals than other EU members – a 40% reduction in greenhouse gas emissions from 1990 levels by 2020 (double the EU target). In addition, it aims to have 30% of its electricity generated from renewable sources by 2020, compared with 15.6% in 2009.[12] The latter target will be difficult to attain given that an earlier government had determined to cease nuclear power generation, which accounted for 22.6% of consumption in 2009, by 2022. Environmentalists will make it difficult to extend this deadline.

The United States has yet to pass comprehensive climate change legislation as noted

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[11] Results reported by Don Roberts, CIBC, in presentations given in early 2010.

[12] See *The Economist*, September 4, 2010, pp. 53-54.

in the introduction, but its farm legislation requires the production of 36 billion gallons of renewable fuels by 2022, including 21 billion gallons of 'advanced' (non-corn starch) biofuels. Some 50 Mt of wood is to be converted to fuel by 2012, with a targeted 70-100 Mt by 2020; the Biomass Crop Assistance Program (announced June 8, 2009) will provide subsidy of $45 per tonne. This has the potential to result in an annual subsidy of $4.5 billion by 2020.

The Kerry-Lieberman-Graham bill promoted by the Obama administration in early 2010 seeks to cut greenhouse gas emissions by 17% from 2005 levels by 2020 and by 80% from 2005 levels by 2050.[13] Subsequent concerns about mid-term elections caused the Senate majority leader, Mr Harry Reid, to drop the bill because the public correctly viewed the cap-and-trade provisions in the bill as the equivalent of a tax. Nonetheless, Democratic Senator Jeff Bingham subsequently introduced a bill (S.3813) to create a national 'Renewable Electricity Standard' (RES).[14] It requires that, by 2021, 15% of the electricity sold by an electric utility be generated from wind or certain 'other' renewable energy sources (presumably solar, wave, geothermal or tidal, and not hydro), although up to four of the 15 percent points could be achieved by 'tightly-defined' actions that improve energy efficiency. Clearly, wind is the renewable energy source of choice.

Even China hopes to produce 10% of all its energy needs from renewables by 2010, with a target of 15% by 2020. Most of this will come from farm biomass and forest plantations. However, it will be a logistical challenge annually to transport 150,000-200,000 tons of bulky straw from thousands of 0.15 ha farms to fuel a large number of 25 MW capacity power plants. The target of planting 13.3 million ha of forests for bio-feedstock will be accomplished with help from rich countries through the Clean Development Mechanism (CDM). In effect, these efforts could be counted twice – they enable China to meet its renewable energy targets, while making it possible for developed countries that purchase CDM offset credits to achieve their targets as well (at least until changes are made to the system of crediting offsets).

Other countries have their own targets. Like the U.S., Canada is in the process of increasing biofuel production, but it also has a target to eliminate all coal-fired power generation by 2020. Both targets will be extremely difficult to meet, requiring large subsidies that will see electricity prices rise, greater reliance on natural gas, and, most likely, expansion of nuclear generating capacity. Consider the case of Ontario as an example of the direction policy has taken in efforts to increase generation of electricity from renewable energy sources.

Feed-in Tariffs: The Case of Ontario

Because electricity grids have their own peculiar dynamics (discussed in section 4), feed-in tariffs tend to be preferred over mandated levels of renewable use. One of the most

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[13] Information based on an editorial in *The Washington Times*, April 27, 2010, entitled "Meltdown of the climate-change bill." Senator Graham subsequently dropped his sponsorship of the bill out of concerns regarding re-election.

[14] http://www.masterresource.org/2010/10/bingamans-national-res/ (viewed October 11, 2010).

ambitious attempts to affect power generation from renewable sources was launched by the Ontario government when it passed the *Green Energy and Green Economy Act* on May 14, 2009. Its feed-in tariff (FIT) schedule is provided in Table 3. With the exception of solar power, Ontario's feed-in tariffs are indexed to inflation, which could dramatically increase the strain on the treasury.

The potential size of the subsidies can be determined from information about electricity rates. Ontario has implemented time-of-use billing to shift load from peak to off peak times, but it cost over $1 billion to install smart meters. Residential customers with smart meters pay 9.9¢ per kWh at peak times (7:00AM to 11:00AM, 5:00PM to 9:00PM), 8.0¢/kWh during mid-peak periods (11:00AM to 5:00PM) and 5.3¢/kWh during off-peak times (9:00PM to 7:00AM). Customers without smart meters pay 6.5¢/kWh for the first 600 kWh (in summer the first 1000 kWh) and 7.5¢/kWh thereafter.

Ontario's average electrical load was some 16,000 megawatts (MW) during 2007, although it has fallen somewhat since then as a result of the financial crisis, which caused some major demanders of power to shut down. Coal and gas generating capacities are both about 4000 MW; nuclear generating capacity amounts to some 10,000 MW, while hydro capacity is nearly 6000 MW. To provide some indication of the costs and benefits of Ontario's FIT program, assume that only 30% of the load is satisfied by fossil fuels, or 4800 MW per hour, and the objective is to eliminate that production. Further, assume that, despite the capacities of coal and natural gas generation, coal-generated power accounts for half or more of fossil fuel generated power. Finally, assume that biomass and wind generated power substitute for fossil fuel power – biomass accounts for either half or one-quarter of the required substitute power with on-shore and off-shore wind accounting two-thirds and one-third, respectively, of the remainder.

Approximately 7500 kWh of energy are generated per tonne of coal burned and 2.735 tonnes of CO_2 are released. Thus, it takes about 320 tonnes of coal to burn half of the 4800 MW of electricity supplied by coal-fired generation each hour, releasing 875 tCO_2 each hour or 7.665 Gt CO_2 per year. At the same time, natural gas plants will release 495.8 tCO_2 each hour or 4.346 Gt of CO_2 annually if they generate 2400 MW of electricity each hour.[15]

The costs to the government of the FIT program depend on the extent to which various renewables substitute for fossil fuel generation and the average amount that final consumers pay for electricity. In Table 4, it is assumed that consumers pay an average of 8.5¢/kWh. Using various biomass and wind combinations and fossil fuel displacement scenarios, and FIT data from Table 3, we can calculate carbon fluxes and costs to the public treasury of reducing CO_2 emissions. Results provided in Table 4 suggest that costs to the treasury could amount to $2.4-$2.6 billion annually, which will put a severe strain on the provincial treasury. In essence, by substituting fossil fuel energy with renewable sources in the generation of electricity, Ontario will pay a subsidy ranging from some $45 per tCO_2 to well over $1000/$tCO_2$, depending primarily on the extent of biomass generation.

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[15] From http://bioenergy.ornl.gov/papers/misc/energy_conv.html (viewed April 26, 2010), coal releases 25.4 metric tons of carbon per terajoule (TJ) compared to 14.4 for natural gas.

Table 3: Ontario Power Authority's Feed-in Tariff (FIT) Program for Renewable Energy Projects, Base Date: September 30, 2009

Renewable type	Size (capacity of generating plant)[b]	Contract price (¢/kWh)	Percentage escalated[a]
Biomass			
	≤ 10 MW	13.8	20%
	> 10 MW	13.0	20%
Landfill gas			
	≤ 10 MW	11.1	20%
	> 10 MW	10.3	20%
Biogas			
on-farm	≤ 100 kW	19.5	20%
on-farm	> 100 kW, ≤ 250 kW	18.5	20%
Biogas	≤ 500 kW	16.0	20%
Biogas	> 500 kW, ≤ 10 MW	14.7	20%
Biogas	> 10 MW	12.2	20%
Wind			
on-shore	Any size	13.5	20%
off-shore	Any size	19.0	20%
Solar			
roof/ground	≤ 10 kW	80.2	0%
roof top	> 10 kW, ≤ 250 kW	71.3	0%
roof top	> 250 kW, ≤ 500 kW	63.5	0%
roof top	> 500 kW	53.9	0%
ground mount	> 10 kW, ≤ 10 MW	44.3	0%
Water power[a]			
	≤ 10 MW	13.1	20%
	> 10 MW, ≤ 50 MW	12.2	20%

Notes:

[a] Performance factor: 1.35 peak, 0.90 off peak.

[b] Generally a 20-year contract with 2-3 year lead time; for hydro, 40 year contracts

[c] Indexed by the Ontario CPI

Source: (viewed April 21, 2010)
http://fit.powerauthority.on.ca/Storage/99/10863_FIT_Pricing_Schedule_for_website.pdf

Table 4: The Costs and Benefits of Ontario's Feed-In Tariff Program: Hourly CO_2 Flux and Cost of Reducing CO_2 Emissions, Various Scenarios

	Biomass 50%; Wind 50%			Biomass 25%; Wind 75%		
Coal : NG ratio →	1 : 0	¾ : ¼	½ : ½	1 : 0	¾ : ¼	½ : ½
CO_2 flux	tCO$_2$					
Coal saving	1749.2	1311.9	874.6	1749.2	1311.9	874.6
NG saving	0	247.9	495.8	0	247.9	495.8
Sequestered[a]	665.8	665.8	665.8	332.9	332.9	332.9
Biomass emission	2058.2	2058.2	2058.2	1029.1	1029.1	1029.1
Net flux	*356.9*	*167.5*	*-21.9*	*1053*	*863.7*	*674.3*
	US dollars					
Subsidy	$272,000	$272,000	$272,000	$300,000	$300,000	$300,000
Subsidy per tCO$_2$	$762.19	$1624.05	n.a.	$284.89	$347.36	$44.92

Notes:

[a] Carbon sequestered in tree growth over 25 years using growth function (9.1), including all above ground biomass with carbon discounted at 2%.

n.a. indicates not applicable because eliminating fossil fuel generation results in a net release of CO_2 – there is no climate change benefit whatsoever in this scenario.

Two points are worth mentioning. First, there exist much cheaper ways to reduce CO_2 emissions, including purchase of certified emission reduction credits on carbon markets. As of mid-September 2010, prices on the Chicago Climate Exchange had not exceeded $0.15 per tCO$_2$ since the January, 2010, while the spot market price of certified emission reduction credits did not exceed €14/tCO$_2$ (approximately US$16-$19/tCO$_2$) during 2009 and 2010. Second, the analysis in Table 4 is crude, focuses only on the costs to the public treasury and excludes any other costs, some of which can be quite high.

What then are the options being considered by various jurisdictions for reducing carbon dioxide emissions in the generation of electricity? These range from continued reliance on fossil fuels, but then in ways that reduce emissions, to greater reliance on nuclear and a variety of renewable energy alternatives. We consider first options related to coal, natural gas and nuclear energy, and then renewable energy sources.

2. Fossil Fuel and Nuclear Options for Reducing CO_2 Emissions

It is unlikely that cheap and abundant fossil fuel resources can be denied their role in the generation of electricity;[16] it simply makes no economic sense to leave valuable resources in the ground, and it is likely that someone will ultimately exploit the associated rents (Gerondeau 2010). When it comes to climate change, therefore, options for their exploitation remain. The same is true of nuclear power. In this section, we examine the 'clean' coal, natural gas and nuclear options for generating electricity in more detail.

Clean Coal

Carbon capture and storage (CCS) is associated with so-called 'clean coal.' CCS involves removing CO_2 from the flue gas and pumping it into an underground reservoir. As of 2007, there were four industrial CCS projects in operation. Two projects are located off the Norwegian coast, on the Norwegian shelf or Utsira formation in the North Sea. Natural gas from the Sleipner gas field contains 9.5% CO_2 and, to avoid paying carbon taxes, Norway's Statoil, pumps the waste CO_2 into a deep underground saline aquifer. Since 1996, it has pumped annually about 1 Mt CO_2 into the aquifer. A similar project at the Snøhvit gas field in the Barents Sea stores 700,000 tCO_2 per year.

The largest CCS project is found at Weyburn in southeastern Saskatchewan, Canada, where the Weyburn-Midale CO_2 Project has since 2000 taken CO_2 from the Dakota Gasification Company plant in Beulah, North Dakota, has injected annually some 1.5 Mt CO_2 underground to enhance oil recovery.[17] The North Dakota company had produced methane gas from coal for thirty years while the oil field was discovered in 1954 and thus had also been in operation for quite some time.

A fourth project at In Salah in Algeria is much like the two Norwegian projects. CO_2 is removed from natural gas and re-injected underground, thereby preventing 1.2 Mt CO_2 from entering the atmosphere.

Many other CCS projects are now under consideration or under construction. For example, in Saskatchewan the electrical system operator, SaskPower, is providing $1.4 billion in subsidies to convert one of its coal-fired generators at the Boundary Dam Power Station to capture CO_2 and pump it underground to enhance oil recovery near Estevan. SaskPower hopes to generate 115-120 MW of base-load electricity from clean coal, thereby avoiding the need to shut down its facility. Although only a demonstration project that received the go ahead in early 2010, it is believed that upwards of 10 Mt CO_2 can be stored underground. Given that Canada hopes to eliminate coal-fired power plants, CCS projects related to coal are likely to constitute a stop-gap measure, especially in Saskatchewan

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[16] A reviewer suggested that wind energy should be developed because political instability in oil producing regions leads to erratic and high oil prices. True, but oil is not a player in the generation of electricity. As noted earlier, coal and gas are ubiquitous and cheap, and coal (and uranium) exporting countries, such as Australia and Canada, are politically stable.

