

## Viewpoint

### Energy use for electricity generation requires an assessment more directly relevant to climate change

Climate change will continue unabated in the coming years unless we rapidly reduce consumption of fossil fuels. The COVID pandemic will provide temporary reductions in overall energy consumption, but this will not last. In the US, for example, in the first six months of 2020 there was a 5% reduction in electricity and 8.5% reduction in total energy use reported by the U.S. Energy Information Administration (EIA) compared to 2019, with an estimated 8% global reduction for the year.<sup>1</sup> The COVID pandemic is just the newest of a series of global events that have temporarily reduced energy consumption, such as the first oil crisis in 1973, the second one in 1979, and several global economic recessions.<sup>1</sup> Each time energy consumption rebounded and energy use continued to escalate. Based on these previous disruptions we can therefore expect that energy use will again return to pre-pandemic levels and climate change will continue unless we do something specifically to avoid the re-growth of CO<sub>2</sub> emissions from the consumption of fossil fuels.

Technical solutions exist but they need more widespread support from the public. To better inform policy makers and the public we need clearer ways to present and explain energy use, particularly as it applies to the electric power sector. We suggest here that several changes are needed in the way we convey energy use to the public, beginning with energy units independent of fossil fuel terminologies, electricity use being clearly presented in terms the amount of fossil fuel consumed to produce it, and a clear path being established that enables energy consumption with minimal use of processes that contribute to CO<sub>2</sub> and other greenhouse gas emissions.

**Convey energy use in units that are not based on combustion of fuels.** A confounding factor in reporting energy use is the wide variety of energy units and their context of fuel combustion. Energy use will need to increasingly rely on carbon-neutral sources so energy units should not be tied to terminology anchored to fuel combustion (or use non-SI units). The energy units used by the US EIA are currently expressed in heating values in quads (a quadrillion British thermal units or qBtu, where 1 quad = 10<sup>15</sup> Btu).<sup>2</sup> These energy units lack relevance for achieving an electrical energy-based infrastructure using renewable sources, as opposed to electricity generated by burning fuels to heat water. Similarly, energy units based on oil heating values should be avoided. The International Energy Association (IEA) and others report energy in million tonnes of oil equivalent (Mtoe), where 1 toe = 10<sup>7</sup> kilocalories or roughly the heat content of 1 tonne of oil.<sup>3</sup> Energy units of billion kilowatt hours (or terawatt hours, TWh) make sense when discussing large amounts of electrical energy but these units are not applied when discussing energy in fuels such as oil and natural gas.<sup>4</sup>

Here, we advocate the use of exajoules (EJ, or 10<sup>18</sup> J) to describe large-scale energy use as these units do not reference oil or imply fuel conversions for energy production (1 EJ = 0.948 quad = 2.39×10<sup>7</sup> Mtoe = 278 TWh).<sup>5</sup> In addition, the amount of electricity used by the US and many other countries is around 100 EJ or less, providing a convenient metric for energy comparisons among countries.

**Avoid exaggeration of energy used for electricity production from renewables.** Many reports on electricity production emphasize primary energy use that is tied to fossil fuel plant efficiencies, implying fuel consumption even for technologies that do not use combustion-based processes. The EIA<sup>4</sup> and others<sup>6</sup> exaggerate primary energy use for renewables by adding an amount of energy that would be

wasted by a conventional fossil fuel steam plant to produce that amount of electricity. For example, in 2019 the US used 2.37 EJ of electricity produced from solar, wind, hydro, and geothermal energy, but the EIA reported that 6.33 EJ of primary energy was used to produce this electricity based on average energy efficiencies (37.5%) for fossil fuel plants.<sup>4</sup> Using this approach based on fossil fuel efficiencies could mislead the public about the amount of renewable energy actually produced and consumed, and the relationships between electricity generation and CO<sub>2</sub> emissions.

There is no need to report primary energy for renewable technologies, defined here to include solar, wind, hydro and geothermal, because there is no fuel consumption (no combustion to generate heat).<sup>7</sup> Energy from sunlight, wind, falling water, and geothermal sources will dissipate as heat energy with or without their conversion to electricity. If primary energy is reported for electricity generated from renewables it should have been reported in 2019 as 2.37 EJ without any additional energy added to that total. There is also no need to focus on primary energy for nuclear or biomass power plants as that energy is not relevant to CO<sub>2</sub> emissions that drive climate change. Electricity production from nuclear fuels is carbon neutral, and the CO<sub>2</sub> from biomass is recycled within the environment (neglecting energy to produce, transport and store fuels or wastes). Although biomass is considered to be a renewable energy source,<sup>4</sup> it is better to classify it as carbon neutral as it requires a combustion-based fuel process to make electricity whereas the other four renewable technologies are not fuel-based processes.

