Chapter 2

Energy

Our book is just about one consequence (climate change) of just one consequence (emissions) of (mostly) just one consequence (energy use) of humanity's huge population.

You read this right. Our book is "just" about byproducts. Human emissions and climate change are just byproducts. They are a sideshow of a sideshow. And if there were a lot fewer of us and/or each of us needed a lot less energy, civilization could tackle climate change much more easily. Indeed, until a few decades ago, it wasn't even fully appreciated that human emissions could cause meaningful climate change on a planetary scale in the first place.

What is so special about energy? It is that energy is a necessary input into almost all economic activity. It permeates every aspect of our lives. It is the life blood of modern economies. It heats and cools our homes, moves us and our goods within cities and across continents, powers our appliances and gadgets, and facilitates modern industry and agriculture. Cheap, reliable energy on demand is one reason why lives in rich countries have been transformed over the last two centuries. It should come as no surprise, then, that rich countries are prodigious users of energy (we will get to some numbers shortly) — and that poorer countries want in on the game.

With energy so central to our world, emissions, and global warming, it is important to explain more of its details. Thus we first have to take a detour and explain how to measure power and energy — especially but not only at large scales — before we return to a global economic analysis.

1 How To Measure Power and Energy

For starters, the description that we are "using" energy is misleading. One of the basic laws of physics is that energy is conserved and therefore cannot be used up. What we are actually using up is not energy, but higher-quality fuels.[1] You can think vaguely of widely dispersed lukewarm heat as being the lowest quality of energy and concentrated electricity as being the highest quality of energy. Our devices use high-quality forms of energy to perform productive work and in the process convert high-quality into low-quality energy.

An example can make this abstract idea more concrete. The chemical bonds in the molecules that comprise gasoline are a form of relatively high-quality energy. When an internal combustion engine burns gasoline, about 25 percent of the chemical energy is converted into useful kinetic energy (car movement). The remaining 75 percent is converted into useless heat and radiated into the environment. When the car is slowed or stopped by friction (for example, from applying the brakes), the kinetic energy is also converted into useless heat. Therefore, the net effect of driving a car is to convert all the energy in the chemical bonds of the gasoline into random atmospheric heat. No energy is lost, but unlike gasoline, the heat is no longer useful.

In this sense, our "energy needs" are not really about lacking energy. Instead, they are about finding high-quality energy that we can eventually convert into useful work, before it ends up as environmental heat. Although misleading, everyone just calls this "using energy," and we will thus do the same.

Measurement Challenges

Most vague statements about power and energy are platitudes. (Sometimes a little knowledge is a dangerous thing.) You (our reader) have to comprehend magnitudes if you want to understand climate change.

For example, everyone (including us) is excited about the progress in battery technology. But cursory knowledge cannot tell you whether batteries can or cannot plausibly satisfy global needs. (Spoiler: the answer is *not yet,*

[1] Physicists call high-quality fuels by the moniker of *low-entropy* fuels. Entropy is a fancy word for disorder and randomness.

but hopefully sooner rather than later.) You have to understand the energy storage problem not only in principle but also in scale. You need appropriate perspective.

Physicists themselves have tried hard *not* to make this easy. The famous physicist Richard Feynman once quipped that "if energy is one thing that is conserved, why do we need so many names for it"? Table 1 shows what Feynman was talking about: energy can be measured in terms of joules, calories, watt hours (Wh), British Thermal Units (BTUs), and (metric) tonnes of oil equivalents, to name just a few of the possible units.

Moreover, nobody normal can understand numbers that have a dozen zeros at the end. To make it "easier," the metric system uses standard abbreviations. 1 KWh ("Kilo") is 1,000 Wh; 1 MWh ("Mega", i.e., million) is 1,000 KWh; 1 GWh ("Giga", i.e., billion) is 1,000 MWh; 1 TWh ("Tera", i.e., trillion) is 1,000 GWh; and 1 PWh ("Peta", i.e., quadrillion) is 1,000 TWh.

Energy is power applied for a unit of time. A lightbulb has a certain power rating, and energy is running it for a certain time period. The Kilo-Watt-hour (KWh) is perhaps the most familiar unit of energy, because it is used for pricing electricity. However, watt-hours should not be thought of as merely an "electrical" measure. It makes perfect sense to speak of the number of kilowatt-hours of chemical energy in a gallon of gasoline. To make it easier, we will use only the standard "metric" measure. We will quote all energy in Watt-hours (Wh), appropriately modified by the metric zeros prefixes, like "Kilo" or "Mega."

Energy and power are also sometimes confused.[2] Power is the rate at which energy is being used. It is typically measured in Watts. A second prominent power measure is the horsepower (hp), which equals 746 watts. A horse can deliver much more than 1 hp — ironically, a mistake made by none other than James Watt in the 18th century. Most of the world is now abandoning horsepower in favor of the metric standard unit, the Watt. (Maybe Watt made the horsepower mistake intentionally to get his name onto the correct unit?!) As usual, the United States remains a laggard in adopting international measuring standards.

[2]It's also common to get the units mixed up. Even some scientific papers use phrases such as "a battery holds 100 KW of energy." The battery may be able to release power at a rate of 100 KW, but it does not hold 100 KW. Battery capacity must be measured as units of energy (as in KWh), not in units of power (as in KW).

Table 1. Energy and Power Conversion Factors

Power	
1 Joule Per Second	1 W
1 Horsepower	746 W

Energy	
1 Tonne of Oil Equivalent	11,630 KWh
1 Barrel of Oil	1,700 KWh
1 Therm	29.3 KWh
1 Cubic feet of natural gas	1/3.6 KWh
1 (Kilo) calories	1/860 KWh
1 BTU	1/3,412 KWh
1 Kilojoule	1/3,600 KWh
1 Exajoule	278 **T**Wh
1 “Quad” (quadrillion BTUs)	293 **T**Wh

Note: This is a reference table. It is not necessary to remember any details. For more units and more conversions, see www.convert-measurement-units.com. Our book primarily uses W and Wh as measures for power and energy, respectively.

In an electric car, the quoted power is the rate at which batteries can supply useful electricity. For instance, a 2020 Tesla Model 3 has a battery pack that holds 75 KWh of energy. Driving at a steady speed of 55 mph requires a power output of 15 KW. Therefore, a fully-charged battery can power the car for about 5 hours at 55 mph, giving it a range of about 275 miles.

The fact that energy conversions invariably involve losses (usually to heat) is important. You can think of electricity as the jack-of-all trades when it comes to energy. It can be transported instantly over wires and converted into other forms of energy with relatively high efficiency. (Admittedly, it is not cheap to store — *yet*!)

However, converting other types of energy into electricity often incurs severe conversion losses. For example, when natural gas is burnt to generate electricity, only about 30–50% of the energy in the molecular bonds of the gas is converted into electricity. The remaining 50–70% is lost to environmental heat. In this example, the natural gas bonds are called *primary energy*. Secondary energy is the useful electricity that is left after converting primary energy. Most electricity is secondary energy, having been derived from other forms first.

