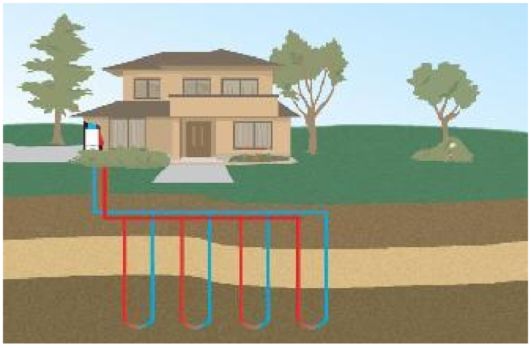
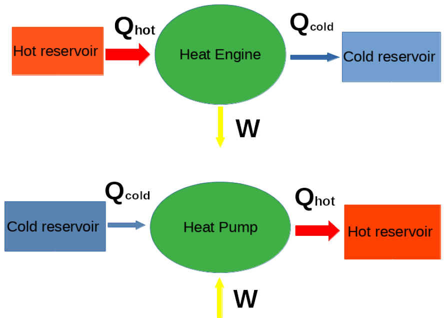
HEAT PUMPS IN SECONDARY EDUCATION





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1 Introduction

One of the greatest problems of the 21st century is whether mankind is able to establish sustainable development and able to manage the increasing demand for energy, whilst the fossil fuel energy resources are depleting, or not. It is getting more and more urgent to mitigate the burning of fossil fuels and to find other alternatives both for heating homes and for covering the energy demands. The aim is twofold, first it is urgent to find renewable energy sources, and second the emission of carbon dioxide should be reduced.

Heat pumps provide a way of using energy more efficiently, and in the future they may play a significant role in conserving our energy resources and also in the decrease of the emission of CO_2. (Heat pumps are reversed heat engines, which "pump" heat from the cold reservoir to the hot one whilst work is performed. In this sense the freezer, the refrigerator, and the air conditioners are all heat pumps, since they extract heat from the cold reservoir, however the term heat pump is often used only for devices which are used for heating.)

2 Secondary Education

In secondary schools students are susceptible to the topics of energy crisis and climate change; they are very interested in learning about some possible alternatives which may help reducing the use of fossil fuels, and the emission of carbon-dioxide.

In Hungarian secondary schools (where physics is taught) the basics of thermodynamics, (as well as the laws of thermodynamics) are taught, but nearly nothing is stated about heat pumps – apart from that in the higher level refrigerator is mentioned to be a reversed heat engine.

We take it for granted that we have refrigerators and air conditioners in our homes, but it usually seems miraculous to use a heat pump for space heating and people may believe that using an air conditioner for heating in winter is inefficient and expensive. This is why it would be important to explain how heat pumps work, and what type of heat pumps can be used. In the sections below some ideas and facts of the discussable points are advised for brainstorming (a non exhaustive list).

3 History Behind

Even in the 19th century William Thomson (Lord Kelvin) proposed to use heat pumps (or as he called heat-multipliers) instead of just burning fossil fuels[1], (as rumours said, according to his plans in Switzerland a heat pump was installed into a house in order to heat it) but they really gained greater popularity in this century.

The demand for cooling has aroused for some hundreds of years, and the history of refrigerator began in the early nineteenth century, although the greatest development occurred in the middle of the twentieth century, when the DuPont corporation introduced refrigerators which used freon as a working substance. (Later, in 1987 Freon was banned, due to its high ozone depleting potential.)

From 1930 onward several heat pumps were installed to buildings in order to heat them in winter and to cool them in summer. Among one of the first ones for example an air sourced heat pump was installed in a building in Scotland in 1927, which provided both hot water and space heating. The first major heat pump installation in Europe was completed in 1939 in Zurich. This unit used the water of the nearby river as a source and R12 (a type of freon) refrigerant was used as a working substance to heat the town hall. Switzerland was one of the first countries where the installation of heat pumps was encouraged, and the motivation behind it was to reduce the burning of coal (since they did not have much). Although, both in Europe and in the USA heat pumps of different heat sources were installed, the selling of heat pumps declined in the 1960-s because of their unreliability in colder climates, where in cold winters their efficiency dramatically drops, and also because of the huge cost of the installation. However, when the energy crisis began in the 70-s the interest in heat pumps began to grow again and since then there is an increasing demand for both their improvement and their use.

