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California Dreaming: The Economics of Renewable Energy

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Abstract:

California was the first jurisdiction to mandate a reduction in greenhouse gas (GHG) emissions by 80% below 1990 levels by 2050. This target was subsequently endorsed by the G8 in 2009 and the European Commission in 2014, and is the guiding principle of the 2015 Paris Agreement. To achieve these targets will require near elimination of fossil fuels and/or a technological breakthrough that might be considered a black swan event. Eschewing nuclear power, countries are relying on renewable energy sources to meet future energy needs. In this paper, I examine the prospects of reducing GHG emissions by 80% by first summarizing extant global energy sources and production, trends and projections of energy demand, and the potential mix of future energy sources. I consider the role of conservation and then focus on the electricity sector to determine how wind and biomass could contribute to the 80% target. I conclude that these ambitious targets cannot be attained without nuclear power.

Key Words: Climate change; intermittent energy; biofuels; nuclear power; fossil fuels

JEL Categories: H41, L51, L94, Q42, Q48, Q54

1. Introduction

At the 21st Conference of the Parties (COP-21) to the 1992 UN Framework Convention on Climate Change (FCCC) at Paris in December 2015, 195 countries agreed to what the European Commission claims is a legally binding agreement to reduce greenhouse gas (GHG) emissions so that the projected increase in temperatures would be kept below 2°C.[1] Much like the 1997 Kyoto Protocol, the Paris Agreement relies on countries to meet their self-declared targets, known as Intended Nationally Determined Contributions (INDCs), with shaming the main mechanism to enforce compliance. The Paris Agreement comes into force once 55% of countries accounting for 55% of GHG emissions ratify it. This implies that one of China, the United States or the EU must ratify the agreement. However, even if the Agreement is ratified, INDC targets are sufficiently vague to permit countries wiggle room to avoid meeting their obligations.[2]

Consider some examples of INDCs. Russia agreed to reduce GHG emissions by 70-75% from its 1990 level by 2030, but only 20-30% through emission reductions as the remainder would come from rational forest use, protection, maintenance and regeneration. Interestingly, Russia's current emissions are already 35% below 1990 levels. The U.S. would "make best efforts" to reduce emissions by 26-28% from a 2005 baseline by 2025. China agreed to begin reducing carbon dioxide (CO_2) emissions no later than 2030; lower CO_2 emissions per unit of GDP by 60% to 65% from the 2005 level by 2030; increase the share of non-fossil fuels in primary energy consumption to around 20%; and sequester an additional 900 gigatons (Gt) of CO_2 in forests between 2005 and 2030.[3]

Meanwhile, Canada committed to reduce its GHG emissions by 30% below 2005 levels by 2030. It intends to do this mainly by preventing construction of new coal-fired power plants and phasing out existing plants or converting them to co-fire with biomass, implementing regulations on vehicle fuel standards, and relying on forestry activities. There are two problems: (1) If Canada's past performance is a harbinger of what is to come, it will likely abrogate on its INDC commitment. CO_2 emissions fell by 3.1% as the economy grew by 12.9% between 2005 and 2013; this implied annual emission reductions of only 0.038% and economic growth of only 1.5% (which is much lower than expected in the future). Canada would need to reduce its CO_2

[1] Information from the European Commission's Climate Action website: http://ec.europa.eu/clima/policies/international/negotiations/paris/index_en.htm [accessed 11 April 2016]. The 2°C target implies that the atmospheric concentration of CO_2 would not exceed 450 parts per million.

[2] INDCs for each country are found at http://www4.unfccc.int/submissions/indc/Submission%20Pages/submissions.aspx [accessed 11 April 2016].

[3] As a guide for what follows: kilo is abbreviated k and equals 10^3; Mega (M, 10^6); Giga (G, 10^9); Tera (T, 10^{12}); Peta (P, 10^{15}). Watt (W) = 1 joule (J) per second, and is a measure of power; a measure of energy = power × duration (often in hours). Thus, a kWh = 10^3 W × 1 hour. Also, since CO_2 is the main concern, I often employ CO_2 emissions rather than GHG emissions.

emissions at an annual rate of 1.93% between 2013 and 2030 in order to achieve its Paris target (although had it started in 2005 the rate of reducing emissions would only have been 1.44%). (2) The burden of emissions reduction will fall on individual provinces, and they may not have great appetite for imposing costs on citizens.

The EU committed to "a binding target of an at least 40% domestic reduction in greenhouse gas emissions by 2030 compared to 1990," which explains why the European Commission claimed the Paris agreement to be legally binding. This target is "in line with the EU objective … to reduce its emissions by 80-95% by 2050 compared to 1990," pointing out in its INDC submission that this latter target had been agreed to by the developed countries (see also European Commission 2014). This was at the G8 meeting in L'Aquila, Italy in 2009 where countries agreed to limit the increase in global average temperature to 2°C by reducing global GHG emissions by 50% and their own emissions by 80% or more by 2050.

As usual, California has led the way. California's Global Warming Solutions Act of 2006 and Executive Order S-3-05 require the state to reduce its GHG emissions to 80% below 1990 levels by 2050, while accommodating projected population and economic growth.[4] Given California's population is projected to grow from 37 million in 2005 to 55 million in 2050, and assuming modest economic growth and business-as-usual efficiency gains in energy use, this would require that emissions fall from 470 $MtCO_2$ in 2005 to 85 $MtCO_2$ by 2050. In per capita terms, emissions would need to decline from 12.93 tCO_2 per person in 2005 to 1.56 tCO_2 by 2050, or an annual reduction in per capita CO_2 emissions of 4.8% over the next 45 years (compared to an annual rate of decline of only 0.8% in the previous 15 years). How likely is it that California's mandated target will be met? Or is it a case of California dreaming? What are the prospects that parties to the Paris agreement will meet their INDC targets?

In this paper, I seek to provide at least a partial answer to this question. To achieve a 50% reduction in global GHG emissions will require near elimination of fossil fuels in developed countries with no increase in fossil fuel use by developing countries. I show that it will be impossible to curtail global fossil fuels and simultaneously meet UN poverty-reduction objectives, at least not without a technological breakthrough reminiscent of a black swan event. I begin by summarizing the existing global energy mix, trends in energy demand, and projections of what the energy future might look like. Then, to limit the scope of the discussion, I examine the prospects for reducing fossil fuel use within the electrical generating sector (section 3) focusing on intermittent (section 4) and wood biomass (section 5) sources of energy. I conclude by arguing that the ambitious Paris targets cannot be attained without nuclear power.

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[4] The discussion in this paragraph is based on information from Long and John (2011).

2. Background

One argument used to justify public spending on alternative energy is that the globe will run out of fossil fuels and we need to prepare for that eventuality. Predictions that global oil production will soon scale 'Hubbert's peak' and begin to decline – that there will be an impending world oil shortage (Deffeyes 2001) – have been around for a long time. Hubbert's peak is predicated on the notion that prices and technology remain unchanged, but recent developments have shown that the 'peak' shifts outwards with improvements in technology and higher prices. From an economic standpoint, the idea that we will run out of oil (or gas or coal) is misguided (Mann 2013). As these resources become increasingly scarcer, prices increase, which, in turn, signals scarcity and thereby induces technological innovations that increase supply, reduce demand and lead to new sources of energy. This is evident from recent outputs of tight oil and shale gas; indeed, we may never run out of fossil fuels (Mann 2013; Covert et al. 2016). Therefore, arguments promoting renewable energy cannot be based on energy security and/or the potential scarcity of fossil fuels. Rather, the only arguments for reducing or eliminating fossil fuels relate to their economy (renewables are less costly) or to the need to mitigate climate change, or both.

While renewable energy can contribute to the needs of developing nations, economic growth will depend primarily on t coal, oil and natural gas, because they are relatively cheap and ubiquitous and an enormous improvement over heating with wood biomass, agricultural wastes, dung, et cetera. The proportion of those living in extreme poverty in China declined from 60% to 12% between 1990 and 2010, thereby enabling the UN to surpass its Millennium Development Goal of halving the number of people living below the poverty line of $1.25 per day by 2015 (United Nations 2014).[5] To accomplish this, China's primary energy consumption increased by an annual average of 8.9% since 1995, leading to a more than threefold increase in energy consumption from 904.7 million tons of oil equivalent (Mtoe) to 2,972.1 Mtoe in 2014.[6] During the same period, energy consumption in India increased slightly less than threefold, or by 7.4% annually. Coal consumption in both China and India grew at an annual rate of 5.4% between 1995 and 2014, while consumption of oil and gas grew annually in China (India) by 6.1% (4.5%) and 12.3% (5.2%), respectively.[7] China now accounts for 23.0% of total global primary energy consumption, more than the proportion accounted for by North America (21.8%) or Europe plus Eurasia (21.9%), while India accounts for 4.9%. As expected given its high level of consumption, China's annual increase in energy consumption has slowed to 2.6%, while India's

[5] The numbers living in extreme poverty went from 47% in 1990 to 22% in 2010, although absolute numbers declined only from 1.9 billion to 1.2 billion (UN 2014, pp.8-9). If China is excluded, the proportion living in extreme poverty went from 41% to 26%.

[6] Data are from *BP Statistical Review of World Energy* (January 2014), found at http://www.bp.com/statisticalreview [accessed 11 April 2016]. The unit 'toe' refers to tons of oil equivalent, with 1 Mtoe = 11,630,000 MWh of electricity.