The difference matters. For example, running a 10 W light bulb for two hours per day for a whole year consumes about $10W \times 2h \times 365 \approx 7.3$ KWh of electricity. This 7.3 KWh is secondary energy. If the plant generating electricity is natural-gas based, then it requires about 15–25 KWh of primary chemical energy to generate this 7.3 KWh of electricity.

To avoid double counting, national and global energy usage is almost always measured in terms of primary energy. And because most energy in use today is from fossil fuels, and because their conversion into useful energy is mostly quite inefficient, primary energy use figures are markedly higher than the secondary energy that consumers actually end up using.

Typical Power Magnitudes

Tables 2 and 3 provide a more intuitive perspective on what power and energy scales mean. They go from the very small to the very large. They are not meant to be memorized but admired (or at least inspected).

Table 2 is all about power. It shows that human civilization can already generate and use primary power at a rate of about 18 TW. Future power plans must either provide the equivalent of 18 TW of primary fossil fuel energy, plus whatever is required for future growth (appropriately adjusted for conversion losses) — or induce civilization to get by with less power — something that has never happened in the past.

Table 2. Typical Power (Approximate Numbers)

Lifting 1kg at a rate of 1 meter per 10 seconds	1 W	
Light bulb, 800 lumen, LED	10 W	
Incandescent	60 W	
Human		
at rest (metabolism)	100 W	
Cycling (metabolism)	600 W	
Output at Pedals	150 W	
Automobile engine, 100hp, max power output	75,000 W	(75 KW)
cruising 65mph, typical power	15,000 W	(15 KW)
Direct Solar Power, Noon Clear Day, Earth Average, Per m^2 (about 10 sqft)		
Solar Cell Harvest, per m^2	150 W	
Ground, per m^2	1,000 W	
Above Atmosphere	1,360 W	
Typical Roof Solar Electricity peak output	6,000 W	
(20 panels each 300W, about $20k installed in 2021)		
Typical New Wind Turbine, 2021, 50m	2,500,000 W	(2.5 MW)
Typical Coal Plant	600,000,000 W	(600 MW)
Typical Nuclear Plant	1,500,000,000 W	(1.5 GW)
Worldwide Bitcoin Mining, early 2022	16,500,000,000 W	(16.5 GW)
USA, Consumption Rates		
Average US Electricity, circa 2021	500,000,000,000 W	(500 GW)
Peak US Electricity, circa 2021	850,000,000,000 W	(850 GW)
Installed US Electricity Power, circa 2021	1,200,000,000,000 W	(1.2 TW)
Average US Primary Power, circa 2021	3,000,000,000,000 W	(3 TW)
World, Average Consumption Rates		
Global Electricity, circa 2021	2,600,000,000,000 W	(2.6 TW)
Average US Primary Power, circa 2021	18,000,000,000,000 W	(18 TW)
Consumption rate for all life	130,000,000,000,000 W	(130 TW)
Sunlight Striking Earth	174,000,000,000,000 W	(174 TW)
World Population, 2023	8,000,000,000	(8 B)

Note: It is not important to remember these numbers, but it is important to look at them to understand the relative magnitudes involved. Power is always fluctuating, which strictly speaking means it requires modifiers on U.S. and World power use rates — average, peak (ever), or a hypothetical fully installed and running rate. We quote power for wind and solar generation at nameplate capacity, i.e., when operating at maximum. It is important to read Section 6 for appropriate qualifications.

Typical Energy Usage Magnitudes

Table 3. Typical One-Time or Non-Annual Energy Uses

Lift/drop 60 kg meters		1 Wh	
Light bulb, 800 lumen, LED	1 hour	10 Wh	
incandescent	1 hour	60 Wh	
Cyclist Pedal Output	1 hour	150 Wh	
Food Diet, 2000 (k)cal	1 day	2,300 Wh	
Automobile, 100hp/2, One Commute	1 hour	35,000 Wh	(35 KWh)
Tesla Battery for Model 3	Full	75,000 Wh	(75 KWh)
Primary Energy Use, Per Person, 2022			
Africa	1 Day	14,000 Wh	(14 KWh)
OECD Europe		109,000 Wh	(109 KWh)
USA		232,000 Wh	(232 KWh)
Electricity Component, USA		30,000 Wh	(30 KWh)
One Roundtrip Flight, LA to London	11 h$\times$2	10,000,000 Wh	(10 MWh)

Table 3 is about energy. Remember that energy measures how long power is applied. For example, the average American adult typically consumes about 2.3 KWh in calories per day, about 30 KWh in electricity, and 230 KWh in total energy. A round trip flight to Europe or Asia consumes about 10,000 KWh. Although flying is among the most efficient forms of transportation per mile, flying quickly racks up a lot of miles!

Table 4 sums the numbers over a typical year. For example, the seventh line in Panel B calculates that if commuting uses about 35 KWh per day, then driving would consume about 365×35 KWh/day ≈ 13 MWh per year.

As with the power data, the energy numbers are really just for gawking at, more professionally called "perspective." They contain many interesting tidbits.

For example

- The round-trip airplane vacation to Europe or Asia (from Los Angeles) uses roughly as much energy (10 MWh) as a whole year's worth of either all of a household's electricity (10.6 MWh) or all of someone's car driving (13 MWh).

Table 4. Typical Annual Energy Use

	Use Pattern		
LED Lightbulb, 800 lumen	2h/day	7,500 Wh	(7.5 KWh)
	24h/day	90,000 Wh	(90 KWh)
Incandescent Lightbulb, 800 lumen	2h/day	44,000 Wh	(44 KWh)
(60 Various Device) "Wall-Warts"	24h/day	189,000 Wh	(189 KWh)
Air Conditioning	3h/day	3,500,000 Wh	(3.5 MWh)
All Household Electricity (US)	avg/day	10,600,000 Wh	(10.6 MWh)
Automobile, 100hp/2, Commute	1h/day	13,000,000 Wh	(13 MWh)
Roof Solar, 20 panels	5h/day	13,000,000 Wh	(13 MWh)
Typical Wind Turbine	6h/day,	3,285,000,000 Wh	(3.3 GWh)
Typical Coal Plant	20h/day	4,380,000,000,000 Wh	(4.4 TWh)
... typical utilization rate in 2019	12h/day	2,628,000,000,000 Wh	(2.6 TWh)
Average US Nuclear Plant	22h/day	10,000,000,000,000 Wh	(10.0 TWh)
Global Annualized Bitcoin Mining, early 2022	24/7	150,000,000,000,000 Wh	(150 TWh)
U.S. Electricity Consumption, circa 2021	Annual	4,500,000,000,000,000 Wh	(4.5 PWh)
World Electricity Consumption, circa 2021	Annual	27,000,000,000,000,000 Wh	(27 PWh)
U.S. Primary Energy Usage, circa 2021	Annual	26,000,000,000,000,000 Wh	(26 PWh)
World Primary Energy Usage, circa 2021	Annual	165,000,000,000,000,000 Wh	(165 PWh)
Approx World Population, 2023		8,000,000,000	(8 B)

Note: Sources are varied. It is not important to remember these numbers. It is important to read Section 6 for appropriate qualifications. The quoted numbers here are from different sources. The most prominent sources are the British Petroleum Annual review of World Energy and the U.S. Energy Information Administration. See the references for more explanations.

