19. Every BIG helps

Previously, we saw that we won't be able to meet our energy needs with renewables.

Question: What to do know? Can we meet our needs if everybody does a little, such as, for example, by not letting phone chargers plugged in?

Phone chargers $\simeq$ 1 W. 25 million phone chargers, that is 25 MW which is equal to $\frac{25\times10^6\times24}{60\times10^6\times1000} \simeq$ 0.01 kWh/d per person. By not leaving phone chargers plugged in, we achieve very little.

To solve our energy crisis, we will need big changes rather than small ones

Large reductions in **demand** could be achieved in three ways:

1. by reducing our population

2. by changing our lifestyle

3. by keeping our lifestyle, but reducing energy intensity through "efficiency" and "technology".

Supply could be increased in three ways:

1. by investing in "clean coal" technology

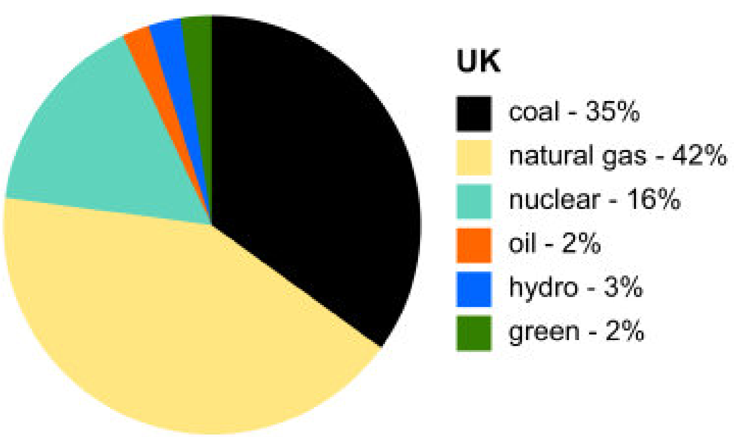
2. by investing in nuclear fission

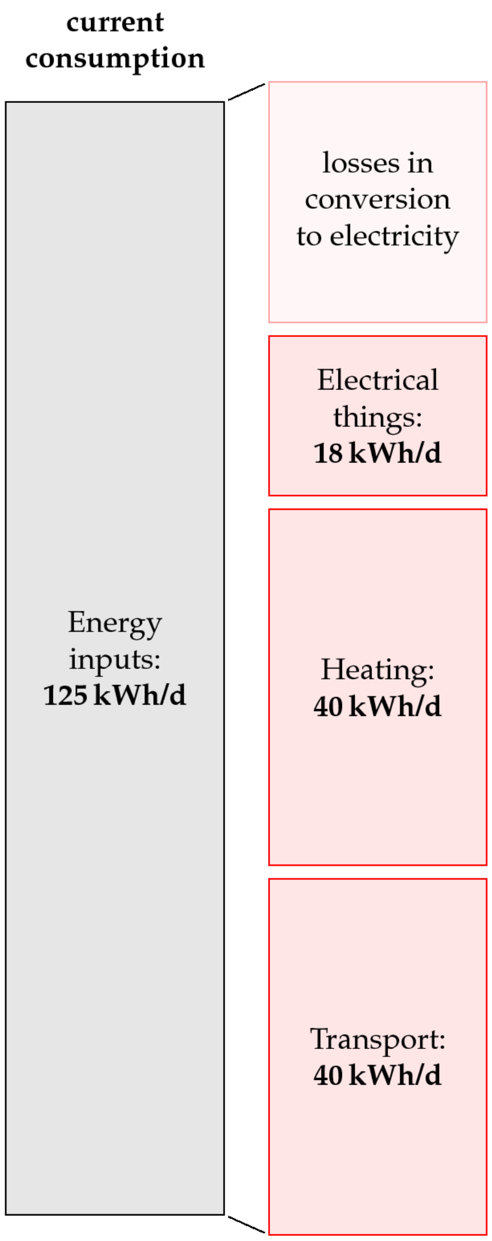
3. by buying, begging or stealing renewables from other countries.

Cartoon Britain

For simplifying discussions, we will work with the current primary energy consumption stack of the UK where electricity consumption accounts for 18 kWh/day per person.

Losses come from the conversion of fossil fuel energy into electricity. Fossil fuels are used to produce three-quarters of the electricity in the UK.





20. Better transport

Two types of transport: passenger transport and freight transport.

Unit for passenger transport: passenger-kilometer (p-km). Example: if a car travels 100 km with 1 person in it, it delivers 100 p-km. If it travels 100 km with four persons, it delivers 400 p-km.
Unit of freight transport: tons-kilometer (t-km). Example: if a truck carries 5 t of cargo over a distance of 100 km, it has delivered 500 t-km.

Measure of energy consumption of passenger transport: kWh per 100 passenger-kilometres.
Measure of energy consumption of freight: kWh per ton-km.

A few values of energy consumption already mentioned in class

Chapter 3. Cars. Car with 1 occupant = 80 kWh per 100 p-km

Chapter 5. Planes. Typical values for the energy per unit weight per unit of distance for planes are in the order of 0.4 kWh/ton-km. Helium-filled balloon = 0.06 kWh/ton-km. Around same value for trains.

	energy per distance (kWh per 100 p-km)
Car (4 occupants)	20
Ryanair's planes, year 2007	37
Bombardier Q400, full	38
747, full	42
747, 80% full	53
Ryanair's planes, year 2000	73
Car (1 occupant)	80

Chapter 15. Stuff. Energy of road transportation in the UK is around 1 kWh per t-km. For a container ship it is around 0.015 kWh per t-km.

Surface transport: where the energy is going and key concepts for reducing consumption

1. In **short-distance travel** with lots of starting and stopping, the energy goes mainly into speeding up the vehicle and its content. Key strategies for consuming less in this sort of transportation are: (i) less weight (ii) go further between stops (iii) move slower (iv) move less (v) use regenerative brakes.

2. In **long-distance travel** at steady speed, the energy goes mainly into making the air swirl around. Key strategies for consuming less are: (i) move slower (ii) move less (iii) reduce the frontal area of the vehicle or use long, thin vehicles into which many people can be packed.

3. There is **an energy-conversation chain** which has inefficiencies. So a final strategy for consuming less is to make the energy conversation chain more efficient.

In the coming sections:

1. we analyze the energy consumption of bikes and discuss strategies for fostering the use of bikes.
2. we build the case for public transportation.
3. we discuss what can be done to mitigate the energy consumption of cars.
4. we (briefly) discuss the future of flying.
5. we discuss freight.

