Energy IS the economy

Energy is the lifeblood of the economy, and natural resources are its food.

Energy can be heat energy or work energy, the ability to do useful, physical work such as lifting an elevator, moving a truck, or generating electric energy. Useful energy includes work energy, gravitational potential energy such as water behind a dam, electricity, and chemical potential energy in a charged battery.

Kilowatt-hours (kWh) are a common measure of energy, including heat energy. We will use kWh(e) to indicate electric energy and and other such forms of energy readily converted to work. Joules (J) are another common energy measure. One joule is one watt of power flowing for one second, so one kilowatt-hour is 1000 x 60 x 60 watt-seconds, or 3.6 megajoules.

Our global economy uses energy to process limited natural resources into heat and waste. Our society consumes almost 1 kg of natural resources to produce $1 of goods and services. On average each $1 also requires 1 kWh of energy and releases 0.20 kg of CO2.

Many environmentalists are concerned with that single aspect of energy, CO2 emissions from burning fossil fuels. They often ignore resource depletion, energy reliability, and energy cost. Industry, commerce, and transportation require ample, reliable, low cost energy to operate the economy. Society should optimize its overall global economic system, balancing lower CO2 emissions, pollution, energy reliability and cost, and limited natural resource consumption.

Energy drives the economy. There is no substitute for energy. This chapter will show that on average in 2022 each $1 of economic production, gross world product (GWP),

- demands 1 kWh of heat energy,
- uses 0.27 kWh(e) of electric energy,
- emits 0.21 kg of CO2, and
- requires 0.96 kg of mined minerals.

Thermodynamics

The **first law** is conservation of energy. Energy is never lost. The useful gravitational potential energy of an apple becomes kinetic energy as it falls from a tree, then heat energy from its impact on the ground. The energy conservation law also includes matter, a static form of energy, related by Einstein's famous $E=mc^2$ equation.

The **second law** means energy in a system always degrades its usefulness to do work. Without external supply of energy, a closed system's disorder, entropy, always increases. As orderliness decreases, utility value decreases.

Entropy increases when you dissolve a cube of sugar in a cup of tea and the sugar molecules disperse throughout the water. Undoing this dispersion would be difficult and require external energy.

Mathematically, entropy is proportional to the number of bits in the very large binary number counting all the possible micro states of a system.

Earth's energy system

Earth absorbs the Sun's radiating light, including photons that oscillate faster or slower than those we can see. Faster photons are more energetic than slower, infrared ones. To maintain a stable temperature, the energy absorbed by Earth is balanced by infrared energy radiating to space. The radiated energy is low-grade heat, of less utility than incoming, collimated, bright, short-wavelength, energetic photon sunlight that can power solar panels or chloroplasts in leaves.

All systems evolve, entropy increases as orderly structures are dispersed and useful energy degrades to heat radiated to space. Water and wind abrade the Earth, but as Earth's interior cools active geology will no longer refresh mountains and rifts.

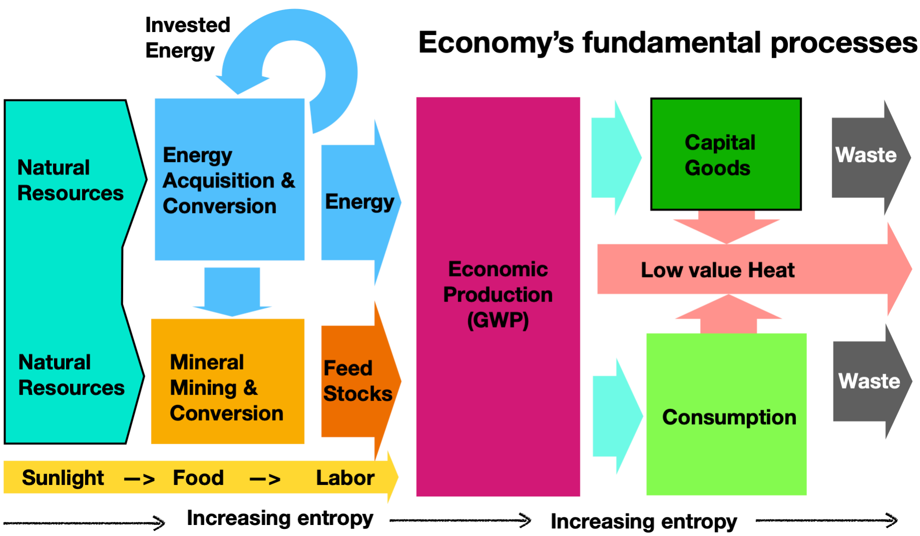
Why doesn't everything on the planet earth system degrade to useless disorder as entropy increases? It would if it were a closed system, but the Earth system absorbs the Sun's orderly, low entropy, high value energy. Life on earth prospers from the energy's transformations of natural resources, emitting less useful, infrared heat to space.

Consider the Sun and its planets as a larger, closed system. It constantly increases entropy and uses up energy. Processes in the Sun release energy as they combine hydrogen atoms to heavier, more stable atoms, radiating photons to the planets and beyond.

Economic system

The economy is a system that employs energy to transform Earth's natural resources to goods and services that degrade to waste and heat. The popular idea of sustainability runs counter to physics and thermodynamics, which dictate that our economy, driven by energy and natural resources, will devolve.

Our modern economy system performs by using high quality, low entropy materials and energy to provide the services we enjoy. Measured as gross world product (GWP), economic production uses materials and energy.



Energy and natural resources create economic activity.

Outlined graphics indicate stocks; other graphics represent processes.

The economic system exemplifies the second law of thermodynamics, with entropy rising as valuable energy becomes low value heat and concentrated natural resources devolve to high entropy, dispersed waste.

Capital goods are the long-lived machinery of the economy, such as factories, buildings, ships, highways, tools, and computers. Use and time deplete capital goods; the economy adds to them.

