

COMPARATIVE ANALYSIS OF POSSIBILITIES FOR RAISING THE EFFICIENCY IN THERMAL POWER PLANT BY UTILISATION OF WASTE HEAT ENERGY

by

Vladimir MIJAKOVSKI*, **Vangelce MITREVSKI**,
and Tale GERAMITCIOSKI

Faculty of Technical Sciences, University St. Kliment Ohridski, Bitola, Macedonia

Original scientific paper
DOI: 10.2298/TSCI160322136M

The possibility to use flue gases waste heat for increasing the efficiency of thermal power plant explained in this work refers to lignite fired thermal power plant "Bitola" in Macedonia (3 × 233 MW installed electric capacity). Possibility to utilize low-temperature heat energy at the plant's cold end is also considered in the analysis. Specific fuel consumption is used as an analysis and comparison parameter. Its reduction, compared to the basic power unit ranges between 0.4% and 3.4%. An analysis presenting economic feasibility of the low-temperature heat energy utilization concept for two different refrigerants used in the heat pump is also presented.

Key words: waste heat energy, efficiency, savings, improvements

Introduction

A significant by-product of power generation plants is rejected (or *waste*) heat. Rejected heat resulting from inefficiencies of the power generation process is then rejected into the atmosphere [1, 2]. Waste heat from the power plant can also be defined as the energy that is being exhausted to the atmosphere, which may be recovered and used for a variety of purposes, ranging from heating of process water, district heating of nearby settlements, heating of pre-combustion gases to heating of greenhouses that are constructed nearby power plants just for this purpose [3]. When utilization of flue gas is in question, the quality of the heat depends upon its temperature, the higher the temperature the better the quality. Utilization of this heat lowers the temperature of exhaust gases. In order to prevent low temperature corrosion on the heat – exchanging surfaces, the temperature of the flue gases, in theory, can be lowered to a temperature higher than the acid dew point without affecting the efficiency of thermal power plant [4, 5].

Thermal power plant (TPP) *Bitola* (3 × 233 MW) is the largest thermal unit in the Republic of Macedonia. It provides almost 80% from the whole electricity production in the country. Average annual electricity production is approx. 4200 GWh with average annual coal consumption of 6 million tons. The average low heating value (LHV) of lignite used at *Bitola* TPP is about 7.5 MJ/kg. Three possibilities for flue gas heat energy usage by raising the efficiency of lignite fired TPP *Bitola* are presented in this paper. A comparison calculation of common parameters between all three possibilities is also given. Fourth possibility refers to utilization of waste heat from plant's cold end to provide heat for foreseen greenhouses to be located nearby.

* Corresponding author; e-mail: vladimir.mijakovski@tfb.uklo.edu.mk

Materials and methods

First option for flue utilization involves replacement of water economiser (WE) with additional heat-exchanging surface, called turbine economiser (TUE) into the flue-gas air tract of the boiler (fig. 1). A part of the supply water, that bypasses three regenerative high pressure heaters (HPH) is heated up in TUE, and afterwards mixes with the basic flow of supply water in front of the WE. In a steam generator of this type, there is additional cooling of the flue gas resulting in higher efficiency. The proposed modernisation of the unit (233 MW) can result in additional increase of the power ($\Delta N = 5.7$ MW) without increasing the steam production rate of the boiler (700 t/h).

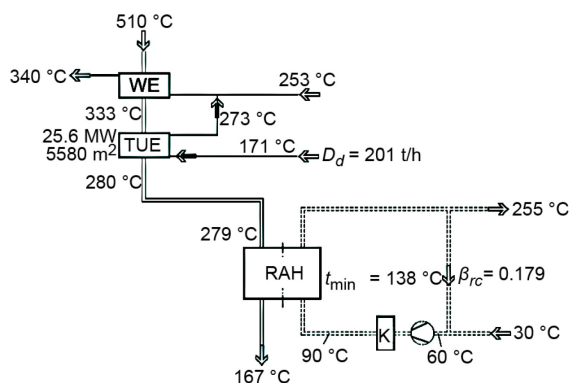


Figure 1. The TUE in the proposed modernisation of flue gas-air tract in TPP Bitola's steam generator, RAH – regenerative air heater, K – unit heater, D_d – water flow

The second efficiency improvement refers to additional heat-exchanging surface installment, called high temperature economiser (HTE), after the WE. The HTE is water heating surface that has no need for special rooms, nor equipment for handling flue gas or servicing personal. In the modernised block, with installed HTE, savings on specific energy consumption compared to the basic block can reach up to 3.4% (fig. 2).

