

The Cost of Energy – Ethics and Economics

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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 are 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 tWhrs/yr) by mid-century, 6.5 tWhrs/yr in the U.S alone (Wright and Conca 2007). This growth is essential because humanity requires about 3,000 kWhrs/yr/person to eradicate poverty, with the desirable side-effects of increased life span, decreased population growth, and decreased terrorism and war. While large unconventional fossil fuel resources are still available to be developed, particularly natural gas shales and tar sands, 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 analysis of how much it costs to produce energy from each primary energy source: coal, natural gas, nuclear, wind, solar and hydro. These costs are separate from investments, taxation, subsidies, loan structure, and other costs associated more with pricing and financing than with what the actual costs are to produce that energy. For society to develop a long-term sustainable energy mix able to meet future demand, it is imperative to know the actual production costs over the total life cycle of these units. Only then can appropriate and wise planning and financing be developed to meet those needs, build those units, fuel them and operate them in ways that do not destroy the environment or damage the long-term economic health of the nation.

Normalizing to capacity factor, life-span, and a total production of 469 billion kWhrs over 60 years, the costs per kWhr for each source is 4.1 ¢/kWhr for coal, 5.2 ¢/kWhr for natural gas, 3.5 ¢/kWhr for nuclear, 4.3 ¢/kWhr for wind, 7.7 ¢/kWhr for solar and 3.3 ¢/kWhr for hydro. Costs include construction, operation and maintenance (O&M), fuel, and decommissioning. Costs not discussed include electrical grid upgrade, transportation issues, connectivity of renewables and buffering of their intermittency by rapid cycling of fossil fuel plants presently practiced in this country, and non-carbon-tax externalities such as pollution and health care costs associated with energy sources, especially for coal and solar. Costs for coal are strongly dependent on the cost of gasoline, and the costs for wind are highly dependent on material costs like steel and concrete. Comparing apples to apples, hydro and nuclear are the most cost-effective sources over the next 60 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, and flawed financing mechanisms. All decommissioning and waste disposal costs are relatively small compared to other costs, even for nuclear. Costs of a carbon tax @\$15/ton of CO₂ emitted are significant for the fossil fuels over this time period but, on their own, are still insufficient to force any change in fossil fuel use, or the total mix of sources.

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 tWhrs generated between 1910 and 1990 emitted over 140 billion tons of CO₂ with significant damage to human health and the environment, it also lifted almost 2 billion humans out of abject poverty (United Nations 2009) and significantly increased life-spans for the poor and middle class. 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 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 most 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 at an acceptable cost. 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 CO₂ 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*. In order to develop a sustainable mix to achieve this level of production requires careful long-term planning and an understanding of the actual costs to produce this amount of energy from each source. Only then can rational planning and financing be developed.

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 worldwide, and none in the U.S. 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, a situation we are presently seeing with gas shales. Large hydroelectric is not considered to change significantly over this period, as most large rivers are already developed, and the ecological damage from large dams is being recognized as more severe than once thought (McCully 1996; Pacca 2007).

Energy for transportation will not be discussed here, although the advent of 800 million fully plug-in electric vehicles worldwide by 2050, consuming over 1 trillion kWhrs/year, is captured in the base-load electric generation from nuclear, coal and gas, and will dramatically reduce the use of petroleum. Non-electric vehicles are estimated to utilize 100 billion gallons of biofuels and 200 billion gallons of petroleum annually by 2040 (Wright and Conca 2007).

Finally, these costs do not include externalities not generally factored into direct costs, e.g. footprint costs, material supply problems (e.g., steel, copper and cement which are the most important hurdles to wind expansion), connectivity and distribution, or human health and environmental factors. Most externalities make fossil fuel, wind and solar more expensive relative to hydro and nuclear (Bickel and Friedrich 2005). All values are in 2011 US\$.

COMPARING COSTS

Any reasonable long-term energy plan must account for the actual costs well into the future, in this discussion 2060, the time at which all existing power plants will be dead, and replaced by new units. The cost data is needed to plan for these new units, to understand the costs throughout their life, and to finance them correctly. 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. Some of 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. Also, the first few built of any new design 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 discussion of levelized costs reflect 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 life using capacity factors and lifespans. Key assumptions used to normalize costs are given in Table 1. Other relevant assumptions include the following recent commodities spot prices: \$70/barrel for oil; \$40/ton for coal; \$4/tcf for natural gas; \$500/ton for steel; \$2⁵⁰/lb for copper, \$70/ton for cement, and \$100/lb for yellowcake (U₃O₈). 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. Capacity factors used are historic averages over the last 5 years, not theoretically high values often quoted, particularly important for the renewables and natural gas in this country.

Construction

Normalizing to a specific total output of 469 billion kWhrs gives a set of size, cost and number of different energy units required to produce 469 billion kWhrs over the life of the unit/farm/array (Figure 1, Table 2). As an example, TVA spent \$820 million dollars to build a natural gas power plant that produces 880 MW 42% of the 8,766 hours each year over its 40-year life, producing 130 billion kWhrs, more or

less (Table 2). To produce 469 billion kWhrs over their lives will require building about 4 of these plants at a cost of about \$3.2 billion. Theoretically, gas can operate at higher capacity, and does in some countries like Dubai, but never in the United States. This may change but for this discussion, historic numbers will be used. Table 2 and Figure 1 give these results for all six energy sources, but these costs are for construction only. Once built, they now have to be fueled, operated and maintained.

