



# The Future of Global Energy

## Problems for Undergraduate and Graduate Students

### Based on the AGCI Energy Table

It is a generational challenge to meet the world's energy requirements, while remaining within the bounds of acceptable costs and environmental impacts. To this end, substantial research has explored various energy futures on a global scale. These questions and activities walk undergraduate and graduate level students through exercises that explore the pace and scale of the global energy transition that will unfold over the coming century.

The questions draw on the AGCI Energy Table ([https://www.agci.org/energy\\_table](https://www.agci.org/energy_table)) - an open-access, comprehensive energy reference featuring data on the availability, production, costs, and growth rates of energy sources and storage technologies currently in use or development. Energy sources include coal, oil, natural gas, nuclear, solar, wind, hydropower, ocean, geothermal and biomass. Each cell in the Energy Table provides data from recent peer reviewed publications and major institutional reports (such as the International Energy Administration), with hyperlinked references provided.

AGCI Interactive Energy Table					Energy Storage Technologies				<a href="#">Glossary</a>	<a href="#">References</a>	<a href="#">View Live Data</a>	<a href="#">Download</a>	<a href="#">Energy Tool</a>
Energy Source	AVAILABILITY				INSTALLED SCALE				GROWTH		Capital Costs (USD/kW)		
	Resource (TWh)	Resource (TWh/yr)	Reserve (TWh)	Reserve (TWh/yr)	Installed Capacity (GW)	Production (TWh)	Total Primary Energy (TWh)	Capacity Factor (%)	Current Rates (%)	Projected Rates (%)	min	max	
Totals	840,826,918	41,852,286			10,062	53,077							
<div><div></div><div>COAL</div><div></div></div>	187,630,100 <sup>[1]</sup>	9,275,294 <sup>[2]</sup>			1,646 <sup>[3]</sup>	9,538 <sup>[4]</sup>		53.3 <sup>[5]</sup>	-5.93 <sup>[6]</sup>	0.2 <sup>[7]</sup>	226 <sup>[8]</sup>	4,620 <sup>[9]</sup>	
<div><div></div><div>OIL</div><div></div></div>	16,670,994 <sup>[37]</sup>	5,111,111 <sup>[38]</sup>			452 <sup>[39]</sup>	1,023 <sup>[40]</sup>		13.0, 2.0 <sup>[41]</sup>	0.11 <sup>[42]</sup>	-1.1 <sup>[43]</sup>			
<div><div></div><div>GAS</div><div></div></div>	216,112,365 <sup>[72]</sup>	4,361,111 <sup>[73]</sup>			1,682 <sup>[74]</sup>	9,822 <sup>[75]</sup>		54.8, 9.4, 11.3 <sup>[76]</sup>	0.8 <sup>[77]</sup>	1.2 <sup>[78]</sup>	678 <sup>[79]</sup>	1,342 <sup>[80]</sup>	
Conventional Gas	2,930,711 <sup>[89]</sup>	1,930,987 <sup>[90]</sup>			1,682 <sup>[91]</sup>	5,543 <sup>[92]</sup>			2.202 <sup>[93]</sup>	2.2 <sup>[94]</sup>	678 <sup>[95]</sup>	1,342 <sup>[96]</sup>	
Shale gas	4,721,374 <sup>[102]</sup>	2,220,482 <sup>[103]</sup>				4,279 <sup>[104]</sup>			54.13 <sup>[105]</sup>	3.6 <sup>[106]</sup>			
Coalbed methane	3,310,531 <sup>[110]</sup>	993,159 <sup>[111]</sup>								3.6 <sup>[112]</sup>			
Methane hydrates	205,149,749 <sup>[114]</sup>	1,963,576 <sup>[115]</sup>								3.6 <sup>[116]</sup>			
<div><div></div><div>NUCLEAR</div><div></div></div>					383 <sup>[119]</sup>	2,476 <sup>[120]</sup>		92.2 <sup>[121]</sup>	1.3 <sup>[122]</sup>	1 <sup>[123]</sup>	5,945 <sup>[124]</sup>		
<div><div></div><div>SOLAR</div><div></div></div>	1,500,000,000 <sup>[136]</sup>	720,000 <sup>[137]</sup>	763.8 <sup>[138]</sup>	253.6 <sup>[139]</sup>				18-34 <sup>[140]</sup>	20.7 <sup>[141]</sup>	4.9 <sup>[142]</sup>	Vary from technology	Vary from technology	
<div><div></div><div>WIND</div><div></div></div>	1,611,111 <sup>[180]</sup>	278,000 <sup>[181]</sup>	486.7 <sup>[182]</sup>	826 <sup>[183]</sup>				36.7 <sup>[184]</sup>	17 <sup>[185]</sup>	3.1 <sup>[186]</sup>	Vary from technology	Vary from technology	
<div><div></div><div>HYDRO</div><div></div></div>	52,000 <sup>[223]</sup>	10,000 <sup>[224]</sup>	1,246 <sup>[225]</sup>	3,996 <sup>[226]</sup>				48 <sup>[227]</sup>	2.8 <sup>[228]</sup>	1 <sup>[229]</sup>	1,535 <sup>[230]</sup>		
<div><div></div><div>OCEAN</div><div></div></div>	2,040,000 <sup>[238]</sup>	9,200 <sup>[239]</sup>	0.536 <sup>[240]</sup>	1.0 <sup>[241]</sup>						22.4 <sup>[242]</sup>	Vary from technology	Vary from technology	
<div><div></div><div>GEOTHERMAL</div><div></div></div>	394,200 <sup>[280]</sup>	6,000 <sup>[281]</sup>	36.5 <sup>[282]</sup>	78.0 <sup>[283]</sup>				79 <sup>[284]</sup>	2.4 <sup>[285]</sup>	4 <sup>[286]</sup>	2,959 <sup>[287]</sup>		
<div><div></div><div>BIOMASS</div><div></div></div>	805,556 <sup>[293]</sup>	75,000 <sup>[294]</sup>	433 <sup>[295]</sup>	504 <sup>[296]</sup>				86 <sup>[297]</sup>	8.62 <sup>[298]</sup>	1 <sup>[299]</sup>	2,668 <sup>[300]</sup>		
Wood and residues		91,944 <sup>[308]</sup>	13,611 <sup>[309]</sup>			344 <sup>[310]</sup>		50.7 <sup>[311]</sup>	6.79 <sup>[312]</sup>	1 <sup>[313]</sup>	200 <sup>[314]</sup>	5,500 <sup>[315]</sup>	
Waste		33,333 <sup>[320]</sup>	3,055 <sup>[321]</sup>			94.2 <sup>[322]</sup>		70.9 <sup>[323]</sup>	0.23 <sup>[324]</sup>	1 <sup>[325]</sup>			
Energy crops		6,111 <sup>[330]</sup>						NA		<sup>[331]</sup>			

