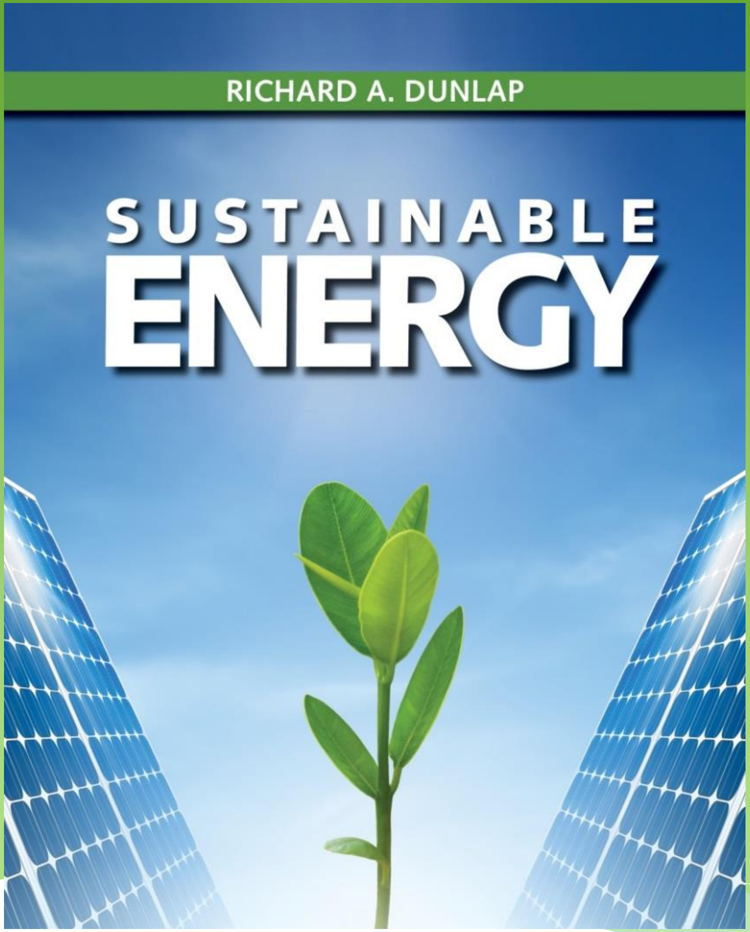
Sustainable Energy



Chapter 19

- Battery Electric Vehicles (BEV's)

Learning Objectives

- The properties and applications of different types of batteries.
- The use of the Ragone plot to illustrate energy-power relationships for energy storage mechanisms.
- Energy requirements for vehicle propulsion.
- The historical development of electric vehicles and reasons for changes in their popularity.
- The advantages, disadvantages, and economic viability of electric vehicles.
- The utilization of supercapacitors for energy storage and their significance in electric vehicle design.

Energy requirements for transportation

Transportation requires a portable energy source with a high energy density.

Gasoline (or other liquid or gaseous fossil fuels) are ideal.

Ethanol (or other liquid or gaseous biomass fuels) are one alternative (Chapter 16).

Other alternative energy sources typically produce electricity which needs to be stored for transportation use.

Electricity storage mechanisms

Electricity storage mechanisms are

- Batteries (this chapter)
- Hydrogen (Chapter 20)

Battery types

Energy is extracted from a battery when ions travel from the cathode to the anode.

Electrons produced by the ionization of atoms in the cathode travel through an external circuit and can do work.

Batteries are either

- Primary (non-rechargeable) or
- Secondary (rechargeable)

Secondary batteries

Secondary batteries can be recharged by applying a voltage between the cathode and anode and transporting the ions back to the cathode.

Battery electric vehicles (BEVs) require secondary batteries.