**Removing the additional energy for electricity generation from renewables will provide a more accurate representation of actual energy use.**<sup>2,6</sup> For example, electricity generation in 2019 is shown in **Figure 1A** with primary energy consumption separated into electricity from renewables and all other technologies, additional primary energy for renewables, and the rejected energy using other sources.<sup>4</sup> Primary energy used for electricity production in the US in 2019 was 39.0 EJ, with a total primary energy consumption including all other uses of 105.6 EJ.<sup>2</sup> Removing the 4.0 EJ of additional primary energy for electricity production from renewables (wind, solar, hydro, and geothermal) reduces the total to 35.0 EJ for all energy sources used for electricity production (and total primary energy consumption to 101.6 EJ), an overall reduction of 10.2% compared to the originally-reported 39.0 EJ. Energy use in the US is commonly summarized in Sankey diagrams prepared by the Lawrence Livermore National Laboratory (LLNL), showing primary energy use for different sources in heat-based units (quads).<sup>8</sup> We advocate that Sankey diagrams prepared by LLNL and others in the future report energy in EJ, and that these reports by LLNL and others should not include additional primary energy for renewables.

Further clarity in energy use could be obtained by conveying this energy use within some context relative to our daily lives. Therefore, we suggest it would be helpful for the public and policy makers to explain energy use relative to the food energy needed for 1 person every day (2000 Calories = 8.4 MJ = 2.32 kWh).<sup>9</sup> The annual use of 35.0 EJ of energy for electricity generation, normalized to the US population, was therefore 35 D in 2019 (**Figure 1B**). Thus, the amount of primary energy for electricity generation in the US for each person is 35 times the energy in the food that each person eats every day.

**Present only the primary energy in fossil fuels for electricity production.** To aid in focusing on the fuels that impact climate change we should only present the amount of primary energy in fossil fuels used to produce electricity. As an example, consider the electricity used in the US in 2019 shown by energy sources aggregated within three categories: renewable, carbon neutral, and fossil fuels (**Figure 2A**). This energy is then aggregated and compared to the energy only in the fossil fuels as they are the only primary energy source relevant to CO<sub>2</sub> emissions (**Figure 2B**). Based on this categorization we see that 2.37 EJ of electrical energy was provided by renewables, 3.02 EJ by carbon neutral technologies (nuclear and biomass), and 8.83 EJ by fossil fuels. Overall, 14.22 EJ of electricity was produced, which

required consumption of 23.2 EJ of CO<sub>2</sub>-emitting fossil fuels (natural gas, coal, and petroleum) (**Figure 2C**). When energy use was normalized per person for one day, relative to the daily energy in food, there was 14.2 D<sub>e</sub> in energy in the electricity, and 23.2 D<sub>ff</sub> in the energy in fossil fuels that contributed to electricity generation. The magnitude of electricity consumption is not nearly as important as the amount of fossil fuel energy that went into producing that electricity due to CO<sub>2</sub> emissions from these fuels.

The US is making better progress towards carbon neutral electricity production than that implied by the EIA analysis. For example, the overall electricity production in 2010 (14.3 EJ) was only slightly higher than that in 2019 (14.2 EJ). The reported primary energy use for electricity production showed a 6.5% decrease between 2010 (41.7 EJ) and 2019 (39.0 EJ) due to increased use of natural gas rather than coal, and increased use of renewables. However, there was an 18.5% decrease in primary fossil fuel energy between 2010 (28.5 EJ) and 2019 (23.2 EJ), despite a 9% increase in the US population. This successful reduction in primary fossil fuel use was not obvious given the current reporting methods that include additional primary energy for renewable energy production. Electricity production accounted for 27% of US greenhouse gas emissions in 2018.<sup>10</sup> To produce 100% carbon neutral electricity in the US would require replacing the remaining 8.83 EJ of fossil fuel-derived electricity with renewables and carbon neutral fuels (**Figure 2B**). While 8.83 EJ is a substantial amount of energy, it is much less than the 23.2 EJ of that is currently consumed using fossil fuels.

