Lecture Note #12 (Spring, 2022)

Energy storage and conversion for hybrid & electrical vehicles

1. Why electric systems?
2. Power demand in vehicles
3. Battery electrical vehicle
4. Hybrid vehicle
5. Fuel cell hybrid systems

Fuller & Harb (textbook), ch.12

Why electric and hybrid-electric systems?

-Renewable energy
-Rechargeable energy storage system (RESS)

-Motivation & goals for electric and hybrid-electric vehicles

(1) Reduce petroleum use
(2) Lower releases of greenhouse gases
(3) Decreased emissions of criteria pollutants
(4) Increased energy efficiency

ICE(internal combustion engine) vehicle

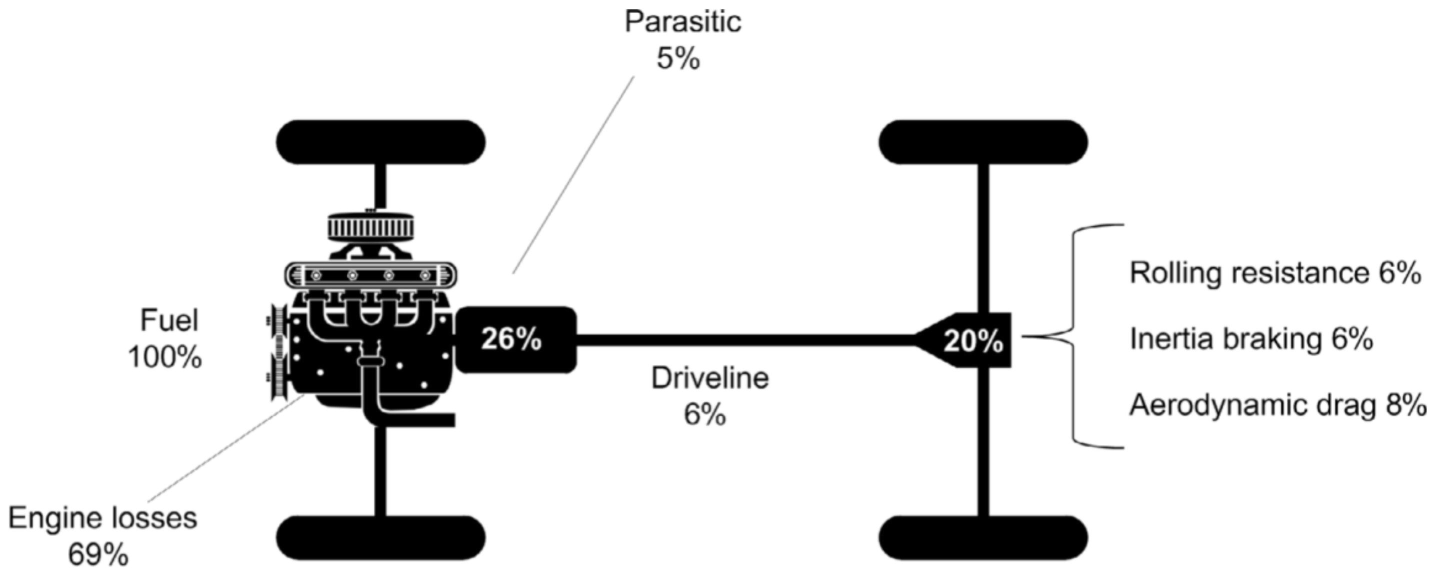

Figure 12.1 Representation of where the energy of the fuel goes for a typical vehicle driving a combination of city and highway. *Source:* Data taken from http://www.fueleconomy.gov/feg/atv.shtml

not efficient use of the energy!