Secondary battery chemistries

Properties of some common secondary batteries are shown

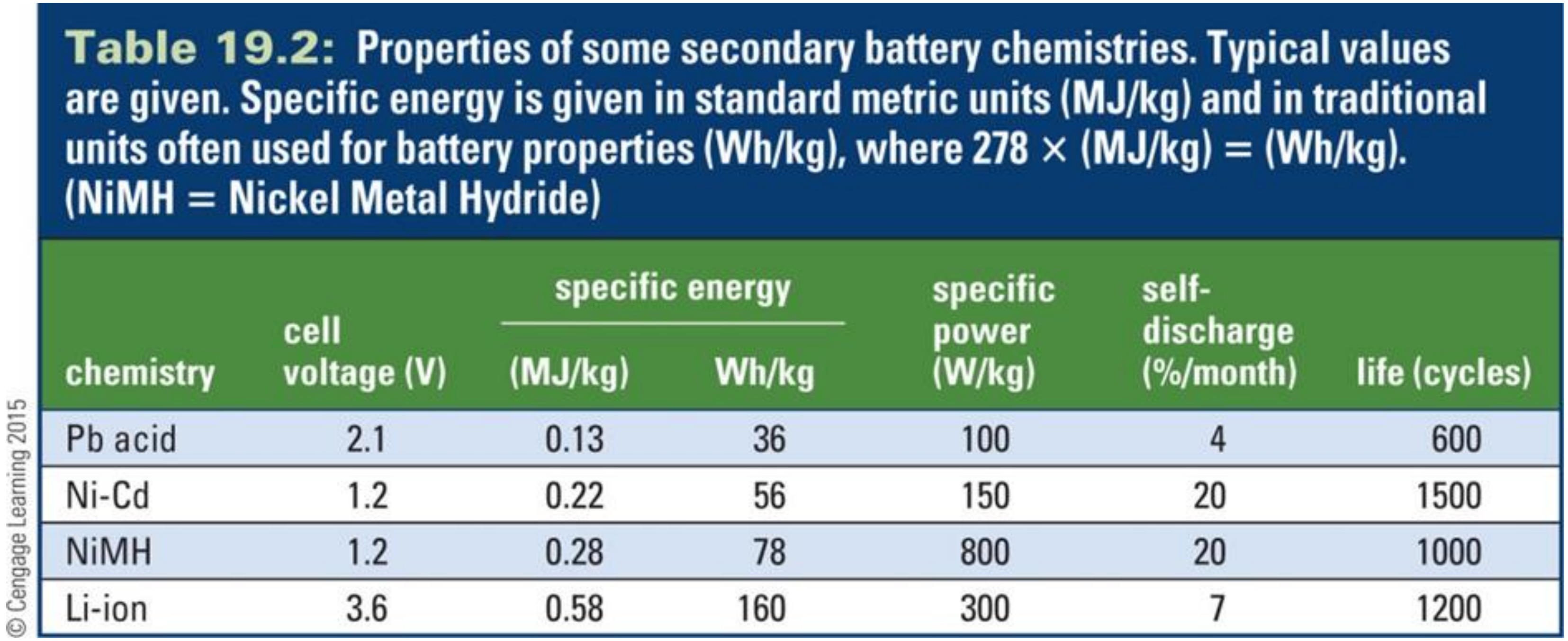


Table 19.2: Properties of some secondary battery chemistries. Typical values are given. Specific energy is given in standard metric units (MJ/kg) and in traditional units often used for battery properties (Wh/kg), where 278 × (MJ/kg) = (Wh/kg). (NiMH = Nickel Metal Hydride)

		specific energy				
chemistry	cell voltage (V)	(MJ/kg)	Wh/kg	specific power (W/kg)	self-discharge (%/month)	life (cycles)
Pb acid	2.1	0.13	36	100	4	600
Ni-Cd	1.2	0.22	56	150	20	1500
NiMH	1.2	0.28	78	800	20	1000
Li-ion	3.6	0.58	160	300	7	1200

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Battery capacity

Total battery energy capacity depends on the specific capacity and the mass

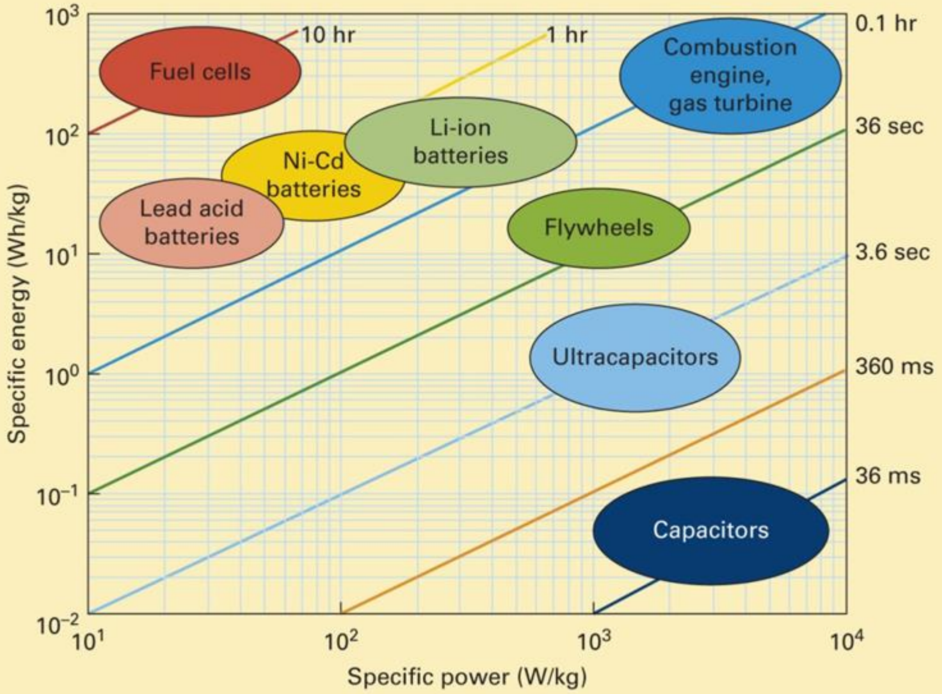
$$\text{energy} = (\text{specific energy}) \times (\text{mass}) \tag{19.1}$$

