Energy density

From Wikipedia, the free encyclopedia

Energy density	
SI unit	J/m^3
In SI base units	$kg \cdot m^{-1} s^{-2}$
Derivations from other quantities	U = E/V

Energy density is the amount of energy stored in a given system or region of space per unit volume or mass, though the latter is more accurately termed specific energy. Often only the *useful* or extractable energy is measured, which is to say that chemically 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 the pressures described in the next paragraph.

Energy per unit volume has the same physical units as pressure, and in many circumstances is a synonym: for example, the energy density of a magnetic field may be expressed as (and behaves as) a physical pressure, and the energy required to compress a compressed gas a little more may be determined by multiplying the difference between the gas pressure and the external pressure by the change in volume. In short, pressure is a measure of the enthalpy per unit volume of a system. A pressure gradient has a potential to perform work on the surroundings by converting enthalpy until equilibrium is reached.

Contents

- 1 Introduction to energy density
    - 1.1 Energy densities of common energy storage materials
- 2 Energy density in energy storage and in fuel
    - 2.1 Energy densities ignoring external components
- 3 Energy density of electric and magnetic fields
- 4 See also
- 5 Footnotes
- 6 External links
    - 6.1 Density data
    - 6.2 Energy storage
    - 6.3 Books

Introduction to energy density

There are many 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.

Chemical reactions are used by animals to derive energy from food, and by automobiles to derive energy from gasoline. Electrochemical reactions are used by most mobile devices such as laptop computers and mobile phones to release the energy from batteries.

Energy densities of common energy storage materials

The following is a list of the thermal energy densities of commonly used or well-known energy storage materials; it doesn't include uncommon or experimental materials. Note that this list does not consider the mass of reactants commonly available such as the oxygen required for combustion or the energy efficiency in use.

The following unit conversions may be helpful when considering the data in the table: 1 MJ ≈ 0.28 kWh ≈ 0.37 HPh.

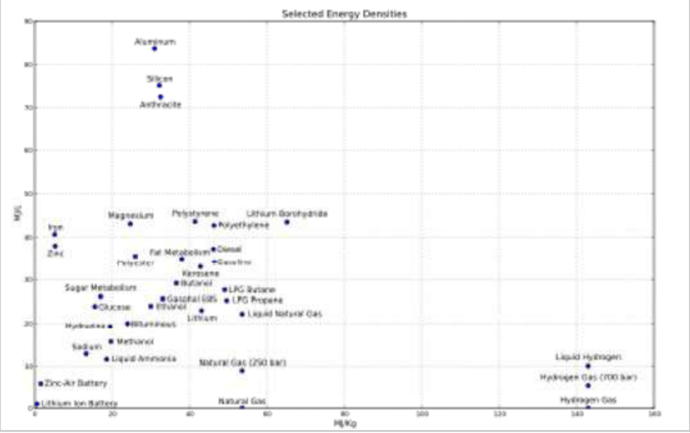
Storage material	Energy type	Specific energy (MJ/kg)	Energy density (MJ/L)	Direct uses
Uranium (in breeder)	Nuclear fission	80,620,000[2]	1,539,842,000	Electric power plants (nuclear reactors), industrial process heat (to drive chemical reactions, water desalination, etc.)
Thorium (in breeder)	Nuclear fission	79,420,000[2]	929,214,000	Electric power plants (nuclear reactors), industrial process heat
Plutonium	Nuclear decay	2,239,000	?	Thermal-Electric Generator (Space)
Tritium	Nuclear decay	583,529	?	Electric power plants (nuclear reactors), industrial process heat
Hydrogen (compressed at 700 bar)	Chemical	142	5.6	Rocket engines, automotive engines, grid storage & conversion
Methane or natural gas	Chemical	55.5	0.0364	Cooking, home heating, automotive engines, rocket engines
Liquified Natural Gas (LNG)	Chemical	53.6	22.2	mostly methane with a variable amount of ethane (so numbers are approximate), liquified for transport by ship
Diesel / Fuel oil	Chemical	48	35.8	Automotive engines, power plants[3]
LPG (including Propane / Butane)	Chemical	46.4	26	Cooking, home heating, automotive engines, lighter fluid
Jet fuel (Kerosene)	Chemical	46	37.4	Aircraft
Gasoline (petrol)	Chemical	46.4	34.2	Automotive engines, power plants[4]
Fat (animal/vegetable)	Chemical	37	34	Human/animal nutrition
Dimethyl ether (DME)	Chemical	28.8[5]	19.3	Diesel cycle, Gas turbine, LPG applications
Ethanol fuel (E100)	Chemical	26.4	20.9	Flex-fuel, racing, stoves, lighting
Coal, anthracite	Chemical	26-33	34-43	Electric power plants, home heating
Coal, bituminous	Chemical	24-35	26-49	Electric power plants, home heating
Methanol fuel (M100)	Chemical	19.7	15.6	Racing, model engines, safety
Carbohydrates (including sugars)	Chemical	17		Human/animal nutrition
Protein	Chemical	16.8		Human/animal nutrition
Wood	Chemical	16.2	13	Heating, outdoor cooking
TNT	Chemical	4.6		Explosives
Gunpowder	Chemical	3		Explosives
Lithium battery (non-rechargeable)	Electrochemical	1.8	4.32	Portable electronic devices, flashlights
Lithium-ion battery	Electrochemical	0.36[6]–0.875[7]	0.9–2.63	Laptop computers, mobile devices, electric vehicles
Alkaline battery	Electrochemical	0.5[8]	1.3[8]	Portable electronic devices, flashlights