Bikes

What is the energy consumption of a bicycle [A] travelling at a constant speed $v = 21$ km/h (5.31 m/s) [B] travelling at speed $v = 21$ km/h with stops every $d = 200$ meters? How does it compare with the consumption of a car (with a single occupant) travelling [C] at the same speed or [D] at 110 km/h (30.55 m/s)?

Data: (i) Density of air $\rho = 1.3$ kg/m^3 (ii) Typical values for mass of a car $m_c = 1000$ kg, for frontal area of a car A_{car}=3 m^2, for drag coefficient of a car $c_d^{car} = \frac{1}{3}$ and for engine efficiency of a car $\epsilon_{engine} = 0.25$. (iii) Typical values for frontal area of bike $A_{bike} = \frac{3}{4}$ m^2, for drag coefficient of a bike $c_d^{bike} = 1$, for mass bicycle plus driver 80 kg. The efficiency of human muscle has been measured at 18% to 26%. We assume here that $\epsilon_{muscle} = 0.25$. (iv) Rolling resistance is neglected.

Remember: We know from Chapter 3 that, under some assumptions compatible with those made here, the energy per meter travelled for surface transport is: $\frac{1}{\epsilon_{veh.}}[\frac{1}{2}m_{veh.}v^2/d + \frac{1}{2}\rho A v^2]$ where $A = A_{veh.}c_d^{veh.}$

[A] Bike at speed 21 km/h without stop: $\frac{1}{0.25}[\frac{1}{2} \times 1.3 \times \frac{3}{4} \times (5.31)^2] \simeq 59.98$ J/m $\simeq$ **1.527 kWh per 100 km.**

[B] Bike at speed 21 km/h with stops:
$\frac{1}{0.25}[\frac{1}{2} \times 80 \times (5.31)^2/200] + 59.98 \simeq 22.55 + 59.97$ J/m $\simeq$ **2.30 kWh per 100 km.**

[C] C-1: Car at speed 21 km/h without stop: $\frac{1}{0.25}[\frac{1}{2} \times 1.3 \times 1. \times (5.31)^2] \simeq 73.30$ J/m $\simeq$ **2.036 kWh per 100 km**.

C-2: Car at 21 km/h with stops:
$\frac{1}{0.25}[\frac{1}{2} \times 1000 \times (5.31)^2/200] + 73.30 \simeq 281.875 + 73.30$ J/m $\simeq$ **9.86 kWh per 100 km.**

[D] D-1: Car at speed 110 km/h without stop:
$\frac{1}{0.25}[\frac{1}{2} \times 1.3 \times 1. \times (30.55)^2] \simeq 2426.58$ J/m $\simeq$ **67.40 kWh per 100 km**.

D-2: Car at 110 km/h with stops:
$\frac{1}{0.25}[\frac{1}{2} \times 1000 \times (30.55)^2/200] + 2426.58 \simeq 9333.02 + 2426.58$ J/m $\simeq$ **326.65 kWh per 100 km.**

What do these results suggest? And what comments would you make if we were to replace the car characteristics used in our computation by those of an extreme eco car (see right)?

1. At low speed and without stops, a bike does not consume much less energy than a car. If the car was packed with several occupants, it could even score better in terms of *kWh per 100 passenger-kilometres*.

2. When there are stops, bicycles are much more energy efficient due to their low weight.

3. At high speed, energy consumption of the car is significant but we cannot say that energy consumption of cars at high speed is worse than energy consumption of bicycles, since bicycles cannot reach such speeds.

4. Extreme eco-cars obviously have c_d and $A_{veh.}$ values which are smaller than those of bicycles. They do not have a larger weight either. So, **when only taking into account our measure of energy consumption per passenger, eco-cars should be favored over bicycles.**

5. Bikes work without fossil fuels.

Strategies for fostering the use of bikes

Since bicycles are a low-energy option of transport, it is worth developing strategies for fostering their use. These strategies could be:

1. Providing excellent cycle facilities.

2. Providing appropriate legislation such as, for example, lower speed-limits and collision regulations that favour cyclists.

3. Introducing bicycle networks such as the Velib in Paris.

A Velib station

Map of Velib stations in Paris

A bad example of policy-making:

In 1993, the city of Guangzhou (China) has tried to ban bicycles in the city center on the basis that they were causing chaos in the traffic.

Public transport

Is public transport really more energy-efficient than individual car-driving?

NO BECAUSE: **(i)** Buses, trains, trolleys, etc. are much heavier than individual cars and so the energy for accelerating is higher. **(ii)** They have larger frontal area and may have a worse drag coefficient. **(iii)** People often have to travel longer distances with public transport than they would with their car.

YES BECAUSE: **(i)** Buses, trains and trolleys can carry many people. Therefore, even if the energy they spend in kWh per km is higher than for cars, they can lead to much smaller energy costs when the latter are measured in kWh 100 p-km. **(ii)** Less prone to be stuck in congestion where a lot of energy is spent accelerating and decelerating. **(iii)** Trains and trolleys use electricity. Since conversion rate to mechanical power is much higher from electricity than from fossil fuel, trains and trolleys have an advantage.

Numbers for public transport

A **diesel power coach** carrying 50 passengers travelling at 100 km/h consumes 7 kWh per 100 p-km. It would consume around 50 times more with one single passenger.

High-speed trains, which go twice as fast as cars and weigh much more, have if full an energy cost of 3 kWh per 100p-km.

In 2006-2007, the total energy cost of all London underground trains (including lighting, lifts, etc) was 15 kWh per 100 p-km. Energy cost of all London buses was 32 kWh per 100 p-km.

	Energy consumption (kWh per 100 p-km)
Car	68
Bus	19
Rail	6
Air	51
Sea	57

Overall transport efficiencies of transport modes in 1999 in Japan.

What comments/conclusions do these numbers suggest?

Public transport and energy efficiency: comments/conclusions

1. When full, surface public transport consumes **at least ten times less energy** (in kWh per 100-km) than cars with single occupancy.

2. Numbers for overall transport efficiencies suggest that a bus is at least two times more efficient than a car. They also suggest that trains are at least twice as efficient as buses. This may be partially explained by the fact the energy conversion chain is more efficient in trains than in buses.

3. Overall transport efficiencies for buses, especially for small distance trips, may perhaps not be as flattering as the numbers may suggest since people may travel longer distances with buses than they would with their cars.

Cars

Public transport and bicycles were good solutions for more energy efficient transport. However, they have several shortcomings: **(i)** they do not provide the flexibility that users may require, **(ii)** may be too slow or **(iii)** physically too demanding. We may therefore reasonably suppose that the love story of people with their cars is not going to end.

