WHAT ENGINEERS AND SCIENTISTS SHOULD KNOW ABOUT SCALES FOR MEASURING PRIMARY ENERGY: WHY THEY ARE NECESSARY AND HOW TO USE THEM

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Abstract

The amount of primary energy for producing one unit of electricity from fossil fuels, hydro, wind and solar energies is different by an order of magnitude. Thus, valid comparison between annual world primary energy consumption and primary energy consumption between countries is very difficult. To solve these problems, the Energy Information Administration of Washington, D.C., USA; the International Energy Agency of Paris, France; and Working Group III of the Intergovernmental Panel on Climate Change each developed a different scale for measuring primary energy. Therefore, it is essential in any energy analysis to specify the primary energy measurement scale in use.

1. Introduction

The wide variation in the conversion rates of renewable primary energies to electricity creates a problem for primary energy measurement scales. This is important because renewable energies usually supply electricity to the world's energy system. The only exceptions are a small amount of solar energy used to heat water directly in appropriate locations, and solid biomass, sometimes used to generate electricity or converted to liquid fuels.

The quantities of primary energy in the form of renewable energies to produce a given amount of electricity vary so widely that comparisons between them are difficult. For example, 1.18 Joules (J) of physical units of hydropower [1] delivers 1 J of electricity, as does 13.3 J of physical units of sunlight collected by 15% efficient photovoltaic cells where the land to collector ratio is 2:1.

Using the example of hydropower and sunlight above, the primary energy intensity can be different by a factor of 13.3/1.18 = 11.3. Thus, two countries might each use 1 J of electricity to manufacture the same value of goods and services. However, in this example the country using sunlight to generate electricity would appear to be much less energy efficient. In other words, primary energy per unit of output (J/$), referred to as primary energy intensity, would be 11.3 times higher for the country using solar electricity. Such a comparison is misleading because the inefficiency is in converting sunlight to electricity, not necessarily in the method of consuming electricity.

This example is based on the definition of Joules as used in physics, where one calorie = 4.184 Joules, i.e., one Joule is defined as the amount of heat energy required to raise the temperature of 0.239 g of water by 1_o Celsius. This is a very specific scientific definition.

There are legitimate differences of opinion about how to make comparisons of renewable energies meaningful, how to record the energy value of fossil fuels, and whether or not non-commercial energies should be included.

To try to get around the problem, the Energy Information Administration (EIA) converts both the electricity from hydropower and sunlight, which is in physical units, to the amount of fossil fuel energy that would be required to generate 1 J of electricity. In 2005 this figure was (9,999/3412) = 2.93 J [2]. In the example above, the primary energy is now the same for each country and the energy intensities are identical. However, the EIA definition of Joules for renewable primary energy is no longer that used in physics, it is the "EIA Joule".

The International Energy Agency (IEA) accounts for the primary energy [3] for hydro and all nonthermal means of producing electricity as one unit of primary energy equals one unit of the electricity energy produced. For nuclear energy, the IEA assumes 33% efficiency. The energy unit used is the "IEA Joule".

In the scenarios of the Special Report on Emissions Scenarios, Working Group III (WG III) of the Intergovernmental Panel on Climate Change (IPCC) specifies that the primary energy for all electricity generated by renewable and nuclear energies be recorded as 1.0 times the gross amount of electricity produced [4]. This results in a third definition, the "WG III Joule".

The key point is that when analyzing energy situations one must be aware that not "all Joules are equal". Identification of and consistent use of a specific primary energy scale is essential.
A summary of these methods for determining the primary energy from the electricity produced by renewable and nuclear energies is in Table 1 [5].

Table 1. Methods for determining the primary energy from the electricity produced by renewable and nuclear energies for each of the three scales

Primary energy	EIA scale	IEA scale	WG III scale
Nuclear	Energy content of uranium	0.33 x energy content of electricity	1.0 x energy as electricity
Hydro	Fossil fuel equivalent	1.0 x energy as electricity	1.0 x energy as electricity
Solar PV	Fossil fuel equivalent	1.0 x energy as electricity	1.0 x energy as electricity
Solar thermal	Fossil fuel equivalent	0.33 x energy content of Electricity	1.0 x energy as electricity
Wind	Fossil fuel equivalent	1.0 x energy as electricity	1.0 x energy as electricity
Geothermal	6.16 x electricity	Actual or 0.10 x energy content of electricity	1.0 x energy as electricity
Combustibles, renewables and waste	Fossil fuel equivalent	1.0 x energy as electricity	1.0 x energy as electricity

2. Temperature scales

The way temperature is measured using different scales of degrees is somewhat of an analogy for the different scales of measuring primary energy expressed as “Joules”.

