Supplemental Material A1

Table A1.1
Performance data of historical storage devices in energy storage

Year	Lead-Acid			NiCd			Capacitor		
	Wh/Liter	Wh/kg	*Wh/$	Wh/Liter	Wh/kg	Wh/$	Wh/Liter	Wh/kg	**Wh/$
1884	4.46 [22]	4.13[22]	-	-	-	-	-	-	-
1890	-	-	-	-	-	-	-	-	-
1901	9.40 [11]	8.70[1]	-	-	-	-	-	-	-
1911	13.18 [10]	12.20[1]	-	-	-	-	-	-	-
1914	19.44 [10]	18.00[1]	-	-	-	-	-	-	-
1920	17.82 [10]	16.50[1]	-	-	-	-	-	-	-
1935	-	-	-	-	-	-	-	-	-
1937	20.20 [10]	18.70[1]	-	-	-	-	-	-	-
1940	-	-	-	-	-	-	-	-	-
1941	-	-	-	-	-	-	7.06E-07[31]	-	-
1942	-	-	-	-	-	-	-	-	-
1943	24.84 [10]	23.00[1]	-	-	-		4.68E-05[31]	-	-
1945	13.50 [10]	12.50[1]	-	-	-	-	-	-	-
1946	-	-	-	-	-	-	1.94E-2[31]	-	-
1947	-	-	-	-	-	-	-	-	-
1950	29.16 [10]	27.00[1]	3.94	-	-	-	2.59E-04[31, 38]	-	-
1952	-	-	-	32.13[23]	14.64[23]	-	-	-	-
1955	-	-	-	-	-	-	-	-	-
1956	-	-	-	-	-	-	2.14E-03[31, 29]	-	-
1960	-	-	-	-	-	-	-	-	-
1962	-	-	-	-	-	-	-	2.78E-03[33]	-
1965	-	-	-	-	-	-	-	-	-

Year	Wh/Liter	Wh/kg	*Wh/$	Wh/Liter	Wh/kg	Wh/$	Wh/Liter	Wh/kg	**Wh/$
1968	-	29.10[1]	4.76	-	-	-	-	9.72E-03 [33]	-
1970	-	-	-	-	-	-	-	-	-
1972	-	-	-	-	-	-	-	-	-
1973	-	-	-	-	-	-	-	0.021[33]	-
1975	-	-	-	58.78[21]	24.86[21]	-	-	-	-
1977	-	-	-	-	-	-	-	0.042[33]	-
1978	46.00 [3, 13]	32.60[1]	5.65	-	-	-	-	-	-
1979	46.00 [3, 13]	18.00[3]	2.77	-	-	-	-	-	-
1980	48.00 [3, 13]	18.00[3]	2.92	-	-	-	2.50E-03[37]	-	-
1981	52.00 [3, 13]	34.00[1]	5.80	-	-	-	-	-	-
1982	52.80 [3, 13]	21.00[3]	3.94	-	-	-	-	-	-
1983	57.00 [3, 13]	21.60[3]	4.55	-	-	-	-	0.056[33]	-
1984	64.00 [3, 13]	23.20[3]	5.17	-	-	-	-	-	-
1985	67.00 [3, 13]	25.00[3]	5.86	-	-	-	-	0.097[33]	0.0017
1986	-	30.00[3]	7.15	-	-	-	1.94E-1[39]	-	
1987	-	30.80[3]	6.98	-	-	-	-	-	-
1988	-	-	-	-	-	-	-	-	-
1989	69.59[20, 13]	25.64[2]	6.11	-	-	-	-	-	-
1990	-	-	-	-	55.00[5, 7]	-	2.78E-2[37]	0.194[33]	0.0045
1991	-	-	-	-	-	-	2.50E-1[39]	-	-
1992	-	-	-	-	-	-	-	0.417[33]	0.0106
1993	80.00 [15, 12, 13]	35.00[15]	10.16	-	-	-	-	-	-
1994	70.00[16, 13]	35.00[16]	10.22	-	58.00[5, 7]	-	-	-	-
1995	80.00[16, 13]	40.00[16]	11.25[14]	94[24]	30.0024		2.78E-1[39]	0.694[33]	0.0189
1996	-	-	-	-	60.00[5]	-	-	-	-
1997	-	-	-	-		-	-	-	-

Year	Wh/Liter	Wh/kg	*Wh/$	Wh/Liter	Wh/kg	Wh/$	Wh/Liter	Wh/kg	**Wh/$
1998	-	50.00[2]	14.02	-	62.00[5]	-	1.11E-1[37]	-	-
1999	70.00[17]	35.00[17]	9.92	-		-	2.22E-1[39]	-	-
1999	-	-	-	-	-	-	3.61E-1[37]	-	-
2000	-	-	-	-	65.00[5]	-	3.06E-1[37]	-	-
2001	-	-	-	-	-	-	-	-	-
2002	164.00[2]	80.00[19]	23.86	-	65.00[5]	-	-	0.417[37]	0.0122
2003	-	-	-	150[19]	45.00[5]	-	-	-	-
2004	-	-	-	-	68.00[5]	-	-	1.208[32]	0.0667[32]
2005	-	-	-	-	-	-	-	2.66[40]	0.1709[40]

Table A1.1 (*continued*)

Year	Li-Polymer			FlyWheel			NiMH			Li-ion		
	Wh/Liter	Wh/kg	Wh/$	Wh/Liter	Wh/kg	Wh/$	Wh/Liter	Wh/kg	Wh/$	Wh/Liter	Wh/kg	Wh/$
1975	-	-	-	-	5.6 [9]	-	-	-	-	-	-	-
1977	-	-	-	-	18 [9]	-	-	-	-	-	-	-
1980	-	-	-	-	-	-	-	-	-	-	-	-
1983	-	-	-	-	-	-	-	-	-	-	-	-
1985	-	-	-	-	-	-	-	-	-	-	-	-
1986	-	-	-	-	13.8 [26]	-	-	-	-	130.00[8]	73[4]	-
1987	-	-	-	-	-	-	-	-	-	175.0[18]	63[4]	-
1988	-	-	-	-	-	-	-	-	-	190.0[18]	85[4]	-
1989	-	-	-	-	-	-	-	-	-	225.0[18]	100[4]	-
1990	-	-	-	-	-	-	-	65.00[5,7]	-	236.0[18]	99[4]	-
1991	-	-	-	-	35 [9]	-	-	-	-	-	-	-
1992	-	-	-	-	-	-	200.00[6]	-	-	214.0[18]	88[4]	-
1993	-	-	-	-	-	-	-	-	-	240.0[18]	100[4]	-
1994	-	-	-	-	-	-	210.00[6]	80.00[5,7]	-	280.0[18]	110 [4, 14]	-
1995	-	-	1.67[14]	-	-	-	200.00[6]	80.00[5,7]	-	310.0[18]	-	-

Year	Wh/Liter	Wh/kg	Wh/$	Wh/Liter	Wh/kg	Wh/$	Wh/Liter	Wh/kg	Wh/$	Wh/Liter	Wh/kg	Wh/$
1996	-	125 [5]	-	-	50 [25]	-	250.00[6]	85.00[5]	-	-	125 [5]	-
1997	-	-	-	-	67 [10]	-	-	-	-	-	-	-
1998	265 [8]	140 [5]	-	-	-	-	300.00[6]	88.00[5]	-	390.0[18]	130 [5]	-
1999	-	-	-	-	-	-	-	-	-	-	-	-
2000	330 [8]	150 [5]	1.43[8]	-	82 [28]	-	340.00[6]	95.00[5]	0.27[8]	420.00[8]	140 [5]	0.63[8]
2001	-	-	1.67[8]	-	-	-	-	-	0.43[8]	-	-	0.93[8]
2002	-	170 [5]	1.82[8]	-	-	-	-	98.00[5]	0.59[8]	-	145 [5]	1.05[8]
2003	400 [8]	-	-	-	116[28, 27]	-	-	-	-	-	-	-
2004	-	190 [5]	-	-	-	-	-	101.00[5]	-	-	1505	-
2005	-	-	-	-	-	-	-	-	1.00[40]	-	-	0.83[40]

Superscript numbers represent the following references:

-: Not Available

*: Estimation value. Theses values have been estimated with data of Wh/kg, Wh/$ at 1995, and Producer Price Index from 1950 to 2005