4 Coefficient of Performance

The term of efficiency for measuring the performance of a heat engine is introduced in secondary schools, and also the second law of thermodynamics is quoted that the efficiency of heat engines must be less than one. However, the coefficient of performance is not even mentioned in secondary schools. It is not difficult to make the students understand this concept. In order to characterise how well a heating or cooling unit works we have to introduce a number which is the ratio of the energy which is useful to us to the total thermal energy which was put in the process. This ratio is (usually) called coefficient of performance (abbreviated as COP) and it is different for heat pumps used for heating or used for cooling. In case of space cooling it is also often called energy efficiency ratio, abbreviated as EER.

[1]D.A. Reay, D.B.A. Macmichael: Heat Pumps, Pergamon Press, Oxford, 1988, pp.3-12

The definitions are the following:
The coefficient of performance of a heat pump (used for heating):

$$COP_{heating} = \frac{Q_{hot}}{W} = \frac{Q_{hot}}{Q_{hot} - Q_{cold}} = 1 + \frac{Q_{cold}}{Q_{hot} - Q_{cold}}$$

The coefficient of performance of a refrigerator:

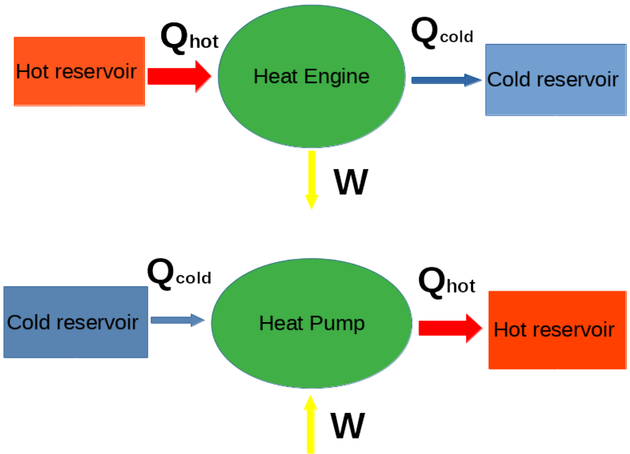
$$COP_{cooling} = \frac{Q_{cold}}{W} = \frac{Q_{cold}}{Q_{hot} - Q_{cold}}$$

Where Q_{hot} is the heat released to the hot reservoir, Q_{cold} is the heat absorbed from the cold reservoir, and W is the external work done during one cycle. If the first definition is compared to the efficiency of a heat engine, it can be realised that they are the reciprocal of each other, thus the COP of heating is always greater than 1. This is why heating with a heat pump is always a better choice than just burning fuel. Also with a little mathematics it can be derived that if a heat pump is once used for heating and then it is used for cooling – provided that it is operated between the same heat reservoirs – then the COP of heating is exactly one more than the COP of cooling. So if we use the refrigerator to cool down the food inside, then also the kitchen is warmed up with a COP which is exactly 1 more than the COP for cooling the food inside. (A refrigerator has small cold heat reservoir, so it cannot extract significant amount of heat from the food in the cold compartment, with which the room could be efficiently heated, so its heating effect is not significant. However, the heat pumps which are installed to houses can usually be used in both ways, for heating in winters and for cooling in summers. The schematic figure of the heat engine and the heat pump can be seen in Figure 1.

Using the figure it is easy to understand that in case of a heat engine the heat absorbed from the hot reservoir is partly released to the cold reservoir and partly the engine does work. In case of a heat pump the sum of the heat absorbed from the cold reservoir and the external work is released in the hot reservoir, and if this release is the "useful" energy then the COP value is greater than one. (In case of a refrigerator it depends on which energy is greater, the absorbed heat from the cold reservoir or the work performed. It is also important to emphasize that in case of heat pumps we do *not* gain energy, just with performing a small amount of work a greater amount of thermal energy can be "pumped" from the cold reservoir to the hot one.

Because it is difficult to measure the transferred heat as well as the work done the COP values are often estimated by the COP of the reversed Carnot cycle. (Obviously the operation of real heat pumps is very far from the idealised Carnot cycle, but at least some estimation can be gained.) The following two formulas are the COP values of the idealised Carnot heat pumps,

Figure 1: Schematic figures of a heat engine and a heat pump.



expressed with the temperature (measured in Kelvins) of the hot and the cold reservoirs, denoted by T_H and T_C, respectively:

$$COP_{Carnot\ heating} = \frac{T_H}{T_H - T_C}$$

$$COP_{Carnot\ cooling} = \frac{T_C}{T_H - T_C}$$

.

