The Cost of a Sustainable Energy Future - 10494

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ABSTRACT

As in all steady-state systems, humanity must attain a sustainable energy mix sometime in the future. Unless nuclear and renewable energy is a considerable part of that mix, humanity will go through a period of environmental and economic upheaval. If energy growth estimates are even marginally correct, the world will achieve a consumption of over 30 trillion kilowatt-hours per year (30 tkWhrs/yr) by mid-century. While large unconventional fossil fuel resources are still available to be developed, the economic and environmental costs are large. How the rise of renewables and nuclear will alter our dependence on fossil fuels depends upon economic and political forces. This work presents an ethical annual energy requirement for the world, 30 tkWhrs/yr, that can be achieved by 2040, and also proposes a sustainable mix to achieve that level, i.e., a third fossil fuels, a third renewables and a third nuclear ($^1/_3$, $^1/_3$, $^1/_3$). The costs of energy produced for each primary energy source, coal, natural gas, nuclear, wind, solar and hydro, and the total energy produced between 2010 and 2060 using this mix, are calculated. The total cost to produce 1,260 tkWhrs over that time period is $62.3 trillion in 2009 dollars, or about 2% of global GDP annually, and the CO_2 emissions are cut in half relative to the baseline mix. The cost of this alternative mix is about 20% lower than the $75.4 trillion to produce the same amount of energy from the more anticipated expectations of energy growth and distribution that still have fossil fuels producing about 60% of world power. Adoption of this $^1/_3$, $^1/_3$, $^1/_3$ alternative energy mix, therefore, provides substantial benefits, both economic and environmental. Costs include construction, operation and maintenance (O&M), fuel, decommissioning and a possible carbon tax. Costs not discussed include electrical grid upgrade and connectivity of renewables, transportation issues, and non-carbon-tax externalities such as pollution and health care costs associated with energy sources especially coal and solar. Comparing apples to apples, hydro, nuclear and wind turn out to be the most cost-effective sources over the next 50 years, almost identical per kWhr produced. The high installation costs of nuclear compared to other non-fossil fuel sources that are often cited are incorrect and stem from a misunderstanding of capacity factor and lifespan. All decommissioning costs are relatively small, even for nuclear, and costs for a carbon tax @$15/ton of CO_2 emitted are significant for the fossil fuels over this entire time period ($4.4 trillion combined) but relatively small for all alternatives (less than $0.5 trillion combined). Higher C-taxes are needed to force any change in fossil fuel use on their own.

INTRODUCTION

The present global discussions of energy in a carbon-constrained world pit two ethical philosophies against each other – justice for the planet and justice for the poor (Wright and Conca 2007). Although the approximately 150 tkWhrs generated between 1910 and 1990 emitted over 140 billion tons of CO_2 with significant damage to human health and the environment, it also lifted almost 2 billion humans out of abject poverty (United Nations 2009). The ethical drivers for and against energy production cannot be ignored and are the reasons for China's recent expansion of coal and the rise of its middle class to over 500 million. But 800 million in China still remain in poverty, along with over a billion others across the globe, and their needs must be balanced with the need to preserve the planetary ecosystem, or we will fail to achieve either a peaceful or a prosperous future.

In order to develop a long-term global energy plan, one has to decide what amount of energy is needed, both globally and nationally, by some target date, given estimates of population growth (Deutch and Moniz 2006). An holistic approach to a long-term ethical and sustainable energy plan for the world and for the United States was outlined in Wright and Conca (2007) in which all humans would have between

3,000 and 6,000 kWhrs/year, and the total global power production would level off at about 30 tkWhrs/yr by 2040. The U.S. share would be about 6.5 tkWhrs/yr. This total is the least amount needed to end world poverty, war and terrorism by raising all humans up to 0.8 on the United Nations Human Development Index (HDI). The HDI embodies safety and security in human life, and being above 0.8 HDI requires about 3,000 kWhrs per person per year. Being above 0.9 HDI enjoyed by the developed world requires over 9,000 kWhrs per person per year, but increased efficiency and conservation, and serious societal changes, could drop this to less than 6,000 kWhrs per person per year by 2040. This 30 tkWhrs/yr total results from the needs of 1.6 billion people who presently live in abject energy poverty with no access to electricity (Collier, 2007), 2.4 billion who burn wood and manure as their main source of energy, 2 billion that have access to sufficient energy resources, and 3 billion who will be born between now and 2040.

In a just and ethical future we cannot, and should not, prevent all of Earth's citizens from having access to sufficient energy. The challenge is providing it in a sustainable manner. Presently, fossil fuel provides two-thirds of the 15 tkWhrs/yr of global power, with the other third split almost evenly between nuclear and hydro. Since all fossil fuel use today generates 10 tkWhrs/yr world-wide, if we level consumption at 30 tkWhrs/yr without increasing CO_2 levels much above the present (about 380 ppm), then *two-thirds of production must come from non-fossil fuels, and only one-third can come from fossil fuels*. But this means that fossil fuel production will continue on at present rates, and not decrease as is assumed by Kyoto-type protocols. Rather than cutting production, advances in carbon sequestration and dramatic increases in efficiency and conservation will have to be used to reduce CO_2 levels below those of today.

A target distribution, or energy mix, that would provide two-thirds of the world energy consumption from non-fossil fuels by 2040 is $^1/_3$, $^1/_3$, $^1/_3$: a third fossil fuels, a third renewables and a third nuclear, each providing 10 tkWhrs/yr. Energy for transportation will not be discussed here, although the advent of fully plug-in electric vehicles is captured in the base-load electric generation from nuclear and coal and dramatically reduces the use of petroleum. Non-electric vehicles are assumed to utilize 100 billion gallons of biofuels and 200 billion gallons of petroleum annually by 2040 (Wright and Conca 2007). This $^1/_3$, $^1/_3$, $^1/_3$ mix reduces carbon emissions by about 50% over more traditional scenarios (EIA 2009).

