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Energy density

In physics, **energy density** is the amount of energy stored in a given system or region of space per unit volume. It is sometimes confused with energy per unit mass which is properly called specific energy or *gravimetric energy density*.

Energy density	
SI unit	J/m^3
Other units	J/L, W·h/L
In SI base units	$m^{-1}·kg·s^{-2}$
Derivations from other quantities	$U = E/V$
Dimension	$L^{-1}MT^{-2}$

Often only the *useful* or extractable energy is measured, which is to say that inaccessible energy (such as rest mass energy) is ignored.[1] In cosmological and other general relativistic contexts, however, the energy densities considered are those that correspond to the elements of the stress-energy tensor and therefore do include mass energy as well as energy densities associated with pressure.

Energy per unit volume has the same physical units as pressure and in many situations is synonymous. For example, the energy density of a magnetic field may be expressed as and behaves like a physical pressure. Likewise, the energy required to compress a gas to a certain volume may be determined by multiplying the difference between the gas pressure and the external pressure by the change in volume. A pressure gradient describes the potential to perform work on the surroundings by converting internal energy to work until equilibrium is reached.

Overview

There are different types of energy stored in materials, and it takes a particular type of reaction to release each type of energy. In order of the typical magnitude of the energy released, these types of reactions are: nuclear, chemical, electrochemical, and electrical.

Nuclear reactions take place in stars and nuclear power plants, both of which derive energy from the binding energy of nuclei. Chemical reactions are used by organisms to derive energy from food and by automobiles to derive energy from gasoline. Liquid hydrocarbons (fuels such as gasoline, diesel and kerosene) are today the densest way known to economically store and transport chemical energy at a large scale (1 kg of diesel fuel burns with the oxygen contained in ≈15 kg of air). Electrochemical reactions are used by most mobile devices such as laptop computers and mobile phones to release energy from batteries.

Types of energy content

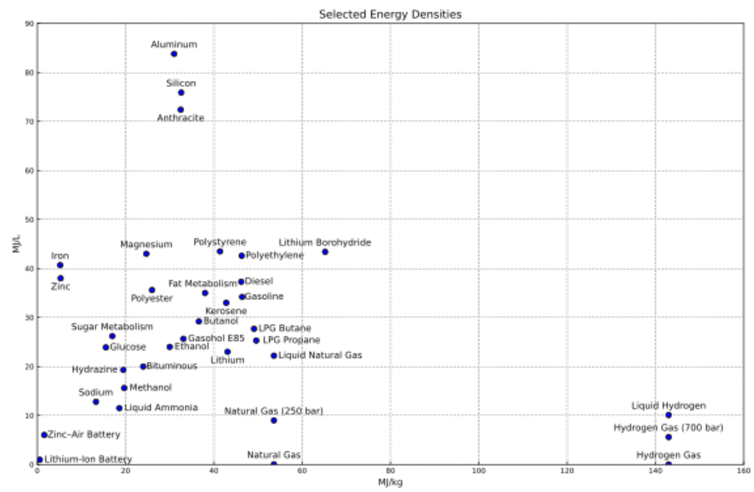
There are several different types of energy content. One is the theoretical total amount of thermodynamic work that can be derived from a system, at a given temperature and pressure imposed by the surroundings. This is called exergy. Another is the theoretical amount of electrical energy that can be derived from reactants that are at room temperature and atmospheric pressure. This is given by the change in standard Gibbs free energy. But as a source of heat or for use in a heat engine, the relevant quantity is the change in standard enthalpy or the heat of combustion.

There are two kinds of heat of combustion:

- The higher value (HHV), or gross heat of combustion, includes all the heat released as the products cool to room temperature and whatever water vapor is present condenses.
- The lower value (LHV), or net heat of combustion, does not include the heat which could be released by condensing water vapor, and may not include the heat released on cooling all the way down to room temperature.

A convenient table of HHV and LHV of some fuels can be found in the references.[2]

In energy storage and fuels



Selected energy densities plot[3][4][5][6][7][8][9]

In energy storage applications the energy density relates the energy in an energy store to the volume of the storage facility, e.g. the fuel tank. The higher the energy density of the fuel, the more energy may be stored or transported for the same amount of volume. Given the high energy density of gasoline, the exploration of alternative media to store the energy of powering a car, such as hydrogen or battery, is strongly limited by the energy density of the alternative medium. The same mass of lithium-ion storage, for example, would result in a car with only 2% the range of its gasoline counterpart. If sacrificing the range is undesirable, it becomes necessary to carry that much more fuel.