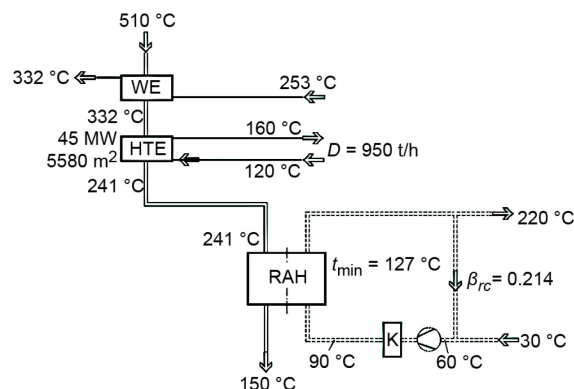


Figure 2. The HTE in the flue-gas tract of the steam boiler with corresponding parameters; RAH – regenerative air heater, K – unit heater, D – water flow

Third possibility for efficiency improvement presented in this article is achieved by installing heat exchanger (RRK) in the air duct of the system for sufficient air. Like in the previous cases, this heat exchanger is used for heat extraction from the flue gas (fig. 3).

Partial utilization of the low temperature waste heat from cooling towers of TPP can lead to overall efficiency improvements. 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* in order to supply heat to greenhouses. One set should consist of 21 module, each with 1.5 ha of greenhouses with dimensions: length $21 \times 35 = 735$ m and width of 428.6 m. Total area covered by one heat system is $21 \times 15000 = 315000 \text{ m}^2$ or 31.5 ha. Required heat energy for heating of 1.5 ha of greenhouse is 3457 kW [6].

Low temperature system of heat pumps is supplied with water from the cooling tower's basin (fig. 4). Basin has a volume of 10100 m^3 [7]. Water with temperature of $33 \text{ }^\circ\text{C}$ enters in parallel in every evaporator of the heat pumps where it is cooled down to a temperature of $25 \text{ }^\circ\text{C}$ and through a common pipeline brought back into cooling tower's basin.

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 orangeries' heating medium $75/35 \text{ }^\circ\text{C}$), as shown in fig. 5.

Results and discussion

Determination of the turbine power loss on the account of unit heater and fuel losses

Basic power unit

Heat energy gained by the unit heater from the low-pressure heater (LPH-2), for basic power unit (without modifications) equals to:

$$Q_{kal,B} = q_{v0,kal-B} \rho_0 c_{p,B}(t_{v1} - t_{v2}) \quad (1)$$

$$Q_{kal,B} = 9.6 \text{ MW}$$

where $q_{v0,kal-B} = 236.8 \text{ m}^3/\text{s}$ is the air flow through unit heater for basic power unit, $\rho_0 = 1.18 \text{ kg/m}^3$ – the air density at external

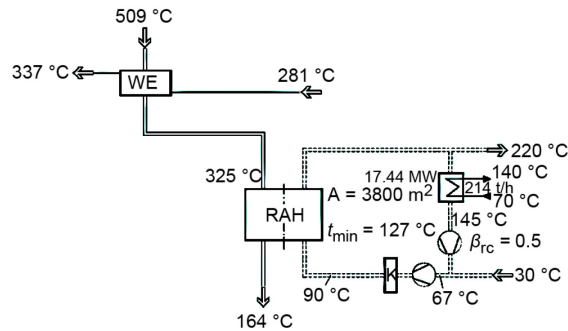


Figure 3. Usage of flue gas heat energy by installing RRR, RAH – regenerative air heater, K – unit heater, RRR – heat exchanger installed in recirculation air duct

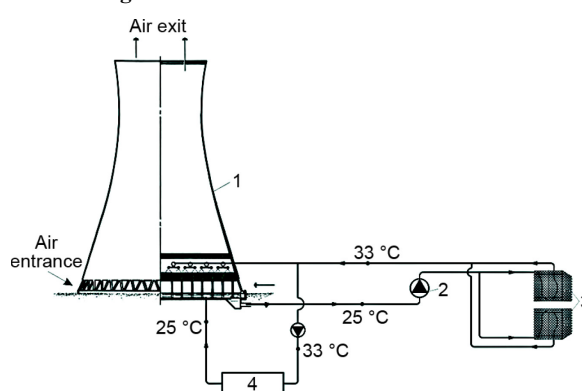


Figure 4. Heat pumps connected to TPP cold-end; 1 – cooling tower, 2 – circulation pump station, 3 – condenser, 4 – heat pumps