To supply energy of 1 kWh (3.6 MJ) a Li-ion battery would require a mass of

$$\text{mass} = (1\ \text{kWh})/(0.160\ \text{kWh/kg}) = 6.25\ \text{kg}$$

Ragone plot

The Ragone plot shows the relationship between specific energy and specific power for some different energy storage technology



Based on Moura, J. B. Siegel, D. J. Siegel, H. K. Fathy, A. G. Stefanopoulou "Education on Vehicle Electrification: Battery Systems, Fuel Cells, and Hydrogen," Proceedings of the 2010 IEEE Vehicle Power and Propulsion Conference, Lille, France, 2010

Figure 19.1: Relationship of specific energy and specific power for secondary battery types (Ragone plot). Other energy storage methods relevant to vehicles are shown for comparison.

BEV battery requirements

The range of a BEV depends on the energy capacity of the batteries.

The power available to a BEV depends on the total power that can be provided by the batteries.

The Ragone plot shows that internal combustion engines running on (e.g.) gasoline have the best combination of energy and power.

To understand battery requirements for a BEV we need to know how much energy and power a vehicle needs.

Characteristics of some vehicles

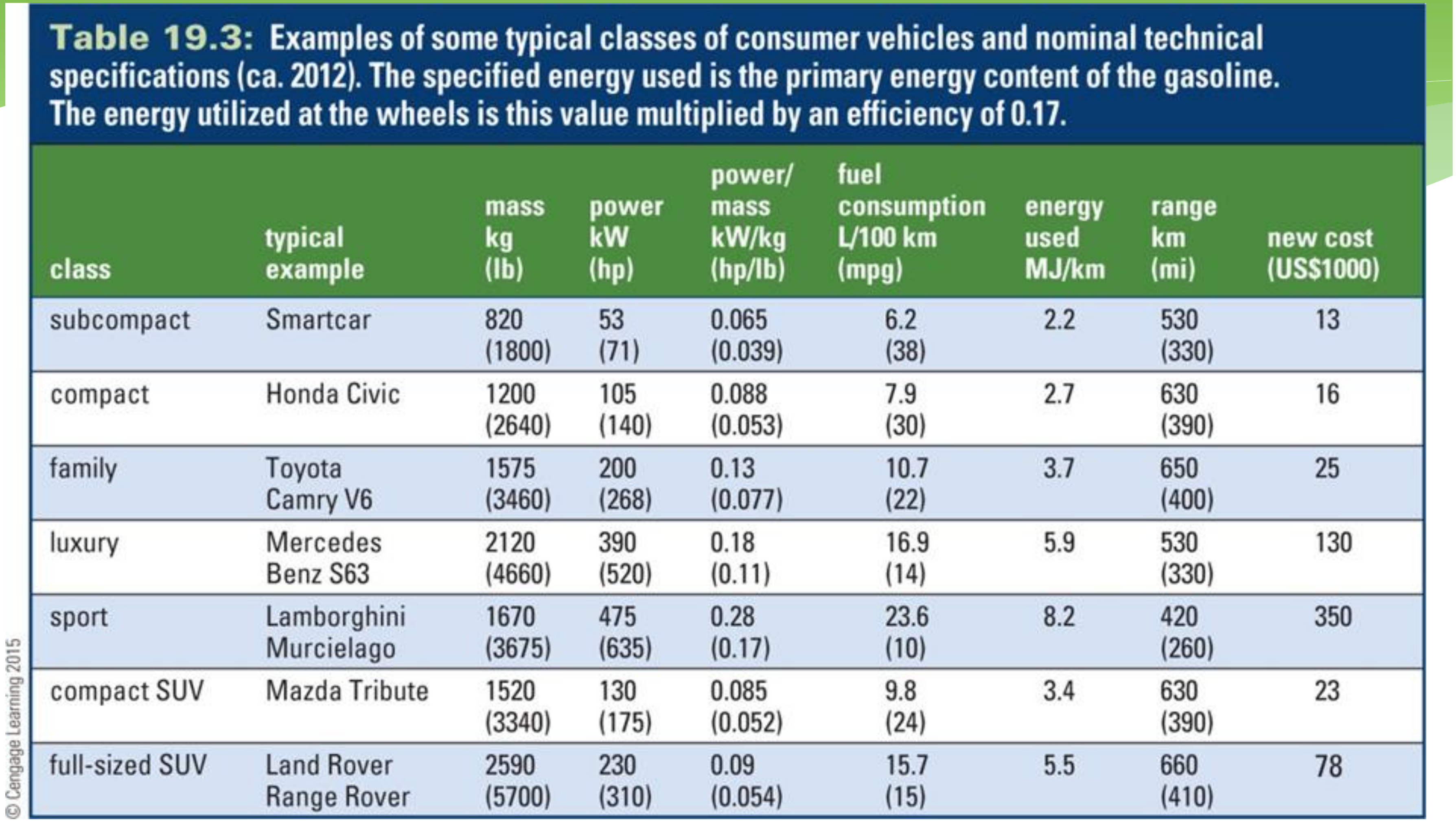


Table 19.3: Examples of some typical classes of consumer vehicles and nominal technical specifications (ca. 2012). The specified energy used is the primary energy content of the gasoline. The energy utilized at the wheels is this value multiplied by an efficiency of 0.17.

class	typical example	mass kg (lb)	power kW (hp)	power/ mass kW/kg (hp/lb)	fuel consumption L/100 km (mpg)	energy used MJ/km	range km (mi)	new cost (US$1000)
subcompact	Smartcar	820 (1800)	53 (71)	0.065 (0.039)	6.2 (38)	2.2	530 (330)	13
compact	Honda Civic	1200 (2640)	105 (140)	0.088 (0.053)	7.9 (30)	2.7	630 (390)	16
family	Toyota Camry V6	1575 (3460)	200 (268)	0.13 (0.077)	10.7 (22)	3.7	650 (400)	25
luxury	Mercedes Benz S63	2120 (4660)	390 (520)	0.18 (0.11)	16.9 (14)	5.9	530 (330)	130