From the two formulas it can be seen (which is quite evident from our experiences), that when the temperature difference between the two reservoirs is smaller, then the heat pump works more effectively. This fact should always be bear in mind especially, when the heat pump is used for heating a whole building.

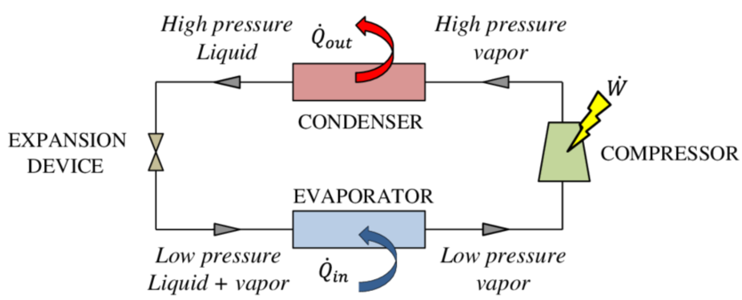
5 Operation of Heat Pumps

There are several different methods for pumping heat, the most common one is the so called vapour compression method. The basics of the operation is quite understandable, that when a sample of gas expands or is compressed quickly, then it cools down or heats up, respectively. (Students may have experiences that the soda cartridge gets freezing cold when the cartridge holder is screwed in the head of the soda syphon; and another that bicycle pumps get hot when they are used.) The gas which is periodically compressed and make expand is called the refrigerant or the working fluid (substance) of the heat pump. Although the operation is a bit more complicated in case of the vapour compression heat pumps, for not only the temperature of the working fluid changes, but its phase as well from gas to liquid and back from liquid to gas.

The schematic view of the vapour compression cycle is shown in Figure 2 below. Any similar figure or you-tube video can be used to explain the process.

The high pressure liquid goes through the expansion (or throttling) device, where its pressure drops. At low pressure the gas evaporates at lower temperature, but doing so it cools down. A sample of low pressure liquid and gas mixture enters into the evaporator, (which, for example in case of the refrigerator is in the cooling compartment). Here the remaining liquid evaporates taking away heat from the compartment. Then the low pressure gas is compressed to the initial pressure in the compressor. This is the part where the external work is performed, usually by means of an electric motor to drive the compressor. The high pressure vapour has high temperature as well, and when it goes to the condenser (in case of the refrigerator it is at the back of the refrigerator outside) it changes its state to liquid .

Figure 2: Vapour compression cycle



6 Heating Ventilating and Air Conditioning Devices

As it is explained in the previous section the refrigerant of the heat pump extracts heat from a cold heat reservoir and releases heat at a hot reservoir. These reservoirs are called the source and the sink. In order to heat a house the source is outside and the sink is inside. (When the house is cooled in summer the source and the sink are reversed.) The main categories of heat pumps according to the type of the heat source and the sink are the following(In heating mode, the first is the source and the second is the sink connected with a to .)

air to air,
air to water,
water to air,
water to water, or often brine to water[2] .

(For example an air conditioner is usually an air to air device or air to water describes a system that extracts heat from the air to produce hot water (for radiators or tap water).

Heat can be extracted from a variety of places:

outside air,
the ground (either horizontal trenches or vertical boreholes),
surface water: river, stream or lake,
ground-water,
waste heat, heat recovery. [3]

(Often heat pumps are classified according to these places and called for example a ground sourced heat pump in case of ground.)

6.1 Air Source Heat Pumps

They are usually air to air heat pumps, but nowadays the air to water units are also available. The most common heat pumps that are used for all air conditioners are air sourced heat pumps. Initially they were designed to cool buildings, but nowadays many of them can be operated to heat buildings as well. In this case the operation of the heat pump is reversed in the sense that in cooling mode the source is the air in the room and the sink is the outside air; whilst in heating mode the source is the ambient air outside the house and the sink is the air of the room.