**Highlight the importance of natural gas versus coal for reducing CO<sub>2</sub> emissions.** The 8.2% reduction in CO<sub>2</sub> emissions by the US to 5.13 Gt (10<sup>9</sup> kg) in 2019 compared to 2010 (5.59 Gt) was due in part to the larger percentage of renewables for electricity production in 2019 (16.7%) compared to 2010 (9.3%). However, it was primarily due to the shift from coal to natural gas for two reasons: a lower CO<sub>2</sub> output for energy content of natural gas compared to coal, and high electricity conversion efficiencies. The lower CO<sub>2</sub> content of natural gas is generally well recognized, with coal combustion releasing 92.3 metric tons (Mt) per EJ of energy (subbituminous coal) which is 1.8 times more CO<sub>2</sub> than natural gas (50.4 Mt/EJ) for the same energy.<sup>11</sup> However, large and modern combined-cycle natural gas power plants (CCPs) have much higher electricity conversion efficiencies than coal power plants. Between 2010 and 2019 natural gas plants increased efficiencies from 41.7% to 43.6%.<sup>4</sup> In contrast, coal plant efficiencies remained relatively constant over the same period (32.8% in 2010, and 32.6% in 2019).<sup>12</sup>

Natural gas plants have a much greater potential to further reduce CO<sub>2</sub> emissions than other fossil fuel technologies as they can produce even higher efficiencies. Modern commercial CCPs can reach 63.5% efficiencies when operating at full capacity. Lower average efficiencies result from a combination of less efficient simple-cycle turbine plants still in service combined with these systems operating at less than full capacity. Based on 2019 electricity production a complete replacement of coal plants with more efficient natural gas plants could further reduce primary fossil fuel energy consumption from 23.2 to 20.5 EJ assuming 2019 conversion efficiencies. A further reduction to 14.2 EJ could be achieved if CCPs operated at maximum efficiencies of 63.5%, resulting in a 56% decrease in CO<sub>2</sub> emissions without any change in the amount of electricity generation. Natural gas will therefore remain crucial to the global energy infrastructure in the coming years due to both its high energy conversion efficiency and low carbon content as we transition towards a renewable energy electricity grid.

**Challenges for globally decarbonizing electricity generation.** Increasing the use of electricity to reduce CO<sub>2</sub> emissions through electrification of technologies faces substantial challenges in many countries and regions around the world due to the high reliance of fossil fuels as energy sources for electricity generation (**Figure 3**). For example, the Middle East uses a mix of petroleum and natural gas,

the US and EU use mainly natural gas and coal, while China primarily uses coal. The EU currently has about an equal balance between electricity energy and fossil fuel consumption, while ratios of electricity production to fossil energy consumption range 1.6 for the US to 2.1 for China. Normalizing total energy use for electricity generation (relative to daily food consumption) by the populations in these regions shows daily electricity use ( $D_e$ ) for China to be on par with other countries. When the primary energy in only the fossil fuels used to generate this electricity is similarly normalized to population of that region ( $D_{ff}$ ), the US is calculated to have the highest fossil fuel use per person of 26  $D_{ff}$  compared to 7 – 15  $D_{ff}$  for the others. All of these nations and regions need substantial reductions in fossil fuel use to achieve the needed reductions in greenhouse gas emissions. For some countries such as China, given the rapid growth in electricity demand and the young age of the current fossil fleet, strong policy support to enable accelerated deployment of low-carbon generation and storage technologies is particularly important for the transition away from fossil fuels. Despite these challenges, tangible local co-benefits of reducing air pollution and associated health damages have provided additional incentives for many countries to decarbonize their electricity sector.

**Electrification of our energy infrastructure will not solve climate change without a rapid transition to renewables for electricity production.** Identifying how energy is used for electricity production based on fossil fuels provides a more realistic view of energy use in the US and the world. Significant reductions in CO<sub>2</sub> emissions are only possible by a concerted and focused international effort to reduce the dependence of electricity generation on fossil fuels by shifting to renewable sources. The approach of adding energy demands not currently dependent on electricity, for example by replacing combustion engine cars with electric vehicles, will only result in decreased carbon emissions if the electricity grid is greatly shifted to solar, wind and other renewable energy sources. Every country and region will need to decarbonize electricity generation while they simultaneously shift towards increased use of electricity and reduced use of fossil fuels. Careful presentation of the magnitude of electricity production showing different sources that emphasizes the amount of fossil fuels consumed will better inform policymakers and consumers about electricity generation relevant to climate change than current methods that inflate primary energy consumption for renewables.