Table 1. Key assumptions for different energy systems from recent 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	880 MW	\$0.82 billion	TVA
Nuclear	0.92	60 years	960 MW	\$7 billion	Westinghouse
Wind	0.27	20 years	1 MW	\$0.0015 billion	Shell Wind Division
Solar	0.20	25 years	92 MW	\$0.3 billion	NRG Energy
Hydro	0.44	80 years	600 MW	\$ 3.0 billion	Susitna Hydro Project

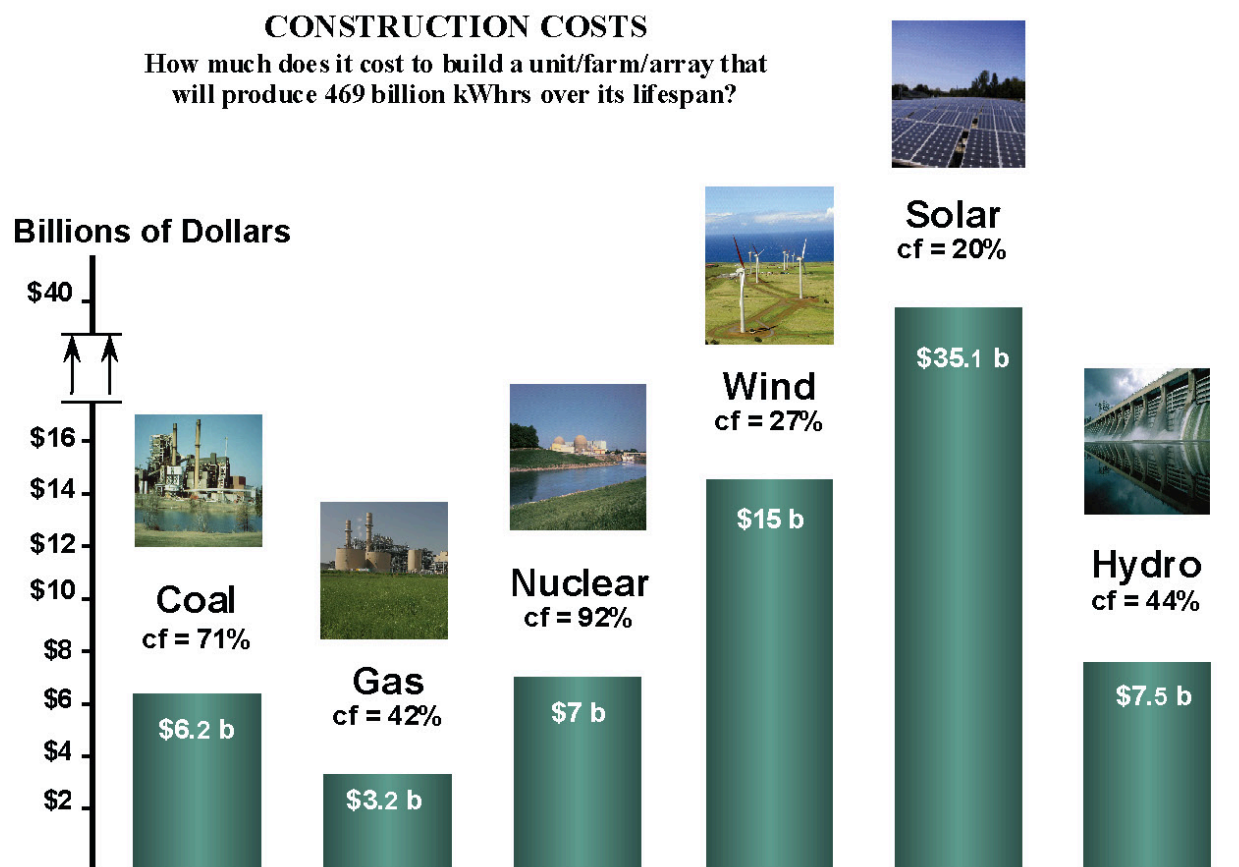


Figure 1. Comparison of construction costs in 2011 dollars among various energy sources required to install systems that will produce 469 billion kWhrs over their lifespan. Total costs are a function of installation cost, installed capacity (MW), capacity factor (cf), and lifespan.

Fuel, O&M and Decommissioning

From Figure 1 and Table 2, gas is the cheapest to install per kWhr produced, followed by coal, nuclear and hydro in a close group. Solar is the most expensive, and wind is intermediate. However, this ranking changes by the continued need to fuel coal and natural gas with these fossil fuels. Fuel costs are presently (DOE EIA): 2¢/kWhr for coal @\$40/ton, 4¢/kWhr for natural gas @\$4/thousand cubic feet (mcf), 0.6¢/kWhr for nuclear @\$100/lbU₃O₈, and 0¢ for wind, solar and hydro which have no fuel costs (Figure 2).