For the purposes of this discussion, we will evaluate coal and natural gas as providing the fossil fuel portion of power production, nuclear providing its portion, and wind, solar and hydro providing the renewable portion. The remaining oil-fired power plants will be folded into natural gas as a proxy for similar costs and few if any oil-fired plants will be constructed in the future. Other renewables such as marine current, tidal and geothermal are folded into wind as a proxy for similar costs. Unconventional fossil fuels will not be discussed as their development will be significantly more expensive and their usage will depend upon advances that reduce that cost to close to that of conventional fossil fuels. If we are forced into large-scale development of unconventionals, then most of the favorable environmental and economic projections fail. The contribution of large hydroelectric is not considered to change significantly worldwide. Most large rivers are already developed, some U.S. and European dams will be decommissioned as some Asian ones are constructed, and the ecological damage from large dams is being recognized as more severe than once thought (MucCully 1996: Pacca 2007). We will adopt a 30% increase in hydro worldwide for this discussion.

Therefore, the target mix to be evaluated for the 30 tkWhrs/yr from 2040 to 2060 is 5 trillion kWhrs/yr from coal, 5 trillion kWhrs/yr from natural gas, 10 trillion kWhrs/yr from nuclear, 4.2 trillion kWhrs/yr from wind, 3 trillion kWhrs/yr from solar, and 2.9 trillion kWhrs/yr from hydro. This drop in coal and rise in natural gas would be best achieved by having coal plants run out their natural life with modest replacement in coal, with natural gas, nuclear and renewables providing most of the increased production. This scenario is very different from those generally projected (EIA 2009) in which over half of the increased capacity comes from natural gas and a fifth from coal, essentially doubling fossil fuel use and CO_2 emissions, and resorting to rapid development and widespread implementation of carbon sequestration technologies to address environmental issues.

The numbers for this scenario are large - over 2 million one-plus MW wind turbines requiring almost 2 billion tons of steel, over a thousand 1000-MW nuclear power plants, twice the present number of natural gas plants, and several hundred thousand square miles of renewables (Wright and Conca 2007). For the United States alone, the mix is about 200,000 one-plus MW wind turbines and 0.5 tkWhrs/yr from solar arrays covering only 10,000 square miles assuming significant distributed solar, 200 GenIII 1000-MW nuclear reactors, 0.8 tkWhrs/year from other sources, a modest number of new natural gas plants and no new coal plants. The following discussion does not include externalities associated with footprint costs, material supply problems, especially steel, copper and cement which is the most important hurdle to wind expansion to these levels, connectivity or human health and environmental factors not generally factored into direct costs. Most externalities make fossil fuel, wind and solar more expensive relative to other alternatives (Bickel and Friedrich 2005). All values are in 2009 US$.

COMPARING COSTS

Any reasonable long-term energy plan must account for the actual costs well into the future, in this discussion 2060. Unfortunately, actual costs for any energy system are difficult to determine from information normally provided. Systems with good historic data are usually old technologies that are not going to be constructed in the future, e.g., traditional coal-fired power plants, GenII nuclear power plants, and solar PV cells from before 1990. The latest technologies such as GenIII nuclear, thin-film solar, HPGe-cell solar and newer combined cycles have not been in operation long enough to obtain firm operational and maintenance data. The few built or under construction do not reflect anticipated final costs as the first few units are always more expensive until routine construction and manufacturing is achieved. The reason for subsidies, incentives, tax breaks and loan guarantees is to overcome these initial hurdles, but such subsidies cannot be sustained indefinitely without hidden economic damage to society.

The common terms of ¢/kWhr or $/MWhr are variable constructs reflecting many short-term controls including specific financing vehicles, permitting, licensing and regulatory fees, construction and production incentives and subsidies, of which the most common examples are the investment and production tax credits. Of particular importance are the arbitrary local/state/federal mandates such as the California legislated 33% renewable portfolio by 2020, Ohio's 25% by 2024, New Mexico's 20% by 2020 and Nevada's 20% by 2015. These will be further complicated by any carbon tax or trading system that may get adopted. Underlying these variables are the more fixed costs of fuel, construction, replacements, labor and materials, pensions, insurance and taxes, decommissioning/waste costs, and administrative/overhead costs.

Our present energy policy is a hodge-podge of reactionary and self-interested decisions in which, to paraphrase Zacharia (2009), "the urgent is driving out the important". It is crucial that we adopt a policy that is long-term and is not derailed by monthly or annual changes in prices, commodity supplies or political upheavals. Long-term planning requires actual cost data for construction, fuel, O&M, and decommissioning. How the nation finances these costs is a related, but separate, issue and cannot be decided intelligently without knowing the actual costs. True comparisons among various energy systems requires normalization to total power produced from each system over its lifespan using capacity factors and lifespans. Key assumptions used to normalize costs are given in Table 1. Other relevant assumptions include the following November 2009 commodities spot prices: $70/barrel for oil; $40/ton for coal; $4/tcf for natural gas; $500/ton for steel; $\$2^{.50}$/lb for copper, and $70/ton for cement. The following discussion is an amalgam of information drawn from various sources including Beaty (2000), Boyce (2001), Bryan and Dudley (1974), Meier (2002) Pacca and Horvath (2002), Paffenbarger and Bertel (1998), Petereson (2003 and 2005), Sampattagul et al. (2005), White and Kulcinski (1998) and organizations such as the U.S. Department of Energy (DOE) and its many divisions (Energy Efficiency and Renewable Energy, National Renewable Energy Laboratory and the Energy Information Administration), the International Energy Agency, the Organisation for Economic Co-operation and Development, and the U.K. Parliamentary Office of Science and Technology.

Table 1. Key assumptions for different energy systems from recent designs, builds and buys.