# Instructions

Answer the following questions based on the data, glossary, and references provided in the AGCI Energy Table ([https://www.agci.org/energy\\_table](https://www.agci.org/energy_table)).

Answers are denoted below the questions.

## Questions

- 1 Using the Energy Table data on coal, if the current rate of growth for coal has remained constant, what will be the approximate global primary energy supply for coal in 2025? What if the rate of growth for coal is based on the projected growth rate instead? Note that calculations will start from 2018, when data on primary energy and growth rates were most recently published.

Build a spreadsheet where 43,870 TWh is increased an annual rate of 4.3% (current growth rate as of 2018) for 7 years =  $43,870 \times (1.043^7) = 58,906$  TWh.

VS. Increase 43,870 TWh annually by only 0.2% (projected growth rate) for 7 years =  $43,870 \times (1.002^7) = 44,488$  TWh

- 2 If the current growth rate listed for wind energy continues, after what year in the future will the primary energy produced from wind exceed half of present day total primary energy? Note that calculations will start from 2018, from when data is most recently available on global primary energy for wind.

From the energy table the present global total primary energy is given as 170,785 TWh. Half of present primary energy is  $170,785 / 2 = 85,392.5$  TWh

As in (1) build a spreadsheet to calculate 12.6% growth on 1,128 TWh starting in 2018...

