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COMPARISON OF HEAT PUMP SYSTEM AND BOILER PLANT FOR ONE-FAMILY HOUSE

Heat sources in one-family house

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DESCRIPTION

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Abstract

The aim of this work is to look through, compare and choose the cheapest heat source for typical new Finnish one-family house. We will speak about renewable heat sources. They are heat pump systems and boiler plants based on wood fuel.

At first, historical, theoretical and economical aspects of heat pump systems and wood based boiler plants will be presented. Then pellet boiler plant and ground source heat pump system with horizontal loops will be economically compared.

As a result the conclusion about more cost efficient system will be given.

Subject headings, (keywords)

Ground sourse heat pump, pellet boiler plant, capital costs, investment costs, operational costs.

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CONTENT

LIST OF SYMBOLS

dS - gain of entropy (kJ/K)

dQ - dimensionless quantity of heat gain in the system (kJ),

T - temperature of the process (K)

η_s – isentropic efficiency,

η_e – electric motor efficiency,

Δh - real work in compressor machine (kJ),

Δh_s- ideal isentropic work in compressor machine (kJ)

P_k- shaft power of the compressor (kW)

P_e- input power of the compressor (kW)

COP_1-coefficient of performance of a heat pump cycle,

Q_1-heat from condensation (kW)

COP_{1c}-is coefficient of performance of Carno heat pump cycle

T_1-temperature of condensation refrigerant (K)

T_2-temperature of evaporation refrigerant (K)

C – capital costs

O – operational costs

T – total costs

c_b- boiler price

c_f- feeding system price

c_s- storage system price

m – maintenance and repairing costs

c_{fuel} - costs for fuel during the year

Q_a- annual energy consumption (MWh)

c_p-price for pellets

$\eta_{a.b}$-annual efficiency of pellet boiler plant

Q_{DHW}- annual energy consumption for domestic hot water (kWh)

q_s- specific heat flow through 1 meter of the pipe

c_{hp}- heat pump price

c_i- installation costs

c_{ghe}- price of ground heat exchanger

L - length of ground heat exchanger

c_y - price per year during life cycle

τ – life cycle

p_e-price for consumpted electricity

$\eta_{a.hp}$-annual efficiency of ground source heat pump

a - annuity

1 INTRODUCTION

Living in a detached house is very popular in Finland because it is very comfortable. Also it is good for people to be near to the nature. But if you want to live in detached house you have to decide several issues. One of them is how to heat your house and how to make domestic hot water.

The most common way to get heating energy is to connect to district heating network. It is easy and quit cheap. But what are you going to do if you are outside the district heating network?

Nowadays there are a lot of small heat sources for one family houses, for example: solar heating, direct electrical heating, boiler based on different types of fuel and several types of heat pumps.

In our work we overview and compare two different heat sources based on renewable energy and most common in northern countries. The first one is still very popular boiler plant and the second one is modern and more and more common heat pump system.

In the first part we will present the main parts of a heat pump system and its operational principle. We will also discuss different types of heat pumps, suitable for our case study. Both ground source and air/water source heat pumps will be presented. Then we will choose one of them for the future comparison with boiler plant.

The second part of our paper presents main parts and operational principle of the system with boiler and different types of boilers based on wood pellets, wood chips and chopped wood. We will show their technical properties and also choose one for comparison with heat pump system.

The last part of our work consist economical comparison of two chosen heat sources, for a typical Finnish new one-family house. We will calculate capital, installation, operational costs, and annual energy costs. So in conclusion we will be able to say what heat source is cheaper or more environmentally friendly.

2 HISTORY OF HEAT PUMPS

Principles of heat pump's work based on Carnot cycle was published in 1824.
Ten years later first compression machine was built by Jackob Perkins built. Refrigerant was ether. In 1852 William Tompson (or Lord Kelvin) suggested to build real practical work heat pump system. Tompson called it "Heat multiplier" (Figure 1).

1. Ambient air
2. Entrance cylinder
3. Heat exchanger
4. Drive actuator
5. Steam engine
6. Entrance
7. Cylinder
8. Heated space

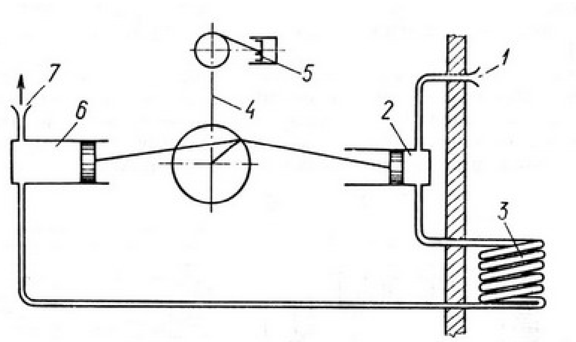
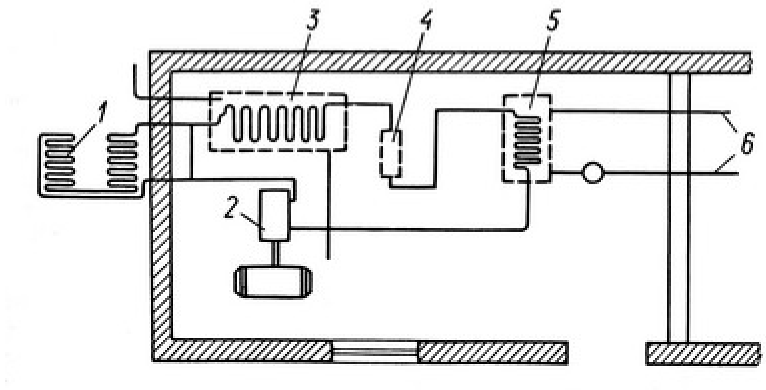


Figure 1. Tompson's "Heat multiplier" /1, p.9/.

This type of heat pump uses ambient air as a working medium. Ambient air goes to the cylinder. Then it expands and becomes cool. Then cool air gets warm in the heat exchanger from ambient temperature and goes to the cylinder number 6. In this cylinder air compresses to the atmospheric pressure and the heated air goes to the space. Tompson thought that this machine can produce required heat by using only 3 % of energy of usual heating.

The first compression cooling machine with ammonia as refrigerant was built in 1873 Munich by Karl fon Linde. Then in 1912 heat pump got a patent in Switzerland, but technology started to develop only in 1920s years. The next step of development took place in 1927 in England when engineer T. Holdein made first heat pump in his own house. Principle of Holdein's heat pump scheme is shown in *Figure 2*. Holdein's heat pump included two evaporators. First was outdoors. It took heat from indoor air. The second evaporator was dipped in the tank with flowing water in the room. Both evaporators could work together or independently. Their work depended on outdoor temperature. Water for heating system was heated up to 37,8°C in condenser so the surface of radiators should be bigger. Water for household needed heated up to 55°C by electricity. In summer time machine was used only during night. This machine produced water for household needs and ice. /38/



1-outdoor evaporator, 2-compressor, 3-evaporator in reservoir-accumulator, 4-throttle valve, 5-condenser, 6-connection with radiators

Figure 2. Principal scheme of first heat pump /38/

In 1930 started the production of Refrigerant Freon (R12) which was used in refrigerators. Later in 1938 first gross heat pump machine started to work in Zurich. Machine used heat of the river and refrigerant was R 5. It was made for heating and cooling system in town hall. Water was heated up to 60 °C. The main goal of this machine was decrease consumption of coal /1, p.10/. In 1950 a lot of small heat pumps were built in England for households needs /1, p.13/. In US in 1960 situation was another. Prices for electricity were decreased and it was profitable to use electricity directly. Heat pumps at those times weren't very reliable, that's why the demand for heat pumps decreased. But in 1973 situation was changed when energy crises in USA initiated growth of production of heat pumps. Also in 1974 University of cooling and conditioning in USA suggested a program of attestation of heat pumps and their classifications. /1, p.15/

3 THEORY OF HEAT PUMP

3.1 Carnot cycle

In 1824 Carnot published his dissertation about his invention. Nowadays his invention is called Carnot cycle and it is fundamental for comparing and evaluating the efficiency of heat pumps. Carnot cycle is reversible process of transformation of heat to work. It consists of 2 adiabatic curves and 2 isomeric curves working one by one (*Figure 3*).

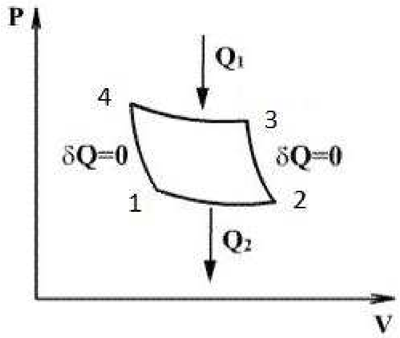


Figure 3. Ideal Carnot's heat pump.

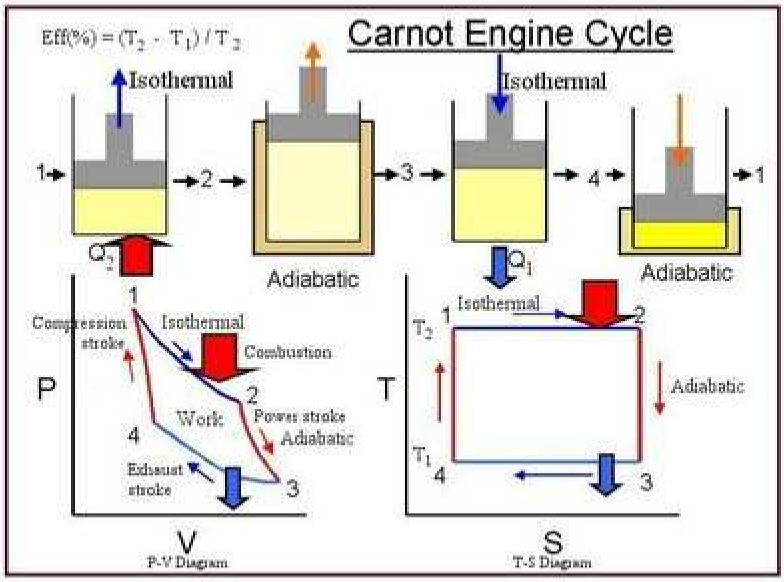


Figure 4. Heat engine work with using piston /2/.

