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Energetic and Ecological Benefits of Heat Pump Application in Energy Transformation Systems

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Abstract

In 1900, Nikola Tesla published a paper: *The problem of increasing human energy*, stressing that generating electricity from burning of coal we would be destroying material, which would be a barbarous process. This message is still vitally important, and one method to mitigate the barbarous effects is e.g. application of heat pump. Its benefits are twofold: economical and ecological. Heat pump reduces fuel consumption and lessens the burden on the environment through combustion products. As example, we have quantified its application in the area of heating, but the results obtained are extendable to any energy system. The most significant parameters are the efficiency of the energy conversion process and the COP of the heat pump. When the product of these two parameters is equal to one, part of energy losses, occurring in the energy conversion process which is associated with the heat pump application, can be completely utilised by the heat pump as useful heat. This is of paramount importance for reduction of energy conversion losses and protection of the environment. In general, both the fuel consumption and amount of combustion products decrease with increasing COP, that is, with increasing evaporation temperature and/or decreasing condensation temperature of the working fluid used in the heat pump.

Keywords: Heat pump, Heating, Environment, Energy losses, Energy balance

1. Introduction

Limited resources of fossil fuels and pollution of the environment have strengthen the discussion in the last years on handling the energy resources gently, calling for more efficient energy transformation and rendering other energy kinds accessible. Due to the imperfection of devices and thermodynamic limitations arising from technological restrictions, the efficiencies of energy conversion processes are still very low. In 1996, J. H. Ausubel [1] asked the question: *Can Technology Spare the Earth*? His analysis suggests that technology could restore the environment, even as population grows, if efficiencies of energy conversions correspondingly evolved. Meanwhile, numerous studies have appeared, dealing with the interactions within the triangle *society-production-environment*, thereby discussing future developments in this area, see e.g. [2]. The analysis is mostly based on the exergy concept [3, 4]. As shown below, this concept is not indisputable, particularly regarding the environment as the reference system.

In order to protect the environment from harmful technical wastes, several ideas have been developed and tested under real conditions. One of them is the application of heat pumps which should reduce the primary energy required for process operation. However, despite the extensive research, there are apparently no papers in the literature stressing economical and ecological benefits of heat pump application. The same is true regarding the interaction of heat pump efficacy and energy losses in conversion processes of primary energy. Also detailed comparisons of different heating systems are missing in literature, a paper by Acikkalp and Aras [5] being an exception, to some extent. The authors compared a natural gas boiler with a heat pump heating system. They found the heat pump system to be more efficient, but their statement, the heat pump would not release CO2, does not generally hold.

2. The Scope of the Present Paper

In this paper we quantify benefits of heat pump application in energy conversion systems (heating) regarding primary energy requirements for its operation and environmental impact. We compare some heating possibilities with each other assuming various sources of primary energy and different processes of its transformation. In particular we include following cases:

1. Combustion of a fossil fuel (e.g. coal), alternatively bio-fuel, for direct heating.
2. Conversion of electric energy into heat, whereby electric energy may stem from various sources of primary energy.

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3. Application of a heat pump when the energy for its operation is taken from different sources:

   a) Thermal power plant, b) Hydro-energy, c) Geothermal energy, d) Solar/wind energy.

In addition, we evaluate losses of energy conversion in view of heat pump use, pursuing the following question: If the energy for heat pump operation is generated from primary energy in a process at certain efficiency, can a heat pump convert these losses into heat applicable for heating? In other words, is it possible to convert the primary energy in combination with heat pump application without energy losses? As is shown below, this is possible at specific conditions.

We first address some questions regarding the environment and its protection; then the working principle of heat pump is sketched, followed by exemplifying determination of its coefficient of performance. With the results obtained, we quantify the benefits of heat pump application concerning the primary energy consumption and environment protection. Lastly, the interaction of heat pump and energy losses is considered, and the main results are summarised.

3. Environment and its Protection

The term environment is frequently used in science and everyday life, but a precise definition of its meaning is still vague. As environment we consider the space of the Earth occupied by humans. This is the upper most layer of the lithosphere and the lower most layer of the atmosphere. Taking the thicknesses of these layers to be some 10 km each, and the radius of the Earth of 6370 km, the volume of the environment would be 10 billions of cubic kilometres ($10.2 \cdot 10^9$ km^3). This spherical shell corresponds to a 0.0785 mm thick film covering a sphere of 50 mm in diameter. The size of the environment becomes more impressive if its volume is divided by the world population, at present more than 7 billion people; this allows about 1.4 km^3 per capita, which reduces down to about 0.42 km^3 if the sea surface area is disregarded. The assumed thickness of the atmospheric layer may appear to be too small, but the situation would change only by a factor of about 5, if we extend the margin of the outer layer up to von Karman's line (100 km) and completely include the biosphere.

Our environment is exposed to many internal and external influences. The external influences arise from celestial bodies, mainly from the Sun, and manifest themselves as radiation fluxes. Man-made impacts are associated with flows of energy and matter sustained by our activities. As far as external effects like thermal radiation are concerned, long term variations of radiation fluxes (Earth's insolation) have been modelled in detail by Milankovic [6] taking into account variations of the main degree of freedom of the Earth. Meanwhile, his theory, well-known as the long-term Milankovic cycles, has been largely validated. The external fluxes may amplify terrestrial processes and unpredictably affect the environment.

Protection of the environment has occupied the minds of scientists for centuries. In connection with exploitation of natural resources, Vernadsky, in 1928, asked the question about the adequate unit to express man's impact on the environment as follows (taken from Brodianski [7]):

We still do not have a general measure that is the unified unit for quantitative comparison of all natural productive forces; we should develop such a unit but it must be suitable for dealing with the energy patterns o human surroundings judging from the standpoint of the life support.

This demand immediately follows from Lord Kelvin's [8] famous dictum, see also [9]:

... when you can measure what you are speaking about, and express it in numbers, you know something about it; . . . but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind ...

In recent time, exergy has been considered as suitable quantity for monitoring/quantifying the impact of man-made processes on the environment. This quantity expresses the maximum useful work that can be obtained from a system when it is brought to equilibrium with a reference system, see e.g. [10]. It takes into account the process irreversibility arising from finite differences of process' coordinates; to understand its deeper meaning, one has to quantify the irreversibility. According to Feynman [11], the irreversibility comes from order going to disorder, and to understand it, the origin of the order must be known. As far as the authors comprehend the issue, this is most probably impossible.

