



How to compare energy sources—Apples to apples

By James Conca

The recent increase in investments and in new designs for nuclear power is essential if energy growth estimates are even marginally correct. The world will achieve a consumption of well over 35 trillion kilowatt-hours per year (35 tKWh/yr) by mid-century, with about 5 tKWh/yr of that in the U.S. This growth is essential because humanity requires about 3,000 kWh/yr per person to eradicate poverty, with the accompanying benefits of increased life span, decreased population growth, and decreased terrorism and war.

Unfortunately, we generally base decisions about what energy systems to emplace on cost, and if the costs are not favorable to specific strategic or political goals, then we try to adjust costs with subsidies, mandates, tax relief, reduced land leases, or other mechanisms that often shift costs from the ratepayer to the taxpayer, where they cannot

easily be seen by the public. However, even these policies must be informed by the correct values for the costs of each energy source or they will not achieve their goals without a great deal of financial waste.

This work presents an analysis of the direct costs of construction, operations and management (O&M), and fuel to produce energy from each primary energy source over the total life of those units: coal, natural gas, nuclear, wind, solar, and hydro. These costs, unlike levelized costs, are the actual direct costs to produce electricity and are separate from investments, taxation, subsidies, mandates, loan structure, depreciation, and other costs associated more with pricing and financing than with what the actual costs are to produce that energy.

Normalizing to power output

True comparisons among various energy systems require normalization to total power produced from each system over its life using installed capacity, capacity factors (Fig. 1), and life spans (List 1). The capacity factors shown in Fig. 1 are national and recent historic averages of all units in America. Wind and solar produce whenever the weather is favorable in whatever geographical region they reside. Not much we can do about that. And it may seem strange that gas, coal, and hydro are so low. They could be higher, but market forces and extreme weather do drop them significantly. Hydro-power is so low because the dams and their water are used for so many different things: flood control, navigation, water supply and irrigation, power, recreation, fish and

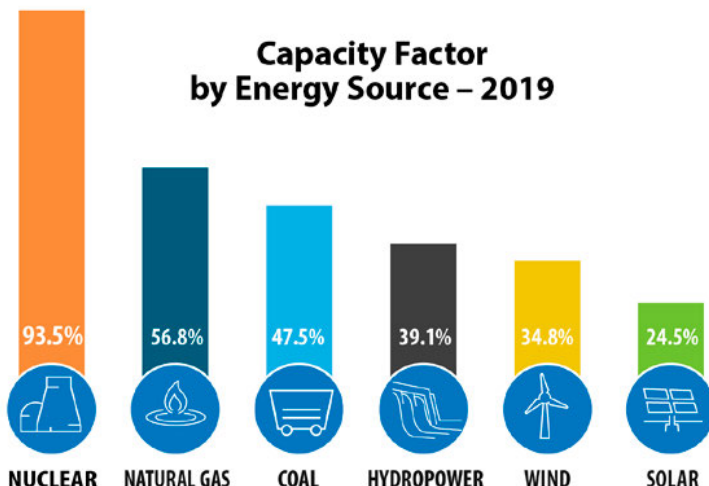


Fig. 1. The national average for the capacity factors of various energy systems. There will be a geographic dependence for wind and solar.



wildlife, fish migration and water quality, and cultural resources.

The limits on natural gas and coal reflect variable fuel costs and grid-balancing physics. They could run longer, but often it is not cost-effective to do so, given the fluctuations in the price of natural gas and coal and the diurnal price variations of electricity in deregulated markets. Sometimes gas is limited by lack of sufficient pipeline supply. Maintenance and refueling are additional considerations that drop coal's capacity factor, since a large coal plant requires about a hundred 100-ton coal cars rolling into the plant every day.

First, we need to find an approximate least common multiple for the lifetime output of individual whole-generation units. Because of their large output and high capacity factor, this will be the lifetime output of a single 1,000-MW pressurized water reactor nuclear power plant.¹ Various numbers of the other plants will be needed to meet that single output.

Contrary to the media's understanding, and even much of the scientific literature, the design life for nuclear is about 80 years. The 40-year relicensing period was simply a regulatory number selected by the Atomic Energy Commission as a reasonable time to revisit a reactor in detail, as if it were being licensed for the first time. Similarly, the design life of large hydro, like the Grand Coulee Dam, is closer to 120 years.

To determine the total lifetime power output (PO) using the figures above, multiply as follows:

$$\text{installed capacity (in MW)} \times \text{capacity factor (unitless)} \times 8,766 \text{ hrs/yr} \times \text{life span (yr)} = \text{total PO.}$$

So for a 1,000-MW nuclear plant with a 93.5 percent capacity factor and 80-year life span, the total power output is 656,000,000 MWh, given in List 2 along with the POs for the other sources.