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 - \$820 million 880 MW combined cycle gas plant with a cf = 42% and lifespan = 40 yrs

⇒ 880 MW x 1000 kW/MW x 0.42 x 8,766 hrs/yr x 40 yrs = 130 billion kWhrs

∴ to produce 469 billion kWhrs ⇒ 4 units at \$3.2 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 = 27% and lifespan = 20 yrs

⇒ 1 MW x 1000 kW/MW x 0.27 x 8,766 hrs/yr x 20 yrs = 47 million kWhrs

∴ to produce 469 billion kWhrs requires 9,978 units at \$15 billion

Solar - \$300 million 92 MW thin film solar with a cf = 20% and lifespan = 25 yrs

⇒ 92 MW x 1000 kW/MW x 0.20 x 8,766 hrs/yr x 25 yrs = 4.0 billion kWhrs

∴ produce 469 billion kWhrs requires 117 units at \$35.1 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

O&M costs are more difficult to elucidate, especially for new technologies (Meier 2002; Paffenbarger and Bertel 1998; Sampattagul et al. 2005). The best estimate is \$6/MWhr (0.6¢/kWhr) for coal, \$5/MWhr (0.5¢/kWhr) for natural gas, \$13/MWhr (1.3¢/kWhr) for nuclear, \$10/MWhr (1.0¢/kWhr) for wind, \$1/MWhr (0.1¢/kWhr) for solar and \$8/MWhr (0.8¢/kWhr) for hydro (Figure 3). Long-term solar O&M costs are poorly known but other countries building large arrays have found these to be higher than expected, but for now we will assume they are extremely low. The wind O&M 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 such as WA State.

Decommissioning costs are a factor for most systems beyond the ordinary site operation 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). 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).

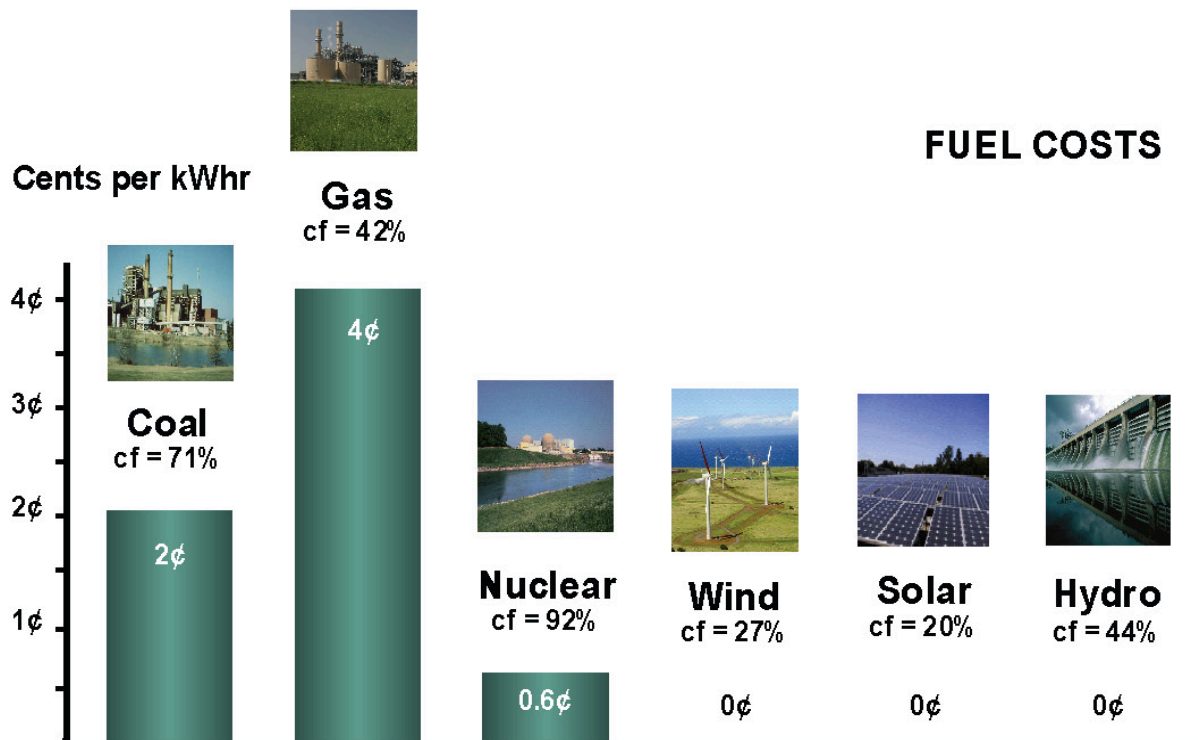


Figure 2. Comparison among various energy sources of fuel costs in 2011 dollars to produce 1 MWhr. 2011 prices are: Coal - \$40/t NG - \$4/tcf U - \$100/lb yellowcake