[7] China also has the largest wind power capacity of any country (see section 4).

remains high at 7.1%.

Future growth in energy use will come almost exclusively from developing countries, including China and India that together account for about one-third of the world's population. Attempts by rich countries to reign in economic growth in poor countries for the purpose of mitigating climate change will be strongly resisted, although rich country subsidies for clean energy and investments in renewable energy will be welcomed by developing nations. Energy policies that lower rates of economic growth in developing countries will simply perpetuate the misery of millions of people who live in poverty, and such policies will be opposed *de facto* if not *de jure*.

It is difficult to forecast the future mix of energy sources since it is difficult to forecast future demand and technologies. Indeed, the California Council on Science and Technology report on California's prospects for achieving an 80% reduction in CO_2 emissions is rife with speculation concerning technological developments, because projections are 40 years into the future (Long and John 2011; Long and Greenblaat 2012). The BP projection of energy production over the next two decades is provided in Table 1. As expected, the proportion of total energy produced from coal and oil will decline, although energy produced from fossil fuels will continue to rise. While the growth rate in energy produced from coal does not exceed 0.5% per year and that of oil is only 0.75% per annum, natural gas use will rise at an annual rate of 1.74%. These expected low rates of growth partially reflect the fact that these energy sources already account for a large proportion of total production, so low rates of growth are accompanied by high absolute increases. But it also reflects policies to reduce CO_2 emissions, with the highest emission intensities associated with coal and then oil, followed by gas. Natural gas is expected to grow significantly because of its falling price relative to coal and oil, lower CO_2 emissions, and because it is reliable, easily transportable and crucial for backstopping wind power (van Kooten 2016a,b; van Kooten et al. 2013).

Growth in intermittent renewables, bioenergy and even hydroelectricity and nuclear energy is expected to increase by 45% or more overall during the period in question. Annual rates of growth in renewables and bioenergy exceed three percent simply because they begin from a low base and policies favor their use. Surprisingly, nuclear capacity is also expected to grow. At the end of 2013, 434 nuclear power plants were in operation with a combined capacity of 392 GW, accounting for 11% of global electricity production (down from a peak of 18% in 1996). Of these plants, some 200 are an older vintage, especially those in OECD countries, and are likely to be decommissioned in the next several decades. Japan and Germany have explicit policies to reduce or eliminate nuclear power, with both countries having to increase coal generation to compensate (Nicola and Andresen 2012). Meanwhile, the International Energy Agency (IEA 2014a) projects nuclear capacity in China, India and Russia to increase by 132 GW, 33 GW and 19 GW, respectively, so that, along with expanded capacity in other countries, global nuclear generating capacity will increase by nearly 60% to 624 GW by 2040.

Table 1: Forecast of Global Energy Production by Source, 2014 to 2035

	Proportion of Total[a]		Growth	
Energy Source	2014	2035	2014-2035	Annual rate
	Percent			
Renewables (solar, wind, etc.)	2.4	7.9	329.0	7.55
Bioenergy	0.5	0.8	86.6	3.17
Hydroelectricity	6.7	7.4	44.9	1.87
Nuclear	4.4	5.0	49.7	2.04
Coal	30.0	25.1	10.2	0.49
Natural gas	23.8	25.6	41.3	1.74
Oil	32.2	28.4	16.1	0.75

[a] Total energy production in 2014 was 13,122.0 Mtoe; production in 2035 is projected to be 17,279.4 Mtoe.

Source: *BP Energy Outlook to 2035* (http://www.bp.com/energyoutlook accessed April 11, 2016).

The IEA also provides forecasts of future energy requirements. Three scenarios are presented in Table 2. A comparison of Tables 1 and 2 indicates similar trends. The Central Scenario is much like the scenario in Table 1, with some 80% of energy demand and production originating with fossil fuels. In all scenarios, natural gas use expands along with that of oil and coal, except where the increase in the atmospheric concentration of CO_2 is held to 450 parts per million. The main difference between the two projections concerns the role of bioenergy. In Table 1, bioenergy is expected to play a minor role (less than 1% of future energy production) in 2035. In contrast, in Table 2 bioenergy accounts for about 10 percent of total energy in the Central Scenario (10.1% in 2020, 9.6% in 2040), but 10.8% (2020) to 16.2% (2040) in the 450 Scenario. That is, the IEA scenarios rely on solid biomass (primarily wood) and biogas produced from wet manure and maize to produce electricity and heat, with the shift to bioenergy accounting for the decline in coal use between 2020 and 2040 in the 450 Scenario.

The IEA (2014a) predicts coal use to increase by 50% if no further action is taken to address climate change (Central Scenario), while more modest efforts to reduce fossil fuels (New Policies Scenario) will still lead to a 15% increase in coal use. Only if drastic action is taken to prevent temperatures from rising more than 2^oC (450 ppm of CO_2 in the atmosphere) does reliance on coal decline by one-third by 2040, although it will still surpass current use in 2020.

Table 2: Primary World Energy Demand by Fuel and Scenario (Mtoe)[a]

Fuel	Current (2012)	Central Scenario 2020	Central Scenario 2040	New Policies 2020	New Policies 2040	450 Scenario 2020	450 Scenario 2040
Coal	3,879	4,457	5,860	4,211	4,448	3,920	2,590
Oil	4,194	4,584	5,337	4,487	4,761	4,363	3,242
Gas	2,844	3,215	4,742	3,182	4,418	3,104	3,462
Nuclear	642	838	1,005	845	1,210	859	1,677
Hydro	316	383	504	392	535	392	597
Bioenergy[b]	1,344	1,551	1,933	1,554	2,002	1,565	2,535
Other renew	142	289	658	308	918	319	1,526
Total	13,361	15,317	20,039	14,978	18,293	14,521	15,629
Fossil fuel share	82%	80%	80%	79%	74%	78%	59%

[a] Under the Central scenario, the growth rate of energy consumption falls from 2% to 1% after 2025; the New Policies scenario assumes that policies proposed or enacted by various countries to reduce CO_2 emissions as of mid-2014 are fully implemented; and the 450 Scenario caps the concentration of CO_2 in the atmosphere at 450 ppm as required to stabilize the projected temperature increase at 2^{o}C.
[b] Includes traditional and modern uses of biomass for energy.
Source: International Energy Agency (IEA 2014a, p.56)

In the remainder of this paper, I first examine the prospects of intermittent energy sources and biomass in the production of electricity. I ignore the role of biofuels that engages the agricultural sector more directly. One reason is that crops grown to produce biofuels for transportation, and advanced biofuels (based on waste and residues) that are under development, have little ability to reduce CO_2 emissions while negatively impacting grain and oilseed markets (de Gorter et al. 2015; van Kooten 2013, pp.394-397).

3. Global Electricity Sector

In order to reduce GHG emissions, it will be necessary to expand power output by a significant amount, while, at the same time, greatly reducing use of fossil fuels for generating electricity. Electricity is an increasingly important source of energy in many countries, because it is used for space heating, cooking, lighting, manufacturing, public transit (trains, trolleys, trams, subways), and personal mobility (electric and hybrid vehicles). Electricity is also important for powering the digital age – computers and digital storage are reliant solely on electricity. The IEA (2014a) forecasts that the share of electricity in total energy consumption will increase from 18% in 2012 to 23% in 2040, but technological developments related to hydrogen fuels, computers, electric vehicles, renewable energy, et cetera, could well increase the use of electricity to a much greater extent than anticipated. After all, there is a great deal of flexibility in generating electricity from various renewable and clean energy sources, including solar, tidal, geothermal, wave, biomass, run-of-river and traditional hydro, wastes, wind and even nuclear. The problem with some energy sources is their intermittency, which is best illustrated in the case of wind power (Baker et al. 2013). The problem with geothermal, tidal, wave and waste sources is that they are extremely expensive and difficult to implement on a significant scale, and their contribution to future power production is likely to be small. Solar power is promising but expensive and limited in northern regions, while environmental lobbying remains an obstacle to greater reliance on hydroelectricity, as evidenced by continued opposition to the Site C dam in northeastern BC.

Currently coal accounts for the majority of the world's power generation, followed by oil (including diesel) and hydraulics (Figure 1). Consider only electricity (Table 3). The annual growth in power generation is projected to surpass two percent in all countries except the OECD region, with rates of growth in electricity production below 1% only in Europe and the U.S. As a result, global electricity demand is projected to expand from 19,600 terawatt hours (TWh) in 2012 to 34,900 TWh in 2040, or by some 78%, even under a conservative scenario where steps are taken to reduce GHG emissions.