**: Estimation value. Theses values have been estimated with data of Wh/kg, Wh/$ at 2004 and 2005, and Producer Price Index (industrial capacitor) from 1985 to 2005

A1.1. Alvini, Salkind, Batteries for underwater propulsion, proceeding of symposium on history of battery technology, 1987
A1.2. Reversible (Unitized) PEM Fuel Cell Devices, Portable Fuel Cells Conference, 1999,Lucerne, Switzerland
A1.3. Kizawa, A, Recent new designs and new technologies of lead/acid batteries in Japan, Journal of power resource, Vol. 31, 1990, 379-382
A1.4. Brandt, K., Historical development of secondary lithium batteries, Solid state ionic 69, 1994, 173-183
A1.5. End User Perspective – Industrial Consumer Electronics Power, Fuel Cell Portable Power Workshop, Motorola Labs
A1.6. Powers, R.A., Advances in Sealed Nickel Cadmium and Nickel Metal Hydride Cells, Battery Conference on Applications and Advances, 2000. The Fifteenth Annual , 11-14 Jan. 2000 pp 95-96
A1.7. Powers, R.A., Advances and Trends in Primary and Small Secondary Batteries, IEEE AES Systems Magazine, April 1994 pp32-36
A1.8. Morrison, David G., Li-ion Batteries Reach for higher performance, Electronic Design, Mach 18, 2002 pg 59
A1.9. Hall, Christopher D., Integrated spacecraft power and attitude control system using flywheels, AFIT/ENT/TR-000,Air Force Institute of technology, technical report, 1997
A1.10. Bitterly, J.G., Flywheel technology Past, Present, and 21st century projections, IECEC-97 proceeding of the 32 rd intersociety Energy Conversion Engineering Conference, 1997
A1.11. A standard battery, Physical review (series 1, 1908)
A1.12. Joseph P. Martino, Technological forecasting for decision Making, McGRAW, 1983
A1.13. P.T. Moseley, Research results from the Advanced Lead-Acid Battery Consortium point the way to longer life and higher specific energy for lead/acid electric-vehicle batteries, Journal of Power Sources 73, pp 122-126, 1998
A1.14. Oman, H.; Morchin, W. C.; Jamerson, F. E., Electric-bicycle propulsion power, WESCON/'95. Conference record. Microelectronics, Communications Technology Producing Quality Products Mobile and Portable Power Emerging Technologies, 7-9 Nov. 1995 Page(s):555
A1.15. Henry Oman, 9th Annual Battery Conference on Advances and Aplications,IEEE Aerospace and Electronic system Magazine, Volume: 9 Issue: 4 Date: Apr 1994
A1.16. Powers, A.R., Batteries for low power electronics, Proceedings of the IEEE Volume 83, Issue 4, April 1995 Page(s):687 - 693
A1.17. Riezenman, M.J., Spectrum, IEEE, Volume 32, Issue 5, May 1995 Page(s):51 - 56
A1.18. Sieminski, D., Primary zinc-air for portable applications, Battery Conference on Applications and Advances, 1999. The Fourteenth Annual, 12-15 Jan. 1999 Page(s):209 - 213

A1.19. Szymborski, J, Lead-acid batteries for use in submarine applications, Autonomous Underwater Vehicles, 2002. Proceedings of the 2002, Workshop on20-21 June 2002 Page(s):11 - 17
A1.20. Tsubota, Masaharu, Development of lead/acid batteries for photovoltaic power systems, Journal of Power Sources, Volume 35, Issue 4, September 1991, Pages 355-358
A1.21. Artjur J. Catotti, Nickel-cadmium Battery Application Engineering Handbook, General Electric, 1975
A1.22. Warwick, P.B., How to make and use the storage battery-history, theory, Maintenance and the installation of plants, Bubuer Publishing Co., 1896
A1.23. Bergstrom, Sven., Nickel-Cadmium Batteries- Pocket type", Journal of the Electrochemical Society, Vol. 99. No. 9, pp249C, 1952
A1.24. Martin J. Milden, Stage of the art - Aerospace batteries, AIAA, Aerospace Sciences Meeting and Exhibit, 34th, Reno, NV, Jan. 15-18, 1996
A1.25. Rose, M.F., Space power technology, Twenty-Second International Power Modulator Symposium, 25-27 June 1996 Page(s):9 - 14
A1.26. Walls, W.; Weldon, Wm.; Driga, M.; Manifold, S.; Woodson, H.; Gully, J.; Improved energy density homopolar generator, IEEE Transactions on Magnetics, Volume 22, Issue 6, Nov 1986 Page(s):1793 - 1798
A1.27. Thelen, R.F.; Herbst, J.D.; Caprio, M.T.;A 2 MW flywheel for hybrid locomotive power, VTC 2003-Fall. IEEE 58th Vehicular Technology Conference, 2003. Volume 5, 6-9 Oct. 2003 Page(s):3231 - 3235 Vol.5
A1.28. Lankford, Craig B., New Developments in Power Storage Technologies, Proceedings 33rd Annual Frontiers of Power Conference, I1-17, 2000
A1.29. Wakino, K.; Tsujimoto, Y.; Morimoto, K.; Ushio, N, Technological progress in materials application for electronic capacitors in Japan - IEEE Electrical Insulation Magazine, Volume 6, Issue 3, May-June 1990 Page(s):29 - 43
A1.30. Darnell, Paul S., "History, Present Status, and Future Developments of Electronics Components, IRE Transactions on Component Parts, Volume: 5, Issue: 3, Sep 1958, On page(s): 124- 129
A1.31. Kahn, Louis, Capacitors- 1959, IRE Transactions on Publication, Volume: 6, Issue: 3, On page(s): 150- 174 Sep 1959
A1.32. Andrew Burke, The Present and Projected Performance and Cost of Double-layer and Pseudo-capacitive Ultracapacitors for Hybrid Vehicle Applications, IEEE Conference on Vehicle Power and Propulsion, 7-9 Sept. 2005 Page(s):11 pp. 356-366
A1.33. Sarjeant, W.J. and Staffiere, D.T., Capacitors as an Element in Advanced Power Sources un Power Electronics System, APEC '97 Twelfth Annual Conference Proceedings on Applied Power Electronics Conference and Exposition, 1997 pp 596-601
A1.34. J. Connolly, M. Dunn, High Energy Density Capacitor Development at ABB Power T & D., ICSD '98. Proceedings of the 1998 IEEE 6th International Conference on Conduction and Breakdown in Solid Dielectrics, 22-25 Jun 1998 On page(s): 110-113
A1.35. Low, Gordon K., A business plan for entering the ceramic capacitor industry, MIT Thesis Mgt 1985 M.S., pp 42-43

A1.36. Unite States Department of Labor, Bureau of Labor Statistics, www.bls.gov
A1.37. Fazio, Michael V., Ultracompact Pulsed Power, Proceedings of the IEEE Volume 92, Issue 7, July 2004 Page(s):1197 – 1204
A1.38. Okazaki, Kiyoshi: History of ferroelectric ceramics in Japan-glimpse of historic ferroelectric ceramic technology in Japan before 1955, ISAF '94. Proceedings of the Ninth IEEE International Symposium on Applications of Ferroelectrics, 7 Aug 1994, 10-13 (1994)
A1.39. MacDougall, F.W., Ennis, J.B., Cooper, R.A., Bates, J., and Seal, K.: High energy density pulsed power capacitors, 14th IEEE International Pulsed Power Conference, Volume 1, 15-18 June 2003 Page(s):513 – 517
A1.40. Miller, J.M. and Auer, J., Battery-Ultracapacitor Combinations: Sizing up the Benefits, Advanced Automotive Battery Conference 2006, Presentation

Example Data Reduction for Capacitors:

A Capacitor is an electronic device that can store energy between a pair of conductors as it is widely used in electrical circuits. As opposite charges accumulate on the pair of conductors of a capacitor, a voltage develops across the capacitor owing to the electric field of these charges. The farad (SI unit, F) is used to measure the amount of charge between two conductors and is shown as Equation A1.1

$$C = \frac{q}{V} = \frac{A \cdot s}{V} \qquad \text{(Equation A1.1)}$$

where C is capacitance, q is charge in coulombs, V is the voltage across the capacitor, A is current in amperes, and s time in seconds is second.