The suitability of the exergy concept for estimating the impact of conversion processes on the environment is not undisputable. Dewulf et al. [10] arrived at the conclusion that exergy may basically be used when analysing the waste effect on the environment, but at present it had not gained the required maturity, while Gaudreau et al. [12] state several requirements that need be satisfied for the exergy to be a useful tool for analyzing the environmental impact. One of these is the definition of the state of the reference system, taken to be the environment. This system is neither unlimited nor homogeneous; substances and energies involved in conversion process are withdrawn from this reference system, as its parts. These facts pose serious restrictions on the environment to be a reference system in a strict sense. Moreover, without external fluxes, e.g. solar radiation, terrestrial conversion processes would be impossible, and the biodiversity on Earth would probably disappear. These fluxes are, therefore, components of the environment and must be considered accordingly. However, the main difficulty arising with the exergy in context with the environment is contained in the above mentioned Feynman thought on necessity of understanding the origin of order to value the irreversibility.

Some ideas of Nikola Tesla

In 1900, Nikola Tesla [13] published a paper dealing with the increasing of human energy; he pictured an energy scenario in the future which almost perfectly coincides with the actual energy discussion[1]. Also his ideas regarding the protection of the environment ideally fit into the current discussion of the issue. Tesla viewed exploitation of natural resources of fuels as irreversible invasion in our living system. He was apparently the firsts who rejected getting of motive power by consumption

[1] Tesla used mechanical analogy, particularly the kinetic energy of a moving body, to illustrate his thoughts on increasing the human energy. This energy is affected by body mass, net acting force, and moving velocity. The body mass is the human "thinking" mass; the net force corresponds to education, whereas the increase in moving velocity measures the progress of thinking ability associated with the quality of the thinking mass.

From Tesla's paper one observes that the development of the energy segment strictly follows his prophecy, the nuclear energy being excluded. At present, only a few of his ideas has been realised; his glorious though of energy transport wirelessly, or through the Earth, is still not completely understood. His papers [13, 14] dealing with the energy conversion and transport, are still actual and worth reading.

of materials, strictly opposing production of electricity from burning of coal [13], p. 16 right column:

... to burn coal, however efficiently, would be a mere makeshift, a phase in the evolution toward something much more perfect. After all, in generating electricity in this manner, we should be destroying material, and this would be a barbarous process.

In the same paper Tesla analysed several far-reaching ideas on obtaining power from alternative energy sources, like wind energy, hydro-energy, solar power plants, geothermal energy and direct conversion of the Sunrays into electricity. Regarding the utilisation geothermal energy in technical systems, he wrote [13], p. 18, right column:

The superficial layers of the earth and the air strata close to the same are at a temperature sufficiently high to evaporate some extremely volatile substances, which we might use in our boilers instead of water. There is no doubt that a vessel might be propelled on the ocean by an engine driven by such a volatile fluid, no other energy being used but the heat abstracted from the water. But the amount of power which could be obtained in this manner would be, without further provision, very small.

Obviously, Tesla foresaw the development of Organic Rankine Cycle (ORC), stressing that the quality of the energy taken from the superficial Earth layer must be enhanced. A few years later, in 1904, Prince Piero Ginori Conti installed the first geothermal power plant at the Larderello dry steam field in Italy.

In 1931, Tesla is more specific on the geothermal energy [14]:

All that is necessary to open up unlimited resources of power throughout the world is to find some economic and speedy way of sinking deep shafts.

As his ideas became older, alternative energy sources became more and more important. The Chernobyl disaster in 1986 and the Fukushima catastrophe in 2011 have substantially changed the notion on nuclear energy that was originally considered as the energy source of coming generations. Indeed, some 40 years ago the exploitation of coal began to decline, but the two nuclear catastrophes changed the situation; fossil fuels, particularly coal, are again an important energy source and will probably occupy a significant position within the energy scenario in the next decades.

While closing this part of the paper we mention two recent publications devoted to the environment, its biodiversity, destruction and protection [15, 16] along with a pioneering book on man's destruction of the natural environment by G. P. Marsh [17]. On page 33, following the heading Destructiveness of Man, Marsh writes:

Man has too long forgotten that the earth was given to him for usufruct alone, not for consumption, still less for profligate waste.

This warning, appeared in 1874, tells the same story as the Tesla's barbarous destruction of materials mentioned above.

4. Illustration of Heat Pump Principle

4.1. The Working Principle

The operation method of heat pump follows from the second principle of thermodynamics stated in 1854 by Clausius [18]:

Es kann nie Wärme aus einem kälteren in einen wärmeren Körper übergehen, wenn nicht gleichzeitig eine andere damit zusammenhängende Änderung eintritt, or

Heat can never pass from a colder to a warmer body without some other change, connected therewith, occurring at the same time. (Translation by Clausius himself, in 1856 [19]).

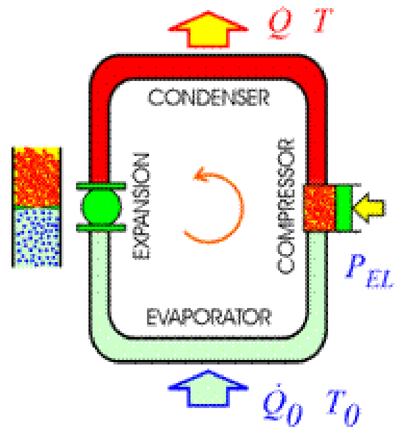

Figure 1: Schematic of a heat pump, from [20], modified.

The constraint, *wenn nicht gleichzeitig eine andere damit zusammenhängende Änderung eintritt,* allows heat transport from cold to warm body if simultaneously a reverse process occurs, by which heat flows from warm to cold body. Heat pump accomplishes these processes, Figure 1. It takes the heat $\dot{Q}_0$ from a body of temperature T_0 and transports it to a body of the temperature $T > T_0$; it pumps heat from lower to higher temperature, hence the name ***heat pump***. The simultaneous reverse process is associated with the generation of its operation energy in a thermal power plant, for instance.

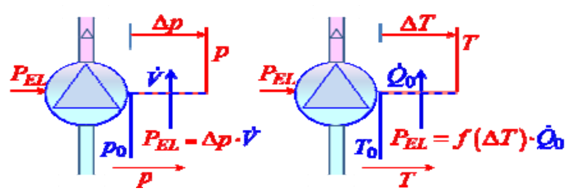

Figure 2: Heat pump in compression with fluid pump: Heat flow rate $\dot{Q}_0$ corresponds to volume flow rate $\dot{V}$, Δp and ΔT are resistances to be surmounted by respective flows [21].