These air conditioners are the cheapest, but their COP values vary with the temperature of the outside air. So for example in heating mode in autumn or in spring they have high COP (e.g. 4. or even more) since the temperature of the outside air is not very cold. But on a cold winter's day when the

[2] John Cantor: Heat Pumps for the Home, The Crowood Press, Ramsbury, 2011, pp. 22

[3] John Cantor: Heat Pumps for the Home, The Crowood Press, Ramsbury, 2011, pp. 31

ambient air temperature is $-15°C$ its COP value may dramatically drop. Another disadvantage of this type of heat pump is that it is noisy especially the outdoor unit. (Because it is usually an air to air unit, fans are used to move the air in the heat exchangers, which may generate significant noise as well.) Also if too many units are put close to each other, a localised cooling might happen, decreasing the efficiency.

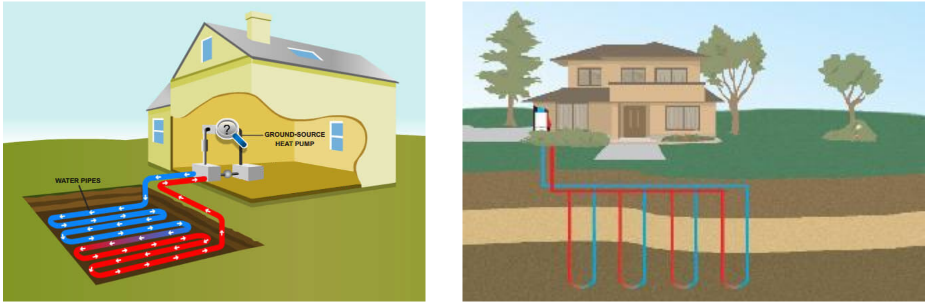
Another problem of this type of heat pump is that in the outdoor unit there is always some condensed water which freezes in cold weather, and thus it may damage the outside unit, which stops operating. Defrosting is not a big technical problem but the outdoor unit must be "winterized", which means that a heating element has to be built into the outside unit in order to defrost it. (Usually reversible air conditioners, in heating mode, can work within the temperature range of approximately $-15°C$ to $20°C$, on the outdoor side, when the outdoor unit is *not* frozen, so if defrosting is assured.)

6.2 Ground Source Heat Pumps

Ground sourced heat pumps are often called geothermal heat pumps, which might be a bit misleading, since these ground source heat pumps still use the thermal energy coming from the Sun (the Sun heats up the soil) and not the geothermal energy of the Earth. In case of ground source heat pumps a plastic pipe containing some antifreeze solution – often referred to as brine (although it is not necessarily salt water) – is buried under the ground, either horizontally or vertically. The brine absorbs heat from the ground and on the sink side of the pump there is usually water (which is circulated in the radiators or in the underfloor heating system), so these pumps are usually brine to water pumps.

The plastic pipe can be arranged either horizontally or vertically. In the first case horizontal trenches at a depth of 1 or 2 m are dug, and the straight or coiled pipe is placed there to extract the heat. At a depth of 3 m the temperature of the ground is approximately constant 10 °C over the whole year. At a depth of 1 or 2 m it may vary from 5 °C to 15 °C, depending on the local circumstances. When heat is extracted from the ground it gets colder, so to be able to use the heat pump a very long trench is required. Also it may happen in a long cold winter that the ground gets so cold that the COP value of the heat pump drops. In this case heat should be pumped back in summer by operating the heat pump in cooling mode. A big disadvantage of this heat pump is that a big area is needed for the trenches. (The area where the tranches are laid is approximately two or three times as big as the area of the house.) This area should be re-heated in the summer and in order that the pump works efficiently, no trees can be planted.

Figure 3: Ground source heat pumps. The collector pipes can be placed either horizontally or vertically.



If the pipes are placed vertically then vertical boreholes of depth from 60 m to 150 m should be drilled, into which the collector pipes are placed. This type of heat pump is more reliable, less space is needed for the installation, but it is also more expensive and careful planning is required for the drilling. (E.g. in the Town Hall of Staufen, Germany, a heat pump was to be installed, but during the exploratory drilling, after a few millimetres of sinking the city centre began to rise, and several buildings were damaged in the area. The main reason was probably that there was an anhydrite layer in the ground which came into contact with groundwater beneath it due to the drilling. When mineral anhydrite absorbs water gypsum is formed and also causes the anhydrite to expand.[3])

In the internet many figures can be found which show the layout of the collector pipes in the ground, two of them can be seen in Figure 3.