Hybrid-electric vehicle

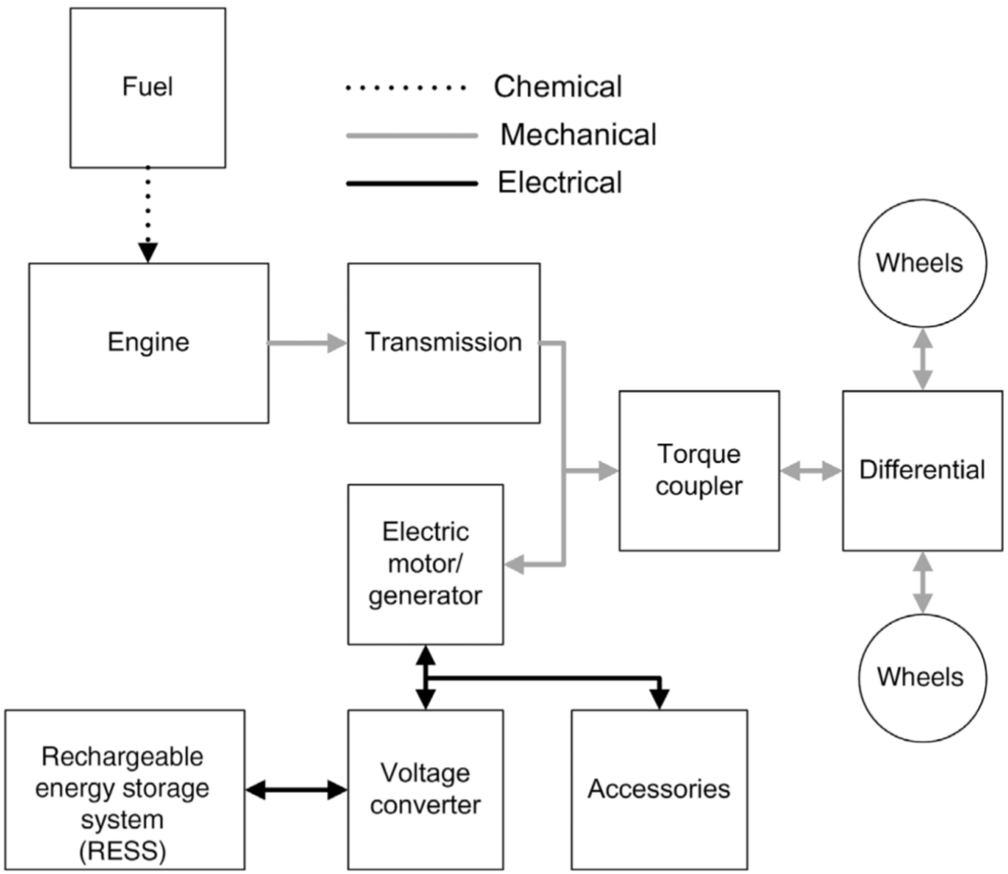

Figure 12.2 Parallel-hybrid architecture, one implementation of a hybrid vehicle.

Parallel hybrid system

Power demand in vehicles

Driving schedule: speed as a function of time

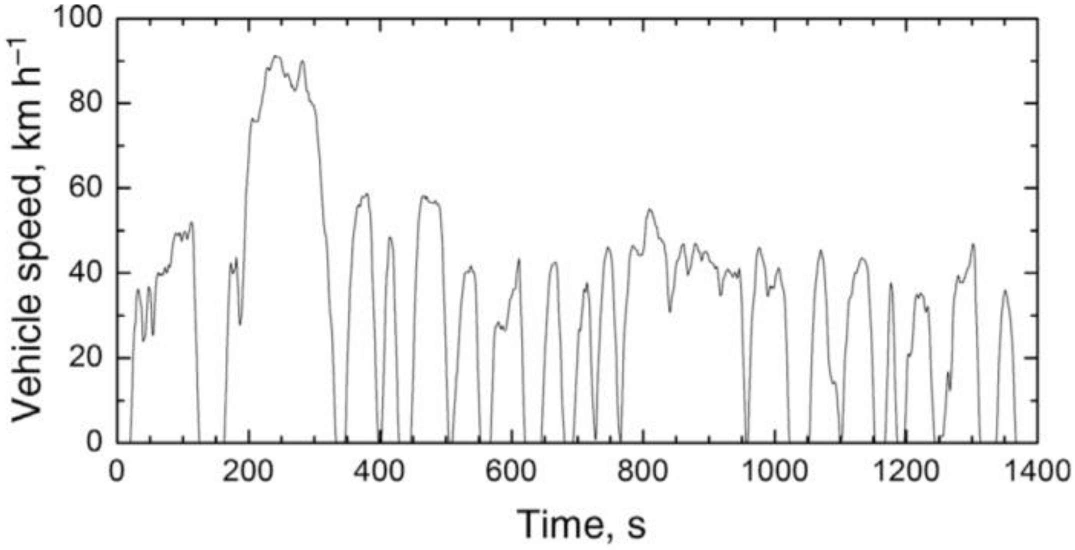

Figure 12.3 Urban dynamometer driving schedule produced by the EPA.

Urban driving, average speed, 40 km/h

Electrochemical Engineering, First Edition. Thomas F. Fuller and John N. Harb.