- A U.S. household uses about 32 MWh of electricity per year, so one typical wind turbine generating 3.3 GWh can supply the energy-needs equivalent of about 100 households, i.e., a small village. This ignores the discrepancy between when households need electricity and when wind turbines can supply it.
- Dividing 170 PWh by the population of 8 billion in 2022 tells us that the average human consumed about 21 MWh/year of primary energy. This is about 60 KWh/day — about the equivalent of 250 LED 10 W light bulbs continuously burning, or a 50–70 one-square-meter panels of roof solar working for about 5–6 hours per day.

Our nerdish side tempts us to look at these figures all day long, but we need to move on.

Our book is about the very largest scales of energy usage. The United States generates about 4–4.5 PWh (or trillion KWh) of electric energy from about 10 PWh of primary energy (mostly chemical bonds in fossil fuels) — the remaining 18 PWh of primary energy are used for transportation, heat, etc.

I want to offset my carbon footprint, Jenkins...cancel your holiday flights

Although 4 PWh is a huge number (as the many trailing zeros make clear), electricity is only about 35–40% of the total primary energy consumption of the United States (28 PWh in 2022) and 10 PWh is only about 5% of the total primary energy consumption of the world. Think about that. Even if the United States managed to eliminate all fossil fuels from *all* of its electricity generation — which is an impossible feat for many decades — the world would have *barely* moved towards zero net emissions! The world's challenge is not to clean up the U.S. electricity grid consuming 10 PWh but to clean up the entire 187 PWh in 2022 (plus an additional ≈70–75 PWh that it will also consume by 2050).

Our job is to convey to you, our reader, this quantitative information in an understandable fashion. You job is to grapple with comprehending these huge magnitudes if you want to understand climate change and be qualified to discuss possible solutions. Don't be easily swayed one way or another by half-truths.

2 Where Does All Our Energy Go?

How can humanity possibly use so much energy? Where does it all go?

Table 5 shows two aerial snapshots of what civilization is doing with all this energy. The two panels are somewhat disjointed, because they come from different sources, and it is unclear how they reconcile. Nevertheless, together, they convey a good overall impression.

Panel A shows that the largest use category is home and work, followed by transportation and industry. Within these broad categories, home heating and cooling (including refrigerators and water heaters), cars, and the production of cement, metals, and chemicals loom large. But even if we could eliminate those altogether, the remaining uses would not be trivial, either. For example, it would leave a lot of energy needed to fly around the world and to grow plants.

Panel B provides another view of energy usage. We use a lot of energy making stuff and plugging devices into electrical outlets. But agriculture and travel are large contributors, too, as is our need to heat or cool our buildings.

The panels make it clear that it is not enough to clean up just any one category (e.g., the electricity sector) and ignore the rest. There are too many big contributors to the problem. Humanity will need many solutions to many problems — many reductions by many different emitters.

Table 5. Estimating Primary Energy Use By Activity

Panel A: Classification 1.

			World	
	USA		BP	EIA
Home and Work		40%	30%	40%
Heating (Water, Air), A/C	50%			
Transportation		28%	20%	30%
Cars	60%			
Trucks	20%			
Aircraft	10%			
Boats or Buses, each	5%			
Industry		32%	50%	30%
Chemical	27%			
Petroleum Refining	22%			
Paper	17%			
Metals	17%			
Cement	4%			

Panel B: Classification 2 (Worldwide).

Making Things (cement, steel, plastic)	31%
Plugging In (electricity)	27%
Growing Things (agriculture)	19%
Getting Around (planes, cars, ships)	16%
Keeping Warm and Cool (heating, cooling)	7%

Source: For USA, NAS.edu and U.S. Energy Information Administration (EIA). For world, British Petroleum (BP) Statistical Review of World Energy [often named the Factbook] and Wikipedia World Energy and Supply (bottom right table), itself based on dated International Energy Agency data. Refining, metals, and paper are educated guesses. Component percentages are also stated in terms of total primary consumption (e.g., heating is 50% of home and work consumption). Of course, like most estimates in our book, these are just approximations. However, these particular estimates are also a little unusual in that they are a case in which some of our primary information sources disagree. Thus, we present two versions. Most of the time, though, the data sources align well. Panel B is from Gates (2021, p.55).

Table 6. Total and Per-Person Energy Consumption, 2022

	Population (million)	×	Primary Energy Consumption: Per Capita Day (KWh/P/Day)	=	Primary Energy Consumption: Total Per Year (PWh/Year)
OECD	1,380	×	141	=	71
USA	335	×	232	=	28
Europe	593	×	109	=	24
Not OECD	6,502	×	49	=	116
China	1,449	×	90	=	48
India	1,408	×	23	=	12
Other Asia	1,177	×	32	=	14
Africa	1,367	×	14	=	7
Sub-Sahara	≈1,100	×	≈5	=	≈2
World	7,882	×	65	=	187

Note: The product omits the conversion factor from days to years. Sub-Sahara excludes South Africa and was inferred from equivalent shares in EIA data from 2019.

Source: US EIA International Energy Outlook, Oct 2021. The input series were Primary Energy and Population.

3 Rich and Poor Today

Obviously, air-conditioning and jet travel are not as common in Africa as they are in Florida. Is world energy consumption then primarily a luxury problem? Is it about too much air-conditioning and jet travel? Is it about the careless wasting of energy by richer people? Where could we cut its use? To answer this question, we need to look at energy consumption in different regions.

Table 6 shows the population numbers from the previous chapter on the left, their per-person per-day primary energy consumption in the middle, and the total annual primary energy consumption on the right. We will first discuss the per-person per-day numbers, measured in KWh, because they help us understand what luxury and what poverty consumption is.

The table shows that residents of rich OECD countries consumed almost three times as much energy per person (141 KWh per day) in 2022 as residents of poor non-OECD countries (49 KWh per day).

The average American was especially profligate, consuming about 230 KWh of primary energy per day (pPpD). For a meaningful economic perspective, if 230 KWh of primary energy were used only to generate about 100 KWh of electricity (and it is not) and if this electricity were sold at the typical electricity retail price of $0.15 per KWh, then the per-person energy bill would be about $15 of energy per day or $5,000 per year. In context, this would be the equivalent of (expensive) cappuccinos at Starbucks every morning for a family of four.

The average European consumed about half as much energy as the average American, at 110 KWh per person per day. This is commonly referred to as the *European standard*, but it also applies to other non-English speaking OECD countries like Japan and Korea.

China (with 90 KWh per person per day) has almost reached the European standard. However, because China burns more coal, its per-person greenhouse gas emissions have already exceeded those of the OECD. (We will describe emissions in the next chapter.)

Residents of most other poorer non-OECD countries were much more frugal. At 23 KWh per person per day, Indians consumed only about one quarter of what Chinese consumed. Hundreds of millions of Indians still don't have access to regular electricity. Many millions more suffer regular electricity outages even when they are connected to the grid. Residents of other Asian countries consumed about a third as much per-capita electricity as the Chinese, at 32 KWh per person per day.