Figure 2 displays the analogy of heat pump to a mechanical fluid pump. The operation energy P_{EL} overcomes the transport resistance caused by the pressure difference Δp with fluid pump and the temperature difference $\Delta T = T - T_0$ with the heat pump [21]. Actually, the energy P_{EL} is required for fluid transport against the pressure difference in both cases, but the temperature jump to be surmounted by the heat flow is stated instead of the pressure difference, thus

$$P_{EL} = f(\Delta T) \cdot \dot{Q} \tag{1}$$

The function $f(\Delta T) = 1/(\varepsilon - 1)$, $\varepsilon = \varphi(\Delta T)$ is to be obtained from thermodynamic and process calculations. Some hints on this point are given below.

First attempt of practical realisation of compression heat pump has occurred simultaneously with the Clausius theory. Namely, in 1853, Peter Rittinger designed a single evaporation effect with vapour compression [22]. This year is usually taken as the beginning of the heat pump era; its historical perspective is given by Zogg [23]. However, viewed more broadly, Denis Papin devised, in 1681, an apparatus – the pressure cooker – which may be ascribed to the heat pump family with vapour compression occurring thermally at constant volume [24, 25]. By this invention, Papin aimed to save firewood in food preparation, open new sources of food (softening bones and horny materials) and making soap for ordinary people.

4.2. Determination of the COP

Given the working fluid (Refrigerant R134a), the determination of the Coefficient Of Performance (COP) requires the knowledge of the evaporation and the condensation temperatures, ϑ_{EV} and ϑ_C, and the heat flow rate $\dot{Q}$ or $\dot{Q}_0$, Figure 1. In our case $\dot{Q}$ is set equal to heat losses of a building that have to be provided by the condenser of the HP, hence $\dot{Q} = 300\,kW$. The values of ϑ_{EV} and ϑ_C have been varied as parameters in the following ranges: $0°C \le \vartheta_{EV} \le 5°C$, $45°C \le \vartheta_C \le 50°C$; also the superheating of vapour at compressor inlet and the sub-cooling of condensate, $\Delta\vartheta_{SUP}$ and $\Delta\vartheta_{SUB}$, have been varied: $0°C \le \Delta\vartheta_{SUB} \le 5°C$, $0°C \le \Delta\vartheta_{SUP} \le 5°C$.

The vapour compression was treated nearly poly-tropic. The values of c_p/c_v for R134a, were taken from [26] at compressor inlet and outlet, averaged linearly and the average value was used as the polytrope exponent. This is not an isentropic compression. The values of COP, denoted by ε, were calculated from

$$\varepsilon = \frac{\dot{Q}}{P_{EL}}\,, \tag{2}$$

where P_{EL} was obtained from the enthalpy difference at the compressor and the flow rate of R134a. Note that some authors include in P_{EL} the electric energy of the whole system, which is economically explicable, but thermodynamically incorrect.

Figure 3 shows the results relevant for the present discussion.

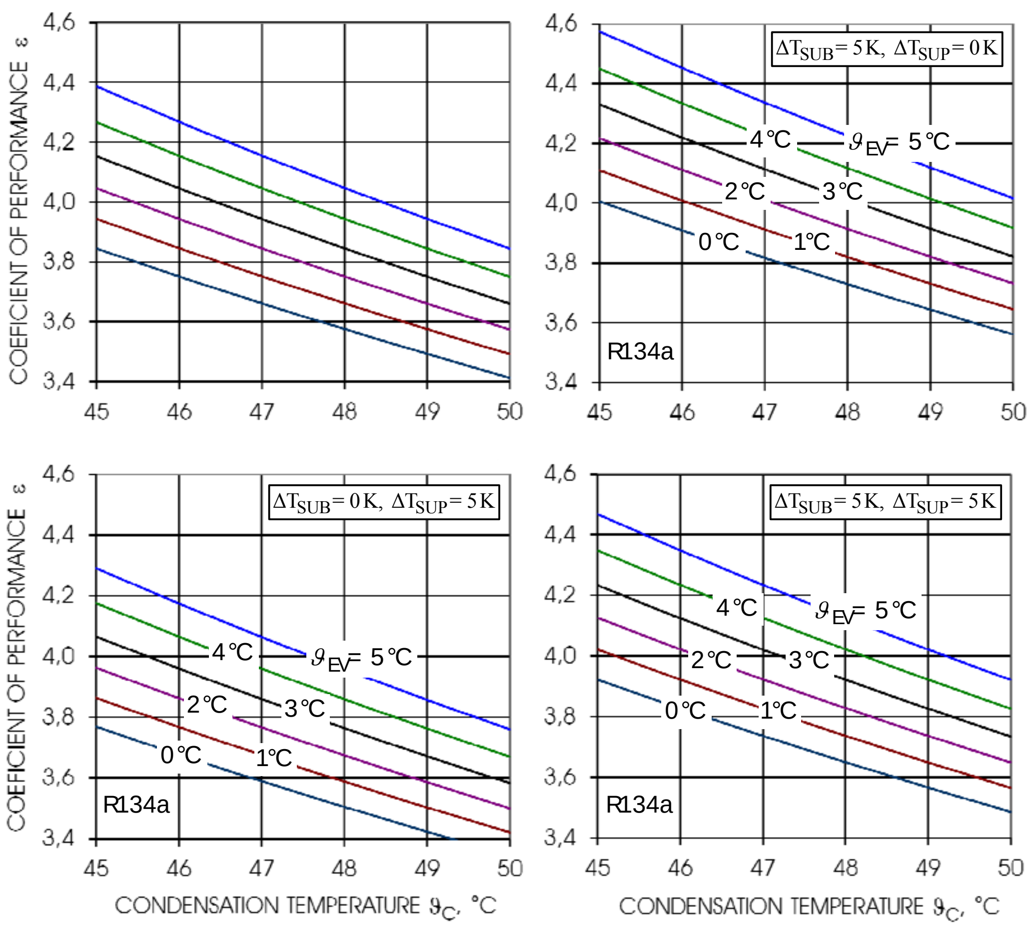

Figure 3: Coefficient of performance ε of heat pump calculated by Eq.(2) for the parameters displayed on diagrams

The COP ε increases with decreasing condensation temperature and increasing evaporation temperature. The vapour superheat lowers, while the condensate sub-cooling raises the COP ε.

5. Energetic and Ecological Evaluations

Next, an evaluation of different heating modes is undertaken under basically identical conditions and the results obtained are compared with each other. As example of combustible fuels, only combustion of coal is considered. The considerations remain basically the same if gas or biomass is used instead of coal. Regarding the environment, only the gaseous combustion products are considered.

The chemical composition of coal usually depends on its origin and varies in wide boundaries. Some properties of the coal, chosen for the calculations, are listed in Table 1. With the displayed data, the quantities required for the analysis are calculated as follows.

