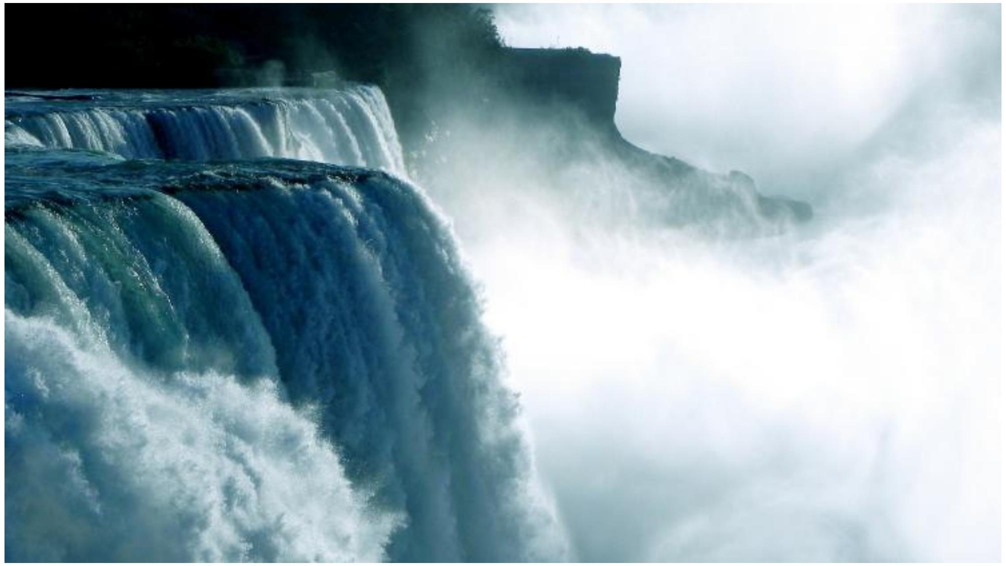
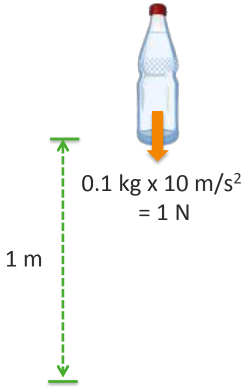
Measuring energy

Professor Arno Smets





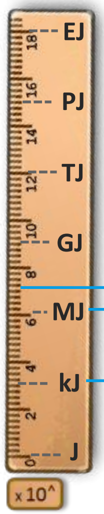
Energy

The ability of a system to do work

Joule (J) – *the unit of energy*

The energy required to move an object by 1 metre (m) against a force of 1 Newton (N)

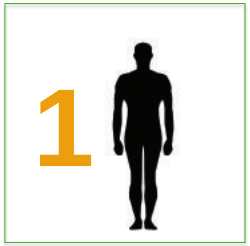
$1 J = 0.1 kg \times 10 m/s^2 \times 1 m = 1 N.m$



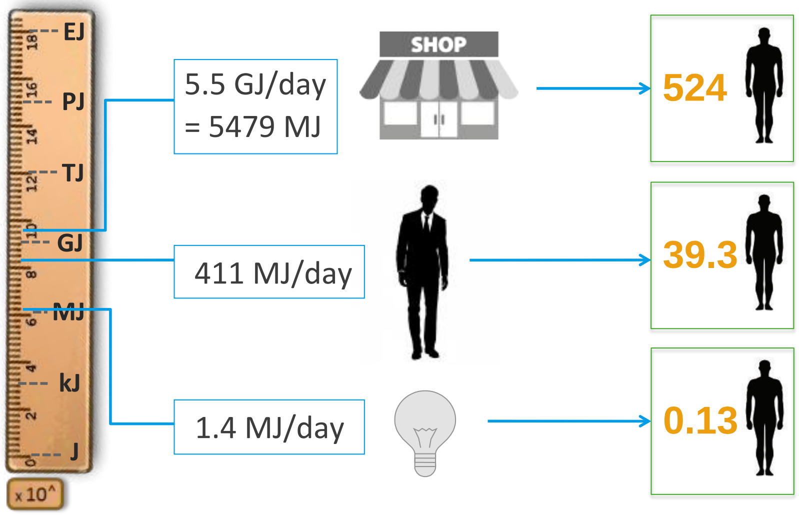
1 Human unit = 10.46 MJ

1 Mega Joule = 10^6 J

1 kilo Joule = 10^3 J



Daily food requirement
= 10.46 MJ



5.5 GJ/day
= 5479 MJ

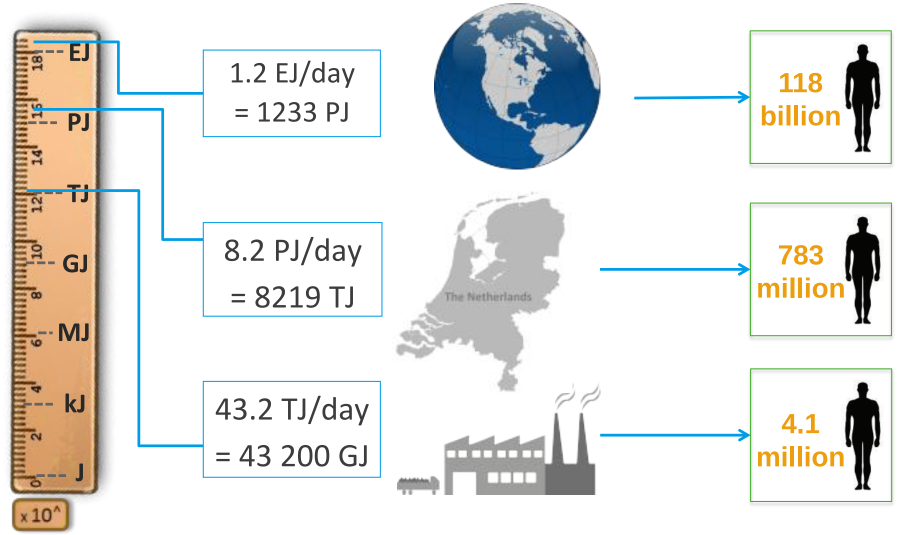
524

411 MJ/day

39.3

1.4 MJ/day

0.13



1.2 EJ/day
= 1233 PJ

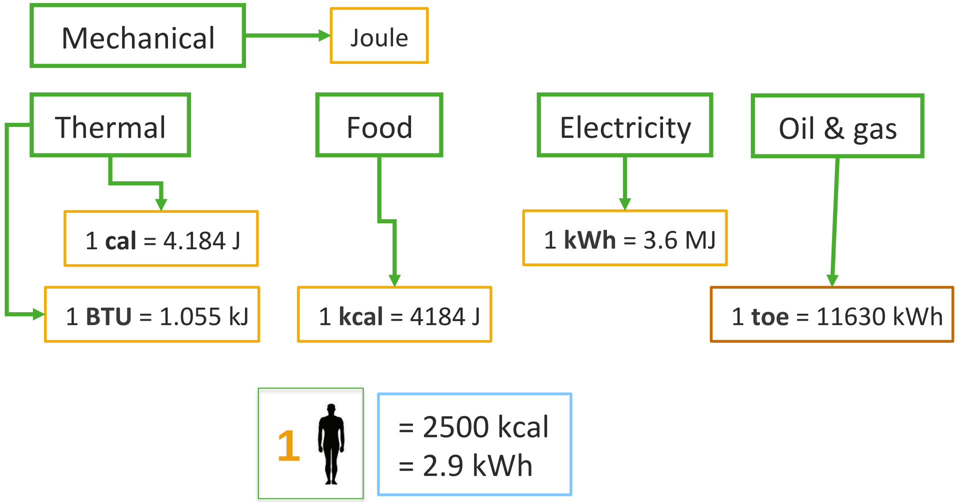
118 billion

8.2 PJ/day
= 8219 TJ

783 million

43.2 TJ/day
= 43 200 GJ

4.1 million



Mechanical → Joule

Thermal → 1 **cal** = 4.184 J

Thermal → 1 **BTU** = 1.055 kJ

Food → 1 **kcal** = 4184 J

Electricity → 1 **kWh** = 3.6 MJ

Oil & gas → 1 **toe** = 11630 kWh

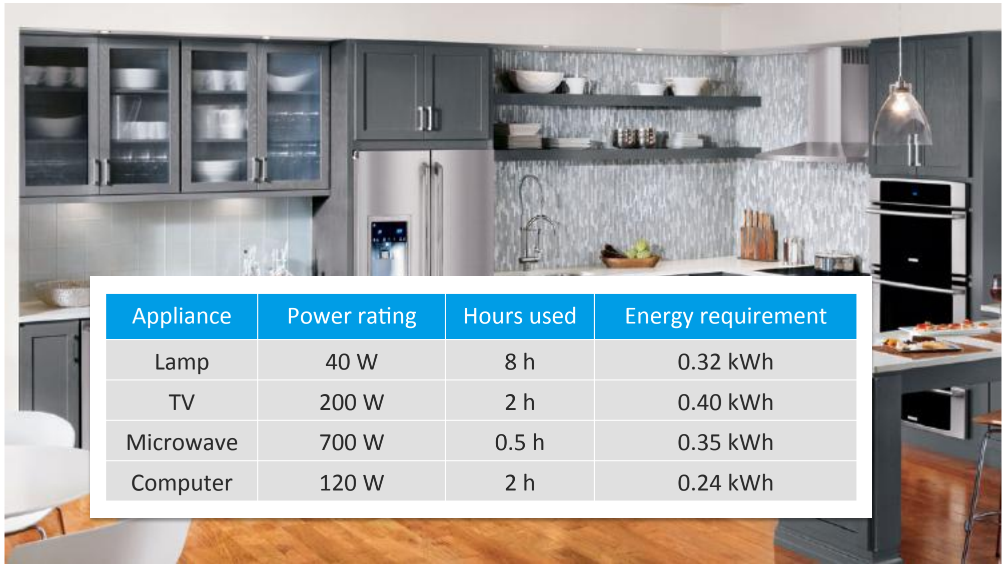
1
= 2500 kcal
= 2.9 kWh

Power
The rate at which work is done; the amount of energy spent per unit time.

Watt – *the unit of power*
When a system produces/consumes 1 Joule of energy in 1 second, the system has 1 Watt (W) of power.

$$1\ W = 1\ J/s$$

1 **hp** = 746 W



Appliance	Power rating	Hours used	Energy requirement
Lamp	40 W	8 h	0.32 kWh
TV	200 W	2 h	0.40 kWh
Microwave	700 W	0.5 h	0.35 kWh
Computer	120 W	2 h	0.24 kWh

Energy Conversion

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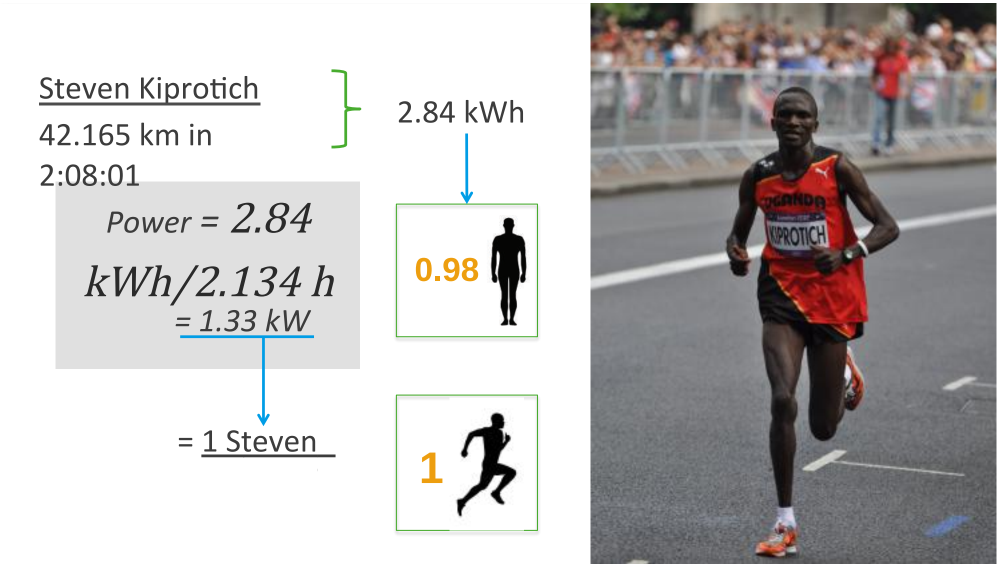