List 1. Characteristic inputs

Nuclear plant (1,000 MW; 93.5% capacity factor): 80-year life span.

Wind turbine (5 MW; 34.8% capacity factor): 25-year life span.

Solar array (1 MW; 24.5% capacity factor): 25-year life span.

Large hydroelectric plant (1,000 MW; 39.1% capacity factor): 120-year life span.

Natural gas plant (1,000 MW; 56.8% capacity factor): 40-year life span.

Coal plant (1,000 MW; 47.5% capacity factor): 60-year life span.

List 2. Life cycle total power outputs

Nuclear: $1,000 \text{ MW} \times 0.935 \times 8,766 \text{ hrs/yr} \times 80 \text{ yrs} = 655,696,800 \text{ MWh}$, rounded to 656,000,000 MWh.

Wind: $5 \text{ MW} \times 0.348 \times 8,766 \times 25 = 381,321 \text{ MWh}$, rounded to 400,000 MWh.

Solar: $1 \text{ MW} \times 0.245 \times 8,766 \times 25 = 53,692 \text{ MWh}$, rounded to 54,000 MWh.

Hydro: $1,000 \text{ MW} \times 0.391 \times 8,766 \times 120 = 411,300,720 \text{ MWh}$, rounded to 412,000,000 MWh.

Gas: $1,000 \text{ MW} \times 0.568 \times 8,766 \times 40 = 199,163,520 \text{ MWh}$, rounded to 200,000,000 MWh.

Coal: $1,000 \text{ MW} \times 0.475 \times 8,766 \times 60 = 249,831,000 \text{ MWh}$, rounded to 250,000,000 MWh.

List 3. Installed capacity of plants needed to produce 656,000,000 MWh over plant life span

Nuclear: $1 \times 1,000 \text{ MW nuclear plant} = 1,000 \text{ MW}$.

Wind: $1,640 \times 5 \text{ MW turbines} = 8,200 \text{ MW}$.

Solar: $12,148 \times 1 \text{ MW solar arrays} = 12,148 \text{ MW}$.

Hydro: $1.6 \times 1,000 \text{ MW hydrodams} = 1,600 \text{ MW}$.

Gas: $3.28 \times 1,000 \text{ MW gas plants} = 3,280 \text{ MW}$.

Coal: $2.6 \times 1,000 \text{ MW coal plants} = 2,600 \text{ MW}$.

To make an apples-to-apples comparison with respect to construction costs and the amounts of steel and concrete needed for this much power output, keeping in mind the installed capacity differences, one has to compare one nuclear plant to the capacity of the other types of units (List 3).

Opinion continues



List 4. Material and cost needs for each energy source normalized to 1 MW

The numbers below are derived from a variety of sources referenced, particularly the DOE and EIA²⁻⁵.

- 1 MW of wind requires \$2 million, 180 MT of steel (300 MT for offshore wind), and 400 MT concrete.
- 1 MW of coal requires \$3.5 million, 90 MT of steel, and 400 MT of concrete.
- 1 MW of solar requires \$1 million, 56 MT of steel, and 170 MT of concrete (plus 70 tons of glass and 47 MT of aluminum).
- 1 MW of large hydroelectric requires \$4.5 million, 20 MT of steel, and 1,300 MT of concrete.
- 1 MW of nuclear requires \$8 million, 45 MT of steel, and 170 MT of concrete.

List 5. Total life span operational costs

- Nuclear: \$22/MWh × 656,000,000 MWh = \$14 billion in total life span operational costs.
- Wind: \$11/MWh × 656,000,000 MWh = \$7 billion in total life span operational costs.
- Solar: \$11/MWh × 656,000,000 MWh = \$7 billion in total life span operational costs.
- Hydro: \$13/MWh × 656,000,000 MWh = \$8 billion in total life span operational costs.
- Gas: \$25/MWh × 656,000,000 MWh = \$16 billion in total life span operational costs.
- Coal: \$35/MWh × 656,000,000 MWh = \$23 billion in total life span operational costs.