sport	Lamborghini Murcielago	1670 (3675)	475 (635)	0.28 (0.17)	23.6 (10)	8.2	420 (260)	350
compact SUV	Mazda Tribute	1520 (3340)	130 (175)	0.085 (0.052)	9.8 (24)	3.4	630 (390)	23
full-sized SUV	Land Rover Range Rover	2590 (5700)	230 (310)	0.09 (0.054)	15.7 (15)	5.5	660 (410)	78

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Vehicle energy requirements

A typical gasoline powered family vehicle uses gasoline with an energy content of about 3.5 MJ/km.

As the Carnot efficiency of the engine is about 17% then the power to the wheels is about

(3.5 MJ/km)×(0.17) = 0.6 MJ/km

Since a battery/electric motor is about 85% efficient, 0.6 MJ/km at the wheels requires battery energy of (0.6 MJ/km)/(0.85) = 0.7 MJ/km.

Characteristics of a BEV

Consider a Li-ion battery BEV with a range of 600 km

The mass of batteries required would be

(600 km)×(0.7 MJ/km)/(0.58 MJ.kg) = 724 kg

These batteries could produce a maximum power of

(724 kg)×(0.3 kW/kg) = 217 kW (about 290 hp)

BEV concerns

- Range
- Initial cost
- Battery replacement cost
- Recharge time
- Recharging infrastructure

BEV carbon footprint

A gasoline vehicle has an efficiency of about 17% (from primary energy to energy at the wheels).

If electricity is produced (exclusively) from coal and a coal generating station has a Carnot efficiency of about 40%, the net efficiency of the BEV is about

$$(0.4)\times(0.85) = 0.35 \text{ (or } 35\%)$$

Thus the net carbon emissions per km for the BEV is about half that for a gasoline vehicle.

History of BEVs

BEVs were more common than gasoline powered vehicles up until the 1920s.

Reasons why BEVs were more popular than gasoline vehicles during the early 20th century

- Cleaner
- Quieter
- More reliable
- Easier to start
- More power

Early electric vehicle

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Figure 19.4: A 1916 Detroit Electric vehicle.

Dominance of gasoline vehicles

By 1930 gasoline vehicles became more common than BEVs.