Africans consumed only 14 KWh per person per day. The numbers are even lower in the sub-Saharan regions (South Africa excepted), with estimates of under 5 KWh per person per day. Such low energy consumption is a symptom of a subsistence economy with widespread extreme poverty. It is inconsistent with a healthy modern economic living standard. Many Africans still spend much of their day walking just to obtain and carry the necessities of life.

Are Americans and Europeans not only richer (in terms of income) but also more wasteful in their energy use? Do they use energy for careless luxuries, not paying attention to energy costs because they are so rich? Can we make progress by pushing them towards dealing with energy as efficiently and frugally as residents of poorer countries?

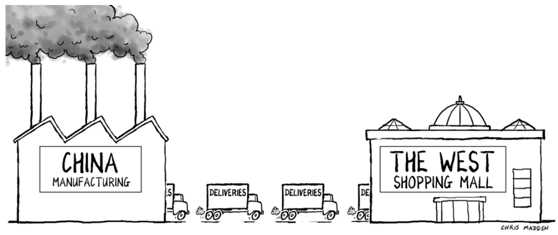
To assess this, we want to determine how efficient regions are in converting energy into economic output (which, for the most part, translates into income). The average American earned a gross income of about $61,000 per year in 2022. (Many households have of course multiple earners, and the average income even ascribes income to children. This means that the average gross income per household is considerably higher.)

Table 7. Per-Person Energy Use and Efficiency, 2022

	Per Capita Day (KWh/P/Day)	×	GDP/Person ($-1,000/Yr)	=	Efficiency (KWh/$)
OECD	141	×	43	=	1.19
USA	232	×	61	=	1.39
Europe	109	×	42	=	0.95
Not OECD	49	×	12	=	1.54
China	90	×	19	=	1.75
India	23	×	7	=	1.18
Other Asia	32	×	11	=	1.04
Africa	14	×	5	=	1.06
World	65	×	17	=	1.38

Source: US EIA International Energy Outlook, Oct 2021. The input series were Primary Energy, Population, and GDP in purchasing power parity.

Table 7 shows that OECD countries required about 1.19 KWh in energy to produce each dollar of income. Europeans earned less than Americans ($42,000/person), but they also worked about 20% less (mostly voluntarily!) and were more energy efficient per dollar earned. There was quite a bit of heterogeneity, though: Germans earned more and worked less than their American counterparts; Poles worked more and earned less.



Why China's carbon footprint is so large...

Unfortunately, it is the poorer non-OECD countries that produced less with more energy. They required about 1.54 KWh of primary energy for each dollar of output. The Chinese were particularly inefficient in their energy use, using 1.75 KWh. (However, China's economy produced relatively more manufactured goods than, say, Europe. This may be the reason for China's lower energy efficiency.)

The big picture does not seem to be that rich OECD countries care less about wasting energy. If anything, wealthier countries are producing more with less energy. They have spent more money on insulation, bought more energy-efficient machines, and reoriented themselves towards less energy-intensive activities. Rich countries have not been particularly wasteful. Their primary responsibility for the world's large energy consumption is that they produce more economic output, which has given them higher incomes that needed more requisite energy. Bringing their efficiencies into line with those in poorer countries would be counterproductive.

After you have gotten over the natural urge to point fingers — at Americans, Europeans, or Chinese for using too much energy per head, or at China for using energy too wastefully — you should reflect again that the global problem today is not about blame. It is not about *per-person* emissions (or energy consumption).

Instead, the global problem is about finding a way out of our collective malaise. It is about *total* emissions and energy consumption, i.e., per-capita resource use multiplied by population. As we already mentioned, despite its large per-capita consumption, the OECD contains only a small part of the planet's population. More than four out of five people in the world live in non-OECD countries. If we want to solve global problems, we need to contemplate primarily the world's total energy consumption and not just the energy consumption of the one in five.

With only 20% of the population living in the OECD, Table 7 shows again that OECD emissions are no longer as important as you may have thought. At

71 PWh per year, the OECD is already responsible for only about one-third of total world emissions. With its much higher population, China is responsible for about one-quarter of the world's energy use. China's energy consumption is already almost twice as large as that of the United States. In fact, China's consumption is already almost as large by itself as that of the U.S. and Europe *combined*. And China is not alone. If the OECD vanished tomorrow, primary energy consumption would still be a gigantic 116 PWh, growing fast.

4 The Future

Looking at longer-term trends can help us understand where we have come from and where we are going. We can still use both historical and forecast data from the U.S. Energy Information Administration. These are the best that we are aware of. (Pointing to them will also allow us to shift blame to them if — as will be inevitably the case — the forecasts will prove to be less than perfect.)

Per-Capita Consumption

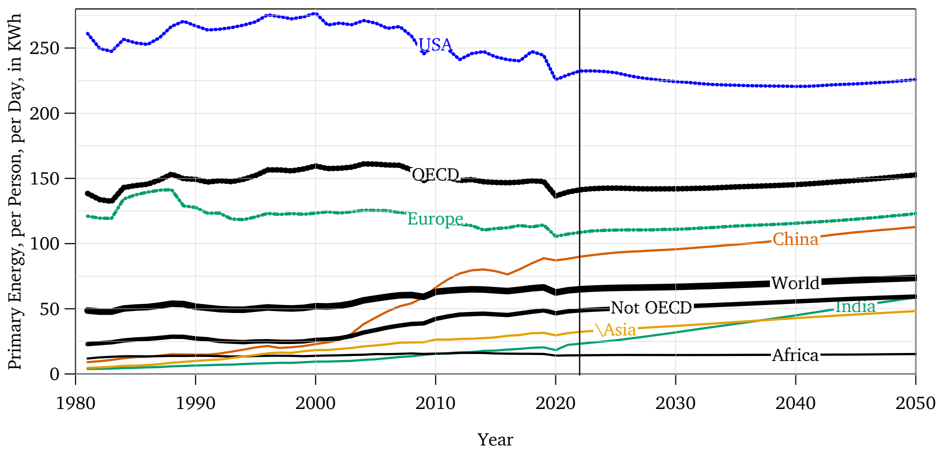
Figure 8 shows generational trends in per-capita energy consumption.

OECD residents have been reducing their energy consumption since about the turn of the millennium. This was primarily due to the three English-speaking members of the OECD — the USA, Australia, and Canada — which have reduced their consumption more than other OECD countries. However, this was also easy for them, because they have been the most wasteful OECD countries for decades and continue to be so — and not by a small margin. (Australians consumed a little less, Canadians a little more than Americans.)

Looking forward to 2050, per-capita energy consumption in the OECD will likely remain stable. The predicted modest per-person increase to 2050 is well within the margin of prediction error.

In contrast to the stagnant OECD, non-OECD countries have been increasing their per-person energy use since the turn of the millennium. This was mostly due to China. The average Chinese consumed under 10 KWh per day in 1980 compared to about 90 KWh in 2022. Although Chinese energy consumption has been decelerating, it is still growing faster than those in the

Figure 8. Energy Use Per Person Per Day (pPpD)



Note: The average American consumes about twice as much energy per capita as the average European and three times as much as the average Chinese. Per-capita consumption in Africa and India remains tiny.