The energy density of a fuel per unit mass is called the specific energy of that fuel. In general an engine using that fuel will generate less kinetic energy due to inefficiencies and thermodynamic considerations—hence the specific fuel consumption of an engine will always be greater than its rate of production of the kinetic energy of motion.

Energy density differs from energy conversion efficiency (net output per input) or embodied energy (the energy output costs to provide, as harvesting, refining, distributing, and dealing with pollution all use energy). Large scale, intensive energy use impacts and is impacted by climate, waste storage, and environmental consequences.

No single energy storage method boasts the best in specific power, specific energy, and energy density. Peukert's law describes how the amount of useful energy that can be obtained (for a lead-acid cell) depends on how quickly it is pulled out.

Alternative options are discussed for energy storage to increase energy density and decrease charging time.[10][11][12][13]

The figure above shows the gravimetric and volumetric energy density of some fuels and storage technologies (modified from the Gasoline article).

Some values may not be precise because of isomers or other irregularities. See Heating value for a comprehensive table of specific energies of important fuels.

Generally the density values for chemical fuels do not include the weight of the oxygen required for combustion. The atomic weights of carbon and oxygen are similar, while hydrogen is much lighter. Figures are presented in this way for those fuels where in practice air would only be drawn in locally to the burner. This explains the apparently lower energy density of materials that contain their own oxidizer (such as gunpowder and TNT), where the mass of the oxidizer in effect adds weight, and absorbs some of the energy of combustion to dissociate and liberate oxygen to continue the reaction. This also explains some apparent anomalies, such as the energy density of a sandwich appearing to be higher than that of a stick of dynamite.

List of material energy densities

The following unit conversions may be helpful when considering the data in the tables: 3.6 MJ = 1 kW⋅h ≈ 1.34 hp⋅h. Since 1 J = 10^{-6} MJ and 1 m^3 = 10^3 L, divide joule/m^3 by 10^9 to get MJ/L = GJ/m^3. Divide MJ/L by 3.6 to get kW⋅h/L.

In chemical reactions (oxidation)

Unless otherwise stated, the values in the following table are lower heating values for perfect combustion, not counting oxidizer mass or volume. When used to produce electricity in a fuel cell or to do work, it is the Gibbs free energy of reaction (ΔG) that sets the theoretical upper limit. If the produced H_2O is vapor, this is generally greater than the lower heat of combustion, whereas if the produced H_2O is liquid, it is generally less than the higher heat of combustion. But in the most relevant case of hydrogen, ΔG is 113 MJ/kg if water vapor is produced, and 118 MJ/kg if liquid water is produced, both being less than the lower heat of combustion (120 MJ/kg).[14]

Energy released by chemical reactions (oxidation)

Material	Specific energy (MJ/kg)	Energy density (MJ/L)	Specific energy (W·h/kg)	Energy density (W·h/L)	Comment
Hydrogen, liquid	141.86 (HHV) 119.93 (LHV)	10.044 (HHV) 8.491 (LHV)	39,405.6 (HHV) 33,313.9 (LHV)	2,790.0 (HHV) 2,358.6 (LHV)	Energy figures apply **after** reheating to 25 °C.[15] See note above about use in fuel cells.
Hydrogen, gas (681 atm, 69 MPa, 25 °C)	141.86 (HHV) 119.93 (LHV)	5.323 (HHV) 4.500 (LHV)	39,405.6 (HHV) 33,313.9 (LHV)	1,478.6 (HHV) 1,250.0 (LHV)	Date from same reference as for liquid hydrogen.[15] High-pressure tanks weigh much more than the hydrogen they can hold. The hydrogen may be around 5.7% of the total mass,[16] giving just 6.8 MJ per kg total mass for the LHV. See note above about use in fuel cells.
Hydrogen, gas (1 atm or 101.3 kPa, 25 °C)	141.86 (HHV) 119.93 (LHV)	0.01188 (HHV) 0.01005 (LHV)	39,405.6 (HHV) 33,313.9 (LHV)	3.3 (HHV) 2.8 (LHV)	[15]
Diborane	78.2	88.4	21,722.2	24,600	[17]
Beryllium	67.6	125.1	18,777.8	34,750.0	
Lithium borohydride	65.2	43.4	18,111.1	12,055.6	
Boron	58.9	137.8	16,361.1	38,277.8	[18]
Methane (101.3 kPa, 15 °C)	55.6	0.0378	15,444.5	10.5	
LNG (NG at −160 °C)	53.6[19]	22.2	14,888.9	6,166.7	
CNG (NG compressed to 247 atm, 25 MPa ≈ 3,600 psi)	53.6[19]	9	14,888.9	2,500.0	
Natural gas	53.6[19]	0.0364	14,888.9	10.1	
LPG propane	49.6	25.3	13,777.8	7,027.8	[20]
LPG butane	49.1	27.7	13,638.9	7,694.5	[20]