Measurement of temperature is by an arbitrarily defined unit called a “degree”. Several temperature scales are in current use, such as Celsius, Fahrenheit, Kelvin and Rankin. To ensure the reader knows which scale is used, the first letter of the scale name follows the degree sign, e.g., 20$_o$C, 68$_o$F, 293$_o$K and 527.6$_o$R, all of which represent the same temperature.

To the non-engineer or non-scientist these definitions may be of little or no consequence or interest. On the other hand, engineers and scientists must know how to use them accurately and consistently in engineering and scientific analyses. Lack of knowledge and understanding of the differences can have serious consequences, and put life and limb in danger. Although lack of knowledge and understanding about the current primary energy scales may not be life threatening,
it does lead to serious misinformation and confusion.

3. Energy scales

The purpose of Table 2 is to show the different values of primary energy that results from using each of the four scales for measuring primary energy to produce 500 J of electricity from the same
five primary energy sources.

Table 2. Comparison of the primary energy measured by physical Joules, “EIA Joules”, “IEA Joules” and “WG III Joules” to produce 500 J of electricity

	Examples:	1 Physical primary energy Joules	2 “EIA primary energy Joules”	3 “IEA primary energy Joules”	4 “WG III primary energy Joules”
1	Final energy as electricity	500	500	500	500
2	Hydro	118	293	100	100
3	Oil, natural gas or coal	293	293	300	300
4	Solar PV energy	1,330	290	100	100
5	Solar thermal energy	2,330	293	300	100
6	Nuclear energy	306	306	300	100
7	Total primary energy recorded	4,377	1,478	1,100	700
8	Value of goods and services produced by 500 J of electricity	$100	$100	$100	$100
9	Primary energy intensity, J/$	43.77	14.78	11.00	7.00

In Table 2, each primary energy in the form of hydro, fossil fuels, nuclear, solar PV or solar thermal energy as in Lines 2 to 6, produces 100 J of final energy as electricity, the sum of which is 500 J as in line 1. Line 7 shows the total primary energy values for each scale to supply 500 J of electricity.

The relationship between the final energy of line 1 and the primary energy of lines 2 to 7, is given by the definition in the Special Report on Emissions Scenarios [6] prepared by Working Group III of the Intergovernmental Panel on Climate Change (IPCC) on page 216 as follows:

> "Primary energy harnessed from nature (e.g., coal from a mine, hydropower, biomass, solar radiation, produced crude oil, or natural gas) is converted in refineries, power plants, and other conversion facilities to give secondary energy in the form of fuels and electricity. This secondary energy is transported and distributed (including trade between regions) to the point of final energy use. Final energy is transformed into useful energy (i.e., work or heat) in appliances, machines, and vehicles. Finally, application of useful energy results in delivered energy services (e.g., the light from a light bulb, mobility)."

Below is a description of the method for determining the amount of primary energy required to produce each 100 J of electricity as measured by physical Joules, "EIA Joules", "IEA Joules" and "WG III Joules". For purposes of this comparison, assume the value of all goods and services produced by 100 J of electricity is $100. Then, energy (J) per unit of output ($), or energy intensity (J/$), is given in Line 9 of Table 2.

Wind, geothermal and biomass are not part of this analysis for simplicity. Adding them would not change the conclusions of this analysis.