Source: Pre-2020 figures are from the EIA. Post-2010 numbers are from the US EIA International Energy Outlook, Oct 2021, specifically the EIA World total primary energy consumption by region and the EIA World population by region. We aligned the data series to minimize discrepancies.

OECD countries. Thus, its *per-person* energy consumption will soon equal that of Europe's — and there are a lot more *persons* in China than in Europe. Fortunately, it does not seem as if China is aspiring to reach the U.S. energy standard anytime soon.

Of course, it would be hypocritical for the U.S. to complain to China about its high per-capita energy growth. China was only escaping abject poverty, and our own per-capita energy use remains twice as high. This is also why China's leaders usually bristle when U.S. leaders request that China reduce its emissions.[3]

Fortunately for Indians and unfortunately for global emissions, India's economy is already taking off as we are writing this book. Its energy use

[3] In the (now superseded) Kyoto protocol of 1997, China was even explicitly exempted from *any* obligation to curtail its emissions.

is predicted to reach half of the European standard by 2050 and more a generation later. Some population predictions further suggest that there could be more people on the Indian subcontinent by 2100 than in China, Europe, and the US combined. Multiply India's population count by European per-capita energy standards and you can see the problem.

High per-capita energy growth is also the case for other developing regions — except Africa. Africa is economically still in the poorhouse and its per-person energy consumption is not expected to increase much even by 2050. Simply put, the average African is poor and predicted to remain so. (And it's even worse in sub-Saharan Africa.) Yet the population of Africa is also expected to surpass India's, China's, and the OECD's *combined* by the end of the century. Pent-up demand for energy will explode if and when Africa develops.

Total Consumption

As we already stated, the world's energy problem is not about finger-pointing or per-capita consumption. It is about finding solutions to reduce total energy consumption and emissions.

Figure 9 catches the situation beginning in 1980. It plots OECD and non-OECD total energy consumption on the same scale.

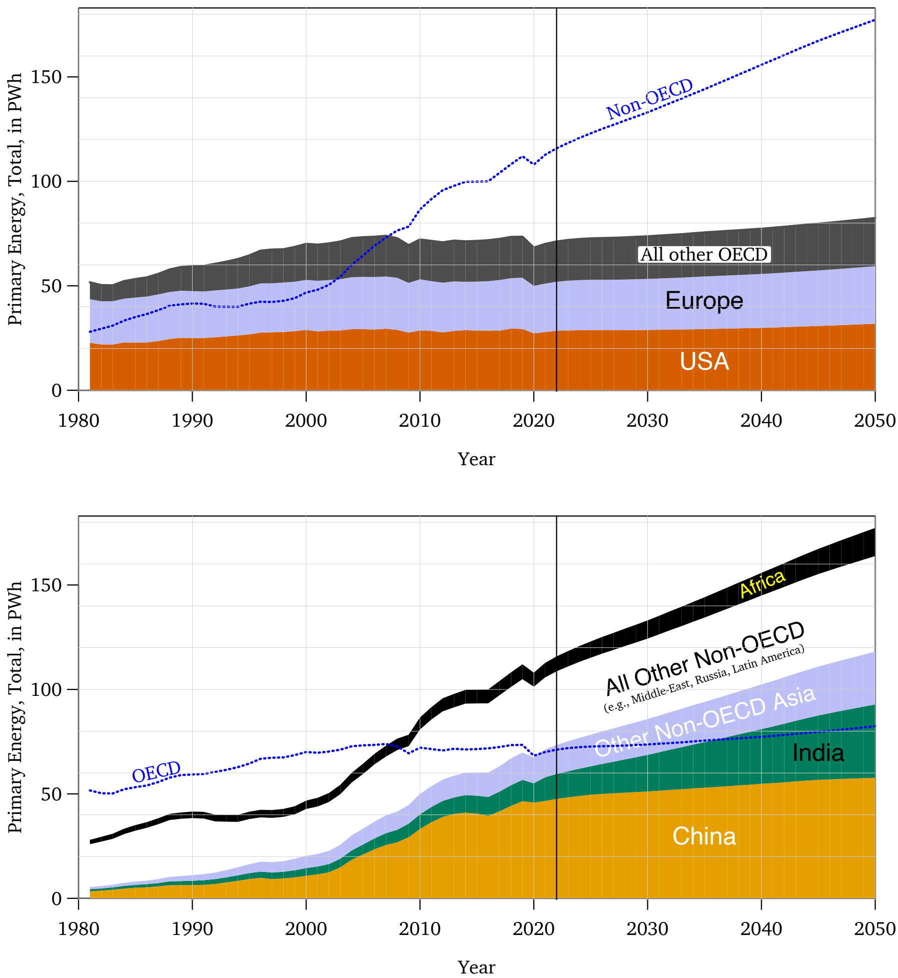
In 1980, OECD emissions were still twice as large as non-OECD emissions. Europe and the US each easily exceeded China and India combined. After some modest growth, OECD total energy consumption stabilized around the turn of the millenium.

Yet just when OECD energy use plateaued, non-OECD energy use took off. Many countries were escaping poverty. China's transformation into a market economy under Deng Xiaoping had raised not just millions but hundreds of millions of Chinese out of poverty. (Moreover, China's population doubled from about 700 million people in 1965 to about 1.4 billion people today.)

Thus, today, the world's shares of energy use by OECD and non-OECD countries have reversed. The majority of the world's energy is now consumed by non-OECD countries. China now easily exceeds the energy consumption of the USA and Europe combined, and India will exceed either the USA or Europe by 2050, and both combined another generation later.

Fortunately, China's energy growth is now decelerating. Its population is no longer growing. The same cannot be said for other non-OECD countries.

Figure 9. Primary Energy Use



Note: The two graphs are drawn on the same scales. OECD energy consumption has been stable since the turn of the millennium. Non-OECD consumption has not been. China accounted for most of the dramatic growth in world energy use over the last two decades. Its consumption is now larger than that of North America and Europe *combined* but has also largely stabilized. The energy consumption of India remains small but is about to increase greatly.

Source: US EIA. Predictions are from the US EIA International Energy Outlook, Oct 2021. The input series was Primary Energy. We aligned the EIA data series to minimize discrepancies.

India's population is still growing, as are those of other countries. Sub-Saharan Africa is a rounding error as far as global energy consumption is concerned, but if and when it escapes poverty, its energy increase will be dramatic. This seems unlikely to occur within one generation, but it should not be discounted over longer timespans.

Summary Forecasts

As we explained in our preface, our main concern is about what we can do to move the needle in the next 10-30 years, not in the next 100-200 years. Table 10 puts together the most important numbers for the EIA's 2050 world energy consumption forecast.

Table 10. Total and Per-Person Energy Consumption, 2050e

			Primary Energy Consumption		
	Population (million)	×	Per Capita Day (KWh/P/Day)	=	Total Per Year (PWh/Year)
OECD	1,478	×	153	=	82
USA	386	×	226	=	32
Europe	613	×	123	=	28
Not OECD	8,177	×	59	=	177
China	1,402	×	113	=	58
India	1,640	×	59	=	35
Other Asia	1,432	×	48	=	25
Africa	2,413	×	15	=	13
World, 2050e	9,655	×	74	=	260
World, 2022	7,882	×	65	=	187

Note: This table is the equivalent of Table 6 but 30 years into the future.