The energy stored in a capacitor can be estimated by the capacitance and the voltage in the circuit. It is equal to the amount of work required to establish the voltage across the capacitor [A1.31 and A1.37]. The energy stored is represented by following equation.

$$\mathrm{E}_{\mathrm{stored}} = \frac{1}{2}CV^2 = \frac{1}{2}\frac{A \cdot s}{V}V^2 = \frac{1}{2}VA \cdot s = \frac{1}{2}W \cdot s \qquad \text{(Equation A1.2)}$$

where C is capacitance of the capacitor, and W is power of the capacitor.

Therefore the energy stored in a capacitor is a product of power and time as shown in Equation A1.2. References 30-37 use these to calculate the performance and cost data have been collected in order to measuring the technological progress of energy storage in the table A1.1

For example, let us calculate the stored energy in a capacitor using the data of table A1.2. The capacitance of the capacitor is 0.001μF and the circuit voltage is 50 V in 1941 as shown in table A1.2. When these data are inserted into Equation A1.2, the stored energy in the capacitor is:

$$E_{stored} = \frac{1}{2}CV^2 = \frac{1}{2} \cdot (1.0E-9) \cdot 50^2 = 1.25E-6 \text{ (Joule) = 3.47E-10 (Wh)}$$

which is also shown in Table A1.2.

Table A1.2 Performance of capacitors from 1940s to 1950s [A1.31]

Year	Capacitance	Voltage	Stored Energy
	μF	V	Wh
1941	0.001	50	3.47E-10
1943	0.005	300	6.25E-8
1946	14.5	20,000	0.81
1950	0.01	200	5.56E-8
1956	7000	6	3.50E-5

Supplemental Material A2

Table A2.1 Performance data of energy transportation devices in energy transportation

Year	Voltage	Power	Transmission Distance	Powered Distance	γ	Cost per unit distance	Construction Cost*	Powered Distance per cost	Remarks
	KV	W	Km	W·Km		$/Km	$	W·Km/$	
1889	4	3.25E+04	2.25E+01	7.32E+05	0.53	2136	4.81E+04	15.2	AC [3, 14, 15]
1890	1.1	1.20E+05	2.25E+01	2.70E+06	0.54	597	1.35E+04	200.8	AC [4, 14, 15]
1892	5	1.20E+05	2.09E+01	2.51E+06	0.56	2810	5.88E+04	42.7	AC [5, 14, 15]
1897	-	7.46E+05	4.18E+01	3.12E+07	0.61	-	-	-	AC [6, 14, 15]
1897	0.07	1.40E+04	2.13E+01	2.99E+05	0.61	43	9.14E+02	326.7	AC [7, 14, 15]
1919	110	1.20E+07	1.61E+02	1.93E+09	0.89	98105	1.58E+07	122.3	AC [9, 14, 15]
1936	220	1.60E+08	5.60E+01	8.96E+09	0.71	156884	8.79E+06	1,019.9	AC [10, 14, 15]
1936	-	5.04E+03	6.50E-04	3.27E+00	-	-	-	-	Chain [16]
1936	-	6.71E+02	2.73E-03	1.83E+00	-	-	-	-	Belt [16]
1936	-	8.49E+03	4.61E-03	3.92E+01	-	-	-	-	Shaft [16]
1941	-	7.15E+03	6.50E-04	4.65E+00	-	-	-	-	Chain [17]
1941	-	6.71E+02	2.73E-03	1.83E+00	-	-	-	-	Belt [17]
1941	-	6.63E+03	4.61E-03	3.06E+01	-	-	-	-	Shaft [17]
1955	-	7.15E+03	6.50E-04	4.65E+00	-	-	-	-	Chain [18]
1955	-	1.34E+03	2.73E-03	3.66E+00	-	-	-	-	Belt [18]
1955	-	1.19E+04	3.04E-03	3.63E+01	-	-	-	-	Shaft [18]
1962	400	7.20E+08	4.70E+02	3.38E+11	1.67	666608	4.20E+08	806.0	DC[26]
1967	200	3.00E+08	4.23E+02	1.27E+11	1.31	261395	1.47E+08	862.9	DC [14, 15]
1967	-	7.15E+03	6.50E-04	4.65E+00					Chain [19]
1967	-	3.13E+03	1.96E-03	6.14E+00	-	-	-	-	Belt[19]
1968	500	1.00E+09	1.51E+02	1.51E+11	2.05	1026304	1.55E+08	974.4	AC [11, 14, 15]
1969	330	5.00E+07	4.30E+02	2.15E+10	1.74	574995	2.47E+08	87.0	AC [12, 14, 15]

1973	450	1.62E+09	8.90E+02	1.44E+12	2.24	1009857	8.40E+08	1715.7	DC[26]
1977	533	1.92E+09	1.41E+03	2.71E+12	2.64	1408169	1.47E+09	1842.5	DC[26]

Year	KV	W	Km	W·Km	γ	$/Km	$	W·Km/$	Remarks
1977	250	5.00E+08	7.49E+02	3.75E+11	2.64	660492	4.85E+08	772.5	DC[26]
1977	533	1.93E+09	1.42E+03	2.74E+12	2.64	1408169	1.48E+09	1852.1	DC [14, 15]
1978	250	9.00E+08	9.30E+02	8.37E+11	2.29	572183	4.66E+08	1797.6	DC[26]
1978	-	7.15E+03	6.50E-04	4.65E+00	-	-	-	-	Chain[20]
1978	-	3.35E+03	1.96E-03	6.58E+00	-	-	-	-	Belt[20]
1982	500	5.60E+08	1.70E+03	9.52E+11	2.55	1274076	1.62E+09	586.0	DC [14, 15]
1983	220	7.00E+07	6.99E+02	4.89E+10	2.72	599335	4.19E+08	116.8	AC[12, 14, 15]
1985	500	9.00E+08	7.20E+02	6.48E+11	2.10	1052323	7.27E+08	890.9	DC[26]
1985	400	5.00E+08	2.56E+02	1.28E+11	2.10	841859	3.34E+08	383.2	DC[26]
1986	450	6.90E+08	1.75E+02	1.21E+11	4.88	2195008	5.99E+08	201.5	DC[26]
1986	450	6.90E+08	1.75E+02	1.21E+11	4.88	2195008	5.99E+08	201.5	DC[26]
1987	500	1.20E+09	1.08E+03	1.30E+12	4.98	2489021	2.34E+09	554.2	DC[26]
1987	500	1.60E+09	7.94E+02	1.27E+12	4.98	2489021	1.98E+09	642.8	DC[26]
1987	500	1.00E+09	1.00E+03	1.00E+12	4.98	2489021	2.09E+09	478.3	DC[26]
1987	600	3.15E+09	7.85E+02	2.47E+12	4.98	2986825	2.32E+09	1065.3	DC [14, 15]
1988	-	7.60E+03	6.50E-04	4.94E+00	-	-	-	-	Chain [21]
1988	-	3.20E+03	1.96E-03	6.29E+00	-	-	-	-	Belt [21]
1988	-	1.19E+04	4.32E-03	5.15E+01	-	-	-	-	Shaft [21]
1989	364	1.60E+09	4.00E+02	6.40E+11	3.86	1405065	7.31E+08	876.0	DC[26]
1990	450	2.00E+09	1.48E+03	2.96E+12	-	-	-	-	DC [14, 15]
1990	500	1.50E+09	8.14E+02	1.22E+12	-	-	-	-	DC [14, 15]
1991	500	1.20E+09	1.05E+03	1.25E+12	-	-	-	-	DC [13, 14, 15]
1992	500	2.00E+09	9.30E+02	1.86E+12	2.97	1487019	1.20E+09	1545.9	DC[26]
1994	450	6.00E+08	2.50E+02	1.50E+11	0.57	257982	1.06E+08	1409.5	DC [14, 15]
1997	-	8.87E+03	6.50E-04	5.76E+00	-	-	-	-	Chain[22]
1997	-	3.35E+03	1.96E-03	6.58E+00	-	-	-	-	Belt[22]
1997	-	1.19E+04	4.32E-03	5.15E+01	-	-	-	-	Shaft[22]