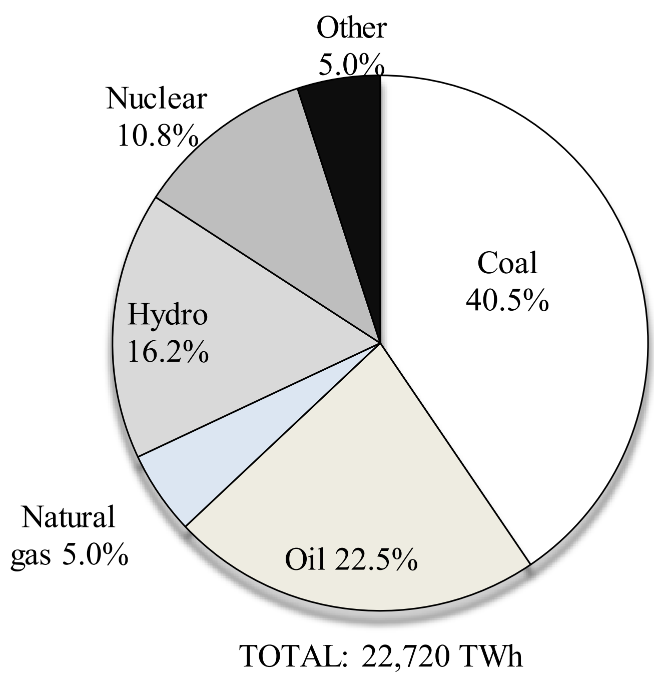

Figure 1: Global Electricity Production by Energy Source, 2012
Source: International Energy Agency (2014a, p.208)

Table 3: Electricity Generation by Region/Country, 2012, and Projected Generation for 2040 under the IEA's New Policies Scenario, TWh[a]

Region/Country	2012	2040	Rate of growth
United States	3,818	4,721	0.8%
OECD Europe	3,188	3,881	0.7%
Eastern Europe/Eurasia	1,400	2,086	1.4%
China	4,370	9,560	2.8%
India	869	2,915	4.4%
Africa	620	1,868	4.0%
Latin America	948	1,895	2.5%
Rest of World	2,337	5,921	3.4%
TOTAL	19,562	34,887	2.1%

[a] Excludes power consumption used to generate electricity.
Source: International Energy Agency (IEA 2014a, p.206)

Coal-fired power will dominate electricity production into the foreseeable future unless natural gas prices continue to remain low or even decline relative to those of coal, and/or nuclear energy becomes a politically acceptable alternative. China added 36 GW of coal generating capacity in 2013 and another 39 GW in 2014, and is expected to add the equivalent of a coal-fired power plant of 800-MW capacity every ten days for the next decade (Institute for Energy Research 2015). Japan is scheduled to add 43 new coal-fired power plants with a total capacity of 7.2 GW over the next five to seven years to provide reliable electricity output after closing many of its nuclear plants, while India expects to double its electricity production from coal to approximately 2,000 TWh (Business Standard 2015). China and India continue to rely on coal to generate electricity because it is cheap, secure, reliable (providing baseload capacity), and increasingly a clean source of energy, with only CO_2 emissions remaining a problem. These investments in coal-fired capacity could well be locked in for the next 50 or more years.[8]

As indicated in Table 4, the U.S. and China are by far the largest producers of electricity and of coal-fired power. They are followed by a rapidly expanding India, which went from being the fifth-largest producer of electricity in 2008 to third place in 2012 while increasing electricity from coal by 36%. U.S. production of electricity from coal fell by 33% between 2008 and 2012, while gas-generated power increased by 39%. The U.S. remains the largest producer of electricity from natural gas primarily as a result of shale gas plays. While gas plays an insignificant role in China (although this may change as a result of gas discoveries), China accounts for more than 23% of total global hydropower generation, followed by Brazil, Canada and the U.S. (Table 4), although the latter imported 47 TWh of hydroelectricity from Canada.

[8] A coal-fired power plant built in 1919 and operated by Alcoa Power Generating Inc. in North Carolina still generated electricity in 2013 (U.S. Energy Information Administration 2013).

India is also a major producer of hydroelectricity along with Russia. Yet, hydraulics account for less than 17% of total global generation compared with over 40% from coal and nearly 23% from natural gas. Oil accounts for less than 5% of electricity production, with Japan the largest producer followed by the oil producing states.

Table 4: Electricity Generation from Coal, Natural Gas and Hydropower, and Hydroelectric Generating Capacity, Selected Major Countries, 2012

Country	Total Electricity	Electricity from: Coal	Natural Gas	Hydro	Hydro Capacity
	-------------------------- TWh			------------------------	GW
China	4,985	3,785	[a]	872	194
United States	4,271	1,643	1,265	298	101
India	1,128	801	[a]	126	40
Russian Federation	1,069	169	525	167	49
Japan	1,026	303	397	84	49
Canada	634	[a]	[a]	381	76
Germany	623	287	[a]	[a]	[a]
France	559	[a]	[a]	[a]	25
Brazil	552	[a]	[a]	415	84
Rest of World	7,821	2,180	2,913	1,413	407
TOTAL	**22,668**	**9,168**	**5,100**	**3,756**	**1,025**

[a] Data directly unavailable since the country does not rank in the top ten of producers, and the data are included in the 'Rest of World' category.
Source: International Energy Agency (IEA 2014b)

Two things are clear from this discussion. First, rich countries are rich because they consume large amounts of energy per capita, especially electricity. Second, fossil fuels account for nearly 68% of global electricity generation, and with nuclear power and hydroelectricity, these sources account for 95% of electricity generation. While the non-hydro renewable share has increased from 0.6% in 1973 to approximately 5% today, it remains small. Clearly, the ambitious target of reducing reliance on fossil fuels as demand for electricity expands by 80% or more presents a tremendous challenge.

4. Prospects for Wind Energy

Wind energy is the poster child for the renewable energy sector. At the end of 2015, cumulative global wind generating capacity reached 432.4 GW (Figure 2); China installed more than 30 GW of wind power capacity during 2015, raising its total installed capacity to 145.1 GW compared to

141.6 GW in the EU, 74.5 GW in the U.S., and 11.2 GW in Canada.[9] Globally, wind farms have the potential to generate 3,790 TWh of electricity per year (=8760 hrs × 0.432 TW), or almost 17% of total electricity demand based on Table 4. However, this assumes that wind turbines would operate at or near full capacity all the time – that they would generate 432 GW of power every hour of the year. In practice, a baseload coal or nuclear power plant might operate at a capacity factor (CF) of 85-95%, but wind farms operate at much lower capacity factors.[10]

Winds are highly variable and turbines are unable to produce their maximum nameplate capacity most of the time. No electricity is generated until wind speeds reach a minimum threshold (about 3 m/s), while, at wind speeds exceeding 28-34 m/s (depending on turbine design), the blades must be turned to avoid wind damage and output could be severely restrained. Power output also changes as a function of wind speed, so power fluctuates rapidly and even unpredictably. This intermittency causes capacity factors for wind to be much lower than for thermal power plants. Hoskins (2015) reports that, for Europe, the CFs for onshore and offshore wind power averaged 21.2% and 30.0%, respectively, in 2013; for solar, CFs were approximately 11% (see also Darwell 2015). Finally, capacity factors vary across regions. The average CF for wind turbines in the EU is reported to be 22% compared with 33% for the U.S. and only 17% for China; based on 2012 data, wind energy accounted for 4.3% of global electricity production, which implied a CF of approximately 25% (Lacal-Arántegui and Serrano-González 2015, pp.29, 60).

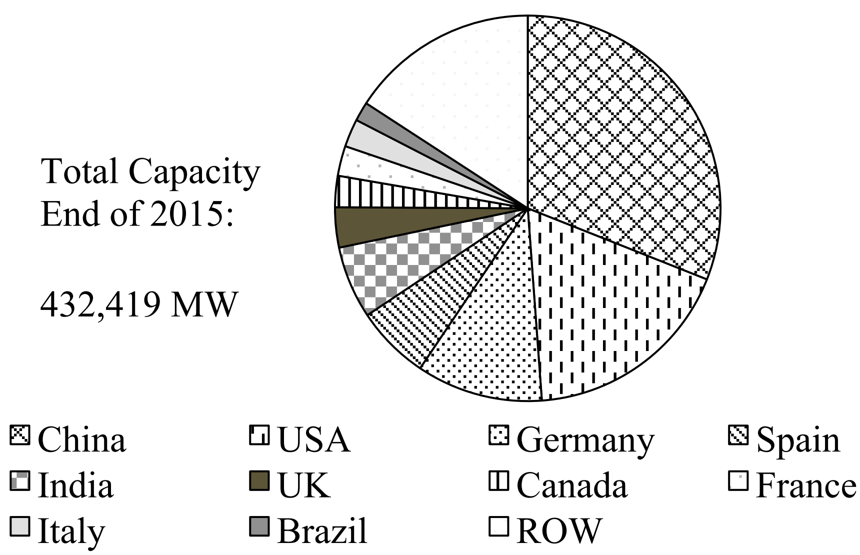

Figure 2: Installed Global Wind Generating Capacity, Top Ten Countries & Rest of World, 2015

[9] Developments in wind generation can be found at the Global Wind Energy Council's website: http://www.gwec.net/global-figures/wind-energy-global-status/ [accessed 13 April 2016].

[10] The CF is the ratio of the actual amount of power generated in one year to the potential power that could be generated if the asset operated at full capacity each hour during the year.