Companion Website: www.wiley.com/go/fuller/electrochemicalengineering

Illustration A.1 (p.296) speed → power

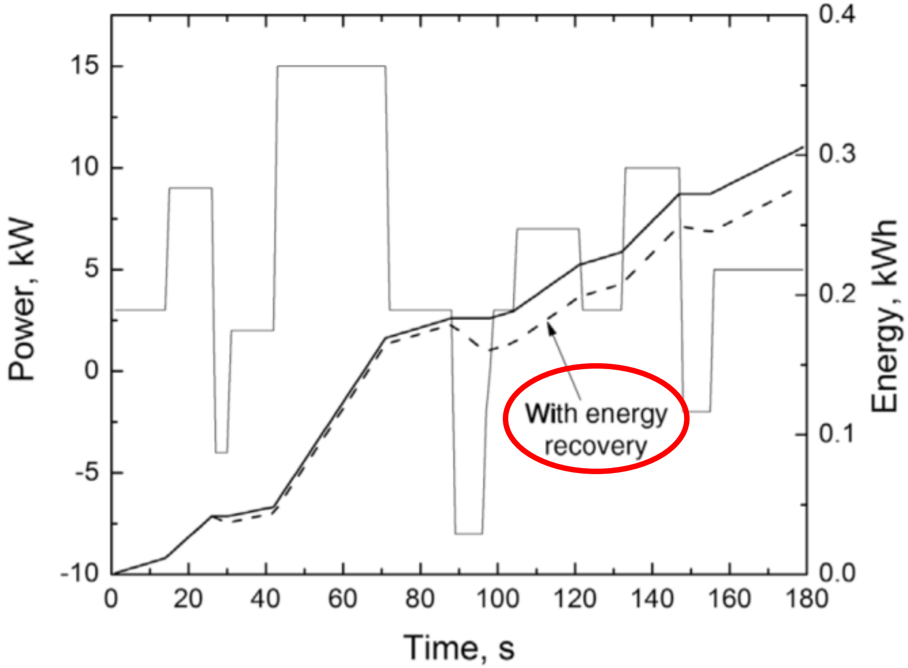

Figure 12.4 Driving schedule converted to power (left axis) and energy in kWh on right axis.

Power:
Positive: power is needed
Negative: deceleration
(energy recovery and storage)

Energy:
Solid: no energy recovered
Dashed: energy recovered
(hybrid system)

Table 12.1 Energy Associated with Different Driving Schedules for a 1500 kg Vehicle

	FTP-75, city driving, frequent stops, idling	FTP-75, highway driving, no stops	US06, high speed, aggressive driving
Average speed [$km \cdot h^{-1}$]	27.9	79.3	77.5
Maximum speed [$km \cdot h^{-1}$]	86.4	97.7	128.05
Traction energy [$kWh \cdot 100\,km^{-1}$]	10.47	10.45	17.03
Traction energy efficiency [$km \cdot kWh^{-1}$]	9.6	9.6	5.9
Braking energy, [$kWh \cdot 100\,km^{-1}$]	4.52	0.98	5.30

The traction energy is at the wheels.
Source: Adapted from Ehsani 2009.

city driving: braking energy ~50% of total energy

Illustration 12.1

Battery electric vehicle

$V = V_{ocv} - IR_{\Omega}$

$P_{max} = V_{ocv}^2 / 4R_{\Omega}$

Run-time = energy / power

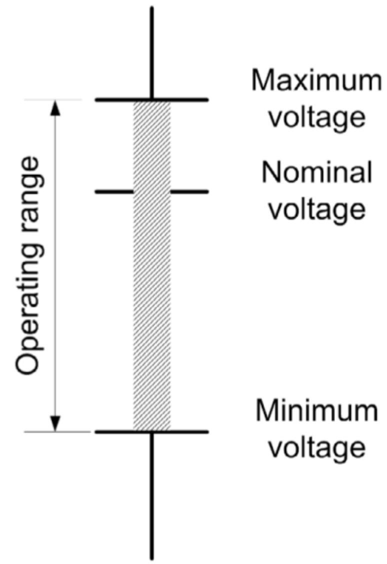

Figure 12.5 Range of operating voltage for electrochemical device.

Illustration 12.2

An electric vehicle (battery) Specification

e.g. 300 km driving distance

40 kWh battery, Power 90 kW

(Energy density 140 Wh/kg, Power density 250 W/kg) 550 Wh/L

Battery weight 300 kg

Efficiency 7 km/kWh

cf. Gasoline engine: ~800 km, 60~70 *liter* tank, 12 km/*liter*

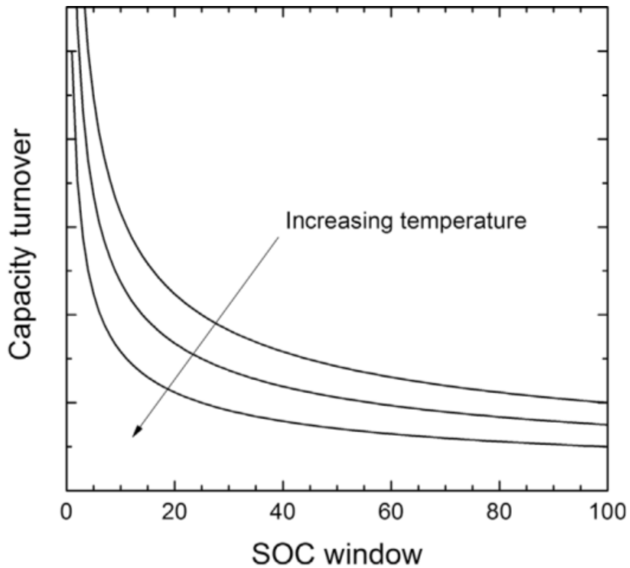

Figure 12.6 Capacity turnover for a hypothetical rechargeable battery.