[17] A graduate student associated with the Institute for Integrated Energy Systems at the University of Victoria told the author that, after working with other engineers on measuring the success of CO_2 storage, it appeared they could not track the eventual destination of CO_2, except for that which actually enhanced oil recovery. There was no guarantee in other words that CO_2 did not leak out of the underground formation at some unknown location.

which had invested heavily in coal generated power in recent decades.

The province of Alberta has announced it would provide funding of $2 billion for carbon capture and storage projects. CCS is required to offset emissions related to oil sands development. Germany, Australia, China and the United States are also looking into 'clean coal,' while Norway, the Netherlands and possibly British Columbia are looking into CCS as they develop natural gas fields that contain high proportions of CO_2.

Although CCS could well be technically feasible on a large scale at some time in the future, it certainly will not be economically feasible. There are two crucial obstacles. First, removing CO_2 from the flue gas, and then compressing, storing, transporting and finally pumping the carbon dioxide into a permanent underground storage facility is extremely costly. For a coal-fired power plant, output would have to increase by 28% just to cover the costs of removing the CO_2, although some of this can be done in off-peak hours when it is difficult to ramp down power output. Since not all regions have readily available places to store CO_2, it will be necessary to build a large pipeline transmission infrastructure and/or pipeline infrastructure plus storage and ship loading and offloading facilities.

Suppose that the objective is to capture and store just 10% of the world's CO_2 emissions, or about 3 Gt CO_2. Bryce (2010, pp.162-165) estimates that, if CO_2 is compressed at 1000 pounds per square inch (psi), or 68 atmosphere (atm),[18] it would amount to an oil equivalent volume of 81.8 million barrels per day. If all of this CO_2 were to be moved by ship, it would require filling 41 very large crude carriers (each holding about 2 million barrels) each and every day. Of course, much of the CO_2 would simply be transported by pipeline to a suitable underground location, but clearly not all. Even if only a quarter had to be shipped, this would require loading ten supertankers per day. Clearly, carbon capture and storage is a very expensive, and probably unrealistic, proposition.

But it is the second issue that is the real obstacle to large-scale CCS. There is always a risk that captured CO_2 is released, which could potentially lead to large loss of life, as when an underwater landslide in 1986 naturally 'burped' a large mass of CO_2 from Lake Nyos in Cameroon, forming a low-lying cloud that killed over 1700 people before it dispersed. Unless carbon storage occurs in remote regions, which increases its costs, people would need to be compensated to have a storage facility nearby. Research pertaining to the transportation and storage of nuclear wastes indicates that this could be an enormous cost (see Riddel and Shaw 2003).

In essence, the only real options appear to be those of conservation (e.g., via smart grids), greater reliance on natural gas and/or nuclear power, or development of alternative renewable sources of energy.

Natural Gas

During the 1990s and into the new millennium, a Texas oil and gas well driller,

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[18] 1 atm = 14.696 psi = 101,325 Pascal (Pa), where 1 Pa = 1 kg $m^{-1}s^{-2}$ = 1 kg/m^2. Note that CO_2 reaches a supercritical stage (where it becomes liquid) at about 70 Pa (measured at 31°C), but to get it there would take a great deal of energy.

George Mitchell, experimented with various techniques to cause gas to flow from shale deposits. In 1997, he and his crews found that, if water under extreme pressure was injected into wells along with sand and certain chemicals, this caused the gas to flow.[19] Then, in 2003, they discovered horizontal drilling. Thereby, they could drill down some ½ to one kilometre and then turn the drills sideways, and drill horizontally (lateral) for several km. At various locations along the lateral (about every 120m), the rock formation could be 'fractured' by injecting water and sand. The water would force openings in the rock, which were filled with sand that, along with the chemicals, facilitated the flow of natural gas.

As a result of horizontal drilling and hydraulic fracturing that opened up the pores to allow gas to flow, the Texas' Barnett shale vaulted into the top ten of the globe's natural gas fields. Its recoverable reserves of unconventional or shale gas are estimated to be about 44 trillion cubic feet, or energy equivalent of 8 billion barrels of oil. This compares with the 6 billion barrel, East Texas oil field discovered in 1931, which was the largest oil field in the world at that time.

Further, recoverable reserves of unconventional gas in the United States are now estimated at 649.2 trillion cubic feet (Bryce 2010, p.241). This is a huge increase over 1989 estimates of recoverable gas reserves. Further, unconventional gas can be found elsewhere in the world as the technological advance resulting from lateral drilling methods and fracturing formations can be adopted in other locations. Thus, for example, total gas reserves in north-eastern British Columbia are about equal to what total U.S. reserves were estimated to be in 1989. However, some of this gas contains large amounts of CO_2, which will be released as the gas is brought into production.

Given the tremendous increase in global natural gas reserves that the new technology has brought about, many countries will pursue a strategy of substituting highly energy efficient natural gas for coal in the production of electricity. As shown in Table 5, natural gas is generally composed of methane (CH_4), ethanol (C_2H_6) and other hydrocarbons. Consequently, compared to coal, it releases much less CO_2 into the atmosphere. Further, natural gas power plants can be simply and quickly built; the up-front construction costs of gas plants is half or less than that of coal plants, and much lower that of nuclear, solar, wind or other power generating facilities (NEA & IEA 2005). Fuel costs tend to be much higher, however. Hence, it is not surprising that countries are opting for natural gas, although in some cases the decision to build natural gas power plants is the result of political indecision concerning the extension of old or construction of new nuclear power plants.

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[19] Chemicals constitute about 1% of the volume of water. There remains some concern that chemicals could enter the water supply, but this is unlikely because wells are significantly deeper than the porous layers from which water may be taken.

Table 5: A Comparison of the Potential Release of Greenhouse Gases from Various Fossil Fuels

Item	Chemical structure
Natural Gas	
75% methane	CH_4
15% ethanol	C_2H_6
10% other hydrocarbons	
Hydrocarbons	
Propane	C_3H_8
Butane	C_4H_{10}
Octane	C_8H_{18}
Benzene	C_6H_6
Hexane	C_6H_{14}
Naphthalene	$C_{10}H_8$
Bituminous Coal	
Carbon (C)	75-90%
Hydrogen (H)	4.5-5.5%
Nitrogen (N)	1.0-1.5%
Sulfur (S)	1-2%
Oxygen (O)	5-20%
Ash	2-10%
Moisture	1-10%
Coal[a]	C_nH_m (n>m, n large, m small)
Glucose	$C_6H_{12}O_6$
Gasoline (average)	C_8H_{18} Range: C_6H_{14} to $C_{12}H_{26}$
Diesel	$C_{16}H_{34}$

[a] Macromolecules consisting of clusters of aromatic coal linked by bridges of sulfur, oxygen or other element(s)

Source: Author's own construction from internet sources.

Nuclear Power

Together the United States and France produce some 47% of global nuclear energy output, and account for 45% of installed capacity (Table 6). More than three-quarters of France's domestic consumption of electricity comes from its nuclear power plants and it exports nuclear power to other countries. It is difficult for a country to expand reliance on nuclear energy much beyond that experienced by France because nuclear plants are base load, so peaking gas plants or hydro facilities are needed to address short periods of high demand. France avoids some of its need for peaking capacity by selling nuclear power to other European countries, especially ones such as the Netherlands that are looking to reduce their CO_2 emissions and are closing coal and/or gas plants.

The top ten nuclear power producing countries are found in Table 6. The rest of the world accounts for only 13% of global nuclear generating capacity, and only 6.6% of the consumption in countries outside the top ten with nuclear capacity is accounted for by nuclear energy. For example, China is not included in the list but, as a nuclear power, has some generating capacity. Nonetheless, the generation of electricity from nuclear energy is confined to a small group of countries. Yet, nuclear power is a sensible and realistic (and some would argue only) option for achieving the strict CO_2 emission-reduction targets indicated above. For a country, such as Canada, 70% of electricity demand is already met from hydro and nuclear sources; because it is difficult to expand hydro capacity and given the obstacles posed by biomass energy, Canada might wish to expand its nuclear capacity in order to mitigate climate change.

How realistic is the nuclear option? Despite its promise, there are severe challenges facing expansion of nuclear energy. Nuclear wastes, the potential risk of enriched nuclear material being used by terrorists, high construction costs, cost over-runs, and general opposition to nuclear power plants by citizens, and especially environmental groups, militate against nuclear power. Storage of wastes in central facilities such as Nevada's Yucca Mountain makes sense as the amount involved is relatively quite small (no more than the volume of a large room), while the status quo of storing wastes on site is likely riskier. Given that far less than 5% of the available energy in nuclear fuel is used to generate power, enriching the spent uranium fuel can extend the usefulness of the fuel and, eventually, reduce its radioactive half life. Because enrichment leads to bomb grade material, governments have sought to prevent further refinement or recycling of spent fuel, preferring instead to store the more radioactive material. Although recycling adds to the costs of nuclear fuel, it is fear of nuclear weapons proliferation that makes the future for nuclear power more uncertain.

Table 6: Nuclear Power Production and Capacity, Top Ten Producers, 2007

Country	Production (TWh)	Capacity (GW)	% of domestic consumption
United States	837	106	19.4
France	440	63	77.9
Japan	264	49	23.5
Russia	160	22	15.8
Korea	143	18	33.6
Germany	141	20	22.3
Canada	93	13	14.6
Ukraine	93	13	47.2
Sweden	67	9	45.0
United Kingdom	63	11	16.1
Rest of World	418	48	6.6
WORLD	**2719**	**372**	**13.8**

Source: International Energy Agency (2010b)

Despite these obstacles, some countries will necessarily choose to expand reliance on nuclear energy to meet greenhouse gas emission targets and deflect concerns about energy security. As of 2009, there were 44 nuclear power plants under construction globally, with 11 in China, eight in Russia, six in India, five in Korea, two in each of the Ukraine, Bulgaria, Taiwan and Japan, and one in each of Argentina, Finland, France, Iran, Pakistan and the United States (Deutch et al. 2009). Estimates provided by Deutch et al. (2009) indicate that the life-cycle costs of producing nuclear energy are 8.4¢ per kWh, compared with 6.2¢/kWh for coal and 6.5¢/kWh for gas, although the latter costs would rise to 8.3¢/kWh and 7.4¢/kWh, respectively, if a carbon charge of $25 per tCO_2 emissions were imposed.[20] Further, if the added risks of capital used in building nuclear reactors were eliminated, so that the carrying costs of capital investments were the same as those of coal and gas plants, nuclear energy would cost 6.6¢/kWh rather than 8.4¢/kWh.

It is difficult to compare costs of producing electricity from renewable sources with those from traditional sources. Using data from a survey conducted by the International Energy Agency (International Energy Agency 2005), it is possible to provide some

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[20] These costs are significantly higher than those reported in the earlier MIT study (Ansolabehere 2003), but are probably higher than they would be today given that construction costs have declined since the financial crisis. This needs to be taken into account in the following discussion as well.

comparison of costs on a per megawatt hour (MWh) basis. Estimates are provided in Table 7. These indicate that electricity generated from renewable energy sources is significantly higher than that from traditional sources. Waste incineration is only the lowest cost means of generating electricity if there is a payment to dispose of municipal and industrial waste (which explains the negative value in the table, indicating a benefit). Further, the contribution of wastes to total electricity generation will be small, which is also true of combined heat and power (CHP). Coal and nuclear energy are the lowest cost realistic alternatives. Gas is more expensive because of high fuel costs, but gas plants are cheap to build and are needed for fast response to shifts in load.

The argument made by proponents of renewable energy generation is that the costs in Table 7 do not reflect externality costs, in particular the costs associated with CO_2 emissions (and other pollutants) from fossil fuel plants and the health and safety risks associated with nuclear power. Assuming that coal emits 0.9 to 1.0 tCO_2 per MWh of electricity (van Kooten 2010) – an emission level that is dropping as more efficient plants come on line – it would take a carbon tax well above what CO_2 emissions have been trading for under the Europe's Emission Trading System or the Chicago Climate Exchange before even wind energy is competitive with coal. But there remains another problem: With the exception of biomass and large-scale hydro, only nuclear and closed-cycle gas turbine (CCGT) plants can replace coal because, without storage, intermittent sources of power cannot serve base-load needs (van Kooten 2010).

3. Renewable Alternatives to Fossil Fuels

In the electricity sector, fossil-fuel sources of energy are primarily coal and natural gas, while renewable sources include large-scale hydro, small-scale run-of-river hydro, geothermal, wind, tidal, solar, wave, municipal solid wastes, and biomass. Some of these sources are severely constrained. Consider biomass. While there has been a great deal of emphasis on the use of terrestrial carbon sinks for reducing atmospheric concentrations of CO_2, and even offsetting fossil fuel emissions, the costs of sequestering carbon in agricultural and forest ecosystems are generally quite a bit higher than emission-reduction options (van Kooten et al. 2009; van Kooten and Sohngen 2007). There are some fundamental problems with the use of terrestrial sinks that make them a very dubious means of mitigating climate change; these include their ephemeral nature, high monitoring and transaction costs in establishing CO_2 baselines and flux, and potential for corruption (van Kooten 2009a, 2009b).