2000	450	6.00E+08	2.60E+02	1.56E+11	1.82	821102	3.52E+08	442.9	DC[14, 15]
2000	-	8.87E+03	6.50E-04	5.76E+00	15.73	7864271	1443723032	92.5	Chain[23]

Year	**KV**	**W**	**Km**	**W·Km**	**γ**	**$/Km**	**$**	**W·Km/$**	**Remarks**
2000	-	3.35E+03	1.96E-03	6.58E+00	-	-	-	-	Belt[23]
2000	-	1.19E+04	4.32E-03	5.15E+01	-	-	-	-	Shaft[23]
2001	500	8.00E+08	1.67E+02	1.34E+11	5.76	2880339	4.81E+08	277.7	AC[13, 14, 15]
2001	400	5.00E+08	3.10E+02	1.55E+11	5.76	2304271	1.11E+09	139.1	DC [14, 15]
2001	500	1.80E+09	9.80E+02	1.76E+12	5.76	2880339	2.51E+09	702.2	DC [13, 14, 15]
2002	150	2.20E+08	1.77E+02	3.89E+10	3.69	553077	1.53E+08	255.0	DC [14, 15]
2003	500	6.00E+08	2.10E+02	1.26E+11	3.75	1875386	3.94E+08	319.9	AC [13, 14, 15]
2003	500	3.00E+09	8.90E+02	2.67E+12	3.75	1875386	1.57E+09	1701.8	DC [13, 14, 15]
2004	500	3.00E+09	9.50E+02	2.85E+12	3.82	1907731	1.58E+09	1807.5	DC [13, 14, 15]
2005	450	7.00E+08	5.80E+02	4.06E+11	3.88	1746570	1.20E+09	339.6	DC [14, 15]

Superscript numbers represent the following references:

AC: Alternating Current
DC: Direct Current
-: Not Available
*Cost: Estimated value. Inflation of the price of commodities was applied to the cost and its fluctuation in the price (2005) is also applied to the cost with the GDP deflator method.

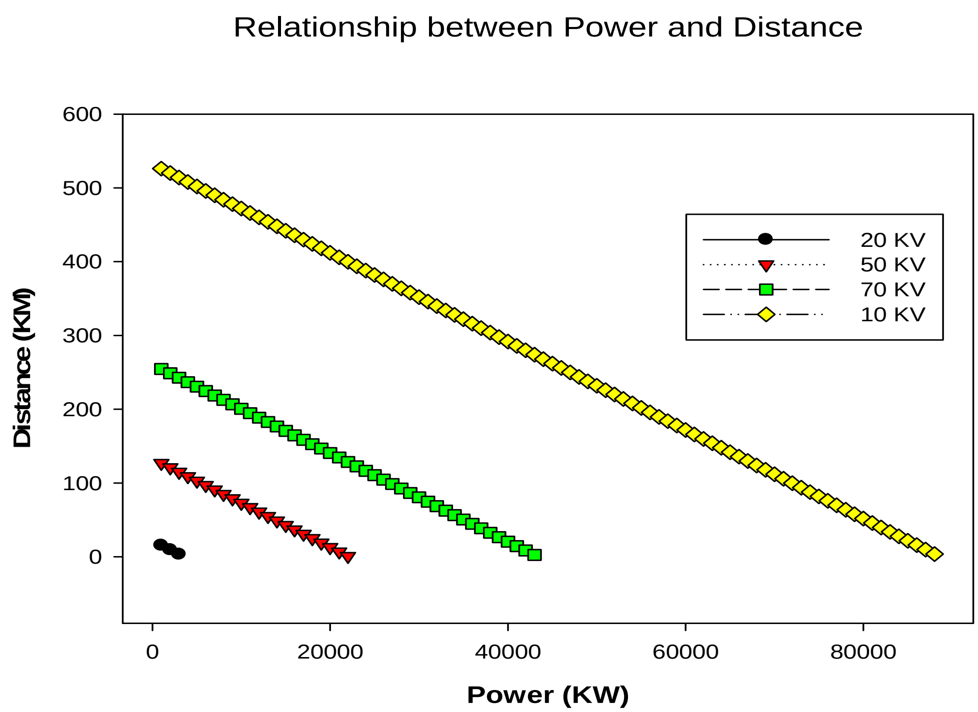
A2.1. Cotton, H., The transmission and distribution of electrical energy, London, The English Universities Press, 1937
A2.2. Aldred Still, Overhead electric power transmission -Principles and Calculation, McGraw-Hill Book, NY, 1913, pp 50-51
A2.3. Willamette Falls Heritage Foundation, see: http://willamettefalls.org/Hist/Elec
A2.4. History and reflections on the way things were, IEEE Power Engineering Review, Feb. 1997
A2.5. U.S. Department of the Interior, Bureau of Reclamation, see: http://www.usbr.gov/power/edu/history.html
A2.6. IDOL's Hydroelectric Generating Station Forsyth County, N.C., The American Society of Mechanical Engineers Carolina Section, September 7, 1984, see: http://files.asme.org/ASMEORG/Communities/History/Landmarks/5575.pdf
A2.7. Peterson, Gary: The Snoqualmie Falls Power Plant - An 1898 Milestone in Electric Power Generation. Newsletter, Twenty First Century Books, see: http://www.tfcbooks.com/articles/tac8.htm
A2.8. Energy Information Administration, see: http://www.eia.doe.gov/kids/history/timelines/electricity.html
A2.9. Southern Company, see: http://www.southernco.com/gapower/about/pdf/History.pdf
A2.10. Black, R.M., The history of electric wire and cable, Peter Peregrinus Ltd, Science Museum, London, 1983
A2.11. U.S. Department of the Interior, Bureau of Reclamation, see: http://www.usbr.gov/dataweb/html/pninter.html
A2.12. Muttik, P.K., Thanawala, H. L., and Sadullah, S. :Planning And Design Studies For The Far North Queensland Georgetown And Normanton AC Transmlsslon Scheme, International Conference on AC and DC Power Transmission, 17-20 Sep., 44 - 49 (1991)
A2.13. China's Future in Electric Energy, IEEE Power and Energy Magazine, 3 (4) 32 - 38 (2005)
A2.14. German Aerospace Center (DLR), Institute of Technical Thermodynamics Section Systems Analysis and Technology Assessment, Trans-Mediterranean Interconnection for Concentrating Solar Power, Federal Ministry for the Environment, Nature Conservation and Nuclear Safety Germany, 23 (2006)
A2.15. Rudervall, Roberto, Charpentier, J.P., and Sharma, Raghuveer: High Voltage Direct Current (HVDC) Transmission Systems Technology Review Paper, Energy Week 2000, Washington, D.C, USA, March 7-8, 2000
A2.16. Oberg, Erik, Jones, Frankin D., Horton, Holbrook L, and Henry H. Ryffell, Machinery's Handbook, 26th Edition, Industrial Press Inc., NY, 2000
A2.17. Oberg, Erik, Jones, Frankin D., and Horton, Holbrook L, Machinery's Handbook, 23th Edition, Industrial Press Inc., NY, 1988
A2.18. Oberg, Erik, Jones, Frankin D., Horton, Holbrook L, and Henry H. Ryffell, Machinery's Handbook, 25th Edition, Industrial Press Inc., NY, 1997
A2.19. Kent, William, Kent's Mechanical engineers' Handbook -Design. Shop Practice, John Willey & Sons Inc., NY, 1936
A2.20. Oberg, Erik, and Jones, Frankin D., Machinery's Handbook, 15th Edition, Industrial Press Inc., NY, 1955

A2.21. Baumeister, Theodore, Standard Handbook for Mechanical Engineers, 7th Edition, McGraw-Hill, NY 1967
A2.22. Marks, Lionel S., Mechanical Engineers' Handbook, 4th Edition, McGraw-Hill, NY, 1941
A2.23. Marks, Lionel S., Acallone, Eugene A., and Theodore Baumeister III, Mechanical Engineers' Handbook, 8th Edition, McGraw-Hill, NY, 1978
A2.24. Statistical yearbook of the electric Utility Industry, Edison Electric Institute, NY, from 1926 to 2005
A2.25. Hrist, Eric and Kriby, Brendan, Transmission Planning for a Restructuring U.S. Electricity Industry, Edison Electric Institute, Washington D.C., 2001
A2.26. Graneau, Peter, Underground Power Transmission – the science, technology, and economics of high voltage cables, John Wiley & Sons, NY 1979
A2.27. Fuldner, Arthur H., Upgrading Transmission Capacity for Wholesale Electric Power Trade, Electric Information Administration (Washington, D.C.) see: http://www.eia.doe.gov/cneaf/pubs_html/feat_trans_capacity/w_sale.html
A2.28. Rudervall, R., Charpentier, J.P., and Raghuveer, Sharma, High Voltage Direct Current Transmission Systems, Technology Review Paper, Presented at Energy week 2000, Washington , USA, March 7, 2000
A2.29. Thompson, W.G., A Critical Analysis of the possibilities of High Voltage Direct Current Transmission, Journal of G.E.C. (General Electric Company), Volume 14, 1947, 239-252