Source: US EIA International Energy Outlook, Oct 2021. The input series were Primary Energy and Population.

Here is our summary:

- In the OECD, population numbers have largely stabilized.

  Beyond the OECD, population is still growing. In particular, Africa and Asia (but not China) will continue to grow — and from higher baselines than they had just 50 years ago. Their growth will continue trends that have existed at least since the 1980s.
- The world has been improving its energy efficiency, producing more output with less energy. Compared to 30 years ago, the world now produces its output with one-third less energy. Scientists are expecting this efficiency growth to remain as strong over the next 30 years.
- Over the last 30 years, per-capita energy consumption in the OECD has shrunk. This was due to large efficiency gains (more output given the same amount of energy). Beyond the OECD, per-capita energy consumption has increased greatly. This was due to much faster increases in the standard of living and not fully offset by (relatively smaller) efficiency gains. In particular, China, India, and the rest of Asia have been climbing out of poverty, with China having led the way. Sadly, most Africans will remain poor, consuming 15 KWh per person per day. In sub-Saharan Africa, it is even worse: 5 KWh per person per day.
- Over the next 30 years, efficiency gains are likely to continue, though they may or may not be enough to keep OECD per-capita energy consumption exactly constant over the next 30 years. A reasonable forecast is energy use growth of 15% over 30 years in the OECD.

  Beyond the OECD, total energy consumption will grow dramatically — at three times the OECD rate. In terms of living standards, the Chinese people are about halfway between Europeans and other non-OECD nations. Thus, they will likely still increase their per-capita energy consumption faster than Americans or Europeans, but no longer as fast as they have in the past. China will also improve its energy productivity, creating more GDP with less energy — indeed likely improving its efficiency more so than other regions of the globe.

  India and the rest of Asia are a little behind. They are thus expected to grow faster than China in per-capita consumption over the next 30 years. Indians are likely to double their energy consumption per person in one generation. Africa's consumption will grow by about 60% due to its population growth, but from so low a base that it barely matters.
- Thus, the OECD share of energy consumption will fall from about one-third of the world to about one-quarter.

5 Clean and Dirty Energy

Let's take stock. In the previous chapter, we explained why it is misleading to blame only the industrial revolution and capitalism for our increasing use of energy (and emissions). It was not just the industrial revolution, but also the second agricultural, hygiene, and medical revolutions that facilitated our population explosion.

- Without the population explosion, fossil fuel use — with all its nasty emissions (discussed in detail in the next chapter) — would not have endangered the climate (discussed in the chapter thereafter).
- Without fossil-fuel use, the population explosion would not have caused so many emissions and changed the climate.

The two needed each other. Population growth and fossil fuels have become the two horsemen of the climate-change apocalypse.

Realistically, our leaders will not be able to do much to curtail population growth. Nor do we see how they could do much to curtail the world's energy consumption.

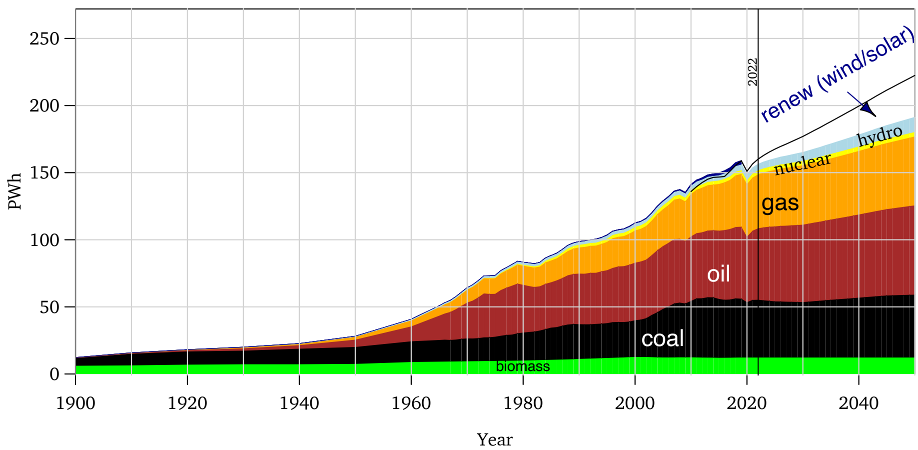
Humanity's best hope, then, is to improve its efficiency — either the efficiency with which it uses energy to make its living or the efficiency with which it creates energy with fewer emissions. (Emissions and their effects are the subjects of our next chapters.)

Can we produce the same energy with fewer emissions? That is, can we switch from dirty fossil fuels to clean energy sources on a sufficient scale to meet global energy demand? And how quickly could we switch? This is the trillion dollar question.

Figure 11 is perhaps the most important illustration in our book. It stacks energy sources in order of dirtiness.

Biomass is the layer at the bottom, because it has the dubious distinction of being the dirtiest fuel in wide use. It consists primarily of the burning of wood plus agricultural waste (by farmers). Used since pre-biblical times, biomass still accounts for about 7% of humanity's energy use today. Healthwise, it's terrible. Its particle emissions create some of the worst health hazards among common pollutants studied by scientists. Its greenhouse gas emissions per useful energy beat even fossil fuels (in a bad way). Even in the United States, the EPA reports that about 10 million homes (30 million people) still use

Figure 11. Energy Breakdown, 1900 to 2020



	Bio	Coal	Oil	Gas	Nuc	Hydro	Wind	Solar	Total
PWh 2019	11	44	54	39	7	10	3.5	1.8	173
Percent	6%	26%	32%	23%	4%	6%	2%	1%	100%

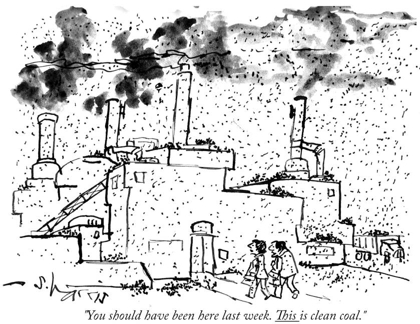
Note: This figure is based on the "fossil-fuel" equivalent way of counting non-fossil fuels as primary energy. (It grosses them up as if they had similar conversion losses.) About 80% of the world's energy is still supplied by the three fossil fuels. Wind and solar are rounding errors. The projection of energy use is from the EIA. Energy sources are stacked by order of dirtiness when burned (CO_2 emissions per Wh over 170 years). However, if Natural Gas production leaks are accounted for, natural gas would be as dirty as coal.

Source: Ritchie and Moser, Our World in Data, Energy Mix, originally based on Smil and British Petroleum. Forecasts are from the US EIA International Energy Outlook, Oct 2021. The input series were Forecasts by Fuel and Forecasts of Hydro. We aligned the data sources to minimize discrepancies.

wood as their primary or secondary heat source, causing an estimated 10,000 premature deaths per year. However, biomass is renewable, which is why it has (unfortunately) been exempted from many global emission treaties.