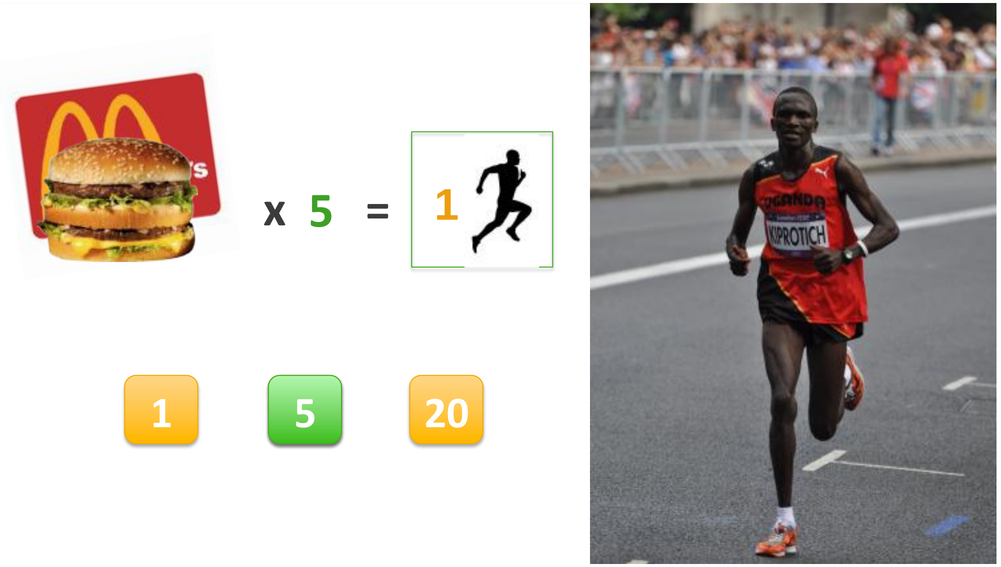
Steven Kiprotich

42.165 km in 2:08:01

2.84 kWh

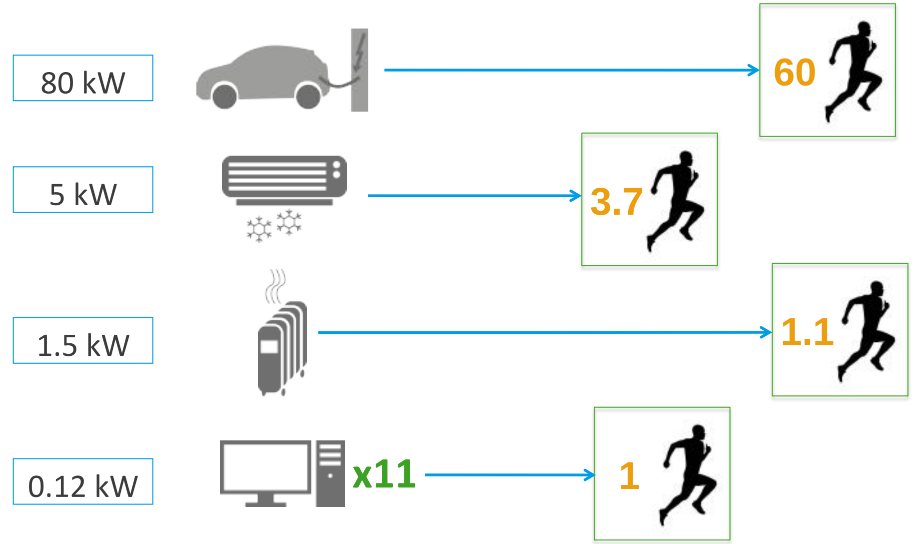
Power = 2.84 kWh/2.134 h = 1.33 kW

= 1 Steven



x 5 = 1

1 5 20



80 kW

60

5 kW

3.7

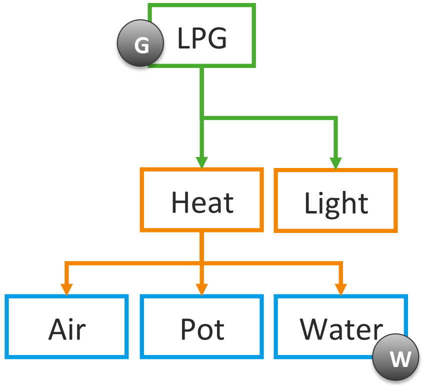
1.5 kW

1.1

0.12 kW

x11

1

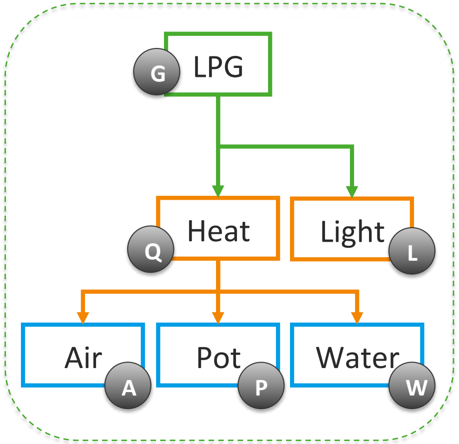


Law of conservation of energy

Energy can neither be created nor destroyed; it can only be *converted* from one from to another

$$G = Q + L$$

$$Q = A + P + W$$

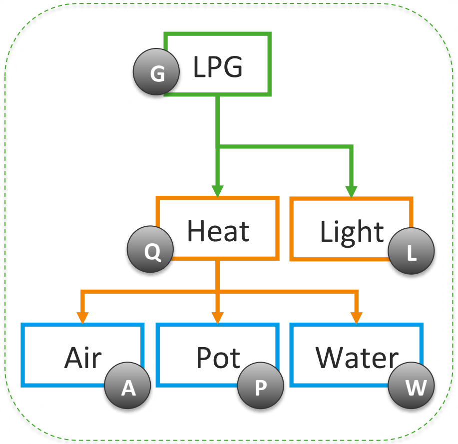


$$G > Q$$

$$Q > W$$

Exergy

The *exergy* content of an energy carrier is the maximum amount of work that can be extracted from it



Steven Kiprotich

54kg → speed 5.5 m/s } 724 W

↓

Exergy: 1.5 kWh

Total power consumption: 2.84 kWh

↓

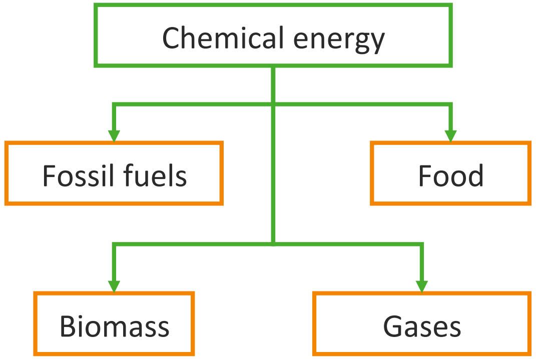
1.34 kWh

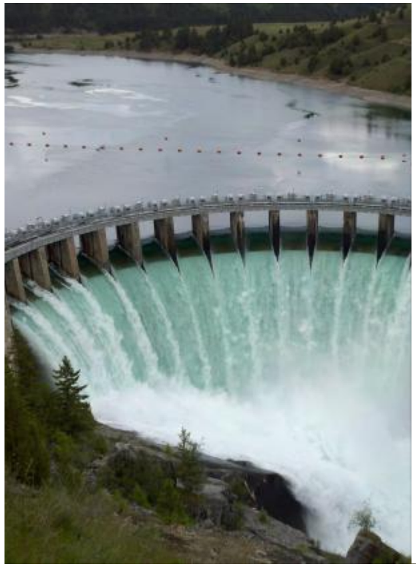
Energy carriers

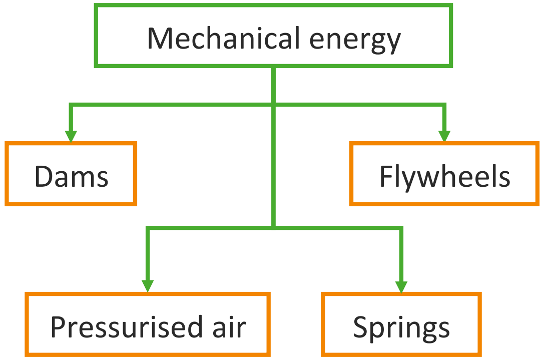
Professor Arno Smets

Energy carrier

An energy carrier is a substance or phenomenon that contains energy which can be converted to mechanical work or heat, or used to operate chemical or physical processes

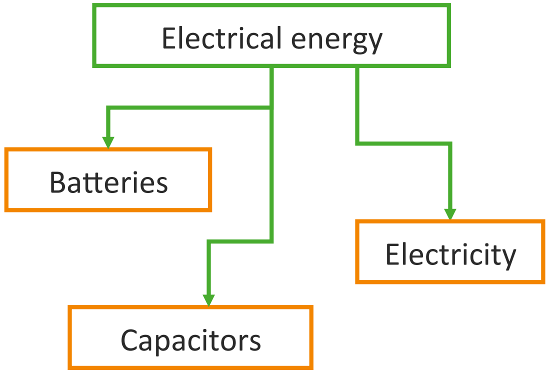






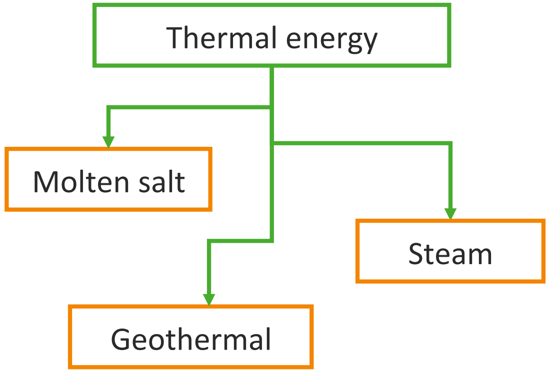
Mechanical energy

- Dams
- Flywheels
- Pressurised air
- Springs



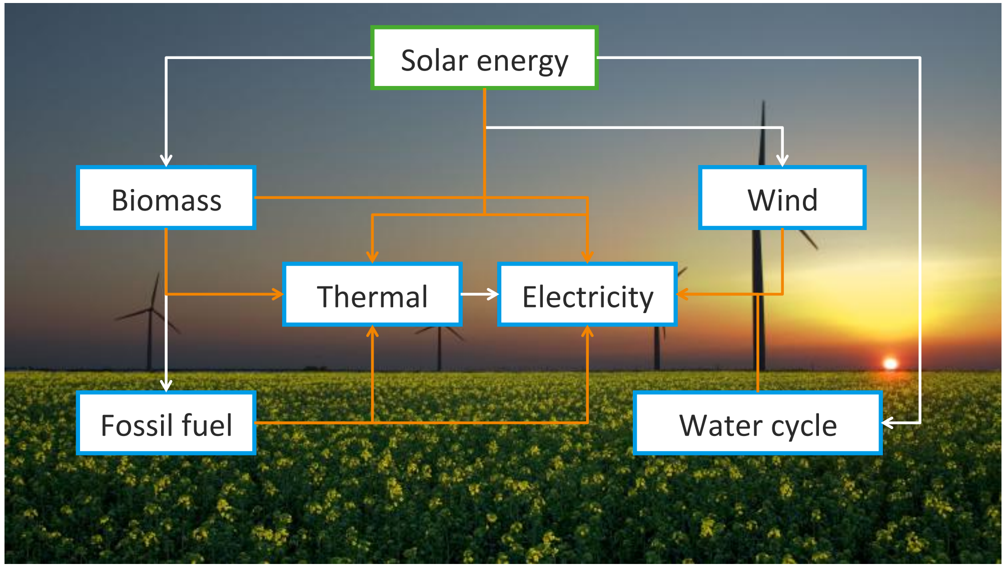
Electrical energy

- Batteries
- Electricity
- Capacitors



Thermal energy

- Molten salt
- Steam
- Geothermal



Solar energy

Biomass

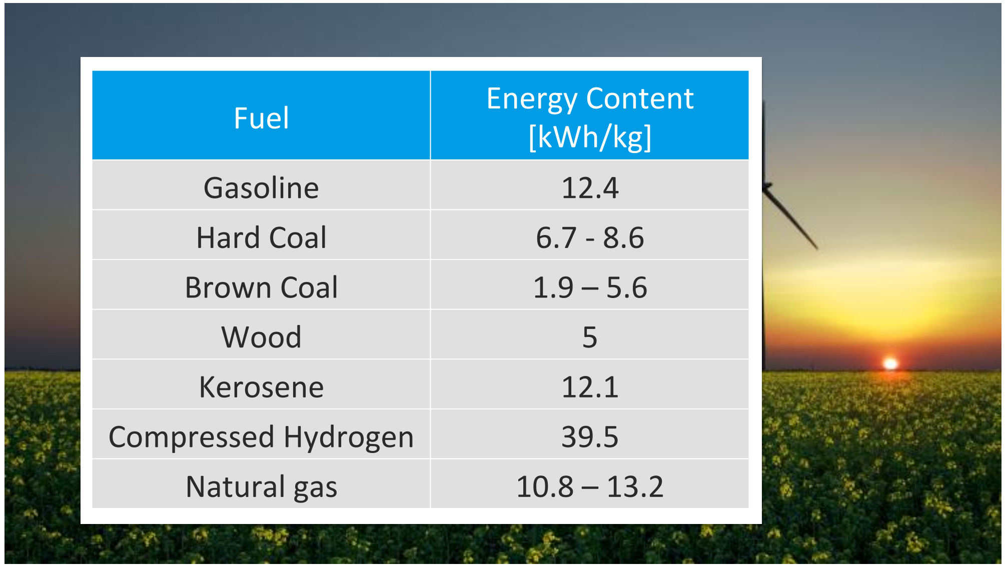
Wind

Thermal

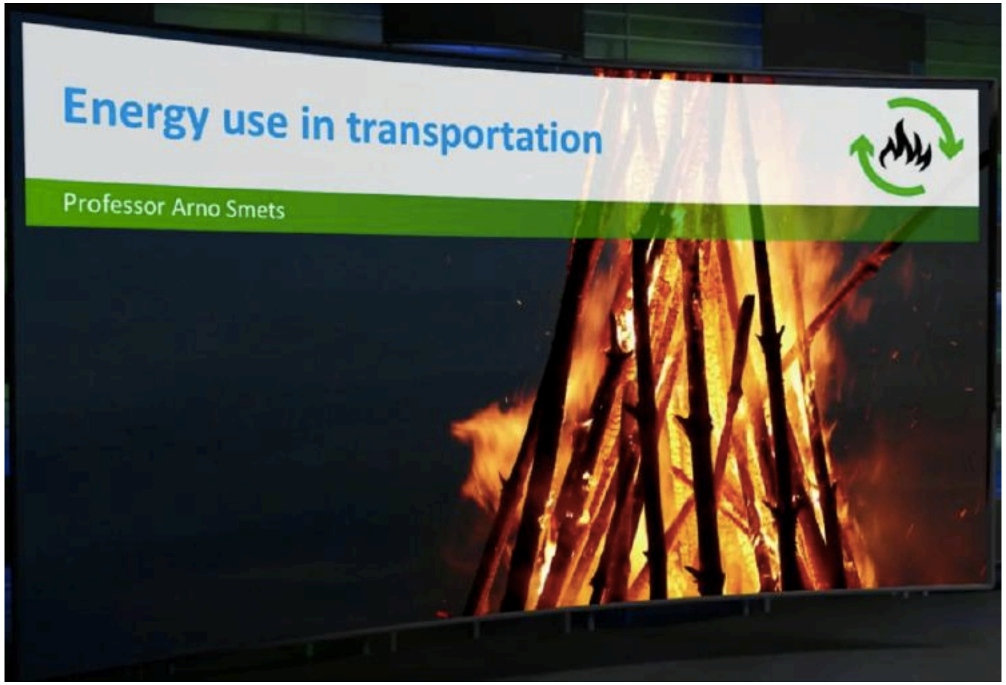
Electricity

Fossil fuel

Water cycle

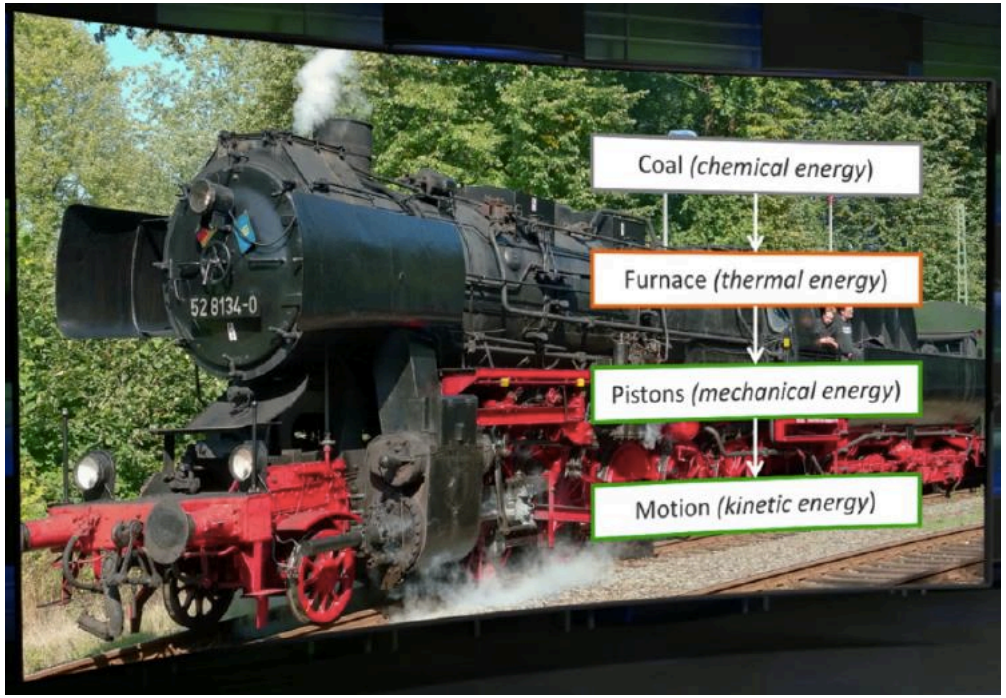


Fuel	Energy Content [kWh/kg]
Gasoline	12.4
Hard Coal	6.7 - 8.6
Brown Coal	1.9 – 5.6
Wood	5
Kerosene	12.1
Compressed Hydrogen	39.5
Natural gas	10.8 – 13.2