Consumption is production output consumed within one year by people. Their labor is largely the expertise that controls capital goods, powered by energy, for production. People are sustained by food, grown using sunlight energy.

Energy is dissipated by production through dispersion and friction, becoming low quality heat. Consumption creates waste and heat. The capital goods use energy to function. Eventually capital goods cease to function and become waste.

Natural resources such a petroleum, coal, and uranium are raw material sources for valuable energy delivered as high temperature heat or electricity. Mining requires ever more energy as raw materials such as copper ore and phosphates are harvested from less concentrated sources.

The world is not about to exhaust its natural resources; “peak oil” has been repeatedly disproven. However, more energy and productivity must be invested in energy acquisition and conversion as the best sources become depleted, leaving less for economic production of capital goods and for consumption. Energy and natural resources must be invested for finding, acquiring, and converting the uranium, coal, oil, and gas natural resources.

Waste

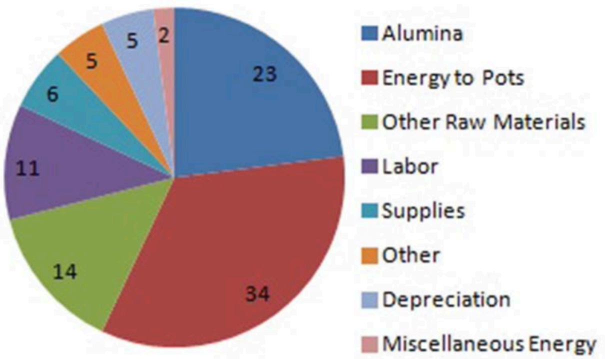
The second law of thermodynamics applies to the world economy, transforming energy and natural resources to heat and waste. Though some environmentalists dream of a circular economy, recycling waste is not very effective. Materials are strongly dispersed in high entropy waste and much energy would be needed to recover them. For example, car tires and shoe soles wear down as tiny particles rub off and are widely dispersed.

High value metals may be recovered by investing energy; aluminum is an example. Energy-intensively manufactured aluminum sells for $2.3/kg. The recycling expense of collecting and baling clean used aluminum cans costs $1.4/kg, saving more than half the cost of producing new aluminum, but requiring $0.9 more of GWP. Hardly any other recycling opportunities are that efficient.

Embedded energy in goods

Embedded energy is the total of all energy used to create a good or service, including the embedded energy of all inputs.

Energy is stored in natural resource materials such as coal, releasing its chemical potential energy when burned. Two hundred million years ago sunlight powered plants that removed oxygen from atmospheric CO2 and used the carbon. The plants later decayed underground without oxygen becoming the natural resource coal, which contains about 2 kWh per kg. Subsequent economics calculations do not count the value of this embedded energy of “free” natural resources such as coal, iron ore, or sand. Let’s illustrate embedded energy with this example of aluminum[11].



Cost percentages of inputs to aluminum production.

The direct cost of electric energy totals 36% of the cost of aluminum. Cheap electricity in the Columbia River basin led Alcoa to build electrolysis aluminum smelters there, and the cheap aluminum led Boeing to build airplanes in Seattle. Aluminum is whimsically termed solid electricity because electricity is the biggest ingredient.

The next biggest cost, 23%, is for the material alumina, aluminum oxide refined from mined bauxite natural resource. Alumina is typically transported by ship to the smelter, so there is transportation energy cost in this alumina cost. Alumina is produced using energy to heat bauxite ore in a pressure vessel at 150-200°C in a sodium hydroxide solution. Shipping bauxite ore requires propulsion energy. Bauxite is harvested by energy intensive strip mining. Including these energy expenditures brings aluminum’s embedded energy far over the direct 36% smelter component.

The aluminum smelter itself is a capital good, which required materials, transportation, and energy use during construction. The smelter's embedded energy is rationally allocated to its produced aluminum, proportionately to the 5% depreciation over its lifetime.

Where do we stop such analysis? Continuing for the strip mining equipment, trucks, ships, transportation fuel, etc reveals that energy is the principal component of the economy. The originating upstream source of these production processes is natural resources, transformed by capital goods, powered by energy, directed by labor.

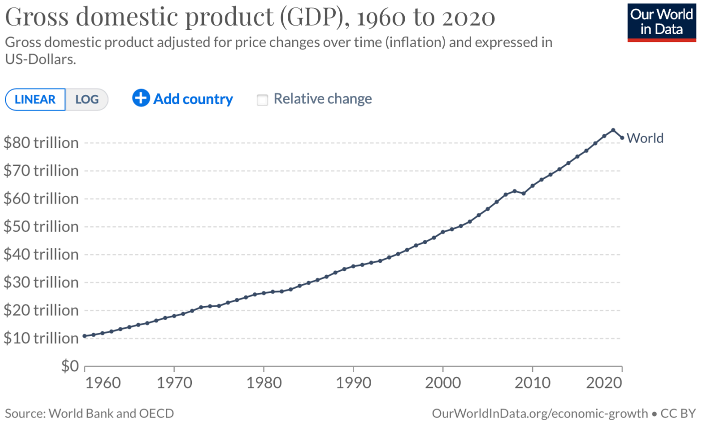
Embedded energy in labor services

Labor in such an aluminum production factory is largely the expertise to operate the capital goods that move and process materials. Two centuries ago people were paid for physical work, say lifting 16 tons of coal per day onto a cart 2 meters high. Tennessee Ernie Ford sang[12] "You load sixteen tons and what do you get, another day older and deeper in debt." That worker's energy is 16,000 kg x 9.8 n/kg x 2 m = 313,000 joules = 0.087 kWh(e), worth about 2 cents today. Today's worker is paid 10,000 times that.

Today labor service does not provide work energy but expertise to operate a capital asset, such as a truck, Bessemer furnace, computer, or a pencil. Humans develop their embedded expertise while consuming food, education, healthcare, housing, protection, and other services that depend on energy, natural resources, and other goods and services. At work the laborer's services use the embedded energy of vehicles for commuting, living in a home, obtaining food, and wearing appropriate clothing, Your doctor's expertise and skills depend on energy enabled education and experience. With no energy enabled economy your doctor would be a witch doctor.