My students and I collected hourly wind speed data for 17 locations scattered throughout Alberta for the period 2004 through 2015. The location with the highest average wind speed (8.58 m/s) over the period for which we had data was Pincher Creek in southwestern Alberta; Barnwell, which is about 40 km east of Lethbridge, came a distant second with an average wind speed of 4.71 m/s, followed by Raymond, Lethbridge and Killam as the only five sites with average wind speeds above 4.0 m/s. Only Killam is not in southern Alberta as it is located in east-central Alberta. Based on the technical specifications for a 3.5-MW capacity Enercon E-101 wind turbine, we converted the wind speed data into power output. Then, by weighting each location equally, but Pincher Creek at four times the weight of the other locations, we aggregated the potential power production at each location into a single wind power profile for an Alberta-wide, 3.5 MW turbine. As indicated in Figure 3, the proportion of time that an Alberta-wind wind farm would produce more than about 60% of its capacity is surprisingly low – less than 8% of the time. The capacity factor averaged 28.7% over the 12 years reaching a high of 33.4% in 2013 and a low of 23.3% in 2010; for Pincher Creek, the CF averaged an incredible 55.5%, ranging from 33.9% (2010) to 79.8% (2013).[11]

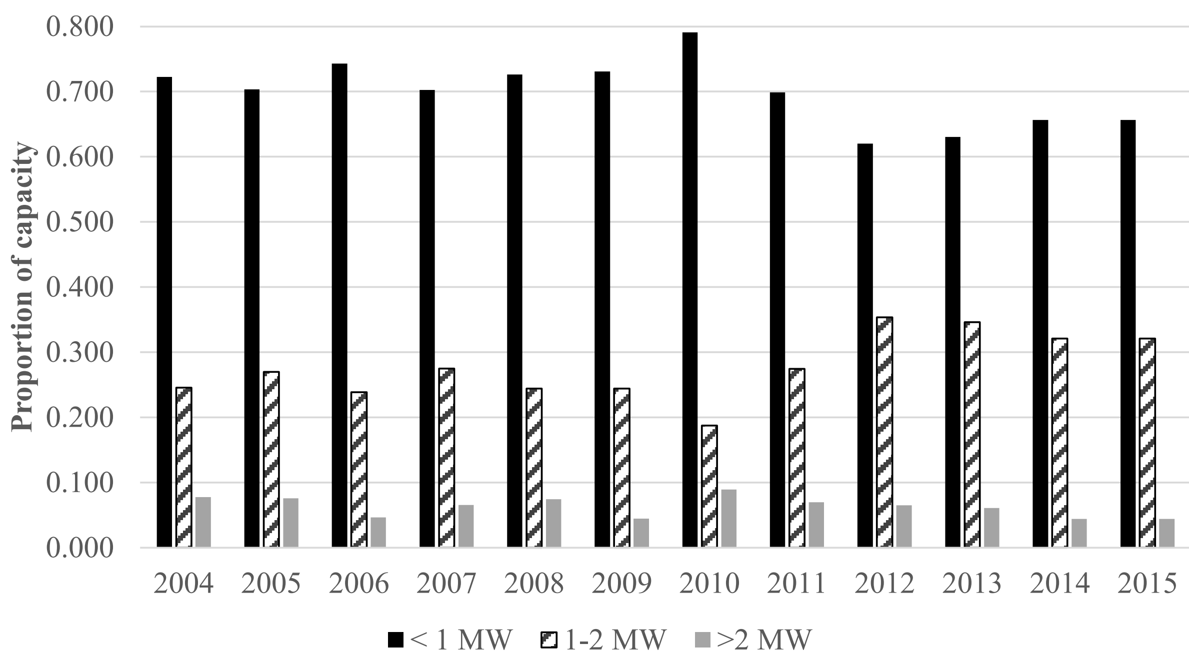

Figure 3: Proportion of the Time that a 3.5-MW Capacity Alberta Aggregated Wind Turbine would Produce less than 1 MW, 1-2 MW and more than 2 MW of Electricity during a Year, 2004-2015

[11] These numbers are potential and not actual CFs. Yet, for 2014, our calculations based on wind speed data indicate a CF of 32.7% while the realized CF was 35.6%.

An alternative perspective is given in Table 5. In this case, we reduced the sample to the period 2006-2015 to avoid some years when we considered the wind data to be less reliable due to missing observations. In the table, we provide the number of hours that wind power would supply various proportions of the installed nameplate capacity. Even if Alberta were to build wind farms across a vast area, about 60% of the time the power produced would be less than one-quarter of the installed capacity. Worse yet, about 96% of the time, wind power would be below half of the rated capacity; on average, there were only 17 hours per year when the potential electricity available from wind exceeded 75% of capacity. In some cases, there would be no wind output whatsoever; on average, there are five hours during the year when wind power output would be zero, ranging from zero hours in 2004 to 12 hours in 2008. That is, no matter how much wind capacity is installed in Alberta, or where it is located, there are times when no wind power will be produced and many, many times when wind power output is inadequate.

Table 5: Alberta Wind Power Output as Proportion of Available Capacity, Hours by Category, 2006-2015 and Average, Based on Averages across 17 Alberta Sites

% of Capacity	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Average
<1%	75	77	94	157	180	79	56	43	53	48	86
<10%	3,213	3,051	3,203	3,521	4,022	2,536	978	870	901	941	2,324
<20%	5,171	4,910	5,020	5,225	5,749	4,478	1,736	1,536	1,634	1,649	3,711
<25%	5,995	5,689	5,861	6,005	6,528	5,605	4,249	4,315	4,507	4,559	5,331
<50%	8,440	8,385	8,339	8,369	8,471	8,343	8,355	8,337	8,371	8,400	8,381
<75%	8,750	8,746	8,746	8,749	8,732	8,737	8,747	8,748	8,742	8,738	8,744
>50%	320	375	421	391	289	417	405	423	389	360	379
>75%	10	14	14	11	28	23	13	12	18	22	17

Source: Author calculations

Lacal-Arántegui and Serrano-González (2015, p.31) expected installed wind generating capacity to grow to 353 GW in the EU by 2030 and 1,391 GW globally, with 32% and 14% constituting offshore capacity. By 2050, they expect 503 GW to be installed in the EU (with 44% offshore) and 2,446 GW installed globally (22% offshore). Assuming a 25% capacity factor (see above), wind would provide 5,400 TWh of electricity in 2050 or some 12-15% of predicted future global electricity demand. To incentivize investments in wind energy, governments have implemented various policies, including carbon taxes, carbon offset credits (to be sold in mandatory or voluntary carbon markets), production and capital investment subsidies, and feed-in tariffs that provide producers with a guaranteed price irrespective of the market price (and whether there is even a buyer). Before implementing policies to incentivize wind energy, however, it is necessary to determine whether the benefits to society of implementing wind energy might exceed the costs. The benefits are generally associated with the reduction in pollutants and CO_2 emissions that can be attributed to wind replacing fossil fuel generation of electricity. Costs are perhaps harder to identify because, in addition to the capital costs of building turbines and additional transmission lines, and operating and maintenance costs, it is necessary to determine the effects on other assets in the generation mix and the externality costs associated with wind turbines (e.g., noise, visual dis-amenities and harm to wildlife). Consider first the benefits and then costs.

Where wind power displaces conventional thermal generation, benefits relate to improved human health and, importantly, mitigation of global warming because fossil fuel use is reduced. The health and climate benefits depend on the extent to which wind displaces fossil fuel generation, which is determined by the wind regime and the existing generation mix. The displacement of wind-for-thermal generation is not one-to-one (Kaffine et al. 2013), while benefits depend on the social cost of carbon, which is a controversial measure (Dayaratna et al. 2016; Pindyck 2015). Regardless of the shadow damage of carbon, the reduction in CO_2 emissions needs to be determined. Using an econometric model and 2005-2007 data for the ERCOT (Texas) power grid, Cullen (2013) found that, on average, one MWh of wind replaced 0.85 MWh of gas-generated power and only 0.18 MWh of coal-generated power, despite the fact that coal accounted for about 40% of production (values do not add to 100% because of trade). If ramping was taken into account (via a dynamic econometric model), 1.0 MWh of wind displaced 0.92 MWh of gas-generated electricity and a negligible amount of coal power. Similarly, using ERCOT data for 2007-2011, Novan (2015) found that wind displaced coal at night when demand was low, while it displaced gas at times of high demand during the day.[12] It is difficult to justify substituting wind for fossil fuel generation on externality grounds – it all depends on the pre-existing generation mix, the social cost of carbon and other factors.[13] However, what many studies fail to take into account are the indirect costs that intermittent wind power imposes on an electricity grid, and these depend on the generation mix.

I have studied the penetration of renewable energy into electricity grids, focusing on Alberta. Alberta's electricity is generated primarily from fossil fuels, there has been significant investment in wind energy, the Alberta grid is connected to that of British Columbia (so excess power from Alberta can be stored behind hydroelectric dams in BC), Alberta's grid is deregulated (as opposed to that of BC), and the Alberta Electric System Operator (AESO) provides detailed data on its operations (and I am familiar with Alberta/BC region). I modelled the Alberta grid and its interties, and simulated the decommissioning of fossil fuel plants and investment in carbon-free generating assets using a carbon tax as the driver (see van Kooten 2016a; Duan et al. 2016). Scenarios with current and double-current capacities of the Alberta-BC transmission intertie (providing greater opportunity for storing intermittent energy in BC) were considered, as were scenarios that allowed and disallowed investments in nuclear power plants. A summary of results is provided in Table 6.

[12] I came to the precisely the same conclusion using a mathematical programming model of the Alberta electricity grid (see van Kooten et al. 2013).

[13] Externality costs associated with wind turbines, such as noise and visual dis-amenities, matter only in certain situations (e.g., wind farms placed near shore). What is generally ignored in calculations are the high costs of building transmission infrastructure to accompany wind power.