Energy use in transportation

Professor Arno Smets

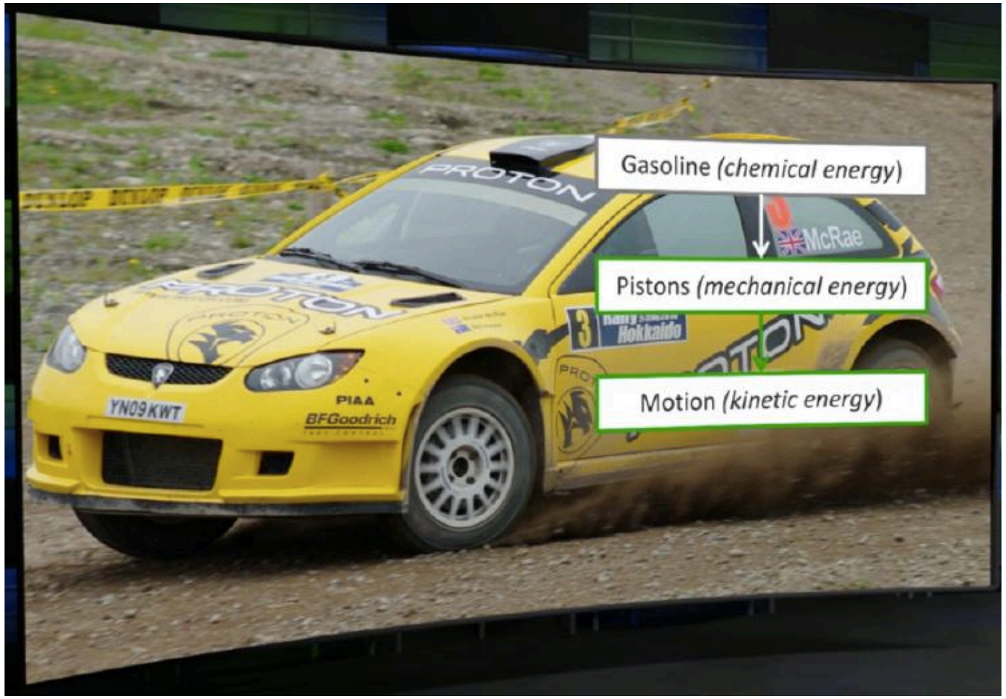


Coal *(chemical energy)*

Furnace *(thermal energy)*

Pistons *(mechanical energy)*

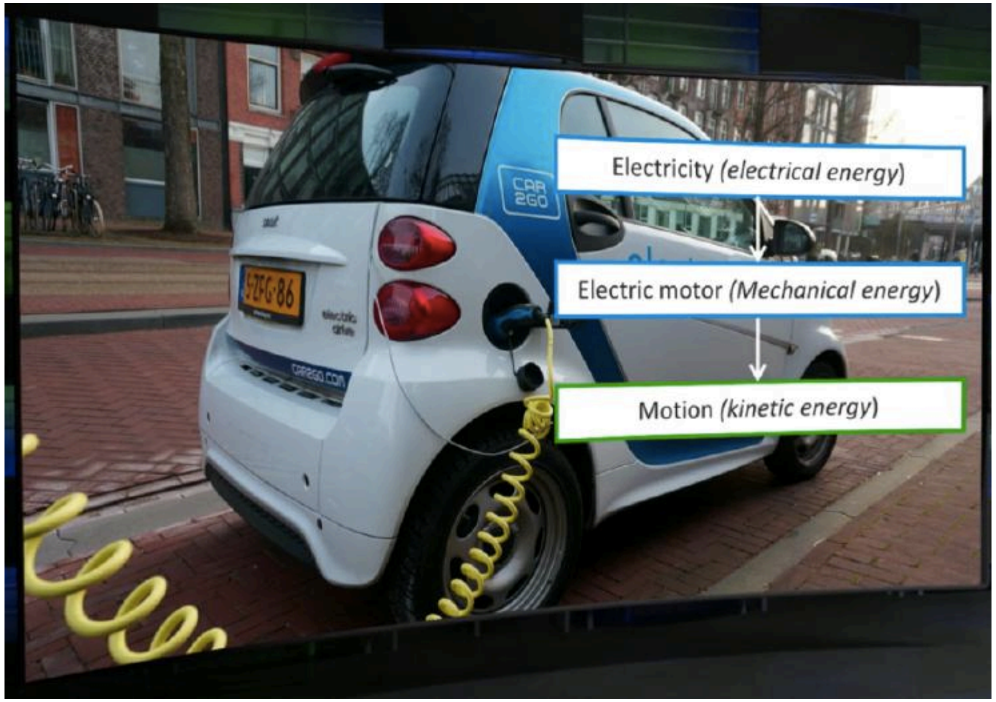
Motion *(kinetic energy)*



Gasoline *(chemical energy)*

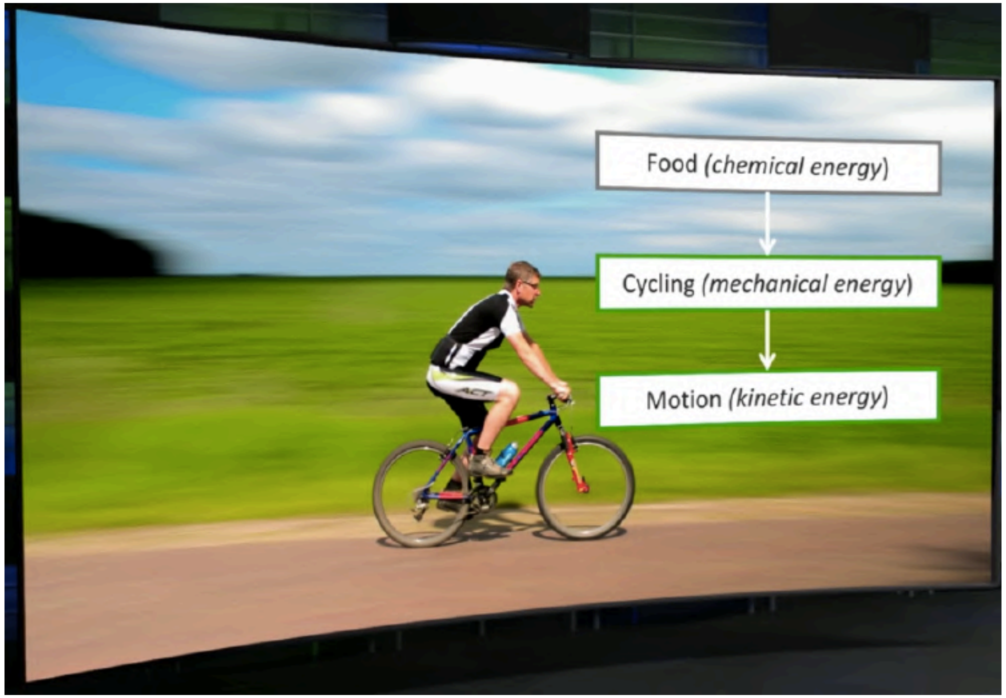
Pistons *(mechanical energy)*

Motion *(kinetic energy)*


Electricity *(electrical energy)*

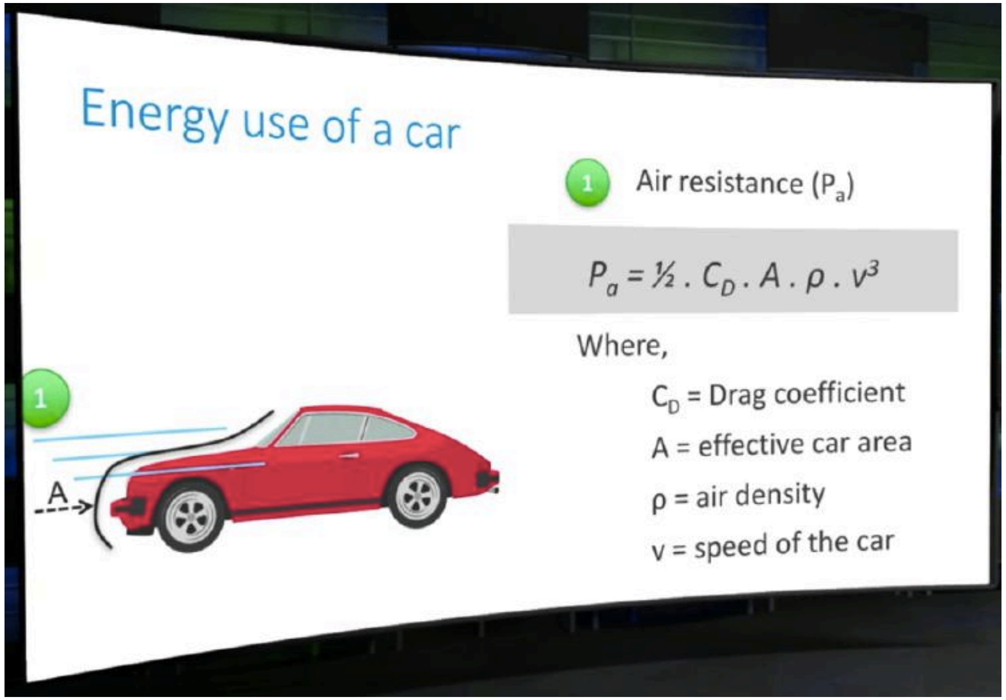
Electric motor *(Mechanical energy)*

Motion *(kinetic energy)*


Food *(chemical energy)*

Cycling *(mechanical energy)*

Motion *(kinetic energy)*


Energy use of a car

① Air resistance (P_a)

$$P_a = ½ \,.\, C_D \,.\, A \,.\, \rho \,.\, v^3$$

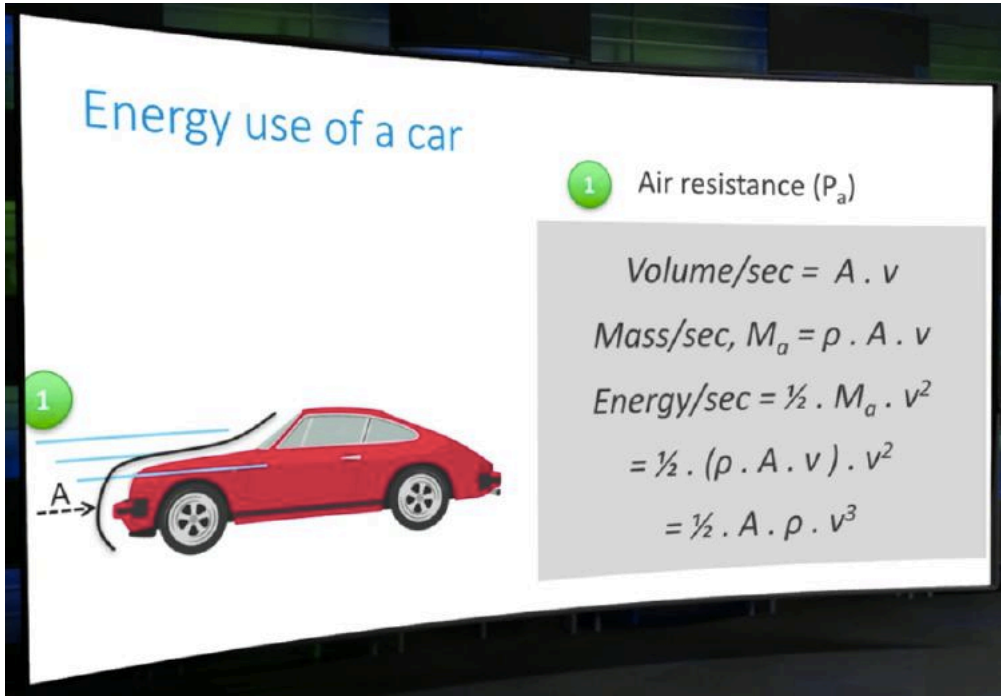
Where,

C_D = Drag coefficient

A = effective car area

ρ = air density

v = speed of the car


Energy use of a car

① Air resistance (P_a)