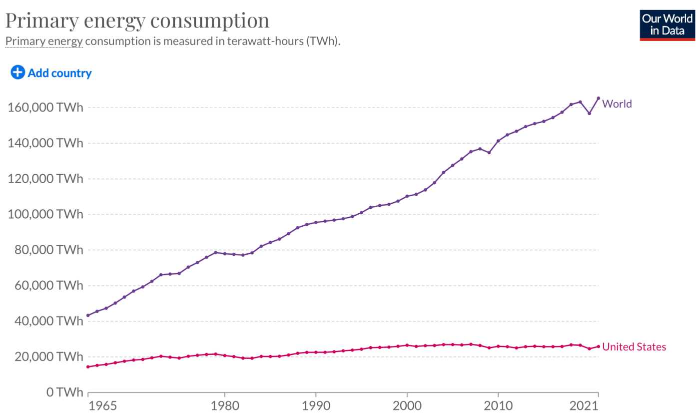
$1 of Gross World Product requires 1 kWh of energy.

Gross Domestic Product (GDP) is essentially the market value of goods and services produced by a nation during one year. National GDPs include adjustments for imports, exports, government taxes and subsidies, and foreign ownership. The sum of all nations' GDPs is Gross World Product (GWP) is simpler because international components cancel.



Gross World Product, constant 2015 dollars

GWP is plotted[13] above, though labeled GDP (nation=World). For 2022 GWP sums to $104 trillion.

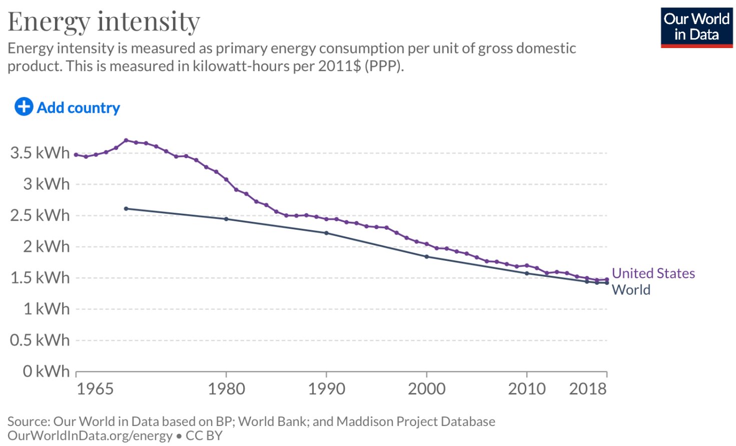


World and US heat energy consumption.

The chart[14] above from Our World in Data shows global heat energy consumption (excluding food) through 2021 at 176,000 TWh per year, or 176 PWh/year, or 20,000 GW. BP reports[15] 165,000 TWh/year. We'll assume 176,000 TWh/year for 2022.

This chart also shows US energy consumption, which is essentially flat. **This flatness has given rise to false hopes[16] that countries will be able to increase their GDPs without increasing energy consumption.** The reality is that stricter environmental controls and government regulations have made energy intensive industries such as aluminum, steel, and cement manufacturing uneconomic in the United States. Energy intensive industries have relocated to developing nations.

The graph of GWP looks much like the graph of world heat energy consumption. The ratio of GWP to annual energy consumption is termed energy intensity, plotted[17] below.



World energy intensity, kWh/$, in 2011 dollars

Though labeled as PPP the data are actually GWP (world summed GDP) in nominal US dollars at their 2011 value. PPP (purchasing power parity) is defined to be nominal GDP for the United States. Energy intensity has fallen with time, but the decline is slowing and leveling out at about 1.42 kWh per (2011) dollar in 2018, the data available from Our World In Data.

One reason for the decline of energy intensity has been the technology improvement in conversion of heat energy to useful energy. Higher temperature heat sources permit more efficient conversion to work, electricity, and other useful energies. For example, legacy coal-fired electric power plants have a conversion efficiency of about 33%, while new, advanced combined cycle natural gas power plants can achieve conversion efficiencies of 60%. Efficiency improvements and energy intensity decline may be leveling out because physics (Carnot's Law) caps the opportunity to improve conversion of heat to useful energy. World and United States energy intensities may be merging because new plants in the rapidly developing world use modern, efficient energy technology as they install new power plants.

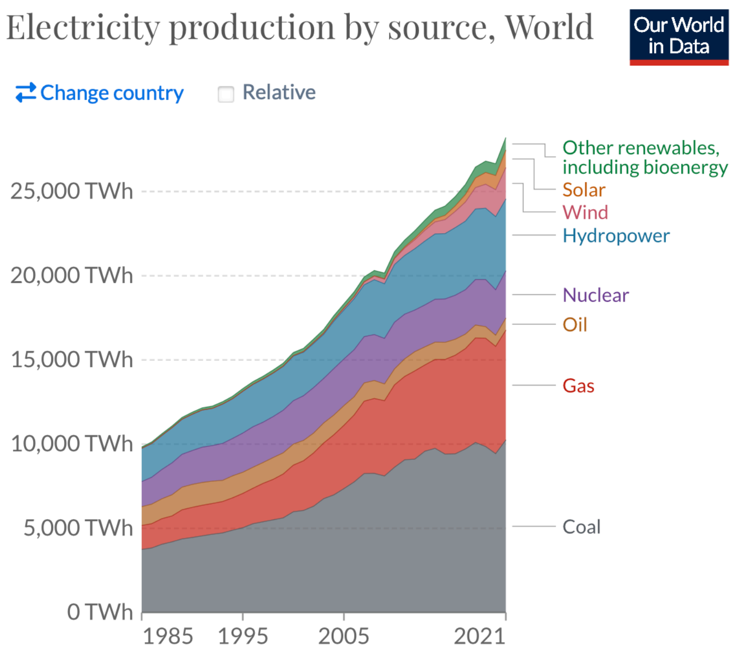
Measures of energy intensity vary significantly depending on the information source.