Wind energy will exceed half the present total energy production after 36 years, or for a 2018 start, in the year 2055.

- 3 If wind and solar installations grow at projected rates, after what year will the combined energy produced exceed half of present day total global installed capacity for all energy sources? Note to again use 2018 as the base year for calculations.

Half of present day total global installed capacity =  $11,797 \text{ GW} / 2 = 5,898.5 \text{ GW}$

The installed capacity for solar is 990.5 GW, and for wind is 620 GW. The projected growth rates for solar is 4.9%, and wind 3.1%. And using the spreadsheet method outlined above, the combined installed capacity from wind and solar increasing annually at their respective projected rates will exceed 5,898.5 GW after 31 years from 2018 or in 2049.

## Questions [cont.]

4

Using the reference cited in the Energy Table for proven conventional crude oil reserves (Ref 54, BP Statistical Review of World Energy 2019) and the annual oil consumption for 2018 in a separate table in the same report, when will the proven reserves be exhausted assuming the annual consumption remains constant?

From the energy table reference 54 (BP Statistical Review of World Energy 2019, p. 14), the proven oil reserve as of 2018 is 1729.7 thousand million barrels oil equivalent (1729.7 billion barrels oil equivalent (BBOE)). The annual consumption for 2018 is given as 4662.1 million tonnes oil equivalent (mtoe), also in Ref 54, p. 21. Converting the annual consumption from mtoe to BBOE and subtracting that amount from the proven reserve gives the result.

Helpful conversions:

1 tonne of oil equivalent = 6.84367 barrels of oil equivalent

1 TWh = 588441 barrels oil equivalent

1 TWh = 85984.52 tonnes oil equivalent

1 Mtoe = 7.142857 Million barrels oil equivalent

Using a spreadsheet to reduce the 2018 proven reserves by 31.906 BBOE each year exhausts the proven reserves in the 55th year, or in 2073.

5

If hydropower capacity factor remains constant each year, what would be the expected annual electric production when the total annual hydro available resource is fully utilized? During what year will that level of electric production be reached assuming the current growth rate remains constant? Note to use 2018 as the base year for calculations.

Looking up the hydro resource availability in the Energy Table gives 52,000 TWh per year. If the capacity factor remains 39.1% then the amount produced is  $52000 \times 0.391$  when the resource is utilized to its fullest.  $52000 \times 0.391 = 20,332$  TWh per year.

Using a spreadsheet as in early questions and starting at present (2018) electric production of 4,200 TWh per year and an annual growth rate of 1% gives a solution of 20,332 TWh being reached in the 159th year or in the year 2177.

## Questions [cont.]

### 6 For wind and coal; what explains the difference between total primary energy supply and production (Elec)?

Wind: Total primary energy supply = 1128 TWh

Wind: Electric Production = 1128 TWh

In the Energy Table for wind, total primary energy supply and electric production they are the same because the electric energy produced by the turbine is what can be supplied to the grid. (Aside: It's important to note that wind machines don't capture all of the kinetic energy in the wind at the turbine. The efficiency of extraction of wind energy at the turbine is limited by the Betz coefficient of ~59%. Modern turbines can capture about 3/4ths of the Betz limit.)

Coal: Total energy supply = 43,870 TWh

Coal: Electric production = 10,101 TWh

The difference between these two numbers stems from that total primary energy supply accounts for all the coal burned in a year (whether used as a direct fuel or in electricity production), whereas electric production is limited to the amount of that that is turned into electricity via steam turbines, excluding efficiency and heat losses in conversion processes.

### 7 What factors go into the levelized cost of energy from nuclear, wind, and solar? Is it fair to compare these technologies by levelized cost? If not, why? Why is the capacity factor of the supply technology important?