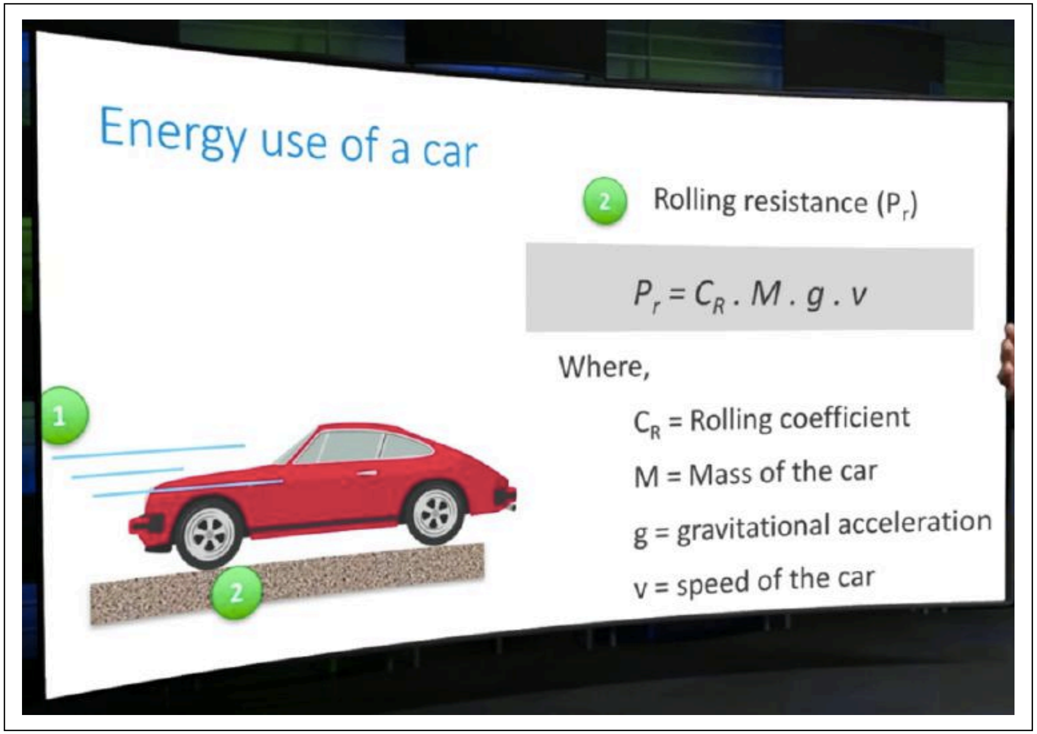
$$\text{Volume/sec} = A \,.\, v$$

$$\text{Mass/sec, } M_a = \rho \,.\, A \,.\, v$$

$$\text{Energy/sec} = ½ \,.\, M_a \,.\, v^2$$

$$= ½ \,.\, (\rho \,.\, A \,.\, v) \,.\, v^2$$

$$= ½ \,.\, A \,.\, \rho \,.\, v^3$$



Energy use of a car

② Rolling resistance (P_r)

$$P_r = C_R \, . \, M \, . \, g \, . \, v$$

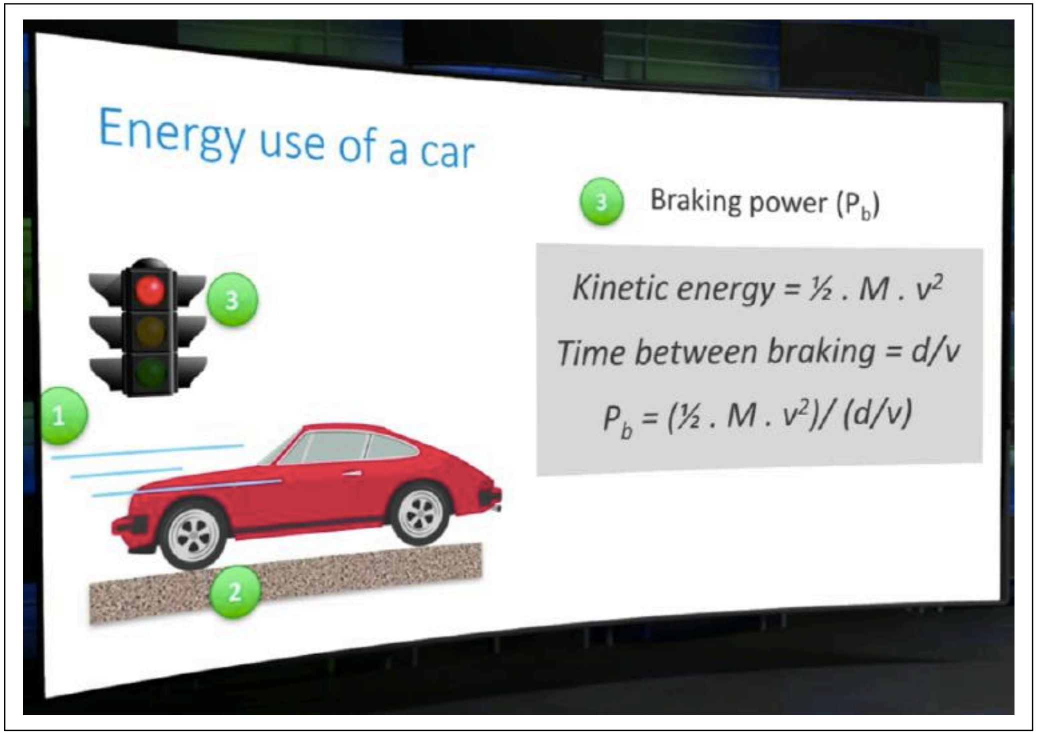
Where,

C_R = Rolling coefficient

M = Mass of the car

g = gravitational acceleration

v = speed of the car



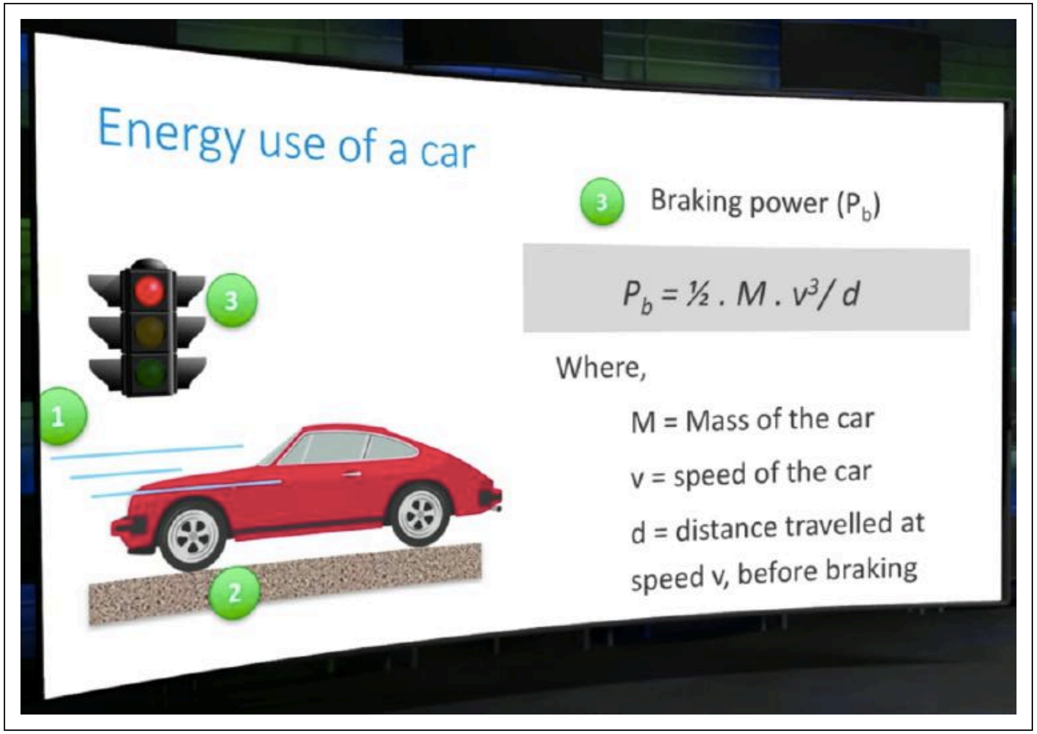
Energy use of a car

③ Braking power (P_b)

$$\text{Kinetic energy} = ½ \, . \, M \, . \, v^2$$

$$\text{Time between braking} = d/v$$

$$P_b = (½ \, . \, M \, . \, v^2)/(d/v)$$



Energy use of a car

③ Braking power (P_b)

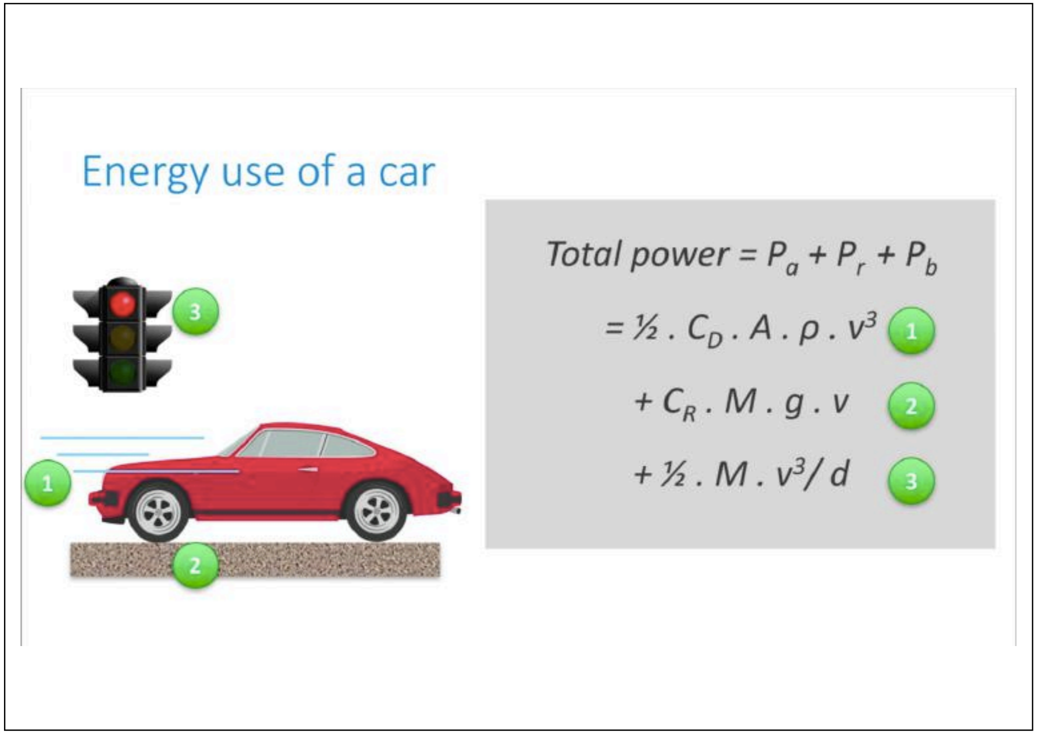
$$P_b = ½ \, . \, M \, . \, v^3/d$$

Where,

M = Mass of the car

v = speed of the car

d = distance travelled at speed v, before braking



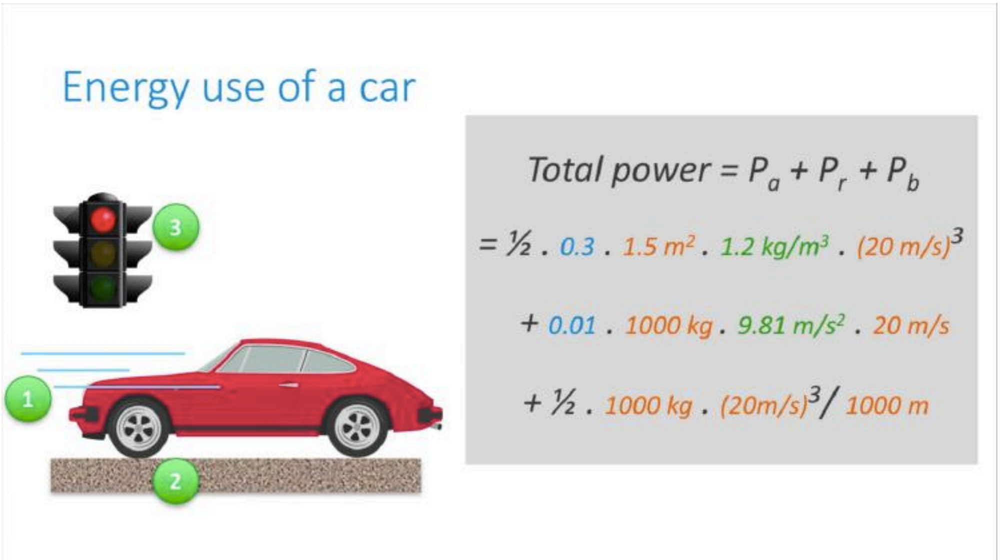
Energy use of a car

$$\text{Total power} = P_a + P_r + P_b$$

$$= ½ \, . \, C_D \, . \, A \, . \, \rho \, . \, v^3 \quad ①$$

$$+ \, C_R \, . \, M \, . \, g \, . \, v \quad ②$$

$$+ \, ½ \, . \, M \, . \, v^3/d \quad ③$$



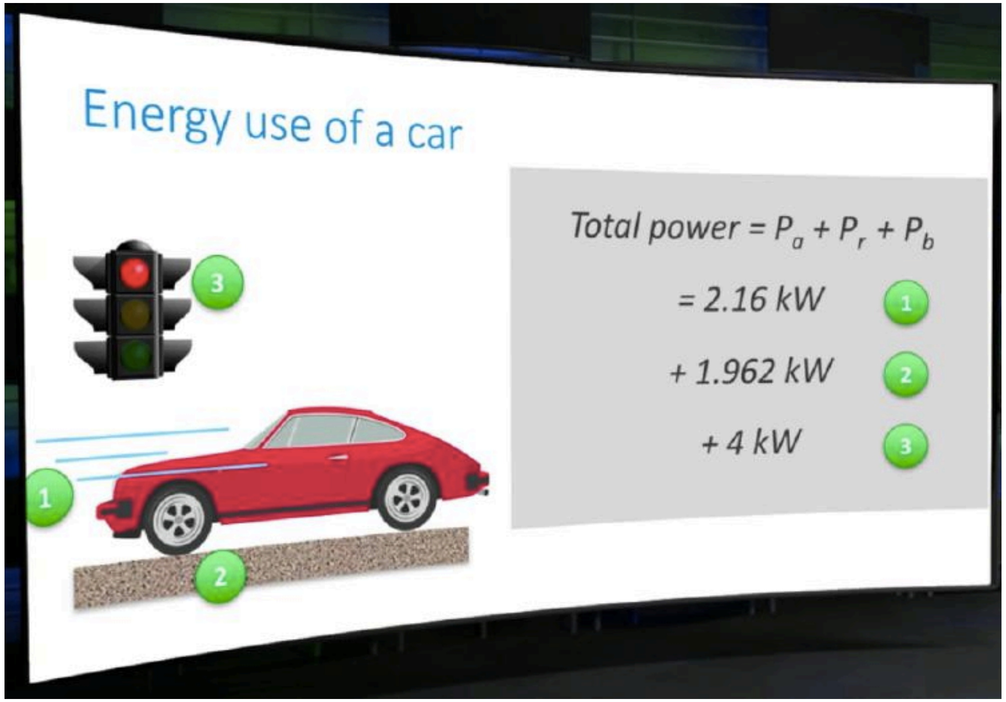
Energy use of a car

$$\text{Total power} = P_a + P_r + P_b$$

$$= \tfrac{1}{2} \cdot 0.3 \cdot 1.5\ \text{m}^2 \cdot 1.2\ \text{kg/m}^3 \cdot (20\ \text{m/s})^3$$

$$+\ 0.01 \cdot 1000\ \text{kg} \cdot 9.81\ \text{m/s}^2 \cdot 20\ \text{m/s}$$

$$+\ \tfrac{1}{2} \cdot 1000\ \text{kg} \cdot (20\text{m/s})^3 / 1000\ \text{m}$$