> From 2011 to 2022 the GDP deflator[18] rose 29%. Enerdata's estimate[19] of world energy intensity is an annual decrease of 1.5% in 2019, slowing to 1% thereafter, altogether 4.5% for 2018 to 2022. To adjust Our World In Data 2018 energy intensity measured in 2011 dollars, the 2022 global energy intensity in 2022 dollars, is 1.42 x (1-0.29) x (1-0.045) = 0.96 kWh/$.
>
> IEA estimates[20] 2019 energy intensity is 4.7 MJ/$ in 2017 dollars. or 1.31 kWh/$. Adjusting for the GDP deflator from 2017 to 2022 (0.85) and Enerdata's 1%/year gives 2022 energy intensity in 2022 dollars as 1.31 x 0.85 x 0.98 = 1.09 kWh/$.
>
> However simply dividing 2022 world energy (176 TWh/year) by IMF's 2022 GWP ($104 trillion)[21] gives 1.69 kWh/$.

We'll use 1 kWh/$ as our estimate.

Wide variations of supply and demand make energy prices volatile in the short term. In the longer term high prices incentivize production, so prices drop but not so low as to become uneconomic for the producer. Prices for competitive goods drop to levels based on costs of production, strongly dependent on the cost of energy.

$1 of GWP demands 0.27 kWh(e) of electric energy.



Electricity production by source

Electric energy use reported[22] by OurWorldInData for 2021 above was 28,000 TWh(e), or 28 PWh(e), or about 3200 GW average power. World Bank and Statista[23] estimate GWP for 2022 at $104 trillion, so electric energy intensity is 28/104 = 0.27 kWh(e)/$.

36% of heat energy is used to make electric energy.

The 28 PWh(e) electric energy use[24] includes 7 PWh(e) generated directly from solar, wind, and hydro sources. The remaining 21 PWh(e) was sourced from 63 PWh of heat energy, converted to electric energy at a ratio about 3 kWh to 1 kWh(e). Annual world energy use is 176 PWh, so 63/176 or 36% of all heat energy is used for electric energy generation.

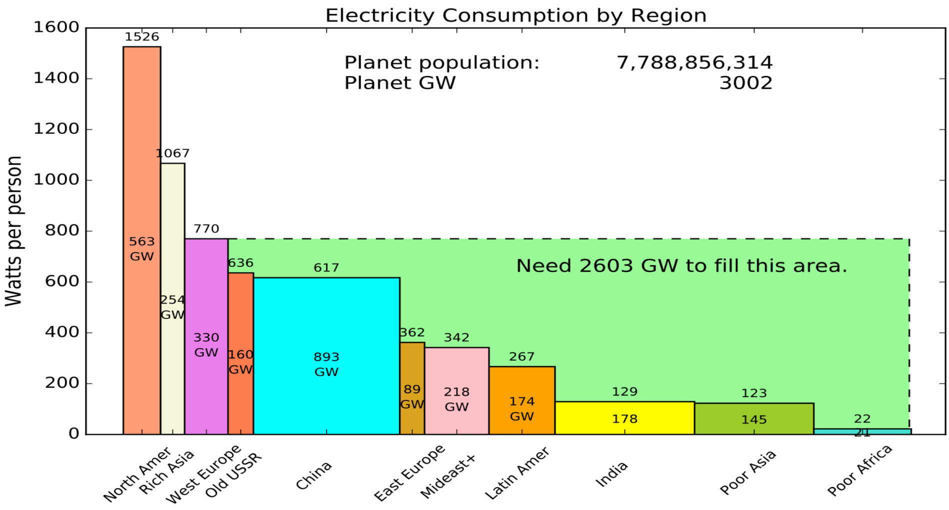
Only 3 PWh of that 63 PWh of that annual heat energy comes from nuclear fission, so 60 PWh comes from combustion. **This is a huge opportunity to use fission heat instead of combustion heat to generate electricity.** Because *new nuclear* technology is hot, we can now generate electricity with even less heat energy. *New nuclear* fission power plants operating at 700°C raise thermal-electric conversion efficiency from typical 33% to over 46%.

Solar panels and wind turbines produce electric energy without heat energy, but there are drawbacks. The large up-front embedded energy and embedded CO2 from manufacturing and installing such dispersed energy sources should be allocated over their lifetimes.

Intermittency is another, difficult problem. Typically gas turbines operate when wind or solar energy is reduced. Modern combined cycle gas turbine with steam turbine (CCGT) power plants in steady operation achieve over 60% conversion efficiency of natural gas heat to electric energy. However simpler combustion turbines that power up and down quickly (peakers) to supplement intermittent wind and solar generators operate at lower, 34% efficiency, generating nearly twice the CO2 emissions of CCGTs. This erases much of the CO2 savings compared to using CCGTs steadily without wind and solar interruptions.

World electric power demand growth

ThorCon analyzed global electric power growth due to economic development of developing nations, estimating 770 watts per person would be required to achieve prosperity levels of western Europe.



Developing nations' shortfall in electric energy use[25]

> The height of each colored block represents the average electric power consumption per capita. The width is proportional to the regional population, so the area represents regional average electric power generated and used.

For developing nations' people to use as much power as western Europeans, electric power demand would increase by 2,600 GW, or 23 PWh/year. This could be provided with 2,600 GW of nuclear power plants. Over the 26 years to 2050 the build rate would be 100 GW per year.

To zero global CO2 emissions of all nations by 2050, IEA estimates[26] that replacing all energy from fossil fuels will increase clean electricity generation demand to 8,000 GW, or 1,000 watts per person.