We will discuss:

1. The legislative opportunities that exist for having on the road cars which are more energy-efficient (the law-maker point of view).

2. Technologies for enhancing cars.

Legislative opportunities

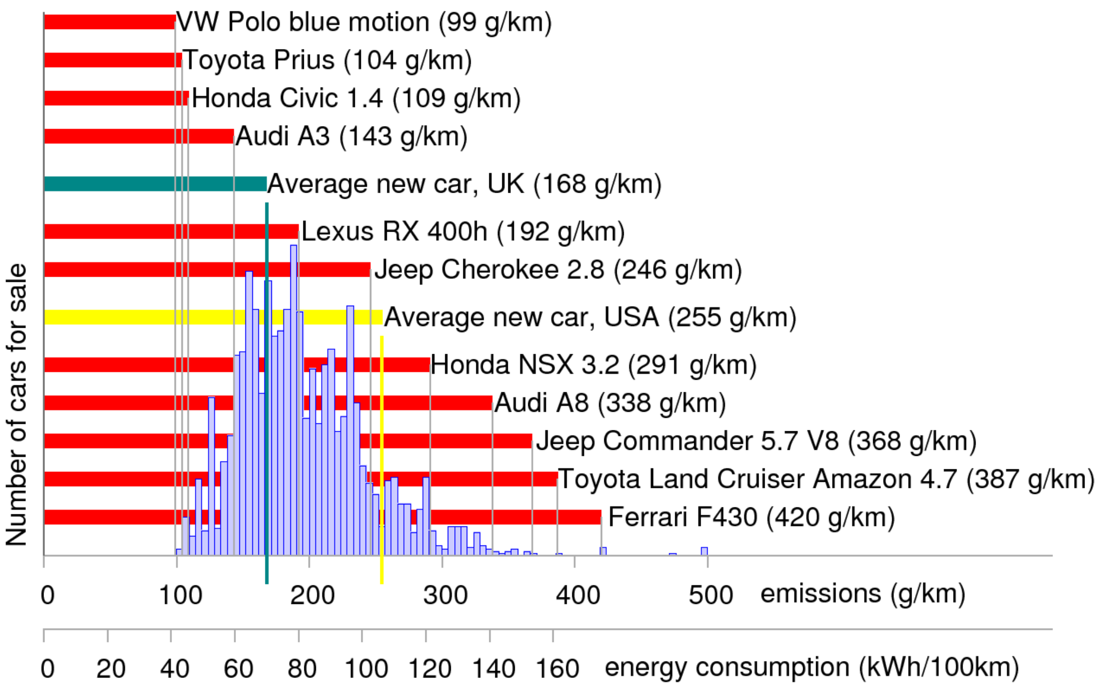
Challenges for lawmakers: They face a tradeoff between enforcing measures for cars consuming less and keeping their voters happy.

Increasing taxes on cars: Efficient for forcing people to use their bikes or public transport but highly unpopular with voters.

Speed limits on cars: We have seen that a car's fuel consumption grows quadratically with its speed. Enforcing lower speed limits is an efficient way for consuming less energy, does not cost anything to the government and is not that unpopular with voters.

Congestion management strategies: A lot of energy is spent by cars when stuck in traffic jams. With a dynamic management of speed limits, it is possible to relieve congestion to some extent (not that unpopular). Another solution would be to charge users extra if they contributed to congestion (unpopular).

Incentives for using more fuel efficient cars: The government gives money to people buying more fuel-efficient cars. With current cars, many savings could already be achieved. Not unpopular because you give people money. In Figure, 240 g CO_2 is associated with 1 kWh of chemical energy.



Technologies enhancing cars

We have seen that there are ways of making cars more fuel efficient that do not, however, provide a solution for getting cars off fossil fuels. Now we will discuss five new technologies that we may suspect will make cars more energy efficient. Three of these technologies lead also to cars that do not use fossil fuels.

These are:

1. Regenerative braking
2. Hybrid cars
3. Electric cars
4. Hydrogen-powered cars
5. Compressed air cars.

1. Regenerative braking

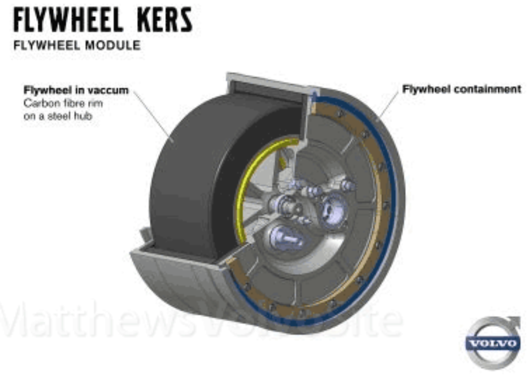
Regenerative braking is for capturing energy as the vehicle slows down. There are three main types of regenerative braking:

1. An electric generator coupled to the wheels can charge up an electric battery or supercapacitor.

2. Hydraulic motors driven by the wheels can make compressed air, stored in a small canister.

3. Energy can be stored in a flywheel.

Electric regenerative braking salvages 50% of the car's energy in a braking event, leading to perhaps a 20% reduction in the energy cost of city driving. Regenerative systems using flywheels can salvage at least 70% of the braking energy. They offer also a way to handle high power with small systems (e.g., a 20 kg flywheel can deliver 60 kW of power. Electric batteries capable of delivering that much power would weigh about 200 kg).



2. Hybrid cars

A hybrid vehicle is a vehicle that uses two or more distinct power sources to move the vehicle. The term most commonly refers to hybrid electric vehicles (HEVs), which combine an internal combustion engine and one or more electric motors. HEVs are equipped with regeneratrive braking and can lead to around a 30% reduction in fossil fuel consumption.

The Toyota Prius third generation consumes 3.7 l of petrol per 100 km. The energy contained in one liter of petrol is 35475 kJ (note that for diesel, it is 38,080 kJ/l). $\Rightarrow$ That's $\frac{3.7\times 35475\times 10^3}{1000\times 3600} \simeq$ 36 kWh per 100 km. Note that in Japan, the overall energy transport efficiency of a bus is 19 kWh per 100 p-km. So TWO people travelling together in a Prius perform almost as well as on a bus!

3. Electric vehicles

An electric car is an automobile that is propelled by one electric motor using electrical energy stored in batteries or another energy storage device. Electric motors give electric cars instant torque, creating strong and smooth acceleration.

Electric vehicles are pretty energy efficient. Here are two examples:
Smart electric car: 19 kWh per 100-km in cities and 24 kWh per 100-km on motorways.
Toyota Scion: 16 kWh per 100-km in cities and 21 kWh per 100-km on motorways.