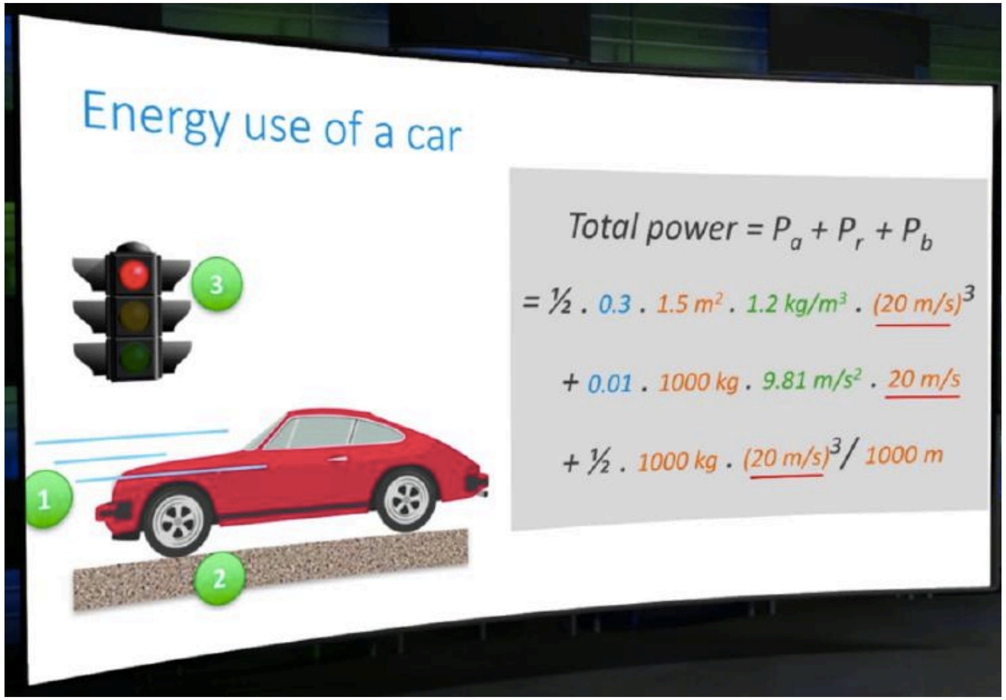
Energy use of a car

$$\text{Total power} = P_a + P_r + P_b$$

$= 2.16$ kW ①

$+ 1.962$ kW ②

$+ 4$ kW ③



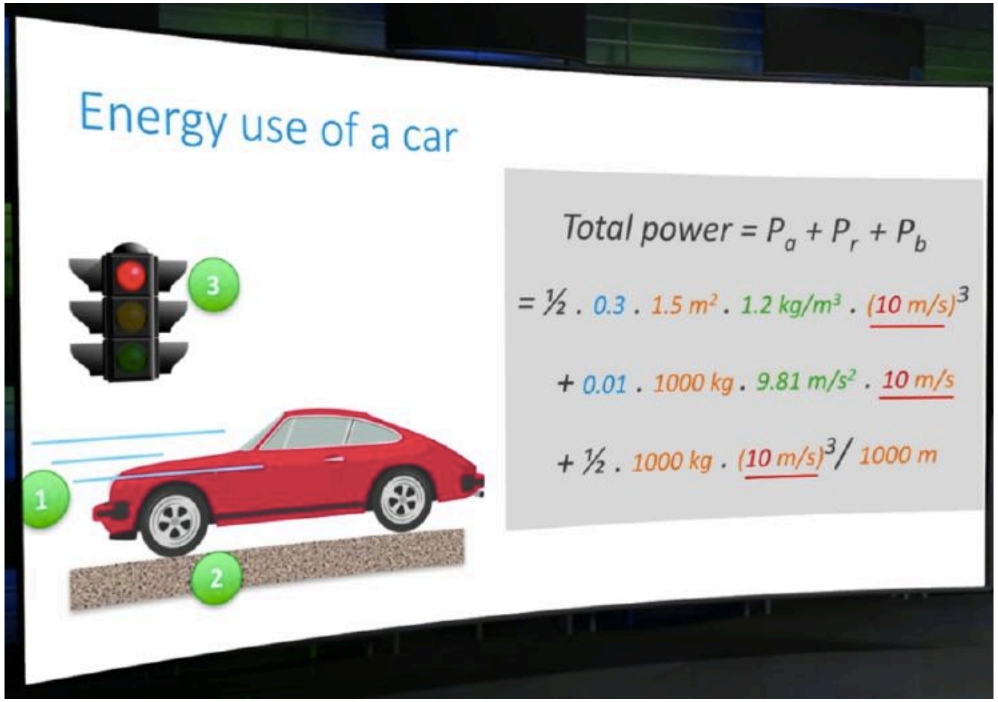
Energy use of a car

$$\text{Total power} = P_a + P_r + P_b$$

$$= \tfrac{1}{2} \cdot 0.3 \cdot 1.5\ \text{m}^2 \cdot 1.2\ \text{kg/m}^3 \cdot \underline{(20\ \text{m/s})}^3$$

$$+\ 0.01 \cdot 1000\ \text{kg} \cdot 9.81\ \text{m/s}^2 \cdot \underline{20\ \text{m/s}}$$

$$+\ \tfrac{1}{2} \cdot 1000\ \text{kg} \cdot \underline{(20\ \text{m/s})}^3 / 1000\ \text{m}$$



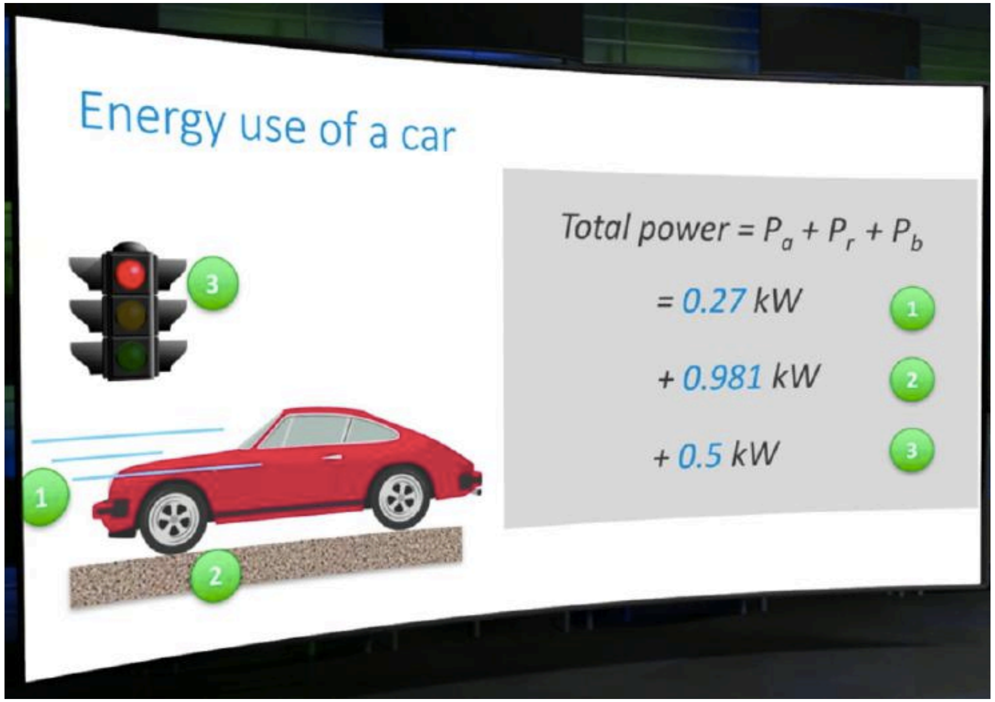
Energy use of a car

$$\text{Total power} = P_a + P_r + P_b$$

$$= \tfrac{1}{2} \cdot 0.3 \cdot 1.5\ \text{m}^2 \cdot 1.2\ \text{kg/m}^3 \cdot \underline{(10\ \text{m/s})}^3$$

$$+\ 0.01 \cdot 1000\ \text{kg} \cdot 9.81\ \text{m/s}^2 \cdot \underline{10\ \text{m/s}}$$

$$+\ \tfrac{1}{2} \cdot 1000\ \text{kg} \cdot \underline{(10\ \text{m/s})}^3 / 1000\ \text{m}$$