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Lifetime → capacity turnover

$$CT = \frac{\text{Coulombs passed before the capacity is no longer acceptable}}{\text{Nominal capacity of the battery}}$$

capacity turnover↓ with SOC window↑

capacity turnover↓ with temperature↑

Illustration 12.2

Ragone plots

-Power and energy are key design aims of an electrochemical system for energy storage and conversion

Power [W, kW], $P_{ave} = (1/t_d)\int IV(t)dt$

specific power [kW/kg],
specific energy [kWh/kg],
power density [kW/L],
energy density [kWh/L]

-Ragone plot:
trade-off between power and energy

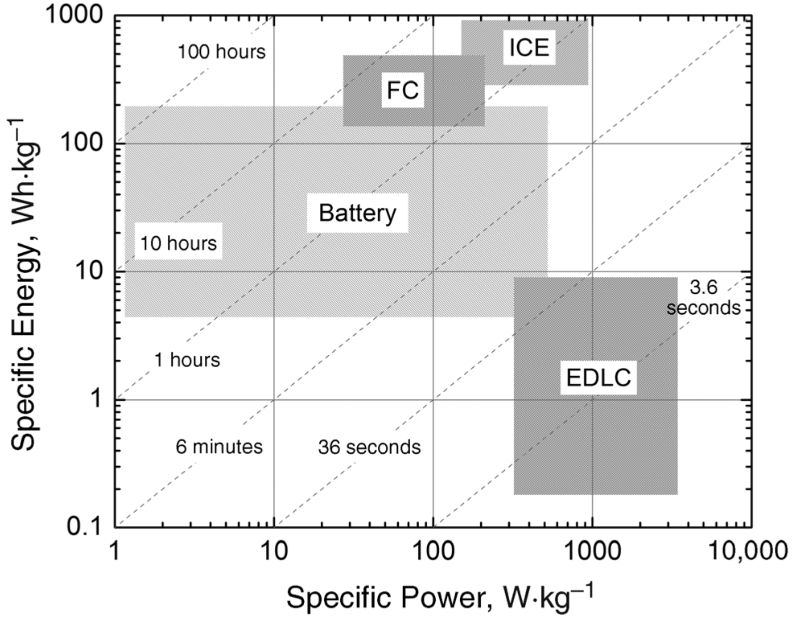

Figure 7.10 Ragone plot illustrating the strengths of different energy storage and conversion devices.

Hybrid vehicle

Start-stop hybrid: micro-hybrid

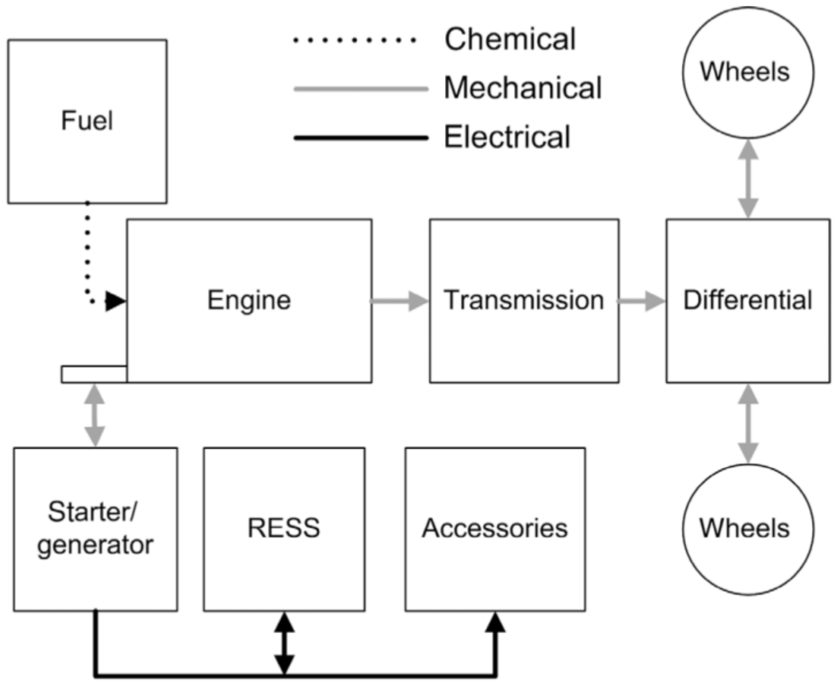

Figure 12.7 Start–stop hybrid.