Storage material	Energy type	Specific energy (MJ/kg)	Energy density (MJ/L)	Direct uses
Nickel-metal hydride battery	Electrochemical	0.288	0.504–1.08	Portable electronic devices, flashlights
Lead-acid battery	Electrochemical	0.17	0.56	Automotive engine ignition
Supercapacitor (EDLC)	Electrical (electrostatic)	0.01-0.036 [9][10][11][12][13][14]	0.06-0.05 [9][10][11][12][13][14]	Electronic circuits
Supercapacitor (Pseudo)	Electrochemical	0.031[15]	0.046[15]	Electronic circuits
Electrostatic capacitor	Electrical (electrostatic)	0.00001-0.0002 [16]	0.00001-0.001 [16][17][18]	Electronic circuits

Energy capacities of common storage forms

Storage device	Energy type	Energy content (MJ)	Typical mass	Specific energy (MJ/kg)	W × H × D (mm)	Uses
Automotive lead-acid battery	Electrochemical	2.6	15 kg	0.17	230 × 180 × 185	Automotive starter motor and accessories
Ham and Cheese Sandwich[19]	Chemical	1.47	145 grams	10.13	100 × 100 × 28	Human nutrition
Alkaline AA battery	Electrochemical	0.0154	23 g	0.669	14.5 × 50.5 × 14.5	Portable electronic equipment, flashlights
Lithium-ion battery [20]	Electrochemical	0.0129	20 g	0.645	54.2 × 33.8 × 5.8	Mobile phones

Energy density in energy storage and in fuel



Selected energy densities plot[21][22][23][24][25][26][27][28]

In energy storage applications the energy density relates the mass of 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. 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.

The greatest energy source by far is mass 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 (.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 (2016), 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,[29] though the full potential of this source can only be realised through breeder reactors, which are, apart from the BN-600 reactor, not yet used commercially.[30] Coal, gas, and petroleum are the current primary energy sources in the U.S.[31] but have a much lower energy density. Burning local biomass fuels supplies household energy needs (cooking fires, oil lamps, etc.) worldwide.