Table 1. Cost and materials to build sufficient units of each energy source to produce 656,000,000 MWh

Energy	Cost	Metric Tons of Steel	Metric Tons of Concrete
Nuclear	\$8.0 billion	45,000	170,000
Wind	\$16.4 billion	1,476,000	3,280,000
Solar	\$12.2 billion	680,000	2,065,000
Hydro	\$7.2 billion	32,000	2,080,000
Gas	\$2.6 billion	13,000	213,000
Coal	\$9.0 billion	234,000	1,040,000

List 4 gives material cost needs for each energy source. While not included here, note that the requirement of greater numbers and lengths of high-voltage transmission lines for wind and solar means significantly more steel, requiring over 20 MT of steel for the average high-voltage transmission tower alone, and 0.4 MT/km of transmission line (40 MT/100 km). The Department of Energy calculated that the cost of transmission for wind is about 25 percent that of the cost of building the wind turbines themselves. A MISO 2006 study^{3,4} determined that installing 1,600 MW of wind in the Midwest, at a cost of \$32 billion, would require \$31 billion in new transmission line installation, effectively doubling the cost of the project. That project was abandoned. These numbers are not included in the totals as there is uncertainty depending on the geographic location relative to the final users, but they should be kept in mind as they will disproportionately increase the costs of renewables and will be critical for any planning process.

Comparisons

Using the numbers from List 4 per MW installed and the number of MW needed for each source to produce 656,000,000 MWh from List 3, one can determine the amount of steel and concrete and the cost required to build equivalent energy systems using each source that would produce 656,000,000 MWh over their life span (Table 1; Fig. 2). Table 2 gives the total combined cost for construction and O&M (including fuel) to produce 656,000,000 MWh by adding Table 1 to List 5.

Normalized combined fuel, maintenance, and operational costs

Using Energy Information Administration numbers⁵ for fuel and O&M costs per MWh gives the total life span operational costs for producing 656,000,000 MWh (List 5). Adding Table 1 to List 5 gives the total cost to produce that normalized amount of power (Table 2).

It is obvious that the costs of wind and solar are dominated by their construction costs and the large amount of materials needed. There are no fuel costs, and operation costs are relatively low. Total hydro costs are the lowest of the six sources,

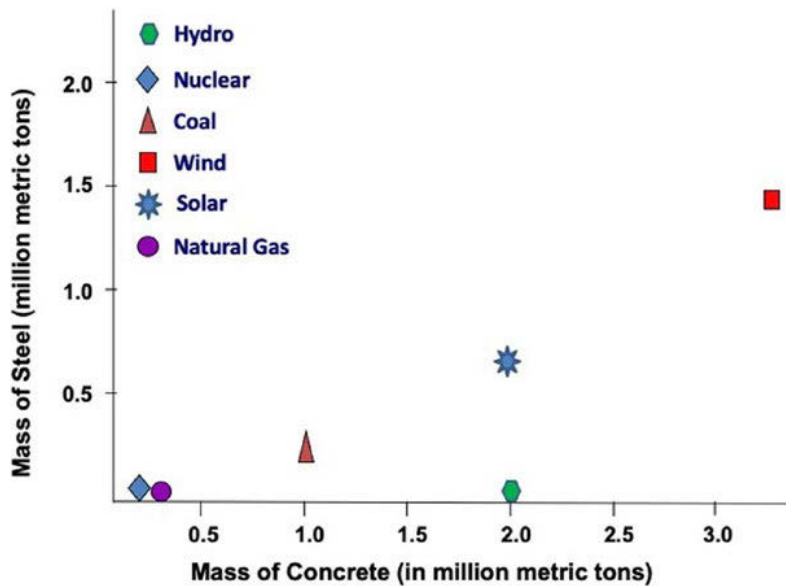


Fig. 2. The amount of concrete and steel needed for various energy systems normalized to the production of 656,000,000 MWh over their life spans.

Table 2. Total cost to produce 656,000,000 MWh from each energy source

Energy	Cost
Nuclear	\$22.0 billion
Wind	\$23.4 billion
Solar	\$19.2 billion
Hydro	\$15.2 billion
Gas	\$18.6 billion
Coal	\$32.0 billion

being distributed fairly evenly between construction and operations and having no fuel costs.

Nuclear costs are dominated by a combination of construction and operations, as fuel costs are low. The total cost of gas is dominated by its fuel costs, as construction costs are by far the lowest of any source, and operations are intermediate. The total cost of coal is the highest of the six sources, distributed between construction, fuel, and operations.

However, the cost of increased transmission lines, not included here, are substantial, about 25 percent of the construction costs for wind and solar according to the DOE,³ thereby adding another \$4 billion to the total cost for wind and \$3 billion to solar, bringing them up to above nuclear. Transmission costs for nuclear, gas, and coal are much smaller because of their location along existing lines, their small areal size, and their ability to be located wherever is most effective (not geographically constrained). Emplacing nuclear plants, especially SMRs, at old coal plant sites is even better as they can take advantage of the existing infrastructure, workforce, and location.