Material	Specific energy (MJ/kg)	Energy density (MJ/L)	Specific energy (W·h/kg)	Energy density (W·h/L)	Comment
Gasoline (petrol)	46.4	34.2	12,888.9	9,500.0	[20]
Polypropylene plastic	46.4[21]	41.7	12,888.9	11,583.3	
Polyethylene plastic	46.3[21]	42.6	12,861.1	11,833.3	
Residential heating oil	46.2	37.3	12,833.3	10,361.1	[20]
Diesel fuel	45.6	38.6	12,666.7	10,722.2	[20]
100LL Avgas	44.0[22]	31.59	12,222.2	8,775.0	
Jet fuel (e.g. kerosene)	43[23][24][25]	35	11,944.4	9,722.2	Aircraft engine
Gasohol E10 (10% ethanol 90% gasoline by volume)	43.54	33.18	12,094.5	9,216.7	
Lithium	43.1	23.0	11,972.2	6,388.9	
Biodiesel oil (vegetable oil)	42.20	33	11,722.2	9,166.7	
DMF (2,5-dimethylfuran)	42[26]	37.8	11,666.7	10,500.0	
Paraffin wax	42[27]	37.8	11,700	10,500	
Crude oil (tonne of oil equivalent)	41.868	37[19]	11,630	10,278	
Polystyrene plastic	41.4[21]	43.5	11,500.0	12,083.3	
Body fat	38	35	10,555.6	9,722.2	Metabolism in human body (22% efficiency[28])
Butanol	36.6	29.2	10,166.7	8,111.1	
Gasohol E85 (85% ethanol 15% gasoline by volume)	33.1	25.65	9,194.5	7,125.0	
Graphite	32.7	72.9	9,083.3	20,250.0	
Coal, anthracite	26–33	34–43	7,222.2–9,166.7	9,444.5–11,944.5	Figures represent perfect combustion not counting oxidizer, but efficiency of conversion to electricity is ≈36%[6]
Silicon	32.6	75.9	9,056	21,080	See Table 1 [29]
Aluminium	31.0	83.8	8,611.1	23,277.8	
Ethanol	30	24	8,333.3	6,666.7	

Material	Specific energy (MJ/kg)	Energy density (MJ/L)	Specific energy (W·h/kg)	Energy density (W·h/L)	Comment
DME	31.7 (HHV) 28.4 (LHV)	21.24 (HHV) 19.03 (LHV)	8,805.6 (HHV) 7,888.9 (LHV)	5,900.0 (HHV) 5,286.1 (LHV)	[30][31]
Polyester plastic	26.0[21]	35.6	7,222.2	9,888.9	
Magnesium	24.7	43.0	6,861.1	11,944.5	
Phosphorus (white)	24.30	44.30	6,750	12,310	[32]
Coal, bituminous	24–35	26–49	6,666.7–9,722.2	7,222.2–13,611.1	[6]
PET plastic (impure)	23.5[33]	< ~32.4	6,527.8	< ~9000	
Methanol	19.7	15.6	5,472.2	4,333.3	
Titanium	19.74	88.93	5,480	24,700	burned to titanium dioxide
Hydrazine (combusted to N_2+H_2O)	19.5	19.3	5,416.7	5,361.1	
Liquid ammonia (combusted to N_2+H_2O)	18.6	11.5	5,166.7	3,194.5	
Potassium	18.6	16.5	5,160	4,600	burned to dry potassium oxide
PVC plastic (improper combustion toxic)	18.0[21]	25.2	5,000.0	7,000.0	
Wood	18.0		5,000.0		[34]
Peat briquette	17.7		4,916.7		[35]
Sugars, carbohydrates, and protein	17	26.2 (dextrose)	4,722.2	7,277.8	Metabolism in human body (22% efficiency[36])
Calcium	15.9	24.6	4,416.7	6,833.3	
Glucose	15.55	23.9	4,319.5	6,638.9	
Dry cow dung and camel dung	15.5[37]		4,305.6		
Coal, lignite	10–20		2,777.8–5,555.6		
Sodium	13.3	12.8	3,694.5	3,555.6	burned to wet sodium hydroxide
Peat	12.8		3,555.6		
Nitromethane	11.3	12.85	3,138.9	3,570	
Manganese	9.46	68.2	2,630	18,900	burned to manganese dioxide
Sulfur	9.23	19.11	2,563.9	5,308.3	burned to sulfur dioxide[38]