Energy density (how much energy you can carry) does not tell you about energy conversion efficiency (net output per input) or embodied energy (what the energy output costs to provide, as harvesting, refining, distributing, and dealing with pollution all use energy). Like any process occurring on a large scale, intensive energy use impacts the world. For example, climate change, nuclear waste storage, and deforestation may be some of the consequences of supplying our growing energy demands from hydrocarbon fuels, nuclear fission, or biomass.

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 we pull it out. To maximize both specific energy and energy density, one can compute the specific energy density of a substance by multiplying the two values together, where the higher the number, the better the substance is at storing energy efficiently.

Gravimetric and volumetric energy density of some fuels and storage technologies (modified from the Gasoline article):

> Note: 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.
> Note: Also it is important to realise that generally the density values for chemical fuels do not include the weight of oxygen required for combustion. This is typically two oxygen atoms per carbon atom, and one per two hydrogen atoms. The atomic weight of carbon and oxygen are similar, while hydrogen is much lighter than oxygen. Figures are presented 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 already include their own oxidiser (such as gunpowder and TNT), where the mass of the oxidiser in effect adds dead 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.

Energy densities ignoring external components

This table lists energy densities of systems that require external components, such as oxidisers or a heat sink or source. These figures do not take into account the mass and volume of the required components as they are assumed to be freely available and present in the atmosphere. Such systems cannot be compared with self-contained systems. These values may not be computed at the same reference conditions. Most of them seem to be higher heating value (HHV).

Energy densities of energy media

Storage type	Specific energy (MJ/kg)	Energy density (MJ/L)	Peak recovery efficiency %	Practical recovery efficiency %
Antimatter	9×10^{10} = 1*c^2 (assuming c is in m/s)	Density would depend on the form the antimatter takes	100	
Hydrogen, liquid[32]	141.86	8.491		
Hydrogen, at 690 bar and 15° C[32]	141.86	4.5		
Hydrogen, gas[32]	141.86	0.01005		
Diborane[33]	78.2			
Beryllium	67.6	125.1		
Lithium borohydride	65.2	43.4		
Boron[34]	58.9	137.8		
Methane (1.013 bar, 15 °C)	55.6	0.0378		
Natural gas	53.6[35]	0.0364		
LNG (NG at −160 °C)	53.6[35]	22.2		
CNG (NG compressed to 250 bar/~3,600 psi)	53.6[35]	9		
LPG propane[4]	49.6	25.3		
LPG butane[4]	49.1	27.7		
Gasoline (petrol)[4]	46.4	34.2		
Polypropylene plastic	46.4[36]	41.7		
Polyethylene plastic	46.3[36]	42.6		
Crude oil (according to the definition of ton of oil equivalent)	46.3	37[35]		
Residential heating oil[4]	46.2	37.3		
Diesel fuel[4]	45.6	38.6		
100LL Avgas	44.0[37]	31.59		
Gasohol E10 (10% ethanol 90% gasoline by volume)	43.54	33.18		
Lithium	43.1	23.0		
Jet A aviation fuel[38]/kerosene	42.8	33		
Biodiesel oil (vegetable oil)	42.20	33		
DMF (2,5-dimethylfuran)	42[39]	37.8		
Polystyrene plastic	41.4[36]	43.5		
Body fat metabolism	38	35	22[40]	
Butanol	36.6	29.2		
Storage type	**Energy density by mass (MJ/kg)**	**Energy density by volume (MJ/L)**	**Peak recovery efficiency %**	**Practical recovery efficiency %**