The reasons for growth of gasoline vehicles were

- Invention of the electric started made them easier to start
- Need to travel longer distances made them more practical
- Mass production techniques made them less expensive
- Improved reliability

Re-emergence of BEVs

Concerns about oil supplies and the environmental consequences of fossil fuel use, there was renewed interest in BEVs in the 1970s and 1980s.

First mass produced BEV in modern times was the General Motors EV1 made from 1996 to 1999.

Toyota produced an electric version of the Rav4 from 1997-2003.

Later versions of both vehicles used NiMH batteries.

General Motors EV1

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Figure 19.6: The GM EV1 (produced from 1996–1999) being charged.

Toyota Rav4 EV

Figure 19.7: Toyota Rav4 EV produced 1997–2003.

Specifications of the GM EV1 and the Toyota Rav4 EV

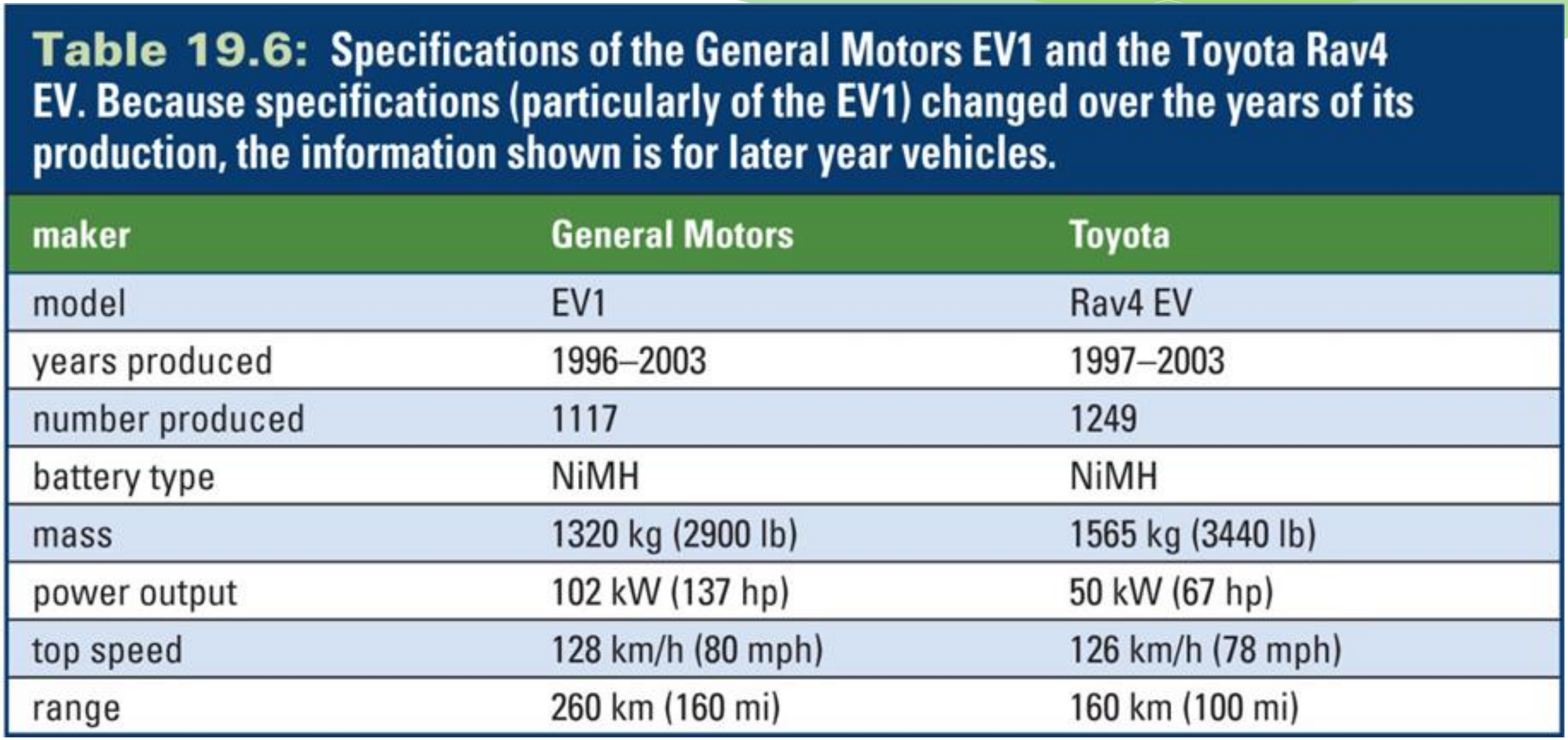

Table 19.6: Specifications of the General Motors EV1 and the Toyota Rav4 EV. Because specifications (particularly of the EV1) changed over the years of its production, the information shown is for later year vehicles.