In this section, we want to consider the future prospects of renewable energy sources in generating electricity, especially their near-term prospects given that many developed countries have ambitious greenhouse gas emission targets that are supposed to come into force within a decade. We consider the prospects for biomass, hydropower and, finally, intermittent resources such as wind, wave, tidal and solar. In section 4, we consider wind power in more detail from an economics standpoint because wind has become the fastest growing renewable energy source. Given the scope of our discussion in this section, however, we provide only a broad brush analysis of the challenges society faces in turning a fossil fuel based economy into one that is much less so.

Table 7: Lifetime Generation Costs by Generating Type, $ per MWh[a]

Generating Type[b]	Midpoint	Low	High
Wind onshore	68.08	36.39	168.71
Wind offshore	78.54	59.09	144.38
Solar thermal	193.64	193.64	315.20
Solar PV	192.21	141.10	2195.39
Run of river/small hydro	108.28	46.45	283.02
Large-scale hydro	53.12	53.12	99.33
Nuclear	30.71	24.34	80.26
Coal (lignite)	39.35	34.40	75.35
Coal (high quality)	31.90	30.30	80.85
Coal (integrated coal gas)	44.73	31.94	69.15
Gas (CCGT)	54.62	44.69	73.24
Gas (open)	54.64	54.64	57.33
CHP (using CCGT)	55.12	33.11	94.65
CHP (using coal)	39.09	29.25	54.87
CHP (using other fuel)	40.01	34.40	116.42
Waste incineration	11.39	-4.68	61.19
Biomass	48.74	43.64	117.59

[a] The costs include capital, operating and maintenance, and fuel costs over the lifetime of a power plant, discounted to the present and 'levelized' over the expected output of the generating source over its lifetime. Values are in 2008 US dollars. The midpoint value is based on a 5% discount rate, as is the low value (except in the case of high quality coal); the high value is derived using a 10% discount rate.

[b] Open-cycle gas turbines lose exhaust heat but can respond quickly to changes in demand; closed-cycle gas turbines (CCGT) recycle exhaust heat, which makes them suitable as base-load plants but makes it more difficult for them to ramp up and down. Combined heat and power (CHP) occurs when instead of using heat for space heating it is used to generate power; such power is usually available at night and in colder climates.

Source: van Kooten and Timilsina (2009)

Biomass for generating electricity

One focus of current policies to mitigate climate change has been on the potential of using biomass to generate electricity. Increasing electrical power production from forest biomass, sawmill residue, and 'black liquor' from pulp mills is constrained by high transportation costs and competition for residual fiber that makes forest biomass an expensive source of energy. Consider the example of British Columbia, which is a major forest products exporting jurisdiction.

Because of the extent of mountain pine beetle damage to forests in the interior of British Columbia, many commentators felt that an obvious use of beetle-killed trees would be power generation. Studies that examined the costs of producing electricity from dead trees argue that this could be done with little in the way of government subsidies. This analysis is based on average past costs of harvesting and hauling timber from the forest to sawmills. However, when one takes into account the rising costs of hauling timber as more remote timber damaged sites need to be harvested, marginal costs rise rapidly with truck cycle times (the time required to travel to and from the harvesting site) of nine hours or more (Niquidet et al. 2010). An electrical generating facility turns out to be only a marginally attractive option for reducing CO_2 emissions when feedstock costs are low; but, as feedstock costs alone rise from an equivalent of 4¢/kWh to 8.5¢/kWh, biomass power is no longer an economically viable option.

Producing char from biomass through a process known as pyrolysis (a form of incineration that chemically decomposes organic matter by heat but without oxygen) suffers from similar problems, although high transportation costs might be mitigated somewhat by producing char on site. Nonetheless, the amount of char available for generating electricity will be negligible in comparison to what is needed and there are concerns that the process produces hazardous wastes.

Perhaps the best option for generating electricity from wood biomass is wood pellets. Wood pellet production plants are relatively inexpensive to construct and can, in some instances, be moved quite easily to new locations (although they are not mobile enough to be located at the harvesting site). Wood pellets can be used directly in coal-fired power plants with little or no adjustments to the burners – pellets can be pulverized much like coal and pellets are preferred over wood chips (which are used for pulp). Wood pellet stoves are also popular for space heating in residential homes.

Because of their flexibility, relatively low production costs, and government programs and subsidies, demand for pellets has risen sharply. European demand for wood pellets has risen rapidly since about 2005 because of subsidies. As a result, British Columbia's wood pellet production capacity has risen to about one million tons by 2010. But, as noted earlier, as demand for pellets, char and other energy uses of wood biomass increase, prices will rise making them less attractive as an alternative form of energy.

Using a regional fiber allocation and transportation (mathematical programming) model, Stennes et al. (2010) demonstrate a major drawback of timber feedstocks. As one of the largest lumber producing and exporting jurisdictions in the world, British Columbia's forest resources are enormous and one would think that these resources would form a logical foundation for a thriving bioenergy sector. Lumber is far and away the most lucrative product that is produced in the province. Chips from sawmilling operations form the mainstay of the province's pulp industry. Other sawmill residues (bark, sawdust, etc.) are already allocated by mills to on-site space heating and power generation, with some excess chips and residues used in the production of such things as wood pellets, oriented strand board and other products. Competition for sawmill residuals occurs between pulp mills and other wood product manufacturers as well as heating and electricity. There is some leeway to increase available wood waste by hauling roadside and other waste from harvest operations to electricity generation and other facilities that might be able to use them. The important point to note is that any residuals and other wood waste are available at a reasonable cost only as a result of timber harvests for sawmilling purposes (Niquidet et al. 2010; Bogle and van Kooten 2010).

When account is taken of the supply and demand of wood fiber for all its different purposes, and when costs of transporting various types of fiber from one location in the province to another, there is little wiggle room. Indeed, the government might wish to implement policies, such as direct construction subsidies or feed-in tariffs, to increase power generation or wood pellet production from a wood biomass feedstock, but this will only lead to increased demand for fiber. This causes prices of wood residuals and wood 'waste' to increase, driving out existing users such as pulp mills, or the bioenergy producers themselves, depending on their ability to compete (Stennes et al. 2010). For example, pulp prices were under $500 per tonne several years ago, but reached $1000 per tonne in 2010. Pulp producers can out bid energy producers for wood fiber at high pulp prices but have a harder time competing at lower prices, especially if bioenergy producers are subsidized.

What is often neglected in discussions of biofuels and biomass-fired power generation is the fact that biomass and biofuels are not carbon neutral as is often claimed. The combustion of biofuels and biomass releases carbon dioxide, indeed more than what is released from fossils fuels to generate an equivalent amount of energy. It is only when crops and trees grow that carbon dioxide is removed from the atmosphere, and this can take quite a long time in the case of trees. Further, CO_2 and other greenhouse gases are emitted in the harvest and hauling of biomass, and their conversion to fuel or power. In the case of ethanol, for example, this could even offset the gains from replacing gasoline. For example, Crutzen et al. (2008) found that, given current nitrogen-use efficiencies in agriculture, the increased fertilizer used to grow energy crops offset the reduction in CO_2 emissions from the gasoline the biofuel replaced. If ethanol came from sugar cane, the contribution of the biofuel to global warming was between 0.5 to 0.9, where a value above 1.0 indicates increased release of greenhouse gases (greater warming rather than cooling); if ethanol came from corn, the warming factor was 0.9–1.5; but, if the biofuel came from canola, it resulted in no benefit as the greenhouse gases released exceeded those associated with the fuel that was replaced (factor of 1.0–1.7).

When wood biomass is burned in lieu of coal, say, more CO_2 is released than with coal. In addition, more CO_2 is released in gathering biomass across a large landscape than is the case with coal as coal deposits are concentrated near a particular location. Thus, there is an increase in the release of carbon dioxide, not a reduction. The reduction comes only as trees grow, which could take as much as 80 years. To mitigate the length of the growing season, fast-growing tree species, such as hybrid poplar, can be grown, or alternative plants such as switchgrass can be used as a biomass fuel. While this tilts the greenhouse gas emissions more favorably towards biomass burning, nitrogen fertilizer is often required to spur growth, and nitrogen oxides are a more potent greenhouse gas than CO_2.

Finally, land is the most important factor in the production of biofuels. Increased demand for energy crops reduces cultivated area devoted to food production as land is diverted into energy crops (Searchinger et al. 2008). It also increases the carbon footprint. Overall, therefore, the process of generating electricity from biomass is hardly carbon neutral.

From a policy perspective, biological methods are not an efficient means of addressing climate change, although promising research into various biological organisms that make this process more efficient is ongoing. These may very well come to fruition, but it could be several decades before such options are commercially viable. However, energy from biological organisms does not appear to be a major component of governments' policy arsenals for combating climate change. Landfill gas generated from solid waste is a potential source of electricity, but even if it is employed on a large scale, its contribution to the globe's electricity needs would necessarily be extremely small. The same holds for the incineration of municipal wastes.

Hydraulics and Storage

A number of countries have developed their hydraulic resources to build large-scale hydropower facilities. With the so-called 'three gorges' dam (affecting the Upper Mekong, Yangtze and Salween Rivers), China now has the greatest hydro capacity in the world (Table 8). In 2007, hydro production only accounted for 14.8% of China's consumption of electricity. This is much less than the proportions accounted for by hydro in Norway (98%), Brazil (84%), Venezuela (72%) and Canada (57%). India relied on hydropower to a greater extent than China, as did Russia despite its relatively abundant fossil fuel resources.

Table 8: Hydro Electric Power Production and Capacity, 2007

Country	Production (TWh)	Capacity (GW)[a]	% of domestic consumption
China	485	126	14.8
Brazil	374	73	84.0
Canada	369	73	57.6
United States	276	99	6.3
Russia	179	46	17.6
Norway	135	29	98.2
India	124	35	15.4
Japan	84	47	7.4
Venezuela	83	n.a.	72.3
Sweden	66	n.a.	44.5
Rest of World	987	n.a.	n.a.
WORLD	**3162**	**889**	**15.9**

[a] Data for 2006

n.a. not available

Source: International Energy Agency (2010b)

Large-scale hydro remains one of the best options for generating ‘clean’ electricity, but its main drawbacks relate to inadequate runoff for power generation (especially in regions where water is scarce, intermittent and/or unreliable) and negative environmental externalities (changes in the aquatic ecosystem, impediments to fish migration, land inundation by reservoirs, etc.). Environmentalists oppose large-scale hydro development, particularly in developing countries because of the ecological damage it causes, while even small-scale, run-of-river projects have been opposed in rich countries on environmental grounds. Because of strong environmental opposition against hydropower developments, hydropower’s future contribution to increases in overall generating capacity will inevitably remain limited in scope. Expansion of water power is not expected to be a large contributor to the mitigation of climate change.

Although unlikely to contribute much in the way of additional clean power, existing large-scale hydro and strategic expansions of reservoir storage capacity (which raise generating capacity) might serve an important purpose when combined with intermittent sources of energy, namely, wind, tidal and solar sources. For example, wind-generated power is often available at night, when base-load power plants are able to supply all demand. Wind energy would then need to be curtailed (wasted) or, where possible (and it may not always be possible), base-load plants would need to reduce output, causing them to operate inefficiently. If a base-load plant is coal fired, inefficient operation implies that CO_2 emissions are not reduced one-for-one as wind replaces coal. In some cases, the tradeoff is so poor that CO_2 emissions are hardly reduced whatsoever. This problem can be overcome if adequate transmission capacity exists so that the excess wind-generated power could be stored behind hydro dams by displacing electricity demand met by hydropower. This is the case in northern Europe, where excess wind power generated at night in Denmark is exported to Norway, with hydropower imported from Norway during peak daytime hours.

Similar relationships are found elsewhere. In Canada, for example, the provinces of Quebec and British Columbia rely almost exclusively on hydropower, while the respective neighboring provinces of Ontario and Alberta generate significant base-load power from coal (or nuclear in Ontario’s case). Ontario and Alberta are both expanding their installed wind capacity. During nighttime, off-peak hours, excess wind and/or base-load power from Ontario (Alberta) is sold to Quebec (British Columbia), with hydropower sold back during peak periods. Given that the rents from these transactions have accrued to the provinces with hydro assets, Ontario and Alberta have been less than keen to upgrade the transmission interties, preferring to look at other possible solutions to the storage problem.

In all three cases, there are net economic and climate benefits from the development of higher capacity transmission interties; or, in the case of northern Europe, simply more interties between jurisdictions where wind power is generated (northern Germany, other parts of Denmark) and those with hydro resources (Norway and Sweden). The main obstacle is the lack of incentives for the wind-generating region to ‘dump’ power into the region with storage, as the latter captures all the rents from such an exchange. This is a game theory problem: If institutions can be developed that facilitate the sharing of both the economic rents and the climate benefits (emission reduction credits), the jurisdictions have the incentive to better integrate the operations of their electricity grids (including construction or upgrading of transmission interties) so that overall CO_2 emissions are minimized.