Questions about electric vehicles

People often argue that the electric car has a range problem that cannot be solved? Is it true?

Data: Electric cars often have less maximum range on one charge than cars powered by fossil fuels, and they can take considerable time to recharge (around 3 hours are needed to charge batteries with 20 kWh using a three-phase 16-amp outlet which can be installed in a home).

We would like to say no for the following reasons:

1. Current EVs have a range between 100 km to 200 km. And this range is well beyond the average range required daily by car users.

2. It would still be possible to increase this length by adding more batteries or better batteries to the car. Note however that there is a theoretical limit defined by two main elements: (i) the consumption of a vehicle grows with its weight (rolling resistance and energy spent accelerating) (ii) the energy density of batteries is finite (and in the order of 120 Wh/kg for modern batteries - more than 200 kg of batteries for a 200 km range).

3. Possible to install fast charging DC stations with a voltage of 400-500 V and a max current around 100 - 125 amps. Less than half an hour needed to charge a 20 kWh battery.

4. Possible to develop battery-exchanging stations where a driver would exchange his batteries for a fresh set at every 200 km or so.

I live in a cold place. How could I drive an electric car? I need power-hungry heating!

The motor of an electric vehicle uses on average 10 kW with an efficiency of 90-95%. Some of the lost power is going to be dissipated as heat which could be piped from the motor to the car.

Are lithium-ion batteries safe in an accident?

No but battery technology is progressing.

Is there enough lithium to make all the batteries for a huge fleet of electric cars?

World lithium reserves are estimated at 9.5 million tons in ore deposit. A lithium-ion battery is made of 3% of lithium. If we assume that a vehicle has 200 kg of battery, that's 6 kg per vehicle. So, we have enough to make 1.6 billion vehicles.

4. Compressed air cars

Compressed air cars are powered by motors driven by compressed air. Compressed air cars use the expansion of compressed air, in a similar manner to the expansion of steam in a steam engine.

Two main problems with compressed air cars:

1. the energy intensity of compressed air vehicle is only about 11-28 Wh/kg, which is five times less than lithium-ion batteries. Their range is therefore limited to a few tens of kilometers.
2. compressing air creates heat which is lost energy. They are therefore prone to be less energy-efficient than electric vehicles.

Advantages over electric cars: cheaper construction, fewer nasty chemicals and fast to refill.

5. Hydrogen cars

A hydrogen vehicle is a vehicle that uses hydrogen as its on-board fuel. Best energy efficient technology works by reacting hydrogen with oxygen in a fuel cell to run electric motors.

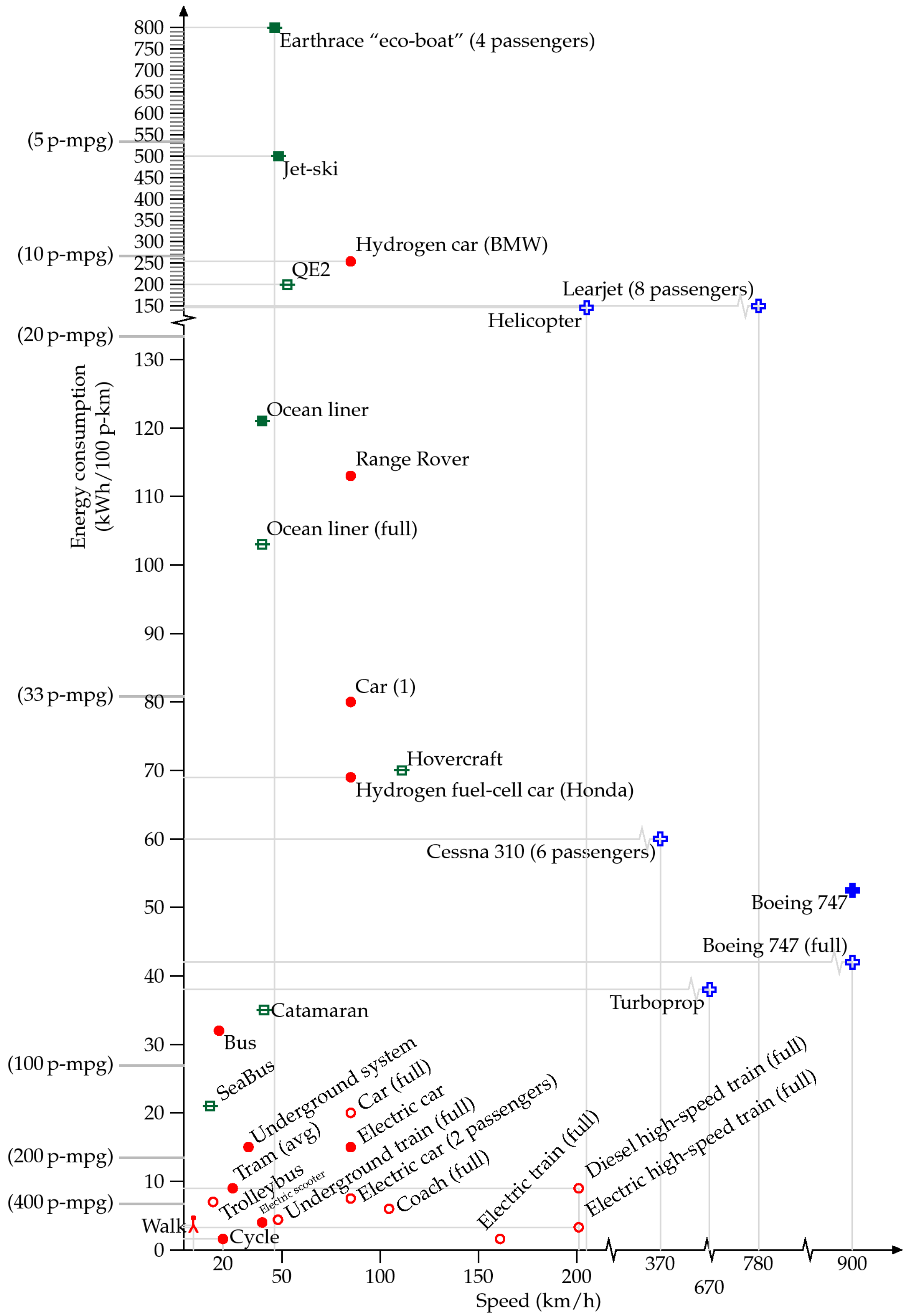
The Washington Post asked in November 2009:
"But why would you want to store energy in the form of hydrogen and then use that hydrogen to produce electricity for a motor, when electrical energy is already waiting to be sucked out of sockets all over America and stored in auto batteries?"
The paper concluded that commercializing hydrogen cars is "*stupendously difficult and probably pointless*".