	Capacity factor	Lifespan	Installed Cap.	Installation Costs	Source
Coal	0.71	40 years	750 MW	$2.5 billion	Nevada Energy
Natural Gas	0.42	40 years	300 MW	$1.1 billion	Alliant Energy
Nuclear	0.92	60 years	960 MW	$7 billion	Westinghouse
Wind	0.35	20 years	1 MW	$1.5 million	Shell Wind Division
Solar	0.26	25 years	92 MW	$300 million	NRG Energy
Hydro	0.44	80 years	600 MW	$ 3.0 billion	Susitna Hydro Project

Construction

Normalizing to a specific output of 469 billion kWhrs gives a set of size, costs and numbers of different energy units required to produce 469 billion kWhrs over the life of the unit/farm/array (Figure 1, Table 2). These normalizations translate into actual construction costs per lifetime MWhr produced of about $13/MWhr for coal $23/MWhr for natural gas, $15/MWhr for nuclear, $23/MWhr for wind, $60/MWhr for solar and $16/MWhr for hydro. Costs and the relative contributions from each energy source, as a function of time depend upon the specific ramp-down times for the aging existing fleet, and the ramp-up times for new builds between now and 2040 to achieve the target mix. But it is possible to make a reasonable estimate of necessary new construction costs, fuel and O&M costs, required to achieve this mix and sustain it for a generation, i.e., from 2010 to 2060.

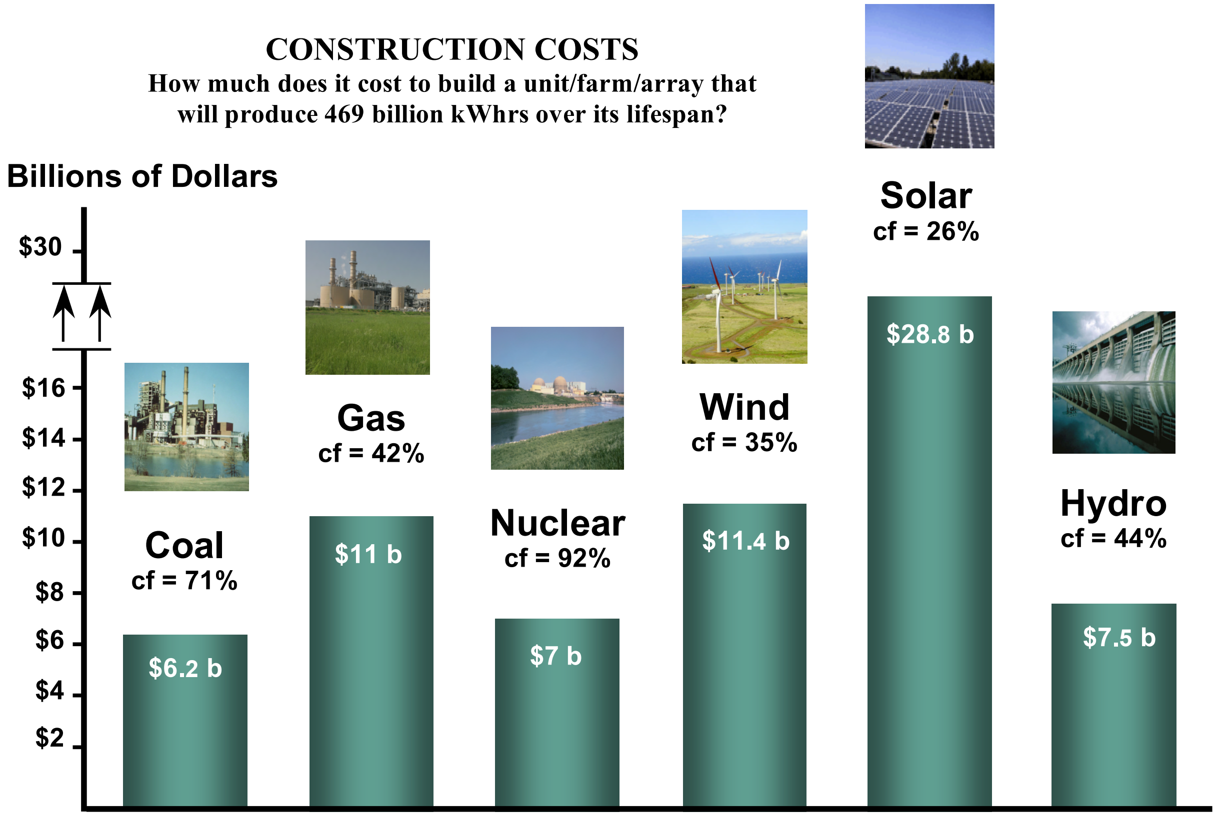

Figure 1. Comparison of construction costs in 2009 dollars among various energy sources required to install systems that will produce 469 billion kWhrs over their lifespan. Total costs are a function of installation cost, installed capacity (MW), capacity factor (cf), and lifespan.

To estimate how much production must be installed to provide the target $^{1}/_{3}$, $^{1}/_{3}$, $^{1}/_{3}$ energy mix by 2040, we can use projections of energy consumption and population growth from the present 15 tkWhrs/yr ending in a leveled consumption of 30 tkWhrs/yr at 2040 and continuing on until 2060 (Deutch and Moniz 2006; Wright and Conca 2007). The total energy consumed between now and 2060 under these projections will be 1260 tkWhrs; 660 tkWhrs between 2010 and 2040 as the world ramps up from 15 to 30 tkWhrs/yr, and 600 tkWhrs between 2040 and 2060 after the world levels at 30 tkWhrs/yr.

Table 2. Construction costs normalized to a lifetime production of 469 billion kWhrs.