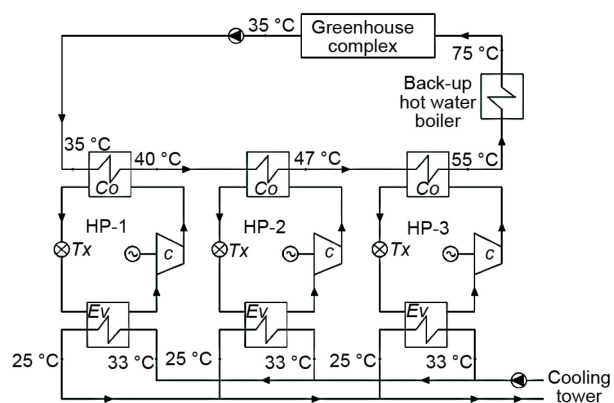


Figure 5. Combined heating system: heat pumps and back-up boiler room; HP – heat pump, Co – condenser, Ev – evaporator, Tx – expansion valve, C – compressor

temperature $t_v = 20^\circ\text{C}$, $c_{p,B} = 1.1375 \text{ kJ/kgK}$ – the specific heat capacity of the air at temperature $t_v = 45^\circ\text{C}$ – basic unit, $t_{v1} = 30^\circ\text{C}$ – the air temperature at unit heater entrance, and $t_{v2} = 60^\circ\text{C}$ – air temperature at unit heater exit.

Steam extraction for unit heater needs reduces the power for $\Delta N_k = 1.011 \text{ MW}$

Power at generator clamps now equals $N = 231.989 \text{ MW}$

Total fuel consumption is $B = 304.952 \text{ t/h}$

Specific fuel consumption:

$$b_B = \frac{B}{N} \quad (2)$$

For the basic power unit, specific fuel consumption is $b_B = 1.31345 \text{ kg/kWh}$.

Power unit with turbine economiser

The amount of heat energy acquired by the unit heater from the regenerative subtractions (LPH-3) equals:

$$Q_{kal,TUE} = q_{v0,ka} \rho_0 c_{p,TUE} (t_{v1,TUE} - t_{v2,TUE}) = 10.7 \text{ MW}$$

where $q_{v0,ka,TUE} = 265.1 \text{ m}^3/\text{s}$ is the air flow through unit heater, $c_{p,TUE} = 1.141 \text{ kJ/kgK}$ – the specific heat capacity of the air at temperature $t_v = 75^\circ\text{C}$ for unit with TUE, $t_{v1,TUE} = 60^\circ\text{C}$ – the air temperature at unit heater entrance, and $t_{v2,TUE} = 90^\circ\text{C}$ – the air temperature at unit heater exit.

Steam extraction for unit heater reduces the power for $\Delta N_k = 1.693 \text{ MW}$.

Growth of the power on the account of bypassing part of the feed water at HPH equals: $D_d = 201 \text{ t/h}$, and $\Delta N_k = 6.4 \text{ MW}$.

Power at generator clamps in this case is $N_{TUE} = 237.707 \text{ MW}$.

Total fuel consumption is $B_{TUE} = 311.156 \text{ t/h}$.

Specific fuel consumption is $b_{TUE} = 1.309 \text{ kg/kWh}$.

Specific fuel consumption reduction in this case (as compared to basic unit):

$$\Delta b_{TUE} = \frac{b_B - b_{TUE}}{b_B} 100 = 0.42\% \quad (3)$$

Unit with high-temperature economiser

The amount of heat energy acquired by the unit heater from the regenerative subtractions (LPH-3) in this case, equals:

$$Q_{kal,HTE} = q_{v0,ka-HTE} \rho_0 c_{p,TUE} (t_{v1,TUE} - t_{v2,TUE}) = 11 \text{ MW}$$

where $q_{v0,ka-HTE} = 272.4 \text{ m}^3/\text{s}$ is the air flow through unit heater.

Other parameters in the equation use the same values as for improvement described in previous chapter.

Steam extraction for unit heater needs reduces the power is $\Delta N_k = 1.74 \text{ MW}$.

Power at generator clamps equals $N_{HTE} = 231.26 \text{ MW}$.

Total fuel consumption is $B_{HTE} = 318.414 \text{ t/h}$.

Fuel consumption for heat production only:

$$B_{H,HTE} = \frac{Q_{H,HTE}}{H_d \eta_k} = 6.88 \text{ kg/s} = 24.785 \text{ t/h} \quad (4)$$

where $Q_{H,HTE} = 45$ MW is the heat energy gained in HTE, $H_d = 7494$ kJ/kg – the LHW of the lignite, and $\eta_k = 0.87736$ – the coefficient of efficiency of the boiler.