There are three fossil fuels that we are digging out of the ground: coal, oil, and natural gas. Like biomass, fossil fuels are primarily used in combustion processes. The figure shows that they are responsible for powering about 85 percent of the world today. Thus, they are also responsible for the majority of harmful emissions of all kinds. Reducing emissions will require tackling fossil fuel use. It will be a huge task.

Coal made a strong entry around 1850 and overtook biomass around 1900. We will cover coal in Chapter 10, but here is a basic description. Today, coal provides about four times as much energy as biomass. Unfortunately, coal is also only mildly less polluting than biomass.



You should have been here last week. *This* is clean coal.

If you look carefully at Figure 11, you will see a jump in coal consumption starting around 2009. This was due to the dramatic economic expansion in Asia, particularly China, where coal still accounts for 60% of electricity generation. Even today, despite claims that it wants to decarbonize by 2060 and despite ongoing *percentage* reduction in reliance on coal, China is building new coal replacement plants at a record pace. They will have an expected life span of about 30-50 years. From humanity's collective emissions perspective, this is a lost opportunity.

Fortunately, coal use has leveled off since around 2014 (though it has experienced a small and hopefully temporary renaissance in 2021). And even more fortunately, coal is not only universally despised for its more localized toxic non-CO_2 pollution (like smog and soot), but it is also expensive to mine and ship. Thus, coal has been becoming increasingly uncompetitive. No new coal plants have been built in the West for over a decade.

We are a little more optimistic than the EIA forecasts in Figure 11. We believe (or maybe just hope) that coal will decline under economic and political pressure from wealthier populations even in non-OECD regions where coal is still heavily used. Yet once a plant is built, it will be difficult not to use it. The decline of coal would be faster if politicians gave it a well-deserved push out the door with appropriate pollution taxation. What's delaying them? Remarkably, in many places, it is no longer the lack of cheaper and better economic alternative energy. Instead, it is the large employment in the coal sector. This is especially the case — where else? — in China and India.

Oil is a cleaner fossil fuel than coal. It is used mostly in transportation, secondarily for heating. Its use is still growing — despite all the Tesla cars in the West. Oil also fuels aircraft, ships, trucks, and so on. In the developing world, oil is also sometimes used to power diesel-electric backup generators, because the electric grid is so unreliable.

Natural gas ("Natgas") is mostly methane. It is cleaner than coal and oil *when burnt*, but this is highly misleading. From a more complete supply-chain perspective, Natgas may well be as polluting as coal. The reason is that it leaks left and right. Bloomberg quotes estimates that about 2.3% of Methane escapes during its extraction and transportation. Methane is about 30–100 times more potent than CO_2 as a Greenhouse gas, so Natgas' true pollution may be *twice* of what it would be without leaks. At this point, given what scientists have learned in the last decade, we should no longer believe that Natgas is our clean "transition" fuel.

Despite all their drawbacks, both oil and gas are still projected to grow — at least for another generation, if not longer.

Other energy sources remain small — in relative terms, of course. In absolute terms, they are big. Nuclear and hydro-electric plants together can account for only 10% of the world's energy needs. Solar and wind power are about 3%, despite a full decade's worth of installations. They are becoming more important every year, though.

What is the outlook for the next generation? Unfortunately, not too different from the past. Fossil fuel use is still increasing, although fortunately now at a decelerating rate. This is mostly due to clean renewables coming online. But clean renewables are not coming on strongly enough even to arrest the growth of fossil fuels — much less to reduce them.

It is fairly straightforward to make good predictions for the world's energy use. Even with the greatest of effort, fossil fuels — the main source of our emissions — will play a key role for at least a few more decades, whether we like it or not. And fossil fuels will *not* play a key role in one to two centuries or so, simply because we will likely have exhausted most of the cheap-to-mine higher-quality fossil fuels. The age of fossil fuels will come to an end. The only question now is how quickly.

Why can't we phase out fossil fuels within, say, one generation? Probably because there are physical limits to the speed of change. (We describe the various challenges clean tech faces in upcoming chapters.) As in all things economic, there are costs and benefits. On the one hand, we know that we cannot eliminate emissions too quickly. Rapid reduction could impoverish the lives of billions of others now and maybe even kill millions. On the other hand, we also know that it is also not a good solution to push emissions down too slowly. The environmental impact — and not only from global warming but also local particle emissions — could again impoverish the lives of billions and kill millions of people. Civilization should try to find a good middle path between the two extremes. We should move the needle toward clean solutions as soon as doing so becomes reasonable.

anecdote

Some prominent thought leaders are on record having made some "interesting" energy proposals. For example:

- Paul R. Ehrlich, Professor, Stanford: "Giving society cheap, abundant energy would be the equivalent of giving an idiot child a machine gun."
- Jeremy Rifkin, Greenhouse Crisis Foundation: "The prospect of cheap fusion energy is the worst thing that could happen to the planet."
- Barack Obama, Presidential Candidate 2008: "Under my plan of a cap-and-trade system, electricity rates would necessarily skyrocket. Coal-powered plants, you know, natural gas, you name it, whatever the plants were, whatever the industry was, they would have to retrofit their operations. That will cost money. They will pass that money on to consumers."

6 Important Details and Clarifications

Before we leave energy, we want to quickly cover a few more details.

Clean and Renewable Energy

First, some clarifications. "Renewable energy" is not the same as "clean energy" and vice-versa. Renewable energy includes solar power (mostly solar photovoltaic cells), wind power (mostly giant turbines standing around the landscape), geothermal power (think of giant pits that tap heat from deep underground), hydro-power (think dams that refill from precipitation when emptied), but also biomass (the aforementioned burning of wood and nastily dirty affair), but not nuclear power. In contrast, clean energy includes solar, wind, geothermal, hydro-power *and* nuclear power (but not biomass). Although "clean" would have been the shorter word when discussing wind and solar, the adjective more commonly used is "renewable." (Maybe it sounds more sophisticated?) We can only hope that speakers don't mean biomass.

The two brightest beacons on the horizon to replace fossil fuels are indisputably solar and wind power. They are both clean and renewable. We are not yet sure about other renewable and clean energy sources — it will depend on their technological progress relative to that of wind, solar, and batteries. (Batteries required but not included.) Civilization could certainly use other energy sources, too, and more horses to bet on. Technology will be the subject of Part III of our book. Here is a very brief preview.

The problem with wind and solar is that their contribution to today's power generation is so small that it is difficult even to see their slivers in Figure 11. Thus, you need to keep perspective. Although they have indeed been growing more rapidly in percentage terms than any other sources of energy, they still account for less than 5% of primary energy as of 2020. This is also why they are not growing more rapidly in absolute terms than fossil-fuel plants. In 2020, the world was still installing about 2 PWh of fossil-fuel energy compared to only about 1 PWh of wind and solar energy. In a few years, wind and solar will overtake fossil fuels — but we are not there yet.

Furthermore, solar and wind have so far made their appearance overwhelmingly only in the electricity sector. As we noted in Table 3, electricity itself accounts for only about one-third of the world's energy consumption today, although it will account for more in the future. Thus, despite a lot of (warranted) hoopla, wind and solar are nowhere near where they will have to be in order to significantly reduce fossil fuels and associated emissions. We have little doubt that they will get there — the only question is how long it will take.