In summary, the global demand for affordable, reliable, clean electric power may increase by 2,600 GW as poor economies develop, plus 8,000 GW if the IEA decarbonization strategy of electrifying everything is implemented.

Each $1 of GWP requires 0.96 kg of natural resources.

The demand for mined minerals is sometimes overlooked, but it is substantial. Natural resources and energy are the materials that drive the economy. The UN reports that natural resource materials consumption, unchanging since 2010, is 0.96 kg/$. Such mined resources include coal and petroleum for energy.

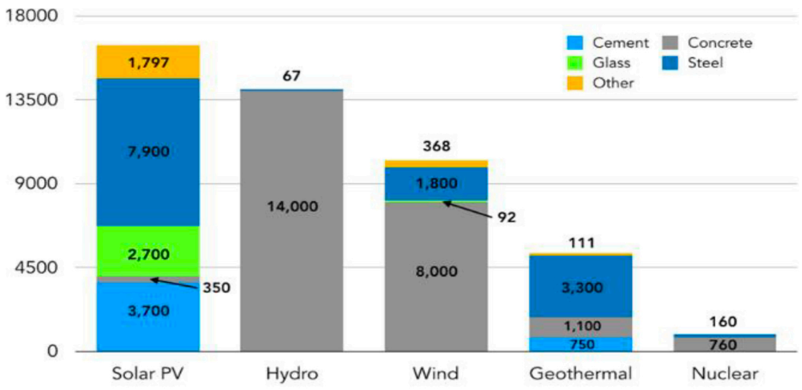
The Society for Mining, Metallurgy & Exploration Foundation reports[27] US per capita annual minerals use at 39,431 pounds. This is roughly 0.26 kg/$, low because the US service economy is not as industrial as the rest of the world's.

10,603 lbs.	**Stone** is used to make roads, buildings, bridges, landscaping and other construction uses, and for numerous chemical uses.
6,952 lbs.	**Sand and Gravel** are used to make concrete, asphalt, roads, blocks and bricks.
794 lbs.	**Cement** is used to make roads, sidewalks, bridges, buildings, schools and houses.
265 lbs.	**Iron Ore** is used to make steel for buildings, cars, trucks, planes, trains, and for other construction and containers.
390 lbs.	**Salt** is used in various chemicals, for highway deicing, and in food and agriculture.
159 lbs.	**Phosphate Rock** is used to make fertilizers to grow food and in animal feed supplements.
146 lbs.	**Clays** are used to make floor and wall tile, dinnerware, kitty litter, bricks, cement and paper.
19 lbs.	**Aluminum (from bauxite)** is used to make buildings, beverage containers, autos and airplanes.
0.02 lb.	**Lithium** – 80% of lithium mined is used to make batteries, increasingly important in many technological devices and electric vehicles.
13 lbs.	**Copper** is used in buildings, transportation, plumbing, electrical and electronic parts, and is integral in renewable energy production.
11 lbs.	**Lead** is primarily used in lead-acid batteries in vehicles and other power systems, such as in communications.
6 lbs.	**Zinc** is used to make metals rust-resistant, to make various metals and alloys, paints, rubber, and in skin creams, health care and nutritional supplements.
30 lbs.	**Soda Ash** is used in all kinds of glass, powdered detergents, medicines, as a food additive, and for water treatment.
6 lbs.	**Manganese** is used to make almost all steel for construction, and in machinery and transportation.
665 lbs.	**Other Nonmetals** are used in glass, chemicals, soaps, paper, computers, cell phones, and more.
23 lbs.	**Other Metals** are used in electronics, TV and video equipment, recreation equipment, and more.
0.04 lb.	**Silver** is used in cars, solar technology, batteries and medical equipment.

US per capita, annual natural resources use.

In addition to the above, the Society estimates per capita energy source minerals include 1,111 gallons of petroleum, 3,077 pounds of coal, 95,633 cubic feet of natural gas, and 0.14 pounds of uranium.

Seemingly wind and solar radiation from the Sun could generate electric energy without mining and consuming Earth's natural energy resources. However, producing the capital goods involved in building such generators consumes ten times more natural resources than building nuclear power plants. The Figure 9 tally below does not even include the natural resources needed to build material-intensive storage batteries to mitigate intermittency, nor transmission lines to collect electricity from the dispersed places solar and wind energy might be generated.



Lifecycle material mass requirements[28] for electric energy sources in tonnes per TWh produced

Nuclear power can supply electric energy using a small fraction of irreplaceable, low entropy, natural resources required for solar, hydro, and wind generation.

World population

The above examples do not account for population growth. Population will likely grow from 8 billion people now to 10 billion in 2085. World population is not growing exponentially. Fewer children are being born. Peak baby was reached in 2013[29].

With increasing economic prosperity people choose to have smaller families.[30] India's population growth has stabilized as its raw birth rate dropped to 2.0 children per woman. The US rate is 1.66. China's birth rate is now only 1.2, and government leadership is concerned about how a smaller contingent of young people can support the economy and an older, retired population.

World population may drop as fast as it rose if globally births drop to the US rate of 1.66 children per woman. The globe might have perhaps to 2 billion people 300 years from now. Birth rates have stayed below 2.0 births per woman in China and Brazil for 20 years, Thailand 30 years, Canada, Germany, and Japan for 50 years.

Ample, reliable, affordable, clean energy encourages prosperity sufficient to reduce the global population That would create a significant turnaround in today's rapid growth in mining out natural resources.

World average energy cost is $0.059/kWh.

Enerdata estimated[31] in 2010 that $6.4 trillion, just over 10% of GWP, was spent for energy. For 2022 the International Monetary Fund estimates[32] GWP to be $104 trillion, suggesting energy expenditure of $10.4 trillion at the Enerdata ratio.

Energy consumption in 2022 is about 176,000 TWh (176 PWh), so average energy cost is $10.4 trillion / 176,000 TWh = $0.059/kWh for the world economy.