Storage type	Specific energy (MJ/kg)	Energy density (MJ/L)	Peak recovery efficiency %	Practical recovery efficiency %
Gasohol E85 (85% ethanol 15% gasoline by volume)	33.1	25.65		
Graphite	32.7	72.9		
Coal, anthracite[41]	26-33	34-43	36	
Silicon[42]	32.2	75.1		
Aluminum	31.0	83.8		
Ethanol	30	24		
Polyester plastic	26.0[36]	35.6		
Magnesium	24.7	43.0		
Coal, bituminous[41]	24-35	26-49		
PET plastic	23.5 (impure)[43]			
Methanol	19.7	15.6		
Hydrazine (toxic) combusted to N_2+H_2O	19.5	19.3		
Liquid ammonia (combusted to N_2+H_2O)	18.6	11.5		
PVC plastic (improper combustion toxic)	18.0[36]	25.2		
Wood[44]	18.0			
Peat briquette[45]	17.7			
Sugars, carbohydrates, and protein metabolism	17	26.2 (dextrose)	22[46]	
Calcium	15.9	24.6		
Glucose	15.55	23.9		
Dry cow dung and cameldung	15.5[47]			
Coal, lignite	10-20			
Sodium (burned to wet sodium hydroxide)	13.3	12.8		
Sod peat	12.8			
Nitromethane	11.3			
Sulfur (burned to sulfur dioxide)[48]	9.23	19.11		
Sodium (burned to dry sodium oxide)	9.1	8.8		
Battery, lithium-air rechargeable	9.0[49]			
Household waste	8.0[50]			
Zinc	5.3	38.0		
Storage type	**Energy density by mass (MJ/kg)**	**Energy density by volume (MJ/L)**	**Peak recovery efficiency %**	**Practical recovery efficiency %**

Storage type	Specific energy (MJ/kg)	Energy density (MJ/L)	Peak recovery efficiency %	Practical recovery efficiency %
Iron (burned to iron(III) oxide)	5.2	40.68		
Teflon plastic (combustion toxic, but flame retardant)	5.1	11.2		
Iron (burned to iron(II) oxide)	4.9	38.2		
ANFO	3.7			
Battery, zinc-air[51]	1.59	6.02		
Liquid nitrogen	0.77[52]	0.62		
Compressed air at 300 bar (potential energy)	0.5	0.2		>50%
Latent heat of fusion of ice (thermal)	0.335	0.335		
Water at 100 m dam height (potential energy)	0.001	0.001		85-90%
Storage type	**Energy density by mass (MJ/kg)**	**Energy density by volume (MJ/L)**	**Peak recovery efficiency %**	**Practical recovery efficiency %**

Divide joule metre^{-3} by 10^9 to get MJ/L. Divide MJ/L by 3.6 to get kWh/L.

Energy density of electric and magnetic fields

Electric and magnetic fields store energy. In a vacuum, the (volumetric) energy density (in SI units) is given by

$$U = \frac{\varepsilon_0}{2}\mathbf{E}^2 + \frac{1}{2\mu_0}\mathbf{B}^2$$

where **E** is the electric field and **B** is the magnetic field. The solution will be 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 normal (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.

See also

- Energy density Extended Reference Table
- High Energy Density Matter
- Power density and specifically
  - Power-to-weight ratio
- Orders of magnitude (specific energy)
- Figure of merit
- Energy content of biofuel
- Heat of combustion