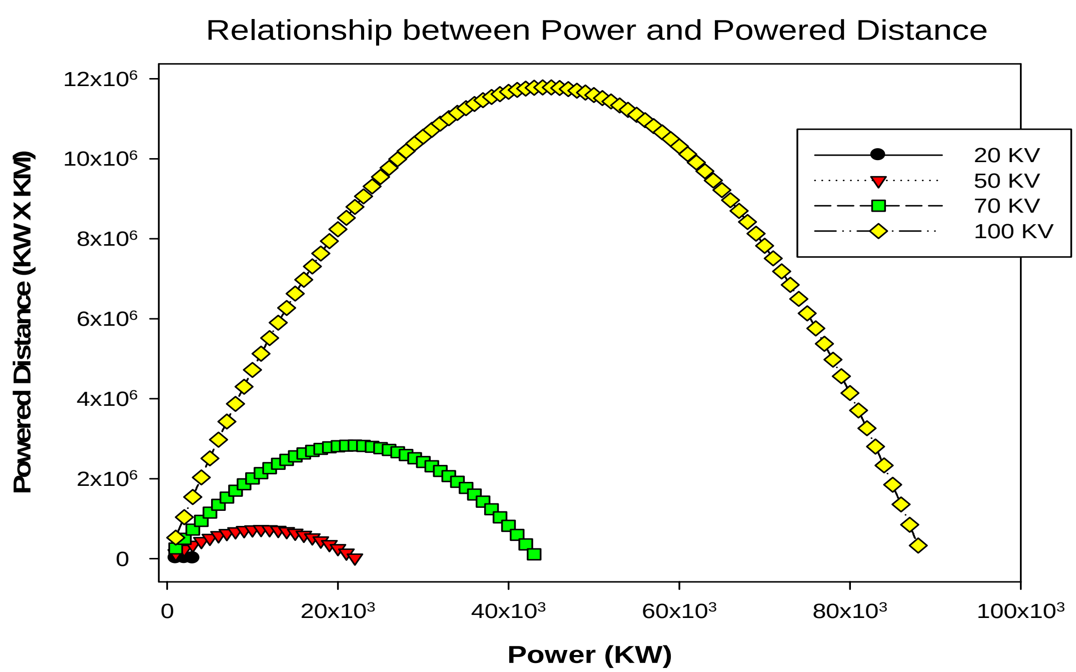
Data Reduction Examples:
As electrical power is increased, the loss of electric energy per distance increases and the economic transmission length is thereby shortened. In order to reduce the losses during transmission of electric energy, the transmission voltage can be increased. Approximate empirical equation relating transmission power, transmission length, and transmission voltage in an alternating current, three phase system is [A2.1]:

$$L = \text{distance of transmission (mile)} = \left(\frac{kV}{5.5}\right)^2 - \frac{0.746 \times Power(kW)}{200} \quad \text{(Equation A21.)}$$

For any voltage, Equation A2.1 gives an inverse linear relation between Power and distance (Figure A2.1a) and thus a parabolic curve for Powered Distance as a function of Power (Figure A2.1b). The parabola is easily solved for the maximum possible Powered Distance and this is reported in the latter part of Table A2.1 and in Figure A2.1 (in both cases the resulting data is labeled as estimates).
As shown in figure A2.1, the maximum power and distance can be estimated at each transmission voltage. The estimated data are shown in table A2.1 and plotted in Figure 3a.



(a)



(b)

Figure A2.1 Relationship between a) Power and Length, and b) Power times Length as a function of Power for different transmission voltages from Equation A2.1

The construction cost data are derived from the statistical year book of the Edison Electric Institute. The cost data in that book are for total construction cost per each year where the construction cost is a sum of cost which is used at various transmission voltage levels. The data includes line length at each voltage level for each year but not cost for specific voltages. Thus, we investigated the relationship between the construction cost and transmission voltage in order to estimate the construction cost at each transmission voltage. As the transmission voltage is increased, Figure A2.2 shows that the construction cost per unit length of the line also roughly proportionally increases. This relationship was used to estimate the cost per length of line at given voltages using the following analysis:

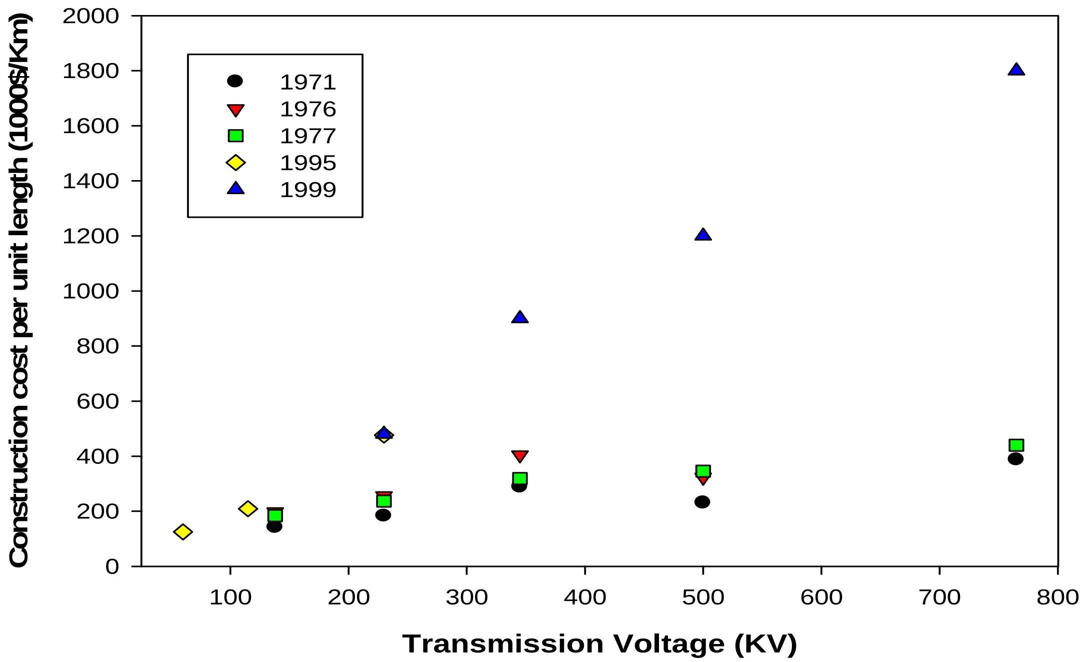


Figure A2.2 Relationship between construction cost per unit length of line and transmission voltage for several years [references A2.25-A2. 27].

Let the cost per unit length of transmission line ($/km) be C_i and the line length at *i*th transmission voltage be l_i:

The construction cost $= C_i l_i$ at given ith voltage

The total construction cost $= \sum_{i=1}^{n} C_i l_i$ (*i*= 1, 2, 3, 4,…, and *n*) (Equation A2.2)

where the n is the number of the transmission voltages

Because the C_i can be represented by a relationship between the cost per unit length and transmission voltage as a linear equation (Figure A2.2),:

$C_i = \gamma V_i$ (Equation A2.3)

where γ is a proportionality constant and V_i is *i*th transmission voltage (V)

When the Equation A2.3 is substituted into Equation A2.2, Equation A2.1 becomes:

The total construction cost = $\sum_{i=1}^{n} \gamma V_i l_i$

$$= \gamma \sum_{i=1}^{n} V_i l_i \qquad \text{(Equation A2.4)}$$

Therefore, γ can be calculated as;

$$\gamma = \frac{Total\,Construction\,Cost}{\sum_{i=1}^{n} V_i l_i} \qquad \text{(Equation A2.5)}$$

The yearly data for total construction cost and the length of transmission lines at all voltages are obtained from the statistical year book of the Edison Electric Institute, so the γ for each year can be estimated using Equation A2.5 and the results are shown in figure A2.3.