Average energy cost varies considerably with the quality of energy, such as the difficulty of converting it to useful energy like work or electricity. These examples below bracket the above average of $0.059/kWh.

> Petroleum is an easily transported liquid with high energy density; diesel energy density is 12.7 kWh/kg. The US August 2022 average[33] price was $5.1/gallon-diesel, or an energy cost of $5.1/3.2 kg / 12.7 kWh/kg = $0.125/kWh.
>
> Coal prices are volatile, so $200/ton for coal is just an informed[34] guess. At 7 kWh/kg its energy cost is $0.028/kWh.
>
> Volatile US natural gas energy cost at $8/MMBTU is $0.027/kWh.

Embedded CO2 is 0.21 kg/$.

Our World In Data estimates[35]148 TWh of energy from combustion of fuels in 2021. At 0.25 kg-CO2/kWh this is 37 Gt of CO2 emissions, closely matching their separate CO2 emissions estimate.

> For a reasonableness check, in one year ending Sept 2022 Mauna Loa observatory measured[36] atmospheric CO2 density rose by 0.64%, or 21 Gt-CO2 of the atmosphere's[37] 3210 Gt-CO2, but this is net of other sources such as forest fires and sinks such as ocean absorption and new forest growth.

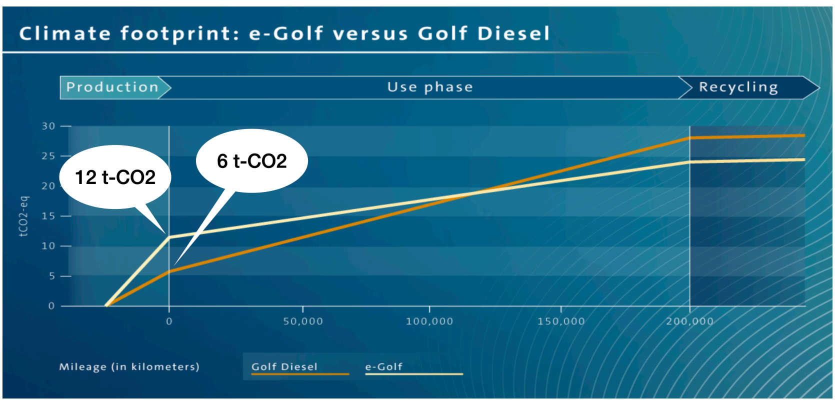
We can use costs to estimate embedded CO2 from constructing capital goods. About 84% of world energy is derived[38] from burning fossil fuels such as oil, coal, or natural gas, and the rest from hydro, fission, wind, and solar sources. CO2 emissions of 0.25 kg/kWh are typical for petroleum products diesel, jet fuel, and gasoline. Emissions range from

0.18 (methane) to 0.28 (coal) kg/kWh. Using 0.25 kg-CO2/kWh for 84% of energy use gives in 2022

1 kWh/$ x 0.84 x 0.25 kg-CO2/kWh = 0.21 kg-CO2/$, in 2022 dollars.

Thus we can roughly estimate atmospheric CO2 emissions for producing a capital good or service by multiplying the dollar cost by 0.21 kg-CO2.

To test this concept consider the cost of a product that is sold in volume in a competitive market — an auto. Least expensive models are priced most competitively. In 2019 Volkswagen estimated[39] the CO2 emissions from producing a VW Golf and VW e-Golf. I trust VW's reformed, good behavior in the wake of dieselgate. For my Dartmouth Osher course I annotated VW's graphic to highlight approximately 12,000 kg-CO2 for an e-Golf including its battery and 6,000 kg-CO2 for a diesel powered Golf. Note 1 t = 1 tonne = 1,000 kg.



VW *estimate of CO2 emissions from manufacturing Golf autos.*

In 2022 the least expensive model VW Golf GTI sold for $28,880. Multiplying 0.21 kg/$ x $28,880 = 6,000 kg-CO2, closely matching VW's own estimate.

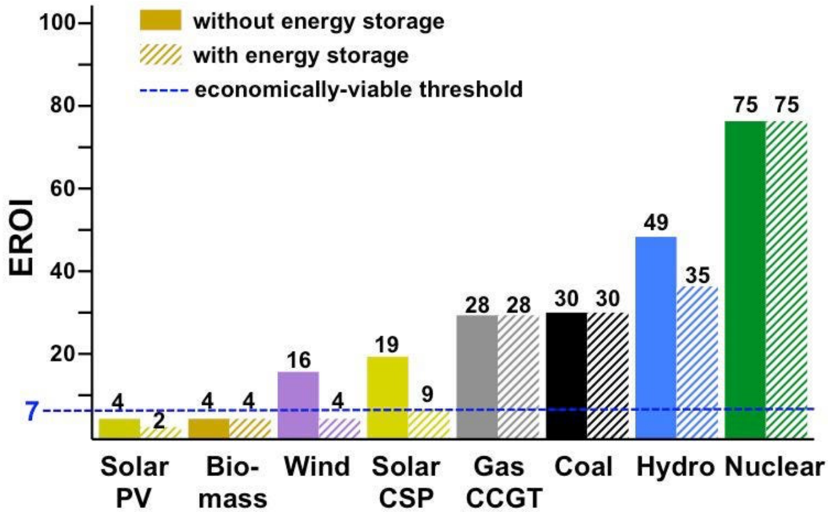
Using the energy/cost ratio of 1 kWh/$ implies that Golf required 28,880 kWh of energy in its manufacture. VW's 2015 analysis was reported to be 24,000 kWh for a Golf, and 56,000 kWh for an e-Golf. Computing accurate embedded energy is difficult. In his *Hot Air* book David MacKay estimated 76,000 kWh to build an unspecified car.

Goehring & Rozencwajg estimate[40] 90,000 kWh of energy is used to manufacture each EV, half for the battery, in a revealing analysis of how Norway subsidized EV penetration.

Global energy return on investment (EROI) is 17:1.