Carno cycle is reversible process, so if we use this cycle in another direction we will get ideal heat pump with Carno cycle where work is transfer to the heat. Ideal heat pump Carno cycle consists of several elements shown in *Figure 5*.

1. Heat source
2. Compressor
3. Actuating motor
4. Heat consumer
5. Expansion machine

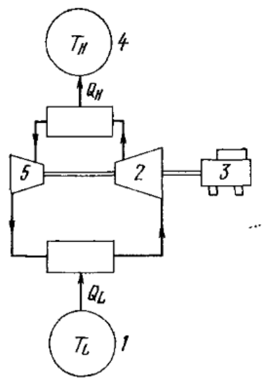


Figure 5. Principal scheme of Carnot's heat pump /1, p.16/.

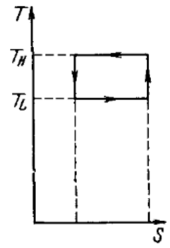


Figure 6. Carnot’s cycle in T-S axes /1, p16/.

In *Figure 6* the pointer shows us direction of this process. Heat is brought to the system and taken from system using isothermal process. The brought heat has lower temperature T_L and heat which we take has higher temperatureT_H. Compression and expansion are running by constant entropy. Entropy-is the quantitative measure of disorder in a system and it definition is:

$$dS = \frac{\delta Q}{T} \quad (1)$$

, where dS is gain of entropy (kJ/K), dQ is dimensionless quantity of heat gain in system (kJ), T is temperature of process (K). This formula proves that expansion and compression processes work without heat./39/

Carnot’s heat pump machine is a theoretical machine which has equal output-input ratio. It means that all work that we bring to the system is transformed to the heat work. In real life we never get 100 % efficiency because we always have losses because of friction and heat losses. Thereby Carnot’s cycle shows us the limit of efficiency; we can only try to reach this efficiency.

3.2 Vapor compression cycle

3.2.1 Ideal vapor compression cycle

To create an effective heat pump it is necessary to make its cycle approximate a Carnot cycle. In practice it means to strive to supply heat to the system by isothermal process. To create this condition we need to find working medium which can turn into aggregative state at necessary temperatures and pressures. This working medium can use heat needed for evaporation and give heat from condensation process. These processes create isothermal lines. Vapor must be dry when it flows to the compression. If this condition isn't met compressor can break.

Let's see a cycle with compression dry vapor and expansion in a throttle valve. Throttle valve is adjustable nozzle or capillary tube. The choice between them is defined by the requirements demand. When the expansion machine is not used part of useful work and efficiency is lost. Cost of expansion machine is very high so it is used only in a big heat pump systems.

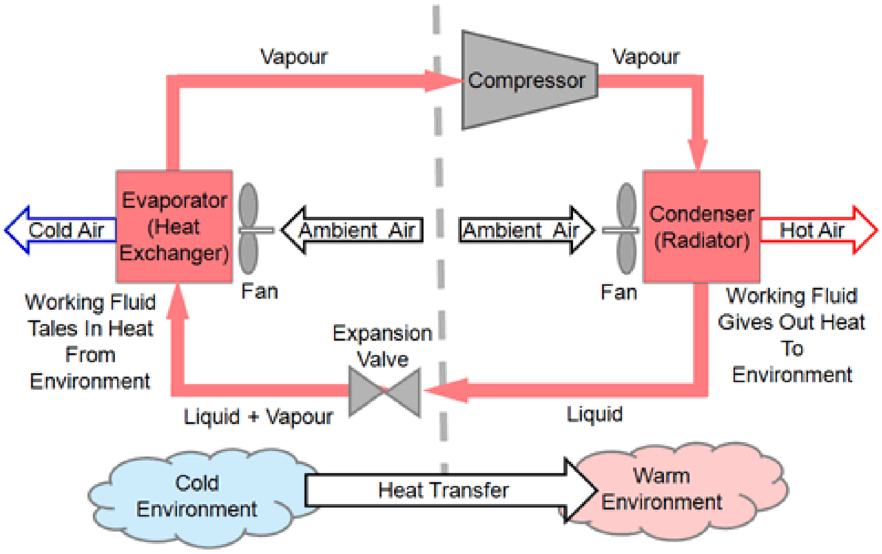
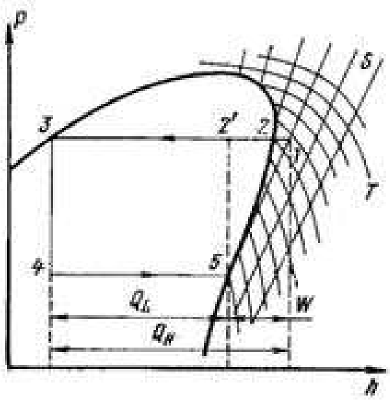


Figure 7. Heat pump vapor compression cycle /3/.

In practice when cycle of vapor compression at heat pump system is analyzed, p-h diagram is used as shown in *Figure 8*.



Q_L- heat needed for evaporation, Q_H- heat we get from condensation,

W- work for compression

Figure 8. Ideal vapor compression heat pump cycle in p-h axes /1, p. 18/.

In p-h diagram (Figure 8) the compressed working medium leaves the compressor in a point 1. Gas in the exit of compressor is superheated because in the compressor we need only dry gas without liquid. Before starting a condensation at point 2 gas is cooled at the constant pressure. Between points 2 and 3 condensation is going on at a constant temperature and pressure. Then between point 3 and 4 adiabatic expansion is going on. Expansion is a vertical line on the diagram. One of the benefits of p-h diagram is that such diagram shows condition in begin and at the end of the compression. Evaporation is going on between points 4 and 5. It should be noticed that expansion 3-4 usually proceed with mixed of gas and liquid. That's why gas and liquid entrance to the evaporator. Part of gas in the working medium doesn't take part in evaporation and heat absorption, so efficiency of the process becomes less. Between points 5 and 1 isentropic compression is going on. In practice it is impossible but now we are considering ideal vapor compression heat pump cycle.

p-h diagram has another advantage. From the diagram we can see directly Q_{H}, Q_L and W. Therefore diagram makes possible to analyze efficiency of process. To get good efficiency for heat transformation heat from condensation Q_{H} should be as big as possible relative to work for compression W. This Vapor compression system is reversible. It can be used for heat pump and also for cooling machine.

3.2.2 Real vapor compression heat pump

The work cycle described above is idealized. There were practical restrictions related with the compression of only dry steam and if the expansion machine isn't used. Also in previous chapter we have supposed that there are no losses. Now we would like to show that other part of real vapor compression heat pump system hasn't 100% efficiency either.

One of the main components of heat pump is compressor. Earlier we wrote that the compressor should work only with dry steam and before entrance to compressor steam must be a slightly superheated.

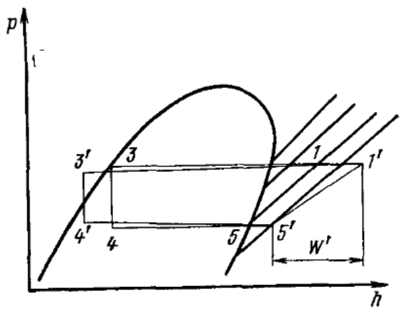


Figure 9. Real vapor compression heat pump cycle in P-h axes /1, p. 21/

We can see that real point for starting compression is $5'$ instead 5. Superheat is precautionary measure to prevent penetration of wet drops to the compressor. Thereby compressor becomes bigger because now it must compress more vacuum steam with the same mass. Also there is one more problem connected with big temperature in the exit of compressor.

Also in real work diagram we can see point $1'$ instead 1. Rising enthalpy is bigger than in ideal cycle. It is connected with the heat exchange between working medium and compressor. And it also increases temperature in the exit of compressor. Compression work with rising enthalpy in compressor designated W' instead W in ideal cycle.

There are 2 ways to define efficiency of compressor. Isentropic efficiency can be defined from the equation /5/

$$\eta_S = \frac{\Delta h}{\Delta h_s} \qquad (2a)$$

, where η_S is isentropic efficiency, Δh is real work in compressor machine (kJ) and Δh_s is ideal isentropic work in compressor machine (kJ) In usual case with piston compressor isentropic efficiency is about 70%. The shaft power is /5/

$$P_k = \frac{P_s}{\eta_s} \qquad (2b)$$

, where P_k is shaft power (kw), P_s is shaft power of isentropic compression (kw).

Input power is /5/

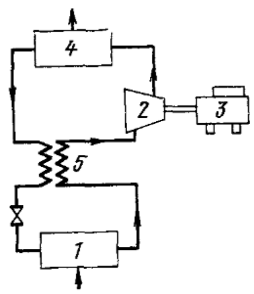
$$P_e = \frac{P_s}{\eta_s \cdot \eta_e} \qquad (3)$$

, where P_e is input power to the compressor (kw), η_e is electric motor efficiency. Usually electric motor efficiency is about 70-95% depending on type of the transmission between motor and compressor.

As stated earlier deviation of the real cycle from ideal cycle occurs not only in compressor but there are differences in the other part of system too. When the working medium goes through heat exchanger the pressure will decrease. In *Figure 9* we can see deviation from exothermic line in evaporator and condenser too. In *Figure 9* deviation is a lit bit bigger than in practice. In practice this deviation is about 1 K. Velocity of working medium should be quite high for preventing formation of dead zone.

The last deviation from the ideal cycle which we would like to show is supercooling after condensation. In the ideal process throttling starts from point 3. In the real cycle there are losses between condenser and throttling that leads to evaporation of working medium. To avoid this it is recommended to use subcooling.

Earlier we have described situation with necessity of superheat working medium before compressor. One way is to use heat exchanger between liquid line and suction line. This type of heat pump system is called vapor compression heat pump system with intermediate heat exchanger (*Figure 10).*



1- evaporator, 2- compressor, 3-motor, 4-condenser, 5- heat exchanger

Figure 10. Principal scheme of heat pump with heat exchanger /1, p.21/.