Best energy efficient fuel car built up to now: the FCX clarity which rolls at 69 kWh per 100 km. If losses incurred when converting electricity to hydrogen are taken into account, hydrogen cars are much less energy efficient than cars running on fuel. They may, however, be of some interest if hydrogen is produced when there is an excess of renewable energy (only hope for the technology to develop).

Planes

We have seen that in cars a two-fold or even ten-fold improvement in fuel efficiency is possible. The superjumbo A380, sold as a "highly fuel-efficient aircraft" burns just 12% less fuel per passenger than a 747. This slender progress rate is imposed by a physical limit for which any plane, whatever its size has to expend an energy of about 0.4 kWh per ton-km $\Rightarrow$ Very unlikely that we will never be able to do much to decrease the energy consumption of the air travel industry.

What about getting the airplane industry off fossil fuels? This would be possible by building engines to run on hydrogen or biofuel. The energy density of batteries is too low to enable electric planes able to fly over long distances.


Energy consumption (kWh/100 p-km)
Speed (km/h)
(5 p-mpg)
(10 p-mpg)
(20 p-mpg)
(33 p-mpg)
(100 p-mpg)
(200 p-mpg)
(400 p-mpg)
Earthrace "eco-boat" (4 passengers)
Jet-ski
Hydrogen car (BMW)
QE2
Learjet (8 passengers)
Helicopter
Ocean liner
Range Rover
Ocean liner (full)
Car (1)
Hovercraft
Hydrogen fuel-cell car (Honda)
Cessna 310 (6 passengers)
Boeing 747
Boeing 747 (full)
Turboprop
Catamaran
Bus
SeaBus
Underground system
Car (full)
Tram (avg)
Electric car
Underground train (full)
Electric car (2 passengers)
Trolleybus
Electric scooter
Coach (full)
Electric train (full)
Diesel high-speed train (full)
Electric high-speed train (full)
Walk
Cycle

Freight

Surface freight transport. Use trains rather than trucks to decrease energy consumption and get the industry off fossil fuels. Use electrical trucks if possible.

Air freight transport. Switch to surface transport, sea transport or a combination of both.

Sea freight transport. Efficient in terms of energy (around 0.01-0.02 kWh per ton-km). Possibility of getting sea freight transport off fuels by using nuclear-powered ships.

NS Savannah - first nuclear power ship - launched in 1962.

21. Smarter heating

Previously, we saw that the power used to heat a building was given by:

$$\text{power used} = \frac{\text{average temperature difference} \times \text{leakiness of building}}{\text{efficiency of heating system}}$$

Obviously, there are three lines of attack to reduce the power used by heating:

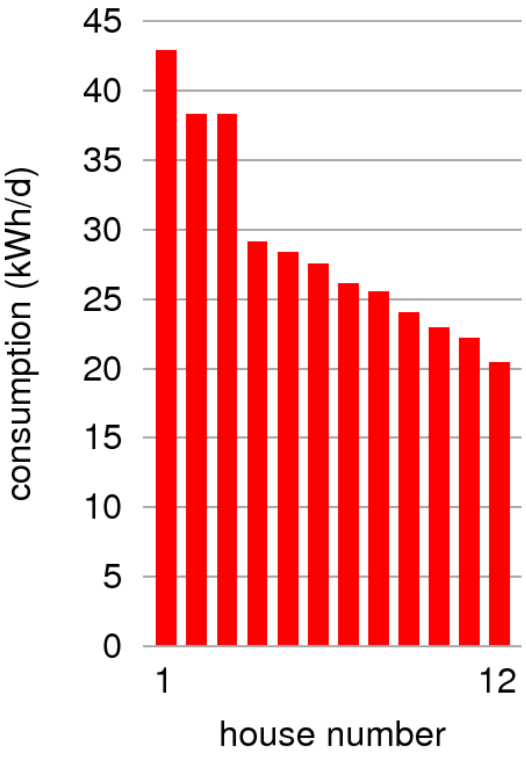
1. Reduce the average temperature difference.
2. Reduce the leakiness of the building.
3. Increase the efficiency of the heating system.

Reduce the average temperature difference

This is achieved by turning thermostats down. In Britain, for every degree you turn the thermostats down, the heat loss decreases about 10%. Thanks to incidental heat gains in the building, the savings in heating power **will be even bigger** than these reductions in heat loss.

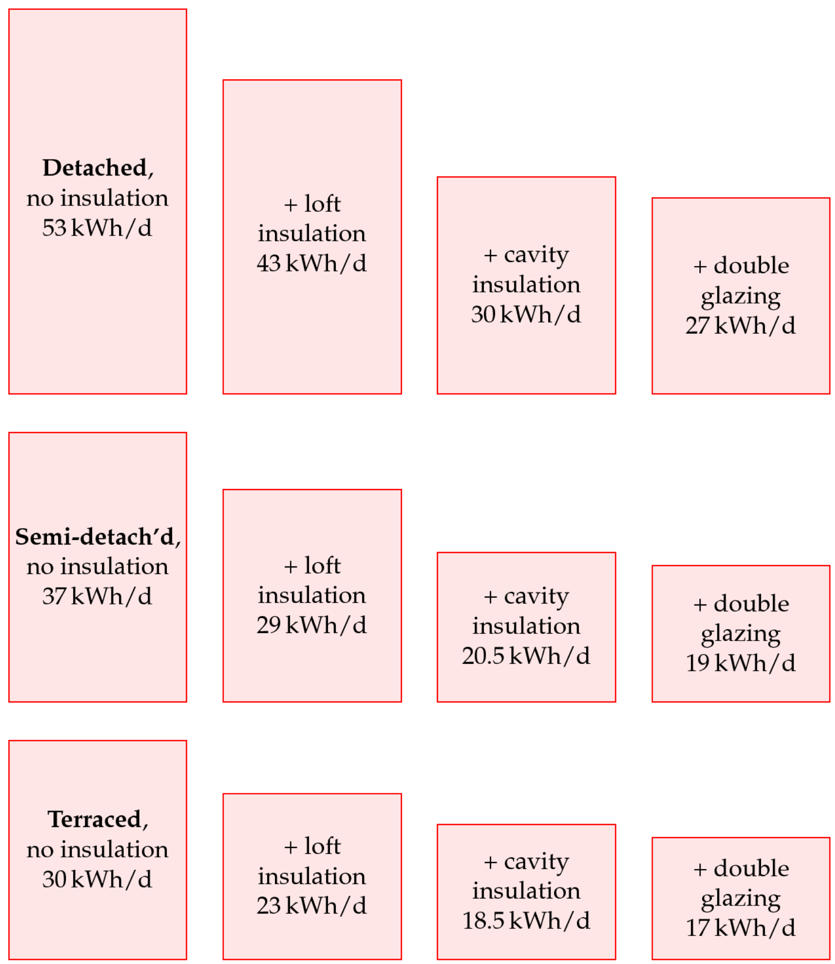
This strategy is controversial because it leads to a lifestyle change.