Table 6: Wind versus Nuclear Power in a Carbon Constrained World, Results for the Alberta Electricity Grid

		AB to/from BC (GWh)		Optimal capacity (MW)		
Scenarios	Mt CO_2	Import from	Export to	Coal	Gas	Nuclear
Base	68.8	0	2,610	6,258	2,592	0
		Current transmission capacity: No nuclear				
$30	65.1	1	2,609	6,258	2,592	0
$100	26.7	4,225	202	0	5,106	0
$200	25.1	4,520	152	0	5,885	0
		Current transmission capacity: With nuclear				
$100	4.2	3,373	349	0	1,186	7,233
$200	2.0	1,908	1,536	0	276	8,136
		Double transmission capacity: No nuclear				
$100	23.4	8,493	230	0	4,737	0
$200	22.4	9,035	163	0	5,321	0
		Double transmission capacity: With nuclear				
$100	3.0	6,621	245	0	710	7,086
$200	1.7	3,697	1,394	0	195	7,862

Source: van Kooten (2016a)

Alberta's CO_2 emissions from the electricity sector are only reduced by 5.5% under a tax of \$30/tCO_2, which is the tax the NDP government will impose after 2018 (and identical to the current carbon tax in BC). With a very high tax of \$200/tCO_2, emissions can be reduced by 63.5% assuming current intertie capacities and by 67.4% with double-current intertie capacities. The costs of reducing emissions in this case are quite high on average: \$253-\$857/tCO_2, depending on the scenario. However, when investment in nuclear power is permitted, emissions can be reduced by 94.0% to 97.5% depending on what one assumes about the intertie capacities. Nonetheless, the average cost of reducing emissions remains high, \$193-\$200/tCO_2. If similar results hold for other jurisdictions, the effort to meet the 80% reduction target will (1) be extremely costly (raising rates to electricity customers accordingly), and (2) require the use of nuclear power as wind can only get Alberta no more than a two-thirds reduction in emissions (even with available storage).[14]

Kyoto's Clean Development Mechanism (CDM) plays an important role in promoting wind power, with governments, NGOs and companies purchasing certified emission reductions (CERs) created under CDM to offset their own emissions. At the same time, the World Bank and

[14] Some would argue that solar might fill the gap. The problem with solar is that its CF is extremely low (11% in Germany), and solar is unavailable at night (although that is not troublesome) and, importantly, much less so in winter months. Nonetheless, this is an open question that needs further research.

IMF will help finance wind power investments, but not the construction of coal plants. As of April 1, 2016, 2,628 wind power projects with a combined capacity of 120,751 MW, and 430 solar projects with a combined capacity of 8,515 MW, were registered under the CDM. The allocation of projects favors China and India, as indicated in Table 7. More details on CDM wind and solar projects is provided in the Appendix. However, it should be noted that wind and solar constitute only 11.0% and 0.2% of all CERs issued, with destruction and/or reduction of hydroflourocarbons (HFCs), perflourocarbons (PFCs), sulphur hexafluoride (SF) and nitrous oxide (N_2O) accounting for more than half of issued CERs.

Table 7: Proportion of Wind and Solar CDM Projects Developed in China and India, Number of Projects and Installed Capacity, as of April 1, 2016

	Projects		Installed Capacity	
Country	Wind	Solar	Wind	Solar
China	57.8%	37.2%	69.6%	39.0%
India	31.0%	36.7%	11.9%	23.4%
Together	**88.8%**	**73.9%**	**69.7%**	**62.4%**

5. Biomass Electricity

In the IEA's energy future (Table 2), biomass plays an important role in reducing reliance on fossil fuels. In Canada, Ontario has converted 517 MW of coal-fired capacity to burn only wood, and Alberta could well follow as a result of the NDP's policy to eliminate coal plants (Government of Alberta 2015). In the EU, biomass has accounted for a stable 65% of renewable energy over the past decade, with solid biomass (i.e., wood) responsible for 46% of all renewable energy (European Parliament 2015). The EU had earlier adopted an aggressive '20-20-20' target to be met by 2020 – a minimum 20% reduction in CO_2 emissions from 1990 levels, a minimum 20% share of renewables in energy production, and a 20% improvement in energy efficiency.[15] The European Commission (2013) estimated that this target could result in an annual wood deficit of 200 to 260 million m^3 by 2020 (for comparison, Canada harvests about 200 million m^3 of wood fiber annually). Under the more ambitious Paris target, renewable energy is to account for 27% of the EU's total energy production (European Commission 2014). Based on projections by Mantau et al. (2010), the annual biomass consumption for energy generation within Europe may grow to 752 million m^3 by 2030.

Increasingly biomass in the form of wood pellets is used for generating electricity, whether in biomass-only plants or co-fired with coal. There are several problems with this: (1) biomass

[15] The EU policy framework for the renewable energy target is set by the 2009 Renewable Energy Directive (http://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1436259271952&uri=CELEX:02009L0028-20130701 [accessed 15 April 2015]).

burning is not carbon neutral as is often assumed, (2) there is a limit to the availability of biomass, and (3) the economics are not very good. These constraints are explored below.

Life-cycle Analysis and Carbon Neutrality

Legislators have declared bioenergy to be carbon neutral because, by planting new trees, the CO_2 emitted would eventually be removed from the atmosphere (see Government of Canada 2011; European Parliament 2015). The argument and its confutation are illustrated with the aid of Figure 4. When biomass is burned to generate electricity, there is an initial carbon debt because biomass emits more CO_2 per unit of energy produced than coal, oil or natural gas. It takes M years of tree growth to overcome this initial debt and a total of N years to remove from the atmosphere the initial CO_2 emitted. Presumably biomass will continue to replace coal for an indefinite number of periods, in which case the picture in Figure 4 morphs from the single- (small) to the multi-period (large) scale of Figure 5. In each period trees are immediately planted in order to sequester the carbon just released by burning biomass for electricity. The (solid) straight line represents the cumulative CO_2 emitted into the atmosphere by burning coal, with the slope of the line representing emissions in each period; the dashed line represents the cumulative emissions from burning biomass instead of coal. After N years, the cumulative fluxes from burning biomass equal those associated with burning the fossil fuel. The dashed line eventually becomes horizontal at the point N where the CO_2 emitted in the first period is fully sequestered by the growing forest planted in that period. "The cumulative analysis makes clear that the time required to begin realizing dividends from biomass energy is considerably longer than one might conclude if only a single year of emissions were evaluated" (Walker et al. 2013, p.150).

Foresters argue that this process depends on a life-cycle analysis (LCA) of carbon. It makes a difference if the biomass comes from sawmill and logging residues (that would otherwise decay) or from trees that would otherwise have been left standing, thereby sequestering carbon. McKechnie et al. (2011) found that the time required to yield any net climate mitigation benefit is 38 years in the case of whole trees and 16 years for residuals. However, ecologists contend that it is necessary to take into account the global warming potential (GWP) of biomass burning, because the extra CO_2 released compared to fossil fuels (the carbon debt) leads to an initial jump in warming. The GWP of CO_2 from fossil fuel burning is taken to equal 1 as a fossil-fuel CO_2 molecule is assumed to remain resident in the atmosphere indefinitely. CO_2 emitted from biomass, on the other hand, is removed from the atmosphere through forest growth, growth in other vegetation and ocean absorption (Cherubini et al. 2011, p.418). If GWP values for bioenergy are greater than 1.0, this means that, for equivalent emissions of bioCO_2 per unit of electricity produced, fossil fuel generation would be the preferred; bioenergy is preferred when its GWP is less than 1.0.

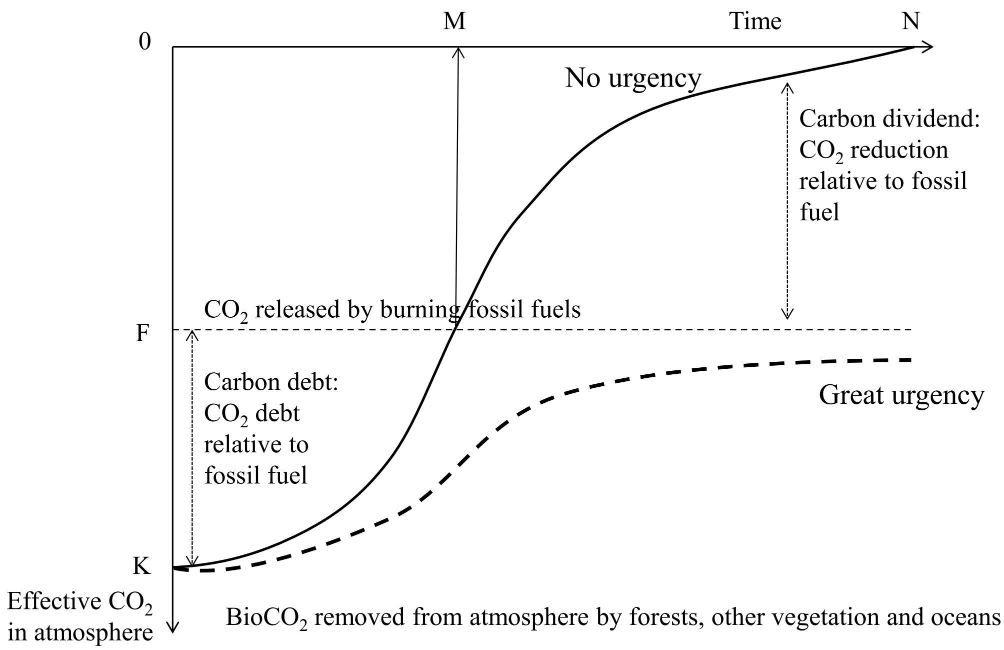

Figure 4: Carbon flux associated with fossil fuel and biomass energy production over time: Comparing lesser and greater urgency to address climate change
Source: Adapted from Johnston and van Kooten (2015)