Globally, on average, we spend \$0.059 to obtain 1 kWh of energy, which can generate \$1 of GWP. The energy investment of \$0.059 can return \$1 worth, so EROI is \$1/\$0.059 = 17:1.

The ratio of energy-out to energy-in is termed EROIE, energy return on invested energy, often shortened to EROI. Global average EROI is 17:1, for heat energy out/in.



Energy return on investment.

Weissbach analyzed[41] EROI for electricity generation sources. The striped bars indicate lower EROI for variable energy sources that require energy storage. Net EROI less than 1:1 is clearly an energy sink, and an EROI less than 7:1 is uneconomic, requiring subsidies to encourage development. Global average EROI is now 17:1. **Neither Wind nor PV Solar generation is sufficiently economic to attract private investment, so subsidies are required.** Lowering energy's EROI from 17:1 to uneconomic levels under 7:1 would collapse the economy. **Powering the world with nuclear fission at EROI of 75:1 would reduce invested energy requirements by \$8 trillion per year.**

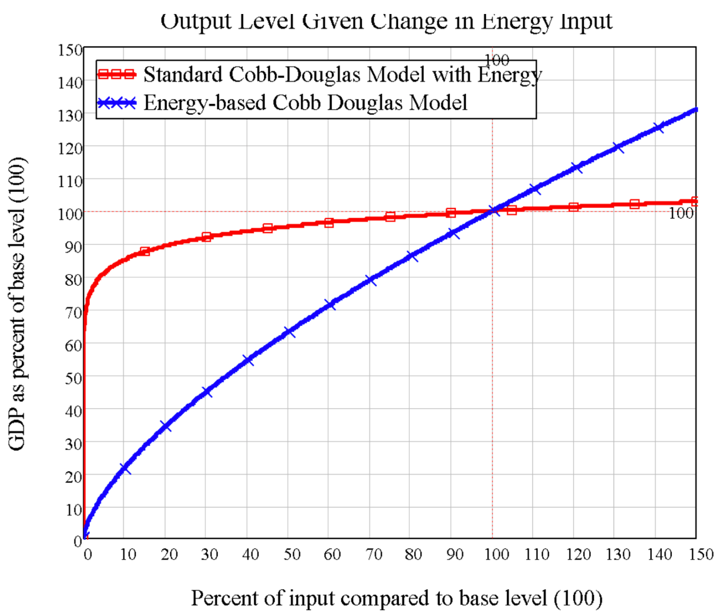
GWP dependence on capital, labor, and energy.

Classical economists realized that the economy's productivity depended on capital and labor. GWP = function { K, L }. Until recently economists considered energy as just another economic system input, like iron ore or soybeans. Modern economists understand energy's critical role and try to model GWP = function { K, L, E }, where K represents the capital goods produced by prior years of economic activity and remaining in productive service. Labor L is largely human expertise, not physical work. Labor L manages the use of energy E by capital goods in service K, such as an automobile or a computer.

Economics professor Steve Keen's 2019 model[42]

$$Q = C \cdot ({E_X}^K)^{\alpha} \cdot K^{\alpha} \cdot L^{1-\alpha},\ \alpha = 2/3$$

is portrayed in the blue line below. He writes that GWP is nearly linearly depending on energy. The slope is about $1/kWh.



GWP dependence on energy in classical and Keen models.

Professor Tim Garrett explored[43] such ideas and noted world energy consumption E was closely proportional to *cumulative* GWP, at 4.3 watts per thousand (2022) dollars. His insight is that the civilization's historically created structures demand ongoing maintenance energy, at 4.3 milliwatts/$.

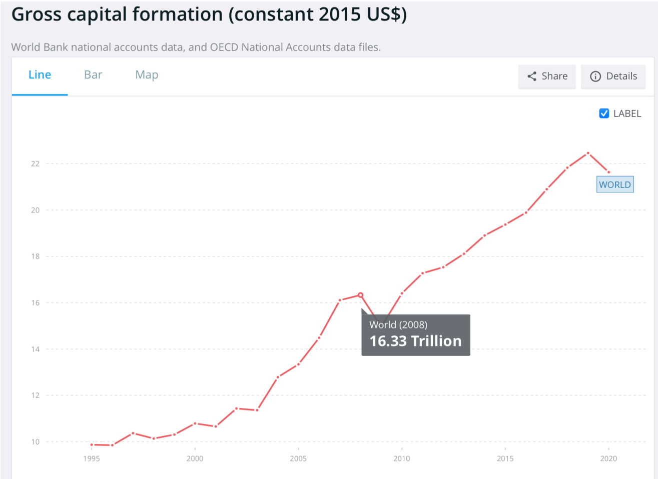
GWP generally increases year after year, so Garrett's sum depends largely on recent years' GWPs. We estimated energy's contribution to GWP at 1 kWh/$ during a year, or 114 mW/$, whereas Garrett found 4.3 mW/$ of historical cumulative production. These two concepts match if capital goods K have an average useful life of 114/4.3 = 27 years, during which they consume energy to produce GWP. A capital goods in service lifetime of 27 years seems reasonable.

Capital goods investment is 26% of GWP.

Capital goods are the world's produced tools, machines, factories, and buildings. GWP output is either consumed in the current year or invested in capital goods for use over multiple years. The World Bank estimated gross fixed capital formation[44] as 26% of GWP in 2020. Using that fraction for 2022 gives

GWP ($104 T) = capital goods ($27 T) + consumption ($77 T).