Geothermal

Deep in the earth, the temperatures are much higher than on the surface. In these places, the magna of volcanoes forms. In some places, heat escapes from underground through vents or geysers and can be captured to generate electricity or used for space heating. The country that relies most on such geothermal energy is Iceland. Proposals to drill deep into the earth and capture heat for power generation suggest that this is a viable source of energy from an engineering standpoint. Economic considerations will prevent the use of geothermal energy on a sufficiently large scale to make a dent in the globe's energy supply in the foreseeable future.

Generating Electricity from Intermittent Energy Sources

There exists a number of promising renewable energy sources that could at some time in the future make a significant contribution to global electrical energy needs. However, the likelihood that these will have a major impact in the short or medium term (five to 50 years) is small. It is evident from Figures 1 and 2 that non-conventional sources of energy constitute only about 4% of global consumption. Raising that to 20% or more constitutes an enormous challenge, especially in a world where energy demand is rapidly increasing as a result of economic development in countries such as India and China. Simply expanding the use of renewable energy and then incorporating renewable energy sources into energy systems will prove difficult, not least because an expansion in the use of renewables will lead to increases in their prices (as we noted with regard to wood biomass).

Among alternative energy sources, tidal and wave energy are promising, especially considering the potential energy that might be harnessed. Tidal energy is considered particularly desirable because of its regularity and predictability. While some tidal barrage systems are in place and experiments are underway with tidal turbines (which function much like wind turbines), huge technological and cost obstacles still need to be overcome. This is even more the case for wave energy conversion systems, which simultaneously suffer from unpredictability and intermittency. For both wave and tidal systems, costs of transmission lines can be prohibitive.

Solar energy is another promising energy source. The energy or irradiance from the sun averages some 1.366 kW/m^2, or 174 PW for the entire globe, but it is difficult to convert to usable energy. Other than through plant photosynthesis, there are two ways to harness this solar energy: (1) solar photovoltaic (PV) converts the sun's energy directly into electricity, while (2) solar heaters warm water (swimming pools, water tanks, etc.). Solar heaters convert up to 60% of the sun's energy into heat, while PV cells convert only 12% to 15% of the energy into electricity, although PV laboratory prototypes are reaching 30% efficiency. One problem with solar electricity is its prohibitive capital costs, which amount to some $13,000 to $15,000 per kilowatt (kW) of installed capacity (IEA 2005), although costs have subsequently fallen (almost to 1/3) in the past several years. In addition, solar power is intermittent (e.g., output is greatly reduced on cloudy days), unavailable at night, and, in high latitudes, less available in winter when demand is high than in summer (due to shorter days). Nonetheless, for remote locations that receive plenty of sunshine and are not connected to an electrical grid, the costs of constructing transmission lines to bring in outside power might make solar PV and solar heaters a viable option.

Given the current drawbacks of many other renewable sources of energy, wind energy appears to be the renewable alternative of choice when it comes to the generation of electricity. As a result, global wind generating capacity has expanded rapidly from only 10 megawatts (MW) of installed capacity in 1980 to 157,899 MW by the end of 2009 (see Figure 4 below), an average annual rate of increase of some 49% (GWEC 2010). Again, it needs to be emphasized that the euphoria about wind energy needs to be accompanied by a realistic view of its potential contribution to a future energy economy. This is discussed in section 4.

Before considering wind energy in more detail, consider one of the main problems facing renewable energy – the problem of energy density. As indicated in Table 9, the energy density of most renewable energy sources is simply too low compared to that of fossil fuels and nuclear power to make them sufficiently competitive with fossil fuels and nuclear power, thereby requiring the types of subsidies we find in Table 3. While subsidies might help in the short run, they are not sustainable in the long run because they distort production decisions resulting in inefficiencies. This is particularly the case if only some countries employ subsidies as these will lower the costs of fossil fuels causing those countries that continue to rely on fossil fuels to use them less efficiently thereby offsetting the climate benefits of the original subsidies.

4. The Economics of Wind Energy in Electricity Generation

Installed global wind generating capacity has expanded rapidly over the past three decades. At the end of 2009, it reached nearly 160 GW (Figure 4). At the end of 2009, The U.S., Germany, Spain, India and China accounted for 75.5% of global wind power capacity, while developed countries alone accounted for about the same proportion (Figure 4). With the exception of China and India, and a few other countries, very little electricity is produced from wind in developing countries, and especially in the least developed countries, although wind is used on a small scale in many developing countries to drive mechanical devices such as water pumps.

Over the period 1990 to 2009, growth in wind generating capacity averaged just over 26% per annum, and was even slightly higher at about 27% over the period since 2000. It is not surprising, therefore, that the growth in capacity is likely to continue at well above 20% until at least 2012. Yet, despite these very high rates of growth over the past several decades, the current role of wind power in meeting global electricity demand is almost negligible as it accounts for much less than 2% of the global electricity supply (Figures 1 and 2). What are the prospects for wind energy? What are the obstacles?

Table 9: Energy Densities: Comparison of the Physical Area Required to Produce Energy from Selected Sources

Energy Source	Energy Density	Index
Corn ethanol	0.05 W/m^2	1.0
Biomass-fuelled power plant	0.4 W/m^2	8.1
Wind turbines	1.2 W/m^2	24.6
Oil stripper well[a] producing 2 barrels per day	5.5 W/m^2	115.4
Solar PV	6.7 W/m^2	138.5
Oil stripper well[a] producing 10 barrels per day	27.0 W/m^2	577.0
Gas stripper well[a] producing 60,000 cu feet (ft^3) per day	28.0 W/m^2	590.4
Average U.S. natural gas well producing 115,000 ft^3/day	287.5 W/m^2	1105.8
Nuclear power plant[b]	56.0 W/m^2	1153.8

[a] A stripper well is one that has passed its peak production (or never was a large producer) but continues to pump oil or gas. Stripper wells are defined by their maximum output – 10 barrels per day for oil wells and 60,000 cubic feet per day for gas wells.

[b] Based on a 4860 ha location in Texas, although the power plant occupies only a very small area within the property.

Source: Bryce (2010, pp.91-93)

Some quick answers to these questions are as follows. First, it is unlikely that, even under the most optimistic estimates, wind will account for more than 5% of total global electricity production (van Kooten and Timilsina 2009). Second, wind energy requires storage, is unreliable, costly to install, harmful to some wildlife (e.g., birds), noisy, visually unattractive, and, above all, destabilizing of existing electrical grids. Wind turbines only produce about one-fifth of their rated output because of vagaries in wind, while attempts to reduce intermittency by scattering wind farms across a large geographic area and integrating wind power into a 'super grid' have not overcome the grid instability that occurs when wind penetration reaches about 30%.[21]

In summary, the economics of wind-generated energy restrict its potential, essentially deflating the euphoria that is often brought to this renewable energy source. This is not to deny that wind energy does have a role to play. For example, van Kooten and Wong (2010), and others, have demonstrated that there are huge savings to be had from investing in wind turbines under certain circumstances (discussed further below). But, in order to understand the limitations of wind energy, we need to first consider the way the electricity grid functions and the challenges that this poses for wind power. We then turn to

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[21] Most of these results are based on various modeling exercises (see, e.g., van Kooten 2010; Prescott and van Kooten 2009; Maddaloni et al. 2008a, 2008b; Lund 2005; White 2004).

studies that have examined the integration of wind power into electricity grids. And we end with a discussion regarding wind energy's future.

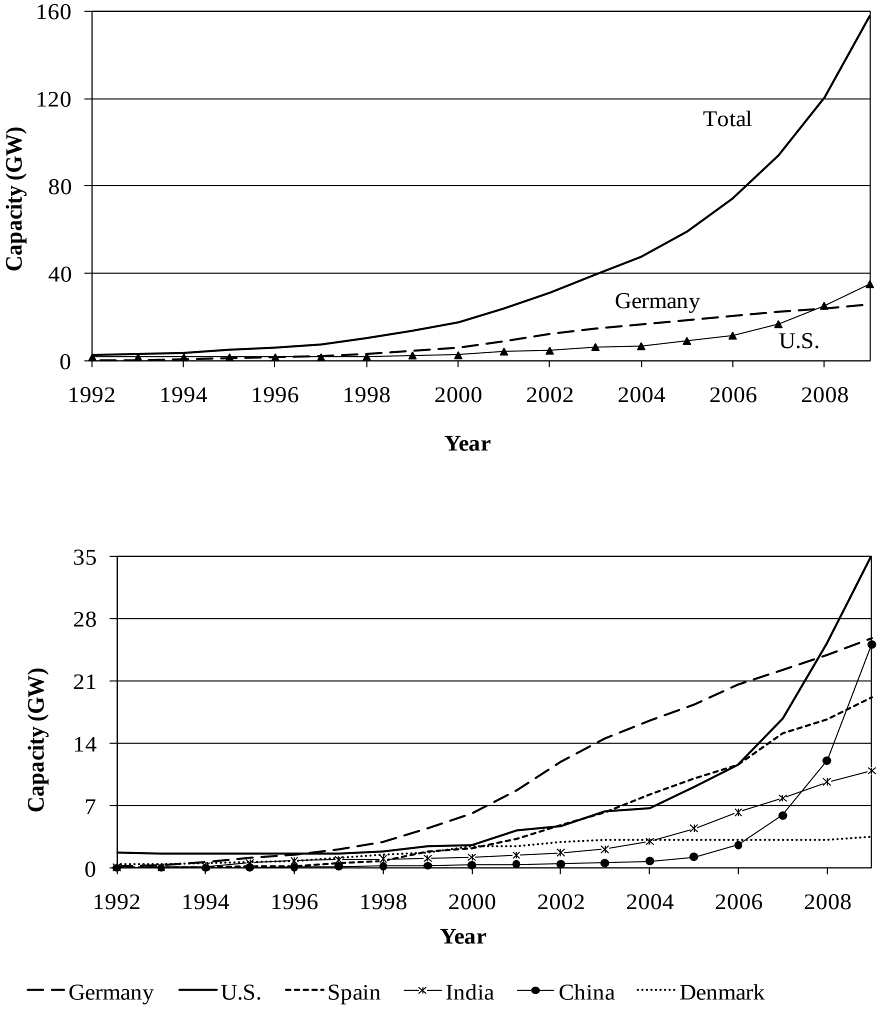

Figure 4: Expansion of Global Wind Generating Capacity, Total and Selected Countries

Structure of Electricity Grids: Economics

Electricity is an unusual commodity in that production and consumption occur simultaneously and at every instant in time. That is, unlike a normal market where there is a mechanism that enables consumers and producers to 'discover' the market clearing price over a period of time, the market for electricity must clear continuously. Nonetheless, supply and demand for electricity remain the essential means for describing the underlying process that enables the electricity grid to function.

Demand Side and Demand Management

Final consumers of electricity have rarely been asked to respond to changes in wholesale prices; with the exception of differences in nighttime and daytime rates, consumers in most jurisdictions face the same price regardless of the time of day. Further, retail prices change only when the regulator permits the system operator to make the change. Prices are regulated because production, transmission and delivery of electricity are inherently monopolistic activities, at least historically. The generation of electricity and its delivery to the final consumer were considered to be the function of a single firm – a monopolistic activity that then had to be regulated. Recently, many jurisdictions have separated generation, transmission and delivery to varying degrees.

The first step in this process is to separate ownership of power generation from transmission and delivery, thereby creating a wholesale market for electricity. An independent (private or public) electricity system operator (ESO) will oversee the allocation of power generation from various facilities, and arrange its transmission and delivery to customers. While the wholesale price might fluctuate widely in this case as power generating companies compete to sell electricity, the retail price is set by a regulator or, in a fully deregulated system, fluctuates hourly with the wholesale price, the difference reflecting the cost of transmission and delivery. Without 'smart' controls that receive price signals and adjust electrical use accordingly, consumers are simply unable to respond to real time price signals – with the exception of large industrial or commercial consumers, it would be too expensive in terms of time and effort for them to do so.

With respect to demand, it is important to distinguish between efforts to shift load from peak periods to off peak periods and a fully deregulated retail market. Most government policies focus on load shifting because smart controls are not widely available to most customers. Even so, time-or-use billing can simply be used to shift load by distinguishing between daytime and nighttime prices (which small customers can handle), but even this requires that smart meters are installed at each consumer's location. An alternative is to provide incentives only to the largest industrial and commercial customers that cause them to reduce demand during peak times, perhaps shifting it to other times of the day. The purpose of these incentives is to shift load (as with daytime-nighttime pricing) or shed load (reduce demand). If peak load can be 'shaved' (reduced) by shifting demand to off-peaks times, substantial cost saving may be found as less overall and reserve generating capacity are required. Shedding load is a different proposition: An ESO will need to shed load in an emergency when the system load exceeds generation. This can be done via built-in incentives or, more often, contracts between the operator and large consumers. However, the purposes here are not to conserve energy as much as reduce system management costs.