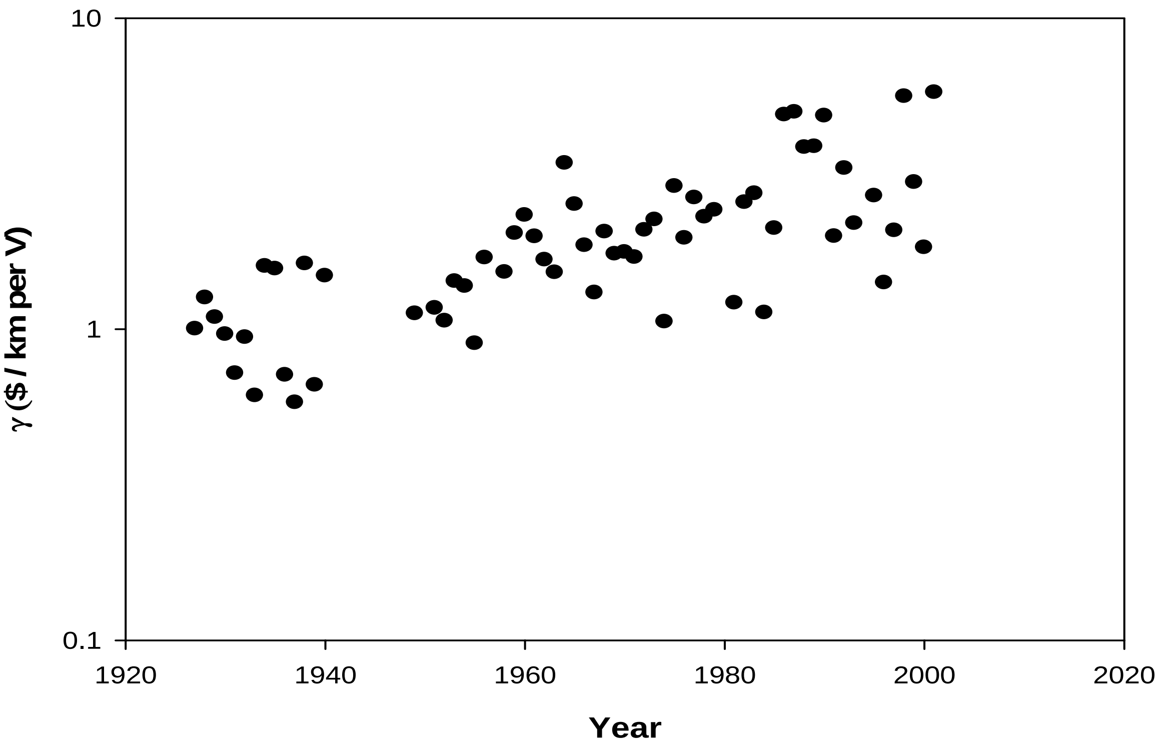


Figure A2.3 shows the estimate of γ from 1927 to 2001 (Inflation is applied) [ref A2.24]

The scatter graph indicates that γ has increased since 1927 through the end of the 1990s. We fit this data to a regression equation which we use to calculate γ for times shown and by extrapolation to earlier dates. Since r^2 for the regression fit is only 0.54, these estimates have considerably higher uncertainty than other data in this paper as noted in the text. Once we have an estimate for γ, we can easily calculate Ci ($/km) using Equation A2.3 -the construction cost at specific transmission voltages. Since we already know the distance of transmission line from actual data and estimation (figure A2.1), we can easily estimate the construction cost at specific transmission voltage for a specific year. C_i ($/km) from Equation A2.3 is multiplied by the transmission distance.

Since the early 1950s, HVDC (High Voltage Direct Current) technology that is advantageous for long distance and high transmission capacity has been developed, and it has now emerged as one of the major electrical transmission technologies. The construction cost per unit length of HVDC is known relative to the construction cost per unit length of HVAC. The construction cost per unit length is estimated using the ratio of the cost rate of HVAC and HVDC at each transmission distance [A2.14, A2.28, A2.29].

In the construction cost comparison of HVAC and HVDC, there is break-even point – the construction cost becomes the same between HVAC and HVDC- at around 600-800km [A2.28]. The initial construction cost of HVDC is higher than the cost of HVAC, but it more slowly increases with length. Beyond the break-even point, HVAC construction costs are higher than HVDC construction costs. For the points at maximum Powered distance, the cost (and powered distance) of HVDC are now superior to HVAC.

Supplemental Material A3

Table A3.1 Performance of energy transformation devices –Passenger car engine

Year	†Power	Volume	Average Car weight	Average Engine Weight	Power density	Specific Power	*Average Car Cost	**Average Engine Cost	Power density per cost	Reference
	W	Liter	Kg	Kg	W/Kg	W/Liter	$ (2005)	$ (2005)	W/$	
1896	1414416	-	680	157	4.8	-	35859	4303	0.001	12
1902	1418892	-	951	215	31.2	-	48595	5831	0.005	12
1903	1419638	-	861	194	46.2	-	46357	5563	0.008	12
1914	1427844	-	1490	323	74.7	-	40409	4849	0.015	12
1915	1428590	-	1250	270	70.6	-	33029	3964	0.018	12
1916	1429336	-	1427	307	71.3	-	33670	4040	0.018	12
1917	1430082	-	1404	302	72.7	-	30818	3698	0.020	12
1918	1430828	-	1359	291	75.4	-	30082	3610	0.021	12
1922	1433812	-	1608	339	74.3	-	10560	1267	0.059	12
1925	1436050	-	1540	321	92.9	-	10235	1228	0.076	12
1931	1440526	6132	1277	261	271.4	235	10304	1236	0.220	13
1932	1441272	5979	1323	269	279.7	241	11517	1382	0.202	13
1933	1442018	5616	1277	259	305.1	257	10507	1261	0.242	13
1934	1442764	5445	1332	269	311.8	265	10548	1266	0.246	13
1935	1443510	5311	1341	270	302.8	272	10260	1231	0.246	13
1936	1444256	5146	1359	273	301.3	281	10648	1278	0.236	13
1937	1445002	5074	1361	272	317.9	285	10615	1274	0.250	13
1938	1445748	5139	922	184	454.1	281	11804	1416	0.321	13
1939	1446494	5104	1357	269	293.5	283	11874	1425	0.206	13
1940	1447240	4975	1394	275	292.3	291	12220	1466	0.199	13
1941	1447986	4920	1432	282	293.6	294	11804	1416	0.207	13
1942	1448732	4757	-	-	-	305	11864	1424	-	13
1946	1451716	4831	1496	289	280.0	300	14375	1725	0.162	13
1947	1452462	4867	1506	289	281.9	298	14266	1712	0.165	13
1948	1453208	4870	1499	287	280.4	298	15336	1840	0.152	13