5~8% fuel efficiency increase

Series hybrid system

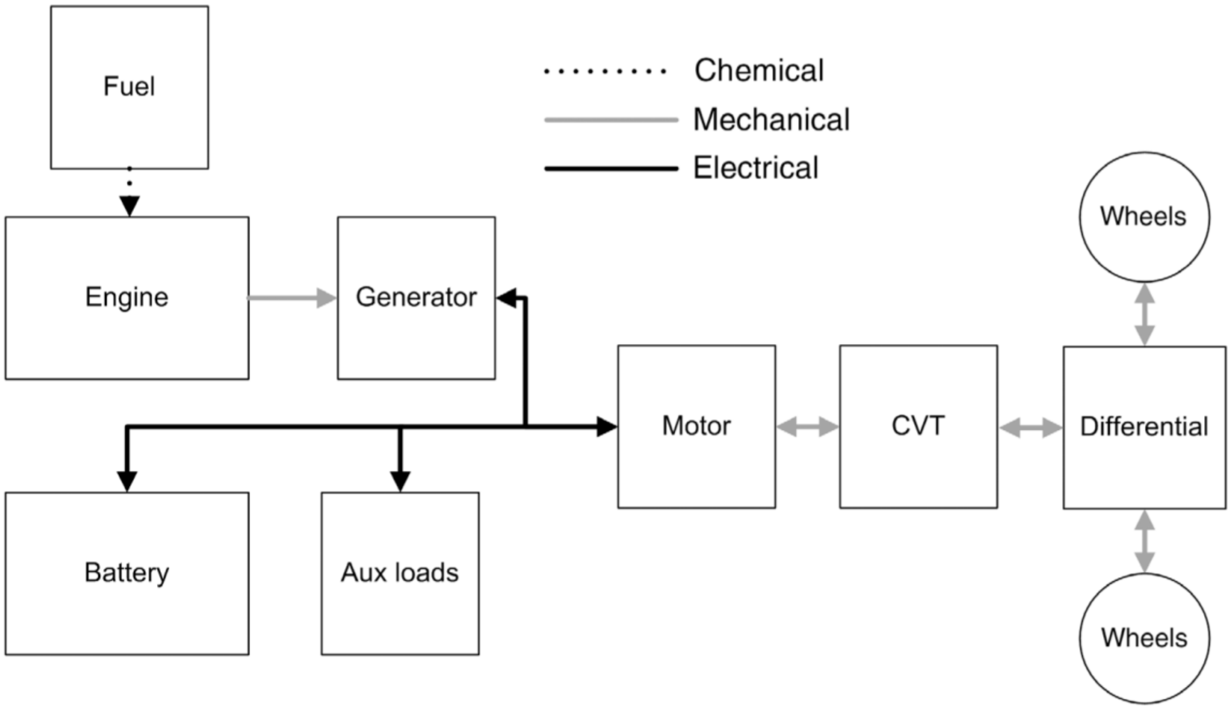

Figure 12.8 Series hybrid system.

Start-stop hybrid

Energy provided by ↑ RESS

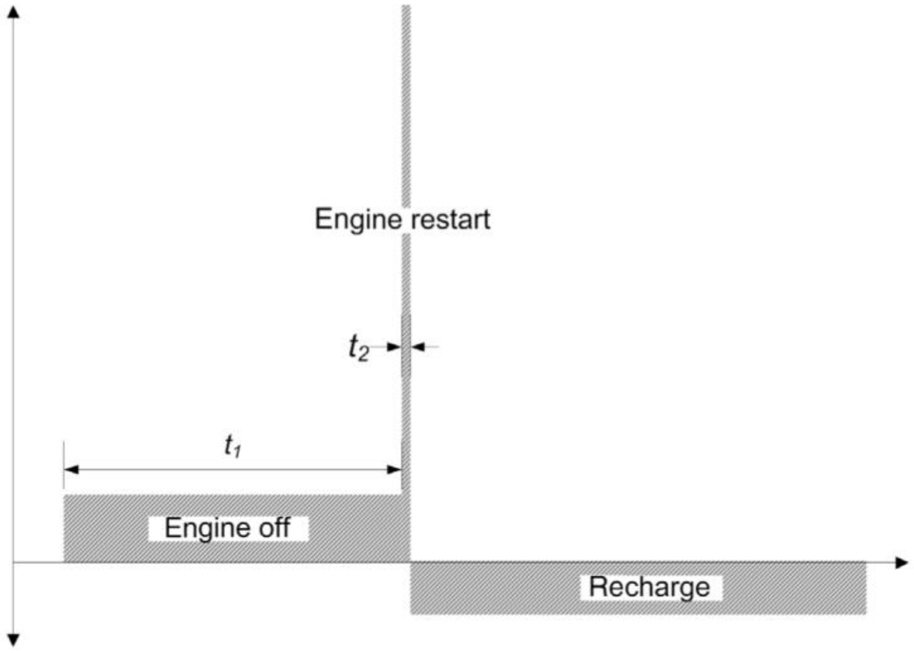

Figure 12.9 Power cycle for a start–stop hybrid.

Useable energy = $(3/4)(1/2CV_{max}^2) = (3/8)CV_{max}^2$

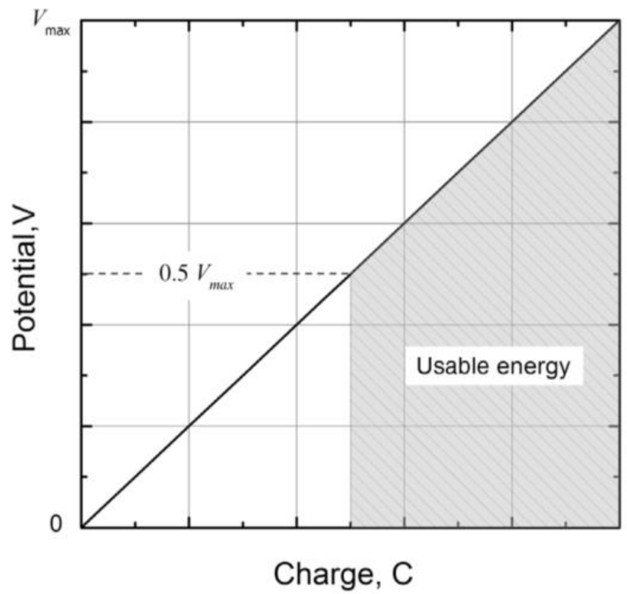

Figure 12.10 Energy for EDLC is equal to the area under the curve. Limiting voltage to half of V_{max} results in 25% of energy unavailable.