Coal - \$2.5 billion 750 MW coal plant with a capacity factor (cf) = 71% and lifespan = 40 yrs
⇒ 750 MW x 1000 kW/MW x 0.71 x 8,766 hrs/yr x 40 yrs = 187 billion kWhrs
∴ to produce 469 billion kWhrs requires 2.5 units at \$6.2 billion

Natural Gas - \$1.1 billion 300 MW combined cycle gas plant with a cf = 42% and lifespan = 40 yrs
⇒ 300 MW x 1000 kW/MW x 0.42 x 8,766 hrs/yr x 40 yrs = 44 billion kWhrs
∴ to produce 469 billion kWhrs requires 10 units at \$11 billion

Nuclear - \$7 billion 980 MW AP-1000 GenIII nuclear with a cf = 92% and lifespan = 60 yrs
⇒ 980 MW x 1000 kW/MW x 0.92 x 8,766 hrs/yr x 60 yrs = 469 billion kWhrs
∴ to produce 469 billion kWhrs requires 1 unit at \$7 billion

Wind - \$1.5 million 1 MW GE turbine with a cf = 35% and lifespan = 20 yrs
⇒ 1 MW x 1000 kW/MW x 0.35 x 8,766 hrs/yr x 20 yrs = 61.3 million kWhrs
∴ to produce 469 billion kWhrs requires 7,650 units at \$11.4 billion

Solar - \$300 million 92 MW thin film solar with a cf = 26% and lifespan = 25 yrs
⇒ 92 MW x 1000 kW/MW x 0.26 x 8,766 hrs/yr x 25 yrs = 5.2 billion kWhrs
∴ produce 469 billion kWhrs requires 96 units at \$28.8 billion

Hydro - \$3 billion 600 MW with a cf = 44% and lifespan = 80 yrs
⇒ 600 MW x 1000 kW/MW x 0.44 x 8,766 hrs/yr x 80 yrs = 185 billion kWhrs
∴ produce 469 billion kWhrs requires 2.5 units at \$7.5 billion

We will assume that half of the production from existing coal, gas(and oil) and nuclear power plants will be replaced between 2010 to 2040 given their average lifespans, and that all existing hydro will continue throughout this period. Therefore, 160 tkWhrs will come from existing plants: 45 tkWhrs from coal, 30 tkWhrs from natural gas (including remaining oil power plants), 19 tkWhrs from nuclear and 66 tkWhrs from hydro. New installed capacity will produce 500 tkWhrs between 2010 to 2040, represented by 45 tkWhrs from coal, 45 tkWhrs from natural gas, 200 tkWhrs from nuclear, 116 tkWhrs from wind, 84 tkWhrs from solar and 10 tkWhrs from hydro, achieving the $^{1}/_{3}$, $^{1}/_{3}$, $^{1}/_{3}$ mix by 2040.

Between 2040 and 2060, the 600 tkWhrs will be a combination of 494 tkWhrs from new builds and 106 tkWhrs during the complete phase-out of existing plants other than hydro. The 106 tkWhrs includes 30 tkWhrs from coal, 20 tkWhrs from natural gas, 12 tkWhrs from nuclear, 44 tkWhrs from hydro, and the. The 494 tkWhrs from new production includes 70 tkWhrs from coal, 80 tkWhrs from natural gas, 185 tkWhrs from nuclear, 84 tkWhrs from wind, 60 tkWhrs from solar, and 14 tkWhrs from hydro.

Therefore, between 2010 and 2060, the total production from existing plants will be 266 tkWhrs represented by 75 tkWhrs from coal, 50 tkWhrs from natural gas (including remaining oil power plants), 31 tkWhrs from nuclear and 110 tkWhrs from hydro. These plants will require O&M, fuel, decommissioning and any carbon-tax costs, that will be estimated later in this paper.

The total production from newly-constructed plants between 2010 and 2060 will be 994 tkWhrs, represented by 115 tkWhrs from coal, 125 tkWhrs from natural gas, 385 tkWhrs from nuclear, 200 tkWhrs from wind, 144 tkWhrs from solar, and 24 tkWhrs from hydro. Using the construction costs normalized in Table 2 for capacity factor and lifetime, total investment in plant/farm/array construction, in 2009 dollars, will be approximately $1.5 trillion for coal, $2.9 trillion for natural gas, $5.7 trillion for nuclear, $4.9 trillion for wind, $8.8 trillion for solar and $0.4 trillion for hydro.

Granted, these are simplistic assumptions unlikely to be met considering the present rate of coal-fired power plant construction in Asia, and the unfortunately slow rise of renewables and nuclear projected for the next ten years when infrastructure development is crucial. To achieve this target mix will require concerted effort and mutual agreements amongst all nations to bring up alternatives to coal more rapidly than is presently planned. Not to do so will condemn the world to the default path of primarily coal and gas for the next century.

Fuel, O&M and Decommissioning

From Figure 1 and Table 2, coal is the cheapest to install per kWhr produced, followed closely by nuclear and hydro. Solar is the most expensive, and natural gas and wind are intermediate. However, this ranking is changed by the continued need to fuel coal and natural gas with increasingly expensive fossil fuel. Fuel costs are presently (DOE EIA): $20/MWhr for coal @$40/ton, $80/MWhr for natural gas @$5/thousand cubic feet (mcf), $6/MWhr for nuclear @$100/lbU_3O_8, and $0 for wind, solar and hydro (Figure 2). Therefore, in 2009 dollars, to produce the target energy totals, fuel costs will be $3.8 trillion for coal, $14 trillion for natural gas, and $2.5 trillion for nuclear. Wind, solar and hydro have no fuel costs.

O&M costs are more difficult to elucidate, especially for alternatives (Meier 2002; Paffenbarger and Bertel 1998; Sampattagul et al. 2005). Our best estimate is $6/MWhr for coal, $5/MWhr for natural gas, $13/MWhr for nuclear, $10/MWhr for wind, $1/MWhr for solar and $8/MWhr for hydro (Figure 3). Long-term solar O&M costs are as yet unknown, and the wind costs include one gear box replacement @$250k for each 1-MW turbine over its lifetime. This latter cost has taken utility companies by surprise (personal communication with Exel, Shell Wind, Exelon and Energy Northwest) and is of great concern to Public Utility Districts having to comply with energy mandates. Therefore, in 2009 dollars, to produce the target energy totals, O&M costs will be $1.14 trillion for coal, $0.88 trillion for natural gas, $5.4 trillion for nuclear, $2.0 trillion for wind, $0.14 trillion for solar and $0.19 trillion for hydro.