3.2.3 COP of heat pump

”Regardless of the application, the best way to measure the efficiency of a heat pump itself is to report the amount of energy that is pumped relative to the amount that must be added to do the pumping.”/4/. This ratio is called the Coefficient of Performance or COP. COP-value, according to /5/, can be calculated as follows

$$COP_1 = \frac{Q_1}{P_e} \qquad (4)$$

, where COP_1 is coefficient of performance of a heat pump cycle, $Q_1$is heat from condensation (kW) and P_e is required net work input (kW). According to /5/ coefficient of performance of the Carnot heat pump cycle is:

$$COP_{1c} = \frac{T_1}{T_1 - T_2} \qquad (5)$$

, where COP_{1c}-is coefficient of performance of Carno heat pump cycle, T_1-temperature of condensation refrigerant (K), T_2-temperature of evaporation refrigerant (K).

4 CLASSIFICATION OF VAPOR COMPRESSION HEAT PUMPS

“Heat pump is a device that extracts heat from one substance and transfers it to another portion of the same substance or to a second substance at a higher temperature”/6,10.1/. So we need two substances. First it is a substance with low potential energy. From this substance we take energy needed for evaporate working medium. The second is a substance which receives high potential energy from condenser.

4.1 Sources with high potential energy

1) Water. It means that low potential heat that we can get from different sources (it which will be described further) we bring to water. Then there are some heat exchangers for making hot water for heating, ventilation and hot domestic water system. Nowadays a lot of heat pumps use this type of substance.

2) Air. It means that low potential heat that we can get from different sources we bring to air. Air can be used directly only for the space heating. Hot domestic water must be produced, for example, by electricity resistor.

According to this we decide to choose water as a substance with high potential energy for following comparing.

4.2 Sources with low potential energy

1) Outdoor air is free and easy source for the heat pump. Outdoor air as a source has disadvantage for few months during the year. In Finnish climate temperature sometimes can be less than -20 °C and in these conditions heat pump works with lower efficiency than in warmer conditions. It leads to underheating water for heating and hot domestic water (air to water heat pump). So we need to use electric coils to get water with required temperature.

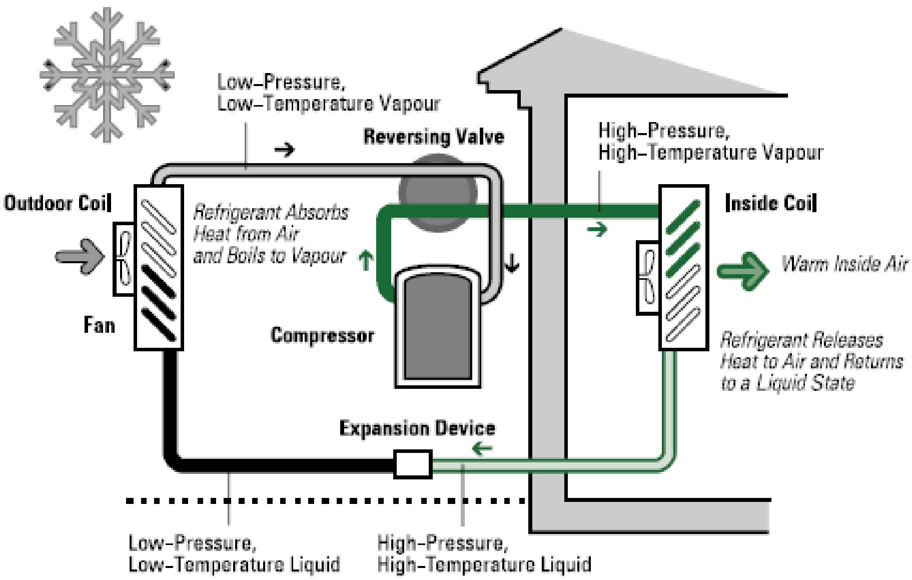


Figure 11. Air to air heat pump /10, p.13/.

Air to water heat pump can be used alongside with oil boiler and with solar collectors. Such systems are called hybrid heating systems.

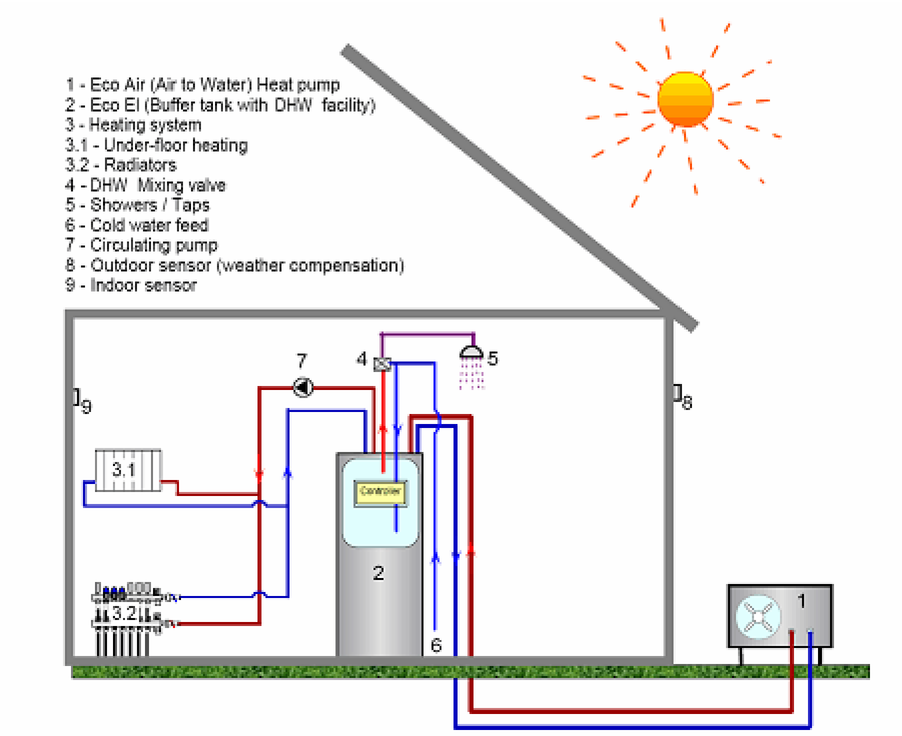


Figure 12. Air to water heat pump /13/

2) Ground. “The term “ground source” covers four different heat sources: rock, surface soil, ground water and lake.” /9, p.6/

a) Rock. It is efficient and reliable source of low potential heat but an expensive because it is necessary to drill a well in the rock “The depth of the hole can vary between 90 – 200 meters, depending on the size of heat pump selected and on local building regulations.” / 9, p.6/. One of the advantages is that we don’t need a lot of space for making a well.

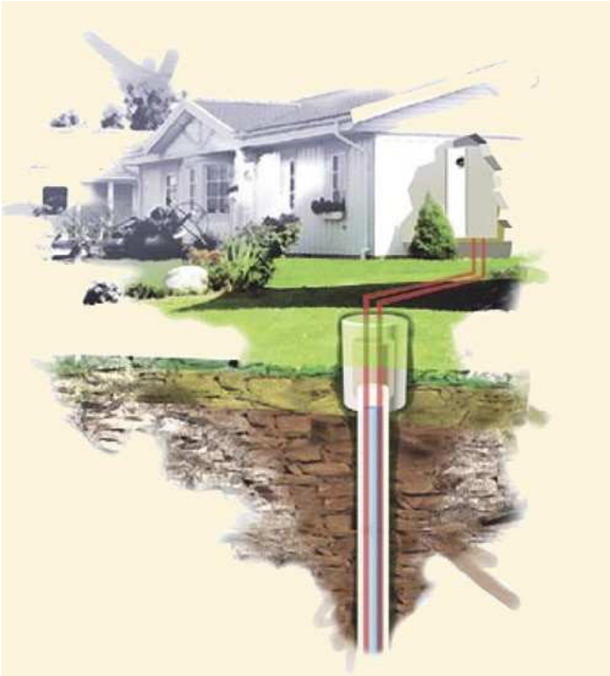


Figure 13. Ground source heat pump using energy from rock /12/.

b) Surface soil. According to Nibe’s brochures /9, p.6/ hose filled with anti-freeze, and buried at a depth of about 80 – 100 cm, the length of the hose varies between 250 and 400 meters, depending on the size of heat pump selected. But it is necessary to have enough space for installing pipes.

Figure 14. Ground source heat pump using energy from surface soil /12/

c) Ground water. “Ground water can also be utilized as a heat source since it has a temperature of between 4 and 12°C all-year round.”/9, p.37/. This system usually consists of two wells with supply and return water. Such system is called an open loop system. It means that we have heat exchanger in side of evaporator of heat pump. Ground water goes to the heat exchanger and takes heat to the refrigerant.

Figure 15. Ground source heat pump using ground water energy /9, p.7/.

d) Lake. “If your home is built beside a water source such as a lake, heat from the lake water can be extracted using a surface soil collector anchored to the bottom of the lake.”/9, p.7/ The system consists of pipes with refrigerant making in the bottom of the lake.

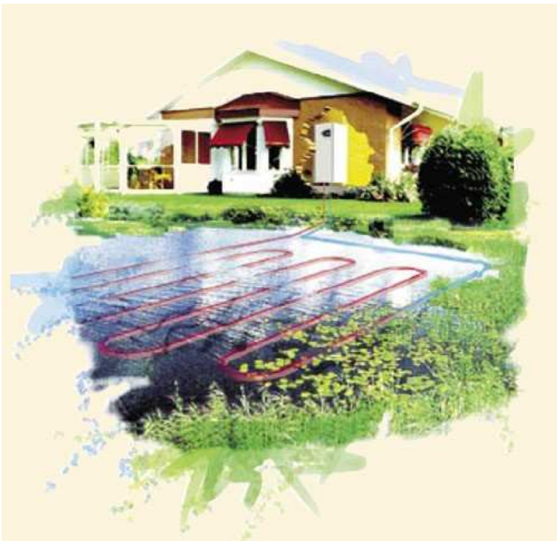


Figure 16. Ground source heat pump using energy from lake /12/.