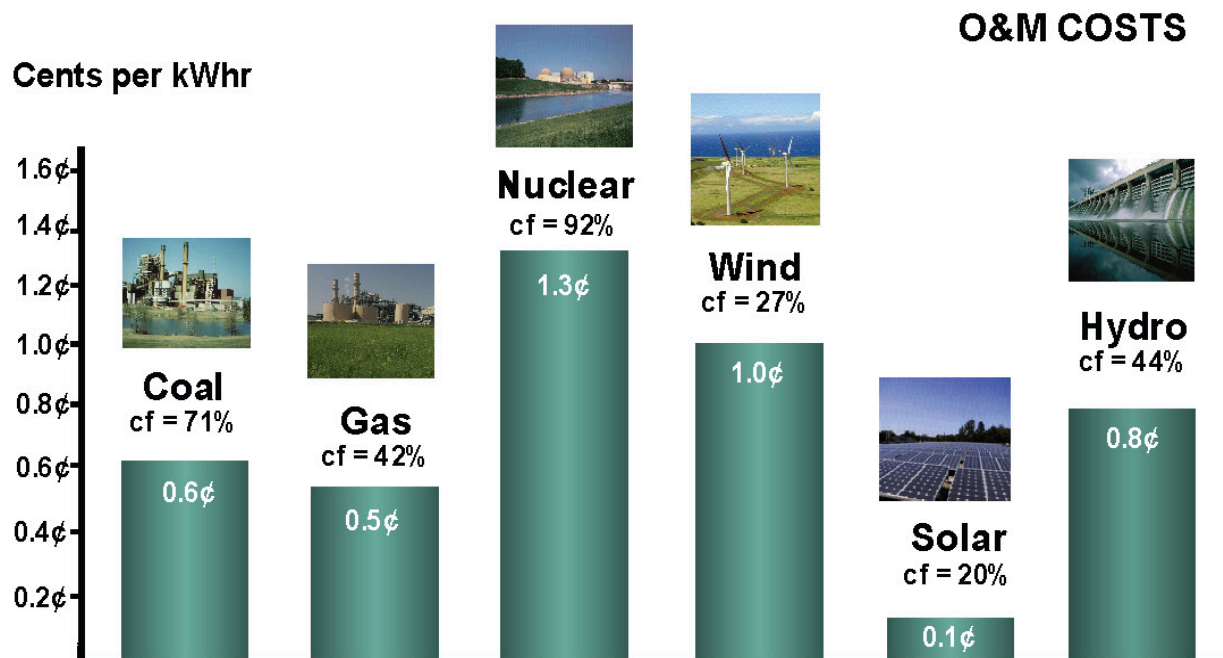


Figure 3. Comparison of O&M Costs per kWhr produced in 2011 dollars. Long-term O&M costs for Solar are unknown but thought to be low.

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 the President's Blue Ribbon Commission on America's Nuclear Future for the United States, and similarly in other nations (BRC 2012). 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; BRC 2012).

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, then the total disposal costs should be about \$10 billion per 15 tWhrs produced (Conca et al. 2008; WSRC 2008). The existing and anticipated monies in the Nuclear Waste Fund (NWF) generated by the 0.1¢/kWhr nuclear waste 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 and/or rate payers. Even under very unfavorable scenarios, such a tax would increase the cost of nuclear energy less than 0.3¢ per kWhr (Conca and Wright 2012), 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.

Total Costs

Combining Figures 1, 2 and 3 and Table 2 gives a total cost per kWhr of energy produced required to produce 469 billion kWhrs from each source over the life-time of the unit (Table 3). These are 4.1¢/kWhr for coal, 5.3¢/kWhr for natural gas, 3.5¢/kWhr for nuclear, 4.7¢/kWhr for wind, 7.7¢/kWhr for solar and 3.3¢/kWhr for hydro. Comparing apples to apples, hydro and nuclear are the most cost-effective sources over the next 60 years, almost identical per kWhr produced. Table 3 illustrates the dominant cost categories for each source, e.g., for hydro and solar, costs are mostly in construction, while for gas, costs are dominated by the fuel. Coal and nuclear are more distributed. Comparing Figures 1, 2 and 3 and Table 2 also reveals the time dependence of the costs, i.e., the longer fossil fuel plants run, the less cost-effective they become, and the longer the alternatives run the more cost-effective they become, because of the fuel costs. Solar costs will most likely decline as new technologies and distribution strategies develop, but significant breakthroughs are necessary for solar to become a meaningful contribution to baseload power.

Table 3. Summary of Total Costs for Producing 469 bkWhrs from New Builds over the next 60 years.

<i>Source/Cost</i> <i>(\$billions)</i>	<i>Construction</i>	<i>Fuel</i>	<i>O&M</i>	<i>Decomm</i>	<i>Total</i>	<i>normalized</i>	<i>w/\$15/tonCO₂</i> <i>emitted carbon tax</i>
Coal	6.2	9.4	2.8	0.98	19.4	4.1 ¢/kWhr	5.6 ¢/kWhr
Natural Gas	3.2	18.8	2.3	0.01	24.3	5.2 ¢/kWhr	6.1 ¢/kWhr
Nuclear	7.0	2.8	6.1	0.52	16.4	3.5 ¢/kWhr	3.5 ¢/kWhr
Wind	15.0	0	4.7	0.61	20.3	4.3 ¢/kWhr	4.3 ¢/kWhr
Solar	35.1	0	0.5	0.37	36.0	7.7 ¢/kWhr	7.8 ¢/kWhr
Hydro	7.5	0	3.8	4.03	15.3	3.3 ¢/kWhr	3.5 ¢/kWhr

These costs assume 2011 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. 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 m³ of concrete compared to the 98 metric tons of steel and 160 m³ of concrete for coal, and the even lower 40 metric tons of steel and 90 m³ of concrete for nuclear. Natural gas is the lowest of all, requiring a little over 3 metric tons of steel and 27 m³ of concrete per MW. Wind is sensitive to transportation costs because of the large volume of materials needing transport during construction and emplacement, 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 becoming a serious contribution to baseload over the next 50 years becomes obtaining sufficient steel and other metals required for its construction and connectivity to the grid, plus 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 much of a problem when compared to the initial expansion of nuclear in the 1960s and 70s from nothing to a few hundred reactors. The major hurdles for coal and gas are 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.