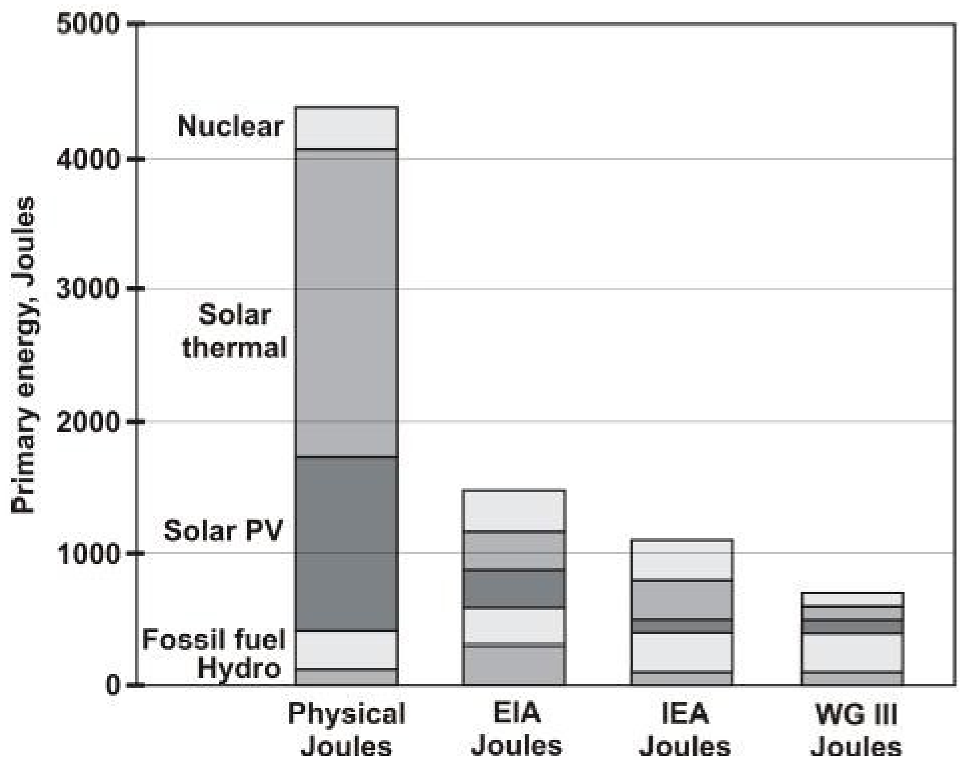

Figure 1. Graphical presentation of Table 2, primary energy to deliver 500 J of electricity.

3.1 Example 1 – physical units:
Measurement of the five primary energies of Example 1 in Table 2 is in actual physical units, and represents Joules as defined in physics.

In each Line of Example 1, the calculation of primary energy is as follows:

a. Line 2: Hydro generates 100 J of electricity from 118 J of hydropower. The conversion of waterpower to electricity is about 85% efficient [1], i.e., 100/0.85 = 118 J of hydropower to deliver 100 J of electricity.

b. Line 3: Oil, natural gas or coal generate 100 J of electricity from 293 J of oil, natural gas or coal.

c. Line 4: Solar photovoltaic (PV) cells generate 100 J of electricity from 1,330 J of solar energy as sunlight. Silicon PV cells are about 15% efficient. The average spacing for fixed panel PV cells is two areas of land for one area of PV surface [7] [8]. Therefore, on average, (15%/2) = 7.5% of sunlight falling on a given area is collected as electricity.

d. Line 5: Solar thermal generates 100 EJ of electricity from 2,330 J by concentrating sunlight with mirrors to produce steam. For a Solar Energy Generating System (SEGS), in the Mojave Desert in California, the peak efficiency from sunlight to electricity is 21% [9], whereas the average is 15.2% and the land to solar collector area is 3.5:1 [10]. On average (15.2/3.5) = 4.3% of sunlight falling on a given land area is converted to electricity by the SEGS.

e. Line 6: Nuclear fission energy generates 100 J of electricity by consuming about 306 J of uranium [2].

f. Line 7: The total amount of primary energy in physical units to produce 500 J of final energy, as electricity is 4,377 J. This is the actual number of physically defined Joules of primary energy.

Physical units of primary energy are important because primary energy is the natural energy available for conversion to the final energy that actually provides energy services. Measurement in physical units is necessary to estimate the quantities of the various primary energies that are available worldwide. For example, hydropower delivers about 10 EJ of electricity today [11], but about half of the potential hydropower sites are currently developed [12]. Thus, only about another 10 EJ of hydropower generated electricity is available worldwide.