5 TECHNOLOGIES IN GROUND SOURCE HEAT PUMP SYSTEMS

5.1 Active superheating technology

The active superheating technology is very modern, reliable and efficient technology for ground source heat pump.

“The Geopro SH superheating ground source heat pump is always connected to a separate buffer tank. The automatic system controls the superheating flow, which is split into two after the condenser. The majority of the flow is returned from the condenser back to the central part of the buffer tank, and a small flow is directed through the superheating heat exchanger.” /12, p.6/.

According to /12, p.6/ this system can achieve maximum water temperature of 80 °C. If domestic hot water isn’t needed or the temperature of water is enough superheating energy goes to the medium part of the boiler for heating system.

“A subcooler can be connected to the Geopro ground source heat pump and used to heat a low-temperature area, such as a garage or storage area for example, or keep outside steps free of ice, for instance.” /12, p.6/.

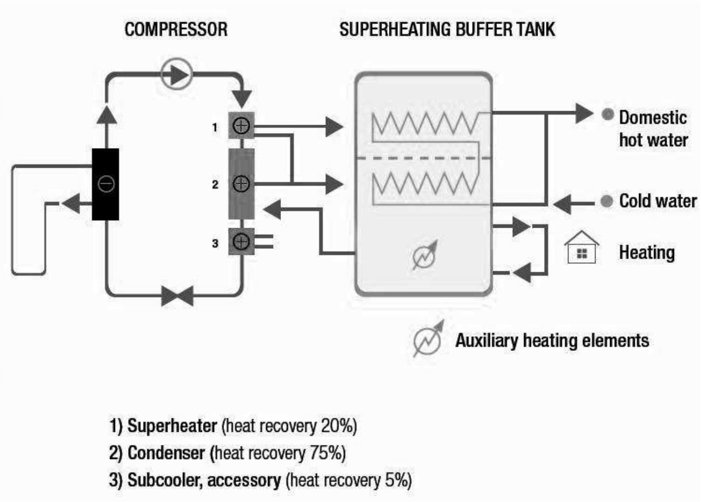


Figure 17. Heat pump with active superheating technology /12, p.6/.

5.2 Reversible valve technologies

"Heat production is usually controlled on the "floating condensing" principle. This means that the temperature level needed for heating at a given outside temperature is produced on the basis of values taken from sensors for outside temperature and flow temperature"/14, p.12/. Condensing temperature can be changed by changing quantity of refrigerant going through condenser.

We can regulate also temperature needed for hot domestic water production and for space heating. We need high temperature for hot domestic water and low temperature of water for underfloor heating.

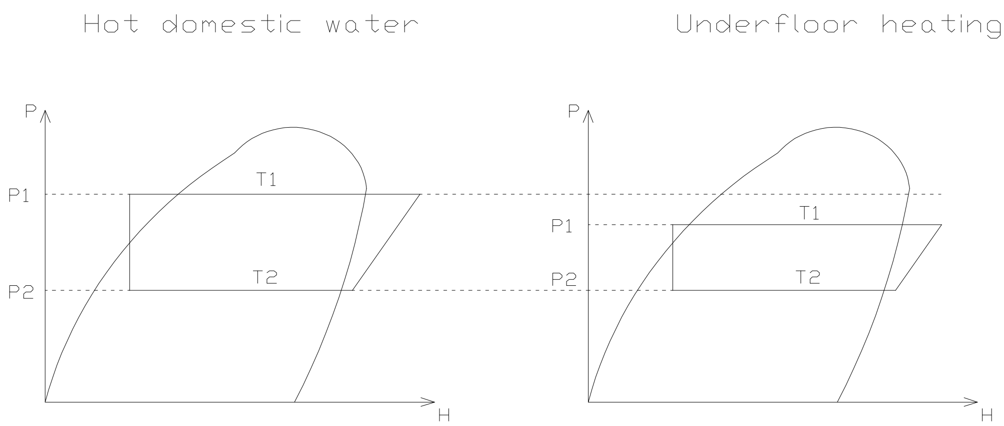


Figure 18. Diagrams of changing condensing temperature.

5.3 Full power and part-power heat pump

"The ground source heat pump can be sized up to full capacity or a partial capacity." /12, p.6/ Full capacity should satisfy all requirement of heat in building. In practice full capacity is defined with reserve. Partial capacity usually is counted as a 60 or 80 % from the heat demand. This capacity provides about 98 % of all requirements in annual heat energy of the spaces /12, p.6/.

6 BOILER PLANT AS A HEAT SOURCE FOR ONE-FAMILY HOUSE

In this chapter we would like to make an overview of history of using boilers and hydronic heating systems, their operational principles, and main components of the system. We decided to start with history, because we think it is interesting to know what was in the beginning to compare it with what we have now. Then we want to devote special attention those types of boilers which can be used as a heat source for a small residential building. There are three alternatives: boiler working on woodchips, pellet boiler or chopped wood boiler.

6.1 History of boilers and hydronic heating

The men who built the first hot water heating system were Jacob Perkins and his son Angier Marsh Perkins. May be some prototypes of such systems were earlier, but they built installation which really works. Jacob Perkins proved the compressibility of water with his first invention, the pressure gauge. But he never used his invention in space heating area. He developed a gun, working on steam, and used the idea in engraving industry. But his son Angier employed his invention to the space heating, and in 1831 got British patent № 6146 for the first boiler and the expansion tube. His system operated with high pressure 45-70 bars and high temperature 260-300 °C. It was closed system where overheated water went through pipes 1” diameter and heat emitters were spirals of this pipe.

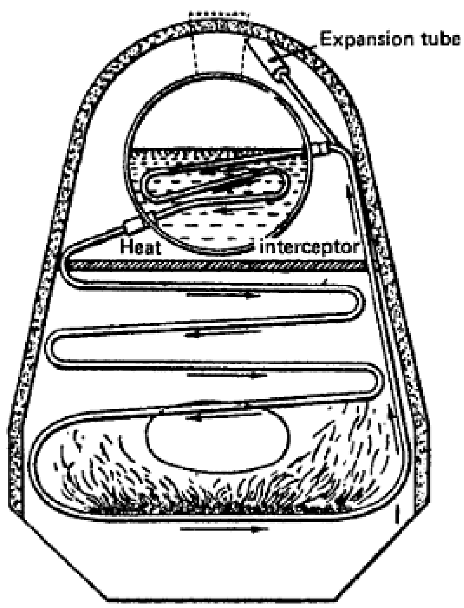


Figure 19. Perkins boiler /15,11/.

In next ages a lot of talented engineers and scientists developed and improved hot water systems. In 1837 in England Charles Hood's book about hot water heating was printed. Two years later engineer Robertson wrote his book, where all elements of the hydronic heating system were described and an idea of water circulation was discussed. Since 1840s this type of heating got wide distribution. In 1854 Stephen J. Gold invented a low pressure steam heater with self-regulating reliable device that was safe for domestic use.

"Gold's boiler was an upright, wrought iron shell boiler with a cast iron internal fire box. To hold the line on cost and make heating affordable for the average American, Gold riveted two thin plates of sheet metal together and made the first radiator. His simple device eliminated the need for coils or lots of costly wall piping.

Much like the Perkins family, Stephen Gold's son Samuel followed in his famed father's footsteps. The younger Gold studied his father's design and envisioned a new way to build boilers. It was made of cast iron sections, flat, oblong boxes, placed in series, the end sections closing and completing the unit. No longer would every unit have to be built to order. Under Gold's system, any size boiler could be made simply by adding sections. The sections also made it easy to fit units through the narrow doorways common in that day."/16/

In Russia first successful installations of hot water heating were built by talented Russian engineer Petr Sobolevskiy in 1834-184.

Since 1870s hydronic heating of low pressure became popular. All heating systems were one-pipe systems.

In 1890 according to leader of German heating techniques G. Ritshel appeared two-pipe heating system, which had two parallel, vertical pipes. One of them brought warm water to heat emitter, and the second one took cold water to boiler.

In 20th century hydronic heating with boilers was uninterruptedly developed. And there are a lot of scientists and researchers, who worked all their life to invent and improve something in this area. They are not so famous like singers or writers, but their contribution to human being not less. And thanks to these people we have now such sophisticated and high performance systems, which we will try to describe later.

6.2 Characteristics of the wood fuels

In our work we are going to speak about chopped wood (another name - firewood), wood chips and wood pellets. Nowadays it is considered that emission of greenhouse gases from burning wood and wood-based fuels is zero, because all CO_2, which is absorbed by plant from the atmosphere during growing, is released again after end of plant life cycle. So all fuels in our thesis are very environmentally friendly. We would like to give definitions and describe main properties. Then a table with exact values of their properties will be given.

- "**Firewood –** cut and oven-ready fuel wood used in household wood burning appliances like stoves, fireplace, and central heating systems. Firewood usually has a uniform length, typically in the range of 150 – 500 mm." /17/
  Units of firewood volume can be solid, stacked (or piled) and loose cubic meters. To explain their relationship, we will use the following picture:

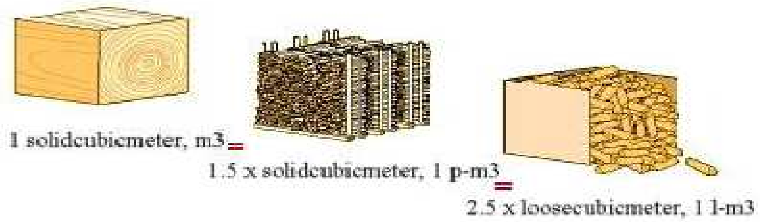


Figure 20. Relationship between firewood volume units /18/.