5.1. Direct Combustion Heating Mode

Figure 4 illustrates a direct combustion heating mode. Combustion is assumed to occur completely according to stoichiometric relations. Only carbon, hydrogen and sulphur undergo combustion reactions, producing carbon dioxide, sulphur dioxide and water vapour which affect the environment. Nitrogen is viewed as inert in this analysis. By contrast, because of its radiation properties, water vapour as combustion product affects the environment; in addition, its low density may cause local instabilities in the atmosphere and trigger stronger air streams. Some radiation properties of water vapour are reported in e.g. [27, 28].

Table 1: Mass fractions of combustible coal species and combustion products, 1 nm^3 = 22.414 m^3/kmol at 0 °C and 101.325 kPa

Species k	Mass fraction ξ_k	Molar mass M_k	Comb. reaction	Reaction enthalpy Δh_k		Combustion products (gas)		
	$kg/kgFuel$	$kg/kmol$		$MJ/kmol$	kJ/kg	Formula	$\psi_k = \xi_k/M_k$ $kmol/kgFuel$	$nm^3/kgFuel$
Carbon C	0.70	12	$C + O_2 \rightarrow CO_2$	-393.5	-32791.7	CO2	0.0583	1.3075
Hydrogen H2	0.06	2	$H_2 + (1/2)O_2 \rightarrow H_2O$	-285.9	-14295.0	H2O	0.03	0.6724
Sulphur S	0.02	32	$S + O_2 \rightarrow SO_2$	-296.6	-9268.8	SO2	0.000625	0.0140
Total	0.78	–	–	–	–	–	0.088925	1.9939

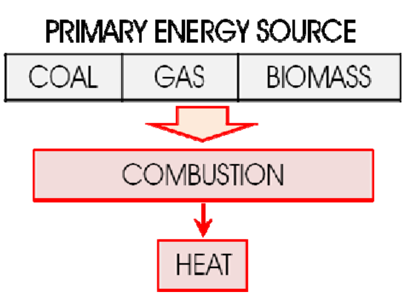

Figure 4: Direct combustion heating mode

5.1.1. Reaction Enthalpy and Mass Flow Rate of Fuel

The reaction enthalpy of fuel Δh_{Fuel} is calculated by mass-averaging the reaction enthalpies of single species without their mutual interactions:

$$\Delta h_{Fuel} = \sum_k \xi_k \Delta h_k \tag{3}$$

where ξ_k and Δh_k are given in Table 1.

The energy balance for an ideal combustion furnace (no heat losses) gives the fuel flow rate $\dot{M}_{Fuel\,id}$ (fuel consumption):

$$\dot{M}_{Fuel\,id} = \frac{\dot{Q}}{\Delta h_{Fuel}} \tag{4}$$

Thermal losses of the combustion facility may be accounted for by a thermal efficiency η_{COM}, hence

$$\dot{M}_{Fuel} = \frac{\dot{Q}}{\Delta h_{Fuel} \cdot \eta_{COM}} \tag{5}$$

Approximate values of η_{COM} for gas, oil and coal combustion furnace are, respectively: 0,85; 0,65 and 0,6.

5.1.2. Flow rate of combustion products

The general scheme for calculating the combustion products is given in Table 1. The flow rates of the single combustion gases are

$$\dot{N}_{CO2} = \frac{\xi_C}{M_C} \cdot \dot{M}_{Fuel} \tag{6}$$

$$\dot{N}_{H2O} = \frac{\xi_{H2}}{M_{H2}} \cdot \dot{M}_{Fuel} \tag{7}$$

$$\dot{N}_{SO2} = \frac{\xi_S}{M_S} \cdot \dot{M}_{Fuel} \tag{8}$$

giving the total flow rate

$$\dot{N}_{Gas} = \psi \cdot \dot{M}_{Fuel} = \psi \cdot \frac{\dot{Q}}{\Delta h_{Fuel} \cdot \eta_{COM}} \tag{9}$$

$$\psi = \sum_k \frac{\xi_k}{M_k} = \frac{\xi_C}{M_C} + \frac{\xi_{H2}}{M_{H2}} + \frac{\xi_S}{M_S} \tag{10}$$

Table 2 shows the flow rates calculated with the coal data from Table 1. For the calculations $\eta_{COM} = 0.6$ is assumed. The molar gas flow rate corresponds to the volume flow rate of $0.0415\ nm^3/s$. Data displayed in Table 2 make a basis for comparison purposes.

Table 2: Flow rates of direct combustion heating; properties of coal see Table 1; $\Delta h_{Fuel} = 23997.27\,kJ/kgFuel$, $\eta_{COM} = 0.6$.

Heat	Fuel	Combustion products (gas)			
$\dot{Q}$	$\dot{M}_{Fuel}$	$\dot{N}_{CO2}$	$\dot{N}_{H2O}$	$\dot{N}_{SO2}$	$\dot{N}_{Gas}$
$\cdot 10^3\,W$	$kgFuel/s$	$\cdot 10^{-4}\,kmol/s$			
300	0.0208	12.13	6.24	0.13	18.5

5.2. Indirect Combustion Heating

With indirect combustion heating, fuel is burned in a thermo-electric power station and the electric energy is then directly transformed into heat (Joule-heating), or is used for operation of a heat pump. Figure 5 illustrates these heating modes. Next, fuel consumptions and the impacts on the environment of these heating modes is calculated and compared with those of direct combustion heating.

5.2.1. Heating by Using of a Heat Pump

The electric energy required for heat pump operation is provided by a thermal power plant that uses the coal of the same quality that has been taken for direct combustion heating, see Table 1. The consumption of coal and production of combustion gases obey the equations stated above.

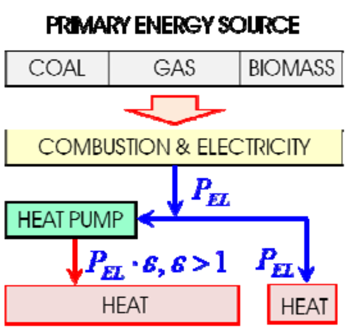

Figure 5: Heat pump heating or Joule heating?

Denoting by η_{TPP} the overall efficiency of the thermal power plant, by P_{EL} the net electric power of the plant, the fuel flow rate $\dot{M}_{Fuel}$ follows from Eq.(5)

$$\dot{M}_{Fuel} = \frac{P_{EL}}{\Delta h_{Fuel}\cdot\eta_{TPP}} \tag{11}$$

Replacing P_{EL} in this expression according to Eq.(2) we get

$$\dot{M}_{Fuel} = \frac{\dot{Q}}{\Delta h_{Fuel}\cdot\eta_{TPP}}\frac{1}{\varepsilon} \tag{12}$$

where ε denotes the coefficient of performance (COP) of the heat pump.