3.2 Example 2 – EIA:
Example 2 in Table 2 is in accordance with the EIA scale for measuring and recording primary energy, often referred to as the fossil fuel equivalent, which specifies that the primary energy for all electricity generated by hydro, solar and wind be recorded as 2.93 times the electricity produced [2]. Therefore, the primary energy to produce each 100 J of electricity in Lines 2 to 5 is recorded as 293 J. In line 6, the ratio is currently 3.06 for nuclear energy.

Thus, the total amount of primary energy in EIA units to produce 500 J of electricity is 1,478 J, as in Line 7.

3.3 Example 3 - IEA:

Example 3 in Table 2 is in accordance with the International Energy Agency (IEA) scale for recording primary energy. The IEA reports energy data in Mtoe, i.e., millions of tonnes of oil equivalent, which converts to EJ by multiplying by 0.041868.
Recorded values of renewable energies are 1.0 times the amount of electricity produced, except for solar thermal, which is 3.0 times. The assumed efficiency for generating electricity with nuclear fission energy is 33%. Total primary energy is 1,100 J to produce 500 J of electricity.

3.4 Example 4 – WG III:

Example 4 in Table 2 is in accordance with the IPCC WG III scale for measuring primary energy. This method specifies that the amount of the primary energy for all electricity generated by renewable and nuclear energies is 1.0 times the amount of electricity produced [4].

Total primary energy is 700 J to produce 500 J of electricity.

In summary, the quantity of final energy as electricity does not change although the primary energy as measured by the four scales is dramatically different.

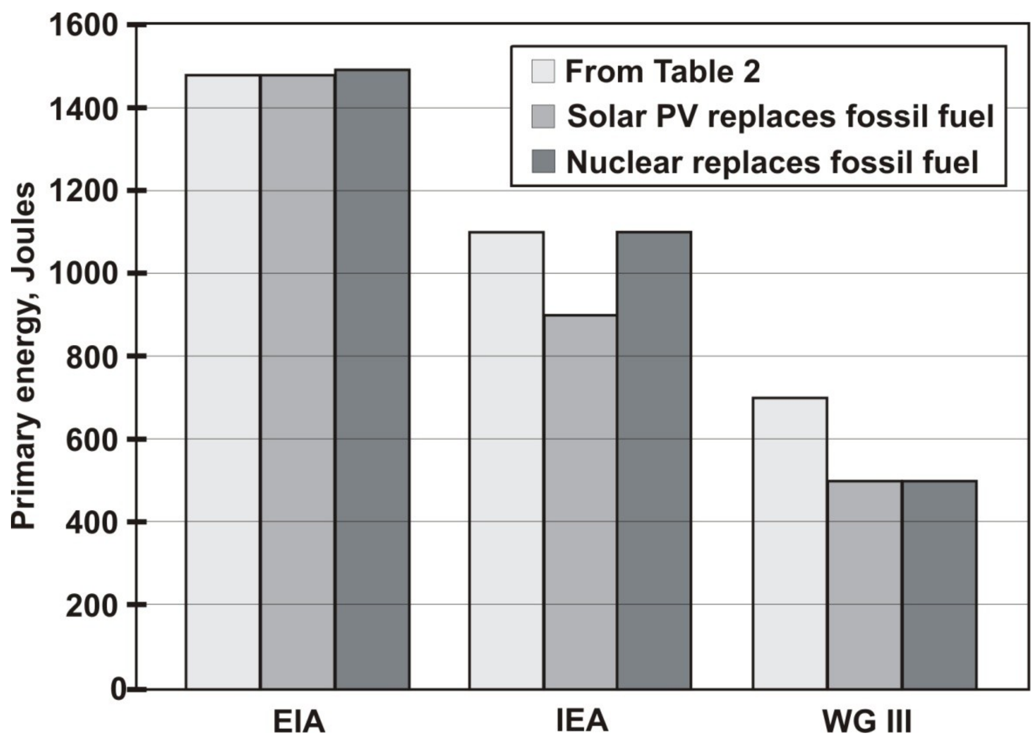

Figure 2. There is little change in total energy measured by the EIA scale as fossil fuels are replaced by renewable energies and nuclear.