Note that heat consumption strongly varies from one family to another as shown in the figure on the right that reports the actual heat consumption in 12 identical houses with identical heating systems. These houses were designed to have a leakiness of 2.7 kWh/d/°C.



Reduce the leakiness of the building

Estimation of the space heating required in old buildings as progressively more effort is made to insulate them:



If you have the chance of building a new house, here are the three key ideas for having a more energy-efficient building:

1. Have really thick insulation in floors, walls and roofs.
2. Ensure that the building is completely sealed and use active ventilation to introduce fresh air and remove stale and humid air, with heat exchangers passively recovering much of the heat from the removed air.
3. Design the building to exploit sunshine as much as possible.

Governments can enforce the building of more energy-efficient buildings.

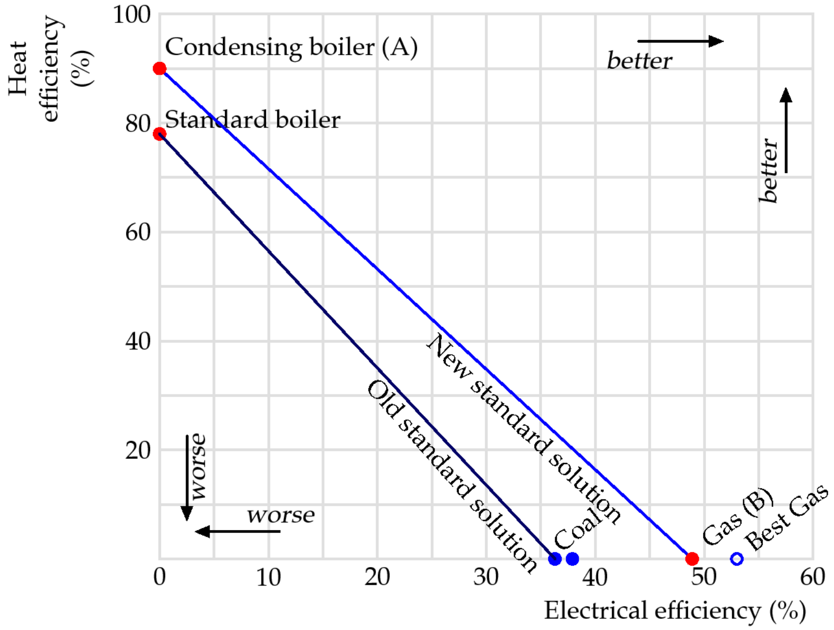
The energy cost of heat

The energy efficiency of a heating system that directly transforms electricity into heat: 1. Energy efficiency of a system that burns fossil fuel in boilers: 75% - 90%

We will now:

1. discuss the performances of classical strategies for obtaining a mix of electricity and heat from gas.
2. discuss two other technologies for making building-heating more efficient. These are "combined heat and power" and heat pumps.
3. compare both technologies.
4. discuss the limitations of large-scale use of heat pumps.

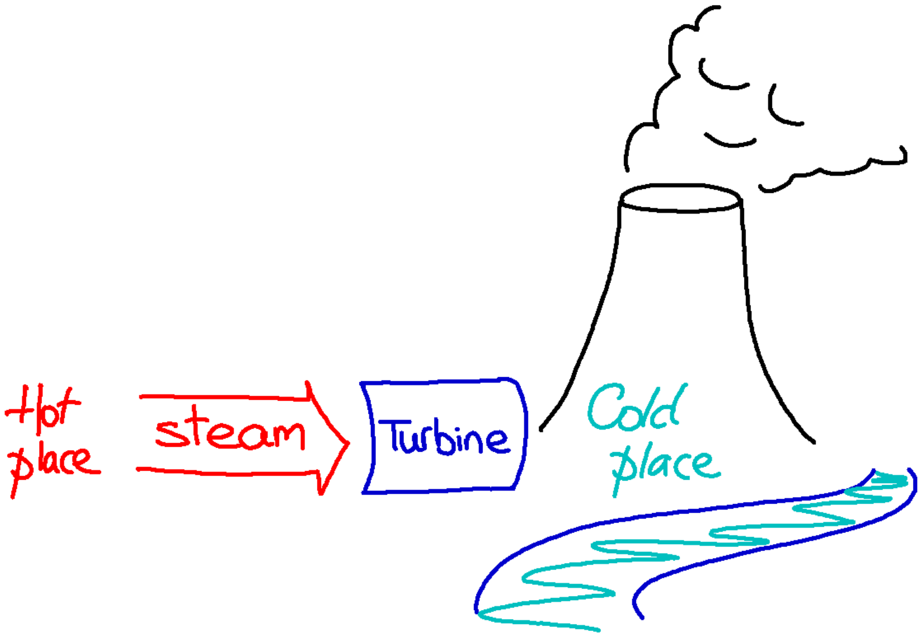
Performances of classical strategies for transforming gas into heat or electricity



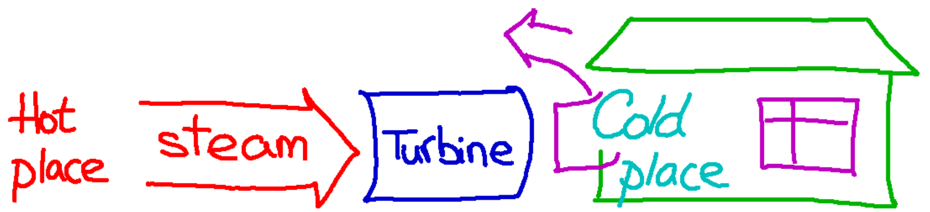
Note: Condensing boilers are water heaters in which a high efficiency (typically greater than 90%) is achieved by using the waste heat in the fuel gases to pre-heat the cold water entering the boiler. They may be fuelled by gas or oil and are called condensing boilers because the water vapour produced during combustion is condensed into water, which leaves the system via a drain.