- "**Wood pellets –** fuel in the form of cylindrical or spherical units. Pellets are usually 8-12 mm in diameter and 10-30 mm in length, with moisture content of less than 10%. Pellets are usually produced from woody, herbaceous and fruit biomass or peat." /17/

- "**Wood chips - c**hipped woody biomass in the form of pieces with a defined particle size produced by mechanical treatment with sharp tools, such as knives. Wood chips have a subrectangular shape with a typical length of 5 to 50 mm and a low thickness compared to other dimensions." /17/

Table 1. Net calorific value, moisture and ash content, energy and bulk densities of fuels in a case study /17/. ($q_{p,net,d}$ = net calorific value (at constant pressure) in dry matter, M_{ar} = moisture content as received, $q_{p,net,ar}$ = net calorific value (at constant pressure) as received, BD = bulk density, E_{ar} = energy density, A = ash content in dry matter)

Fuel	$q_{p,net,d}$ (kWh/kg)	M_{ar} (%)	$q_{p,net,ar}$ (kWh/kg)	BD (kg/loose m3)	E_{ar} (MWh/loose m3)	A (%)
Firewood	5.14-5.28	20-25	3.72-4.03	240-320	0.8-1.0	0.5-1.2
Wood chips	5.14-5.56	45-55	1.94-2.78	250-350	0.7-0.9	1.0-2.0
Wood pellets	5.26-5.42	7-8	4.6-4.9	550-650	2.6-3.3	0.2-0.5

Net calorific value according to CEN/TS 15234 can be calculated by the following equation

$$q_{p,net,ar} = q_{p,net,d} \cdot \frac{(100 - M_{ar})}{100} - 0{,}02443 \cdot M_{ar} \qquad (6)$$

, where: $q_{p,net,ar}$ is net calorific value (at constant pressure) as received, (MJ/kg), $q_{p,net,d}$ is net calorific value (at constant pressure) in dry matter (MJ/kg), M_{ar} is moisture content as received (w-%, wet basis) and 0,02443 is correction factor of the enthalpy of vaporization (constant pressure) for water (moisture) at 25 ℃ (MJ/kg per 1 w-% of moisture).

Table 2. Chemical composition of fuels in a case study /17/.

Fuel	Carbon, C (w-%,d)	Hydrogen, H_2 (w-%,d)	Sulphur, S (w-%,d)	Nitrogen, N (w-%,d)	Chlorine, Cl (w-%,d)	Sodium, Na (w-%,d)	Potassium, K (w-%,d)
Firewood	48-52	6.0-6.5	<0.05	0.3-0.5	0.01-0.03	0.001-0.002	0.02-0.15
Wood chips	48-52	5.4-6.0	<0.05	0.3-0.5	0.01-0.03	0.001-0.002	0.02-0.15
Wood pellets	49-50	6.0-6.1	<0.007	<0.16	0.01-0.03	0.001-0.002	0.02-0.15

Table 3. Consumer prices (including VAT) for fuels in a case study.

Fuel	Price €/MWh
Firewood	36.3[1]
Wood chips	18,23[2]
Wood pellets	51,8[3]

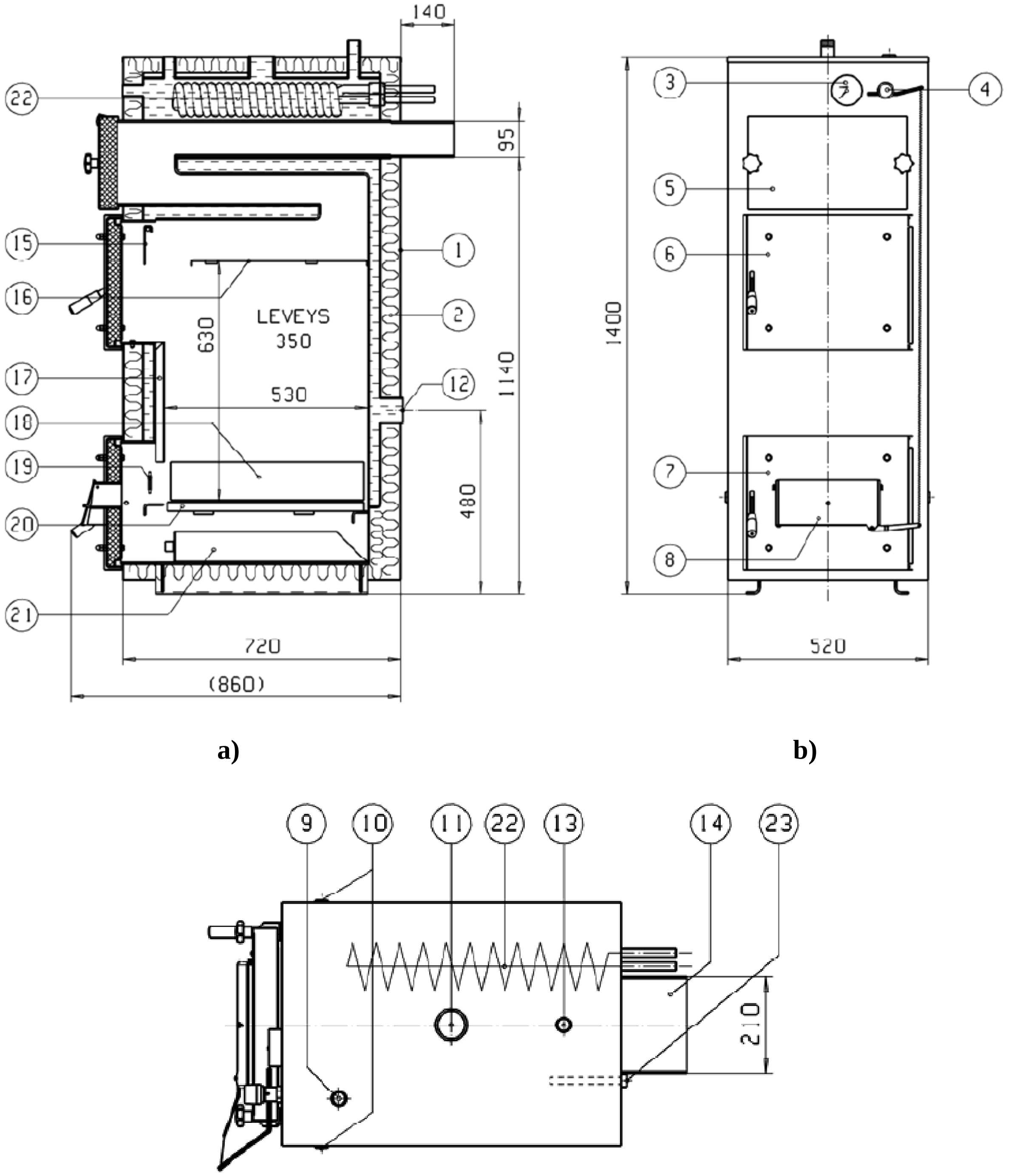
1) Average price for birch logs 50 cm length in Mikkeli area, available for 06.10.2010 /19/
2) Chipped/crushed product, sold on real markets. Nevertheless, includes small amounts of crushed stumps and unchipped shipments. /20/
3) Wood pellets for households, I-class, 6-8 mm, and batch size 5 tons. The price is based on the data for the middle month of the quarter. (February, May, August, November) /20/

6.3 Wood boilers

Chopped wood boilers can be divided into three types according to their combustion technology: first is traditional upper combustion wood boiler, second is traditional bottom combustion wood boiler, and third is the newest type reverse combustion boiler. The storage system (pile) for firewood is usually situated outside the building. Feeding of fire chamber is making by hand only.

6.3.1 Traditional upper combustion wood boiler

In this type the fire goes upwards in the tubes which are connected with water tank. It has quite high efficiency and long combustion time due to big fire chamber. Big volume of boiler water positively affects to the hydraulic conditions. Upper combustion boilers can work by natural draft, or they can be equipped with flue gas fan. The flue gas fan usually has frequency shifter. Typical upper combustion boiler is presented in the Figure 21.



a) b)

c)

1 - casing, 2 – mineral wool insulation, 3 – mano-/thermometer, 4 – draft regulator, 5 - cleaning hole, 6 – filling hole, 7 – furnace service hole, 8 – air damper, 9 – thermostat connection, 10 – drains, 11 – outlet to storage, 12 – return from storage, 13 – boil connection , 14 – flue connection, 15 – protection damper, 16 – furnace turbulators, 17 - combustion air guide, 18 - grate bar side plates (2), 19 - coal grate, 20 - grate bar, 21 – ash box, 22 - cooling coil, 23 - anti-boil valve.

Figure 21. Upper combustion wood boiler JÄSPI YPV 40 a) sectional view, b) front view, c) top view /21,2/.

6.3.2 Traditional bottom combustion wood boiler

The wood fired boiler works according to the principle of ”bottom combustion” where the wood is gasified and combusts efficiently under high temperature in the lower, ceramic lined part of the boiler. There are also self-draught boilers and boilers with flue gas fan. In the following *Figure 22* is presented bottom combustion boiler Ariterm 35+. This model has extra large wood container of 120 litres and can be also equipped with pellet burner.

