Potential for low-temperature energy usage at power plant's cold end in order to increase energy efficiency

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Abstract: Thermal power plant (TPP) 'Bitola' is the largest electricity producer in the Republic of Macedonia with installed capacity of 3x225 MW. It is a lignite fired power plant, in operation since 1982. Most of the installed equipment is of Russian (former Soviet) origin. Power plant's cold end consists of a condenser, pump station and cooling tower. The power plant was built without considerations regarding energy efficiency and usage of waste heat energy.
A possibility to increase energy efficiency through low-temperature heat usage from the power plant's cold end is shown in this work. The system includes connection of heat pump to the power plant's cold end for heating of greenhouse (orangery) complex located close to power plant's cooling towers. An analysis presenting economic feasibility of the concept for two different refrigerants used in the heat pump is also presented.
Comparison between separate production of heat energy in a boiler - house and combined – merged system consisting of three heat pumps working in parallel proves the applicability of the heat pumps concept in terms of increased energy efficiency and pay-back period of investment.

Keywords: *Power plant, Heat pump, Energy efficiency*

1. Introduction

Orangery or greenhouse is a building with microclimate quite different from the external, meaning its internal temperature is substantially different from the external air temperature. Part of the solar energy is absorbed by plants and soil, part is transformed to heat energy, hence heating up the internal air. That is the reason, depending on local climate conditions, heat radiation covers 30 to 60 % of the total heat energy needs of the orangery.

Greenhouse complexes built so far in Macedonia are supplied with heat mainly by boilers using heavy oil as a fuel. At the moment, price of oil on the world market has negative impact on the price of end product. Price of the fuel, for some products, contributes to as much as 70% in the total price of the product, [1]. That does not mean that the rate of growth of orangeries should decrease. It is necessary to substitute the oil with fuel available in the country, especially in the Bitola region.

2. Low temperature heat energy from the cooling towers

One of the possible ways to raise the efficiency of orangery production is by using part of the low temperature waste heat from cooling towers of lignite fired power plant "Bitola".
A complex (combined) system is proposed, comprised of low temperature system (heat pumps) and system with boilers.

One, two or more (up to 10) parallel systems can be located next to the cooling tower of TPP "Bitola". Each system should consist of 21 module, each with 1,5 ha of greenhouses with dimensions: length 21x35 = 735 m and width of 428,6 m. Total area covered by one system is 21x15 000 = 315 000 m^2 or 31,5 ha.

Techno economic analysis presented in the article refers to one orangery complex comprised of 21 module with an area of 1,5 ha in each module. Creation of other parallel systems results in equal economic results.

According to [2], the required installed heat energy for heating of the complex, (for 1,5 ha, required heat energy is 3 457 kW), for total area of 31,5 ha are:

$$Q_{OC} = A_{OC} \cdot q_{OC} = 31{,}5 \cdot 2\,305 = 72\,600 \text{ kW} \quad (1)$$

Two systems, with three heat pumps in each system, should be installed in combination with boiler house for back-up heating of the medium (running on hot water 75/35 °C).
Cooling tower of one of the blocks of thermal power plant "Bitola" works with following design parameters of cooling water:

- volume flow of water through cooling tower q_w = 30 000 m^3/h;
- temperature of hot water entering cooling tower t_{w1} = 33 °C;
- temperature of cold water exiting cooling tower t_{w2} = 25 °C.

Low temperature system of heat pumps is supplied with water from the cooling tower's basin, e.g. Fig. 1. Basin has a volume of 10 100 m^3, [3]. Water with temperature of 33 °C enters in parallel in every evaporator of the heat pumps where it is cooled down to a temperature of 25 °C and through a common pipeline brought back into cooling tower's basin.