If retail prices are fixed, the demand function is essentially a vertical line – load does not respond to changes in wholesale prices. One way to affect consumer demand is to employ a tiered system whereby rates rise (or fall) with increased usage over a specified period. Rather than redistribute some load from peak to off-peak hours, a tiered system of prices can reduce or increase demand, depending on circumstances and prices of alternative energy sources.[22]

Time-of-use (real) time pricing at the retail level affects demand directly, but likely requires the implementation of a 'smart grid' – something beyond just smart meters. There is much discussion about smart grids, but there are some obstacles to its implementation. Currently, if there is a power outage, the local system operator is unable to determine even whether there is an outage let alone where it occurs. It relies on customers to provide the information. A smart grid (or just smart meters) enables the system operator to identify outages by placing computer chips on transmission lines, including lines leading to each home (smart meters). The computer chips send and receive signals, usually in conjunction with the internet. It is also possible to install chips that would enable the system operator (or customer) to control appliances, change thermostat settings and affect other devices that connect to the electrical grid from a distance. For example, appliances such as dishwashers, washing machines, clothes dryers and heaters could be turned off or on depending on the price of electricity. At times of excessive load or when a generator fails, the system operator could curtail consumers' use of electricity or signal certain appliances to shut down. While not all electronic devices have smart technology embedded in them, and installing smart devices could be expensive, perhaps the greatest obstacle to smart grids might be concerns about privacy. One solution might be to allow consumers to opt out of the smart grid, but at a cost (e.g., higher overall average electricity rates).

It is fair to conclude, at this point, that prices vary little at the retail level and, further, that the demand for electricity is probably highly inelastic should a form of real time pricing be implemented. Based on cross-section and time series analyses, the short-run elasticity of demand is often assumed to be about −0.3 (U.S. Energy Information Administration 2010, p.26), while it is between −1.5 and −0.5 in the long run.[23] This implies that a 1% increase in the price of electricity results in a 0.3% reduction in demand in the short run, and a reduction of 0.5% to 1.5% in the long run.

Electricity Supply and the Wholesale Market

In electricity systems that are at least somewhat deregulated at the wholesale level, the ESO requires owners of generating facilities to commit to produce electricity at a given hour one day (24 hours) ahead of actual delivery. Each generator will offer to produce a

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[22] An increase in demand can occur if a large consumer of electricity is generally well below the use that would take it to the next, higher-price tier. Suppose the consumer heats water using natural gas and currently does not reach the next price level in its use of electricity. If gas prices are sufficiently high, it will pay for the consumer to convert its boilers so that water can be heated by gas or electricity. Electricity will be used for heating water up to the point where the power usage encounters the threshold for the higher price tier of use.

[23] Estimates of both the short- and long-run price elasticities of demand for electricity vary widely. In a meta-regression analysis of studies of U.S. residential demand for electricty, Epsey and Epsey (2004) concluded that the best estimate of short-run and long-run elasticities were −0.28 and −0.81. For example, a co-integration study found long-run price elasticity to be −0.5 (Silk and Joutz 1997). However, a more recent Swiss study found long-run price elasticity of demand to range from −1.27 to over −2.0, with demand more elastic during peak than off-peak periods (Filippini 2010).

certain amount of electricity at a particular price, knowing that the final price they will receive is the market-clearing price for that hour (actually, it is the average of the prices that clear the market throughout that hour). In essence, a power plant will offer units of electricity at a single or variety of prices to be produced on a specified hour the next day. This is known as day ahead, unit commitment. Of course, as the hour approaches for which an owner of a generating facility has committed power output more information about the status of generators and the evolution of prices becomes known – some uncertainty is resolved. Therefore, generators are able to make changes to their offers up to one hour before delivery. The extent of permitted changes is increasingly constrained by penalties as the hour approaches.

What do the offers to supply electricity look like? Base load nuclear and coal-fired power plants will bid in lowest. Indeed, for base-load facilities that cannot readily change their power output, or can do so only at high cost, the optimal strategy is to provide very low price bids to ensure that they can deliver power to the grid. Open-cycle, natural gas peaking plants will want to bid in at their true marginal cost of production, which is primarily determined by the price they have to pay for fuel. The facilities to provide the highest bids are those that wish to export electricity to another system, regardless of the energy source used to generate the power; by setting their price high, their output is unlikely to be chosen by the system operator and can thus be exported. (Importers will want to set their prices low to guarantee that the imported power will be chosen.) In between the extreme prices are found a variety of generating facilities, such as biomass plants, combined-cycle, gas plants (CCGT), different importers, and even various sub-units of power plants that might be at different levels of readiness, maintenance, et cetera. Once the ESO has all of the information regarding the amounts of electricity that the various components of the generating system are willing to supply and their associated prices, a merit order is developed to allocate power across the generators depending on demand. An example is illustrated in Figure 5.

In Figure 5, the market clears at price P, which equals the marginal cost (bid value) of generator NG 2 – a natural gas unit or 'peaker.' All units below the dashed horizontal line P receive the market-clearing price, while NG 3, Diesel 1, and other higher-cost units are not asked to deliver power to the grid.

There remains a problem: Transmission constraints have been ignored. Because generators and load centers are found at various locations across the system landscape, they need to be connected by transmission lines. In terms of Figure 5, it may be the case that a load center is nearer generator NG 3 than generator NG 1 and that there is insufficient transmission capacity between NG 1 and the rest of the grid. As a result, the ESO is unable to accept power from NG 1 and must, instead, turn to NG 3. The resulting system price is then equal to P′, the marginal cost of NG 3, rather than P. Thus, all of the generators in the merit order that have a lower cost than that of NG 3, with the exception of generator NG 1, receive the system price P′ rather than P.

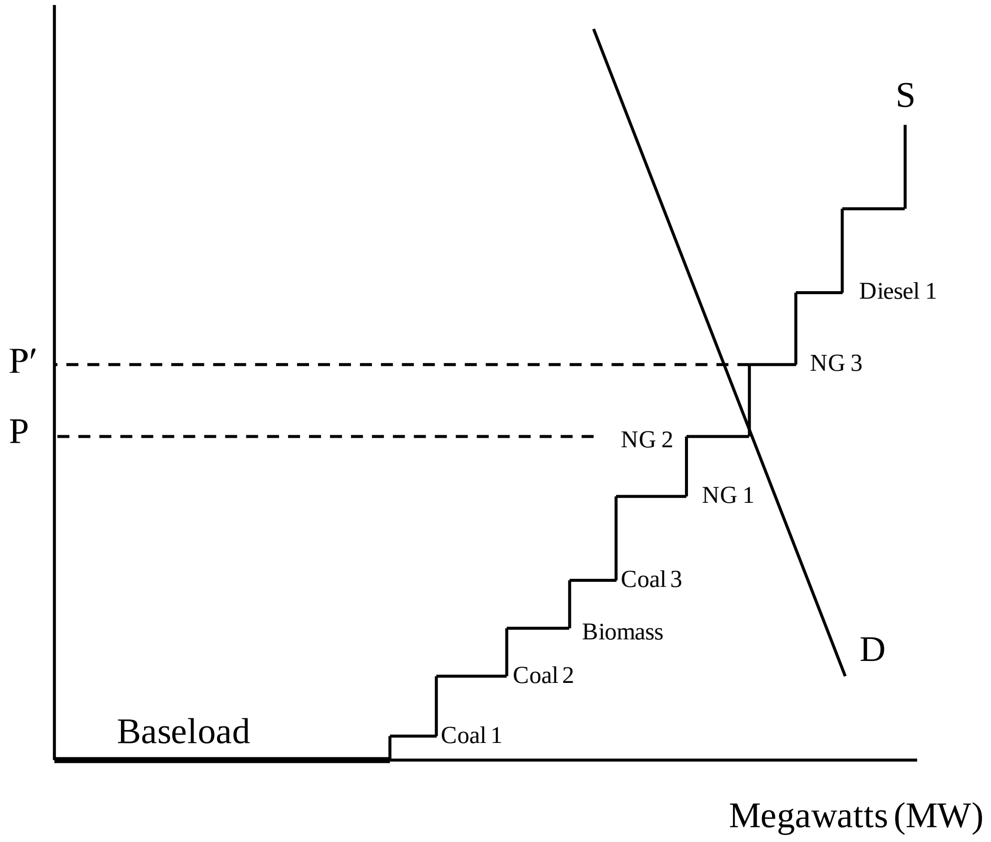

Figure 5: The Merit Order and Intersection of Supply and Demand for Electricity

The higher average system price distorts incentives. As a result, some systems have gone to location-specific pricing, with the prices that generators receive established at a local or regional center within the ESO's operating area rather than averaged over the entire operating area. Knowing this, the bidding in strategy could change, both in the market for power delivery to the grid and in the market for ancillary services (to be discussed next). Further, such location-specific pricing provides incentives to upgrade or build transmission lines connecting regions.

There is also a market for ancillary services. Ancillary services are not homogeneous, and even how they are defined and handled may differ across jurisdictions. Regulatory (fast-response) services are needed to address second-by-second, minute-by-minute fluctuations in demand so that grid reliability is maintained – that the grid delivers 120 volts at 60 MHz (in North America). Such short-term fluctuations are generally met by the on-line generators themselves, as standards require plants to be able to vary their outputs slightly as needed (e.g., slightly more or less gas can be delivered to a turbine, or more or less pulverized coal to the burner). Hence, they are also referred to as 'spinning reserves' as their main function is to ensure the grid remains synchronized. Storage devices, such as batteries and flywheels, might also be used in a regulatory capacity, as might hydropower.

Load following reserves are those that are required to follow shifts in load on time frames that usually do not exceed 10 minutes, and have much in common with regulatory reserves. Contingency (or standby) reserves, on the other hand, are those capable of providing power within about 10 minutes, but are unlikely to cover shortfalls prior to that time. There is a great deal of overlap between the two types of reserves. For example, a peak gas plant might be operating at only 55% capacity, but can power up to 90% or greater capacity within one minute, while an open-cycle gas plant or diesel facility might need 5 to 10 minutes to power up from a cold start.

In addition to the market for the delivery of electricity to the system (Figure 5), there is a market for ancillary services. The merit order in this case is the inverse of what one finds in the former market. The peakers will now want to bid in at the lowest price because they are the ones that can get off the mark the quickest. Peakers such as NG 3 and Diesel 1 (Figure 5) will bid in low knowing that, when there is a demand for ancillary services, they will receive at least the price determined by the marginal generator (NG 2 in Figure 5) plus their own bid in the ancillary market. Base-load plants, on the other hand, will bid in very high, if at all, because they can only ramp up output at great expense. The market for ancillary services will look something like that in Figure 6.

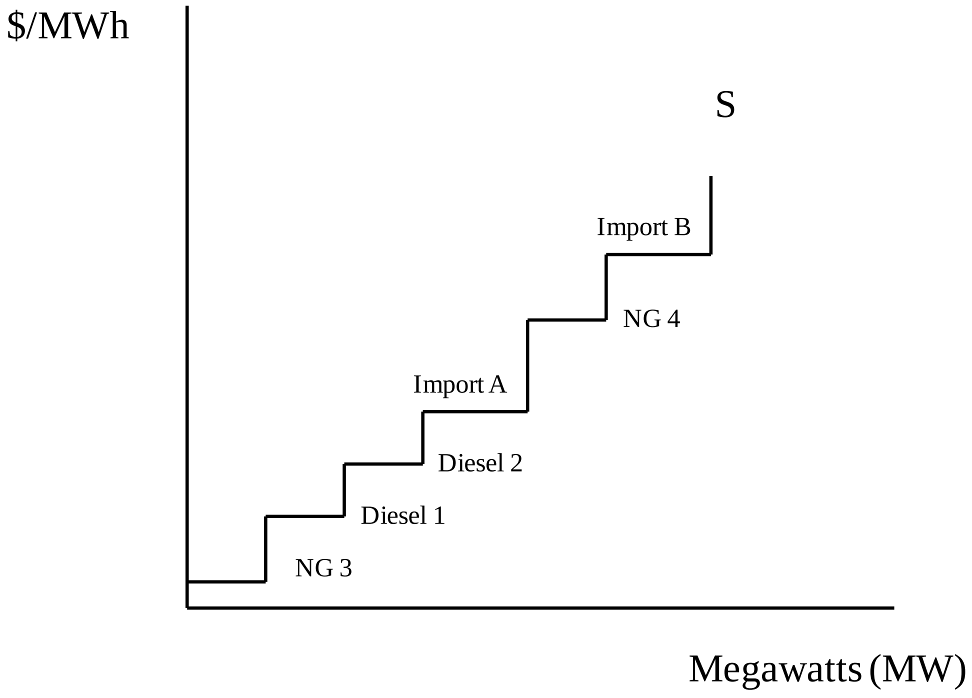

Figure 6: The Market for Ancillary Services: Merit Order

Hydroelectricity is a particularly good provider of ancillary services, although it can also provide base load power. Hydropower can bid in as low-cost provider in the generating services market or as a low-cost provider of ancillary services. It can play either role, although the makeup of the hydroelectric facilities in the system will determine the role it actually plays. For example, in British Columbia, large hydro dams make it ideal for base load power, with an open-cycle gas facility providing power in the rare instances when load cannot be met from hydro plus imports. In Alberta, on the other hand, there is only a limited ability to store water, with reservoirs tending to be small relative to the needs of the grid. Hence, hydropower is used almost solely for providing ancillary services and meeting peak load demand.

Although some renewable services can easily be integrated into electricity markets (e.g., biomass in Figure 5), it is an altogether different proposition when wind and other intermittent sources of renewable energy are introduced into the system. In the remaining sections, we focus on the integration of wind into existing electricity grids.