Bruce E. Logan  
Ruggero Rossi  
Gahyun Baek  
Le Shi  
Jacqueline O'Connor  
Wei Peng

### **Acknowledgments**

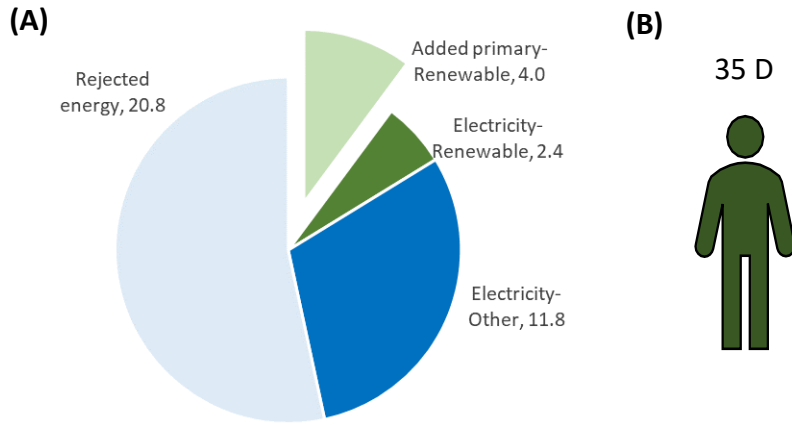
This research was supported by the National Science Foundation (CBET-2027552) and Penn State University.

### **Notes**

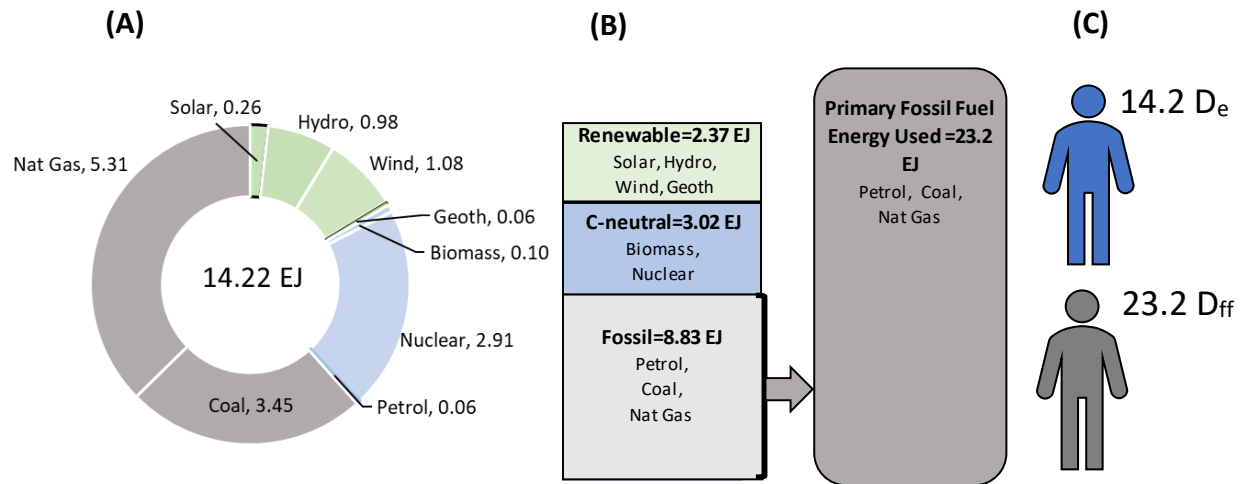
Views expressed in this Viewpoint are those of the authors and not necessarily the views of the ACS. The authors declare no competing financial interest.