maker	General Motors	Toyota
model	EV1	Rav4 EV
years produced	1996–2003	1997–2003
number produced	1117	1249
battery type	NiMH	NiMH
mass	1320 kg (2900 lb)	1565 kg (3440 lb)
power output	102 kW (137 hp)	50 kW (67 hp)
top speed	128 km/h (80 mph)	126 km/h (78 mph)
range	260 km (160 mi)	160 km (100 mi)

More recent BEVs

More recently several BEVs have become available including

- Reva a subcompact commuter vehicle
- Nissan Leaf a compact hatchback
- Tesla Roadster a luxury sports car

Reva

Premkundra

Figure 19.8: The 2001–present Reva electric vehicle made in India.

Nissan Leaf

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Figure 19.9: The Nissan Leaf.

Tesla Roadster


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Figure 19.10: Tesla Roadster.

Comparison of specifications for Reva, Leaf and Tesla Roadster

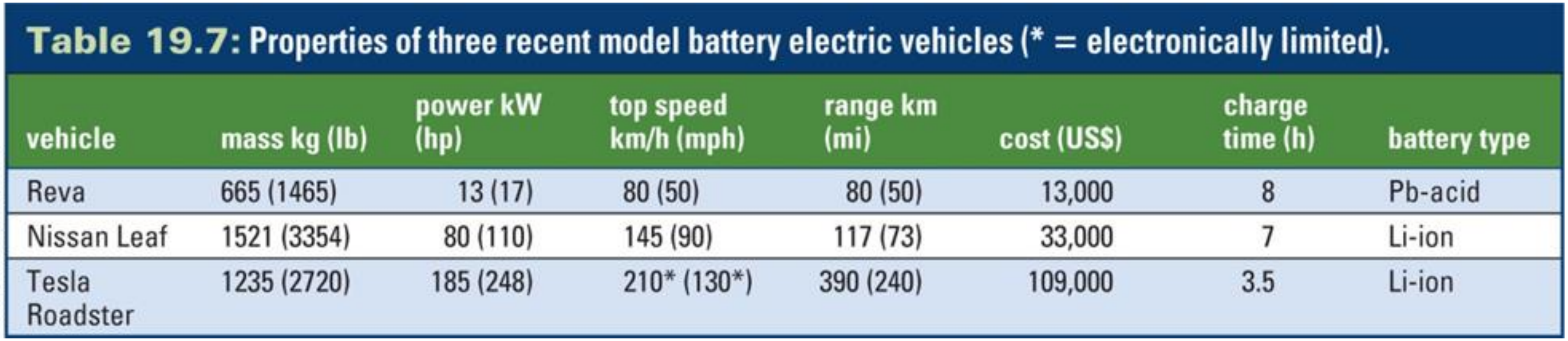

Table 19.7: Properties of three recent model battery electric vehicles (* = electronically limited).

vehicle	mass kg (lb)	power kW (hp)	top speed km/h (mph)	range km (mi)	cost (US$)	charge time (h)	battery type
Reva	665 (1465)	13 (17)	80 (50)	80 (50)	13,000	8	Pb-acid
Nissan Leaf	1521 (3354)	80 (110)	145 (90)	117 (73)	33,000	7	Li-ion
Tesla Roadster	1235 (2720)	185 (248)	210* (130*)	390 (240)	109,000	3.5	Li-ion

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Competition with gasoline vehicles

To compete with gasoline vehicles in the consumer market, the following factors must be considered

- Range
- Charge time
- Charger infrastructure
- Battery replacement cost
- Initial cost

Tesla has dealt with some of these consumer concerns with the Model S

- Range - up to 426 km
- Charge time - full charge in about 1 hour
- Charger infrastructure - Tesla has begun building a network of charger stations in the U.S. and Europe. Some stations offer rapid battery swapping
- Battery replacement cost - battery guaranteed for 8 years with a battery replacement guarantee after 8 years for $10,000-$12,000 (depending on capacity)
- Initial cost - The Model S sells for around $70,000 to $105,000 USD making it competitive (from a cost standpoint) with BMW, Jaguar, Mercedes, etc.

Tesla Model S

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ROBYN BECK/Staff/AFP/Getty Images

(a) (b)

Figure 19.13: The 2011 Tesla Model S electric vehicle: (a) exterior and (b) trunk (the floor folds up to add two rear-facing seats for children).