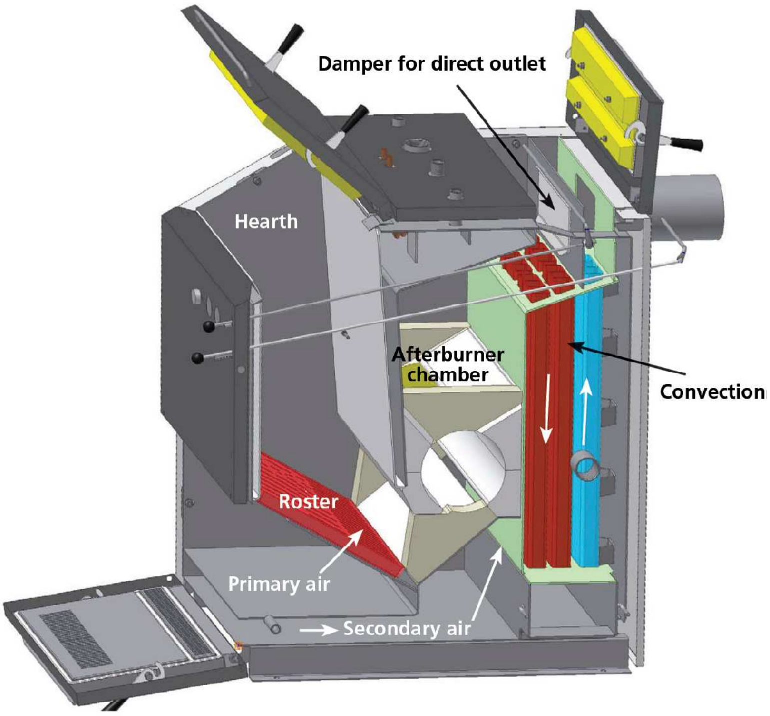
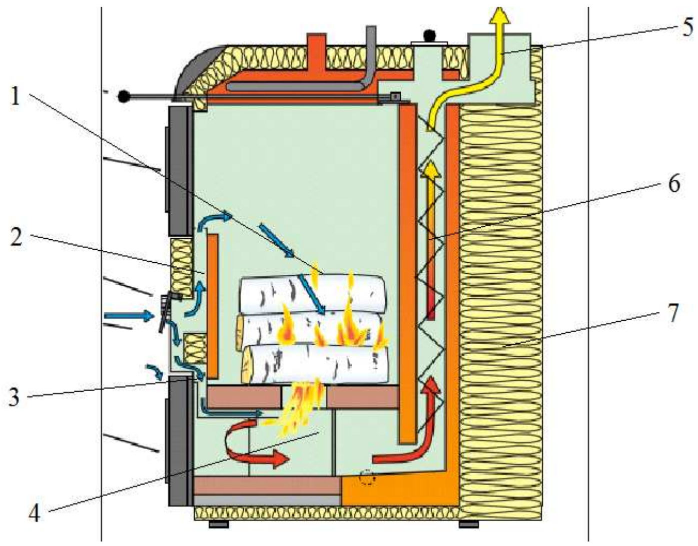


Figure 22. Bottom combustion wood boiler ARITERM 35+ /22/

6.3.2 Reverse combustion wood boilers

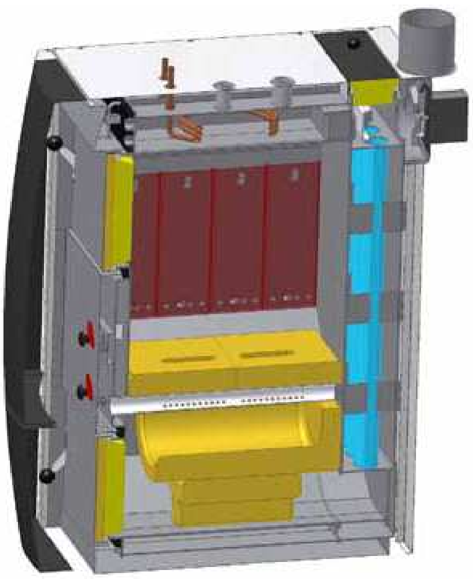
It is the newest type of boilers and not very common in Finland. In the *Figure 23* is presented reverse combustion boiler and combustion process is shown. This model works on natural draught, without flue gas fan. The combustion process works by reverse combustion. The air in the boiler enters through the damper (blue arrow on the figure) and is pushed down to the lower part of the fire where combustion is concentrated. The combustion gases are drawn through the ceramic grate down into the secondary chamber. More oxygen is supplied through the secondary damper and is mixed well, thanks to the turbulent flow, with the hot gases in the secondary combustion chamber where full combustion is achieved. Then these pass into convection part (orange-yellow arrow). The convection part is equipped with removable tur-bulators. Then flue gases go to the chimney (yellow arrow) and outdoors.



1 – first fire chamber, 2 - primary air, 3 – secondary air, 4 – second fire chamber, 5 – chimney, 6 – convection part, 7 – insulation.

Figure 23. Natural draught reverse combustion boiler NIBE VEDEX 1000 /23/.

Figure 24 shows reverse combustion boiler with flue gas fan. Construction of this boiler is almost the same as previous. The difference of this boiler is flue gas fan at the beginning of chimney pipe. Flue gas fan enables even combustion, and there is no height requirement for the chimney.

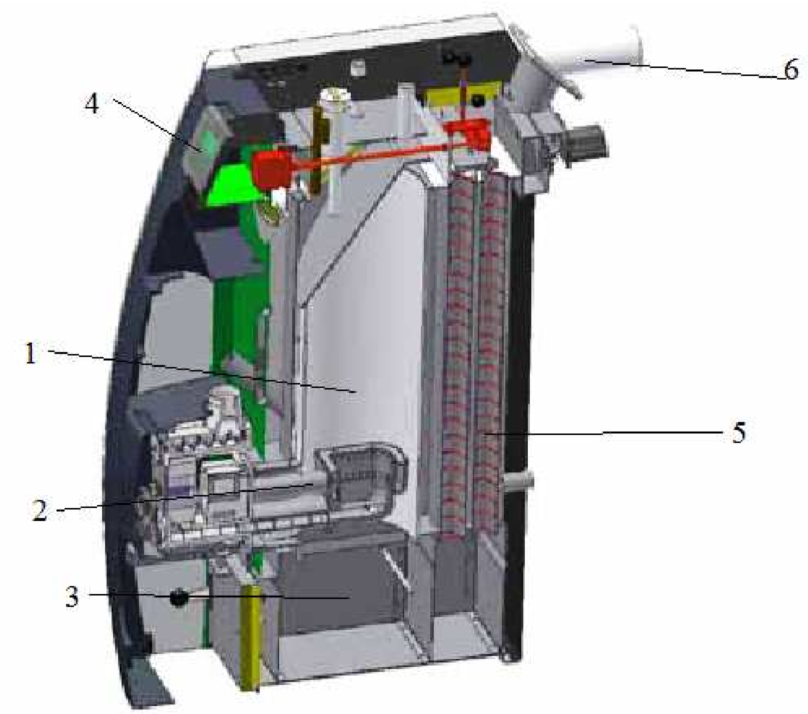


a) **b)**

Figure 24. a) Reverse combustion boiler; b) flue gas fan /24/.

6.4 Pellet boiler plants

Heating with pellet boiler is quite similar to oil heating. The difference is that pellets produce small amount of ash, which must be removed from ash box by defined time periods. Pellet boilers can work automatically with special pellet feeding system. There are also several solutions for storage and feeding systems. In *Figure 25* is presented typical pellet boiler.



1 - fire chamber, 2 - pellet burner, 3 - ash box, 4 - control panel, 5 - convection part, 6 – chimney pipe

Figure 25. Construction of pellet boiler ARITERM BIOMATIC+ 20 /25/.

In the next figure is presented typical pellet burner. The operation of the burner is controlled by temperature sensor in boiler. There is also another type of burners, where pellets are delivered to the fire chamber by fan, installed in the burner.

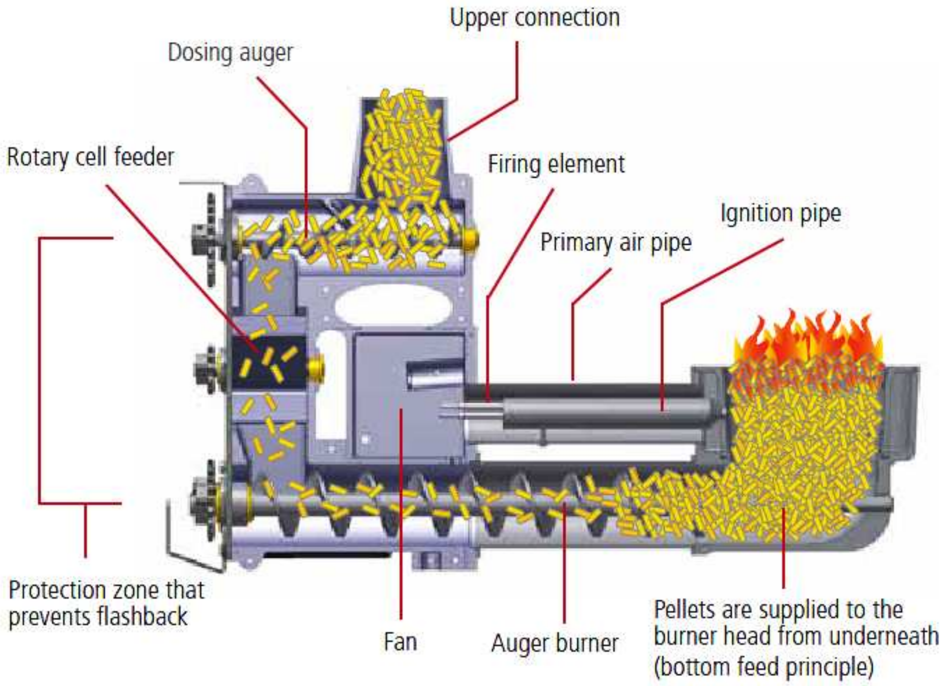


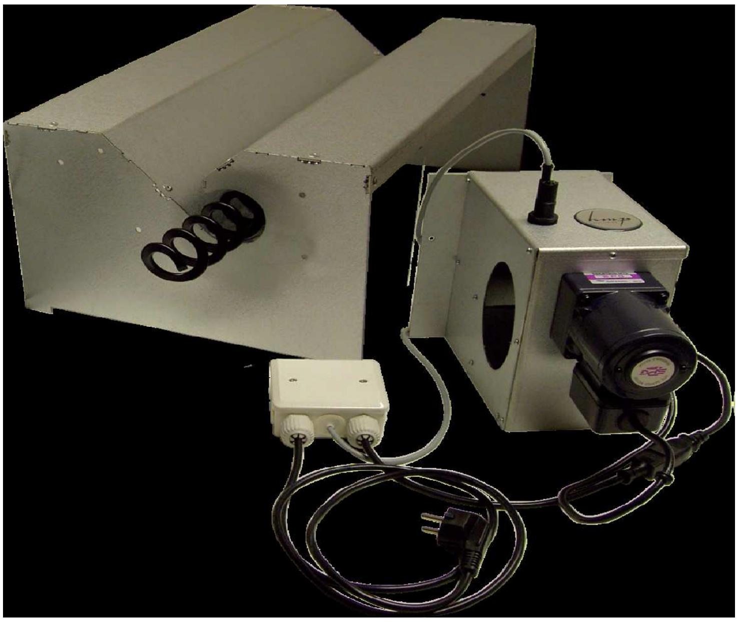
Figure 26. Pellet burner with automatic electric ignition /26/.