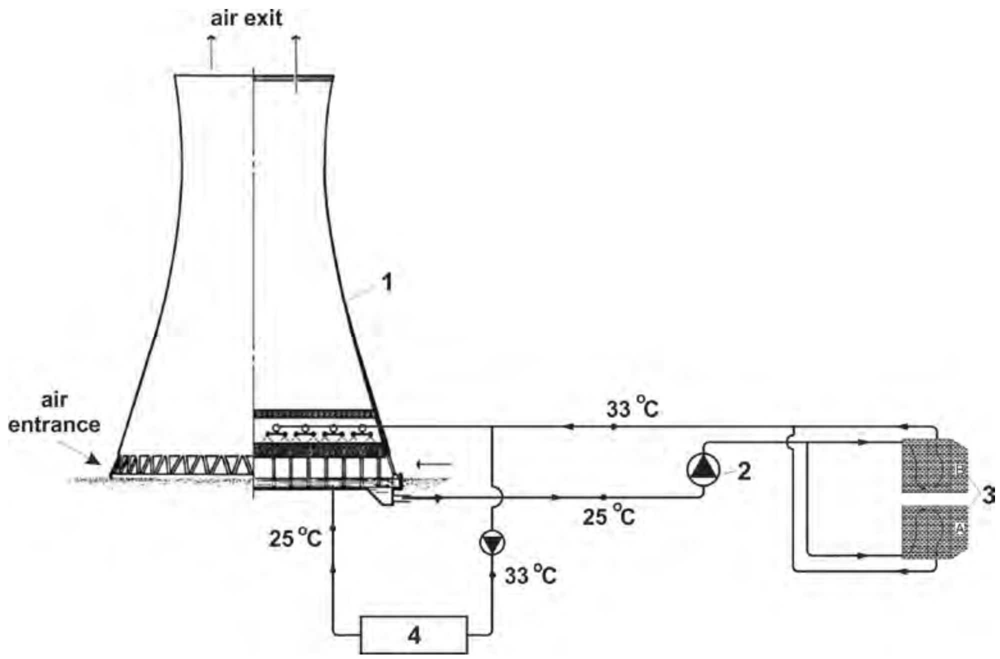

Fig. 1. Heat pumps connected to Thermal Power Plant's cold-end; 1 – cooling tower; 2 – circulation pump station; 3 – condenser; 4 – heat pumps

Mass flow of water from the cooling tower to the heat pumps is 3x359 = 1 077 kg/s, or 12,9% of designed flow of water in the system cooling tower – condenser.

In evaporator of every heat pump, the quantity of heat transferred from the water to the refrigerant is:

$$Q_1 = \dot{m}_{w1} \cdot c_p \cdot (t_{w1} - t_{w2}) = 359 \cdot 4{,}186 \cdot (33\text{-}25) = 12\,022{,}192 \text{ kW}$$

Total transferred heat for one system (made of 3 heat pumps):

$$Q_{total} = 3 \cdot Q_1 = 3 \cdot 12\ 022{,}192 = 36\ 066{,}576 \text{ kW} \quad (2)$$

Evaporators of all three heat pumps are connected in parallel (in respect to circulating water from cooling towers), while corresponding condenser units are connected in series (in respect to orangery's' heating medium 75/35 °C), e.g. Fig. 2.