Two important costs that are missing from Table 4 are 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.

The values in Table 3, however, only include direct costs, not the hidden external costs to society and the planet that are paid for indirectly, either by the toll on human health, future generations, other species, or the planet as a whole.

Carbon Tax and External Costs

Attempts have been made to capture external costs associated with human health and the environment, called externalities, and have focused particularly on carbon emissions and footprint effects. Proposed carbon taxes are in the range of \$15/ton of CO₂ 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 for coal and natural gas, but also for wind if the total life-cycle is analyzed as will be discussed. 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 CO₂ emitted per kWhr produced: 975 gCO₂/kWhr from coal; 600 gCO₂/kWhr from natural gas; 90 gCO₂/kWhr from hydro; 55 gCO₂/kWhr from solar; 15 gCO₂/kWhr from wind, and 15 gCO₂/kWhr from nuclear (Pacca and Horvath 2002; Vattenfall 2003; POST 2006).

Figure 4 shows the carbon and footprint effects for each energy source, and Table 3 lists the cost per kWhr with an applied tax of \$15/metric ton of CO₂ emitted. Since most C-tax or Cap&Trade proposals are in the range of about \$15/metric ton of CO₂ emitted (0.0015¢/g), these additional carbon costs are

significant only for the fossil fuels compared to construction and O&M costs over this time period. Figure 4 also includes a relative footprint size for each energy source to produce 1 billion kWhrs/yr (McDonald et al., 2009) although no costs are assigned. It can be seen that coal and gas are strongly affected by a carbon tax and wind, solar and hydro 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 behind the dams (McCully 1996). For the footprint shown in Figure 4, only an average upstream submergence is used.

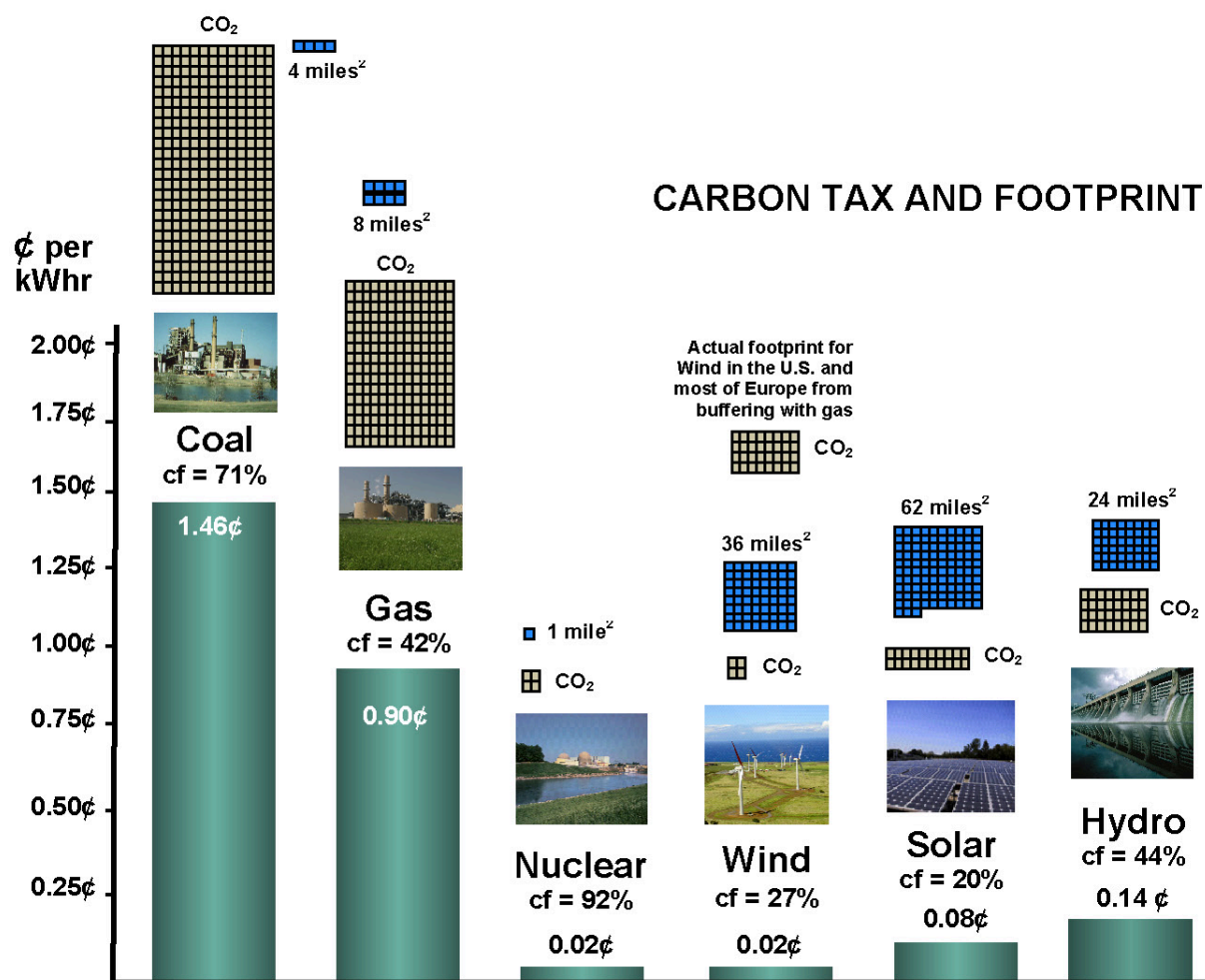


Figure 4. Costs associated with a possible Carbon Tax per kWhr at \$15/tonCO₂ emitted (one square = 4g CO₂ per kWhr produced). Also shown is the footprint for each source required to produce 1 billion kWhrs/yr. Sources: McDonald et al. (2009); POST (2006)