The flow rates of combustion products follow from Eqs.(6) to (10). Inserting $\dot{M}_{Fuel}$ from Eq.(12) in Eq.(9) gives

$$\dot{N}_{Gas} = \frac{\dot{Q}}{\Delta h_{Fuel}\cdot\eta_{TPP}}\frac{\psi}{\varepsilon} \tag{13}$$

Equations (12) and (13) express the consumption of fuel (coal) and production of combustion gases at specified $\dot{Q}$.

5.2.2. The Joule-heating

If the electric energy is used for direct heating (Joule-heating), the consumption of fuel and production of gases follow from Eq.(12) and (13) by setting ε = 1, hence

$$\dot{M}_{Fuel} = \frac{\dot{Q}}{\Delta h_{Fuel}\cdot\eta_{TPP}} , \tag{14}$$

$$\dot{N}_{Gas} = \frac{\dot{Q}}{\Delta h_{Fuel}\cdot\eta_{TPP}}\cdot\psi . \tag{15}$$

These flow rates are by the factor of ε = COP larger than those with heat pump heating.

5.3. The Benefits of Heat Pump Application

In order to quantify the energetic (economical) and ecological benefits of heat pump use, we compare Eqs.(12) and (13) valid for heat pump heating (HPH) with the corresponding ones without heat pump application.

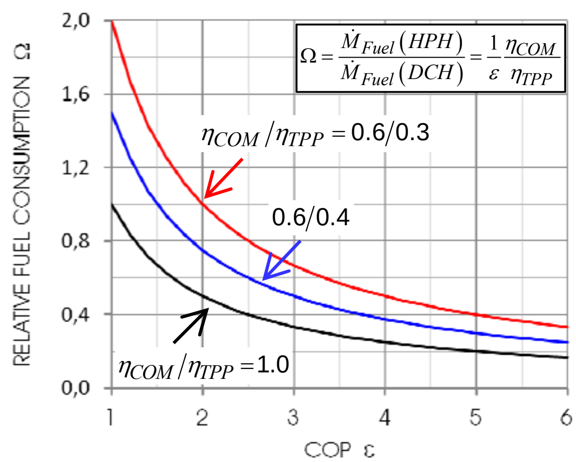

Figure 6: Reduction of fuel consumption by the HPH in comparison to DCH, Eq.(16). Since $\Omega_{Fuel} = \Omega_{Gas} = \Omega$ **, the curve also represent the reduction of combustion gases.**

Comparison of HPH with direct combustion heating (DCH), Eqs.(12) and (5), and Eqs.(13) and (9), gives

$$\Omega_{Fuel} = \frac{\dot{M}_{Fuel}(HPH)}{\dot{M}_{Fuel}(DCH)} = \frac{1}{\varepsilon}\frac{\eta_{COM}}{\eta_{TPP}} , \tag{16}$$

$$\Omega_{Gas} = \frac{\dot{N}_{Gas}(HPH)}{\dot{N}_{Gas}(DCH)} = \frac{1}{\varepsilon}\frac{\eta_{COM}}{\eta_{TPP}} . \tag{17}$$

Comparison of HPH with direct electric heating (DEH), Eqs.(12) and (14), and Eqs.(13) and (15) deliver

$$\Omega_{Fuel} = \frac{\dot{M}_{Fuel}(HPH)}{\dot{M}_{Fuel}(DEH)} = \frac{1}{\varepsilon} \tag{18}$$

$$\Omega_{Gas} = \frac{\dot{N}_{Gas}(HPH)}{\dot{N}_{Gas}(DEH)} = \frac{1}{\varepsilon} \quad (19)$$

By Eqs.(16) to (19), the relative consumption of fuel coincides with the relative production of gases, $\Omega_{Fuel} = \Omega_{Gas} = \Omega$; for $\dot{M}_{Fuel}(DCH)$ and $\dot{N}_{Gas}(DCH)$ see Table 2.

Figure 6 illustrates the equations (16) and (17) for the selected values of η_{COM}/η_{TPP}. The reduction of fuel consumption and gas production increases with increasing COP. The curve for $\eta_{COM}/\eta_{TPP} = 1$ compares the DEH and the HPH if the electric energy in both cases is provided by the same thermal power station, Eqs.(18) and (19). The DEH is the worst heating mode. The values for $\varepsilon = 1$ correspond to heating without heat pump if the thermal energy is generated with combustion facilities having efficiencies stated on the diagram.

The application of heat pump is advantageous in all cases, both economically and ecologically; it reduces the fuel consumption and the impact of gaseous combustion products on the environment.

Figure 7 illustrates the benefits of heat pump application as function of the condensation temperature. The quantity Ω is given by Eqs.(16) and (17) for $\eta_{COM}/\eta_{TPP} = 1$, that is, by Eqs.(18) and (19). Larger heat pump benefits occur at smaller Ω, which means, at lower condensation and higher evaporation temperature. The vapour superheat shows a negative, the condensate subcooling a positive effect. For $\eta_{COM}/\eta_{TPP} \neq 1$, the effect does not change qualitatively; the curves shift up for $\eta_{COM}/\eta_{TPP} > 1$, reducing the heat pump benefit, and down for $\eta_{COM}/\eta_{TPP} < 1$.

5.4. Heating by Application of Blue Energy

Blue energy is considered to be any energy form that can be transformed in electric energy without material consumption. Such are hydro-, aero-, geo- and solar energies; they may be used indirectly for heating (hydro, aero) and/or directly (geo, solar), Figure 8. Hydro- and geo-energies are more or less reliable in availability, while the intensity of aero- and solar-energy varies from zero to a certain maximum. This makes these energy kinds less attractive for heating without combination with other energy sources. However, the analysis performed with fuel is basically applicable also to blue energy sources.