Also not included are costs for balancing, adequacy/backup, and curtailment/overproduction, which are large for grids with significant renewables and, according to IHS Markit,⁶ can add about \$20/MWh to wind

and solar, adding another \$1.5 billion to the total cost of wind and solar. An excellent discussion of this can be found in the book *Shorting the Grid*.⁷ Basically, without significant grid-scale storage, the grid cannot handle nonhydro renewable penetrations greater than 20 percent. In those areas of America where the energy markets have been deregulated, costs have almost doubled while reliability has been seriously degraded.

The recent rolling blackouts in California and Texas are a testament to this problem. Other areas of the country are predicted to have similar problems and frequent blackouts over the next five years as we phase out coal with no serious regard to replacing these firm power sources with reliable sources. Prior to 2019, the plan in all areas of the country was to replace them with natural gas plants over this decade. However, more and more states are legislating gas out of the future plans, choosing nonhydro renewables instead but without any grid-scale storage to make their production useful.

Decommissioning and waste disposal costs are not included since they are relatively small compared with other costs for all energy sources, even for nuclear. The Nuclear Waste Fund, paid for by the nuclear industry, has and will have more than enough funding

Opinion continues



to store and eventually dispose of all commercial nuclear waste, if disposed of in the correct rock type, such as massive salt, in which we have already disposed of a great deal of defense nuclear waste at the Waste Isolation Pilot Plant. WIPP was designed and built for all nuclear waste but has only been permitted for transuranic bomb waste.⁸ On the other hand, the buildup of solid waste from wind and toxic wastes from solar and coal, which already are orders of magnitude larger than nuclear waste, continues and presently has no reasonable solution, although it is assumed we will find one.

The takeaway from this analysis is that hydro is the best way to replace fossil fuel. It is the cheapest overall because of its long life span and flexibility. It does not require exotic elements but does require a lot of cement. While siting new hydro is as difficult as siting new nuclear, the DOE and the National Hydropower Association have a plan to double hydro in America without building a single new dam by powering some of the over 1,000 existing dams that do not generate power.

Nuclear, wind, and solar have about the same direct costs in the long run, but if transmission, distribution, and balancing/curtailment/overproduction/reliability are included, nuclear is significantly cheaper. And the reliability of nuclear is unmatched by any other source, while the reliability of wind and solar is the lowest of any other source.

Coal is simply too expensive and too polluting to continue very long in the developed world. However, coal is the easiest source to install, especially in poor countries that do not have the infrastructure to emplace anything but coal, which explains the continued increase in coal plant construction in the developing world, financed in part by China's foreign infrastructure programs.⁹

The problem for developed countries is that gas is the cheapest after hydro. America has lots of natural gas reserves, more than any country in the world, and we are getting better at extraction. Not using gas will require a combined political will beyond what the world has ever experienced.

The amount of steel needed for each energy

source is also a proxy for other metals, like aluminum, copper, and cobalt. For a detailed accounting of the materials issue and many others related to replacing fossil fuel globally, Simon Michaux wrote an excellent 1,000-page report about the materials necessary to build the "technology units" that the International Energy Agency demands in order to accomplish the Great Green Reset.¹⁰ According to Michaux, the largest need that must be met for decarbonization is the availability of copper. The world's copper reserves are only a fraction of what is needed and are barely able to meet the needs of a "business as usual" energy mix. Even seabed mining may not overcome this hurdle.

There are many variables that can alter these conclusions, but they won't alter them much. Putting wind in Tornado Alley obviously increases its capacity factor and lowers its direct costs, but the high-voltage transmission lines needed to bring that power to where it is needed, and the need to buffer the intermittency, will more than offset that savings. Similarly for grid-scale solar.

In the end, all will be for naught if we do not have a realistic national, and international, energy plan based on actual numbers. Otherwise, we're just singing in the wind. ☒