Integration of Wind Power into Electricity Grids

Unless wind power is readily storable behind large hydro dams, wind requires fast-responding, open-cycle (as opposed to base load closed-cycle) gas plants as backup. However, since any wind energy will first displace electricity produced by fast-responding gas, it cannibalizes existing peak load gas capacity and makes investments in such plants less attractive. Even adding a more stable renewable source, such as tidal power, does little to address the problem of intermittency (Monahan and van Kooten 2010).

Intermittency is the greatest obstacle to the seamless integration of wind generated power into electricity grids. When there is no wind, no power is generated; the wind comes and goes, and does not always blow with the same intensity – it is a whimsical source of power. Wind power enters an electricity grid whenever there is adequate wind; unless provision exists to curtail wind generation, any electricity generated by wind turbines is 'must run' – it is referred to as non-dispatchable. Because of this intermittency, the supply of wind power will fluctuate more than that of traditional generating sources.

Producers of wind power are able to forecast with some degree of accuracy, but with large variance, the likely amount of wind power they can deliver to the grid at a given hour the next day. They bid the expected amount of power into the merit-order at the lowest price (as base load), and can change the expected quantity up to one hour prior to delivery. Nonetheless, there is no guarantee that the amount of power bid into the system can actually be delivered, whether it will exceed the stated or bid amount or be below it. As an incentive, some European systems impose a penalty on wind producers if they exceed the stated amount or come in below that amount.

Consider Figure 5. The entire merit order will shift to the right if wind is bid into the system. If the wind does not materialize, the entire merit order will shift back to the left. That is, the location of the supply function and the eventual market clearing price in each hour becomes uncertain as more wind is bid into the market. This uncertainty has a cost. The direct costs of wind power include those associated with the construction of wind turbines, including the cost of purchasing or renting land, the upgrading and construction of transmission lines, and the environmental costs related to bird kills and impact on human health (Bryce 2010, pp.85, 121-124; Pierpont 2009). The indirect costs associated with intermittency are, most notably, (1) the costs of additional system reserves to cover intermittency, and (2) the extra costs associated with balancing or managing generating assets when power from one (or more) generation sources fluctuates.

Capacity Factors

Consider first the so-called ‘capacity factor.’ If one MW of wind generating capacity is installed, the potential amount of power that can be generated annually is given by the number of hours in a year multiplied by the generating capacity. For a one MW turbine, regardless of the energy source, the potential power output is 8760 MWh. For coal and nuclear plants, actual generation will be about 85 percent to as much as 95 percent of potential. This is the capacity factor. However, given wind variability, the average capacity factor of a wind farm is usually less than 20%. Thus, rather than generating 8760 MWh of electricity, only an average of some 1750 MWh are generated with actual generation varying greatly from one year to the next. Of course, capacity factors at some wind locations exceed 30% and on occasion even 40%, but that is the exception rather than the rule.

To illustrate the types of capacity factors one might encounter, consider the Great Plains region east of the Rocky Mountains in western Canada. This region is considered to be an area of high wind power potential because of prevailing winds off the mountains. In Table 10, we provide data on capacity factors from actual wind farms in southern Alberta and potential capacity factors for several areas in north-eastern British Columbia where wind speeds have been measured for a period of one or more years (but development of wind farms has not yet taken place due to lack of transmission connections).[24] The two regions are about 1000 km apart and are directly east and near to the Rocky Mountains. Capacity factors vary from 7.4% to 36.6% for the region.

While the information in Table 10 is based on a single year of data and wind power output can be expected to vary greatly from one year to the next, the results are illustrative nonetheless. First, the results demonstrate that capacity factors can often be quite low, and are usually lower than expected, even for good wind site locations (Bryce 2010, pp.96-97). Second, even when wind sites are spread across a large landscape so that they are as much as 1000 or more km apart, wind power is generally not available every hour of the year.

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[24] Data can be found at http://web.uvic.ca/~kooten/documents/LSRS2009WindData.xls.

Table 10: Capacity Factors for Some Western Canada Wind Sites

Site	Capacity (MW)	Production (GWh)	Capacity factor (%)
Sites in southern Alberta currently in operation			
Castle River #1	40	350.440	28.7
Cowley Ridge	38	332.918	7.4
Kettles Hill	9	78.849	27.4
McBride Lake	75	657.075	34.4
Summerview	68.4	599.252	34.9
Suncor Magrath	30	262.830	36.6
Taylor Wind Farm	3.6	31.540	18.8
Hypothetical sites in north-eastern British Columbia[a]			
Aasen	2.3	4.250	21.1
Bessborough	2.3	3.387	16.8
Erbe	2.3	3.603	17.9
Bear Mountain	2.3	7.044	35.0

[a] Values are based on wind data for these sites, converted to power output for a single 2.3 MW turbine as described in the text.

Reserve Requirements

Next consider reserve requirements. By installing wind generating capacity, greater system balancing reserves are required than would normally be the case if an equivalent amount of thermal or hydro capacity were installed. This is true even after one adjusts for the lower capacity factors associated with wind. The reliability of power from wind farms is lower than that of thermal or hydro sources because of the high variability associated with wind power, and this variability must be compensated for by greater system reserves.

Suppose that σ_s and σ_d are the standard deviations of supply and demand fluctuations, respectively. Then, as a rule of thumb, a system operator requires reserves equal to three standard deviations of all potential fluctuations, or reserves = $\pm 3\sqrt{\sigma_s^2 + \sigma_d^2}$ (see Gross et al. 2006, 2007; DeCarolis and Keith 2005). If wind farms are added to an existing grid, required reserves must be increased to $\pm 3\sqrt{\sigma_s^2 + \sigma_d^2 + \sigma_w^2}$, where σ_w is the standard deviation associated with wind intermittency. If $\sigma_w > \sigma_s$ and wind replaces other generation that is more reliable, then reserves must increase; if $\sigma_w < \sigma_s$, reserve capacity would decline. How large must the additional reserves be? According to Gross et al. (2006, 2007), assuming no correlation between demand and variable supply from wind, additional reserve requirements would be small. Suppose that, as they find, the standard deviations of wind fluctuations amount to 1.4% of installed wind capacity for a 30-minute time horizon and 9.3% of installed capacity over a four-hour time period.[25] For the shorter time horizon, regulating or fast-response reserves are affected, while contingency or standing reserves are affected in the case of the longer time horizon.

If there is 10 GW of installed wind capacity, then σ_w would equal 140 MW for regulating and 930 MW for contingency reserves. Suppose further that total generating capacity is 24.3 GW and that $\sigma_s+\sigma_d$ = 340 MW. Then regulating reserves would need to equal 1020 MW (= $3 \times \sqrt{340^2}$) without wind and 1181 MW (=$3\times \sqrt{340^2+140^2}$) with wind, while respective contingency reserves would need to be 6780 MW and 7332 MW. Thus, wind intermittency requires increases in regulating reserves of 15.8% (161 MW) and contingency reserves of 8.1% (552 MW).[26] These are not insignificant requirements. Yet, they are likely an underestimate because they are based on the assumption that there is no correlation between wind output and load, which is unlikely as wind blows to a greater extent at night when demand is low (see, e.g., Pitt et al. 2005).

Modeling the Management of an Electricity Grid

In addition to the need for greater system reserves, there is a second cost associated with the need to retain system balance, the added cost of managing the grid (Lund 2005). How the grid is to be managed depends on the policy implemented by the authority. If the grid operator is required to take any wind power that is offered (wind is 'must run' or non-dispatchable), extant generators may need to operate at partial capacity, although they must be ready to dispatch power to the grid in the event of a decline in wind availability. Peak-load diesel and simple (open-cycle) gas plants and, to a much lesser degree, combined-cycle natural gas plants are able to ramp up and down to some extent.[27] If they are unable to match the ups and downs in wind power availability, there will be excess power in the system that must be sold to another operator, usually at low cost. With non-dispatchable wind power entering a grid, there is an economic cost because other generators in the system operate more often below their optimal efficiency ratings (less than their optimal instantaneous capacity factors). In addition, wind variability causes peak-load diesel and open-cycle gas plants to stop and start more frequently, which

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[25] These standard deviations would vary from one location or jurisdiction to another.

[26] These are the current author's calculations using values from Gross et al (2007). Although not given, total generating capacity is approximately 24.3 GW. However, there is no discussion in Gross et al. (2006, 2007) as to whether wind generating capacity simply replaces conventional generating capacity, yet this seems to be the logical assumption based on the discussion found in these sources. The analysis presented here suggests that this is a highly optimistic analysis of wind power.

[27] CCGT plants employ heat that escapes out of the stack in an open-cycle system to generate additional electricity. While CCGT plants can be built to ramp more quickly, there is always a tradeoff that adds to cost. Even coal-fired generators can be built to better track changes in output from variable generating sources, but again at increased cost in terms of reduced efficiency and greater wear and tear of equipment.

increases operating and maintenance (O&M) costs.

A suitable constrained optimization or mathematical programming model of an electricity grid can be used to address these issues. Models assume load and wind power availability are known beforehand (which is referred to as 'rational expectations' in mathematical programming models). A grid optimization model takes explicit account of the need to balance output from existing generators on the grid (Prescott and van Kooten 2009; Maddaloni et al. 2008a; Prescott et al. 2007). Costs of new transmission lines from wind assets to an existing grid are ignored for convenience. Also, the grid management model does not take explicit account of the additional investments in reserve capacity that might be required – the need for additional backup generation should one or more generators in the system fail, given that wind cannot be used for backup generation because of its intermittency. The constrained optimization model that is used to develop outcomes described below is linear, with constant marginal generation costs and simple capacity limits and ramping constraints; it is more fully described in van Kooten (2010). Linear models are often sufficiently robust and useful when the intention is primarily to investigate the effects of government policies.

It is difficult to replace conventional generation capacity with non-dispatchable wind power and maintain system reliability (Liik, et al. 2003; ESB National Grid 2004; Lund 2005; Pitt et al. 2005). To illustrate the problems and, at the same time, provide estimates of the costs of reducing CO_2 emissions, we examine integration of wind into three grids with different generating mixes. We denote the three generating mixes as 'high hydro', 'typical' and 'high fossil fuel,' with details provided in Table 11. The high hydro mix contains 60% hydroelectric generation with the other 40% allocated between nuclear and other thermal generating units. Typical is made up of 50% pulverized coal generation and 20% nuclear generation along with hydro and gas-fired units, while high fossil fuel also has 50% coal fired generation, some gas and hydro but no nuclear units.

Table 11: Generating Mixes as a Percent of Total Installed Capacity

Technology	High Hydro	Typical	High Fossil Fuel
Hydroelectric	60%	8.4%	10%
Nuclear	12%	20%	0%
Pulverized coal	18%	50%	50%
Combined-cycle NG (CCGT)	6%	18%	34%
Other (biomass)	4%	3.6%	6%
TOTAL	**100%**	**100%**	**100%**

Source: van Kooten (2010)

We employ hourly load data from the ERCOT (Texas) system for 2007, and wind data from sites located in western Canada.[28] The ERCOT load data are standardized to a peak load of 2,500 MW (multiplying load data by 2,500 MW and dividing by ERCOT peak load of 62,101 MW). Wind power output consists of actual data from wind farms in southern Alberta and wind speed data for British Columbia (Table 10), converted to wind energy using a turbine manufacturer's power curves. Net load equals demand minus wind output, assuming wind penetration rates of 0%, 10% and 30%, where penetration is the ratio of installed wind capacity to peak load.

The costs and benefits of introducing wind power into an electricity grid depend on the generating mix of the particular grid. To provide estimates of the costs and benefits of wind, the model takes into account fuel costs, operating and maintenance (O&M) costs and investment costs, as well as life-cycle CO_2 emissions. This information is provided in Table 12. Linearity permits optimization over a full year or 8760 hours. Operating reserve requirements (regulating and contingency reserves) are ignored.

Table 12: Example Cost Data for Generating Technologies

Technology	Fuel Cost [$/MWh]	Variable O&M [$/MWh]	Construction Cost [$ 10^6/MW]	Emissions [kg CO_2 per MWh][a]
Hydroelectric	1.13[b]	0.02	1.55	0.009 (0.0284)
Nuclear	6.20	0.07	1.70	0.012 (0.0147)
Pulverized coal	13.70	0.70	1.10	0.980 (1.1340)
Combined-cycle natural gas (CCGT)	37.00	5.00	0.55	0.450 (0.0496)
Open-cycle NG (peak plant)	41.00	4.50	0.46	0.650 (0.0496)
Wind	0	0.17	1.30	0.015 (0.0200)

[a] Emissions data vary from one source to another and depend on the methods used to calculate life-cycle emissions, quality of fuel, etc.. Data in parentheses are from a second source.
One might expect the fuel cost to be zero, but Natural Resources Canada, in a 2005 report entitled 'Greenhouse gas and cost impacts of electric markets with regional hydrogen production' (Report No. 2007), indicates that there is a fuel cost.
Source: van Kooten (2010)

The simplifying assumptions (including linearity) are for simplicity only (although wind power output can be forecast with a relatively high degree of certainty), and they do not in any way jeopardize the main conclusions that are reached. Indeed, it turns out that the main conclusions from linear models with rational expectations are reinforced if nonlinearities and uncertainty are added. This is confirmed by other researchers (e.g., Prescott and van Kooten 2009; Maddaloni et al. 2008a, 2008b; Weber 2005; Lund 2005).