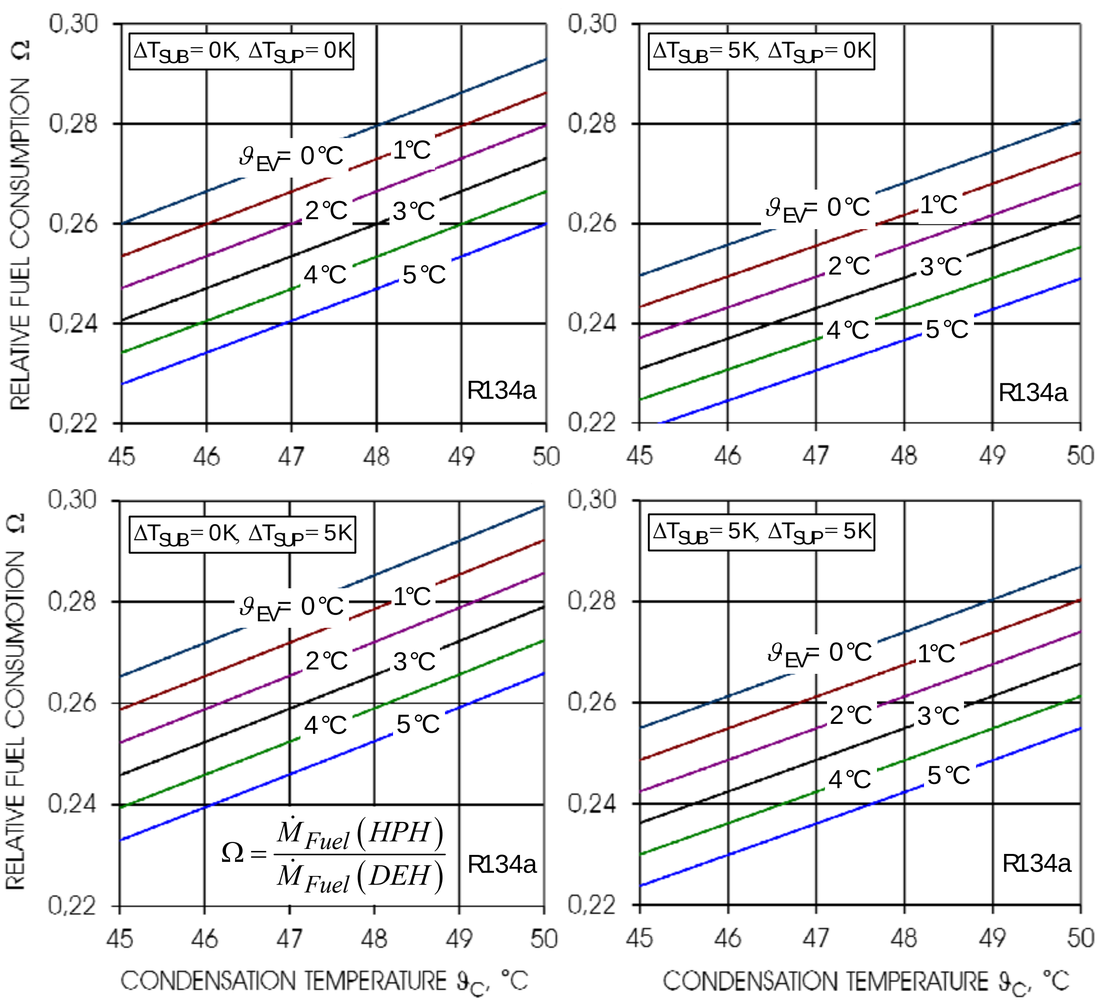

Figure 7: Reduction of fuel consumption by heat pump use (HPH) in comparison with direct combustion heating (DCH)

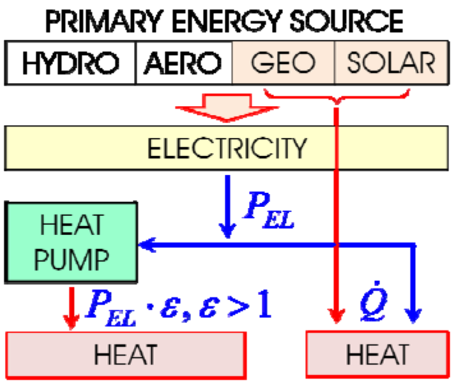

Figure 8: Natural blue energy sources; heating by using heat pump in comparison with electric direct heating.

The efficiency of direct application of geo- and solar-energy depends on the system used, that is, on the design of heat exchangers and the properties of heat-carrying fluid. In any case less energy will be available for application than is received from the respective source. If transformed in electric energy, also these energy sources may be more efficient in connection with heat pump application.

5.4.1. Geothermal Energy

With direct application of geothermal energy, the expression

$$E_{IN}\cdot\eta_{GTD}=\dot{Q} \tag{20}$$

ties the input energy E_{IN} and the useful heating energy $\dot{Q}$, η_{GTD} being the efficiency of geo-thermal direct use.

If geothermal energy is transformed in electric energy (geothermal power station) and used with a heat pump, the relation

$$E_{IN}\cdot\eta_{GTPS}=P_{EL}=\frac{\dot{Q}}{\varepsilon} \tag{21}$$

holds. By comparison of Eqs.(20) and (21), the inequality

$$\frac{\eta_{GTPS}}{\eta_{GTD}}\cdot\varepsilon>1 \tag{22}$$

must be satisfied for efficient heat pump application.

5.4.2. Solar Energy

Similar consideration also applies to solar energy, resulting in the condition

$$\frac{\eta_{SPS}}{\eta_{SDH}}\cdot\varepsilon>1 \tag{23}$$

where the indices SPS and SDH refer to solar power station and solar direct heating, respectively. Depending on the conversion method of solar radiation into electric energy, different values for η_{SPS} will be obtained.

5.4.3. Hydro- and aero-energy

These energies must be converted into electric energy which then may be used directly or in connection with heat pump. Even though conversion of these energies does not directly affect the environment, their use in connection with heat pump is strongly recommended.

5.4.4. Generalization

The above dependencies involving heat pump application may be casted in one single formula, which follows from Eq.(21):

$$\frac{\dot{Q}}{E_{IN}}=\eta_{CONV}\cdot\varepsilon\ , \tag{24}$$

where η_{CONV} denotes the efficiency of the conversion process. This equation measures the heating energy $\dot{Q}$ in terms of the primary energy intake E_{IN} .

5.4.5. Mixed Energy Sources

Because of various origins of primary energy, the electric energy is not a "single component energy" but an "energy mixture"; hence, the conversion efficiency η_{CONV} depends on the fractions of the energy components stemming from different sources. Taking only two sources of electric energy, e.g. thermal power plant and a source X, then η_{CONV} may be linearly weighted by the fractions, giving

$$\eta_{CONV}=x\cdot\eta_X+(1-x)\cdot\eta_{TPP} \tag{25}$$

$$\frac{\eta_{CONV}}{\eta_{TPP}}=1+\left(\frac{\eta_X}{\eta_{TPP}}-1\right)\cdot x \tag{26}$$

where x denotes the fraction of the electric energy stemming from the source X.