1949	1453954	4700	1489	284	297.7	309	16161	1939	0.154	13
Year	**W**	**Liter**	**Kg**	**Kg**	**W/Kg**	**W/Liter**	**$ (2005)**	**$ (2005)**	**W/$**	**Reference**
1950	1454700	4682	1477	281	310.1	311	16063	1928	0.161	13
1951	1455446	4496	1476	279	315.2	324	16527	1983	0.159	13
1952	1456192	4370	1517	286	320.5	333	16685	2002	0.160	13
1953	1456938	4119	1557	292	319.2	354	16555	1987	0.161	13
1954	1457684	3785	1576	295	354.4	385	16394	1967	0.180	13
1955	1458430	3342	1542	287	449.6	436	16452	1974	0.228	13
1956	1459176	3092	1550	287	539.6	472	16782	2014	0.268	13
1957	1459922	2795	1599	295	588.2	522	16952	2034	0.289	13
1958	1460668	2684	1619	298	650.8	544	16953	2034	0.320	13
1959	1461414	2869	1659	304	616.6	509	16748	2010	0.307	13
1960	1462160	2986	1583	289	590.1	490	16703	2004	0.294	13
1961	1462906	3065	1490	271	554.6	477	16759	2011	0.276	13
1962	1463652	3112	-	-	-	470	-	2020	-	13
1963	1464398	3102	-	-	-	472	-	1999	-	13
1964	1465144	2992	-	-	-	490	-	1983	-	1, 2, 13
1965	1465890	2869	-	-	-	511	-	1948	-	1, 2, 13
1966	1466636	2874	-	-	-	510	-	1880	-	1, 2, 13
1967	1467382	2861	-	-	-	513	-	1837	-	1, 2, 13
1968	1468128	2826	-	-	-	520	-	1837	-	1, 2, 13
1969	1468874	2856	-	-	-	514	-	1864	-	1, 2, 13
1970	215188	415	1414	247	872.0	518	15649	1878	0.464	1, 2, 13
1971	222645	404	1429	248	896.6	551	15803	1896	0.473	1, 2, 13
1972	159953	422	1445	250	639.9	379	15704	1884	0.340	1, 2, 13
1973	145163	384	1463	252	575.9	378	15080	1810	0.318	1, 2, 13
1975	104398	314	1341	229	455.8	333	17263	2072	0.220	1, 2, 14, 15
1977	99924	314	1314	222	449.5	319	17781	2134	0.211	1, 2, 14, 15
1978	103652	314	1179	199	521.7	330	18688	2243	0.233	1, 2, 14, 15
1979	104398	403	1215	204	512.2	259	19045	2285	0.224	1, 2, 14, 15
1980	88738	365	1223	204	434.4	243	19769	2372	0.183	1, 2, 14, 15
1981	89484	366	1189	198	452.7	244	20343	2441	0.185	1, 2, 14, 15

1982	103279	361	1217	201	512.9	286	20749	2490	0.206	1, 2, 14, 15
Year	**W**	**Liter**	**Kg**	**Kg**	**W/Kg**	**W/Liter**	**$ (2005)**	**$ (2005)**	**W/$**	**Reference**
1983	130498	314	1347	222	588.4	416	-	-	-	1, 2, 14, 15
1984	126769	314	1346	221	574.6	404	20334	2440	0.235	1, 2, 14, 15
1985	139819	314	1407	230	608.9	446	20072	2409	0.253	1, 2, 14, 15
1986	149140	314	1424	231	644.9	476	19803	2376	0.271	1, 2, 14, 15
1987	167783	314	1397	226	742.9	535	19417	2330	0.319	1, 2, 14, 15
1990	167783	335	1475	235	713.9	501	18936	2272	0.314	1, 2, 14, 15
1991	167783	335	1281	203	825.7	501	18914	2270	0.364	1, 2, 14, 15
1993	164054	335	1272	200	820.9	490	18850	2262	0.363	1, 2, 14, 15
1994	187668	345	1468	230	817.7	545	18601	2232	0.366	1, 2, 14, 15
1995	-	-	-	-	-	610	18502	2220	-	14
1996	-	-	-	-	-	624	-	-	-	14
1997	-	-	-	-	-	633	-	-	-	14
1998	-	-	-	-	-	659	-	-	-	14
1999	-	-	-	-	-	668	-	-	-	14
2000	-	-	-	-	-	693	-	-	-	14
2001	-	-	-	-	-	672	-	-	-	14

-: Not available.

†: The power of engines was originally expressed by horsepower (hp) in the references and pound (lb) and they were converted to kilowatt and kilogram in order to unify the metric as SI unit.

*: Inflation of the price of commodities was applied to the cost and its fluctuation in the price (2005) is also applied to the cost with the GDP deflator method.

**: Estimated value

Table A3.2 Performance of energy transformation devices –Airplane engine (Gas Turbine Engine- Pratt & Whitney, PT6 engine series 1963 to 2002)

Year	Type	W	Liter	†W/kg	W/Liter	*Airplane cost	**Engine Cost	W/$	Reference
1955	-	-	-	-	261.13			-	7
1957	-	-	-	-	332.46			-	7
1963	A-6	431014.6	288.05	3616.71	1496.34	2,833,181	226,654	0.016	3,5
1965	A-20	431014.6	288.05	3534.51	1496.34	2,833,181	226,654	0.016	3
1967	A-27	533175.5	288.05	3863.30	1851.01	7,178,398	574,272	0.007	3
1969	-	-	-	-	832.76				7
1971	A-34	583883.1	288.05	4356.49	2027.05				3,5
1973	A-36	559275	288.05	4520.89	1941.62	5,120,331	409,626	0.011	3
1973	A-41	633845	311.28	4438.69	2036.28	5,638,728	451,098	0.010	3
1974	T-6	1398187.5	899.96	4931.88	1553.61				3
1976	A-45A	-	-	4438.69	-				3
1976	-	-	-	-	895.25				7
1978	A-45B	-	-	4520.89	-				3
1979	A-42	673367.1	311.28	4603.09	2163.25	3,597,830	287,826	0.016	3
1980	A-45R	-	-	4767.48	-				3
1982	A-65R	1026083.2	348.44	5425.07	2944.77				3
1982	A-65B	820270	343.80	5342.87	2385.92				3
1982	A-61	672621.4	315.92	4685.28	2129.08				3
1983	A-65AR	1125261.3	348.44	5507.26	3229.40				3
1983	A-61A	673367.1	343.80	4603.09	1958.62				3
1984	A-62	708415	327.54	4438.69	2162.86				3
1986	A-67R	1125261.3	353.09	5589.46	3186.91				3
1986	A-66	674858.5	325.21	5507.26	2075.13				3
1986	A-67	894840	343.80	5425.07	2602.82				3
1986	-	-	-	-	1050.44				7
1987	A-67A	894840	329.86	5836.06	2712.80				3
1987	A-67AF	1125261.3	353.09	5425.07	3186.91				3
1989	A-64	557037.9	325.21	5918.25	1712.84				3
1990	A-67D	1010423.5	343.80	5425.07	2939.01	5,736,105	458,888	0.012	3
1990	A-67B	948530.4	353.09	5260.67	2686.38	2,435,664	194,853	0.027	3
1996	A-112	372850	288.05	2461.02	1294.41	2,075,210	166,017	0.015	4
1996	A-114	447420	288.05	2818.22	1553.29	1,292,576	103,406	0.027	4
1996	A-114A	503347.5	288.05	3170.49	1747.46	1,392,282	111,383	0.028	4
1996	B-36B	731531.7	289.70	4266.47	2525.10	7,207,672	576,614	0.007	4, 5
1998	A-135B	559275	292.69	3563.50	1910.80				4
1998	B-37	747191.4	315.15	4334.86	2370.90	1,085,690	86,855	0.050	4
1998	T-3DE	1431744	899.96	4574.50	1590.89	5,714,715	457,177	0.010	4
1998	T-3DF	1431744	899.96	4648.60	1590.89	5,714,715	457,177	0.010	4
1998	T-6B	1469029	899.96	4870.08	1632.32				4, 5
1999	A-135A	559275	292.69	3563.50	1910.80				4
1999	B-37A	747191.4	315.15	4334.86	2370.90	1,085,690	86,855	0.050	4
2002	C-67A	1446658	358.99	7629.86	4029.78		945,310	0.008	4, 5
2002	C-67C	1379545	386.35	7328.49	3570.70			0.005	4, 5

Superscript numbers represent the following references:

† The power of engines was originally expressed by horsepower (hp) in the references and pound (lb) and they were converted to kilowatt and kilogram in order to unify the metric as SI unit.

* : Inflation of the price of commodities was applied to the cost and its fluctuation in the price (2005) is also applied to the cost with the GDP deflator method.