Since heat pumps work more efficiently if the temperature difference between the source and the sink is smaller, therefore it is better if the temperature of the water circulated in the house is not very high. So it is always a better choice to use underfloor heating in the house rather than radiators, because in case of underfloor heating the the area which releases heat is greater and thus in order to give the same thermal energy to the house the temperature of the circulated water can be lower, than in case of radiators.

[3] I. Sass, U. Burbaum: Damage to the historic town of Staufen (Germany) caused by geothermal drillings through anhydrite-bearing; Acta Carsologica 39/2, 233–245, Postojna 2010.

6.3 Water Source Heat Pumps

Since water has relatively high specific heat capacity it is a good heat source for a heat pump. There are two types of water source heat pump: the open and the closed loop systems. In case of the open loop system water is pumped directly through the heat pump. The closed loop system is similar to the ground source heat pump: a secondary fluid circulates in a closed loop (in pipes).

In case of the open loop system there are some disadvantages, the surface water that is pumped through the hat pump can be corrosive, and regular maintenance is required.

If there is a river or a lake nearby, then the collector pipes can just laid at the bottom, which is much cheaper than digging trenches, but still it has to be ensured that the collector pipes are not damaged.

Water sourced pumps can also use ground water. In this case at least two wells must be dig, one is the source from which the heat is extracted and another at least 15 m away the sink where the cooled water is released. Since ground water has a constant temperature throughout the whole year, it has a constant quite high COP, provided that groundwater does not dry up.

Students might be asked to search for buildings which are heated by heat pumps. (Two examples: Hotel Stáció in Vecsés utilises the thermal energy of groundwater to heat the rooms and the water pool in winter; the newly built Ikea in Soroksár is heated with ground sourced heat pumps, there are 120 boreholes of depth a 100 m.)

7 Examples and Estimations

7.1 Air Conditioners

In case of a modern air conditioner two data are written on it: a SCOP and a SEER value. These are technical terms the first characterises the heating and the second the cooling effectiveness of the heat pump, as it was explained in section 3. The S in the front stand for "seasonal", which means that according to the climate of the region where the pump is sold the average COP and EER values are calculated, considering the number of colder and warmer days in the year. Usually the COP values are smaller than the EER values, this is partly because in case of heating there is a greater temperature difference between the source and the sink, then when the heat pump is used for cooling. (E.g. when we heat in winter then the temperature of the ambient air outside is approximately 0 °C and the room temperature is 20 °C, and in case of cooling in summer the temperature outside is 35 °C and inside 25 °C, so the difference is smaller.)

7.2 Estimations for COP

We may use the Carnot efficiency to estimate the COP of for example a ground source heat pump. Let us assume that the temperature of the ground is approximately 10 °C and the temperature of the room is 20 °C.

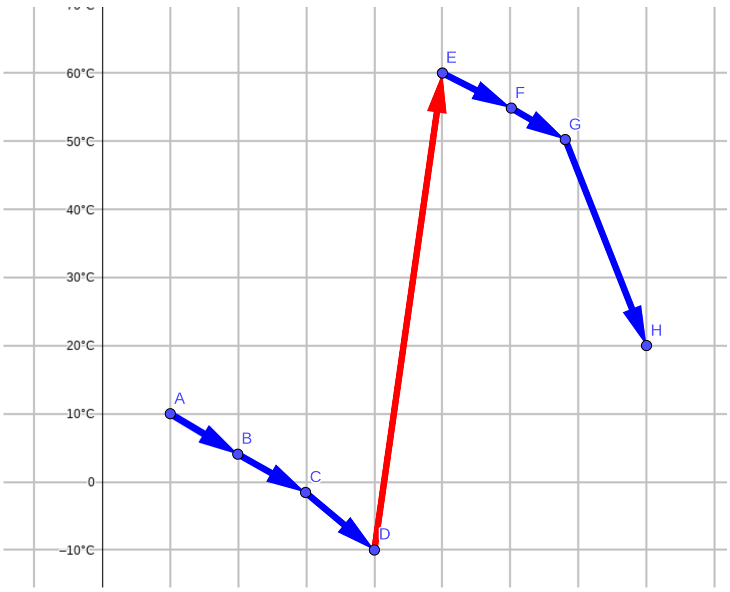
Using the Carnot COP value we gain: $COP_{estimation1} = \frac{T_{hot}}{T_{hot}-T_{cold}} = \frac{293}{293-283} = 29.3$, which is quite big. Actually this is far too big. The reason is that we cannot use the temperature of the ground and the room. The working fluid of the heat pump operates between a greater temperature range.