Supercapacitors

Capacitors store electrical energy in an electric field by separating positive and negative charges (unlike batteries that store energy using chemical reactions).

Supercapacitors are capacitors that store more energy than traditional capacitors.

Position of supercapacitors on the Ragone plot

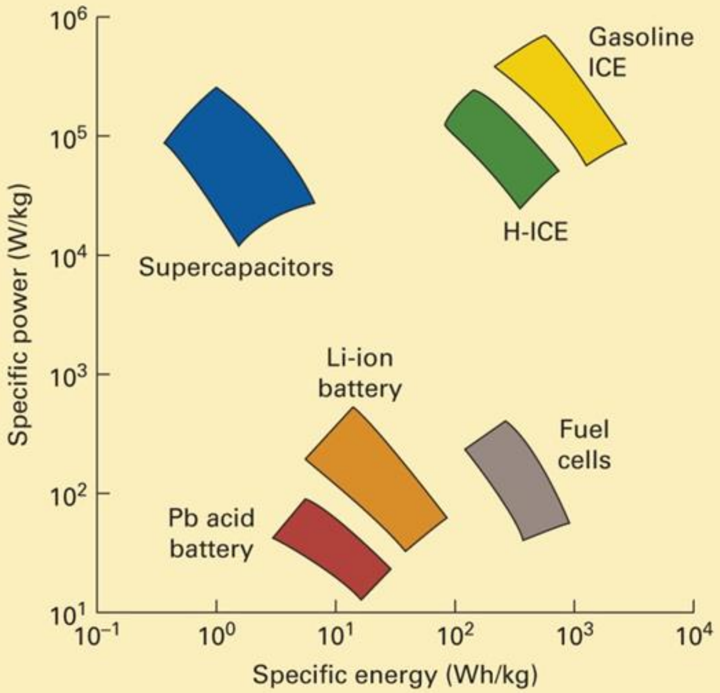
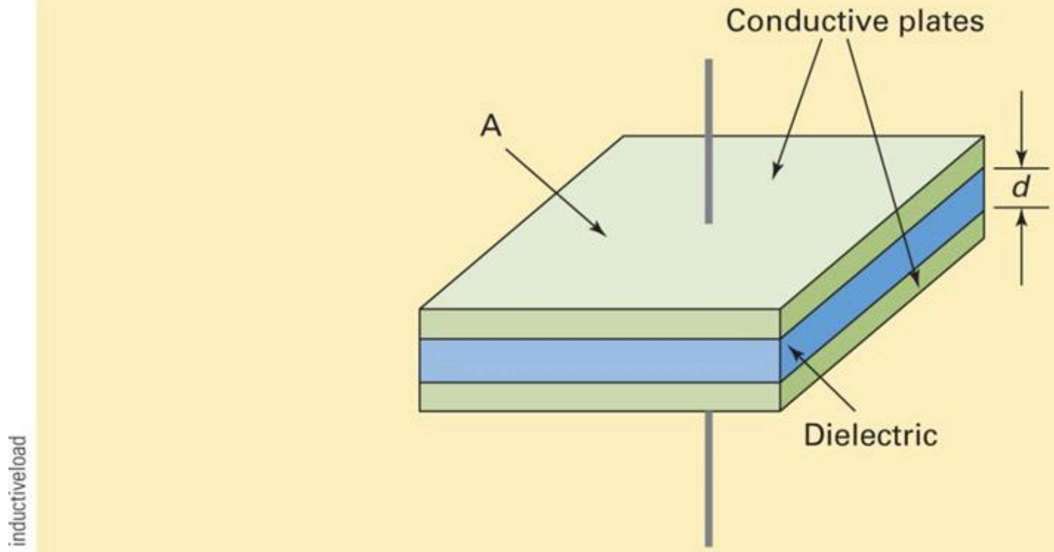


Figure 19.2: Power energy relationship (Ragone plot) for various types of batteries in comparison with other possible energy storage methods that might be used for transportation.

Supercapacitors are high power/low energy devices

Physics of a capacitor



inductiveload

Figure 19.14: Schematic diagram of a parallel plate capacitor.