Material	Specific energy (MJ/kg)	Energy density (MJ/L)	Specific energy (W·h/kg)	Energy density (W·h/L)	Comment
Sodium	9.1	8.8	2,527.8	2,444.5	burned to dry sodium oxide
Battery, lithium-air rechargeable	9.0[39]		2,500.0		Controlled electric discharge
Household waste	8.0[40]		2,222.2		
Zinc	5.3	38.0	1,472.2	10,555.6	
Iron	5.2	40.68	1,444.5	11,300.0	burned to iron(III) oxide
Teflon plastic	5.1	11.2	1,416.7	3,111.1	combustion toxic, but flame retardant
Iron	4.9	38.2	1,361.1	10,611.1	burned to iron(II) oxide
Gunpowder	4.7–11.3[41]	5.9–12.9		1,600–3,580	
TNT	4.184	6.92	1,162	1,920	
Barium	3.99	14.0	1,110	3,890	burned to barium dioxide
ANFO	3.7		1,027.8		

In nuclear reactions

Energy released by nuclear reactions

Material	Specific energy (MJ/kg)	Energy density (MJ/L)	Specific energy (W·h/kg)	Energy density (W·h/L)
Antimatter	89,875,517,874 ≈ 90 PJ/kg	Depends on the density of the antimatter's form	24,965,421,631,578 ≈ 25 TW·h/kg	Depends on the den antimat
Hydrogen (fusion)	639,780,320[42] but at least 2% of this is lost to neutrinos.	Depends on conditions	177,716,755,600	Depends on c
Deuterium (fusion)	571,182,758[43]	Depends on conditions	158,661,876,600	Depends on c
Deuterium+tritium (fusion)	337,387,388[42]	Depends on conditions	93,718,718,800	Depends on c
Lithium-6 deuteride (fusion)	268,848,415[42]	Depends on conditions	74,680,115,100	Depends on c
Plutonium-239	83,610,000	1,300,000,000–1,700,000,000 (Depends on crystallographic phase)	23,222,915,000	370,000,000,000–460,00((Depends on crysta
Plutonium-239	31,000,000	490,000,000–620,000,000 (Depends on crystallographic phase)	8,700,000,000	140,000,000,000–170,00((Depends on crysta
Uranium	80,620,000[44]	1,539,842,000	22,394,000,000	
Thorium	79,420,000[44]	929,214,000	22,061,000,000	
Plutonium-238	2,239,000	43,277,631	621,900,000	