- Heating value
- Rechargeable battery
- Specific impulse
- Food energy

Footnotes

1. "The Two Classes of SI Units and the SI Prefixes". *NIST Guide to the SI*. Retrieved 2012-01-25.
2. "Computing the energy density of nuclear fuel". whatisnuclear.com. Retrieved 2014-04-17.
3. Alternative Fuels Datacenter. "Fuel Properties Comparison" (PDF). *energy.gov*. Retrieved 9 September 2014.
4. IOR Energy. List of common conversion factors (Engineering conversion factors) (https://web.archive.org/web/20100924142555/http://www.ior.com.au/ecflist.html). Retrieved 2008-10-05.
5. "F3 (Fossil Free Fuels) Centre - the Swedish Knowledge Centre for Renewable Transportation - Dimethyl Ether". October 2015.
6. "Overview of lithium ion batteries" (PDF). Panasonic. Jan 2007. Archived (PDF) from the original on Nov 7, 2011.
7. "Panasonic NCR18650B" (PDF).
8. "Energizer EN91 AA alkaline battery datasheet" (PDF). Retrieved 2016-01-10.
9. "Maxwell supercapacitor comparison" (PDF). Retrieved 2016-01-10.
10. "Nesscap ESHSP series supercapacitor datasheet" (PDF). Retrieved 2016-01-10.
11. "Cooper PowerStor XL60 series supercapacitor datasheet" (PDF). Retrieved 2016-01-10.
12. "Kemet S301 series supercapacitor datasheet" (PDF). Retrieved 2016-01-10.
13. "Nichicon JJD series supercapatcitor datasheet" (PDF). Retrieved 2016-01-10.
14. "skelcap High Energy Ultracapacitor" (PDF). *Skeleton Technologies*. Retrieved 13 October 2015.
15. "Nesscap PSHLR series pseudocapacitor datasheet" (PDF). Retrieved 2016-01-10.
16. "Vishay STE series tantalum capacitors datasheet" (PDF). Retrieved 2016-01-10.
17. "nichicon TVX aluminum electrolytic capacitors datasheet" (PDF). Retrieved 2016-01-10.
18. "nichicon LGU aluminum electrolytic capacitors datasheet" (PDF). Retrieved 2016-01-10.
19. "Calories in Ham And Cheese Sandwich". Retrieved 22 May 2014.
20. "Nokia BL-5C datasheet" (PDF).
21. "Green Power Lacks the Energy Density to Run Our Civilization, LENR Might Provide It." LENR & Cold Fusion News. N.p., 24 July 2014. Web.
22. Jeong, Goojin, et al. "Nanotechnology enabled rechargeable Li–SO 2 batteries: another approach towards post-lithium-ion battery systems." Energy & Environmental Science 8.11 (2015): 3173-3180.
23. "Panasonic Develops New Higher-Capacity 18650 Li-Ion Cells." Green Car Congress. N.p., 25 Dec. 2009. Web.
24. Stura, Enrico, and Claudio Nicolini. "New nanomaterials for light weight lithium batteries." Analytica chimica acta 568.1 (2006): 57-64.
25. "Energy Density of Coal - Hypertextbook." The Energy Density of Coal. N.p., 2003. Web.
26. "Heat Values of Various Fuels - World Nuclear Association." World Nuclear Association. N.p., Sept. 2016. Web.
27. "Overview of Storage Development DOE Hydrogen Program." Office of Energy Efficiency & Renewable Energy. N.p., May 2000. Web.
28. Wong, Kaufui Vincent and Dia, Sarah, "Nanotechnology in Batteries." ASME J. Energy Resour. Technol. 2016.
29. "Supply of Uranium". world-nuclear.org. 2014-10-08. Retrieved 2015-06-13.
30. "Facts from Cohen". Formal.stanford.edu. 2007-01-26. Retrieved 2010-05-07.
31. "U.S. Energy Information Administration (EIA) - Annual Energy Review". Eia.doe.gov. 2009-06-26. Archived from the original on 2010-05-06. Retrieved 2010-05-07.
32. College of the Desert, "Module 1, Hydrogen Properties", Revision 0, December 2001 Hydrogen Properties (http://energy.gov/sites/prod/files/2014/03/f12/fcm01r0.pdf). Retrieved 2014-06-08.
33. Greenwood, Norman N.; Earnshaw, Alan (1997), Chemistry of the Elements (2nd ed) (page 164)
34. "Boron: A Better Energy Carrier than Hydrogen? (28 February 2009)". Eagle.ca. Retrieved 2010-05-07.
35. Envestra Limited. Natural Gas (http://www.natural-gas.com.au/about/references.html). Retrieved 2008-10-05.
36. Paul A. Kittle, Ph.D. "ALTERNATE DAILY COVER MATERIALS AND SUBTITLE D - THE SELECTION TECHNIQUE" (PDF). Retrieved 2012-01-25.
37. "537.PDF" (PDF). June 1993. Retrieved 2012-01-25.
38. "Energy Density of Aviation Fuel". Hypertextbook.com. Retrieved 2010-05-07.
39. Nature. "Production of dimethylfuran for liquid fuels from biomass-derived carbohydrates : Abstract". Nature. Retrieved 2010-05-07.
40. Justin Lemire-Elmore (2004-04-13). "The Energy Cost of Electric and Human-Powered Bicycles" (PDF). p. 5. Retrieved 2009-02-26. "properly trained athlete will have efficiencies of 22 to 26%"
41. Fisher, Juliya (2003). "Energy Density of Coal". *The Physics Factbook*. Retrieved 2006-08-25.
42. Silicon as an intermediary between renewable energy and hydrogen (https://web.archive.org/web/20090327030002/http://www.dbresearch.com/PROD/DBR_INTERNET_EN-PROD/PROD0000000000079095.pdf)