Fuel consumption for electricity production in this case:

$$B_{EL,HTE} = B_{HTE} - B_{H,HTE} = 293.629 \text{ t/h} \quad (5)$$

where $B_{EL,HTE}$ is the fuel consumption for electricity production, $B_{H,HTE}$ – the fuel consumption for heat production, and B_{HTE} – the total fuel consumption.

Thus, specific fuel consumption is $b_{HTE} = 1.2697$ kg/kWh.

Reduction in the specific fuel consumption equals to $\Delta b_{HTE} = 3.4\%$.

Unit with heat exchanger installed in recirculation duct (RRK)

Heat energy gained by the unit heater from regenerative extraction (LPH-2) equals:

$$Q_{kal,RRK} = q_{v0,kal-RRK} \rho_0 c_{p,RRK} (t_{v1,RRK} - t_{v2,RRK}) = 11.8 \text{ MW}$$

where $q_{v0,kal-RRK} = 239.4$ m³/s is the air flow through unit heater, $c_{p,RRK} = 1.1375$ kJ/kgK – the specific heat capacity of the air at temperature $t_v = 45$ °C, $t_{v1,RRK} = 30$ °C – the air temperature at unit heater entrance, and $t_{v2,RRK} = 67$ °C – the air temperature at unit heater exit.

Steam extraction for unit heater needs reduces the power for $\Delta N_k = 1.261$ MW.

Power at generator clamps equals $N_{RRK} = 231.739$ MW.

Total fuel consumption is $B_{RRK} = 308.272$ t/h.

Fuel consumption for heat production in the RRK only:

$$B_{H,RRK} = \frac{Q_{H,RRK}}{H_d \eta_k} = 2.71 \text{ kg/s} = 9.74 \text{ t/h} \quad (6)$$

where $Q_{H,RRK} = 17.44$ MW is the heat energy gained in RRK.

The rest of the fuel consumption goes for electricity production:

$$B_{EL,RRK} = B_{RRK} - B_{H,RRK} = 298.532 \text{ t/h} \quad (7)$$

Specific fuel consumption is $b_{RRK} = 1.2882$ kg/kWh.

Reduction in the specific fuel consumption equals for this option is $\Delta b_{RRK} = 2.0\%$

Summarized results from the calculation previously shown are presented in tab. 1.

Low temperature heat energy from the power plant's cold end

Although calculations for two refrigerants (R134a and R410A) and two condensation temperature differences (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 difference will be presented completely, while for the rest, a review of the operating characteristics of heat pumps for different working fluids [8-10] is given in tab. 2.

Techno-economic analysis

Analysis refers to heat production in two cases: (a) separate production of heat in a boiler-room, and (b) combined system.

Table 1. Results obtained from the analysis

Comparison data				
Power unit's characteristics name	Basic unit	TUE	HTE	RRK
Steam temperature at turbine high-pressure cylinder entrance [°C]	540	540	540	540
Feed water temperature after HPH [°C]	252.8	252	252.8	252.8
Feed water temperature acquired by bypass [°C]	/	170.9	/	/
Air temperature after unit heater [°C]	60	90	90	90
Temperature of heated air [°C]	301	255	220	281
Metal temperature in RAH [°C]	141	138	127	133
Flue gas temperature at HTE entrance [°C]	/	/	332	/
Air temperature through RRK [°C]	/	/	/	145
Flue gas temperature at exit [°C]	182	167	150	164
Subtracted energy, Q [kW] –	9359.29	10558.07	10848.77	11720.85
Unit power without losses in the valves, N [MW]	233	239.4	233	233
Unit heater losses [MW]	1.011	1.693	1.74	1.26
Electric power at generator clamps, N [MW]	231.989	237.707	231.260	231.739
Total fuel consumption [th^{-1}]	304.952	311.156	318.414	308.272
Specific fuel consumption, b [$\text{kg kW}^{-1}\text{h}^{-1}$]	1.3145	1.3090	1.2697	1.2882
Power growth on the expense of bypass [MW]	/	6.4	/	/
Reduction in specific fuel consumption, Δb [%]	/	0.42	3.4	2.0

Table 2. Review of operating characteristics of heat pumps for different cooling fluids