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[28] Electric Reliability Council of Texas (ERCOT) data are from http://ercot.com/, but all ERCOT and BC data are available at: http://web.uvic.ca/~kooten/documents/LSRS2009WindData.xls.

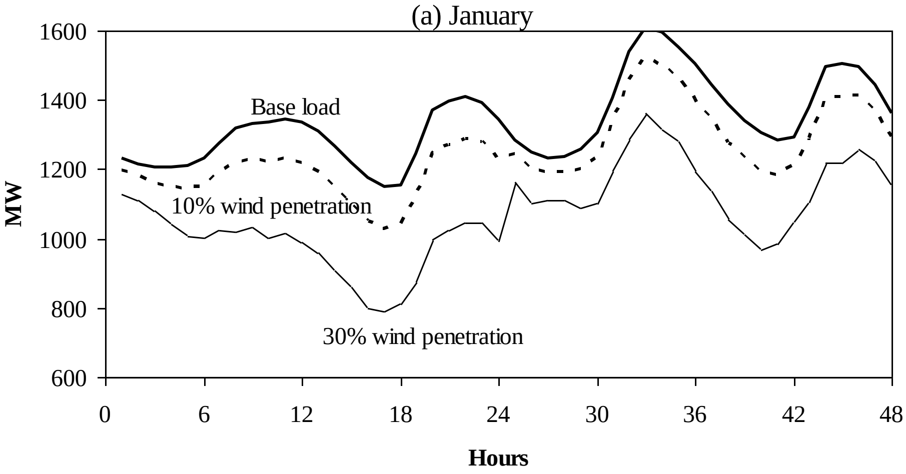
Once we have developed a model to simulate management of an electricity grid, we would like to use it to answer some policy questions. The central question of concern is the following: What is the expected cost of reducing CO_2 emissions by building and operating wind turbines to generate electricity? To what extent will electricity rates have to increase? What are the impacts of wind turbines on existing generating facilities? What if any are the limits to substituting fossil fuel generated electricity with wind power?

Some Model Results

A linear program similar to that described in van Kooten (2010) is employed to simulate the introduction of various levels of wind generating capacity into the electricity grids described in Table 11. Simulation results are provided in Figures 7, 8 and 9.

In Figure 7, we provide the load (demand) profile facing existing generators when available wind power is subtracted from the original load. This assumes that wind power is must run or non-dispatchable. The data are only for two 48-hour periods, one in January and one in July, so that the load profile can be better identified. It is important to recall that, since the data represent a Texas load, summer demand is higher than it would be in more northern latitudes as power is required for air conditioning as opposed to heating; heating is more prevalent in January. Note that, once wind power has been subtracted from the load, the remaining demand profile has greater variability than the non-wind load, although the adjusted series still track the morning (0600-1200) and evening (1800-2300) peaks quite well. The higher the extent of wind penetration, the greater is the volatility of the remaining load. If a longer profile were chosen, the volatility would be even sharper.

Clearly, wind penetration will vary according to the extant generating mix. This is shown in Figure 8, where output is indicated by generation type for various levels of wind penetration. For the generating mix with high hydro capacity in Figure 8(a), hydropower adjusts instantaneously to changes in wind, enabling nuclear and coal-fired base load plants to operate at the same capacity as wind penetration increases. This means that the base-load plants do not need to operate below the most efficient operating levels. In a mix with less hydro capacity, namely, the typical mix in Figure 8(c), outputs of base-load nuclear and coal facilities vary and they operate at lower average capacity (lower capacity factor) as wind penetration increases. Finally, in a fossil fuel generating mix (panel c), hydro's capacity factor changes least because almost all hydro capacity is utilized; hydro and gas adjust to short-term fluctuations in net load. Coal generation is affected by increasing wind penetration, leading to excess generation, because it cannot adjust quickly enough to changes in net load.



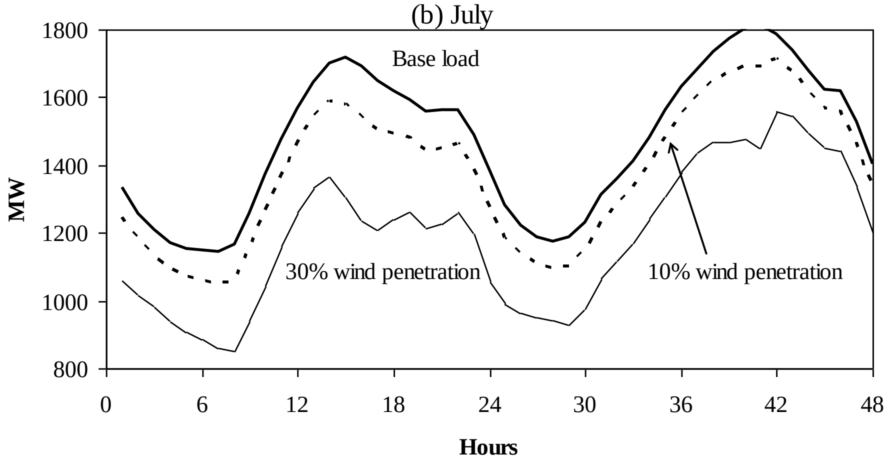
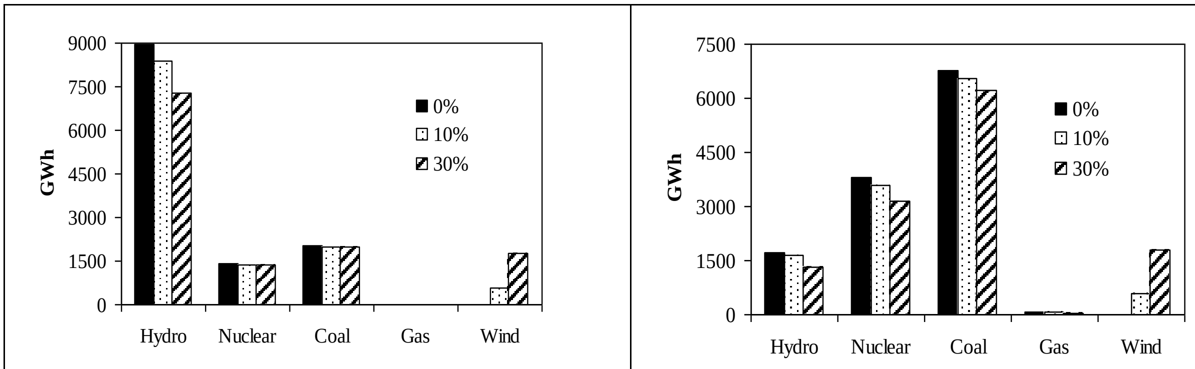


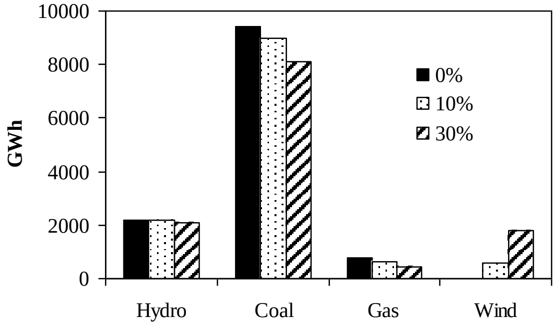
Figure 7: Load or Demand to be met by traditional generators for the first two days (48 hours) in (a) January and (b) July

Despite perfect foresight regarding wind availability, generators cannot adjust their output quickly enough to prevent unnecessary generation, unless there is sufficient hydro generating capacity. Hydroelectric units can be adjusted on extremely short notice. As a result of excess thermal generation, the reduction in CO_2 emissions associated with the integration of wind assets is also relatively small, and is largest for the fossil fuel mix. For 30% wind penetration, the largest reduction in emissions amounts to only 14.5% of the zero wind scenario, and then only for the fossil fuel mix; for the typical and high hydro mixes, CO_2 emissions are reduced by only 8.1% and 1.3% respectively. Clearly, the degree to which wind power is able to reduce CO_2 emissions depends on the amount of hydroelectric and nuclear generating capacity there is in the generating mix, as these emit little CO_2.



(a) High hydro

(b) Typical



(c) High fossil fuel

Figure 8: Effect on Power Production from Various Sources as Wind Penetration Increases, Various Generating Mixes

The average and marginal costs of reducing CO_2 emissions are provided in Table 13 for wind penetrations of 10% and 30%. Average and marginal costs are lowest for the high fossil fuel mix and greatest for the high hydro mix, with marginal costs in the case of the high hydro mix more than $1,000 per tCO_2 even for wind penetration rates as low as 5%. This is the result of introducing zero emissions technology into a generation mix that already produces little in the way of CO_2 emissions. Thus any additional CO_2 reductions come at great cost. For a grid with mainly fossil fuel units, emission reductions can be produced at much lower marginal cost ($43.79/$tCO_2$ vs. $1,622.29/$tCO_2$ for 10% wind energy penetration).

Finally, the introduction of wind power into most electricity grids does not imply that other generating assets can be replaced. There are times when no wind, or too little wind, is available (for the wind profiles of north-eastern BC and southern Alberta there were 18 hours without wind), and the number and times when this occurs vary from one year to the next. As a result, extant generators cannot be replaced with wind turbines, and certainly not one-for-one. Therefore, electricity costs will need to increase whenever wind generation is added to the mix. We find that, electricity costs rise by 16% to 73% for 10% wind penetration, and much more for higher penetration levels (Table 13). These increases are not balanced by an efficient reduction in the externality as costs for reducing CO_2

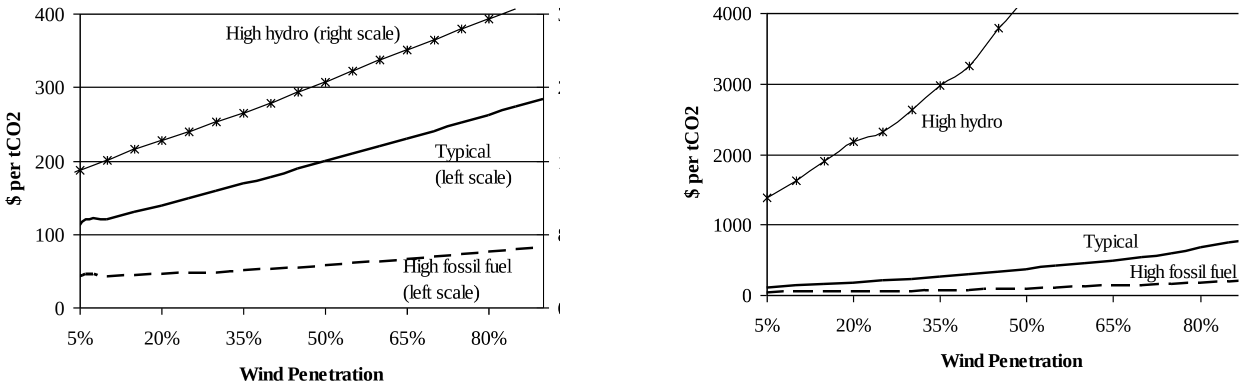
emissions exceed the costs of purchasing emission offsets in markets.

Table 13: Marginal Costs of Reducing CO_2 Emissions

Generation mix/ Wind penetration	Reducing emissions per tCO_2		Increase in costs per MWh	
	10%	30%	10%	30%
High hydro	$1,622.29	$2,639.25	73%	245%
Typical	$130.68	$229.38	26%	88%
Fossil Fuel	$43.79	$57.06	16%	58%

The above results were obtained using a linear mathematical programming model. To see how sensitive our results are to the linearity assumption, we consider results from Maddaloni et al. (2008b). While the linear model assumed per unit generating costs did not vary with the level of a generator's output, Maddaloni and his colleagues investigated the integration of wind into an extant grid using a nonlinear constrained optimization model that permitted declining efficiency at below optimal operation of generators. As a result of computational restrictions, they could only run scenarios over two weeks (336 hours); they used representative winter and summer load and wind profiles. The generation mixes were typical of those found in Canada (closer to 'high hydro' in Table 13), the United States ('high fossil fuel') and the Pacific Northwest Power Pool (NWPP or 'typical'), but normalized to 2054 MW rather than 2500 MW; thus, the generating mixes were not dissimilar from those in Table 11.

Average and marginal costs for Maddaloni et al. (2008b) are provided in Figure 9 for a range of wind penetration levels. For a grid with mainly fossil fuel units, emission reductions can be produced at much lower average and marginal costs than with the typical or high hydro mixes. Only for the fossil fuel mix are average and marginal costs below some $50 per tCO_2 emissions reduction, and then only up to a penetration of about 20%. Nowhere are emission reduction costs below $30 per tCO_2. Results in Figure 9 suggest that wind can be integrated into a U.S. (high fossil fuel) or NWPP (typical) mix at a 'reasonable' cost of reducing CO_2 emissions (say, lower than $50 per tCO_2), but then only to a penetration of about 15% for the U.S. mix but 50% for the NWPP mix.