4. An advantage of the EIA scale for measuring primary energy
The values in Figure 2 come from Table 2 by replacing fossil fuels for generating electricity with solar PV. Total energy for the EIA scale remains at 1,478 J, whereas it drops to 900 J and 500 J for the IEA and WG III scales respectively. By replacing fossil fuels with nuclear, total energy for the EIA scale increases slightly to 1491 J, remains at 1100 J for the IEA scale, and drops to 500 J for the WG III scale.

There is no change in total energy under the EIA scale when replacing fossil fuels by renewable energies, such as solar photovoltaic. There is very little change when replacing them with nuclear.

This is an advantage when comparing scenarios where the mix of renewable and nuclear energies changes over time.

5. Conversion from one primary energy scale to another
There is no simple formula for converting from the EIA scale to the IEA or WG III scales such as exists for temperature scale conversion.

The purpose of Table 3 is to show why there is no simple formula by using each scale to measure 2006 world primary energy consumption. The first difference is in the amounts of oil (liquids), natural gas and coal recorded by the EIA and IEA scales. The second difference is in the primary energy recorded for nuclear. The third difference is for energy recorded for hydro and the fourth is in the quantity of combustibles, renewables (other than hydro), waste and other.

Table 3. There is no simple formula for converting from one primary energy scale to another as shown by 2006 world primary energy consumption measured by the EIA, IEA and WG III scales.

	EIA EJ	IEA EJ	WG III EJ
Oil, liquids	171.9	169.1	-
Natural gas	109.3	100.8	-
Coal, peat	125.8	127.8	-
Sub-total fossil fuels	407.0	397.7	-
Fossil fuel as % of total primary energy	86%	81%	-
Nuclear	27.9	30.5	9.1
Hydro	31.7	10.8	10.8
Combustible renewables, waste, other	5.3	63.4	-
Sub-total	64.8	93.9	-
Total	471.8	491.6	-

The cause of these differences is legitimate differences of opinion. Nevertheless, these differences make it necessary to select the most appropriate scale for a specific energy analysis, identify the scale and use the same scale consistently.

6. Summary and conclusions

The amount of physical primary renewable energy required to supply a given amount of electricity varies widely, by an order of magnitude, and makes comparisons difficult.

Three different scales are currently in use that attempt to get around this problem and facilitate comparisons of annual world primary energy consumption and comparisons of energy consumption between countries. These are the EIA, IEA and WG III scales. The differences between the scales result from legitimate differences of opinion as to how the problems can be resolved.

The measurement of physical units of primary energy is by Joules. A Joule has a specific definition and is the energy to heat 0.239 kg of water by 1oC. However, the EIA, IEA and WG III scales all use the term "Joule", which is different from the physics definition and from each other.

The differences between the scales are in the accounting method for primary energy that produces electricity from renewable energies. The EIA scale uses the fossil fuel equivalent for all renewable energies based on current values of efficiency for electricity generated by fossil fuels. It uses actual uranium consumption for nuclear.

The IEA scale records one unit of primary energy for each unit of electricity produced by hydro, wind, and solar PV. It uses three units for each unit of electricity produced by solar thermal and for nuclear.

The WG III scale records one unit of primary energy for each unit of electricity produced by all renewables and by nuclear.

There is no change in total energy under the EIA scale when replacing fossil fuels by renewable energies, such as solar photovoltaic. There is very little change when replacing them with nuclear. This is an advantage when comparing scenarios where the mix of renewable and nuclear energies for generating electricity changes over time.

Construction of the three primary energy scales is such that there are no simple conversion formulas like those for temperature scale conversions.

Physical units of primary energy are important because primary energy is the natural energy available to us for conversion to the final energy that actually provides energy services. Measurement in physical units is necessary to estimate the quantities of the various primary energies that are available worldwide.

Finally, it is essential in any energy analysis, to select an appropriate primary energy scale, identify it and use it consistently.

7. References

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Biography

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***Note**: Table two and the corresponding part of the text were corrected after publication of the original version.