Energy Generation, Storage, and Transformation

Roderick M. Macrae
3. The Balance Sheet
Consumption

- Transport
- Heating/cooling
- Lighting
- Food
- Manufacturing

Production (sustainable)

- Wind
- Solar (PV, thermal, biomass)
- Hydroelectric/wave/tide
- Geothermal
- Nuclear?
Units

Energy: SI unit = joule \( (1 \text{ J} = 1 \text{ kg m}^2 \text{ s}^{-2}) \)

Power: \( = \text{Energy/time} \)

SI unit = watt \( (1 \text{ W} = 1 \text{ J s}^{-1} = 1 \text{ kg m}^2 \text{ s}^{-3}) \)

Prefixes

\|
10^3 & 10^6 & 10^9 & 10^{12} & 10^{15} \\
\hline
\text{kilo} & \text{mega} & \text{giga} & \text{tera} & \text{peta} \\
(k) & (M) & (G) & (T) & (P) \\
\end{array}

e.g. \( 3.2 \times 10^{17} \text{ W} = ? \)
Units

Alternative units used in this book:

**Energy: kWh (kilowatt-hour)**

(power x time) = energy

(“one unit” on electricity bills)

e.g. Toaster with power 1 kW consumes 1 kWh/h.

1 kW x (1000 W/1 kW) x (1 Js⁻¹/1 W) x 1h x (3600 s/1 h) = 3.6 MJ

**Power: = kWh/d**

1 kWh/d x (3.6x10⁶ J/1 kW) x (24 h x 3600 s/1 d) = 42 W
In general, these values are normalized “per person”

e.g. 80 kWh/d/p = 80 kWh per day per person

cf. Dr. J. Kassebaum’s suggestion of normalization to GDP. (Mackay deliberately chooses not to introduce economics, and to consider only energy.)

Pros and cons?
Energy and Thermodynamics

The first and second laws are the bones and the flesh of thermodynamics; by comparison, the zeroth and third laws are mere hat and slippers.”

Daniel Sheehan

1. Energy can neither be created nor destroyed \[ \Delta U = q + w \]

2. Entropy increases \[ dS \geq 0 \] with \[ dS = dq / T \]

3. Absolute zero \[ S(0K) = 0 \]
High-grade and low-grade energy

Thanks to the second law, low-entropy energy is high-grade energy, and is more valuable than high-entropy energy.

- **Low entropy**
  - “Chemical energy”
  - “Electrical energy”

- **High entropy**
  - “Thermal energy”

Although energy can always be measured in the same units, it is not always freely interchangeable (and there is no universal “exchange rate”).

- e.g. Coal-fired power station:
  - Chemical energy → Electrical energy
  - 40% efficiency
4. Transportation
Cars

We will try to calculate an average energy/power consumption figure in kWh/d/p.

Required data:

1. **Fuel economy** = distance traveled per unit of fuel consumed
   (usually measured in mpg)

**N.B.**

1 UK gallon = 4.54609 L
1 US gallon = 3.78541 L

i.e. Mackay’s “average” 33 mpg (UK) converts to 27.5 mpg (US)

New car figures are much better than average figures.
Cars

We will try to calculate an average energy/power consumption figure in kWh/d/p.

Required data:

2. Energy density of gasoline = 46.4 MJ/kg \textit{(ORNL Center for Transportation Analysis)}

= 34.2 MJ/L
Cars

We will try to calculate an average energy/power consumption figure in kWh/d/p.

Required data:

3. Typical daily distance traveled = 50 km/d/p

Mackay’s figures are for UK:

\[
686 \text{ bn passenger-km/y} \div 365.25 \text{ d/y} = 1.88 \text{ bn passenger-km/d}
\]

\[
\div 37.6 \text{ M people who drive} = 50 \text{ km/d/p}
\]

\{ Not averaged over all UK citizens
Assumes 1p/car
Other options for similar calculations exist \}
Cars

We will try to calculate an average energy/power consumption figure in kWh/d/p.

Commuting strategies:
Cars

We will try to calculate an average energy/power consumption figure in kWh/d/p.

Using (not particularly carefully selected) US data:

77% of workers (102 M people) drive “solo”

Average commute 16 mi

Assuming all commuters drive alone we obtain

$\frac{100}{77} \times 102 \text{ M commuters} = 132 \text{ M commuters}$, and

an average consumption of 26 kWh/d

Neglected: Energy cost of fuel production (1.4 units/unit)

Energy cost of vehicle manufacture (etc.)
Cars

How efficient are cars?

Where does the energy go?

Can significant improvements be made?
Cars

Main routes of energy loss

(1) Starting/stopping (acceleration/braking)
(2) Air resistance
(3) Engine/drive inefficiency
(4) Rolling resistance
Cars

(1) Acceleration/braking

Requires energy

Discards energy

Model stop/start driving as a series of braking events of length $d$, between which car reaches velocity $v$.

$$P_{brakes} = \text{KE/period}$$

i.e.

$$P_{brakes} = \frac{1}{2} \frac{m_c v^3}{d}$$
Cars (2) Air resistance

“Tube” of air disrupted by passage of car (made more turbulent).