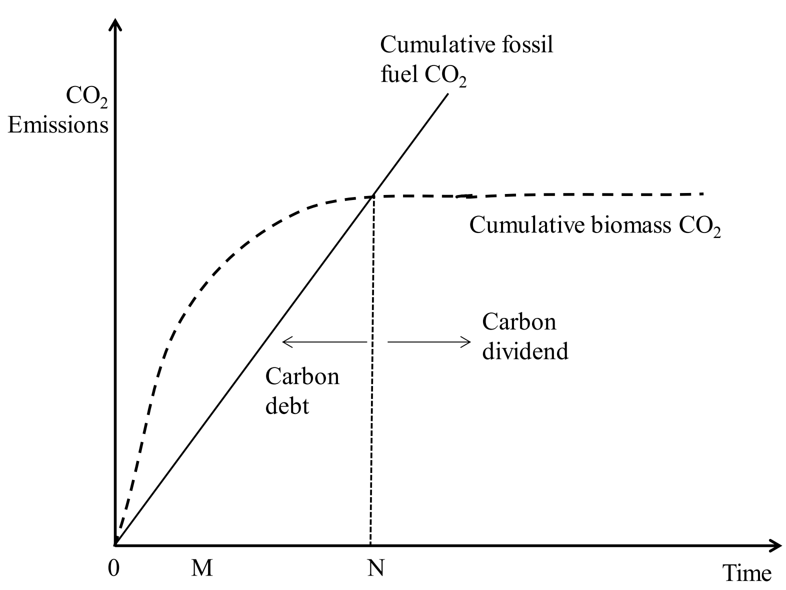

Figure 5: Carbon flux associated with fossil fuel and biomass energy production over time

Cherubini et al. (2011) use a climate model to determine that, if the forest rotation age is 40 years and the time horizon is 100 years, the narrow approaches of Walker et al. (2013) and McKechnie et al. (2011) would result in a GWP of 0.43 compared to 0.16 if all sinks are considered; for a forest with rotation age of 80 years, the comparable GWP values are 0.86 and 0.34, respectively.

The economist takes a different perspective. If there is some urgency to remove CO_2 from the atmosphere to avoid climate forcing, the timing of carbon fluxes is important, with current emissions of CO_2 and removals from the atmosphere by sinks more important than later ones. This implies that carbon fluxes need to be weighted as to when they occur, with future fluxes discounted relative to current ones. The rate used to discount carbon fluxes can be used in the policy arena to put into practice the urgency to which climate change needs to be mitigated. If global warming is not a problem, the economist might use a zero discount rate, as illustrated by the CO_2-recovery path shown with a solid line in Figure 4. In this case, it really does not matter if biomass growth removes CO_2 from the atmosphere today, 50 years, or a thousand years from now – it only matters that the CO_2 is eventually removed. In that case, coal and biomass are on a similar footing and, since coal is more energy efficient, it would be preferred to biomass.

Suppose, on the other hand, that global warming is already "widespread and consequential" (IPCC 2014, p.93) and the once distant concern is now a pressing one as future climate change is largely determined by today's choices regarding fossil fuel use. Then we want to weight current reductions in emissions and removals of CO_2 from the atmosphere much higher than those in future years. This is the same as discounting future uptake of CO_2, with higher discount rates suggesting greater urgency in dealing with global warming. The dashed path in Figure 4 depicts such urgency, but here the discount weight is so high that burning of biomass for energy never results in a carbon dividend. Indeed, if one were to accept that climate change is a more urgent matter (a relatively high discount factor), substituting biomass for fossil fuels may actually lead to a net increase in atmospheric CO_2 emissions.

The outcome from substituting biomass for fossil fuels will depend on the relative emissions intensity of the fossil fuel, as well as the tree species or other type of crop (e.g., straw, hemp) supplying bioenergy. CO_2 released from burning coal and wood varies greatly by the quality of coal and type of biomass. An average of 0.518 tonnes (t) of coal are required to produce 1.0 MWh of electricity, although for commonly used bituminous coal, only 0.397 t of coal are required. For wood, approximately 0.658 t of biomass are required to produce 1.0 MWh of electricity – nearly two times that required for bituminous coal. In terms of emissions intensities, coal releases 1.015 tCO_2/MWh on average compared to 1.170 tCO_2/MWh for hardwoods and 1.242 tCO_2/MWh for softwoods.[16] However, more efficient coal plants that employ bituminous

[16] This ignores extra emissions from transporting biomass (as more tonnage is needed) and emissions from harvesting/gathering biomass or the emissions of retrieving coal, oil or gas.

and subbituminous coal, release 0.940-0.953 tCO_2 per MWh. Clearly, biomass releases significantly more CO_2 into the atmosphere per unit of energy than coal, and even more when compared to natural gas. This militates against reliance on biomass as a future renewable energy source. The economics of biomass may be even worse.

Economics of Wood Biomass Supply

Consider policies that incentivize production of wood pellets for generating electricity as these have international consequences in wood product markets. Raunikar et al. (2010) and Buongiorno et al. (2011) found that an increase in fuelwood demand would lead to the convergence of fuelwood and industrial roundwood prices, while prices of other forest products, including sawnwood and panels, would rise significantly. However, fuelwood is used principally in developing countries for subsistence, while the recent rise in bioenergy demand is a rich-country phenomenon that is currently met by sawmill and logging residues, and sometimes whole logs.

Using a 21-region, forest products trade model, Johnston and van Kooten (2016) found that a doubling of the 8.3 Mt of wood pellets burned in the EU in 2012 would increase the cost of pellets to power producers by nearly 90%. Prices of lumber would decline in Europe by some 7% as bioenergy subsidies incentivize greater production of lumber, but prices of fiberboard, particle board and pulp would increase by some 10% because these products compete for residuals with bioenergy products (wood pellets). The move to reduce CO_2 emissions by 80% will increase the EU's demand for wood biomass resulting in a significant increase in the price of biomass fuel, thus negatively impacting the EU's ability to rely on bioenergy to the extent currently envisioned. And this does not include the increased demand for wood bioenergy in other jurisdictions.

Bioenergy subsidies will increase the price of residuals as pellet producers bid biomass away from other uses (Stennes et al. 2010). This will also result in the removal of more residual fiber from the forest after harvest. Any expansion in wood bioenergy in the U.S. to 2030 is projected to come from logging residues that would normally be left in the forest as there is little room to increase bioenergy from sawmilling residues – availability of logging residues for bioenergy purposes is expected to increase from an insignificant amount in 2006 to 62.1 million m^3 by 2030, while sawmill residues would increase by less than 20 million m^3 (Ince et al. 2011). In the eastern and southern U.S., increased incentives for bioenergy could result in as much as 65% of the logging residues directed to wood pellet production (see Abt et al. 2014). However, forecasts of very large increases in bioenergy from logging residues are unlikely for several reasons.

First, "the level of ease with which land can move between sectors and uses will have a large impact on the effectiveness of biopower policy" (Latta et al. 2013, p.380). Such flexibility would lead to greater reliance on energy crops, agricultural residues, and, to a lesser extent, short-rotation woody crops (hybrid poplar and willow). Latta et al. (2013) examine scenarios to provide between 25 and 200 TWh of biomass electricity annually in the U.S. in the short run (to 2025) and long run (2040). If bioenergy is sourced solely from forests, logging residue requirements would increase anywhere from 3.4 to 21.9 million m^3, mill residues by 2.7 to 31.0 million m^3, and roundwood residues from 8.0 to 156.1 million m^3, depending on the scenario. However, if biomass can be sourced from either agriculture or forestry, or both, and land can move between these sectors, very little of the bioenergy needed to generate this electricity is projected to come from forestry.

Second, the supply of logging residues at a given time is limited by the amount of total timber removed for other products (Abt et al. 2014, p.5). In the vast majority of cases, it does not pay to harvest forests solely for bioenergy – sourcing biomass from agriculture is more cost effective.

Third, coarse and fine woody materials left in the forest upon harvest decay more rapidly than roundwood, thereby releasing CO_2 to the atmosphere. This favors their use for bioenergy as the opportunity cost in terms of carbon flux is small. Nonetheless, there are important environmental benefits to leaving such material behind. Soils in many regions are highly eroded and depleted of organic matter, with forest ecologists recommending longer rotations (older forests produce more coarse and fine woody material) and removal only of stems, leaving slash and other woody materials in the forest (Johnston and Crossley 2002). This aspect is neglected in studies of bioenergy wood supply.

In Canada, there are physical, economic and institutional constraints to the removal of forest residues. A report prepared for the UK's Department of Energy and Climate Change concludes that "in 2020 it may be possible to meet the UK's demand for solid biomass for electricity using biomass feedstocks from North America" (Stephenson and Mackay 2014, p.18). The UK report envisions greatly enhanced supply of wood pellets from British Columbia and Canada's boreal forest under scenarios that require the continuous removal of all coarse and all fine woody materials and faster rates of harvest (pp.8-11, 130-132). However, long haul distances and mountainous terrain militate against collection of coarse and fine woody materials from these forest regions. Indeed, Niquidet et al. (2012) find it is even too costly to haul roadside wastes (wastes left as logs are trimmed to fit onto logging trucks) from forest sites in the BC interior to a dedicated biomass facility. The marginal costs of hauling roadside wastes (let alone logging residues) become exorbitant as distance increases. Further, logging companies with short-term timber contracts have little incentive to remove roadside wastes; rather, they cut logs at roadside to enhance their value and minimize hauling costs.