Combined heat and power

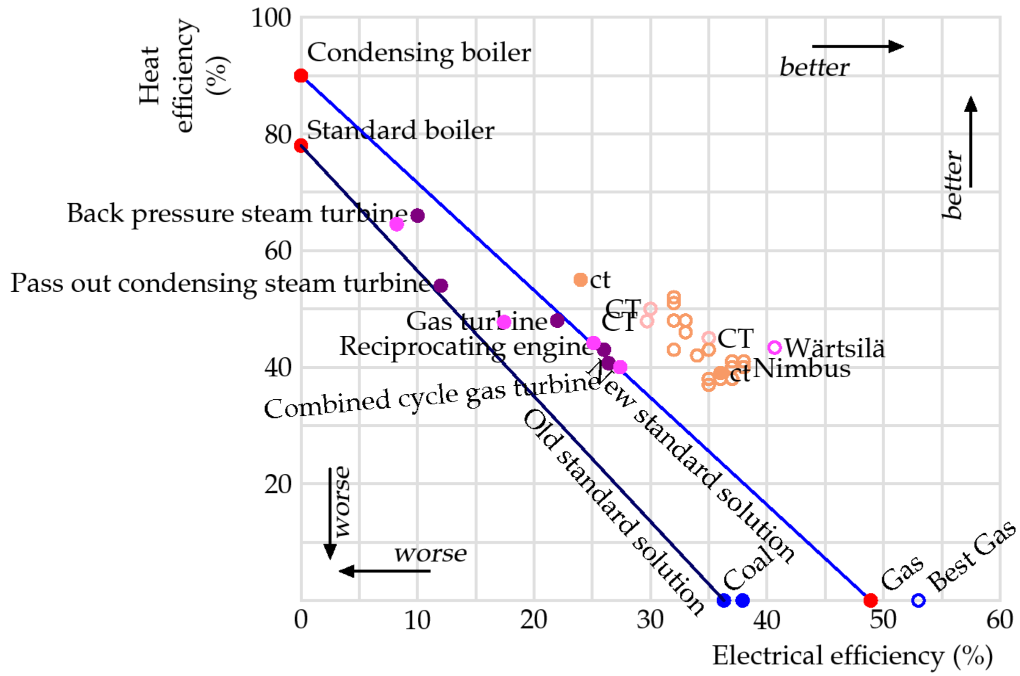
Classical power station:



Combined heat and power:



Performances CHP versus classical strategies



Legend: Filled dots = performances of real CHP systems. Hollow dots = performances of ideal CHP systems.

Questions: What relevant comments can be made on CHP systems?

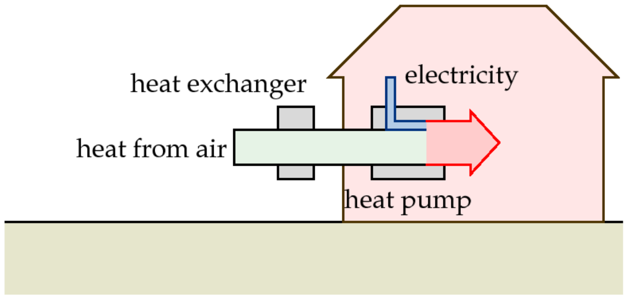
1. The heat generated by CHP is not a free by-product of a standard gas-fired station. Indeed, the electrical efficiencies of CHP systems are significantly smaller than the 49% efficiency delivered by single-minded electricity-only gas power station.

2. Electrical efficiency and heat efficiency of many CHP systems are smaller than the electrical efficiency and the heat efficiency of an energy system made of the "right mix" of condensing boilers and of gas-fired power stations.

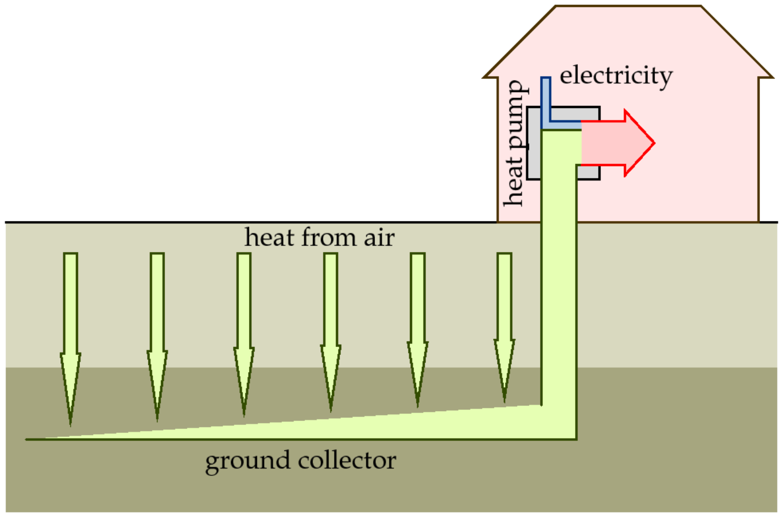
3. CHP systems come with constraints: (i) they are not so flexible in the mix of electricity and heat they deliver; this inflexibility leads to inefficiencies at times, for example, excess production of heat (ii) CHP system delivers heat only to the places it's connected to, whereas condensing boilers can be planted anywhere with a gas main.

Heat pumps

A **heat pump** is a device that transfers heat energy from a heat source to a heat sink against a temperature gradient. A heat pump uses some amount of external high-grade energy to accomplish the desired transfer of thermal energy from the heat source to the heat sink.