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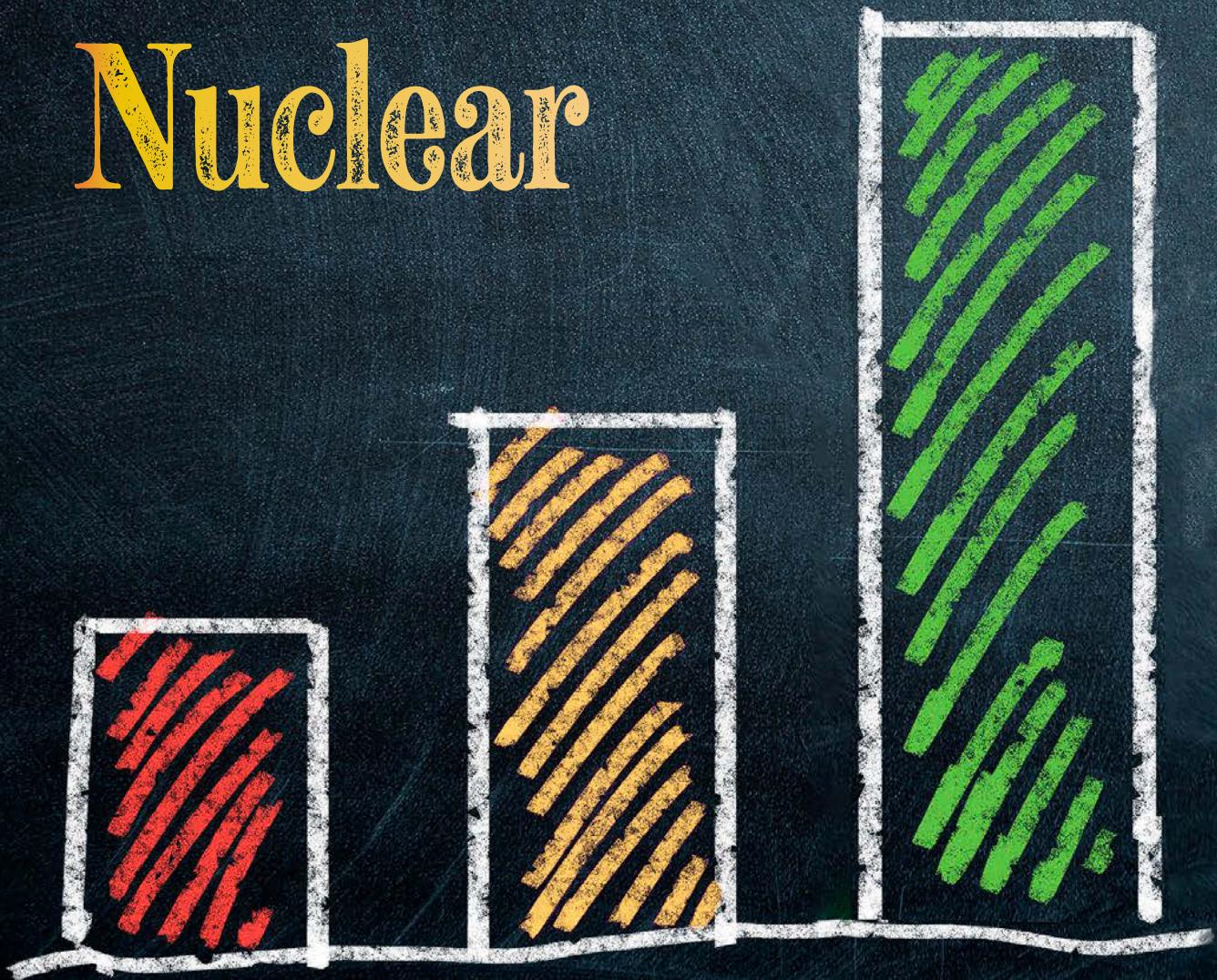
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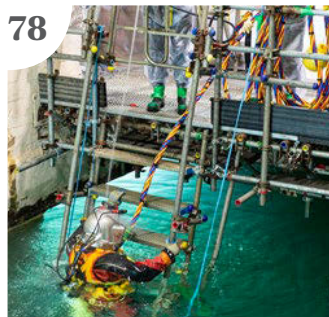
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- | | |
|--|--|
| <p>4 Nuclear Notes
Big plans for a new company</p> <p>6 Readers Write
Can higher ed provide North Carolina's nuclear workforce?</p> <p>7 Letters</p> <p>12 Atoms
Paths to investment</p> | <p>17 Leaders
Evolving finance structures drive new joint ventures for SMRs</p> <p>104 Opinion
How to compare energy sources—Apples to apples</p> <p>120 Nuclear News Asks
How can risk management be applied to advanced reactors?</p> |
|--|--|

Headlines

- 22 Nuclear Trending
- 54 Power & Operations
- 64 Research & Applications
- 72 Waste Management
- 80 Education
- 88 History
- 92 ANS News

Community Updates

- 98 Industry
- 102 Standards
- 103 Index to Advertisers
- 110 People
- 114 Calendar
- 116 Calls For Papers
- 118 Recently Published
- 119 ANS Journals

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