Important parts of the pellet boiler plant are feeding and storage systems. There are several different solutions of these systems. The choice of solution depends on available space for boiler room and distance between storage and boiler.

In a small boiler room a pellet tank with volume of about 500 liters in combination with auger system like KMP Feedo can be used. But small tank need to be filled every week, so it must be some outdoor storehouse also. KMP Feedo is a system of pipes with augers and electrical motor to deliver pellets to burner. In this system pellets are moved by rotation of auger. Maximum length of augers in KMP Feedo is 5 meters. If distance from storage to boiler is longer, several systems can be connected in series. It allows to have distance up to 12 meters.

If space of boiler room is not restricted, it is reasonable to build big storage. Big storage system can be built around KMP Depo system, which includes chute, auger and electric motor. This storage can contain up to 3 tons of pellets.

If storehouse is situated quite far from boiler room the pneumatic transport system can be used for feeding. This system allows to deliver pellets up to 45 meters.

a) **b)**

c)

Figure 27. a) Feeding system KMP Feedo b) Feeding system KMP Depo c) Pellet boiler plant with big storage system and feeding systems Feedo and Depo in cooperation /27,28/

6.5 Wood chips boiler plants

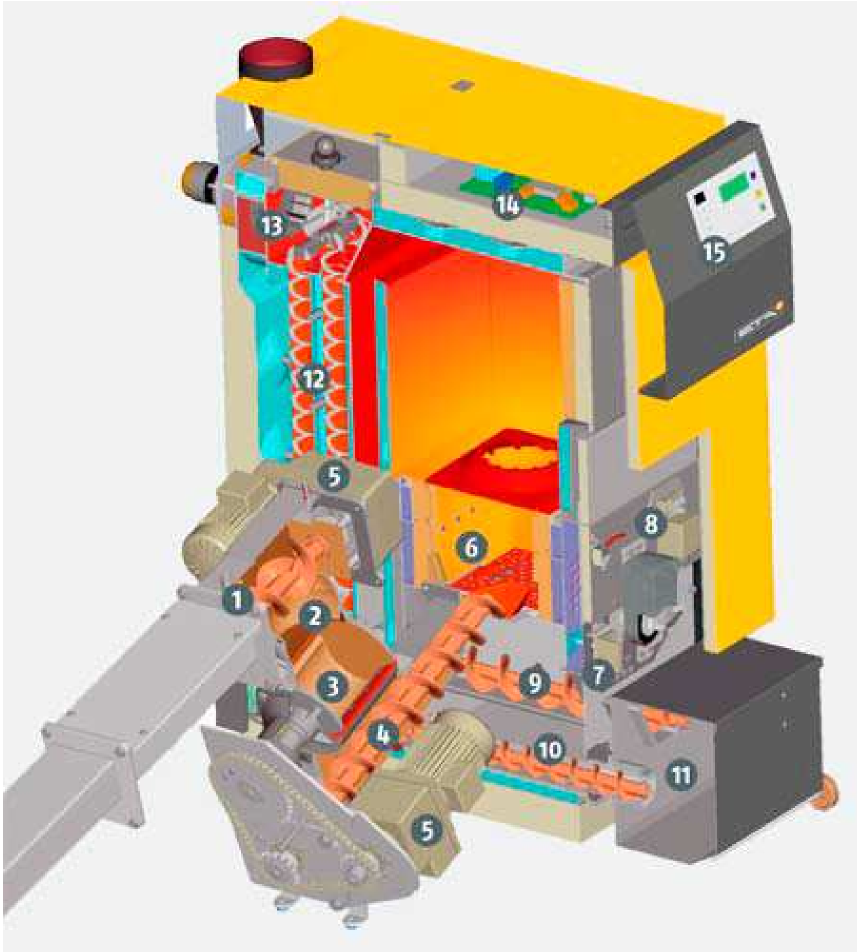
The operational principle of chipped wood boiler is almost the same as wood pellet boiler. So description of this type of boiler plant will consist of the same parts. But the difference in fuel causes the difference in construction. The boilers are characterized by the type of combustion and feed mechanisms.

There are two common types of burners in wood chips boilers. “**Stoker burners** -the stoker burner is like a pressure jet oil burner. Woodchips are delivered by auger to the burner head where air is pumped into the fuel space through a ring of holes. The burner produces a vigorous flame which is fired into the boiler. This type of burner requires dry chips of a small uniform size. The size of the fire is small and an increase in fuel delivery results in a rapid increase in heat output. Stoker burners can respond quicker to fluctuations in heat demands.

Underfeed stoker - fuel is augered in to the base of the boiler and spreads out. These boilers are not so good at drying the fuel and so are suited more to burning dry wood chip (for example from joinery factories).” /30/

In the *Figure 28* is presented wood chips boiler with auger burner, but fuel augered not to the base of boiler but on the grate, where it is mixed with primary air. The feature of this burner is one-chamber rotary valve (3), which is for prevention fire spread back across feeding system to the storage. Also thanks to this construction it allows to use quite big wood chips.

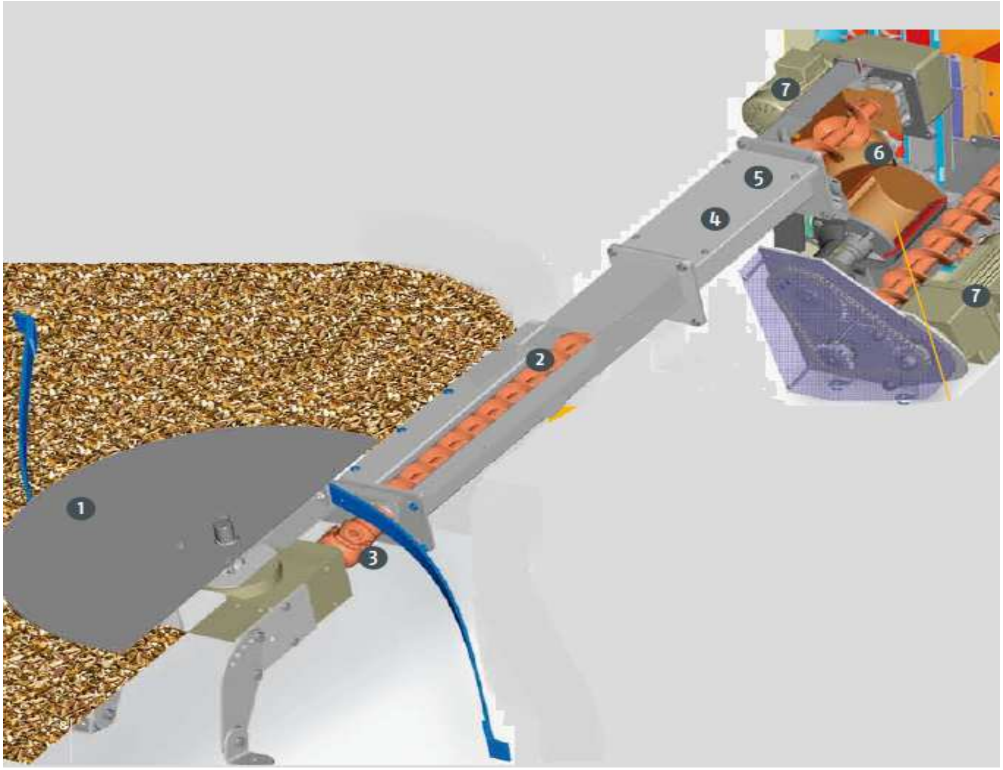
This boiler has lambda sensor, the regulator in the boiler chimney measures the flue gas oxygen and adjusts the input of fuel as well as the air intake for combustion according to the energy density of the wood currently in use. Automatic ash-removal system makes it easy for clean. Also it has flue gas fan with speed regulator.



1 - fuel conveyor screw with removable revision heads, 2 - ball-and-socket joint, 3 - one-chamber rotary valve, 4 - stoker screw, 5 - helical gear motor, 6 - hot, ceramic lined combustion chamber with tilting grate, 7 - primary air actuator, 8 - secondary air actuator, 9 - ash screw for ashes from the grate, 10 - ash screw for ashes from the heat exchanger cleaning, 11 - removable bin for ashes, 12 - heat exchanger with cleaning turbulators, 13 - draft fan, 14 - control board, 15 - control panel.

Figure 28. Construction of wood chips boiler ETA HACK 20 /29/.

In the next *Figure 29* feeding system for wood chips boiler is shown. In such feeding systems fuel at first, with help of round agitator with strong blades, come to the screw conveyor and then to the burner. Free running hub allows reversing the system if a piece of wood locks it. The length of agitator's blades is varied from 1.5 to 6 meters, and the length of conveyor can be up to six meters. It depends on size of the system. "Building block system is needed to add length of conveyor without welding. Ball-and-sock joint allows connecting burner to conveyor in any required angle.