43. "Elite_bloc.indd" (PDF). Retrieved 2010-05-07.
44. "Biomass Energy Foundation: Fuel Densities". Woodgas.com. Archived from the original on 2010-01-10. Retrieved 2010-05-07.
45. "Bord na Mona, Peat for Energy" (PDF). Bnm.ie. Archived from the original (PDF) on 2007-11-19. Retrieved 2012-01-25.
46. Justin Lemire-Elmor (April 13, 2004). "The Energy Cost of Electric and Human-Powered Bicycle" (PDF). Retrieved 2012-01-25.
47. "energy buffers". Home.hccnet.nl. Retrieved 2010-05-07.
48. Anne Wignall and Terry Wales. Chemistry 12 Workbook, page 138 (http://www.wignallandwales.co.nz/Chem-12-WB/Sample-chapter.pdf). Pearson Education NZ ISBN 978-0-582-54974-6
49. Mitchell, Robert R.; Betar M. Gallant; Carl V. Thompson; Yang Shao-Horn (2011). "All-carbon-nanofiber electrodes for high-energy rechargeable Li–O2 batteries". *Energy & Environmental Science*. **4**: 2952–2958. doi:10.1039/C1EE01496J.
50. David E. Dirkse. energy buffers (http://www.davdata.nl/math/energy.html). "household waste 8..11 MJ/kg"
51. "Technical bulletin on Zinc-air batteries". Duracell. Archived from the original on 2009-01-27. Retrieved 2009-04-21.
52. C. Knowlen, A.T. Mattick, A.P. Bruckner and A. Hertzberg, "High Efficiency Conversion Systems for Liquid Nitrogen Automobiles" (https://web.archive.org/web/20081217082655/http://www.aa.washington.edu/AERP/cryocar/Papers/sae98.pdf), Society of Automotive Engineers Inc, 1988.

External links

Density data

- ^ "Aircraft Fuels." *Energy, Technology and the Environment* Ed. Attilio Bisio. Vol. 1. New York: John Wiley and Sons, Inc., 1995. 257–259
- "Fuels of the Future for Cars and Trucks (http://www1.eere.energy.gov/vehiclesandfuels/pdfs/deer_2002/session1/2002_deer_eberhardt.pdf)" - Dr. James J. Eberhardt - Energy Efficiency and Renewable Energy, U.S. Department of Energy - 2002 Diesel Engine Emissions Reduction (DEER) Workshop San Diego, California - August 25–29, 2002

Energy storage

- energy fundamentals (http://www.tinaja.com/h2gas01.shtml)

Books

- *The Inflationary Universe: The Quest for a New Theory of Cosmic Origins* by Alan H. Guth (1998) ISBN 0-201-32840-2
- *Cosmological Inflation and Large-Scale Structure* by Andrew R. Liddle, David H. Lyth (2000) ISBN 0-521-57598-2
- Richard Becker, "Electromagnetic Fields and Interactions", Dover Publications Inc., 1964

Retrieved from "https://en.wikipedia.org/w/index.php?title=Energy_density&oldid=756450784#Energy_densities_of_common_energy_storage_materials"

Categories: Energy | Density