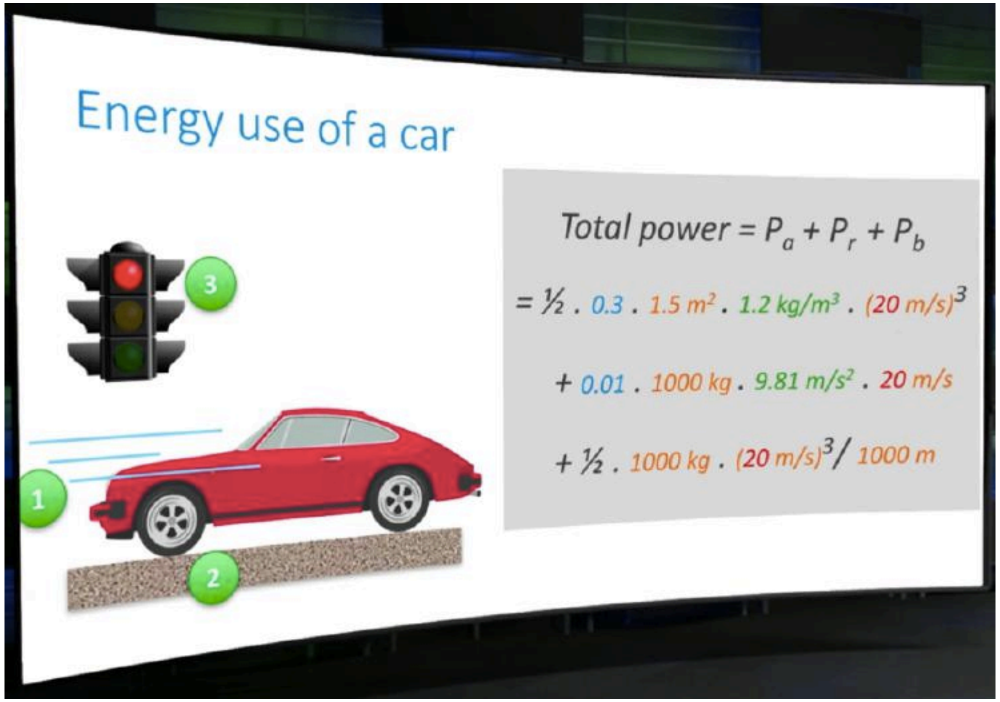
Energy use of a car

$\text{Total power} = P_a + P_r + P_b$

$= 0.27$ kW ①

$+ 0.981$ kW ②

$+ 0.5$ kW ③



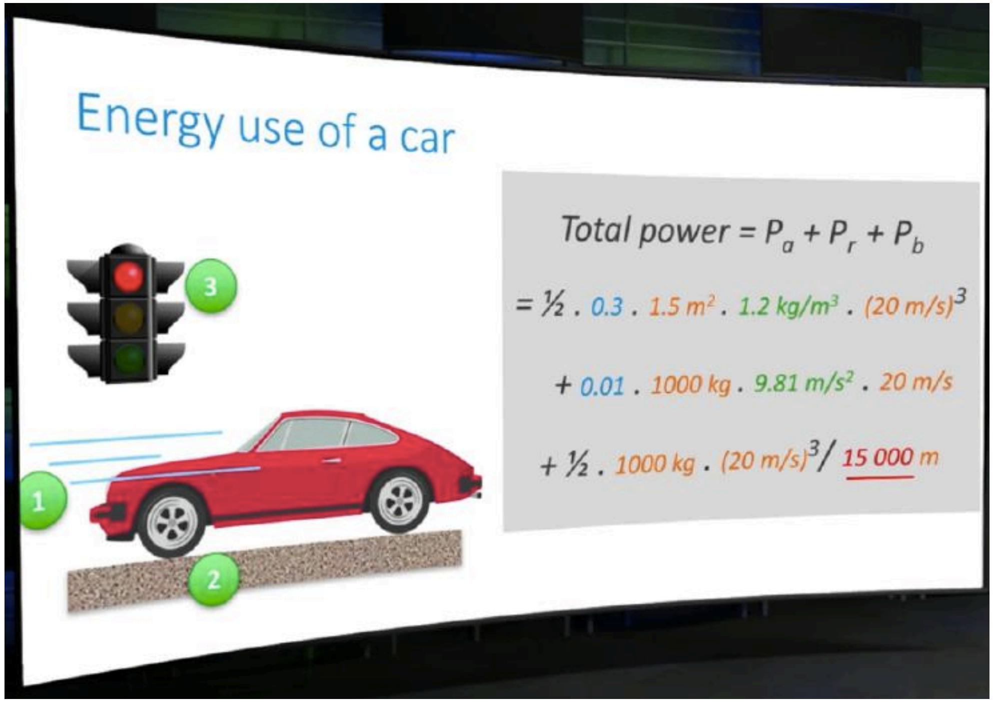
Energy use of a car

$\text{Total power} = P_a + P_r + P_b$

$= ½ \,.\, 0.3 \,.\, 1.5\ m^2 \,.\, 1.2\ kg/m^3 \,.\, (20\ m/s)^3$

$+ 0.01 \,.\, 1000\ kg \,.\, 9.81\ m/s^2 \,.\, 20\ m/s$

$+ ½ \,.\, 1000\ kg \,.\, (20\ m/s)^3 /\ 1000\ m$



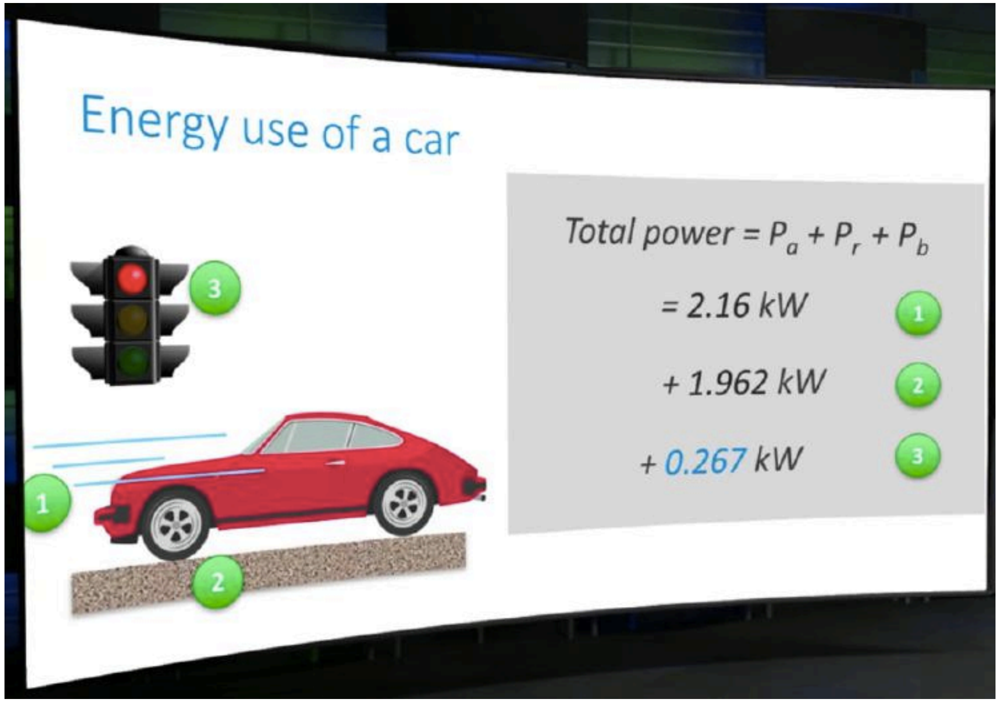
Energy use of a car

$\text{Total power} = P_a + P_r + P_b$

$= ½ \,.\, 0.3 \,.\, 1.5\ m^2 \,.\, 1.2\ kg/m^3 \,.\, (20\ m/s)^3$

$+ 0.01 \,.\, 1000\ kg \,.\, 9.81\ m/s^2 \,.\, 20\ m/s$

$+ ½ \,.\, 1000\ kg \,.\, (20\ m/s)^3 /\ \underline{15\,000}\ m$



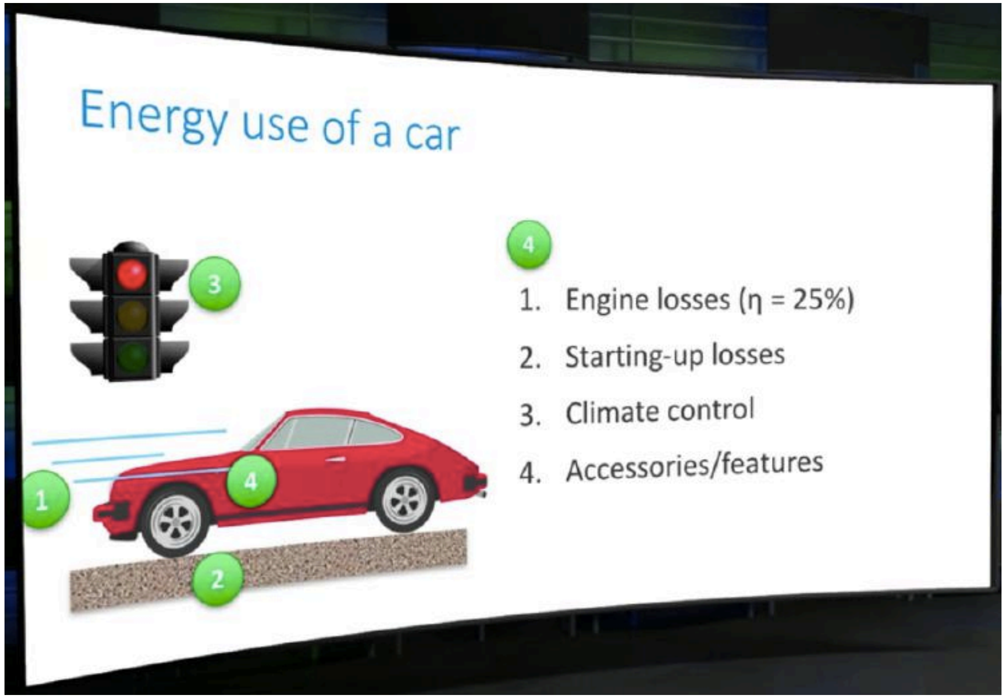
Energy use of a car

$\text{Total power} = P_a + P_r + P_b$

$= 2.16$ kW ①

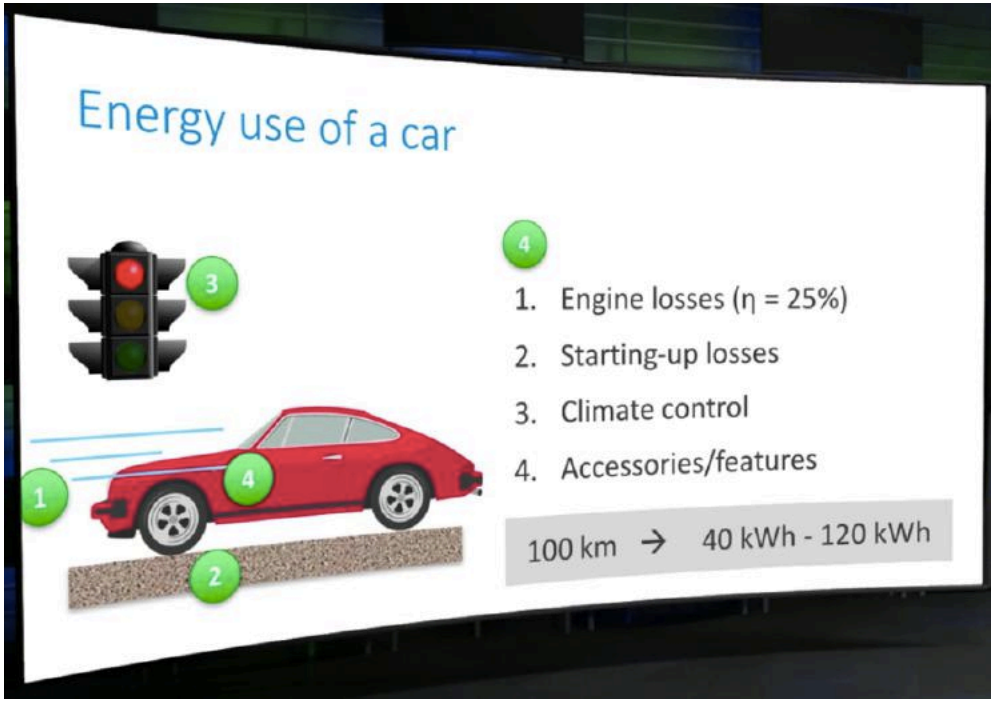
$+ 1.962$ kW ②

$+ 0.267$ kW ③



Energy use of a car

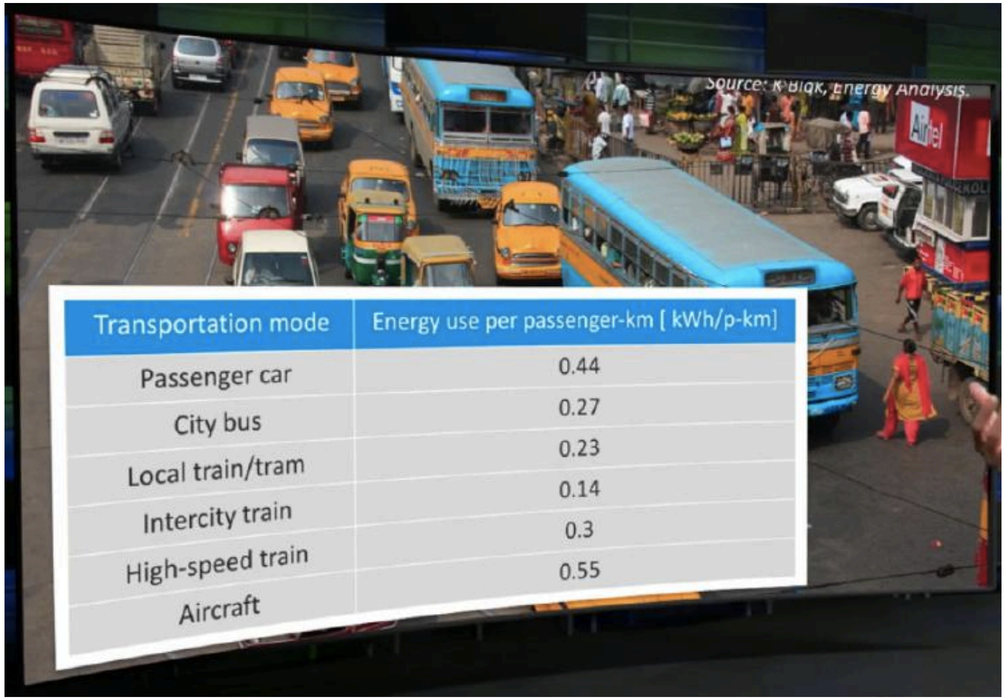
1. Engine losses (η = 25%)
2. Starting-up losses
3. Climate control
4. Accessories/features



Energy use of a car

1. Engine losses (η = 25%)
2. Starting-up losses
3. Climate control
4. Accessories/features

100 km → 40 kWh - 120 kWh

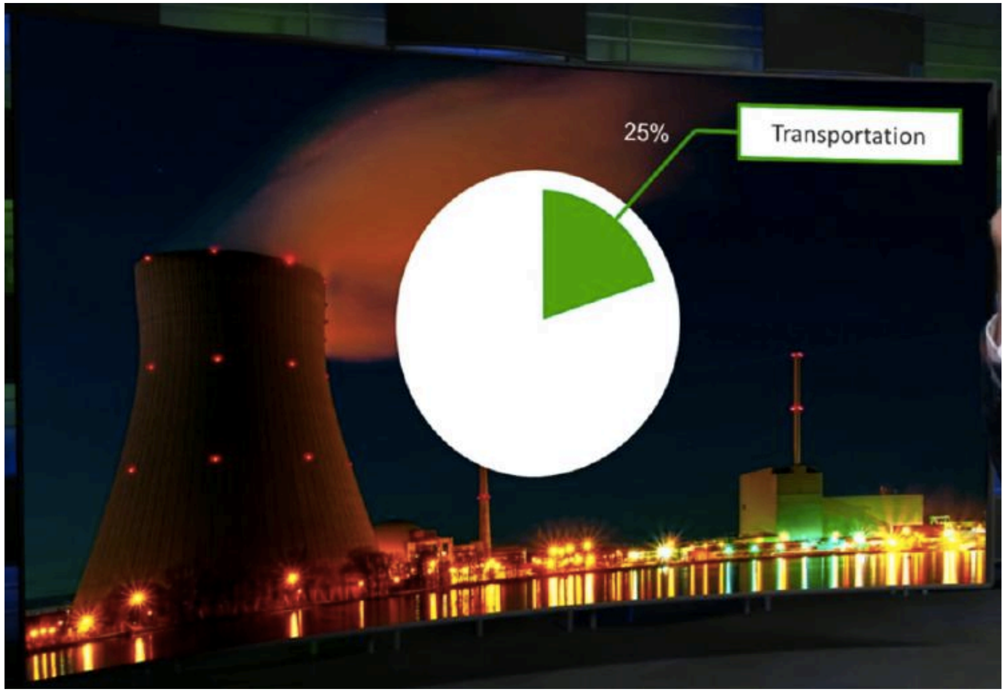


Source: K Blok, Energy Analysis.

Transportation mode	Energy use per passenger-km [kWh/p-km]
Passenger car	0.44
City bus	0.27
Local train/tram	0.23
Intercity train	0.14
High-speed train	0.3
Aircraft	0.55

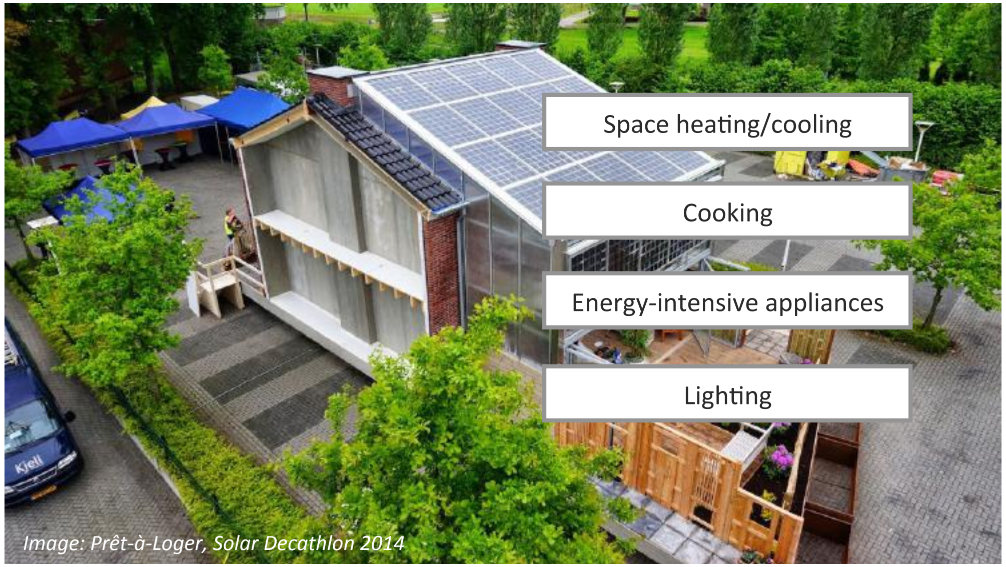
Country	Vehicles per 1000 people
United States	809
The Netherlands	528
United Kingdom	519
Brazil	249
China	128
India	18

Source: World Bank Data, 2014.