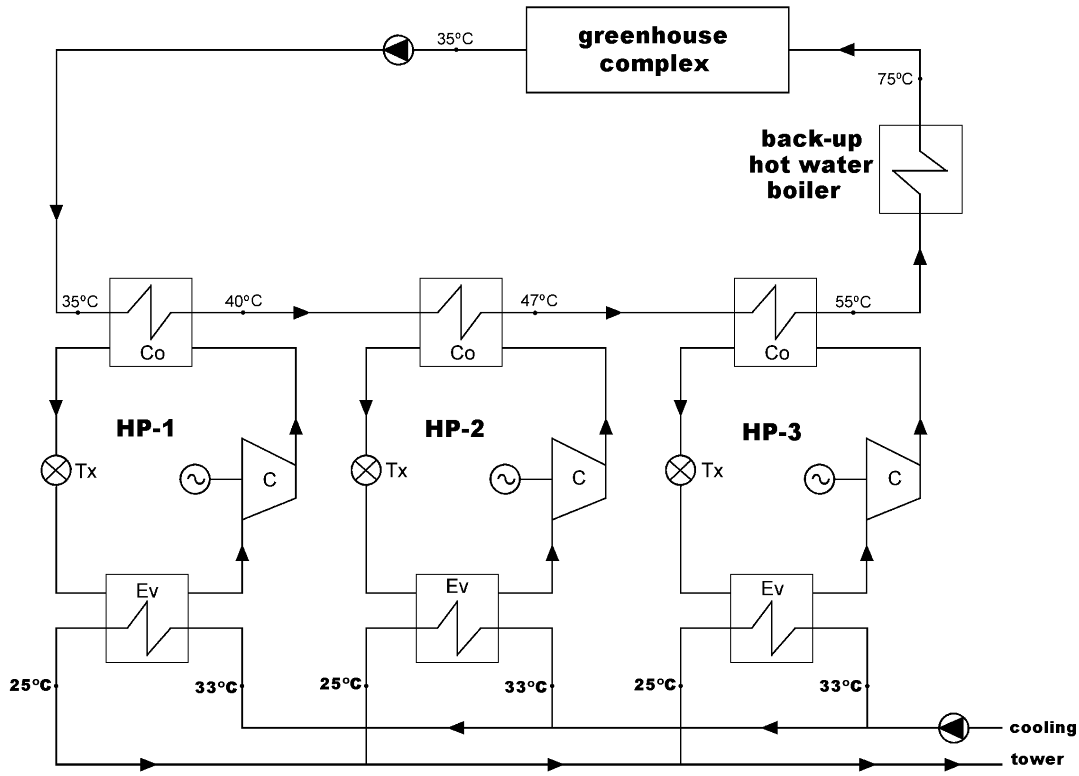

Fig. 2. Combined heating system: heat pumps and back-up boiler house

Although calculations for two refrigerants (HFC-134a and R410A) and two different condensation temperatures (3 K and 5 K) were performed, due to limited space for the article only an example of calculation for one medium and one condensation temperature will be presented completely. Results from other calculations, a review of the operating characteristics of heat pumps for different working fluids, [4], [5] and [6], and condensation temperature of $\Delta t_c = 3$ K, is given on Table 1.

Parameters from techno-economic analysis are shown hereafter, [7].

Total annual consumption of fuel for separate production of heat energy (boilers running on lignite with efficiency 90%) is:

$$Q_{tot,yr} = 132{,}5 \text{ GWh/year} \ ; \ B_{yr} = 69\ 920{,}844 \text{ tons of lignite/year} \quad (3)$$

where $Q_{tot,yr}$ is the total demand for heat energy per year and B_{yr} is the total annual consumption of fuel if separated system is used.

Table 1. Review of operating characteristics of heat pumps for different cooling fluids

Refrigerant	HP No.	Δt_c , K	l_i , kJ/kg	q_c , kJ/kg	m_f , kg/s	N_e , kW	COP_{avg}
HFC-134a	1	5	21,91	168,27	53,93	1 312,84	6,220
HFC-134a	2	5	29,82	164,68	77,15	2 501,76	4,565
HFC-134a	3	5	31,39	154,05	94,25	3 287,23	3,975
HFC-134a	1	3	22,36	171,82	52,82	1 341,63	6,088
HFC-134a	2	3	27,44	166,10	76,49	2 332,10	4,903
HFC-134a	3	3	35,49	161,45	89,93	3 546,24	3,685
R410A	1	5	24,01	178,63	50,80	1 355,23	6,026
R410A	2	5	32,46	184,08	69,02	2 489,31	4,593
R410A	3	5	47,06	168,08	86,38	4 516,70	3,900
R410A	1	3	27,41	185,93	48,81	1 486,53	5,494
R410A	2	3	28,64	173,06	73,41	2 336,10	4,895
R410A	3	3	36,56	162,78	89,20	3 623,50	3,606

Combined system (comparison for heat pumps with HFC-134a and R-410A and Δt_c = 5 K):

HFC-134a ; Δt_c = 5 K	R-410A ; Δt_c = 5 K
$Q_{BH,yr}$ =33,13 GWh/year	
$Q_{TOT,HP}$ = 99,37 GWh/year	
$B_{TOT,yr}$ = 17 482,85 t /year	
COP_{avg} = 4,92	COP_{avg} = 4,84
E_{COMP} = 20,197 GWh/year	E_{COMP} = 20,531 GWh/year
$B_{COMP,yr}$ = 12 150,17 t/year	$B_{COMP,yr}$=12 351,10 t/year
B = 29 633,02 t/year	B = 29 833,95 t/year
ΔB = 40 287,82 t/year	ΔB = 40 086,89 t/year

where $Q_{BH,yr}$ is the total annual production of heat energy of the boiler house, $Q_{TOT,yr}$ is the total annual production of heat from heat pumps, $B_{TOT,yr}$ is the total annual consumption of fuel of the boilers, COP_{avg} is the average value of the coefficient of performance for a heat pump system, E_{COMP} is the total annual energy consumed by heat pump's compressors, $B_{COMP,yr}$ is the total annual consumption of lignite for heat pump's compressors, B is the total consumption of fuel of a combined system and ΔB is the annual savings of fuel if a combined system instead of separated system is used.

3. Economic efficiency

Values for specific investment costs, maintenance costs and average price of coal for year 2006, [8] and [9]:

- Lignite price 0,0556 EUR/kg
- Heat pump investment 142 907,5 EUR/1 MW
- Hot water boiler house investment 43 125 EUR/1 MW

3.1. Investment costs

A. For separate production of heat in a boiler-house:

$$72{,}6\cdot 43\ 125 = 3{,}130875\cdot 10^6 \quad \text{EUR}$$

B. Combined system

- heat pumps: $36{,}3\cdot 142\ 907{,}5 = 5{,}187542\cdot 10^6$ EUR

- hot water boiler house: $36{,}3 \cdot 43\ 125 = 1{,}565437 \cdot 10^6$ EUR

3.2. Exploatation costs

3.2.1. Cooling fluid HFC-134a and Δt_c = 5 °C

- Fuel
  A. $69\ 920\ 844 \cdot 0{,}0556 = 3{,}8876 \cdot 10^6$ EUR/year
  B. $(17\ 482\ 850 + 12\ 150\ 174) \cdot 0{,}0556 = 1{,}647596 \cdot 10^6$ EUR/year
- Maintenance costs
  A. $0{,}06 \cdot 3{,}8876 \cdot 10^6 = 0{,}233256 \cdot 10^6$ EUR/year
  B. $0{,}06 \cdot 1{,}6476 \cdot 10^6 = 0{,}100476 \cdot 10^6$ EUR/year