Nameplate Power, Conversion Losses, and Intermittency

It is difficult to compare energy sources that are so different and that have to be converted to end uses with varying efficiency losses.

The EIA *energy figures* already include adjustments — in particular, they try to put renewables and nuclear energy on an even footing with fossil fuels by grossing up delivery as if its conversion to electricity was instead delivered by fossil fuels with standard inefficiency.

The problem the adjustment fixes is that primary energy is not secondary energy. When we generate electricity from fossil fuels, we lose more than half in the conversion. (Electricity will be the subject of Chapter 10.) If all fuels were used for electricity generation (and they are not!), about 100 PWh in secondary energy (instead of 260 PWh of primary energy) would be sufficient. Solar and wind power, the two most prominent candidates for a clean and renewable energy future, do not have the same large conversion heat waste losses as fossil fuels. Solar photovoltaics in particular generate electricity (nearly) directly.

Unfortunately, solar and wind have a different problem — a problem especially for *power figures*. They work only intermittently. Their so-called capacity factor is low. They cannot operate 24/7.

	Nuclear	Fossil Fuel	Wind	Hydroelectric	Solar PV
Capacity Factor	90%	50–60%	35%	25–50%	20%

Much worse, it is not at the operator's discretion as to when they work. They are at the mercy of the local weather. Consequently, on average, wind farms typically generate about one-third of their so-called nameplate capacity (i.e., their maximum output), more in some places, less in others. Solar farms produce even less. Both are even often turned off when there is too much electricity on the grid already. Nevertheless, wind or solar is usually available in most places on earth in abundance, even near population centers.

To satisfy electricity demand when the sun does not shine and the wind does not blow, wind and solar have to generate even more power to charge energy storage devices while they are operating. This also wastes some energy and costs *a lot* more money. Energy storage is the one critical clean-tech aspect that has not yet been solved. Once storage costs drop far enough in price, the fossil-fuel age will quickly come to an end.

For now, roughly speaking, if energy comes from wind and solar plants and the end product is electricity, civilization will need more nameplate power in wind and solar plants than it needs in primary input power from fossil fuel plants. Intermittent generation may lose more power relative to nameplate power than fossil fuels lose in power in their efficiency conversion, but the two are not too far off in terms of order of magnitude.

It is not a bad approximation to think that we will need about 300 PWh of wind and solar nameplate capacity instead of 220 PWh of primary fossil-fuel energy.

7 The Situation Today

So where is the world in 2022?

We have said this a few times already: Civilization should try to move away from fossil fuels as fast as is reasonable, but no faster. This may sound like a vague statement — and it is — but it is also true.

The world seems to be at the start of the fastest energy transition in its history. We venture to guess that this is not because of increasing environmental conscience but because of declining clean energy costs. Many fossil fuel plants have been shut down by their operators even before they have reached the ends of their lifespans, because they could no longer compete economically against wind and solar farms. In many OECD countries, it's been over a decade since a new coal plant has been built. Even natural gas deployment is no longer growing greatly, despite their remaining economic advantages. Clean wind and solar power are growing at an accelerating record pace.

But not all news is good from an emissions perspective. Clean nuclear power is declining and is often replaced by natural gas. (In Europe 2022, nuclear power is not replaced by Russian Natgas but by old coal plants.) Worldwide, wind and solar are growing faster than fossil fuels only *in relative terms* (about 50% per year), but this is from a very low base, where relative increases are both small and easy. Wind and solar are not yet even growing faster than fossil fuel *in absolute terms*. It will take decades just to arrest the installation of new fossil fuel plants, and then some more decades to retire all existing ones. This is why we are so confidently predicting that fossil fuels will play an important role for decades to come — whether we like it or not. Please don't shoot the messenger.

What about all the wonderful news in the press about how the United States is making progress in cleaning up its electricity grid? Yes, it is wonderful, but the fact is that the entire U.S. electricity grid today transmits "only" 4 PWh/year. Cleaning up American electricity *quickly* will be difficult, but it is *relatively* easy compared to cleaning up other sources of emissions, future demand, and many more other countries, too.

We would love clean energy to limit fossil fuel use to today's consumption of $\approx$150 PWh/year. But it likely won't happen. The ongoing growth in fossil fuel usage will lead to growing emissions. By 2050, clean energy will likely cover 30–50 PWh that would otherwise have been filled by fossil fuels —

about a third of today's energy consumption and about half of the growth of energy from today to 2050. This will be a great success — but it will also be a failure in not going far enough.

We began our chapter with the observation that energy demand and supply is not just a technological problem (Part III of our book) but also a social and economic problem (Part II). And it is not the case, as some allege, that the main reason for global emissions is that evil, unscrupulous big-oil capitalists are willing and eager to destroy the environment in order to satisfy their own greed. If that were the case, it would be easy to fix the problem the Shakespearean way — "first kill all the lawyers." But evil capitalists are not the main problem.

Instead, we have to repeat (again and again) that the global emissions problem presents a harsh dilemma. Turning off the fossil-fuel spigot too quickly would result in economic chaos and condemn billions of people to continued long-term poverty. The 1–2 billion people in rich countries and regions might be upset, but they would come out okay. Not all the remaining 6 billion people in poorer countries would. The world shouldn't cut off fossil fuels too quickly. More importantly, even if the world should have done so (say, if the harm was far worse than it is projected to be), realistically, it also wouldn't do so. Those 6 billion people would not tolerate it.

Further Readings

Books

- Gates, Bill, 2021, How to Avoid a Climate Disaster: The Solutions We Have and the Breakthroughs We Need, Penguin Books, New York.
- MacKay, David J.C., 2009, Sustainable Energy — Without the hot air, UIT Publisher, Cambridge, England. Free online. This book is the classic explanation of the energy dilemma, but it is about the United Kingdom around the turn of the millennium. Many good subsequent books (including our own) have borrowed heavily from MacKay's much more original ideas.
- Smil, Vaclav, 2017, Energy and Civilization — A History, MIT Press. A comprehensive history of energy usage.

Reports

- The *British Petroleum* (BP) Statistical Review of World Energy is a remarkably accurate and reliable source of information — despite the fact that the data is collected by a fossil-fuel company. Kudos where it is deserved.
- US EIA International Energy Outlook, Oct 2021.

Websites

- `https://www.eia.gov/` (*Energy Information Administration*), our primary source.
- `http://www.bp.com/statisticalreview` is another authoritative (and unbiased) *British Petroleum* (BP) source.

The BP numbers can differ by about 10% from the EIA numbers, making it difficult to cross-compare numbers. However, the series are internally consistent and they typically move closely together.

We prefer the EIA data primarily because it provides projections up to 2050. However, even within the EIA data, it is possible to find different numbers for the same series. For example, in February 2022, two series were quoting primary energy consumption for the world in 2019 as either 632.9 quads or 601.0 (due to different treatments of biomass).

- `https://www.eia.gov/outlooks/ieo/` is the main source of our information.
- `https://ourworldindata.org/` curates important data we use repeatedly.
- `https://www.iucn.org/`, *International Union of Concerned Scientists*.
- `https://www.rff.org/geo/`, *Resources for the Future*, offers a meta outlook based on different projections from different sources.