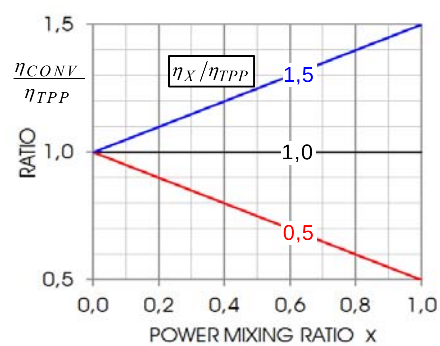

Figure 9: Illustration of efficiency of primary energy source of electric energy on heat pump benefits. Application of heat pump is more effective for $\eta_X/\eta_{TPP}>1$.

By Eq.(24), η_{CONV}/η_{TPP} in Eq.(26) represents the ratio of heating energy originating from different sources (electric part) and from the thermal power plant. The benefits of the heat pump will thus depend on the mixing ratio x. Figure 9 illustrates Eq.(26). For $\eta_X/\eta_{TPP}>1$, the heat pump takes more electric energy from the source having a higher efficiency and its benefit will be larger than in case of $\eta_X/\eta_{TPP}<1$.

6. Heat pump and energy conversion losses

The system of lower temperature with heat pump application is usually our surroundings which absorb the energy losses accompanying energy conversion processes, e.g. in thermal power plants. Now, the question before us may be started thus: To what extent can heat pump convert these losses in useful energy? An answer to this question is of essential importance with regard to overall energy balance and the protection of the environment. With reference to Figure 10, it may be treated by starting from the equation

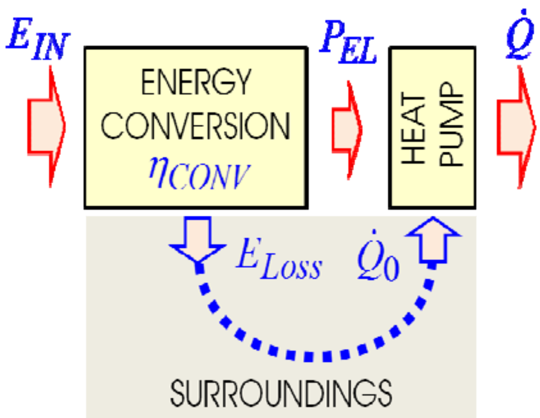

Figure 10: Losses of energy conversion feed heat pump with low temperature energy.

$$E_{Loss} = \dot{Q}_0 . \quad (27)$$

The energy losses E_{Loss} conveyed to the surroundings and the energy $\dot{Q}_0$ received by the heat pump from the surroundings may be expressed as follows:

$$E_{Loss} = \left(\frac{1}{\eta_{TPP}} - 1\right) \cdot P_{EL} \quad (28)$$

$$\dot{Q}_0 = (\varepsilon - 1) \cdot P_{EL} \quad (29)$$

Inserting these in Eq.(27) delivers:

$$\varepsilon \cdot \eta_{TPP} = 1 . \quad (30)$$

This simple equation shows the way how to gently use energy stored in natural substances, not only in non-renewable. Increasing η_{TPP} means reduction of energy losses, while raising ε (COP) means obtaining more energy from the environment. When their product equals one, the energy losses are utilised by the heat pump. In this case, the primary energy is completely transformed in useful energy for different applications. This does not contradict the thermodynamic laws. Then, the energy balance, Figure 10, reads

$$E_{IN} = \dot{Q} . \quad (31)$$

Figure 11 illustrate Eq.(30). In the area above the curve the gain by application of heat pump is larger than the losses in the power plant, $\dot{Q}_0 > E_{Loss}$; the situation is reversed below the curve.

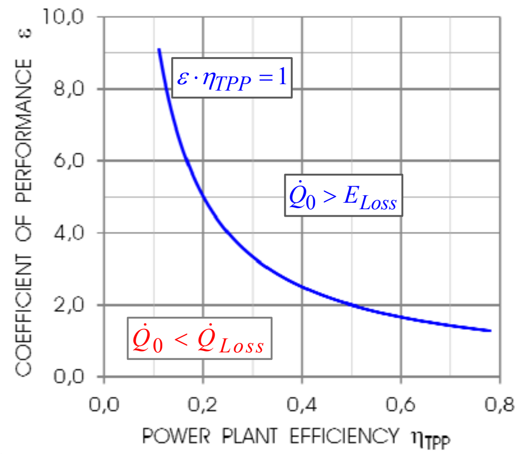

Figure 11: Comparison of power plant energy losses with heat pump gain.

7. Conclusion

In 1900, Nikola Tesla stressed that generating electricity from burning coal we would be destroying material, and this would be a barbarous process. This warning equally applies today, whether by direct combustion of fuel for heating of buildings, or by production of electricity. The combustion products are pivotal regarding the environment and its protection. In this context, several ideas have been put forward and tested with various outcomes.

In the present paper we have quantified the economical and ecological benefits of heat pump application in energy transformation and transport processes, assuming its operation energy to stem from different sources of primary energy. Heating of buildings is adopted as an example of the analysis. Direct combustion heating is used as basis for comparison purposes. From the obtained results, the following main conclusions may be drawn:

1. When the heat pump operation energy stems from a thermal power plant, benefits of heat pump's application are of particular importance. Heat pump reduces both consumption of fuel and impact of combustion products on the environment.
2. If the heat pump is operated from blue energy sources (solar, hydro-, geo- and aero-energy), and the blue energy does not cover the energy demands, it reduces indirectly the fuel consumption and protect the environment.
3. The economical and ecological benefits of heat pump application depend on its COP. The larger the COP the larger its effects. This requires a high evaporation temperature combined with a low condensation temperature.
4. A simple relation is deduced which answers the following question: Can heat pump utilise the energy losses occurring e.g. in thermal power plant while generating electric energy required for its operation? This relation demands that the overall plant efficiency, multiplied by the COP of the heat pump, be equal to, or larger than, one.

Because heat losses are absorbed by the surroundings and the heat pump takes heat from the surroundings, application of heat pump can reduce thermal misbalance of the surroundings arising from the man-made processes.