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Illustration 12.3

Batteries for full-hybrid electric vehicles

Efficiency of ICE $\approx \dfrac{1}{\text{Specific fuel consumption (SFC) (g/kWh)}}$

SFC is function of engine speed

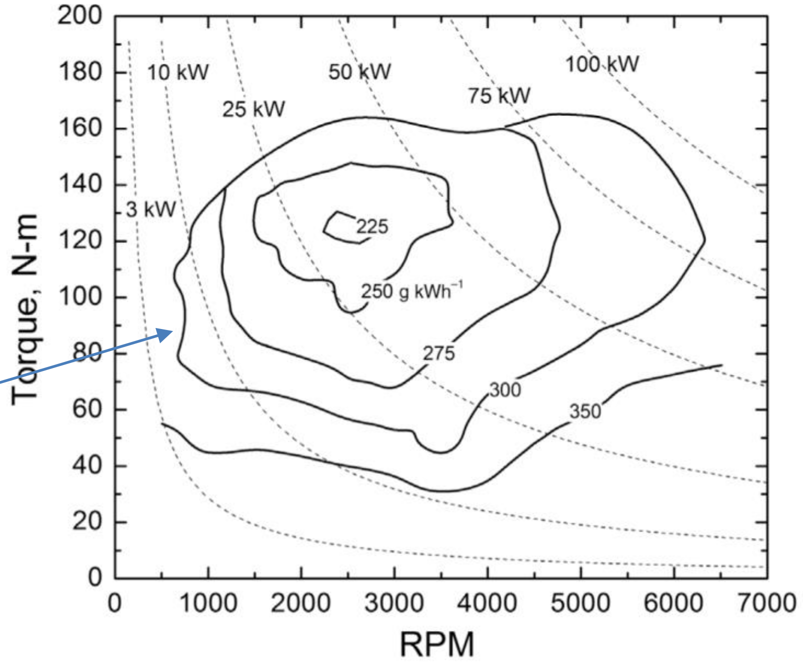

Figure 12.11 Engine map for a 1.9 L spark ignition engine.

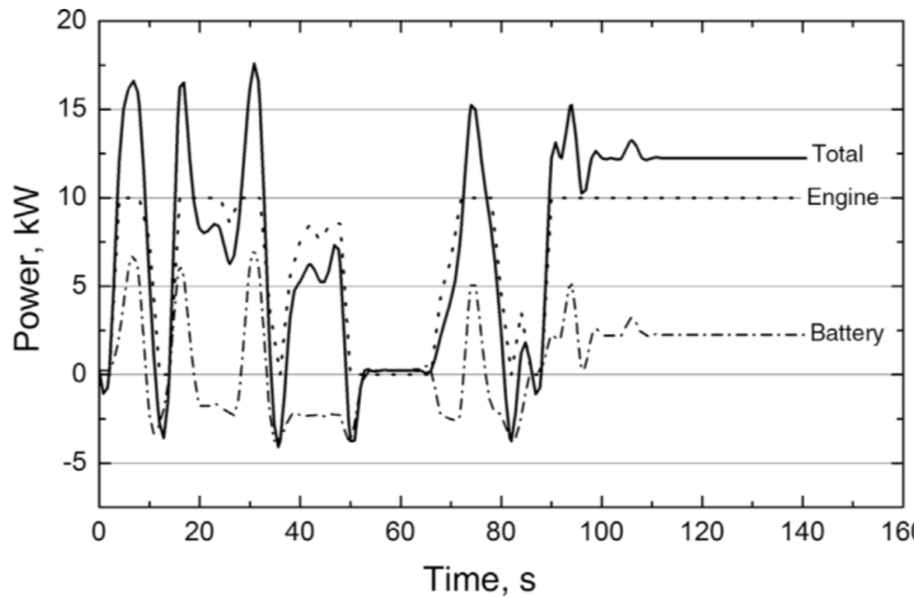

Figure 12.12 Example of power usage for parallel hybrid. Power of RESS (battery) is positive for discharging and negative for charging.

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Charge-sustaining mode

Degree of hybridization (DOH) = battery power / (engine power + battery power)