Likewise, the tenure system prevents forests from being transferred to other uses, including agriculture, and restricts harvests; it also prescribes certain management practices and imposes fees that might discourage greater use of woody materials for bioenergy (Wang and van Kooten

2001). In particular, Bogle and van Kooten (2013, 2015) found that stumpage fees set by the public landowner (principal) to incentivize greater supply of biomass for energy from mountain pine beetle impacted timber were incompatible with the reality faced by logging companies (agents), thereby leading to a greater mix of unaffected trees in the final harvests.

6. Concluding Discussion

Implicit in policies to reduce CO_2 emissions is the assumption that renewable sources of energy can replace fossil fuel sources. In the absence of a formidable technological breakthrough, most countries have turned to wind, biomass and, to a lesser extent, solar as the main energy alternatives of the future. The research discussed in this paper suggests that, while these sources of energy could become important components of a future energy mix, there is no way that intermittent wind (and solar) and more reliable biomass energy sources will enable world economies to reduce global CO_2 emissions by half and rich-country emissions by 80% by 2050. Policies to enhance economic development of poor countries (e.g., the UN's Millennium Development Goal program), variable wind and solar regimes, forest ecosystem limits, high opportunity costs of land resources, technical requirements related to the operation of electricity systems, and other factors simply militate against the attainment of Paris-type emission-reduction targets. To achieve 80% reductions in CO_2 emissions without the carbon-free nuclear option is simply a dream, one originating in California. There are two things to consider.

First, technology does not stand still. As Covert et al. (2016) point out, as technical improvements occur in the provision of energy from solar, wind and other renewable sources, and electric vehicles improve, technological advances with respect to the efficiencies of coal- and gas-fired power plants are also taking place. Likewise, gasoline engines are improving all the time. This implies that the technological gap, which is supposed to improve the economics of renewables relative to fossil fuels, may not be taking place. Relative to traditional fossil fuels, wind, solar and other clean energy sources may become more expensive to use, requiring ever greater expenditures to incentivize movement away from fossil fuels. This is exacerbated by technological advances in the discovery and exploitation of 'limited' fossil fuels, as indicated by the decline in natural gas prices.

Second, environmentalists remain opposed to nuclear power, but countries such as China, Russia and India are investing in the latest generation of nuclear power plants that are safer and less-costly to build than those of early generations. Indeed, Lester (2016) bemoans the loss of human capital related to nuclear energy in the West, and the comparative advantage in building and operating nuclear power plants that China and other emerging countries are gaining. Further, Lovering et al. (2016) find that the capital costs of nuclear power plants have fallen globally, with the U.S. a notable exception. This was because, as an early adopter of nuclear power, the U.S. developed and built nuclear plants using a variety of designs but then had little opportunity to build enough plants that employed the same technology to gain sufficient experience that would lead to economies and technical improvements later on. There was less opportunity for learning. At the same time, developers of nuclear plants needed to make adjustments to meet environmental and other regulations that were evolving even as construction was underway, which added to costs. Elsewhere, countries designed new nuclear plants that were replicas of earlier plants. Construction times were shorter as a result of learning and costs were lower; yet, plants were modified to improve environmental outcomes and reduce risk.

Despite high-profile nuclear accidents such as Three Mile Island (March 1979), Chernobyl (April 1986) and Fukushima Daiichi (March 2011), nuclear power plants have a remarkable safety record. With a new generation of designs and better safety precautions based on experience from these and other plants, nuclear power is currently the only alternative to fossil fuels for reliable baseload capacity. Research presented here indicates that, if California and other jurisdictions are to reduce their CO_2 emissions by 80% or more, nuclear power is the only option on the horizon.

References

Abt, K.L., R.C. Abt, C.S. Galik and K.E. Skog, 2014. *Effect of Policies on Pellet Production and Forests in the U.S. South: A Technical Document Supporting the Forest Service Update of the 2010 RPA Assessment*. Gen. Tech. Rep. SRS-202. 33pp. Asheville, NC: USDA Forest Service, Southern Research Station.

Baker, E., J. Fowlie, D. Lemoine and S.S. Reynolds, 2013. The Economics of Solar Electricity, *Annual Review of Resource Economics* 5: 387-426.

Bogle, T.N. and G.C. van Kooten, 2013. Options for Maintaining Forest Productivity after Natural Disturbance: A Principal-Agent Approach, *Forest Policy & Economics* 26(1): 138-144.

Bogle, T. and G.C. van Kooten, 2015. Protecting Timber Supply on Public Land in Response to Catastrophic Natural Disturbance: A Principal-Agent Problem, *Forest Science* 61(1): 83-92.

Buongiorno, J., R. Raunikar and S. Zhu, 2011. Consequences of Increasing Bioenergy Demand on Wood and Forests: An Application of the Global Forest Products Model, *Journal of Forest Economics* 17: 214-229.

Business Standard, 2015. Coal to Remain Important Mainstay Fuel for India and Japan's Energy Plans. New Delhi, April 29. http://www.business-standard.com/article/news-ani/coal-to-remain-important-mainstay-fuel-for-india-and-japan-s-energy-plans-115042900893_1.html [accessed 13 April 2015].

Cherubini, F., G.P. Peters, T. Berntsen, A.H. Strømman and E. Hertwich, 2011. CO_2 Emissions from Biomass Combustion for Bioenergy: Atmospheric Decay and Contribution to Global Warming, *Global Change Biology Bioenergy* 3: 413-426.

Covert, T., M. Greenstone and C.R. Knittel, 2016. Will We Ever Stop using Fossil Fuels? *Journal of Economic Perspectives* 30(1 Winter): 117-138.

Cullen, J., 2013. Measuring the Environmental Benefits of Wind-Generated Electricity, *American Economic Journal: Economic Policy* 5(4): 107-133.

Darwall, R., 2015. *Central Planning with Market Features. How Renewable Subsidies Destroyed the UK Electricity Market*. March. 96pp. Surrey, UK: Centre for Policy Studies. ISBN No. 978-1-910627-07-5.

Dayaratna, K., R. McKitrick and D. Kreutzer, 2016. Empirically-Constrained Climate Sensitivity and the Social Cost of Carbon. April 5. 18pp. Available at SSRN: http://papers.ssrn.com/sol3/papers.cfm?abstract_id=2759505 [accessed May 10, 2016].

Deffeyes, K.S., 2001. *Hubbert's Peak. The Impending World Oil Shortage*. Princeton, NJ: Princeton University Press.

de Gorter, H., D. Drabik and D.R. Just, 2015. *The Economics of Biofuel Policies. Impacts on Price Volatility in Grain and Oilseed Markets*. New York, NY: Palgrave Macmillan.

Duan, J., R. Lynch and G.C. van Kooten, 2016. The Role of Wind Power and an Optimal Mix of Generation Assets. Contributed paper presented at the Annual Meeting of the Canadian Agricultural Economics Society held in Victoria, Canada, June 21-23, 2016

European Commission, 2013. *A New EU Forest Strategy: Forests and the Forest-Based Sector*. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Brussels, 20.9.2013. Com(2013) 659 Final.

European Commission, 2014. *A Policy Framework for Climate and Energy: The Period from 2020 to 2030*. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Brussels, 22.1.2014. Com(2014) 015 Final.

European Parliament, 2015. Briefing: Biomass for Electricity and Heating. Opportunities and Challenges. (Author: D. Bourguignon) PE 568.329. September. 8pp. European Parliamentary Research Service, European Union.

Government of Alberta, 2015. Climate Leadership Plan will protect Albertans' health, environment and economy. November 22. http://www.alberta.ca/release.cfm?xID=38885E74F7B63-A62D-D1D2-E7BCF6A98D616C09 [accessed 10 February 2016].

Government of Canada, 2011. Reduction of Carbon Dioxide Emissions from Coal-Fired Generation of Electricity Regulations, *Canada Gazette* Vol. 145, No. 35 (August 27).

Hoskins, E., 2015. Charting the Costs and Effectiveness of Renewable Energy in Europe. At https://edmhdotme.wordpress.com/2015/01/22/charting-the-effectiveness-of-renewable-energy-in-europe/ Posted January 22. [accessed 13 April 2016].

Ince, P.J., A.D. Kramp, K.E. Skog, D. Yoo and V.A. Sample, 2011. Modelling Future U.S. Forest Sector Market and Trade Impacts of Expansion in Wood Energy Consumption, *Journal of Forest Economics* 17(2): 142-156.

International Energy Agency (IEA), 2014a. *World Energy Outlook 2014*. 726pp. Paris: OECD/IEA. www.iea.org

International Energy Agency (IEA), 2014b. Key World Energy Statistics 2014. 82pp. Paris: OECD/IEA. http://www.iea.org/publications/freepublications/publication/keyworld2014.pdf [access May 12, 2015].

Institute for Energy Research, 2015. As U.S. Shutters Coal Plants China and Japan are Building Them. April 23. http://instituteforenergyresearch.org/analysis/as-u-s-shutters-coal-plants-china-and-japan-are-building-them/ [accessed April 13, 2016].