Nomenclature

E	Energy
Δh	Enthalpy of reaction
M	Molar mass
$\dot{M}$	Mass flow rate
$\dot{N}$	Gas flow rate
p	Pressure
P	Eelectric power
$\dot{Q}$	Heat flow rate
T	Temperature
ΔT	Temperature difference
$\dot{V}$	Volume flow rate
X	Fraction of electric energy

Abbreviations

COP	Coefficient of performance
DCH	Direct combustion heating
HPH	Heat pump heating

Greek Symbols

ε	Coefficient of performance
ϑ	Temperature
η	Process efficiency
ξ	Mass fraction
Ω	Ratio of flow rates
ψ	Specific combustion products, Table 1

Subscripts

C	Carbon, Condensation
COM	Combustion
CONV	Conversion
EL	Electric
EV	Evaporation
H2	Hydrogen
IN	Input
k	Species k
S	Sulphur
SUB	Subcooling
SUP	Superheating
TPP	Thermal power plant
0	Reference

References

[1] Ausubel J. H. : Can Technology Spare the Earth? American Scientist Magazine 84 (1996)2:166-178. http://phe.rockefeller.edu/sparetheearth/

[2] Hammond G. P.: Engineering sustainability: thermo-dynamics, energy systems, and the environment, Int. J. Energy Res. 2004; 28:613–639; http://dx.doi.org/10.1002/er.988

[3] Wall G.: EXERGY – AUSEFUL CONCEPT, Göteborg 1986 3rd edition, www.**exergy**.se/ftp/thesis.pdf

[4] Szargut J. Exergy method: technical and ecological applications. Ashurst, UK: WIT-press; 2005.

[5] Acikkalp E., Aras H.: Comparing Geothermal Heat Pump System with Natural Gas Heating System, World Renewable Energy Congress – Sweden, 8–13 May, 2011, Linköping, Sweden.

[6] Milankovc M.: Kanon der Erdbestrahlung und seine Anwendung auf das Eiszeitenproblem. Belgrad, 1941; *Canon of insolation and the ice-age problem.* English translation by the Israel Program for Scientific Translations, published for the U.S. Department of Commerce and National Science Foundation, Washington, D.C.: 633 S., 1969

[7] Brodianski V: Earth's available energy and the sustainable development of life support systems. Theories and Practices for Energy Education, Training, Regulation and Standards, from Encyclopedia of Life Support Systems (EOLSS). Online encyclopedia: http://www.eolss.net. Retrieved May 19, 2005.

[8] Thomson W.: Electrical Units of Measurement, Popular Lectures and Addresses, London, 1889-91, Vol. I, 73.

[9] Kuhn T. S.: The Function of Measurement in Modern Physical Science, *Isis* **52** (1961) No. 2, 161-193.

[10] Dewulf J., Van Langenhove H., Muys B., Bruers S., Bakshi B. R., Grubb G. F., Paulus D. M., Sciubba E.: Exergy: Its Potential and Limitations in Environmental Science and Technology, *Environ. Sci. Technol. 42* (2008), 2221–2232; http://dx.doi.org/10.1021/es071719a

[11] R. P. Feynman, Leighton R.B., Sands M.: *The Feynman Lectures on Physics*, Vol. I; Reading, Massachusetts: Addison-Wesley Publishing Company, 1963.

[12] Gaudreau K., Fraser R. A., Murphy S.: The Tenuous Use of Exergy as a Measure of Resource Value or Waste Impact, *Sustainability* 2009, 1, 1444 – 1463; http://dx.doi.org/10.3390/su1041444

[13] Tesla N.: *The problem of increasing human energy*, Century Magazine, June 1900. http://www.kocaeli.org/forum/Attachments/TheProblemOfIncreasingHumanEnergy.pdf

[14] Tesla N.: *Our future motive power*, New York Times, Nov. 8, 1931, also: Everyday Science and Mechanics, December 1931. http://www.tfcbooks.com/tesla/1931-12-00.htm

[15] Zalasiewicz J., Williams M., Fortey R.et al.: *Stratigraphy of the Anthropocene*, Phil. Trans. R. Soc. A 369 (2011), 1036–1055; http://dx.doi.org/10.1098/rsta.2010.0315

[16] Richter D. deB. Jr, Mobley M. L.: *Monitoring Earth's Critical Zone*, Science VOL 326 2009, 20 NOVEMBER, 1067-1068; http://dx.doi.org/10.1126/science.1179117

[17] Marsh G. P. *The Earth as Modified by Human Action. A new edition of man and nature*, New York: Scribner, Armstrong, and Co., 1874.

[18] Clausius R.: *Über eine veränderte Form des zweiten Hauptsatzes der mechanischen Wärmetheorie*, Annalen der Physik Volume 169, (1854), Issue 12, 481–506.

[19] Clausius R.: *On a modified form of the second fundamental theorem in the mechanical theory of heat*, Philosophical Magazine Series 4, 12 (1856)77, 81-98.

[20] Koike A.: *Heat Pumps - Synergy of High Efficiency and Low Carbon Electricity,* www.worldenergy.org/documents/.../54.pdf

[21] Mitrovic J.: *Geothermal energy and heat pump*, Energy seminar, FPM 2010.

[22] Rittinger P.: *Theoretisch-praktische Abhandlung über ein für alle Gattungen vor Flüssigkeiten anwendbares neues Abdampfverfahren mittelst einer und derselben Wärmemenge, welche zu diesem Behufe durch Wasserkraft in ununterbrochenen Kreislauf versetzt wird. Mit specieller Rücksicht auf den Salzsiedeprocess dargestellt*. Mit einer Figurentafel. Friedrich Manz Verlag, Wien, 1855.

[23] Zogg M.: *History of Heat Pumps*, Oberburg, 2008. www.bfe.admin.ch/php/.../streamfile.php?

[24] Papin D.: *A new Digester of Engine for Softening Bones, Containing the Description of its Make and Use in these Particulars: viz. Cookery, Voyages at Sea, Confectionary, Making of Drinks, Chymistry, and Dying with an Account of the Price a good big Engine will cost, and of the Profit it will afford*, London, 1681.

[25] Papin D.: *A Continuation of the New Digester of Bones, Its Improvements and New Uses; ... Together with Some Improvements and New Uses of the Air-Pump*, etc., London, 1687.

[26] Tehnical information: *Thermodynamic Properties of HCF-134a*: DuPont Suva, 2004. http://www2.dupont.com/Refrigerants/en_US/assets/downloads/h47752_hfc134a_thermo_prop_si.pdf

[27] McDermitt D. K., Welles J. M., Eckles R. D.: Effects of Temperature, Pressure and Water Vapor on Gas Phase Infrared Absorption by CO 2, Transactions of the American Geophysical Union, October, 1993, 168. www.licor.com/env/pdf/.../**co2**_abs.pdf

[28] Eldridge R. G.: Water Vapor Absorption of Visible and Near Infrared Radiation, APPLIED OPTICS Vol. 6, April 1967, No. 4, 709 – 713; http://dx.doi.org/10.1364/AO.6.000709