### **References**

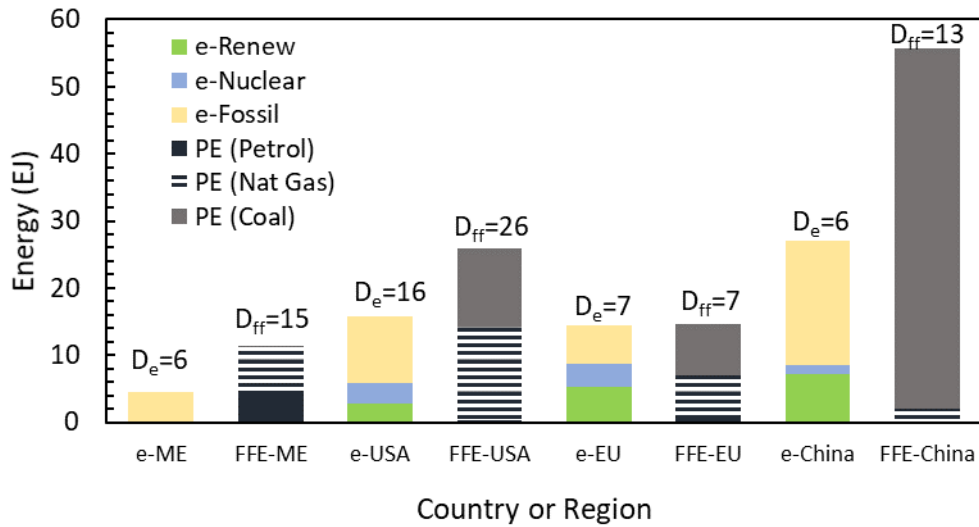
1. Hanna, R.; Xu, Y.; Victor, D. G., After COVID-19, green investment must deliver jobs to get political traction. *Nature* **2020**, *582*, 178-180.
2. Lawrence Livermore National Laboratory Estimated U.S. energy consumption in 2019: 100.2 quads. [https://flowcharts.llnl.gov/content/assets/docs/2019\\_United-States\\_Energy.pdf](https://flowcharts.llnl.gov/content/assets/docs/2019_United-States_Energy.pdf) (May 9, 2020).
3. IEA Projections: Energy policies of IEA countries 2019 edition. <https://webstore.iea.org/ods-projections> (August 7).
4. U.S. Energy Information Administration July 2020 Monthly Energy Review. <https://www.eia.gov/totalenergy/data/monthly/pdf/mer.pdf> (August 7).
5. Holliday, C.; Van Beurden, B. Shell energy transition report. [https://www.shell.com/energy-and-innovation/the-energy-future/shell-energy-transition-report/jcr\\_content/par/toptasks.stream/1524757699226/3f2ad7f01e2181c302cdc453c5642c77acb48ca3/web-shell-energy-transition-report.pdf](https://www.shell.com/energy-and-innovation/the-energy-future/shell-energy-transition-report/jcr_content/par/toptasks.stream/1524757699226/3f2ad7f01e2181c302cdc453c5642c77acb48ca3/web-shell-energy-transition-report.pdf) (August 7).
6. Dudley, B. *BP Statistical Review of World Energy 2019*; 2019.
7. Newell, R. G.; Raimi, D., *Global energy outlook comparison of methods: 2020 update*. Resources for the Future: Vol. 20-06.
8. Lawrence Livermore National Laboratory Energy flow charts. <https://flowcharts.llnl.gov/commodities/energy>
9. Logan, B. E., Energy literacy begins with units that make sense: The daily energy unit D. *Environ. Sci. Technol. Lett.* **2019**, *6*, (12), 686-687.
10. United States Environmental Protection Agency Global Greenhouse Gas Emissions Data. <https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data> (April 19, 2020).
11. US Energy Information Administration How much carbon dioxide is produced when different fuels are burned? <https://www.eia.gov/tools/faqs/faq.php?id=73&t=11> (August 7).
12. US Energy Information Administration Natural gas-fired electricity conversion efficiency grows as coal remains stable. <https://www.eia.gov/todayinenergy/detail.php?id=32572#:~:text=Over%20time%2C%20as%20more%20combined,rate%20of%207%2C340%20Btu%2FkWh> (July 24).



**Figure 1.** Primary energy (EJ) for electricity generation calculated for the US in 2019.<sup>2</sup> (A) Primary energy separated into four categories based on electricity produced from renewables (solar, hydro, wind, and geothermal) or other fuels (petrol, coal, natural gas, nuclear and biomass), the added energy for renewables based on the efficiency of low-efficiency power plants, and the rejected energy using other fuels for comparisons with other low-efficiency fossil fuel plants. (B) Primary energy presented in the daily energy unit D, defined as the ratio of daily energy consumed (revised to remove added primary energy for renewables) normalized by the number of people in the US to the daily energy consumption in food (2000 Calories, 8.4 MJ).



**Figure 2.** (A) Electricity produced by the US in 2019<sup>2</sup> based on energy source. (B) Electrical energy sorted into 3 categories compared to primary fossil fuel (PFF) energy used to produce electricity (not to scale). (C) Daily energy use normalized per person based on electricity energy ( $D_e$ ) or fossil fuel energy used for electricity generation ( $D_{ff}$ ).



**Figure 3.** Energy (EJ) in electricity generated ( $e$ )<sup>6</sup> and fossil fuel energy (FFE) used for electricity generation calculated for selected countries (USA and China) or regions (ME=Middle East, EU = European Union). The average daily energy use normalized by the population of these areas is shown for the electricity energy ( $D_e$ ) and the primary energy used for electricity generation considering only fossil fuels ( $D_{ff}$ ). (Data on fossil fuel primary energy were calculated using electricity generation efficiencies for the US due to an absence of energy efficiencies in source report. Values here for the US are different from those in Figure 2 due to slight differences in assumptions and components of energy used for electricity generation than those in US EIA reports.<sup>4</sup> Biofuels are included in the definition of renewables for these data.)