Decommissioning costs are a factor for most systems beyond the ordinary site operations costs. For a kWhr produced, decommissioning costs are 0.21¢ for coal, 0.002¢ for natural gas, 0.11¢ for nuclear, 0.13¢ for wind (according to the National Wind Watch, $83,000/turbine including salvage credit), 0.08¢ for solar, and 0.86¢ for hydro (DOI 2009). Therefore, in 2009 dollars, to produce the target energy totals, decommissioning costs will be $400 billion for coal, $4 billion for natural gas, $450 billion for nuclear, $260 billion for wind, $110 billion for solar and $1.16 trillion for hydro. Except for hydro, these are quite small compared to all other costs and are not a reason for choosing between energy sources. Uncertainties are large for solar since no large arrays have been decommissioned. Similarly for hydro, as the very large dams have yet to be decommissioned and the disposition of the large contaminated sediment wedges behind the dams is problematic (McCully 1996; Pacca 2007).

For nuclear, the biggest perceived problem is that of disposal of spent fuel and nuclear waste. This cost is strongly dependent upon policy and strategy decisions that will be made in the coming years, hopefully following recommendations from a nascent Blue Ribbon Panel being developed by the present Administration and Congress for the United States, and similarly in other nations. Regardless of which strategies are adopted, whether direct disposal with no further processing, various degrees of recycling, or storage and transmutation or burning in fast reactors, there will be nuclear waste to be disposed. Fortunately, the volumes are quite small, about a million times less than solid waste from coal generation, and many times less than the toxic wastes from silica production of solar cells (Jungbluth 2005), and can be handled best by deep geologic disposal (NAS 1970). Scaling up projections from the Yucca Mountain project, the yearly deep geologic disposal footprint requirements for the target 416 tkWhrs nuclear portion would be about 20-square miles worldwide, five square miles needed in the United States. This volume can be easily met (Conca et al. 2008; Conca and Wright 2009).

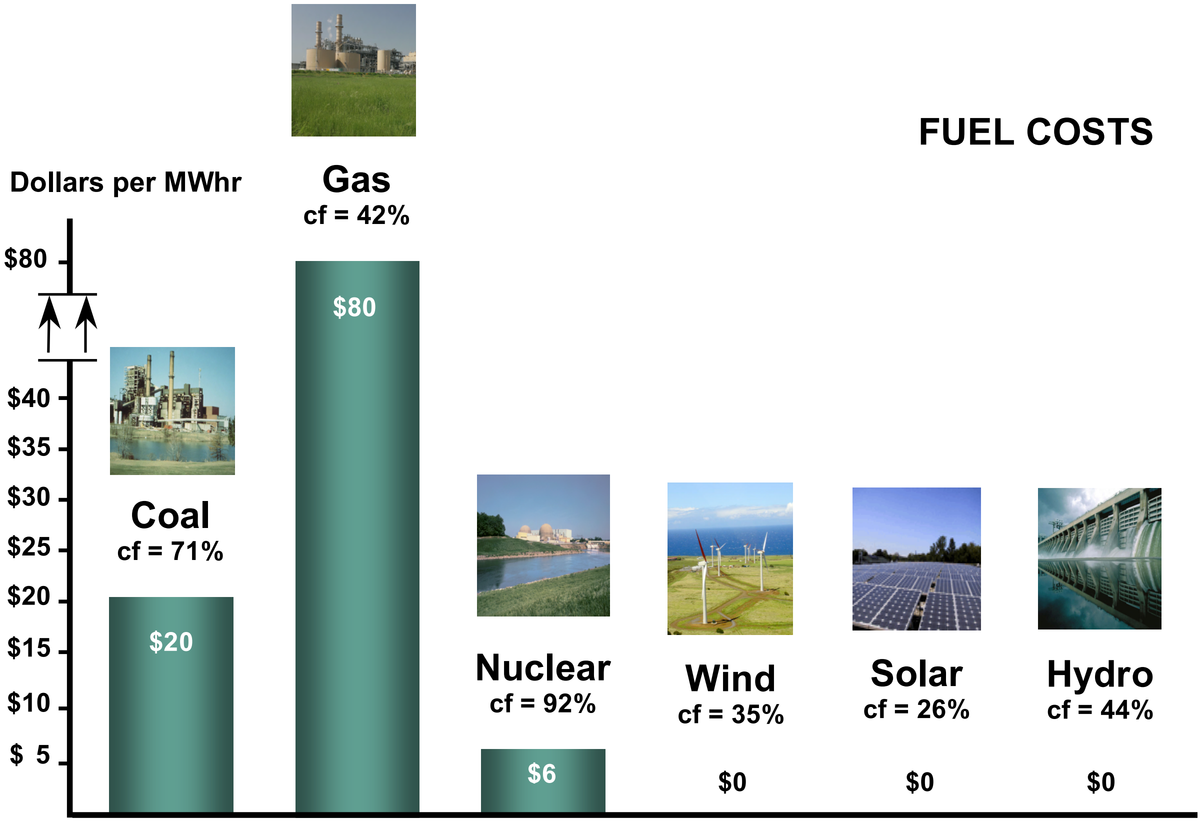

Figure 2. Comparison among various energy sources of fuel costs in 2009 dollars to produce 1 MWhr. 2009 prices are: Coal - $40/t NG - $4/tcf U - $100/lb yellowcake