IPCC, 2014. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects*. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L.White (eds.)]. 1132pp. Cambridge, UK: Cambridge University Press.

Johnston, J.M. and D.A. Crossley, Jr., 2002. Forest Ecosystem Recovery in the Southeast US: Soil Ecology as an Essential Component of Ecosystem Management, *Forest Ecology and Management* 155: 187-203.

Johnston, C.M.T. and G.C. van Kooten, 2015. Back to the Past: Burning Wood to Save the Globe, *Ecological Economics* 120(December): 185-193.

Johnston, C.M.T. and G.C. van Kooten, 2016. Global Trade Impacts of Increasing Europe's Bioenergy Demand, *Journal of Forest Economics* In press: doi:10.1016/j.jfe.2015.11.001

Kaffine, D.T., B.J. McBee and J. Lieskovsky. 2013. Emissions Savings from Wind Power Generation in Texas, *Energy Journal* 34(1): 155-175.

Lacal-Arántegui, R. and J. Serrano-González, 2015. 2014 *JRC Wind Status Report. Technology, Market, Economic and Regulatory Aspects of Wind Energy in Europe*. Brussels, BE: Joint Research Centre of the European Commission. 87pp. ISBN 978-92-79-48380-6. https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/2014-jrc-wind-status-report?search [accessed 13 April 2016]

Latta, G.S., J.S. Baker, R.H. Beach, S.K. Rose and B.A. McCarl, 2013. A Multi-sector Intertemporal Optimization Approach to Assess the GHG Implications of U.S. Forest and Agricultural Biomass Electricity Expansion, *Journal of Forest Economics* 19: 361-383.

Lester, R.K., 2016. A roadmap for U.S. nuclear energy innovation, *Issues in Science and Technology* 32(2 Winter).

Long, J.C.S. and J. Greenblatt, 2012. The 80% Solution: Radical Carbon Emission Cuts for California, *Issues in Science and Technology* 28(3 Spring).

Long, J.C.S. and M. John (co-chairs), 2011. *California's Energy Future – The View to 2050. Summary Report*. 64 pp. May. Sacramento, CA: California Council on Science and Technology. http://ccst.us/publications/2011/2011energy.pdf [accessed 11 April 2016].

Lovering, J.R., A. Yip and T. Nordhaus, 2016. Historical Construction Costs of Global Nuclear Power Reactors, *Energy Policy* 91: 371-382.

Mann, C.C., 2013. What if we never Run out of Oil? *The Atlantic*. May. http://www.theatlantic.com/magazine/archive/2013/05/what-if-we-never-run-out-of-oil/309294/ [accessed May 14, 2015].

Mantau, U., U. Saals, K. Prins, F. Steierer, M. Lindner, H. Verkerk, J. Eggers, N. Leek, J. Oldenburger, A. Asikainen and P. Anttila, 2010. Real Potential for Changes in Growth and Use of EU Forests. Final report. June 30. 160 pp. Hamburg, DE: EUwood. http://www.egger.com/downloads/bildarchiv/187000/1_187099_DV_Real-potential-changes-growth_EN.pdf [accessed 18 April 2016]

McKechnie, J., S. Colombo, J. Chen, W. Mabee and H.l. MacLean, 2011. Forest Bioenergy or Forest Carbon? Assessing Trade-Offs in Greenhouse Gas Mitigation with Wood-Based Fuels, *Environmental Science & Technology* 45: 789-795.

Nicola, S. and T. Andresen, 2012. Merkel's Green Shift Forces Germany to Burn more Coal. BloombergBusiness. http://www.bloomberg.com/news/2012-08-19/merkel-s-green-shift-forces-germany-to-burn-more-coal-energy.html [accessed May 10, 2016].

Niquidet, K., B. Stennes and G.C. van Kooten, 2012. Bio-energy from Mountain Pine Beetle Timber and Forest Residuals: The Economics Story, *Canadian Journal of Agricultural Economics* 60(2): 195-210.

Novan, K., 2015. Valuing the Wind: Renewable Energy Policies and Air Pollution Avoided, *American Economic Journal: Economic Policy* 7(3): 291-326.

Pindyck, R.S., 2015. The Use and Misuse of Models for Climate Policy, *Review of Environmental Economics and Policy* In press. Also NBER Working Paper No. 21097. April. 16pp.

Raunikar, R., J. Buongiorno, J.A. Turner and S. Zhu, 2010. Global Outlook for Wood and Forests with the Bioenergy Demand Implied by Scenarios of the Intergovernmental Panel on Climate Change, *Forest Policy and Economics* 12: 48-56.

Stennes, B., K. Niquidet and G.C. van Kooten, 2010. Implications of Expanding Bioenergy Production from Wood in British Columbia: An Application of a Regional Wood Fibre Allocation Model, *Forest Science* 56(4): 366-378.

Stephenson, A.L. and D.J.C. MacKay, 2014. Life Cycle Impacts of Biomass Electricity in 2020. Scenarios for Assessing the Greenhouse Gas Impacts and Energy Input Requirements of Using North American Woody Biomass for Electricity Generation in the UK. Report #URN 14D/243. July. 154pp. London, UK: Department of Energy and Climate Change, Crown Copyright. https://www.gov.uk/government/publications/life-cycle-impacts-of-biomass-electricity-in-2020 [accessed May 10, 2016]

U.S. Energy Information Administration, 2013. Form EIA-860, Annual Electric Generator Report. Operable Generating Units in the United States by State and Energy Source, 2013. http://www.eia.gov/electricity/data/eia860/index.html [accessed May 5, 2015].

United Nations, 2014. *The Millennium Development Goals Report 2014*. 56pp. New York. http://www.un.org/millenniumgoals/2014%20MDG%20report/MDG%202014%20English%20web.pdf [accessed May 5, 2015].

van Kooten, G.C., 2013. *Climate Change, Climate Science and Economics. Prospects for an Alternative Energy Future*. Dordrecht, NL: Springer.

van Kooten, G.C., 2016a. Wind versus Nuclear Options for Generating Electricity in a Carbon Constrained World. In *Proceedings of the Canadian Society for Mechanical Engineering International Congress 2016*. CSME International Congress 2016, June 26-29, 2016, Kelowna, BC, Canada.

van Kooten, G.C., 2016b. The Economics of Wind Power, *Annual Review of Resource Economics* 8(1): In press.

van Kooten, G.C., C. Johnston and L. Wong, 2013. Wind versus Nuclear Options for Generating Electricity in a Carbon-Constrained World: Strategizing in an Energy-Rich Economy, *American Journal of Agricultural Economics* 95(2): 505-511.

Walker, T., P. Cardellichio, J.S. Gunn, D.S. Saah and J.M. Hagan, 2013. Carbon Accounting for Woody Biomass from Massachusetts (USA) Managed Forests: A Framework for Determining the Temporal Impacts of Wood Biomass Energy on Atmospheric Greenhouse Gas Levels, *Journal of Sustainable Forestry* 32(1-2): 130-158.

Wang, S. and G.C. van Kooten, 2001. *Forestry and the New Institutional Economics*. Aldershot, UK: Ashgate Publishing. (201pp.)

APPENDIX

Table A1: CDM Wind Projects as of April 1, 2016

Country	Projects	MW	Country	Projects	MW
China	1,519	84,083	Egypt	4	406
India	815	14,332	Serbia	4	450
Mexico	30	4,276	Peru	4	233
Brazil	69	5,618	Ecuador	3	24
Chile	20	1,718	Israel	2	34
Uruguay	13	627	Azerbaijan	2	98
South Africa	15	2,421	Jamaica	2	39
South Korea	13	377	Tunisia	2	224
Argentina	11	665	Macedonia	1	37
Morocco	7	603	Guatemala	1	48
Dominican Republic	6	230	Honduras	2	152
Pakistan	8	405	Mongolia	1	50
Costa Rica	6	197	Senegal	1	125
Cyprus	6	268	Columbia	1	20
Philippines	5	321	Angola	1	100
Panama	3	504	Montenegro	1	46
Kenya	5	527	Cape Verde	1	26
Vietnam	5	188	Mauritius	1	18
Sri Lanka	5	51	Iran	1	100
Thailand	3	267	Sudan	1	100
Nicaragua	4	147	United Arab Emirates	1	25
TOTAL	**2,628**	**120,751**			

Source: http://www.cdmpipeline.org/cdm-projects-type.htm [accessed 14 April 2016]

Table A2: CDM Solar Projects as of April 1, 2016

Country	Projects	MW	Country	Projects	MW
China	160	3,321	Mexico	1	100
India	158	1,990	Burundi	1	20
South Korea	30	189	Ecuador	1	50
Thailand	26	709	Saudi Arabia	1	11
Chile	8	541	Tunisia	1	1
Israel	7	318	Philippines	1	35
South Africa	5	230	Brazil	1	3
Peru	5	96	Libya	1	14
United Arab Emirates	5	320	Kuwait	1	10
Morocco	2	168	Mali	1	50
Dominican Republic	2	82	Mauritius	1	15
Argentina	2	20	Burkina Faso	1	23
Pakistan	2	150	Rwanda	2	<1
Senegal	2	50	Lebanon & Indonesia	2	
TOTAL	**430**	**8,515**			

Source: http://www.cdmpipeline.org/cdm-projects-type.htm [accessed 14 April 2016]