“Drag area” - slightly smaller than frontal area of (streamlined) car.

\[ A = c_d A_{\text{car}} \]

KE of displaced air: \[ KE_{\text{air}} = \frac{1}{2} \rho A v^3 t \]

Power = rate of generation of swirling air = KE/t, i.e.

\[ P_{\text{air}} = \frac{1}{2} \rho A v^3 \]

Table A.7. Drag coefficients and drag areas.
Cars

(2) Air resistance

Only really significant way to reduce drag area is tandem seating.

VW prototype
1L/100km = 236 mpg
Cars

Combining braking and air resistance:

\[ P = P_{\text{brakes}} + P_{\text{air}} = \frac{1}{2} \frac{m_c v^3}{d} + \frac{1}{2} \rho A v^3 \]

In both cases, power is proportional to velocity \textit{cubed}.

For a given distance, \( E/d = P x t/d = P/v \), and so energy consumed per unit distance is proportional to \( v^2 \).

Halving speed reduces energy consumed by a factor of 4 (if engine efficiency is ignored).
Cars

$P \propto v^3$ seems reasonable even for real engines.
Cars

For short trips, braking dominates, while for long trips air resistance is more important.

Comparing factors,

If \( m_c > \rho A d \), then braking is more important.

mass of car \hspace{1cm} \text{mass of air in tube}

From this we can calculate the threshold distance between stops separating “city” and “highway” driving.

\[
d^* = \frac{m_c}{\rho A_{\text{car}} c_d}
\]

Typical value around 750 m.
Cars

To reduce vehicle power consumption:

<table>
<thead>
<tr>
<th>(braking dominated)</th>
<th>(drag dominated)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Reduce mass of car</td>
<td>1. Reduce drag coefficient</td>
</tr>
<tr>
<td>2. Regenerative brakes</td>
<td>2. Reduce frontal area</td>
</tr>
<tr>
<td>3. Reduce speed</td>
<td>3. Reduce speed</td>
</tr>
</tbody>
</table>

Overall vehicle efficiency in power use is around 25%, so power consumption figures need to be multiplied by a factor of 4.
Cars

(3) Inefficiency

A. Thermodynamic limit on engine efficiency  
B. Other factors
Cars

Internal combustion engine

Otto vs Diesel

Spark ignition

Compression ignition
Cars
Cars - thermodynamic perspective

Theoretical efficiency:

\[ \eta = \frac{r^{\gamma-1} - 1}{r^{\gamma-1}} \]

(see handout for definitions)
Cars

For the same compression ratio, the Otto cycle is more efficient.

However, diesel engines typically operate at higher compression ratios (20:1 rather than 10:1), making them slightly more efficient overall.

Typical efficiency is around 0.46 for Otto cycle.

Other factors in energy loss: friction, turbulence, drivetrain inefficiency, use of engine power for water pump and electrical generator.
Cars

(4) Rolling resistance

Rolling resistance is due to friction, and is velocity-independent.

\[ F = c_{rr} mg \]

- about 100 N/ton

- (equivalent to climbing a 1% gradient).

\[ E/d = F \times d/d = F = Pxt/d = P/v \]

i.e. E/d is a force

RR exceeds air resistance when

\[ c_{rr} mg = \frac{1}{2} \rho c_d A v^2 \]
Cars (vs. bikes and trains)

Figure A.9. Simple theory of car fuel consumption (energy per distance) when driving at steady speed. Assumptions: the car’s engine uses energy with an efficiency of 0.25, whatever the speed; $c_d A_{car} = 1 \text{ m}^2$; $m_{car} = 1000 \text{ kg}$; and $C_{rr} = 0.01$.

Figure A.10. Simple theory of bike fuel consumption (energy per distance). Vertical axis is energy consumption in kWh per 100 km. Assumptions: the bike’s engine (that’s you!) uses energy with an efficiency of 0.25; the drag-area of the cyclist is $0.75 \text{ m}^2$; the cyclist+bike’s mass is 90 kg; and $C_{rr} = 0.005$.

Figure A.11. Simple theory of train energy consumption, per passenger, for an eight-carriage train carrying 584 passengers. Vertical axis is energy consumption in kWh per 100 p-km. Assumptions: the train’s engine uses energy with an efficiency of 0.90; $c_d A_{train} = 11 \text{ m}^2$; $m_{train} = 400 000 \text{ kg}$; and $C_{rr} = 0.002$. 
Cars

Electric cars?

Range limited by energy density of batteries:

Lead-acid: 40 Wh/kg (200 km)
Lithium: 120 Wh/kg (500 km)

100x less than gasoline

Figure A.14. Theory of electric car range (horizontal axis) and transport cost (vertical axis) as a function of battery mass, for two battery technologies. A car with 500 kg of old batteries, with an energy density of 40 Wh per kg, has a range of 180 km. With the same weight of modern batteries, delivering 120 Wh per kg, an electric car can have a range of more than 500 km. Both cars would have an energy cost of about 13 kWh per 100 km. These numbers allow for a battery charging efficiency of 85%.
Cars

Electric cars have advantages over ICE in terms of torque as well as engine efficiency.

Mackay: Even with “dirty” electrical energy, electric cars are at least as “green” as fossil cars. (Power consumption of 20 kWh/100 km with grid electricity carbon footprint of 500 g/kWh leads to effective emissions of 100 g CO₂/km.)