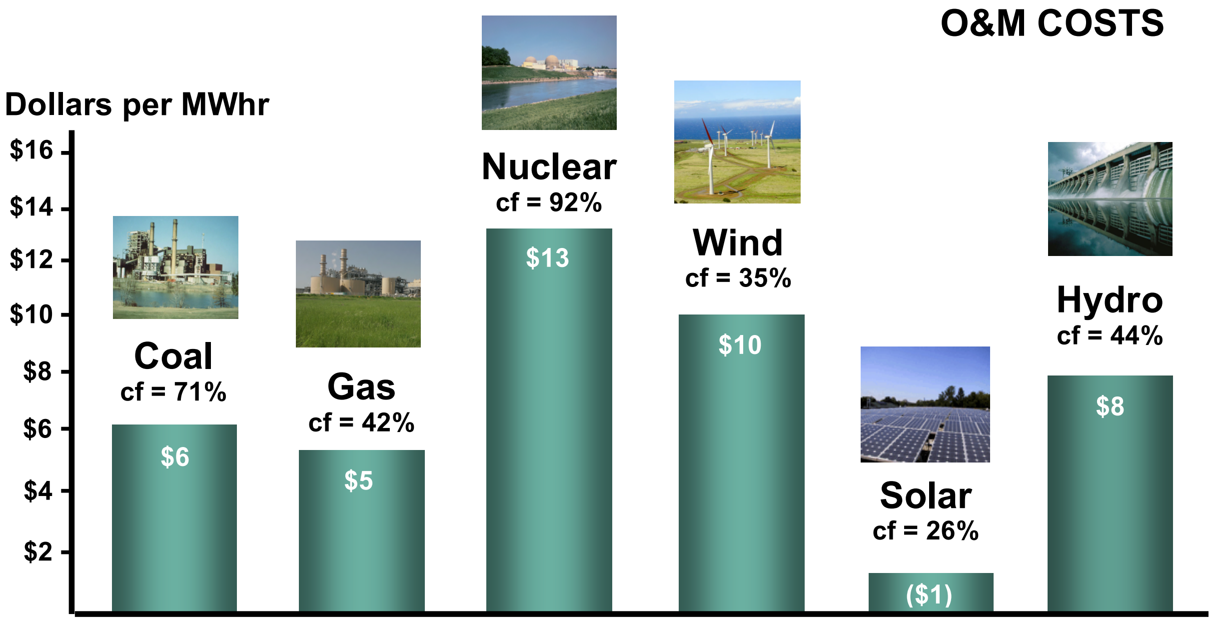

Figure 3. Comparison of O&M Costs per MWhr produced in 2009 dollars. Long-term O&M costs for Solar are unknown but thought to be low.

The cost of nuclear waste disposal depends upon an appropriate geologic formation being chosen. If an optimal formation is chosen that does not require large engineering efforts, canister, containment, material and barrier costs, total disposal costs should be about \$10 billion per 15 tkWhrs produced (unpublished calculations; Conca et al. 2008; WSRC 2008). The existing and anticipated monies in the Nuclear Waste Fund (NWF) generated by the 0.1¢/kWhr nuclear tax on the utility industry is close to this amount, so the fund should be able to offset these disposal costs. However, if a non-optimal formation is chosen requiring large engineering infrastructure and costly materials, canisters, barriers and packaging, then disposal costs will require additional taxes on the nuclear industry. Even under very unfavorable scenarios, such a tax would increase the cost of nuclear energy less than 1¢ per kWhr, still small compared to all other costs. In this discussion we assume that science-based recommendations will be followed, and the appropriate geologic formation will be chosen for the final disposal site, in which costs can be covered by the present and future funds within the NWF.

Carbon Tax

Attempts have been made to capture external costs associated with human health and the environment, called externalities, particularly carbon emissions and footprint effects. Proposed carbon taxes are in the range of \$15/ton of CO_2 emitted, but it has been difficult to assign a footprint cost as it depends upon the specific region, the ecosystem sensitivities and importance, and the previous use to which the land was put. The European Union has proposed various footprint values up to \$350/acre but this level of costs will have little affect on energy costs relative to construction and O&M costs (Bickel and Friedrich, 2005).

If the world adopts a carbon-constrained economy, costs will change significantly only for coal and natural gas. Carbon footprints for various energy sources have been developed by many groups and are dependent upon the geographic location and designs used. For the developed world the following are reasonable averages for grams of CO_2 emitted per kWhr produced (Pacca and Horvath 2002; Vattenfall 2003; POST 2006): 975 gCO_2/kWhr from coal; 600 gCO_2/kWhr from natural gas; 90 gCO_2/kWhr from hydro; 55 gCO_2/kWhr from solar; 15 gCO_2/kWhr from wind, and 15 gCO_2/kWhr from nuclear. Using proposed C-tax or Cap&Trade proposals of \$15/metric ton of CO_2 emitted (0.0015¢/g), additional carbon costs for the total power production between 2010 and 2060 discussed above are \$2.8 trillion for coal (190 tkWhrs), \$1.6 trillion for natural gas (175 tkWhrs), \$94 billion for nuclear (416 tkWhrs), \$45 billion for wind (200 tkWhrs), \$144 billion for solar (144 tkWhrs), and \$119 billion for hydro (134 tkWhrs).

These additional carbon costs are significant for the fossil fuels, but relatively small for the alternatives, compared to construction, fuel and O&M costs over this time period (Figure 4). Figure 4 includes a relative footprint size for each energy source to produce 469 kWhrs although no costs are assigned. It can be seen that coal and gas are strongly affected by a carbon tax and wind and solar are strongly affected by footprint issues. Nuclear is little affected by either. The footprint for solar can be reduced by distributing it over existing facilities and structures, but wind cannot be so distributed and many ideal wind sites are in pristine ecological areas. The footprint impact for hydro is also difficult to define, as the ecological effects of hydroelectric are widespread and include upstream submergence, changes in downstream sediment supply, impacts on fish and wildlife, and accumulation of contaminated sediments (McCully 1996). For the footprint shown in Figure 4, only an average upstream submergence is used.

The discussion on costs assumes 2009 commodity prices for key items such as steel, cement and various fuels, which are relatively low as a result of the present global economic situation. If these costs were estimated using 2008 prices, then the relative costs would be different. O&M costs for coal and gas are naturally sensitive to each of their own fuel prices as well as to petroleum prices for transportation.