air-source heat pump



ground-source heat pump

Theory of heat pumps

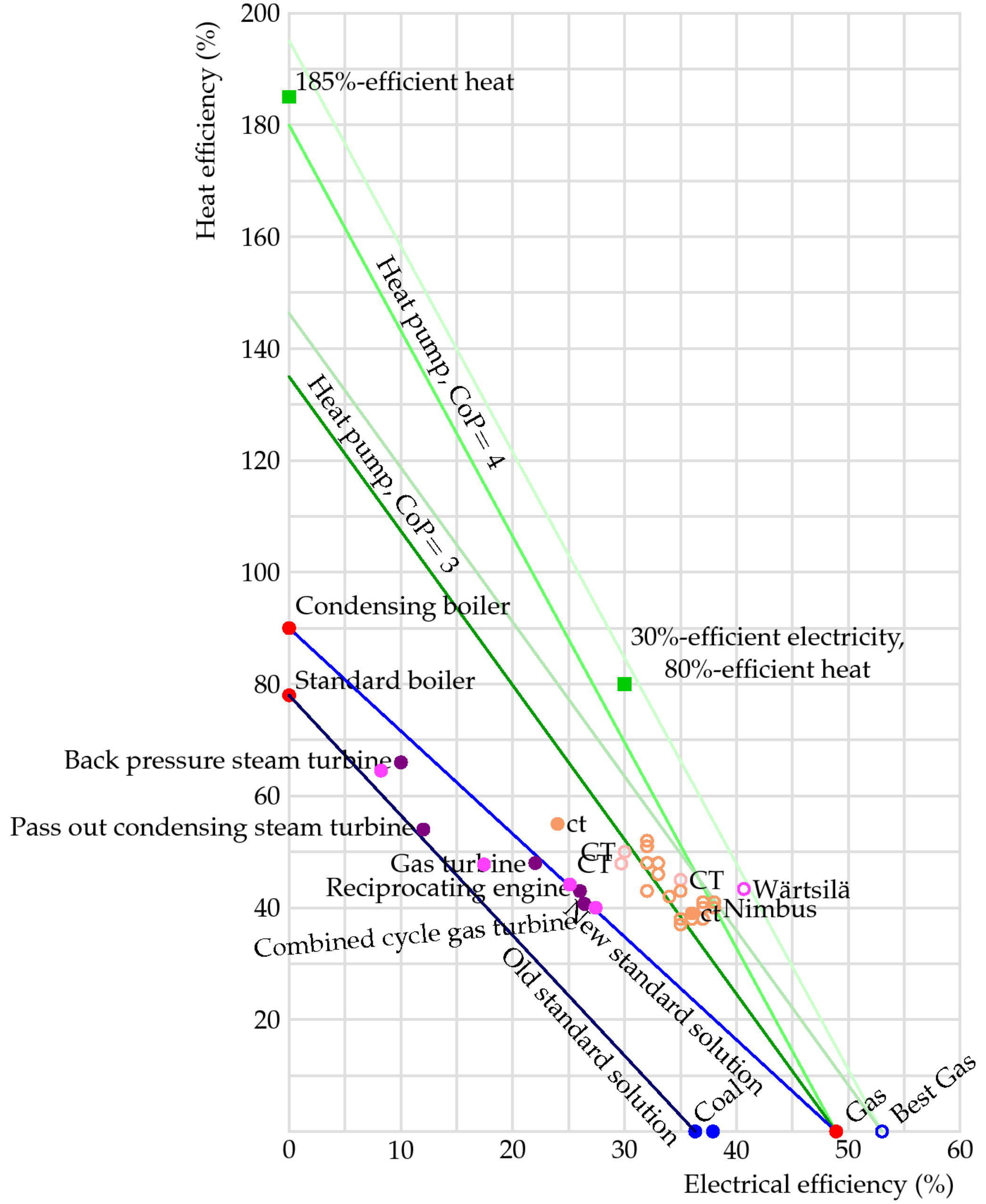
The **efficiency of a heat pump** (or coefficient of performance) is the energy required per unit of heat pumped. If we are pumping heat from an outside place at temperature T_1 into a place at higher temperature T_2, both temperatures expressed relative to absolute zero, the ideal efficiency is:

$$\text{efficiency} = \frac{T_2}{T_2 - T_1}$$

Example: Suppose a ground-source heat pump with a ground temperature equal to 6 °C and a temperature inside the house equal to 21 °C. The ideal efficiency is: $\frac{273.15+21}{21-6} \simeq 19.6$.

Average coefficient of performance for installed heat pumps often between 2 and 4.

Heat pumps compared with combined heat and power

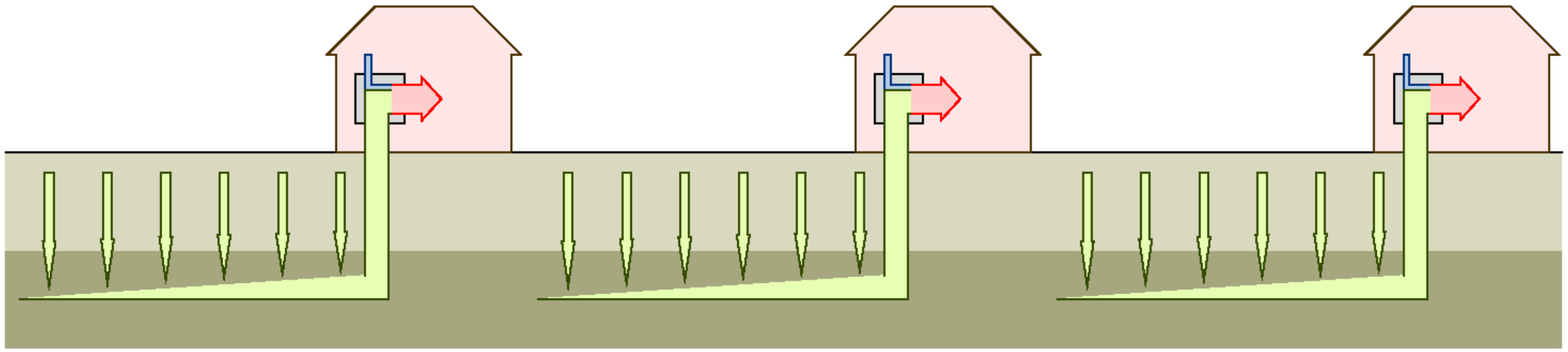


1. When heat pumps with a COP of 4 are powered by an energy-efficient gas-powered station, they are always more efficient than CHP if losses in the electricity network are neglected. They are almost always more efficient if these losses are taken into account.

2. If you want to heat many buildings using natural gas, you could install condensing boilers, which are "90% efficient" or you could send the same gas to a new gas power station making electricity and install heat pumps in the building. The second solution's efficiency would be somewhere between 140% and 185% efficient.

3. Combined heat and power may not be always a bad idea. When we want to get high-grade heat (at 200 °C, for example), heat pumps are unlikely to compete as well because their coefficient of performance would be lower.

Limits of growth of heat power



Because temperature in the ground stays close to 11 °C, whether it's summer or winter, the ground is theoretically a better place for a heat pump to grab its heat than the air, which in the winter may be more than 10 °C colder than the ground. However, the ground is not a limitless source of heat and needs to be replenished by heat during the summer. If we stuck heat too fast from the ground, the ground will become as cold as ice, and the advantages of the ground-source heat pump will be diminished.

22. Efficient electricity use

Can we cut electricity use? Two main solutions:

1. Decrease standby power consumption which accounts for roughly 8% of residential electricity demand. In France and in the UK, it is about 0.75 kWh/d per person. Note that manufacturers could be forced to build devices with low standby power.

2. Use energy-efficient bulbs.