3.3. Total annual costs

3.3.1. Cooling fluid HFC-134a and Δt_c = 5 °C

A. Total annual costs for purely boiler system are equal regardless of the cooling medium used,

$$\Sigma T_A = \left(\frac{3{,}130875 \cdot 10^6}{8} + 3{,}8876 + 0{,}233276\right) \cdot 10^6 = 4{,}512216 \cdot 10^6 \quad \text{EUR/year}$$

B. Investment costs $\frac{(5{,}187542 + 1{,}674596) \cdot 10^6}{8} = 0{,}\ 8577673 \cdot 10^6$ EUR/year

- Fuel $(17\ 482\ 850 + 12\ 150\ 174) \cdot 0{,}0556 = 1{,}674596 \cdot 10^6$ EUR/year
- Maintenance costs $0{,}06 \cdot 1{,}674596 \cdot 10^6 = 0{,}100476 \cdot 10^6$ EUR/year

Total annual costs for the combined system are:

$$\Sigma T_{B,com} = (0{,}8577673 + 1{,}674596 + 0{,}100476) \cdot 10^6 = 2{,}632839 \cdot 10^6 \quad \text{EUR/year}$$

Energy unit (specific) price:

$$C_A = \frac{4{,}512216 \cdot 10^6}{132{,}5 \cdot 10^3} = 34{,}055 \quad \text{EUR/MWh}$$

$$C_B = \frac{2{,}632839 \cdot 10^6}{132{,}5 \cdot 10^3} = 19{,}87 \quad \text{EUR/MWh}$$

The rest or ‘the savings' are:

$$\Sigma T_A - \Sigma T_{B,com} = (4{,}512216 - 2{,}632839) \cdot 10^6 = 1{,}879377 \cdot 10^6 \quad \text{EUR/year}$$

Investment payback period:

$$\tau = \frac{(5{,}187542 + 1{,}565437) \cdot 10^6}{1{,}879377 \cdot 10^6} = \frac{6{,}752979 \cdot 10^6}{1{,}879377 \cdot 10^6} = 3{,}59 \text{ years}$$

4. Conclusion

For the defined optimal orangerie's complex comprised of 21 modules, each having 1,5 ha or 31,5 ha in total, and needed heat energy of 72,6 MW for heating up the complex, two systems are proposed:

A. Separate system, comprised of boilerhouse for production of hot water which meets the total requirements for heating of the complex (72,6 MW, system 75/35 °C), and

B. Combined (merged) system, comprised of low-temperature system with heat pumps (capacity of the pumps 36,3 MW) that will cover around 75% of the total annual heat energy requirements, and boilerhouse with capacity of 36,3 MW that will cover the remaining 25% of the annual heat energy needs. Calculations are done for two cooling fluids, HFC-134a and R410A and at two condensation temperatures (Δt_c = 3 K and Δt_c = 5 K).

Fuel used in the boilerhouse is lignite from the "Suvodol" basin (fuel used by the TPP) with lower calorific value of H_d = 7 580 kJ/kg.

Techno economic analysis is performed under equal energetic efficiencies of both systems. Total annual costs for both systems are compared and results are shown on Table 2:

Table 2. Comparison table for total annual costs for both systems

System type	Energy unit price (EUR/MWh)	Total annual costs (EUR/year) (in millions)	Savings (EUR/year) (in millions)	Investment return period (in years)
System A	34,055	4 512 216	/	/
System B HFC-134a;Δt_c=5K	19,87	2 632 839	1 879 377	3,59
System B HFC-134a;Δt_c=3K	19,90	2 636 624	1 875 592	3,60
System B R410A ; Δt_c=5K	20,33	2 693 458	1 818 758	3,70
System B R410A ; Δt_c=3K	20,88	2 766 522	1 745 694	3,84

From the analysis presented in the article, one can conclude that the combined (merged) system, that is the system that uses HFC-134a as a cooling fluid and Δt_c = 5 K is the most applicable in the turns of savings and investment payback period.

Despite all the benefits of such a system, only basic structure for one greenhouse module was built near one of the cooling towers of above mentioned power plant. Unfortunately, neither pipelines nor other elements of the proposed system were ever built or installed.

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