It must be pointed out that the above cost and carbon emission numbers are for produced electricity at the source and used near the source. For fossil, nuclear and hydro, the units produce more or less continuously and ramp up and down as needed for refueling, maintenance or grid stabilization needs, e.g., river discharge dramatically increases after a major storm or snowmelt such that the hydro must ramp up and the other producers in the region ramp down to maintain baseload for demand. These are generally slow changes that can be predicted and handled ahead of time. Responses to these changes make up a majority of utilities' efforts at stabilizing the grid against large swings in supply. On the other hand, the short-time scale intermittency of renewables requires different tactics depending upon the end-use. If the electricity generated is used locally without being incorporated into the grid, then the amount of carbon emitted per kWhr is close to those given above, i.e., wind energy is used to charge batteries, pump water, drive engines, or somehow perform work that can stop when the wind turbine stops. As an example, in Ireland, wind energy is used to pump water uphill to a small impoundment in coupled pumped hydro storage systems where that water is subsequently used to drive a small hydroelectric turbine as it flows back downhill during times where the wind turbines cannot generate electricity. This stores much of the energy produced by the wind and allows it to be utilized elsewhere more easily and in a more continuous manner.

However, if the wind energy is fed directly into a large grid, as is done in the United States and most of Europe, that energy flow must be buffered and stabilized against the intermittency using another energy source, usually gas power plants, to prevent grid crises and loss of baseload stability. In Texas and California, the buffering gas plants ramp up and down (cycle) many times per day. Such short cycling times result in inefficiencies that dramatically increase the carbon output per kWhr produced because these large fossil thermal systems are designed for continuous operation with little cycling. Wear on the turbines is also dramatically increased as these are not designed for continuous cycling and this has not been factored into O&M costs. Therefore, for every kWhr of wind energy produced in the United States, approximately 3 kWhrs is produced by gas (and even some coal in Texas) as buffering, producing well over 100 gCO₂/kWhr of additional emissions (Udo 2011). The costs in Table 3 do not reflect this additional CO₂ burden from buffered wind in this country. It is critical that these types of couplings are incorporated into carbon models and tax plans in order to correctly account for environmental impacts and costs (Figure 4). We must do a better job in this country of incorporating wind energy into the grid or we will never obtain any of the benefits that wind could provide with respect to climate change.

Except for solar, the production costs in Table 4 are not different enough that the small differences will determine which sources are developed in the future. Even if one adds a \$15/tonCO₂ emissions tax or Cap&Trade equivalent, which changes the ranking of coal relative to wind, it is debatable whether such a carbon tax will significantly alter the energy mix on its own. 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) but that is unlikely given the global economic situation and the unlikely agreement of developing countries such as India and China.

But an energy's deathprint, as it is called, is rarely discussed. According to the World Health Organization, the Centers for Disease Control, the National Academy of Science and many health studies over the last decade (NAS 2010), the adverse impacts on health become a significant effect for fossil fuel and biofuel/biomass sources. Table 4 lists the mortality rate of each energy source as deaths per billion kWhrs produced. For coal, oil and biomass, it is carbon particulates resulting from burning that cause upper respiratory distress. The actual numbers of deaths in China from coal use exceeded 300,000 last year since they have ramped up coal so fast in the last decade and rarely install exhaust scrubbers. The impact on their health care system has been significant in not just deaths, but in non-lethal health effects and lost days of work. It is notable that the U.S. death rates for coal are so much lower than for China, strictly a result of regulation and the Clean Air Act (Scott et al., 2005). Still, almost 20,000 die from coal use in the U.S. each year, and another few thousand from natural gas. Nuclear is the lowest, even with the worst-case Chernobyl numbers and Fukushima projections, and none have occurred in the U.S.

Although it is difficult to assign a cost to these numbers, estimates have been made that point to about a 10% increase in health care costs in countries where coal exceeds 50% of the energy mix, like the U.S. (NAS 2010; Cohen et al., 2005; Pope et al., 2002). These costs rival the total energy costs on an annual basis given that health care costs topped \$2.6 trillion, and electricity costs only exceeded about \$400 billion. Another way to describe these human health costs is that it costs about 8,000 lives per year to keep the lights on in Beijing, but only about 50 lives to keep them on in Tulsa. These are the costs never captured in traditional analyses.

Table 4. Mortality rates for each energy source in deaths per billion kWhrs produced.

<u>Energy Source</u>	<u>Mortality Rate (deaths per billion kWh)</u>	
Coal – global average	161	(50% of global electricity)
Coal – China	278	(75% of China’s electricity)
Coal – U.S.	15	(44% of U.S. electricity)
Oil	36	(36% of global energy, 8% of global electricity, none in the U.S.)
Natural Gas	4	(20% of global electricity)
Biofuel/Biomass	24	(21% of global energy)
Solar (rooftop)	0.44	(< 1% of global electricity)
Wind	0.15	(~ 1% of global electricity)
Hydro – global average	1.4	(15% of global electricity, 171,000 Banqiao dead)
Nuclear – global average	0.04	(17% of global electricity w/Chernobyl&Fukushima - none in the U.S.)