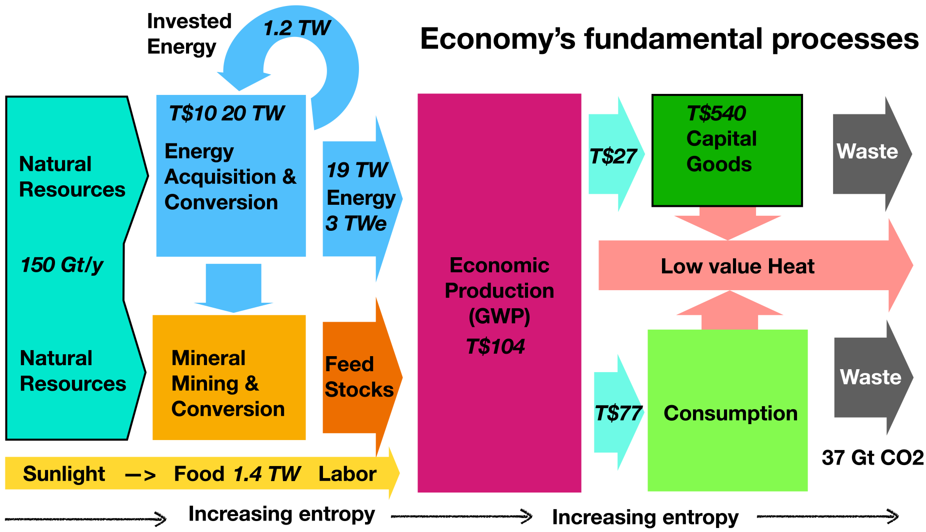
Capital goods in service are $540 trillion.



World capital formation

World Bank's graph in Figure 13 shows that annual capital goods formation over 27 years averages roughly $16 trillion in constant 2015 dollars, or $20 trillion in 2022 US dollars. With a useful lifetime of 27 years, capital goods in service amount to approximately 27 years x $20 trillion/year = $540 trillion.

Quantifying energy in the economy



Economy's transformation of energy and natural resources

These numbers, in 2022 US dollars, are estimates to help understand the continuous, entropy-increasing evolution of the Earth's economic system.

Earth's stock of natural resources is depleted by 150 Gt per year to provide the energy sources of oil, coal, gas, and uranium to generate the low-cost, dispatchable, dense, useful energy used for motive force, lighting, and heat.

The process of energy acquisition and conversion is the exploration, extraction, and refining of materials with dense potential energy used to drive the economy. It is a $10 trillion/year industry, generating 20 TW of power, of which 1.2 TW is invested in obtaining the energy. This leaves 19 TW to drive the economy, including 9 TW of power to generate 3 TW(e) of electric power.

Economic production, gross world product, GWP, valued at $104 trillion, represents the final goods and services consumed within a year plus savings, which are invested in capital goods. GWP excludes intermediate economic activities, such as energy production or minerals refining.

Sunlight provides energy for humans' food caloric requirements of 1.4 TW, necessary to sustain the labor expertise, used to direct the economy.

The economy's stock of capital goods, with a service lifetime of 27 years, is worth $540 trillion. It is augmented by $20 trillion per year. The capital goods are powered by energy, directed by the expertise of the human labor force. At end of life capital goods become waste.

Economic consumption by people absorbs $77 trillion of GWP.

The fate of the 20 TW of high value, high temperature, dense power is to become low value, dispersed, low temperature heat that radiates away from Earth to outer space.

The fate of 150 Gt/year of valuable, concentrated natural resources is to become waste material with mixed, widely dispersed, transformed, economic process leftovers that can not be usefully recovered without exorbitant investments of energy and productivity.

The waste CO2 amounting to 37 Gt/year is widely dispersed into more than 5,000,000 Gt of Earth's atmosphere.

Economic production process increases entropy, the measure of disorder. Entropy increases whenever energy is transformed, say from chemical potential energy to heat energy. Entropy increases when high temperature heat is dispersed to become low temperature heat. That process can not be reversed without using significant energy. Entropy increases whenever concentrated materials are dispersed, as sugar cubes in tea or CO2 in the atmosphere.

Economic system insights

Our world economic system obtains energy and mineral feedstocks from Earth's natural resources, raising entropy, creating low-value heat and waste. One waste is CO2 that contributes to gradual warming of the planet, but this is just one effect in a complex system. As concentrated, low entropy, natural resources are mined out they become more precious. To obtain them the economy must use more energy, more natural resources, and use more capital goods machinery to obtain them, increasing the rate of entropy growth.

Replacing fossil fuel sourced energy with wind and solar sources reduces immediate, short-term CO2 emissions, but creates enormous demand for natural resources to be transformed into capital goods: solar panels, wind turbines, transmission lines, and batteries. Cobalt and manganese demand will triple, while needs for copper, nickel, lithium, and rare earths rise by an order of magnitude.

We shouldn't solve the CO2 waste issue by wasting irreplaceable natural resources.

For example the International Energy Association roadmap[45] *Net Zero by 2050* naively calls for expanding clean energy investments to about $4.3 trillion per year through 2050. Just manufacturing these capital goods will require increasing natural resources consumption by 4 Gt/year and raise energy use by 4,300 TWh/year, partly to generate 130 GW(e) of full-time electricity, just to power manufacturing the capital goods for the clean energy industry.

Replacing fossil fuel power, not with wind and solar sources, but with *new nuclear* power will remove the natural resources depletion problem we are causing by vast expansion of the renewable industry and also cut CO2 emissions.

But would not uranium and thorium natural resources become depleted, too? The atomic energy of uranium and thorium is so concentrated that civilization has enough for hundreds, thousands, millennia, actually billions of years[46], by using both natural uranium isotopes, thorium, and extracting uranium dissolved in seawater, replenished by rain on rocks.

Even if we harness near-endless energy, our world economy may not be indefinitely sustainable. Natural resources are consumed and become harder to get. Waste taints the environment. Recycling waste is energy intensive. Entropy always increases, making the economy less productive. If we use *new nuclear* power and minimize natural resources consumption we may extend humanity's few centuries of prosperity by a few more. The faster we use up precious natural resources the less efficient the economy becomes and the less prosperous people become, engendering conflict and its consequences.

Let us harness *new nuclear* energy and use natural resources efficiently to prolong entropy's inevitable future decline of the world economy.