Wind and solar are most sensitive to prices of construction materials, particularly wind to steel and cement, as wind is the most materials-intensive energy source (Peterson et al. 2005). As an example, a MW of installed capacity for wind requires 460 metric tons of steel and 870 m^3 of concrete compared to the 98 metric tons of steel and 160 m^3 of concrete for coal, and the even lower 40 metric tons of steel and 90 m^3 of concrete for nuclear. Natural gas is the lowest of all, requiring a little over 3 metric tons of steel and 27 m^3 of concrete per MW. Wind is sensitive to transportation costs because of the large volume of materials needing transport during construction, but is insensitive during the operational phase. Nuclear is fairly insensitive to all commodity prices because nuclear fuel is insensitive to the price of uranium as the amount of uranium needed is small (one ounce burned equals 75 tons of coal burned), fueling occurs infrequently, and the cost of the fuel is in the fabrication, not the uranium.

Therefore, the major hurdle for wind in producing its 230 tkWhrs over the next 50 years becomes obtaining the over 2 billion tons of steel required for its construction, not including connectivity, and finding the large footprint necessary for its siting. For nuclear, the major hurdle is political as well as developing the essential manufacturing capabilities and workforce development, the latter not a very big problem when compared to the initial expansion of nuclear in the 1960s and 70s from nothing to a few hundred. The major hurdle for coal and gas is environmental effects and fuel costs. The major issue for solar is construction costs and the need to distribute the footprint over existing facilities and structures.

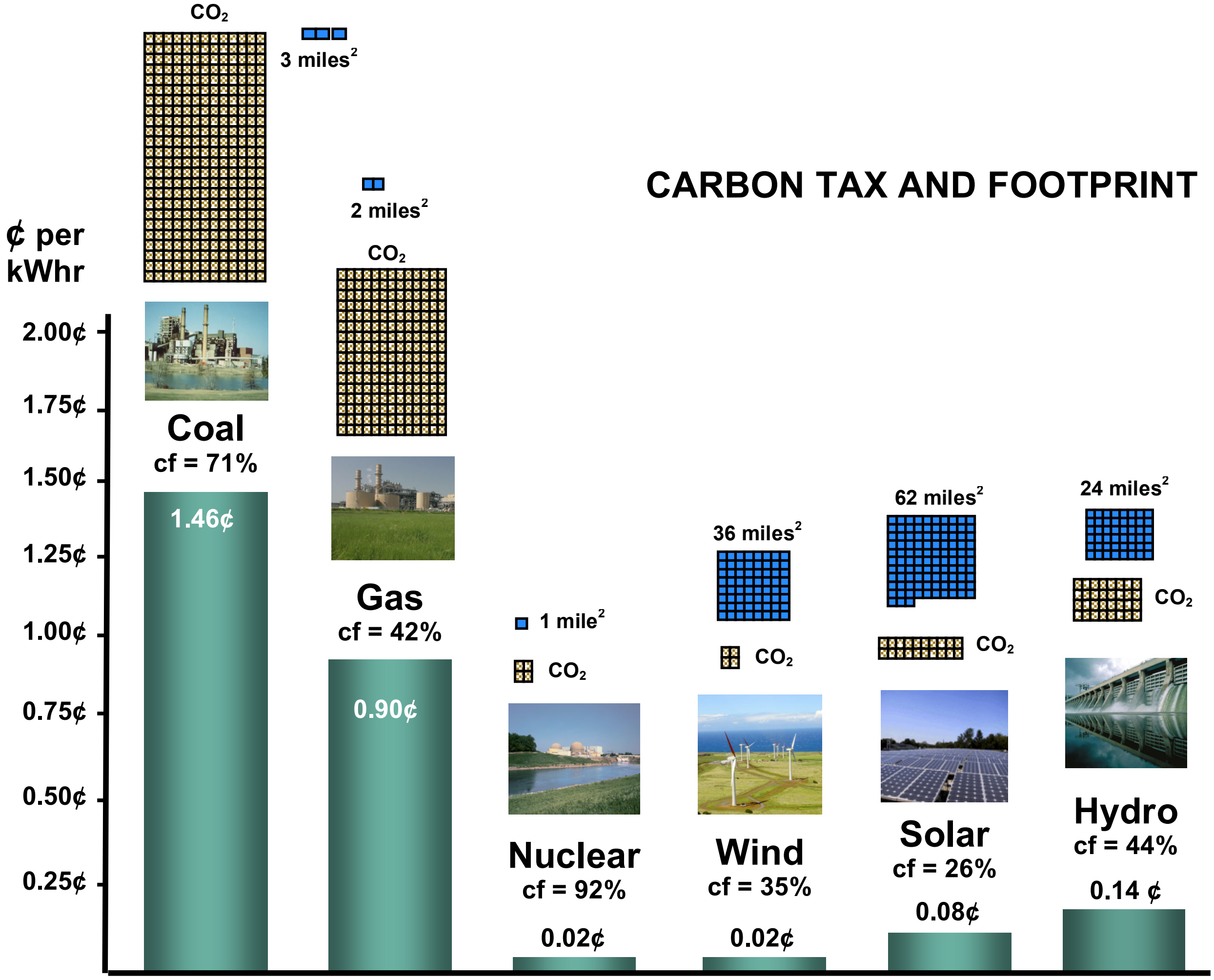

Figure 4. Costs associated with a possible Carbon Tax per kWhr at \$15/tonCO_2 emitted. The footprint is also shown for each source to produce 469 bkWhrs but is not assigned a value.

Total Costs

A summary of the estimates of total costs for producing 1260 tkWhrs from a final target mix of about a third fossil fuels, a third renewables and a third nuclear, between now and 2060, is given in Table 3 for the existing fleet and Table 4 for new builds.