**: Estimated value

Table A3.3 Performance of energy transformation devices –Electric Motor

Year	*Electric Motor		
	W/kg	W/Liter	W/$
1881	9.4 [8,9]	-	-
1890	18.5 [8,9]	40.64 [8]	-
1896	26.9 [8,9]	-	-
1902	136.3 [8,9]	-	-
1904	-	54.18 [8]	-
1906	-	81.27 [8]	-
1914	-	108.36 [8]	-
1917	-	100.23 [8]	-
1923	100.8 [8,9]	-	-
1929	162.12 [8,9]	162.54 [8]	-
1940	217.12 [8,9]	216.72 [8]	-
1955	-	270.91 [8]	-
1960	-	325.09 [8]	-
1964	258.3 [8,9]	-	-
1965		541.81 [8]	-
1966	259.1 [8,9]	-	-
1970	-	541.81 [8]	-
1975	-	541.81 [8]	-
1979	256.4 [8,9]	-	-
1980	312.5 [8,9]	541.81 [8]	-
1985	-	541.81 [8]	-
1990	429.78 [8,9]	541.81 [8]	-
1993	737 [8,9]	-	-
1995	-	541.81 [8]	-

* The historical data of electric motor is made from standard of NEMA 404 frame.
-: Not available

Table A3.4 Performance of energy transformation devices – Early airplane engine (Internal Combustion Engine- Mercedes, Benz and Daimler Benz aero engine 1888 to 1945) [Reference A3.10, A3.11, A3.13]

Year	†Power	†Engine Weight	Engine Displacement	*Volume	Power density	Specific Power	**Engine Cost	Power density per cost
	W	Kg	Liter	Liter	W/Kg	W/L	$ (2005)	W/$
1888	1491	-	0.6	37	-	40	-	-
1890	4400	-	2.4	27	-	160	-	-
1891	4698	-	2.9	24	-	193	-	-
1895	9620	-	6.1	24	-	405	-	-
1896	5294	-	2.7	29	-	180	-	-
1898	8948	-	3.3	41	-	220	-	-
1899	8948	-	3.3	41	-	220	-	-
1900	24608	-	5.9	63	-	393	-	-
1901	29828	-	5.9	76	-	393	-	-
1904	67113	-	12.0	84	-	800	-	-
1905	78299	-	14.0	84	-	933	-	-
1907	113595	-	17.5	98	-	1164	-	-
1908	94704	-	15.9	89	-	1060	-	-
1909	55555	-	7.9	106	-	524	-	-
1910	268452	-	31.7	127	-	2113	-	-
1911	55008	-	6.6	125	-	440	-	-
1912	70618	-	8.3	128	-	553	-	-
1913	100989	-	11.9	127	-	795	-	-
1914	109991	-	13.5	123	-	897	-	-
1915	221622	-	24.8	134	-	1656	-	-
1916	265256	-	31.5	126	-	2101	-	-
1917	215507	-	22.2	146	-	1478	-	-
1918	180779	-	22.8	119	-	1520	-	-
1919	22371	90	1.8	186	249	120	54399	0.005
1922	101713	163	8.3	184	624	553	-	-
1924	14914	49	0.8	298	304	50	-	-
1925	17151	49	0.9	291	354	59	-	-
1926	39671	102	1.2	517	390	77	-	-
1927	471282	453	32.9	215	1042	2195	64,568	0.016
1928	521990	950	47.5	165	549	3167	-	-
1930	596560	935	53.9	166	638	3592	-	-
1931	596560	620	30.0	298	962	2000	39,601	0.024
1933	708415	620	33.9	313	1143	2260	60,348	0.019
1934	800385	593	38.4	312	1350	2562	-	-
1935	633845	565	33.9	280	1122	2260	51,889	0.022
1936	769989	583	33.9	341	1320	2260	-	-
1937	924071	602	30.9	449	1535	2060	51,387	0.030
1938	1157326	1055	50.4	345	1097	3359	-	-
1939	1070494	701	35.7	450	1527	2377	77,279	0.020
1940	1328678	937	46.2	432	1418	3078	51,210	0.028
1941	1736581	1063	53.4	488	1633	3558	80,772	0.020
1942	1750847	1121	54.0	487	1562	3597	95,109	0.016

1943	1943481	1218	57.0	511	1596	3802	92,932	0.017
1944	1598629	1000	46.8	512	1598	3123	110,878	0.014
1945	1976105	1151	51.2	579	1717	3415	135,830	0.013

-: Not available

† The power of engines was originally expressed by horsepower (hp) in the references and pound (lb) and they were converted to kilowatt and kilogram in order to unify the metric as SI unit.

*: Estimated value from displacement

**: Inflation of the price of commodities was applied to the cost and its fluctuation in the price (2005) is also applied to the cost with the GDP deflator method.

A3.1. Ward's automotive yearbook, Ward's Reports, Inc.,1964-1994
A3.2. Ford mustang engine history, (see: http://www.fordcobraengines.com/Mustang%20Engines.htm)
A3.3. Bil Gunston OBG, FRAes; Jane's Aero-Engines, No.13, pp 77, 2003
A3.4. Aviation week and space technology, Aerospace source book, McGraw-Hill, NY 1996 – 2006
A3.5. All the world's aircraft, Jane's all the world's aircraft, London, England, 1963-2002
A3.6. Aviation Week, including Space Technology, McGraw-Hill, NY 1958 – 1959
A3.7. Joseph P. Martino, Technological Forecasting for Decision Making, McGRAW, 1983
A3.8. Tatsumi, Hiromitsu and Yoshino, Hitoshi, High-Efficiency Industrial Motors, Mitsubishi Electric ADVANCE, Vol. 103, 14-16, 2003
A3.9. Basic Training, Industrial-Duty & Commercial-Duty, Leeson Electric, Grafron, Wisconsin, US, 1999
A3.10. Setright, L.J.K.; The power to fly, George Allen & Unwin LTD., London, 1971
A3.11. Neal, Robert J., Master motor builders: the inception, design, production and uses of the non-automotive engines of the Packard Motor Car Company, Aero-Marine History Publication Co, WA, 2000
A3.12. W.C. Madden, Haynes-Apperson and America's First Practical Automobile: a History, McFarland & Company, NC, 2003
A3.13. Automotive industries. Engineering specifications & statistical issue, Chilton Co., 1952-1969, 1972, 1974
A3.14. Automotive Fuel Economy Program Annual Update year 2001, NHTSA
A3.15. Automotive Fuel Economy, National Research Council, National Academy Press, Washington D.C., 1992

Approximations used in data reduction estimates:

I. IC engine weights of early passenger car have been estimated as 20% of the curb weight of a passenger car [A3.1, A3.2, A3.13].

II. The IC engine displacement of early airplanes and passenger cars have been converted to total engine volume [A3.1, A3.13]. According to the Ward's automotive yearbook from 1964 to 1994, the ratio of IC engine displacement and engine volume (displacement per volume) is around 0.016. This fraction is applied to the IC engines to estimate their volume.

III. The engine costs of gas turbine engine and passenger car have been estimated by the average factory price of the whole airplane and passenger car. 20% and 12% of whole passenger car and airplane prices have been applied to the engine costs of ICs in passenger cars and gas turbines in airplanes, respectively. These fractions have been estimated from historical data in the automotive industries [A3.5, A3.13] from 1952 to 1966.

IV. The average engine weight and volume have been used in figure 4 and figure 5. These averages are calculated from table A3.1 and A3.4.

Table A4.1 Result of T test between various FPMs in functional categories

Comparison by FPMs	Storage			Transportation			Transformation		
	t	*p*	*df*	*t*	*p*	*df*	*t*	*p*	*df*
First FPM vs. Second FPM	3.182	0.000	42	-	-	-	1.698	<0.05	50
First FPM vs. Cost-constrained FPM	0.474	<0.05	30	9.035	0.000	13	1.117	<0.05	38
Second FPM vs. Cost-constrained FPM	0.949	<0.05	30	-	-	-	1.988	<0.05	29

The region where the significant difference does not exist

Table A4.2 Result of T test between functional categories in each FPM

Comparison of functions	Comparison of FPMs	*t*	*p*	*df*
Storage vs. Transportation	Wh/kg vs. W·km	14.100	0.000	28
	Wh/Liter vs. W·km	13.124	0.000	27
	Wh/$ vs. W·Km/$	1.109	<0.05	15
Transportation vs. Transformation	W/kg vs. W·km	10.661	0.000	28
	W/Liter vs. W·km	0.331	<0.05	36
	W/$ vs. W·Km/$	1.650	<0.05	23
Transformation vs. Storage	W/kg vs. Wh/kg	5.590	0.000	42
	W/kg vs. Wh/Liter	3.578	0.000	42
	W/Liter vs. Wh/Liter	4.025	0.000	50
	W/Liter vs. Wh/kg	8.050	0.000	50
	W/$ vs. Wh/$	3.051	0.000	26

The region where the significant difference does not exist