Sources –World Health Organization; CDC; Seth Godin; John Konrad

Financing

The biggest omission from Table 4 are the financing costs, subsidies, mandates or other societal costs, which have nothing to do with actual costs to produce electricity, but have everything to do with what we decide to build and how we build them. How society finances these power plants is the most important aspect of energy policy that we can address, and will determine the future energy mix in this country and the world. At present, financing is decided almost strictly on short-term goals and profits, and not on long-term needs for energy and economic security. This is true for the United States, and progressively less so for other countries whose energy production is either nationalized, part of a close government-private relationship, or merely heavily subsidized. Free market forces may be excellent for short-term profits and innovation but cannot address long-term non-market requirements for stability and security. To confront this void, the United States should develop financial mechanisms that provide long-term strategies while allowing market forces to function as desired, such as:

- Establish a Federal Energy Bank or green bank like the proposed Clean Energy Deployment Administration, or a National Infrastructure Bank that can facilitate long-term financing for energy resources.
- Fully fund and improve administration of Loan Guarantee Programs for all energy projects, especially for nuclear and renewable.
- Extend the successful Section 1603 Treasury cash grant program for energy projects expanded to include all alternatives, which provides valuable financing alternatives to the Federal Investment Tax Credits (ITC) and the Production Tax Credits (PTC)

- Create a syndicated loan securitization program (Nukie Mae, Renewie Mae and Fossil Mae) to convey debt financing obligations from the public to the private sector, that could, or could not, be part of the Energy Bank or National Infrastructure Bank.

Unless we change the time-scale of our planning, the future energy mix will be determined more by availability of fuel, transportation costs, and societal issues such as siting and financing, and not by how much a particular source costs society in the long run. If we don't think about the real costs, then fossil fuels will dominate the energy mix for the next two hundred years. We have lots and lots of fossil fuel.

CONCLUSIONS

As in all steady-state systems, humanity must attain a sustainable energy mix sometime in the future. Unless nuclear and renewable energy are a considerable part of that mix, humanity will go through a period of environmental and economic upheaval. Comparing apples to apples, hydro and nuclear are the most cost-effective sources over the next 60 years, almost identical per kWhr produced. When normalized to capacity factor, life-span, and total production over decades, the actual costs to produce energy from each primary energy source (coal, natural gas, nuclear, wind, solar and hydro) are 4.1 ¢/kWhr for coal, 5.2 ¢/kWhr for natural gas, 3.5 ¢/kWhr for nuclear, 4.3 ¢/kWhr for wind, 7.7 ¢/kWhr for solar and 3.3 ¢/kWhr for hydro. Costs include construction, operation and maintenance (O&M), fuel, and decommissioning. Costs not included are 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. These costs are separate from investments, taxation, subsidies, loan structure, and other costs associated more with pricing and financing than with what the actual costs are to produce that energy. Costs of a carbon tax @\$15/ton of CO₂ emitted are significant for the fossil fuels but are still insufficient on their own to force any change in fossil fuel use, or the mix of sources. For society to develop a long-term sustainable energy mix able to meet future demand, it is imperative to know the actual production costs over the total life cycle of these units. Only then can appropriate and wise planning and financing be developed to meet those needs, build those units, fuel them and operate them in ways that do not destroy the environment or damage the long-term economic health or security of the nation.

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REFERENCES

- BEATY, H. W., Handbook of Electric Power Calculations, McGraw-Hill, New York, 608 p., ISBN-13: 978-0071362986 (2000).
- BICKEL, P. and R. FRIEDRICH, Externalities of Energy, European Union Report EUR 21951, Luxembourg (2005).
- BOYCE, M. P., Handbook for cogeneration and combined cycle power plants, Amer. Soc. Of Mech. Engineers, New York, 560 p., ISBN-13: 978-0791801697 (2001).
- BRC. Report to the Secretary of Energy, from the President's Blue Ribbon Commission on America's Nuclear Future (BRC), Washington, D.C. (2012).
http://www.brc.gov/sites/default/files/documents/brc_finalreport_jan2012.pdf
- BRYAN, R. H. and I. T. DUDLEY, Estimated Quantities of Materials Contained in a 1000-MW(e) PWR Power Plant. Oak Ridge National Laboratory, TM-4515 Prepared for the U.S. Atomic Energy Commission. Oak Ridge, Tennessee (1974).