Other release mechanisms

Energy released by electrochemical reactions or other means

Material	Specific energy (MJ/kg)	Energy density (MJ/L)	Specific energy (W·h/kg)	Energy density (W·h/L)	Comment
Battery, zinc-air	1.59	6.02	441.7	1,672.2	Controlled electric discharge[45]
Silicon (phase change)	1.790	4.5	500	1,285	Energy stored through solid to liquid phase change of silicon[46]
Liquid nitrogen	0.77[47]	0.62	213.9	172.2	Maximum reversible work at 77.4 K with 300 K reservoir
Sodium sulfur battery	0.54–0.86		150–240		
Compressed air at 30 MPa	0.5	0.2	138.9	55.6	Potential energy
Latent heat of fusion of ice (thermal)	0.334	0.334	93.1	93.1	
Lithium metal battery	1.8	4.32	500	1,200	Controlled electric discharge
Lithium-ion battery	0.36–0.875[50]	0.9–2.63	100.00–243.06	250.00–730.56	Controlled electric discharge
Lithium-ion battery with silicon nanowire anodes	1.566	4.32	435[51]	1,200[51]	Controlled electric discharge
Flywheel	0.36–0.5	5.3			Kinetic energy
Alkaline battery	0.48[52]	1.3[53]			Controlled electric discharge
Nickel-metal hydride battery	0.41[54]	0.504–1.46[54]			Controlled electric discharge
Lead-acid battery	0.17	0.56			Controlled electric discharge
Supercapacitor (EDLC)	0.01–0.030[55][56][57][58][59][60][61]	0.006–0.06[55][56][57][58][59][60]	up to 8.57[61]		Controlled electric discharge
Water at 100 m dam height	0.000981	0.000978	0.272	0.272	Figures represent potential energy, but efficiency of conversion to electricity is 85–90%[62][63]

Material	Specific energy (MJ/kg)	Energy density (MJ/L)	Specific energy (W·h/kg)	Energy density (W·h/L)	Comment
Electrolytic capacitor	0.00001–0.0002[64]	0.00001–0.001[64][65][66]			Controlled electric discharge

In material deformation

The mechanical energy storage capacity, or resilience, of a Hookean material when it is deformed to the point of failure can be computed by calculating tensile strength times the maximum elongation dividing by two. The maximum elongation of a Hookean material can be computed by dividing stiffness of that material by its ultimate tensile strength. The following table lists these values computed using the Young's modulus as measure of stiffness:

Mechanical energy capacities

Material	Energy density by mass (J/kg)	Resilience: Energy density by volume (J/L)	Density (kg/L)	Y (GPa
Rubber band	1,651–6,605[67]	2,200–8,900[67]	1.35[67]	
Steel, ASTM A228 (yield, 1 mm diameter)	1,440–1,770	11,200–13,800	7.80[68]	210[68
Acetals	908	754	0.831[69]	2.8[70]
Nylon-6	233–1,870	253–2,030	1.084	2–4[70
Copper Beryllium 25-1/2 HT (yield)	684	5,720[71]	8.36[72]	131[71
Polycarbonates	433–615	520–740	1.2[73]	2.6[70]
ABS plastics	241–534	258–571	1.07	1.4–3.
Acrylic		1,530		3.2[70]
Aluminium 7077-T8 (yield)	399	1,120[71]	2.81[74]	71.0[7
Steel, stainless, 301-H (yield)	301	2,410[71]	8.0[75]	193[71
Aluminium 6061-T6 (yield @ 24 °C)	205	553	2.70[76]	68.9[7
Epoxy resins		113–1,810		2–3[70
Douglas fir Wood	158–200	96	.481–.609[77]	13[70]
Steel, Mild AISI 1018	42.4	334	7.87[78]	205[78
Aluminium (not alloyed)	32.5	87.7	2.70[79]	69[70]
Pine (American Eastern White, flexural)	31.8–32.8	11.1–11.5	.350[80]	8.30–
Brass	28.6–36.5	250–306	8.4–8.73[81]	102–1
Copper	23.1	207	8.93[81]	117[70
Glass	5.56–10.0	13.9–25.0	2.5[82]	50–90

In batteries

Battery energy capacities

Storage device	Energy content (Joule)	Energy content (W·h)	Energy type	Typical mass (g)	Typical dimensions (diameter × height in mm)	Typical volume (mL)	Energy density by volume (MJ/L)	E d (
Alkaline AA battery[83]	9,360	2.6	Electrochemical	24	14.2 × 50	7.92	1.18	
Alkaline C battery[83]	34,416	9.5	Electrochemical	65	26 × 46	24.42	1.41	
NiMH AA battery	9,072	2.5	Electrochemical	26	14.2 × 50	7.92	1.15	
NiMH C battery	19,440	5.4	Electrochemical	82	26 × 46	24.42	0.80	
Lithium-ion 18650 battery	28,800–46,800	10.5–13	Electrochemical	44–49[84]	18 × 65	16.54	1.74–2.83	C