Energy use in buildings

Professor Arno Smets



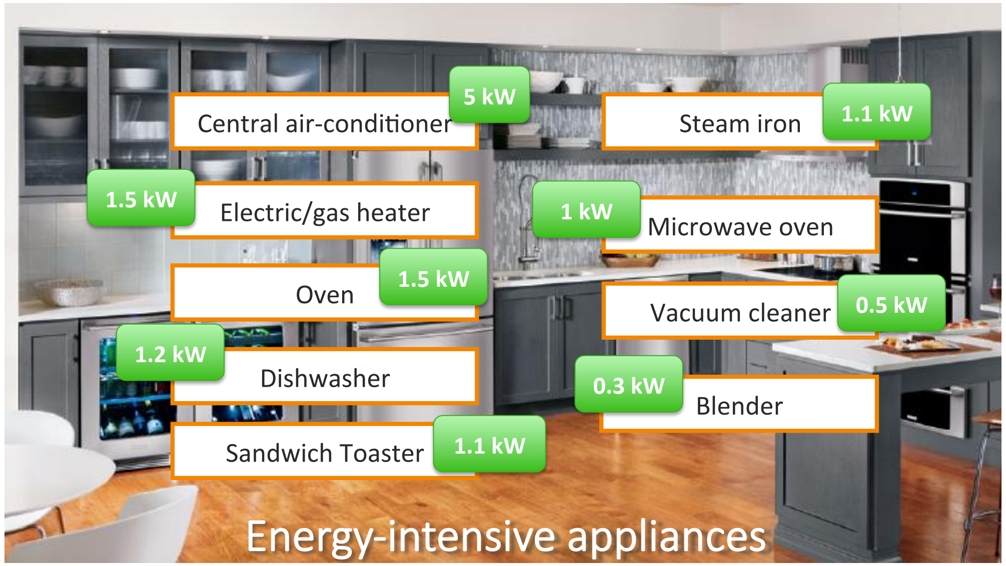
Space heating/cooling

Cooking

Energy-intensive appliances

Lighting

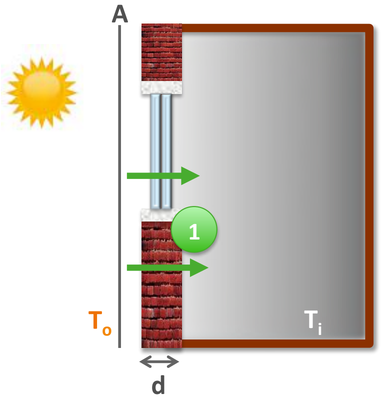
Image: Prêt-à-Loger, Solar Decathlon 2014



Energy-intensive appliances

Central air-conditioner	5 kW
Electric/gas heater	1.5 kW
Oven	1.5 kW
Dishwasher	1.2 kW
Sandwich Toaster	1.1 kW
Steam iron	1.1 kW
Microwave oven	1 kW
Vacuum cleaner	0.5 kW
Blender	0.3 kW

Heat transfer



① Conduction through walls (Q_c)

$$Q_C = \lambda \cdot \Delta T/d \cdot A$$

Where,

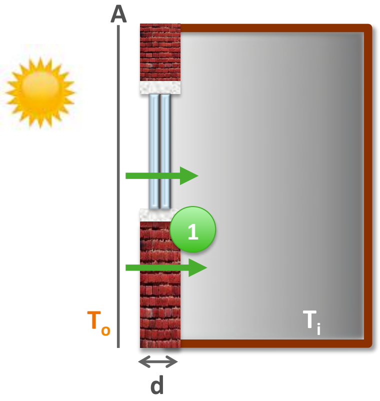
λ = Thermal conductivity of wall

$\Delta T = T_o - T_i$

d = wall thickness

A = wall surface area

Heat transfer



① Conduction through walls (Q_c)

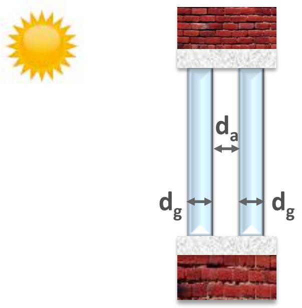
$$Q_C = \lambda \cdot \Delta T/d \cdot A$$

$$\lambda/d = k$$

k = thermal conductivity

$$Q_C = k \cdot A \cdot \Delta T$$

Heat transfer



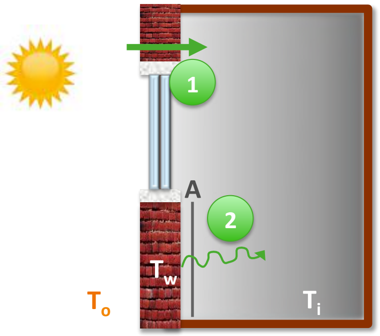
① Conduction through windows (Q_c)

$$1/k = d/\lambda = R$$

R = Thermal resistance

$$\begin{aligned} R_{window} &= R_g + R_a + R_g \\ &= {}^1/k_g + {}^1/k_a + {}^1/k_g \\ &= {}^{d_g}/\lambda_g + {}^{d_a}/\lambda_a + {}^{d_g}/\lambda_g \end{aligned}$$

Heat transfer



② Convection from walls (Q_w)

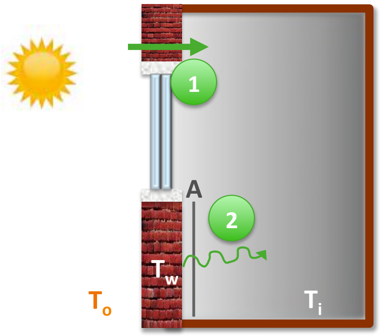
$$Q_w = h \cdot A \cdot \Delta T$$

h = convection heat transfer coefficient

$\Delta T = T_w - T_i$

A = wall surface area

Heat transfer



2 Convection from walls (Q_w)

$$^1/_h = R_{conv}$$

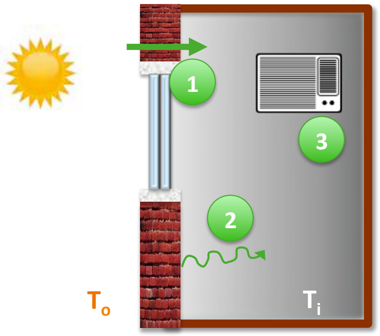
R_{conv} = Thermal resistance to convection

$$R_{wall,total} = R + R_{conv}$$

$$R_{wall,total} = {}^1/k_{wall} + {}^1/h_{wall}$$

$$U = 1/R_{wall,total} \quad [W/(m^2 \cdot K)]$$

Heat transfer



3 Ventilation (Q_v)

$$Q_v = C_P \cdot \dot{m} \cdot \Delta T$$

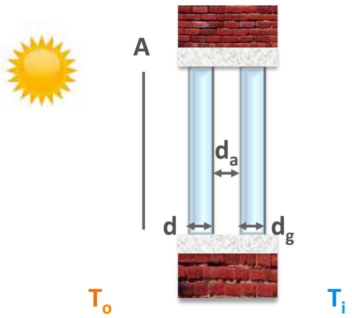
Where,

$\dot{m}$ = mass of air exchanged/second

C_P = specific heat of air

$\Delta T = T_o - T_i$

Heat transfer



1+2 Heat transfer through windows (Q_c)

$T_o = 30\ ^oC \quad T_i = 20\ ^oC \quad \Delta T=10$

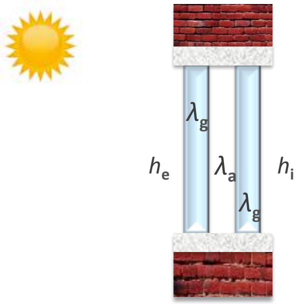
$A= 10\ m^2 \quad d_g = 3\ mm \quad d_a = 1\ cm$

$$\lambda_g = 0.96\ [W/(m \cdot K)]$$

$$\lambda_a\ (25^o) = 0.024\ [W/(m \cdot K)]]$$

Heat transfer

1+2 Conduction through windows (Q_c)



$h_e = 23\ [W/(m^2K)] \quad h_i = 8\ [W/(m^2K)]$

$$R_{d.window} = 1/h_e + {}^{dg}/\lambda_g + {}^{da}/\lambda_a + {}^{dg}/\lambda_g + 1/h_i$$

$$R_{d.window} = 1/23 + 0.003/0.96 + 0.01/0.024 + 0.003/0.96 + 1/8$$

$$R_{d.window} = 0.5914\ [m^2 \cdot K/W]$$

Heat transfer

1+2 Conduction through windows (Q_c)

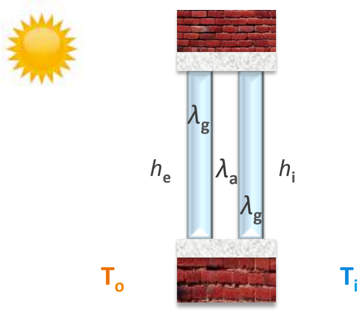
$$U = 1/R_{d.window}$$

$$U = 1.69\ [W/(m^2K)]$$

$$Q_{d.windows} = U \cdot A \cdot \Delta T$$

$$Q_{d.windows} = 1.69 \cdot 10 \cdot 10$$

$$\mathbf{Q_{d.windows} = 169\ W}$$



Heat transfer

1+2 Conduction through windows (Q_c)

$$R_{s.window} = 1/h_e + {}^{d_g}/\lambda_g + 1/h_i$$

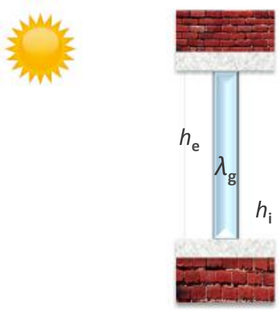
$$R_{s.window} = 1/23 + 0.003/0.96 + 1/8$$

$$R_{s.window} = 0.1716\ [m^2 \cdot K/W]$$

$$U = 1/R_{s.window} = 5.827\ [W/(m^2K)]$$

$$Q_{s.windows} = 5.827 \cdot 10 \cdot 10$$

$$\mathbf{Q_{s.windows} = 582.7\ W}$$



Heat transfer

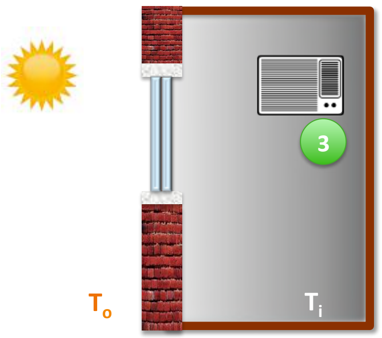
3 Ventilation Heatflow for typical house

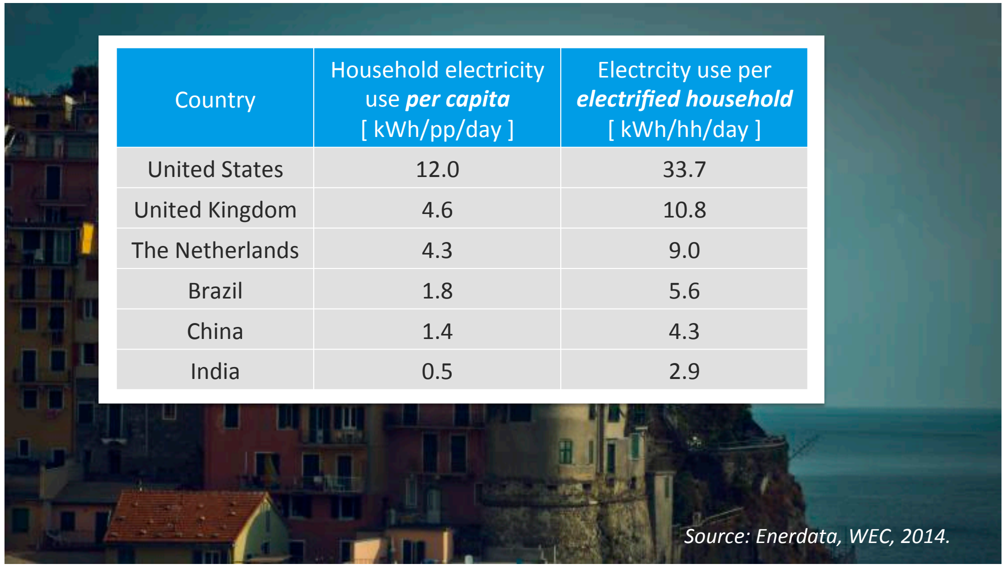
$$Q_v = C_p \cdot \dot{m} \cdot \Delta T$$

$$Q_v = C_p \cdot \rho \cdot \dot{V} \cdot \Delta T$$

$$Q_v = 1005 \cdot 1.205 \cdot 0.03 \cdot 10$$

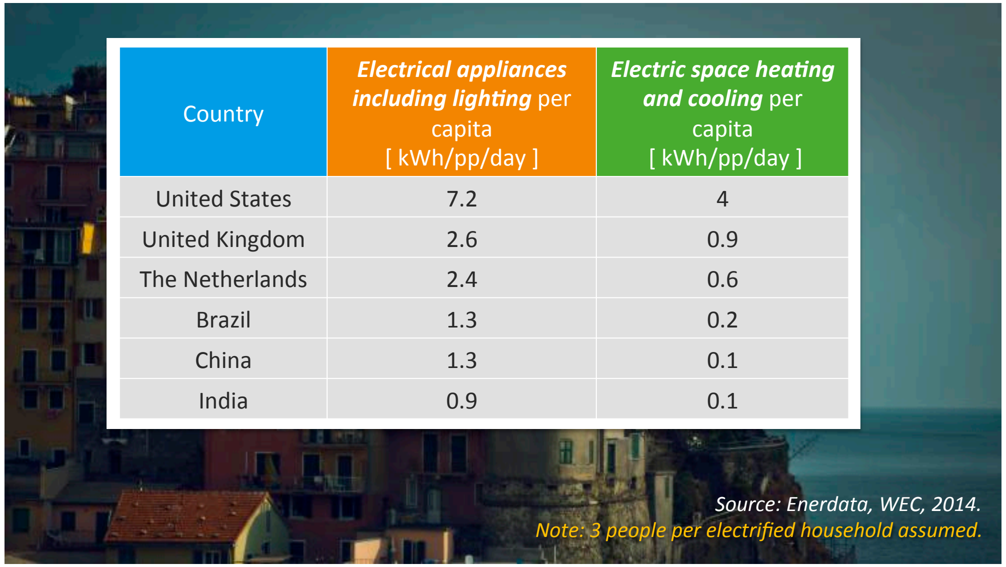
$$\mathbf{Q_v = 363\ W}$$





Country	Household electricity use ***per capita*** [kWh/pp/day]	Electrcity use per ***electrified household*** [kWh/hh/day]
United States	12.0	33.7
United Kingdom	4.6	10.8
The Netherlands	4.3	9.0
Brazil	1.8	5.6
China	1.4	4.3
India	0.5	2.9

Source: Enerdata, WEC, 2014.



Country	***Electrical appliances including lighting*** per capita [kWh/pp/day]	***Electric space heating and cooling*** per capita [kWh/pp/day]
United States	7.2	4
United Kingdom	2.6	0.9
The Netherlands	2.4	0.6
Brazil	1.3	0.2
China	1.3	0.1
India	0.9	0.1

Source: Enerdata, WEC, 2014.

Note: 3 people per electrified household assumed.