In reality spontaneously heat can only flow from hot to cold. So the refrigerant of the heat pump can only absorb heat from a heat reservoir which is warmer then the refrigerant and similarly it can only release heat to a reservoir which is colder than the refrigerant. The absorption and release of heat at the source and at the sink sides of the heat pump occurs at several steps. Figure 4 illustrates the steps of heat exchanges[4].

The trench is cooled down by the brine in the pipes laid in the ground, but still warmer then the brine. So the brine absorbs heat from the ground of the trench, and the brine is warmer then the refrigerant, so the refrigerant absorbs heat. The red arrow shows that due to the work done on the working fluid by the compressor, the refrigerant temperature is increased to approximately 60 °C. Again there are several steps to release heat to the room, the refrigerant heats up the water circulated in the radiators, then the water heats up the radiators, and then the radiators warm up the room. When we estimate the COP of the heat pump we have to consider the temperature range of the refrigerant. So using the data of the figure we gain: $COP_{estimation2} = \frac{335}{335-263} = 4.65$. (Due to other losses this is probably even less.)

[4]John Cantor: Heat Pumps for the Home, The Crowood Press, Ramsbury, 2011, pp. 154.

Figure 4: Heat transfer processes in a real-life geothermal heat pump.



A: temperature of the ground ≈ 10 °C;
B: Temperature of trench ≈ 4 °C;
C: Temperature of brine ≈ −2 °C;
D: Temperature of refrigerant ≈ −10 °C;
E: Condensing temperature ≈ 62°C;
F: Temperature of hot water loop ≈ 56 °C;
G: Mean radiator temperature ≈ 50 °C;
F: Room temperature ≈ 20 °C.

8 Environmental issues

8.1 How green is a heat pump?

The answer is that it depends.

If the compressor is driven by an electric motor, and electricity is gained from hydropower, then the heat pump uses renewable energy and also there is no carbon-dioxide emission at all. Beside the efficiency of the generation of electricity and the performance of the heat pump must also be considered. A hydro power plant has an efficiency of approximately 90% so if the performance of the heat pump on a cold winter day drops to for example 2 then it is still a good choice to use it.

If electricity is generated by a nuclear power plant then there is still no CO_2 emission but the efficiency of power generation in this case is approximately 35%, so on the cold winter day if the COP drops to 2, the heat pump uses more energy to heat the house than a condensing boiler would consume.

If electricity is generated mainly by fossil fuel burning power plants (their efficiency is approximately between 30-55%), then the heat pump is not really "green", considering that on a cold day it not only uses the same or more energy as a condensing boiler would do, but there is also CO_2 emission.

However, heat pumps have a great advantage to home furnaces which burn coal or wood, that they does not emit particulate matter in the close proximity of the houses.

Ground or water source heat pumps are more reliable, than the air source ones, since the performance of the air source hat pumps drop more dramatically in very cold weather. However, this may happen with the geothermal heat pumps as well in a very long cold winter, or if too many heat pumps are operated close to each other, so the ground cools down, and the pump cannot generate enough heat for the house. In this case in summer the lost heat should be "pumped back" by operating the heat pump in cooling mode.

8.2 Refrigerant

The "soul" of the heat pump is the refrigerant. There are many different types, but still scientists are working on finding better ones. Apart from that the ideal refrigerant should have the appropriate thermodynamic properties, it would also be desirable to use fluid which is not toxic, not flammable, not corrosive, its ozone depleting potential should be zero, and also it should not have high global warming potential. A very common branch of the used refrigerants were the chlorofluorocarbons (freons), which were banned for the high ozone depleting potential. Nowadays, mostly different mixtures of hydro-fluorocarbons are used. Their greatest problem is that their global warming potential is several thousands as big as that of carbon-dioxide. However, this becomes a problem only in case of a leakage. (Leakage is more common in the air conditioners of cars.)

Summary

It is important to educate students to be more environmentally conscious, to show them different options which may help to reduce pollution, or to slow down the climate change and to reduce the energy consumption.

Heat pump is a device which is getting more and more popular, but nearly nothing is taught about them. My students were quite interested in them, and found intriguing that whole houses can be heated with the energy of the ground for example, with performing only a little work.