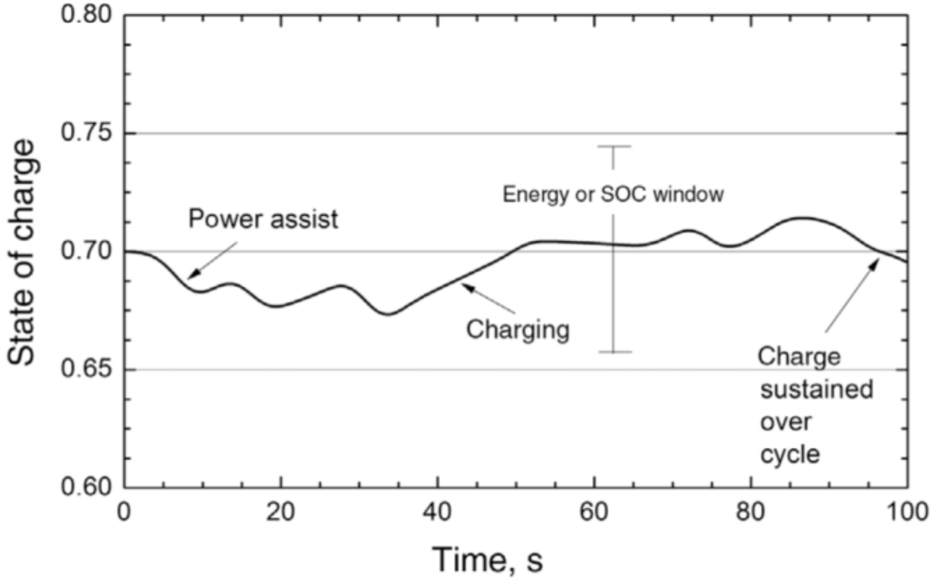

Figure 12.13 Charge-sustaining details. Battery SOC is maintained in a small window.

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Illustration 12.4

Charge-depleting mode

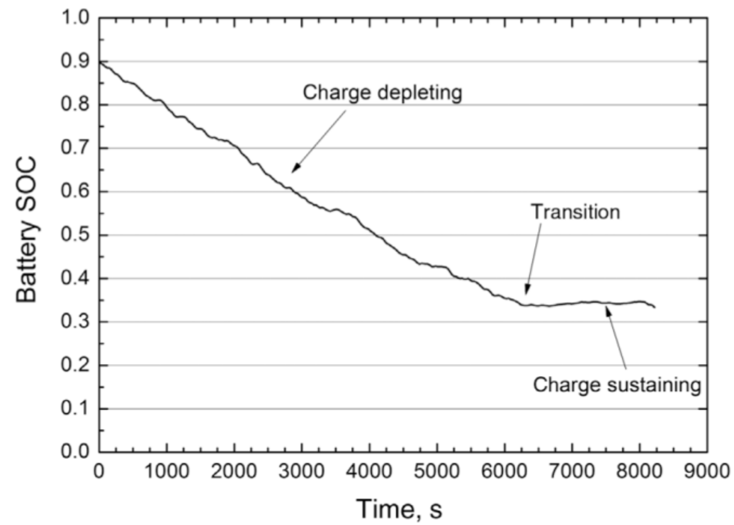

Figure 12.14 Window over which state of charge is varied for a full-hybrid operating in charge depleting mode.

Table 12.2 Comparison of Batteries for Hybrid and All-Electric Vehicles

	Mild hybrid	Strong hybrid	All electric vehicle
Average power	5 kW	20 kW	20 kW
Energy	0.5 kWh	8 kWh	25 kWh
Run-time	0.1 hours	0.4 hours	1.2 hours

Summary of hybrid designs

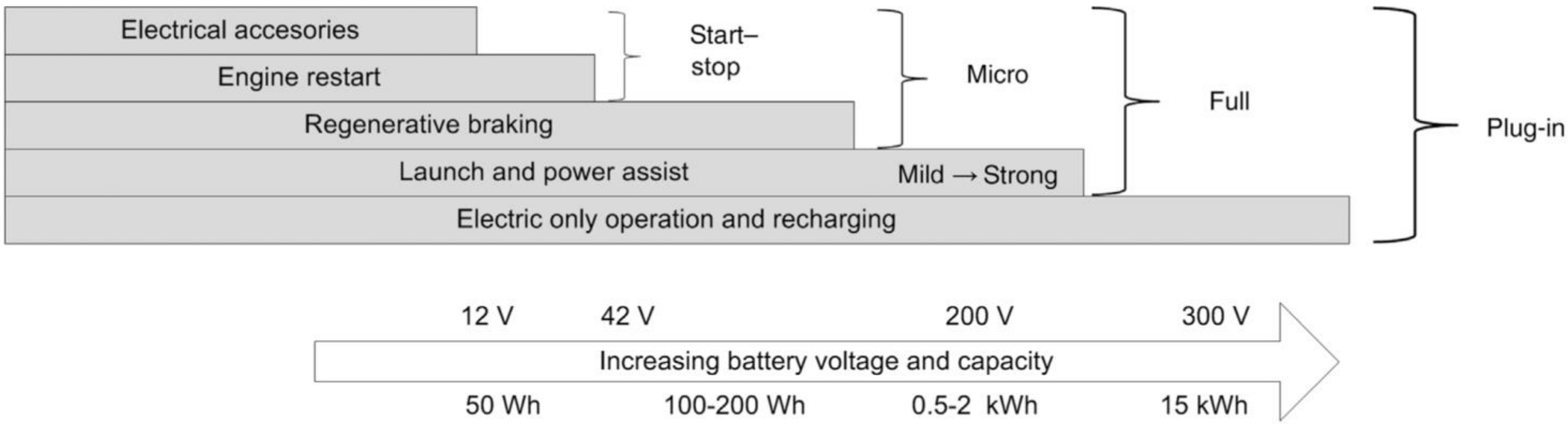

Figure 12.15 Summary of hybrid-electric vehicles. As the degree of hybridization increases, the voltage of the battery and its capacity increase.