Energy use in industry

Professor Arno Smets

Energy-intensive industry

- Iron & steel
- Aluminium
- Petrochemicals
- Cement

Light industry

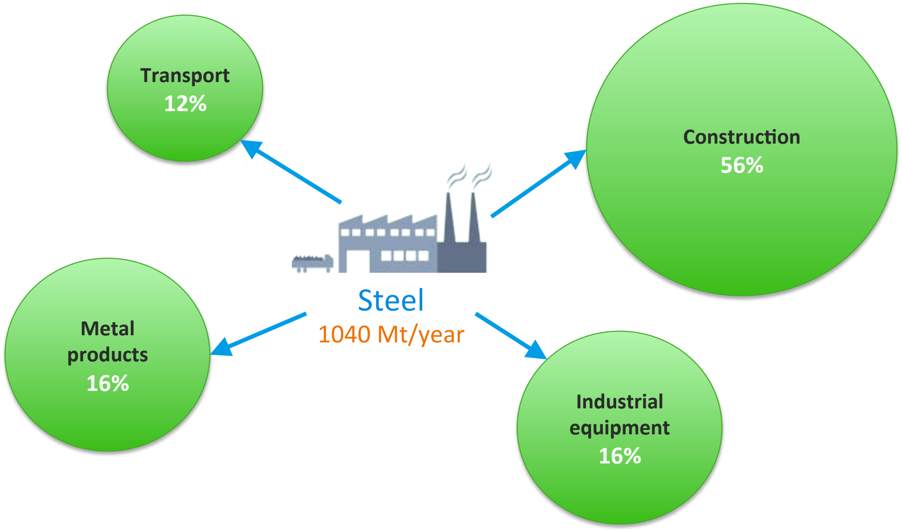
Food & drugs

Textile

Automobile

Pulp & paper

Image: Study Material for Food-tech



Transport
12%

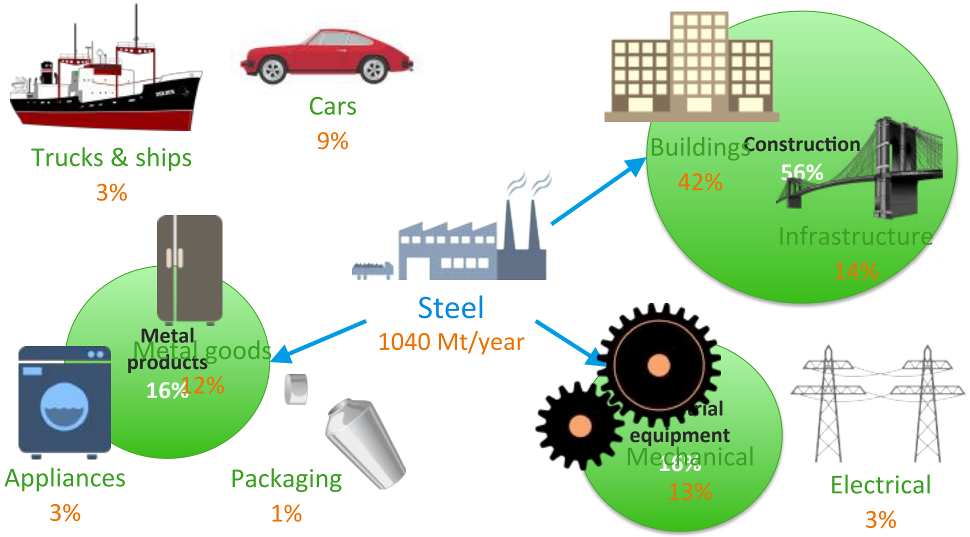
Construction
56%

Steel
1040 Mt/year

Metal products
16%

Industrial equipment
16%

Data From: Allwood & Cullen, 'Sustainable Materials Without the Hot Air', 2015



Trucks & ships
3%

Cars
9%

Buildings
42%

Construction
56%

Infrastructure
14%

Steel
1040 Mt/year

Metal products
16%

Metal goods
12%

Appliances
3%

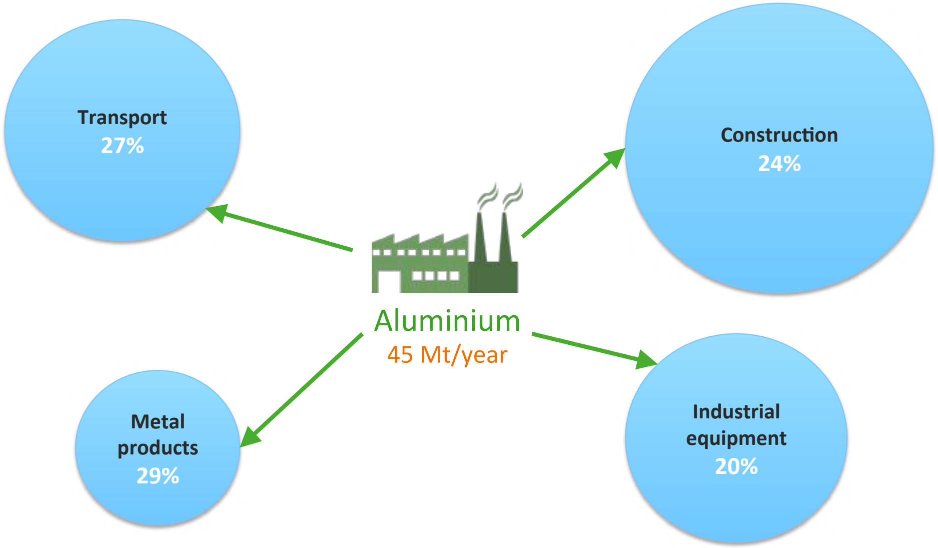
Packaging
1%

Industrial equipment
16%

Mechanical
13%

Electrical
3%

Data From: Allwood & Cullen, 'Sustainable Materials Without the Hot Air', 2015



Transport
27%

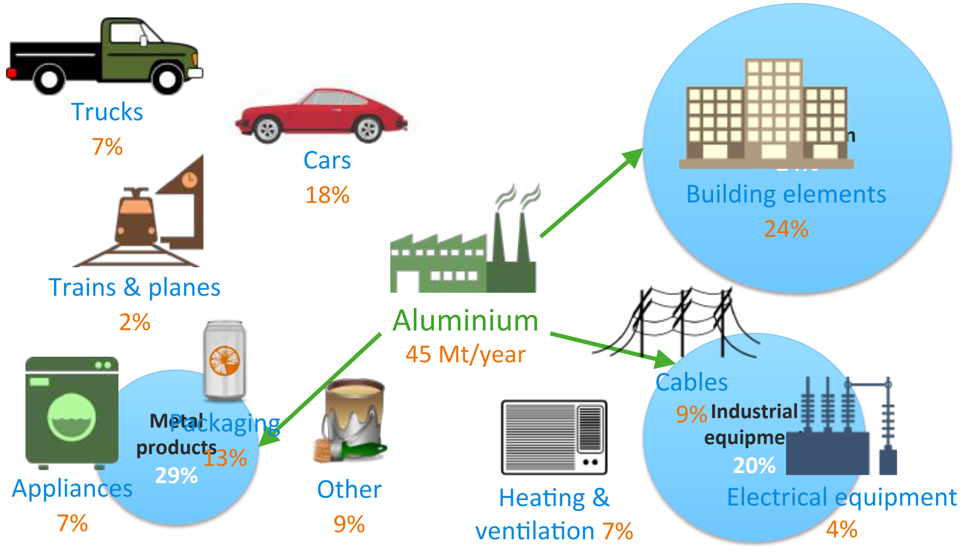
Construction
24%

Aluminium
45 Mt/year

Metal products
29%

Industrial equipment
20%

Data From: Allwood & Cullen, 'Sustainable Materials Without the Hot Air', 2015



Trucks
7%

Cars
18%

Trains & planes
2%

Aluminium
45 Mt/year

Building elements
24%

Cables
9%

Industrial equipme
20%

Electrical equipment
4%

Heating & ventilation 7%

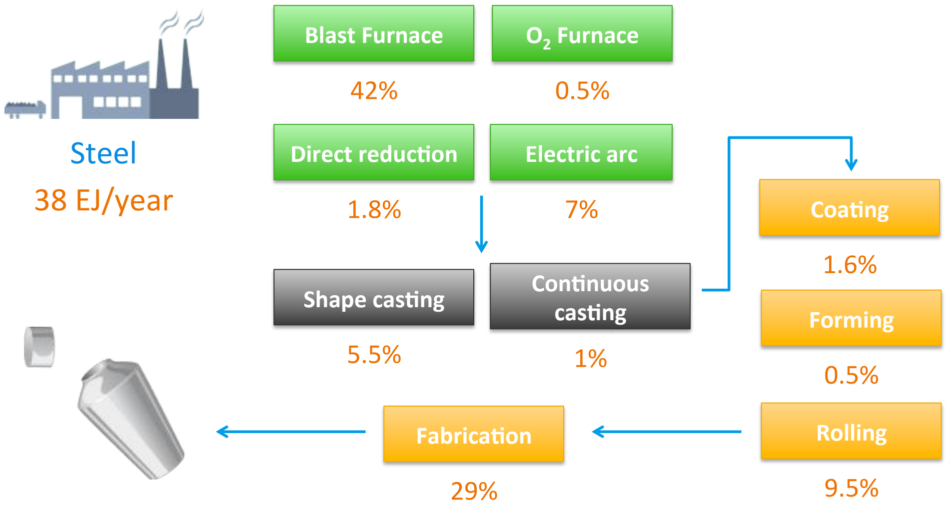
Other
9%

Packaging
13%

Metal products
29%

Appliances
7%

Data From: Allwood & Cullen, 'Sustainable Materials Without the Hot Air', 2015



Steel
38 EJ/year

Blast Furnace
42%

O_2 Furnace
0.5%

Direct reduction
1.8%

Electric arc
7%

Shape casting
5.5%

Continuous casting
1%

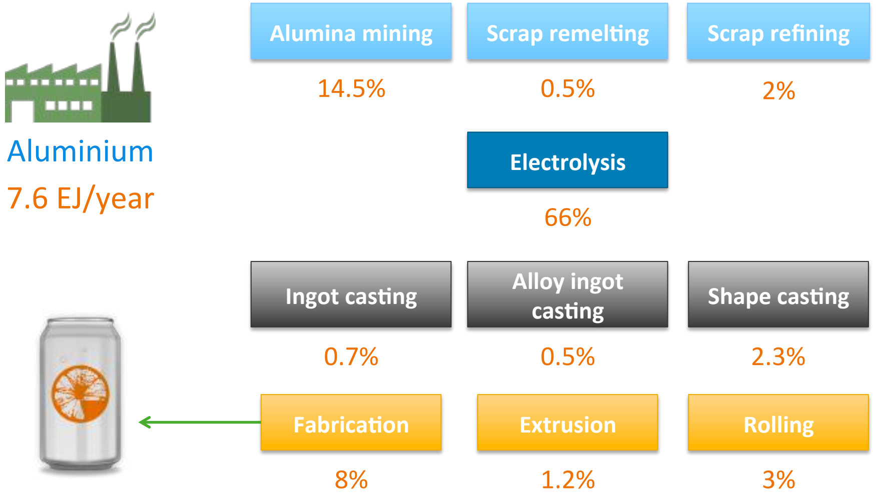
Coating
1.6%

Forming
0.5%

Rolling
9.5%

Fabrication
29%

Data From: Allwood & Cullen, 'Sustainable Materials Without the Hot Air', 2015



Aluminium
7.6 EJ/year

Alumina mining
14.5%

Scrap remelting
0.5%

Scrap refining
2%

Electrolysis
66%

Ingot casting
0.7%

Alloy ingot casting
0.5%

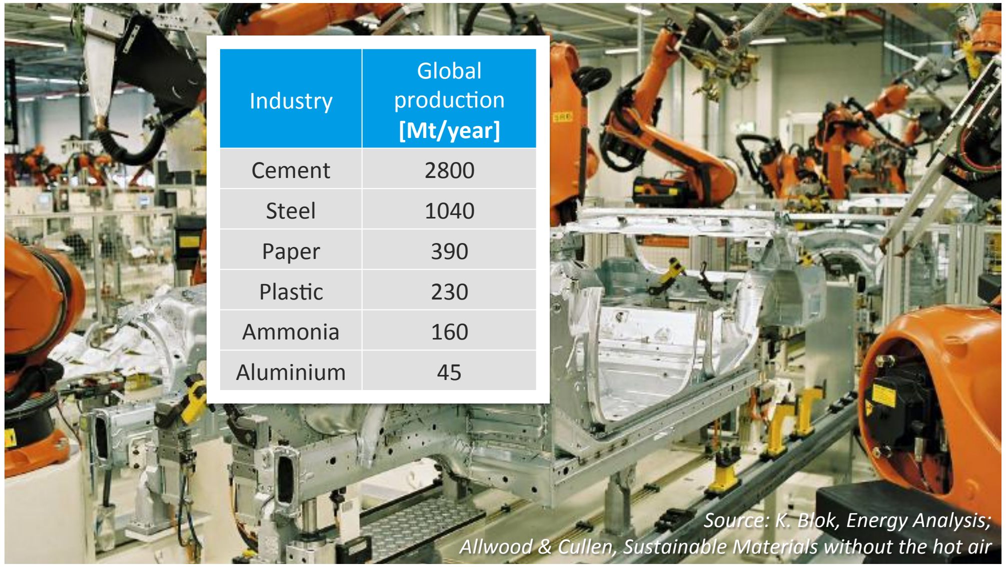
Shape casting
2.3%

Fabrication
8%

Extrusion
1.2%

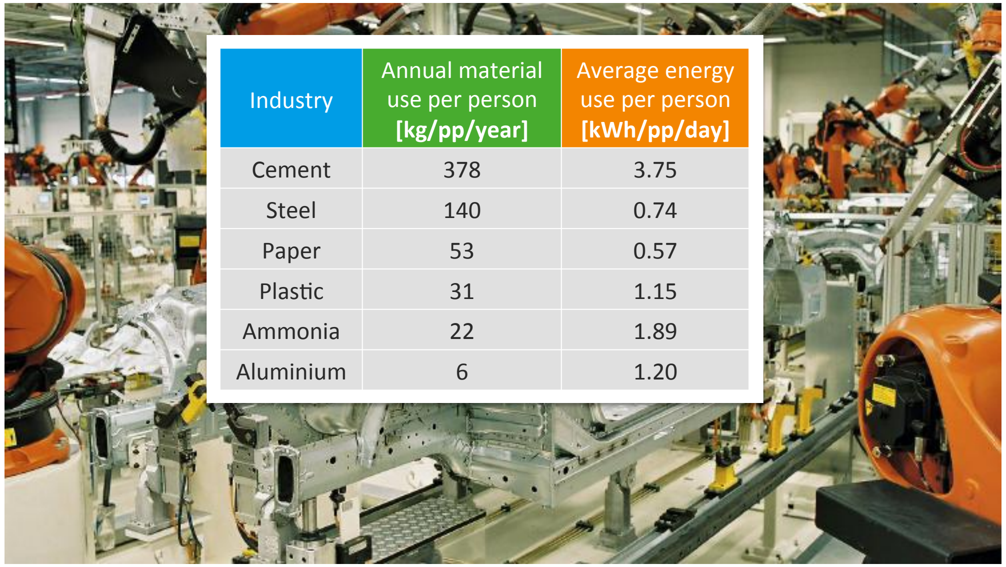
Rolling
3%

Data From: Allwood & Cullen, 'Sustainable Materials Without the Hot Air', 2015



Industry	Global production **[Mt/year]**
Cement	2800
Steel	1040
Paper	390
Plastic	230
Ammonia	160
Aluminium	45

Source: K. Blok, Energy Analysis;
Allwood & Cullen, Sustainable Materials without the hot air



Industry	Annual material use per person **[kg/pp/year]**	Average energy use per person **[kWh/pp/day]**
Cement	378	3.75
Steel	140	0.74
Paper	53	0.57
Plastic	31	1.15
Ammonia	22	1.89
Aluminium	6	1.20