- COHEN, A.J., Anderson, H.R., Ostro, B., Pandey, K.D., Krzyzanowski, M., Kunzli, N., Gutschmidt, K., Pope, A., Romieeu, I., Samet, J.M., Smith, K., The global burden of disease due to outdoor air pollution. *Journal of Toxicology and Environmental Health, Part A*, 68: 1301-1307 (2005).
- COLLIER, P., *The Bottom Billion*, Oxford University Press, New York (2007)
- CONCA, J. and J. WRIGHT “Deep Geologic Nuclear Waste Disposal – No New Taxes”, Proceedings of the 2010 Waste Management Symposia, Phoenix, AZ, paper #12469, p. 1-11 (2012).
<http://www.wmsym.org>. Also, posted to the President’s Blue Ribbon Commission on America’s Nuclear Future December 14, 2011 <http://brc.gov/index.php?q=generalcomment/paper-deep-geologic-nuclear-waste-disposal-%E2%80%93no-new-taxes>
- CONCA, J., S. SAGE and J. WRIGHT, “Nuclear Energy and Waste Disposal in the Age of Recycling,” *New Mexico Journal of Science*, vol. 45, p. 13-21 <http://www.nmas.org/NMJoS-Volume-45.pdf> (2008).
- DEUTCH, J. M. and E. J. MONIZ, “The Nuclear Option”, *Scientific American* 295:76-83 (2006).
- Energy Information Administration, Electricity, www.eia.doe.gov/fuelelectric.html (2007).
- DOI, Klamath Hydroelectric Settlement Agreement, Department of the Interior, (2009).
<http://www.edsheets.com/Klamathdocs.html>
- EIA, Annual Energy Outlook, DOE/EIA-0383, Energy Information Administration, Washington, D.C.
- JUNGBLUTH, N., “Life Cycle Assessment of Crystalline Photovoltaics,” *Progress in Photovoltaics: Research and Applications*, Published online in Wiley InterScience (www.interscience.wiley.com).
 DOI: 10.1002/pip.614 (2005).
- McCULLY, P., *Silenced Rivers: The ecology and politics of large dams*, Zed Books Ltd., London (1996).
- MEIER, P. J., *Life-Cycle Assessment of Electricity Generation Systems and Applications for Climate Change Policy Analysis*, U. Wisconsin Report UWFDM-1181, August (2002).
- NAS, *Disposal of Solid Radioactive Waste in Bedded Salt Deposits*, Board on Radioactive Waste Management, National Academy of Sciences, Wash., D.C. (1970).
- NAS, *Hidden Costs of Energy: Unpriced Consequences of Energy Production and Use* Committee on Health, Environmental, and Other External Costs and Benefits of Energy Production and Consumption; National Research Council, Washington, D.C. ISBN: 0-309-14641-0 (2010).
- McDonald, R., J. FARGIONE, J. KIESECKER, W. M. MILLER and J. POWELL, “Energy Sprawl or Energy Efficiency: Climate Policy Impacts on Natural Habitat for the United States of America”, *PLoS ONE* doi:10.1371/journal.pone.0006802 (2009).
<http://www.plosone.org/article/info%3Adoi%2F10.1371%2Fjournal.pone.0006802>
- PACCA, S., Impacts from decommissioning of hydroelectric dams: a life cycle perspective, *Climatic Change*, 84:281 – 294, DOI 10.1007/s10584-007-9261-4 (2007).
- PACCA, S. and HORVATH, A., Greenhouse gas emissions from building and operating electric power plants in the upper Colorado River basin *Environ. Sci. Technol.*, **36**, 3194-3200 (2002).
- PAFFENBARGER, J. and E. BERTEL, Projected costs of generating electricity, OECD Nuclear Energy Agency, International Energy Agency, Organisation for Economic Co-operation and Development, 244 p. ISBN-13: 978-9264161627 (1998).
- PETERSON, P., “Will the United States Need a Second Geologic Repository?”, *The Bridge*, National Academy of Engineering, Vol. 33(3) (2003).
<http://www.nae.edu/Publications/TheBridge/Archives/V33-3.aspx>
- PETERSON, P. F., H. ZHAO and R. PETROSKI, Metal And Concrete Inputs For Several Nuclear Power Plants, Report UCBTH-05-001, University of California, Berkeley, 20 p. (2005).
- POPE, C.A. et al. Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. *Journal of the American Medical Association*, 287 (9), 1132- 1141 (2002).

- POST, Carbon Footprint of Electricity Generation, Parliamentary Office of Science and Technology, London, October 2006 Number 268 (2006).
- SAMPATTAGUL, S., S. KATO, T. KIATSIRIROAT, N. MARUYAMA, and A. NISHIMURA, "Comparison of Coal-fired and Natural Gas-fired Power Plants as Economically Viable and Ecologically Sustainable Power Generation Systems ," International Journal of Emerging Electric Power Systems: Vol. 3:Iss. 2, Article 1116 (2005).
- UDO, F. Wind Energy in the Irish Power System, <http://www.clepair.net/IerlandUdo.html> (2011).
- UNITED NATIONS, Human Development Index, <http://hdr.undp.org/en/statistics/> (2009).
- VATTENFALL, Swedish wind power plants, Vattenfall AB EPD report, Stockholm (2003).
- WHITE, S. W. and G. L. KULCINSKI, "Birth to Death Analysis of the Energy Payback Ratio and CO₂ Gas Emission Rates from Coal, Fission, Wind, and DT Fusion Electrical Power Plants", The 6th IAEA Meeting on Fusion Power Plant Design and Technology, Culham, England, March 23-27 (1998).
- WRIGHT, J. and J. L. CONCA, The GeoPolitics of Energy: Achieving a Just and Sustainable Energy Distribution by 2040. BookSurge Publishing (on Amazon.com). North Charleston, South Carolina (2007).
- WSRC, Salt Repository Scoping Study Functional & Operational Requirements, EAS-G-FRD-G-00005, (2008).
- ZACHARIA, F. "Interview with Manmohan Singh", Global Public Square (GPS), November 22, CNN, Washington, D.C. (2009).