(a) Average Costs

(b) Marginal Costs

Figure 9: Average and Marginal Costs of Reducing CO_2 Emissions for Various Wind Penetrations and Three Generating Mixes

Other studies find similar high costs of reducing CO_2 emissions, in contrast to the finding by the U.S. Department of Energy (2008) that wind power could reduce CO_2 emissions at a cost of \$5.70/tCO_2. A German study by Rosen et al. (2007) found costs of reducing CO_2 emissions rise from €87.70/tCO_2 to €125.71/tCO_2 and then to €171.47/tCO_2 as wind power production increases from 12.0 TWh (6 GW installed capacity in 2000) to 34.9 TWh (17.3 GW 2005) and 50.4 TWh (22.4 GW 2010) corresponding to respective wind penetrations of about 8%, 23% and 29%.

The results presented above indicate that several factors must be aligned before wind energy can reduce system-wide CO_2 emissions at reasonable cost. These include the load and wind profiles, and crucially the existing generating mix into which wind power is to be integrated. Operating constraints for coal- and gas-fired base load generation lead to overproduction of electricity during certain periods, because units cannot ramp up and down quickly enough when wind energy is available. This results in less emission reductions than anticipated. Wind integration into a system that has high nuclear and/or hydroelectric generating capacity might also see fewer CO_2 benefits than anticipated as wind displaces non-CO_2 emitting sources, despite the ability of some hydro facilities to fluctuate as quickly as wind. Hydro storage is an advantage, but not always. The research indicates that a high degree of wind penetrability is feasible (negative to low costs of reducing CO_2 emissions) for flexible grids such as the NWPP that have sufficient hydro for storage and relatively fast-responding gas plants that track changes in load minus non-dispatchable wind, while keeping base-load nuclear and coal power plants operating efficiently (with only minor changes in output).

Rather than allowing extant generators to vary their output, thus increasing system costs, an alternative policy is to make wind power dispatchable by requiring wind operators to reduce output (by ‘feathering’ wind turbines or simply stopping blades from rotating) whenever the grid operator is unable to absorb the extra electricity. In this case, output from base load plants is effectively given precedence over wind generated power because such plants cannot be ramped up and down, the ramping costs are too great, and/or excess power cannot be stored or sold.[29] In Alberta, for example, further expansion of wind farms was initially permitted only after developers agreed to control power output so that wind power was no longer 'must run.' This policy makes investments in wind farms must less attractive and is usually unacceptable to environmental groups.

Another possibility is to permit wind farms only if they come with adequate storage, which generally means they need to be connected to large-scale hydro facilities that have adequate reservoir capacity, or are bundled with a peaker plant. With respect to the latter, the output of a wind facility would be reliable because any shortfall in wind output would be covered by natural gas. However, as noted earlier, this has a drawback because wind variability tends to increase the costs of a peak gas plant because of the more frequent stops and starts.

Placement of several or many wind farms across a sufficiently large geographic area is also a possibility that has been promoted for mitigating wind's intermittency. To overcome variability, it is argued, wind farms can be located across as large a geographic area as possible, with their combined output integrated into a large grid. By establishing wind farms across the entire country, onshore and offshore, the United Kingdom hopes to minimize the problems associated with intermittency. Further, by connecting all countries of Europe and placing wind farms throughout the continent as well as in Britain and Ireland, the hope is to increase the ability to employ wind generated power. But, as demonstrated by Oswald et al. (2008), large weather systems can influence the British Isles and the European continent simultaneously. Oswald and his colleagues demonstrated that at 18:00 hours on February 2, 2006, electricity demand in the United Kingdom peaked, but wind power was zero (indeed wind farms added to the load at that time). At the same time, wind power output in Germany, Spain and Ireland was also extremely low – 4.3%, 2.2% and 10.6% of capacities, respectively. The wind data presented above suggest that something similar occurs with respect to wind farms located some 1000 km apart in the Great Plains of Canada near the Rocky Mountains (van Kooten 2010). Thus, even a super grid with many wind farms scattered over a large landscape cannot avoid the problems associated with intermittency, including the need to manage delivery of power from various non-wind power generators.

The best strategy for dealing with the issue of integrating intermittent wind and other renewable resources into electricity grids is to provide incentives that cause the intermittent resources to take into account the costs they impose upon the grid. We have already noted that some European jurisdictions penalize wind power providers if they deliver more or less than an agreed upon amount of electricity to the grid – they incur a penalty for variability. This might cause producers to waste renewable energy if they exceed the limit, or pay a fee if they are under it. However, it also provides strong incentives to store electricity or build backup power plants.

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[29] In practice, base-load coal and nuclear power plants do not vary output, while CCGT plants have some ability to ramp up and down (although preference is not to do so). Peak gas plants tend not to be turned off and on more than once during a 24-hour period. Hence, wind variability creates problems that can only be handled in current grids by selling electricity to other jurisdictions or forcing wind plants to reduce output if necessary.

It is also possible that special ancillary markets develop to mitigate intermittency. This amounts to the provision of the same incentives as a penalty regime. Payments for backup services provide service providers with incentives to store electricity and/or ensure sufficient backup services are available at lowest cost.

Finally, upon examining the potential of wind energy to meet global society's energy needs, Wang and Prinn (2010) conclude that, if 10% of global energy is to come from wind turbines by 2100, it would require some 13 million turbines that occupy an area on the order of a continent. Wind turbines themselves would cause surface warming exceeding 1°C over land installations, and alter climate (clouds and precipitation) well beyond the regions where turbines are located – reducing convective precipitation in the Northern Hemisphere and enhancing convective precipitation in the Southern Hemisphere. Wind turbines on such a massive scale would also lead to undesired environmental impacts and increase energy costs because of the need for backup generation, onsite energy storage and very costly long-distance power transmission lines.

5. Discussion

Despite an economic crisis, the United States, Canada, Europe, Japan and Australia, to one degree or another, are implementing climate policies in a major effort to reduce emissions of greenhouse gases. They are using the powers of the state to shift their economies towards ones that are carbon-neutral and even nuclear-free. At the moment, wind energy plays a very important role in this shift. Will this continue or is it a passing fad? What are the prospects for a carbon-neutral world?

In February 2010, a group of climate economists met at Hartwell House, Buckinghamshire, England, under the auspices of Oxford University and the London School of Economics, to examine the next step regarding global climate policy (Prins et al. 2010). The background to the meeting was the failure of countries to agree to limit global emissions of CO_2 at the 15th Conference of the Parties to the UN Framework Convention on Climate Change (UN FCCC) at Copenhagen in late 2009. The economists recognized that fossil fuels are both too cheap and too expensive. They are too cheap because they impose a global externality by way of CO_2 emissions that lead to climate change, but they are also too expensive because many poor people lack access to sufficient energy to enable them to escape poverty.

As reported in *The Economist* (September 25, 2010, p.117), in 2009, 1440 million people lacked access to electricity, while some 2.7 billion still cook their food on inefficient stoves that use dung, crop residues and fuel wood. Perhaps 500,000 people die prematurely each year because of health problems associated with biomass-burning, poorly-ventilated stoves. Collection of biomass for burning occupies much of women and children's time, robs cropland of important nutrients that can only partly be replaced by artificial fertilizers from offsite, and causes deforestation. One-quarter to one-third of the world's population needs to be provided with electricity and high-density energy, such as can currently only be found in fossil fuels, so that they can raise their standards of living. It would be immoral to deny the poor the ability to develop by curtailing their access to cheap energy.

The result is a *huge dilemma*: We can pursue the rich world's environmental climate objectives only by denying developing countries the cheap energy needed for economic development. Wind energy can help in some cases, particularly in developing countries that have unreliable grids and where diesel generation is the most common source of power or backup generation (van Kooten and Wong 2010). However, in most other cases, compared to fossil fuels wind sources of energy simply cannot compete with coal, petroleum and natural gas as a foundation for economic development. After all, there are sufficient fossil fuels and they can be made available cheaply enough to drive economic development of even the least developed nations.

The problem is not lack of resources; it is the obstacles that both rich and poor countries put in the way of exploration, development, transportation and distribution of energy. Rich countries block exploitation of all sorts of natural resources on the grounds of their potential adverse environmental impacts, while poor governance, corruption and failure of rule of law hinder all aspects of the energy supply chain, resulting in huge waste. Sources of low-cost, fossil-fuel energy are plentiful enough to drive economic development. The problem is the lack of will to do so.

The dilemma is that rich countries have agreed to pursue policies of economic development in poor countries, so that living standards of the poor converge towards those of the rich. But rich developed countries have also agreed to de-carbonize the global economy. These objectives are incompatible. China and India recognize this all too well, which is why they refused to allow rich countries to seduce them into limiting their greenhouse gas emissions. The incompatibility between these goals led to the failure to reach a climate accord at Copenhagen.

What has been the response of the developing countries to the aforementioned dilemma? Surprisingly, rather than focus efforts on helping poor countries access sources of energy to enable the economic growth required to adapt to the negative effects of climate change, rich countries are acting as if there is no dilemma whatsoever. They are ramping up efforts to de-carbonize their own economies while continuing to threaten and cajole developing countries into doing the same – the focus is on mitigating climate change and not adapting to it. The developing countries have simply rejected such efforts, continuing to expand their energy consumption and CO_2 emissions as fast as they can. China is in the forefront, with India coming on and others likely to follow in the not-too-distant future.

Consider the evidence. Coal is primarily used by industrial countries to generate electricity and make steel. Coal consumption by the U.S., Russia and Japan has remained relatively flat since 1990, while that of Germany declined slightly, mainly because of unification and the closing of inefficient coal-fired power plants and steel factories in the east. Indian consumption has risen slowly and should overtake U.S. consumption within the next several years. However, Chinese consumption of coal has increased some threefold since 2000, and fourfold since 1990. The same picture emerges if you consider installed electrical generating capacity, which has remained relatively unchanged in most countries over the period 1990-2007, with the exception of the United States and China. U.S. capacity has increased by some 260 GW (or 36%), while that of China increased by a whopping 578 GW (519%) and India by 84 GW (210%).

One thing is abundantly clear. No matter what rich western countries are doing about CO_2 emissions, global emissions of CO_2 will continue to rise inexorably. In addition to wind, nuclear and gas capacity, China is currently adding 1,000 MW of installed coal-fired generating capacity every week, and Chinese consumption of coal in 2009 exceeded the total consumption of Germany, Russia, India, Japan and the United States combined! Despite this, China's generating capacity lags behind that of the United States by more than 30 percent, although total generation of electricity lags that of the U.S. by only about 20 percent. This is partly because the U.S. is a net importer of electricity from Canada.

The response of the developed nations has been to stick to the ill-advised UN FCCC Kyoto process as the roadmap to follow and to try to impose it upon the rest of the globe. In September 2010, U.S. Senators again introduced a bill requiring a Renewable Energy Standard (RES) that would require 3% of electricity to be generated from renewable sources by 2012 and 15% by 2021. Similar to the generous feed-in tariffs provided by the province of Ontario, these provide huge subsidies to wind and solar companies. The costs to the Ontario treasury of its feed-in tariff program are estimated at \$2.4-\$2.6 billion per year, although budgetary pressures will cause politicians to pass costs onto electricity consumers in the form of large rate hikes. In terms of climate change, the Ontario program reduces emissions at a cost of hundreds of dollars per ton of CO_2, but does absolutely nothing to forestall global warming because of what is happening in China, India and elsewhere. The same can be expected of the U.S. program and similar programs in Europe, where targets require countries to a 20% RES in the production of electricity by 2020.

Despite the fact that none of these programs, even collectively, can impact climate change, why do governments continue to pursue them? One reason is the mistaken notion that these large subsidies will lead to greater employment and the development of a renewable energy sector that is a global leader. Every country believes it will be the global leader in the development of wind turbines and/or solar panels. However, research indicates that public funds directed at the renewable energy sector actually reduce employment by crowding out private sector investment or public infrastructural investments elsewhere in the economy (e.g., investments in transportation infrastructure that reduce costs of moving goods and people) (Álvarez et al. 2009; Morriss et al. 2009). Indeed, it appears that the main winner from efforts by countries to expand wind and solar output are the Chinese. China currently controls the supply of rare earth minerals which are used to make solar panels and parts of wind turbines, among other things. Recently, China restricted exports of these minerals as it desires to export the manufactured products in which they are found (Humphries 2010). China gains from subsidies to solar and wind producers.

The other reason for pursuing the Kyoto roadmap comes from environmental groups and the media, which together have convinced politicians to do something about reducing greenhouse gas emissions and reducing the so-called carbon footprint. Doing something, anything, is not always wise. Economists have long known that governments cannot pick winners and, worse, government subsidies can lock-in technologies that become a hindrance to more efficient energy use rather than a solution.

Then what about wind? While a clean source of energy, wind power must be able to compete in the market place. It must be able to compete in the production of electricity without subsidies of any form. But other generating sources must also compete without subsidies – the playing field must be level and the role of government is to ensure that this is indeed the case. The government should not be in the business of trying to pick winners. Under these circumstances and because of problems with intermittency, the future role of wind power might be limited. As with any good thing, there comes a point where more may not be in the best interests of society – where the marginal social benefit from installing more wind capacity equals the marginal social cost. A buoyant and optimistic wind sector is of the opinion that that point is still far in the future. This might be true, but it may also be the case that the bubble is about to burst. Only time will tell.

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