*Table 3. Summary of Total Global Costs for Producing 266 tkWhrs from Existing Fleet 2010 to 2060.**

Source/Cost ($trillions)	*Fuel*	*O&M*	*Decomm*	*C-Tax*	*subTotal*
Coal (75 tkWhrs)	1.5	0.45	0.16	1.1	3.21
Natural Gas(+ Oil) (50 tkWhrs)	4.0	0.25	0.001	0.45	4.70
Nuclear (31 tkWhrs)	0.2	0.40	0.03	0.006	0.64
Hydro (110 tkWhrs)	0	0.88	0.95	0.15	1.98
subTOTAL from aging fleet	5.7	1.98	1.14	1.71	10.53

*no new construction costs for maintaining existing fleet; existing wind and solar negligible

Table 4. Summary of Total Global Costs for Producing 994 tkWhrs from New Builds 2010 to 2060.

Source/Cost ($trillions)	*Construction*	*Fuel*	*O&M*	*Decomm*	*C-Tax*	*subTotal*	*normalized***
Coal (115 tkWhrs)	1.5	2.3	0.69	0.24	1.7	6.43	5.59
Natural Gas (125 tkWhrs)	2.9	10.0	0.63	0.003	1.13	14.66	11.73
Nuclear (385 tkWhrs)	5.7	2.3	5.0	0.42	0.08	13.50	3.51
Wind (200 tkWhrs)	4.9	0	2.0	0.26	0.04	7.20	3.60
Solar (144 tkWhrs)	8.8	0	0.14	0.11	0.12	9.17	6.37
Hydro (24 tkWhrs)	0.4	0	0.19	0.21	0.03	0.83	3.46
subTOTAL from new builds	27.4	14.6	8.65	1.24	3.10	51.79	

**costs normalized to 100 tkWhrs for each source to allow easy comparison

TOTAL GLOBAL ENERGY COSTS from 2010 to 2060

to produce 1,260 trillion kWhrs total by the $^1/_3$, $^1/_3$, $^1/_3$ mix (50% less CO_2)	$62.3 trillion
to produce 1,260 trillion kWhrs total by the anticipated mix $^2/_3$ fossil fuel	$75.4 trillion

Adding Tables 3 and 4 gives a total cost for achieving the target mix of $62.3 trillion between 2010 and 2060, or about 2% annually of the present global GDP (http://web.worldbank.org1). The low costs for coal come from the assumption that new construction will occur only to replace some existing capacity, and the aging fleet will just be maintained. This is a difficult target to achieve, but is the only scenario in which coal use drops appreciably (EIA 2009). The high cost for natural gas comes from the fuel costs, as expected. Nuclear is fairly evenly split between construction and later operating costs. Note that nuclear is producing twice as much of the total energy as any of the other sources. Wind, solar and hydro are mainly up-front costs, but uncertainties exist for long-term O&M for solar. Coal is most affected by a carbon tax, natural gas less so, and the others not significantly at all. Without a carbon tax, the normalized values for 100 tkWhrs for coal and natural gas in Table 4 drop to 4.11 and 10.83, respectively, still maintaining the relative ranking of energy sources. Therefore, it is debatable whether such a carbon tax will significantly alter the energy mix on its own. Most likely, a larger carbon tax, perhaps exceeding $40/ton emitted, is needed to truly force a change in fossil fuel use (Dan Kammen, Berkeley, personal communication).

The same ramp down of the existing fleet from Table 3 can be used together with the normalized costs for

100 tkWhrs from Table 4 for the additional 994 tkWhrs to compare the $^1/_3$, $^1/_3$, $^1/_3$ mix with the more anticipated mix commonly discussed. Adapting EIA (2009) assuming increases of 53% in natural gas and 18% in coal, and increasing renewables to over 20% of the total, a likely mix is 385 tkWhrs of coal, 320 tkWhrs of natural gas, 171 tkWhrs of nuclear, 90 tkWhrs of wind, 50 tkWhrs of solar and 244 tkWhrs of hydro, with a total cost of $75.4 trillion. This is a 20% higher cost than the $^1/_3$, $^1/_3$, $^1/_3$ mix with 50% higher carbon emissions. Note that nuclear and coal essentially reverse places, and wind and solar are a smaller fraction of the more desirable mix. This more traditional scenario has fossil fuel still producing about 60% of all power rather than one-third, increasing the environmental consequences and making implementation of carbon sequestration and storage twice as critical. In summary, between now and 2060, this alternative energy mix produces almost 50% less carbon for a 20% lower total energy cost.

What is not discussed here is the cost of connectivity and the cost of upgrading the electrical grid. These are essential for development of renewables to any significant level and to increase efficiency and conservation in general. This cost is on the order of $1 trillion in the U. S. and $5 trillion worldwide. These costs are necessary no matter what future energy plan is adopted and are relatively insensitive to the mix unless renewables are not developed at all or solar is not distributed at all.

CONCLUSIONS

Simple projections are used to estimate total electric power production from 2010 to 2060 with leveling global consumption at 30 tkWhrs/yr and achieving a target energy mix of about a third fossil fuels, a third renewables and a third nuclear by 2040. This mix produces 1260 tkWhrs between 2010 and 2060 and costs $62.3 trillion in 2009 dollars. About a fifth of these costs will occur in the United States. This $62.3 trillion is about 2% of the global GDP annually. The cost of this alternative mix is about 20% lower than the $75.4 trillion to produce the same amount of energy from more common expectations of energy growth and distribution (EIA 2009) which still have fossil fuels producing about 60% of world power in 2040. Comparing apples to apples, hydro, nuclear and wind turn out to be the most cost-effective sources over the next 50 years, almost identical per kWhr produced. The high installation costs of nuclear compared to other non-fossil fuel sources that are often cited are incorrect. Total costs are calculated in 2009 US$ using historic and recent values for construction, fuel, O&M, decommissioning and a carbon tax of $15/ton of CO_2 emitted. Because of fuel costs, natural gas is the most expensive of all energy sources in the long-run. Therefore, for 20% lower total energy costs between now and 2060, fossil fuel use could be cut in half by 2040 by adopting the $^1/_3$, $^1/_3$, $^1/_3$ mix with enormous environmental benefits.

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