Simple parallel plate capacitor

Analysis of a parallel plate capacitor

Capacitance of the parallel plate capacitor is

$$C = \frac{\varepsilon_r \varepsilon_0 A}{d} \qquad (19.7)$$

The energy stored in a capacitor charged to a voltage V is

$$E = \frac{1}{2} C V^2 \qquad (19.8)$$

Maximum energy capacity of a capacitor

The maximum possible voltage across the capacitor is given by the breakdown voltage of the dielectric

$$V_{\mathrm{max}} = dE_{\mathrm{b}} \qquad (19.9)$$

The maximum energy stored is therefore

$$E_{\mathrm{max}} = \frac{1}{2}CV_{\mathrm{max}}^{2} = \frac{1}{2}\frac{\varepsilon_{\mathrm{r}}\varepsilon_{0}A}{d}(E_{b}d)^{2} = \frac{1}{2}Ad\varepsilon_{\mathrm{r}}\varepsilon_{0}E_{\mathrm{b}}^{2} \qquad (19.10)$$

Since the volume of the capacitor is *Ad* and its mass is ρ*Ad* then the maximum energy density is

$$\left(\frac{E}{m}\right)_{\mathrm{max}} = \frac{1}{2}\left(\frac{\varepsilon_{\mathrm{r}}\varepsilon_{0}}{\rho}\right)E_{\mathrm{b}}^{2} \qquad (19.11)$$

Supercapacitors

Supercapacitors maximize the capacitor energy density by optimizing the parameters in equation (19.11).

Two approaches help in this respect

- Dielectrics with high permittivity
- Nanoporous electrodes to increase surface area

Supercapacitor design

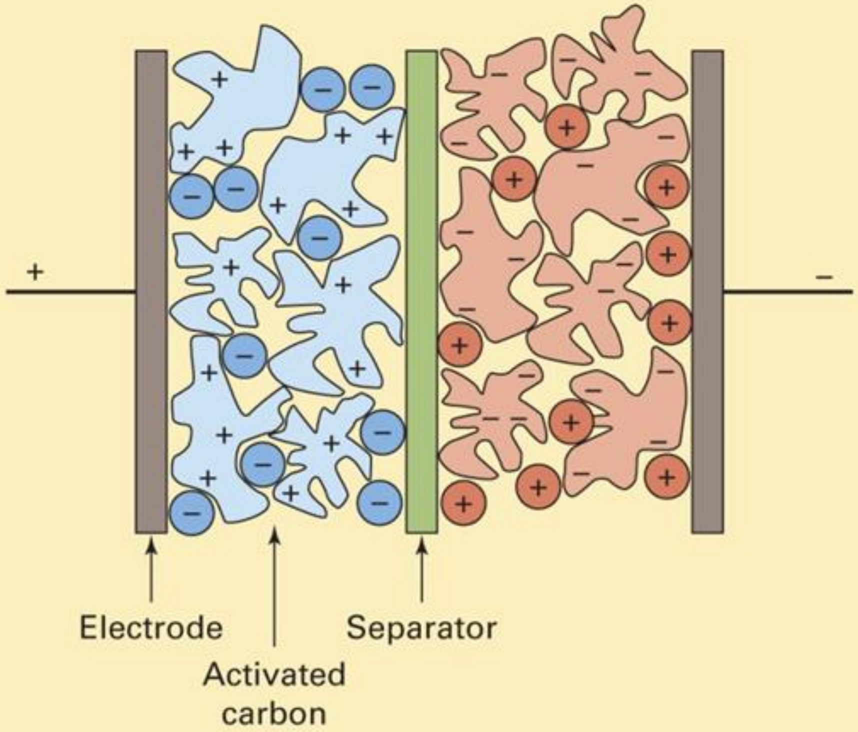


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Figure 19.15: Schematic diagram of a supercapacitor.

Advantages of supercapacitors (compared to batteries)

- High power density
- High voltage available from a single unit
- No chemical reactions
- Up to 10^6 charge/discharge cycles
- Fast charge/discharge
- No sophisticated charge/discharge electronics needed

Disadvantages of supercapacitors (compared to batteries)

- Low energy density
- Linear voltage decrease during discharge
- High self-discharge

Applications of supercapacitors for vehicles

Energy capacity of supercapacitors is not sufficient as a primary energy storage mechanism for a vehicle.

1000 kg of supercapacitors has energy capacity which gives a vehicle range of about 10 km.

Possible applications include

- Additional power for BEVs when there is a demand for more power
- Short term energy storage for regenerative breaking
- Short term power applications such as starter motors

Summary

- Secondary batteries are a convenient energy storage mechanism for electric vehicles
- The relationship between energy density and power density is illustrated on a Ragone plot
- Historically BEVs were common in the early part of the 20th century but were surpassed in popularity by gasoline vehicles in the 1920s
- Diminishing fossil fuel reserves and environmental concerns have resulted in renewed interest in BEVs
- Range, recharge time, charging infrastructure, battery replacement cost and vehicle cost are important considerations for future BEV development
- Supercapacitors can supplement batteries in an electric vehicle to provide additional power