Costs from the table:

Nuclear: 118 – 192 USD/MWh

Wind: 28 – 115 USD/MWh

Solar PV: 32 – 181 USD/MWh

The levelized cost for electricity from nuclear, wind, and solar PV are not a perfect way to compare them, but perhaps the best approach. As in the IPCC definition most important factors go into the levelized calculation including decommissioning for example, capacity factor, cost of money, etc. Nuclear has a higher capacity factor which gives its value in different markets higher value than electricity from highly intermittent sources. Another difference between these technologies is that nuclear requires a fuel supply while wind and solar don't require a fuel but are dependent on solar and wind resources which geographically vary.

## Questions [cont.]

- 8 If a theoretical energy supply system for the world was to provide 10 TWe of power for a year or 87,660 TWh of energy for a year, but the capacity factor of this system was 90%, how much storage would be needed to provide a reliable system for a year?

Using simplistic assumptions about oversupply to cover the gap due to the capacity factor, the gap would be  $10 - (10 \times 0.9) = 1$  TW of power storage. If 1 TW power is converted to a year of energy it would be 8766 TWh.

- 9 What storage types and at what present cost could satisfy the requirement outlined in question number 8?

From the energy table pumped hydro, hydrogen, and electrochemical batteries seem to have the attributes most relevant for short to long gap filling in the source technologies to achieve the highly reliable system. One way to approach this question would be to create a global energy system of wind, PV hydro and nuclear with some bioenergy and other non-carbon emitting approaches. The over sizing the system the over production could then be used to store energy that is dispatchable via a number of means: hydro to electricity, electricity to hydrogen to electricity, thermal to thermal, thermal to electricity, thermal to electricity as in molten salt to electricity, and electro-chemical batteries with minor amounts from other technologies.

Using hydrogen as a proxy for all storage (it fits the bill because it can be used to do so many different applications from synthetic fuels, direct combustion, fuel for a fuel cell, etc). If we assume a cost of \$5 per kg H<sub>2</sub> and the energy content of a kg of H<sub>2</sub> as 142 MJ and H<sub>2</sub> chemical energy to electricity of 1.666 to 1 then need 42g H<sub>2</sub> to make 1 kWh. 42g at 5/kg = \$0.21 per kWh of storage.

## Questions [cont.]

- 10 Create a one-page narrative on an ideal total primary energy system for the world explaining your choices for how to achieve this, what technologies are used and in what proportions. What are the key obstacles to overcome and why does your design solve the problem?

Assume a 13.5 TWe world (as in question (9)) so that the oversupply from 10 TWe goes to storage needs. The design transforms the present TPES dominated by fossil fuels, now providing around 85% of 18 TW. I'll also assume that the TPES is mostly electric and that the total needed is reduced by the higher utility of electricity vs heat and further reduced to 10 TWe because of efficiency being more broadly applied (known efficiency applied in all sectors). There will still be a limited role for fuels, but they will be carbon emission neutral or negative and when not involving carbon based conventional fuels with CC offsets, they will be hydrogen based utilizing C or N (see [https://en.wikipedia.org/wiki/Sabatier\\_reaction](https://en.wikipedia.org/wiki/Sabatier_reaction) and Davis et al 2018 for example)

A possible supply mix to make up 13.5 TW:

- 1.0 TW from hydro
- 4.5 TW from wind
- 7.0 TW from solar
- 0.75 TW from nuclear
- 0.25 TW all other

The above choices are because solar has the greatest potential and low cost. Its likely that next generation nuclear will be cheaper and safer but still more costly than wind or solar but with a very useful higher capacity factor, that hydro is close to maximum already without degrading the environment further. Biomass and ocean resources are only marginally needed for energy.

Key obstacles include a redesign of the electric grid to accommodate long distance high voltage generation with demand foci and utilize micro to regional grid designs all with smart system controls for moving e where needed as needed from known availability slightly ahead of demand that is also responsive to known supply variability. One obstacle is the relatively low capacity factors for solar and wind. Another obstacle to overcome is in how to develop efficient ways of making hydrogen from water and of storing it and transporting it. Hydrogen from electricity solves many of the intermittency issues and potentially long haul transport via synfuel or direct use to electricity. I see an emergence of islanded systems that can be connected to larger systems as needed from home to neighborhood, school, business, factory on up to sub-regions, regions to global connections – all with storage spatially disperse.

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