Fuel cell hybrid systems vehicles

System efficiency,

η_{sys} = (IV – ancillary power – electrical loss) / availability of the fuel

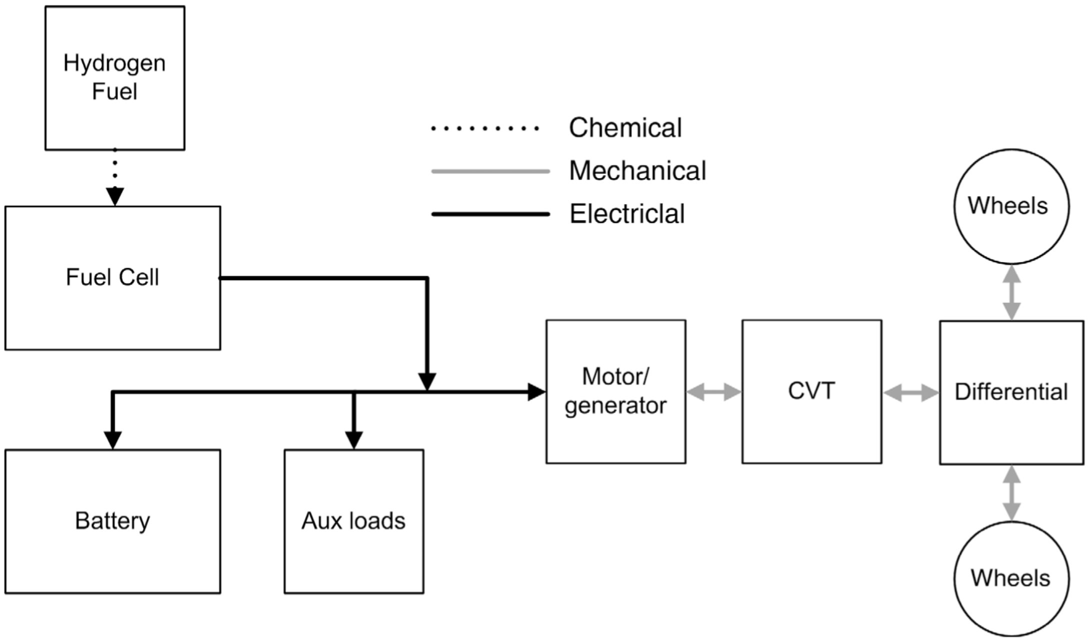

Figure 12.16 Typical architecture for a fuel-cell hybrid system.

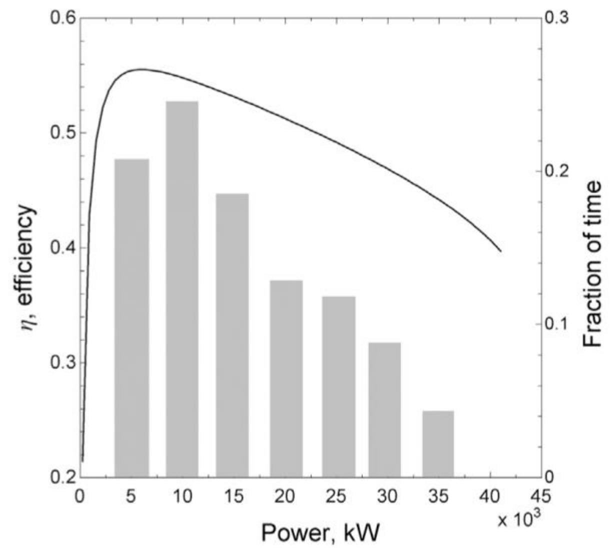

Figure 12.17 Fuel-cell system efficiency (solid line) as a function of fuel-cell power. The bars represent the frequency of time spent at each power level for an example driving schedule.

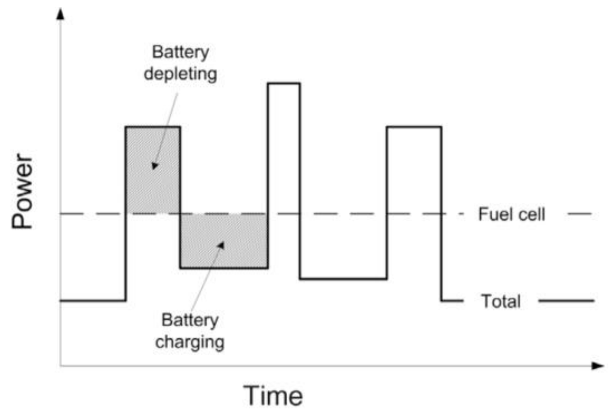

Figure 12.18 Typical method of operating a fuel-cell hybrid. Fuel-cell power is constant.

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Illustration 12.5

Hydrogen fuel cell vehicle 460 km driving distance

Power 113 kW

Power density 3 kW/*l*, 2kW/kg

FC weight 56 kg + (5 kg H_2 in tank (87 kg))

Efficiency 6 km/kWh

cf. Gasoline engine: ~800 km, 60~70 *liter* tank, 12 km/*liter*