1 – agitator, 2 - screw conveyor, 3 – free running hub, 4 – removable cover, 5 – ”buiding block” system, 6 - ball-and-socket joint, 7 - helical gear motor

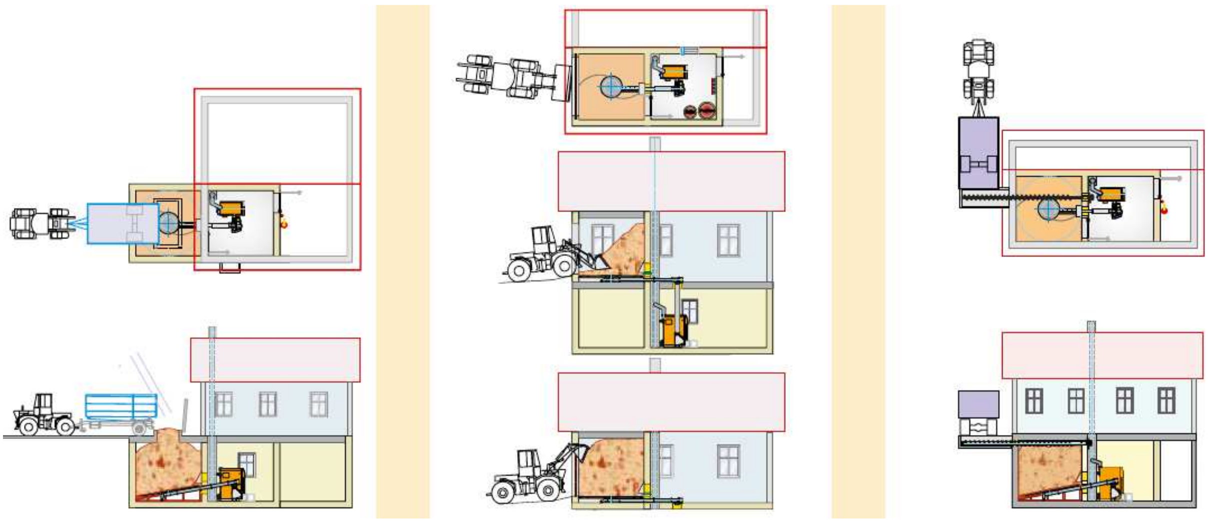
Figure 29. Construction of feeding system ETA HACK 20 /29,14/

There are three most common types of storage systems for wood chips. They are well illustrated in the *Figure 30.*

Tipping through shaft is fast and simple filling of the bunker by simple tipping movement. If a new bunker is being specially constructed for the heating system, then this is the best solution.

Filling with front-loader has low construction costs, the bunkers can also be built as a simple extension to the existing building at reasonable cost. This is the preferred option if a tractor with a front-loader or a wheel loader is available for use.

Bunker filling screw conveyor also has low construction costs, an existing window opening can be used. The bunker filling screw conveyor can be installed at an angle or inclined.



a) Tipping through shaft b) Filling with front-loader c)Bunker filling screw conveyor

Figure 30. Storage systems for wood chips boiler plant /29/

7 ECONOMICAL CALCULATIONS

For economical calculations out of wood based boiler plants we have chosen a pellet boiler plant. Because it is modern system with good automation, so it can work without every day control. Pellet boiler plant requires only to fill storage room once a week or once a month (frequency of filling depends on size of a storage room). We didn't choose chopped wood boiler because it is needed to fill wood container by hand very often. So in winter time you can leave your house for a time longer than time of burning of full wood container, otherwise heating system will be frozen. Also it has lower annual efficiency 0.7 /35, 14/. We didn't choose wood chips boiler plant despite of its lower price, the same annual efficiency and possibility of automatic work. The reasons are that wood chips boilers are usually used for bigger heating demand and require big storage room. So wood chips boiler more suitable heat source for farm house, where a big storage can be easily built. Also disadvantage of wood chips is big difference in moisture content as received, and it can be quite high.

Out of heat pump systems we have chosen ground source heat pump with horizontal loops. We didn't choose air-to-water heat pump because efficiency in cold weather conditions is very low and our case study is house situate in northern country. Also annual efficiency of air-to-water heat pump is only 1,5 /35, 14/, but ground source heat pump has 2,5. Another possibility was ground source heat pump with vertical drills, but it has very high installation cost (for our case study cost of drilling approximately 7000 €).

So this chapter presents investment and operational costs of these systems, mentioned above. Also annual fuel consumption and price for boiler plant and electricity consumption and price for heat pump system will be calculated.

7.1 Energy consumption of one-family house in Finland

As example in our thesis work a typical new Finnish one-family house is considered. The area of a building: A = 200 m², volume: V = 600 m³, number of occupants: 4. Geographical location: Eastern Finland, Mikkeli area. Energy consumption:
-Heating demand - 5 kW
-Annual heating energy consumption - 10000 kWh
-Annual energy consumption for domestic hot water – 10000 kWh

7.2 Cost estimation

These calculations will be made in Excel program. And extra initial data for them is bank loan interest in Finland. Nowadays it is in its lowest point about 2,5 %. But in our calculations 4 % interest was used, because of taking into account possible future growth.
We have chosen pellet boiler plant Ariterm Biomatic +20. This model satisfied our heating demand. Costs of this system can be defined as follows:

Capital costs:

$$C = c_b + c_f + c_s + c_i \qquad (7)$$

, where c_b- boiler price – 4237 € /32/, c_f- feeding system price -610 € /33/, c_s- storage system price 1720 € (volume = 5.6 m³) /34/, c_i- installation costs, can be assumed as 15 % of boiler price – 636 €.

$$C = 4237 + 610 + 1720 + 636 = 7203\ €$$

Operational costs (costs, which should be paid every year):

$$O = m + c_{fuel} = 216 + 1295 = 1511 \text{ €} \quad (8)$$

, where m – maintenance and repairing costs, can be assumed as 3 % of capital costs – 216 €, c_{fuel} - costs for fuel during the year, can be calculated as follows:

$$c_{fuel} = \frac{Q_a \times c_p}{\eta_{a.b}} \quad (9)$$

, where Q_a- annual energy consumption 20 MWh , c_p-price for pellets 51,8 €/MWh /20/, $\eta_{a.b}$- annual efficiency of pellet boiler plant – 0.8 /35,14/

$$c_{fuel} = \frac{20 \times 51{,}8}{0.8} = 1295 \text{ €};$$

A suitable heat pump for our case is NIBE F1226-6 kW. Costs of this system can be defined as follows:

Capital costs:

$$C = c_{hp} + c_i + c_{ghe} \times L = 4968 + 745 + 3 \times 240 = 6433 \text{ €} \quad (12)$$

, where c_{hp}- heat pump price – 4968 € /36/, c_i- installation costs, can be assumed as 15 % of heat pump price – 745 €, c_{ghe}- price of ground heat exchanger ≈ 3 €/meter, L - length of ground heat exchanger can be calculated by following equation:

$$L = \frac{Q_a \times 0.6}{q_s} = \frac{20000 \times 0.6}{50} = 240\, m \quad (13)$$

, where Q_{DHW}- annual energy consumption – 20000 kWh, q_s- specific heat flow through 1 meter of the pipe ≈ 50 kWh/m, 0.6 – share of energy got from ground according to COP1=2.5

Operational costs (costs, which should be paid every year):

$$O = m + c_e = 216 + 813 = 1029\ € \qquad (14)$$

, where m – maintenance and repairing costs, can be assumed as 3 % of capital costs – 216 €, c_e - costs for electricity during the year, can be calculated as follows:

$$c_e = \frac{Q_a \times p_e}{\eta_{a.hp}} \qquad (15)$$

, where Q_a- annual energy consumption 20 MWh , p_e-price for consumpted electricity10,16 c/kWh = 101.6 €/MWh /37/, $\eta_{a.hp}$-annual efficiency of ground source heat pump – 2.5 /35,14/

$$c_e = \frac{20 \times 101.6}{2.5} = 813\ €;$$

Calculations were done by ”annuity method”. Annuity is /40/:

$$a = \frac{i \times (1+i)^{\tau}}{(1+i)^{\tau} - 1} \qquad (16)$$

, where *i* is bank loan interest – 0,04, τ – life cycle of the system.

For heat pump system a is 0.090 and for pellet boiler plant a is 0.064. So payment per year is a sum of capital cost multiplied by annuity, energy cost and maintenance cost.

Table 4. Capital costs, energy costs and payment per year.

	Capital cost	Life cycle, years	Interest, %	Qa, MWh	η_a	Energy price, €/MWh	Energy cost, €/year	Maintenance cost, €/year	Payment per year, €/year
Pellet boiler plant	7203	25	4	20	0,8	51,8	1295	216	1972
Heat pump system	6433	15	4	20	2,5	101,6	813	216	1608

Table 5. Costs per year and cumulative cost.

	years	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Pellet boiler plant	payment per year	1972	1972	1972	1972	1972	1972	1972	1972	1972	1972	1972	1972	1972	1972	1972
	cumulative cost	1972	3944	5916	7888	9860	11832	13804	15776	17748	19720	21692	23664	25636	27608	29580
Heat pump system	payment per year	1608	1608	1608	1608	1608	1608	1608	1608	1608	1608	1608	1608	1608	1608	1608
	cumulative cost	1608	3216	4824	6432	8040	9648	11256	12864	14472	16080	17688	19296	20904	22512	24120
Return because of us-ing heat pump system		364	728	1092	1456	1820	2184	2548	2912	3276	3640	4004	4368	4732	5096	5460

	years	16	17	18	19	20	21	22	23	24	25
Pellet boiler plant	payment per year	1972	1972	1972	1972	1972	1972	1972	1972	1972	1972
	cumulative cost	31552	33524	35496	37468	39440	41412	43384	45356	47328	49300

CONCLUSION

So our calculations show that investment cost of ground source heat pump system is almost the same as cost of pellet boiler plant. But operational cost of heat pump is 15 % less than for pellet boiler plant. And heat pump brings profit since first year of use. Total return because of use heat pump system, during 15 years life cycle is 5460 €.

Cost is very important criteria of choice. But heat pump system has also some other advantages. With heat pump system storage room and feeding system for fuel is not needed. And also buying of fuel every month or every year (it depends on size of storage room) is not needed. Fuel for heat pump system is electricity, which all houses are connected to. Storage room and feeding system is not needed, so boiler room can be smaller than with pellet boiler plant. But disadvantage is, that heat pump with horizontal loops requires about 300 m^2 of ground for the heat exchanger.

Environmental impact of heat pump system depends on way of electricity production. For example, in Mikkeli power plant partly works on wood based fuel, so heat pump system in Mikkeli is an environmentally friendly system.

So heat pump system has not only cheaper costs, but also some other benefits, and we can recommend to choose it as a heat source for one-family house, if required ground area is available.

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