Nuclear energy sources

The greatest energy source by far is matter itself. This energy, $E = mc^2$, where $m = \rho V$, ρ is the mass per unit volume, V is the volume of the mass itself and c is the speed of light. This energy, however, can be released only by the processes of nuclear fission (0.1%), nuclear fusion (1%), or the annihilation of some or all of the matter in the volume V by matter-antimatter collisions (100%). Nuclear reactions cannot be realized by chemical reactions such as combustion. Although greater matter densities can be achieved, the density of a neutron star would approximate the most dense system capable of matter-antimatter annihilation possible. A black hole, although denser than a neutron star, does not have an equivalent anti-particle form, but would offer the same 100% conversion rate of mass to energy in the form of Hawking radiation. In the case of relatively small black holes (smaller than astronomical objects) the power output would be tremendous.

The highest density sources of energy aside from antimatter are fusion and fission. Fusion includes energy from the sun which will be available for billions of years (in the form of sunlight) but so far (2021), sustained fusion power production continues to be elusive.

Power from fission of uranium and thorium in nuclear power plants will be available for many decades or even centuries because of the plentiful supply of the elements on earth,[85] though the full potential of this source can only be realized through breeder reactors, which are, apart from the BN-600 reactor, not yet used commercially.[86] Coal, gas, and petroleum are the current primary energy sources in the U.S.[87] but have a much lower energy density. Burning local biomass fuels supplies household energy needs (cooking fires, oil lamps, etc.) worldwide.

Thermal power of nuclear fission reactors

The density of thermal energy contained in the core of a light water reactor (PWR or BWR) of typically 1 GWe (1,000 MW electrical corresponding to ≈3,000 MW thermal) is in the range of 10 to 100 MW of thermal energy per cubic meter of cooling water depending on the location considered in the system (the core itself (≈30 m^3), the reactor pressure vessel (≈50 m^3), or the whole primary circuit (≈300 m^3)). This represents a considerable density of energy which requires under all circumstances a continuous water flow at high velocity in order to be able to remove the heat from the core, even after an emergency shutdown of the reactor. The incapacity to cool the cores of three boiling water reactors (BWR) at Fukushima in 2011 after the tsunami and the resulting loss of the external electrical power and of the cold source was the cause of the meltdown of the three cores in only a few hours, even though the three reactors were correctly shut down just after the Tōhoku earthquake. This extremely high power density distinguishes nuclear power plants (NPP's) from any thermal power plants (burning coal, fuel or gas) or any chemical plants and explains the large redundancy required to permanently control the neutron reactivity and to remove the residual heat from the core of NPP's.

Energy density of electric and magnetic fields

Electric and magnetic fields store energy. The (volumetric) energy density is given by

$$u = \frac{\varepsilon}{2}\mathbf{E}^2 + \frac{1}{2\mu}\mathbf{B}^2$$

where **E** is the electric field, **B** is the magnetic field, and ε and μ are the permittivity and permeability of the surroundings respectively. The solution will be (in SI units) in joules per cubic metre. In the context of magnetohydrodynamics, the physics of conductive fluids, the magnetic energy density behaves like an additional pressure that adds to the gas pressure of a plasma.

In ideal (linear and nondispersive) substances, the energy density (in SI units) is

$$u = \frac{1}{2}(\mathbf{E}\cdot\mathbf{D} + \mathbf{H}\cdot\mathbf{B})$$

where **D** is the electric displacement field and **H** is the magnetizing field.

In the case of absence of magnetic fields, by exploiting Fröhlich's relationships it is also possible to extend these equations to anisotropic and nonlinear dielectrics, as well as to calculate the correlated Helmholtz free energy and entropy densities.[88]

When a pulsed laser impacts a surface, the radiant exposure, i.e. the energy deposited per unit of surface, may be called **energy density** or fluence.[89]

See also

- Energy content of biofuel
- Energy density Extended Reference Table
- Figure of merit
- Food energy
- Heat of combustion
- High-energy-density matter
- Power density and specifically
- Power-to-weight ratio
- Rechargeable battery

- Solid-state battery
- Specific energy
- Specific impulse

Energy portal

Footnotes

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