Refrigerant	HP* No.	Δt_c^{**} [K]	l_i [kJkg^{-1}]	q_c [kJkg^{-1}]	m_f [kgs^{-1}]	N_e [kW]	COP_{ave} [-]
R134a	1	5	21.91	168.27	53.93	1312.84	6.220
R134a	2	5	29.82	164.68	77.15	2501.76	4.565
R134a	3	5	31.39	154.05	94.25	3287.23	3.975
R134a	1	3	22.36	171.82	52.82	1341.63	6.088
R134a	2	3	27.44	166.10	76.49	2332.10	4.903
R134a	3	3	35.49	161.45	89.93	3546.24	3.685
R410A	1	5	24.01	178.63	50.80	1355.23	6.026
R410A	2	5	32.46	184.08	69.02	2489.31	4.593
R410A	3	5	47.06	168.08	86.38	4516.70	3.900
R410A	1	3	27.41	185.93	48.81	1486.53	5.494
R410A	2	3	28.64	173.06	73.41	2336.10	4.895
R410A	3	3	36.56	162.78	89.20	3623.50	3.606

* HP is the heat pump, ** Δt_c is the condensation temperature difference

(a) Separate production of heat energy (in boiler room)

If the system uses heat energy produced only in boiler-room for hot water, system 75/35 °C, total installed capacity of the system would be 72600 kW.

With boiler efficiency $\eta_k = 0.9$, total quantity of consumed fuel with lower heating value of $H_d = 7494$ kJ/kg is:

$$B_k = \frac{Q_k}{H_d \eta_k} \text{ [kgs}^{-1}\text{]} \quad (8)$$

Parameters from techno-economic analysis are shown hereafter, [11]. Total annual fuel consumption for separated system (boilers running on lignite with efficiency 90%):

$$B_{yr} = \frac{Q_{tot,yr} \cdot 3600}{H_d \eta_k} \text{ [kg per year]} \quad (9)$$

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

(b) Combined system (example for system with R134a and $\Delta t_c = 5$ K)

Fuel consumption for heat energy production in hot water boiler-room for heat demand of $Q_{tot,yr} = 33.13$ GWh per year is $B_{tot,yr} = 17683.48$ ton of lignite per year.

For low-temperature system with heat pumps, annual production of heat energy is $Q_{tot,HP} = 99.37$ GWh per year.

For an average $COP_{avg} = 4.92$, total energy for powering of compressors:

$$E_{COMP} = \frac{Q_{tot,HP}}{COP_{avg}} \text{ [GWh per year]} \quad (10)$$

For production of electrical energy, following quantity of fuel is required:

$$B_{COMP,yr} = b_g \frac{E_{COMP}}{H_d \eta_k} \text{ [kg of lignite per year]} \quad (11)$$

where $b_g = (1.08-1.2)$ kg/kWh is the specific fuel consumption for production of 1 kWh of electricity, when lignite is used.

Total consumption of energy when combined system is used (heat pumps and hot water boiler-room) is:

$$B = B_{tot,yr} + B_{COMP,yr} = 29973.09 \text{ tons of lignite per year} \quad (12)$$

Fuel savings between hot water boiler-room and combined production of heat energy is:

$$\Delta B = 70723.45 - 29973.09 = 40750.43 \text{ tons of fuel per year} \quad (13)$$

Combined system (comparison for heat pumps with R134a and R410A, and $\Delta t_c = 5$ K):

R134a; $\Delta t_c = 5$ K

R410A; $\Delta t_c = 5$ K

$$Q_{BH,yr} = 33.13 \text{ GWh per year}$$

$$Q_{\text{tot,HP}} = 99.37 \text{ GWh per year}$$

$$B_{\text{tot,yr}} = 17683.48 \text{ t per year}$$

$$COP_{\text{avg}} = 4.92$$

$$COP_{\text{avg}} = 4.84$$

$$E_{\text{COMP}} = 20.197 \text{ GWh per year}$$

$$E_{\text{COMP}} = 20.531 \text{ GWh per year}$$

$$B_{\text{COMP,yr}} = 12289.61 \text{ t per year}$$

$$B_{\text{COMP,yr}} = 12492.84 \text{ t per year}$$

$$B = 29973.09 \text{ t per year}$$

$$B = 30176.32 \text{ t per year}$$

$$\Delta B = 40750.43 \text{ t per year}$$

$$\Delta B = 40547.13 \text{ t per year}$$

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

Economic efficiency

Values for the specific investment costs, maintenance costs and average price of coal for year 2014 [12, 13] are adopted in the analysis. Analysis for the combined system presented below refers to refrigerant media R410a and $\Delta t_c = 5 \text{ K}$:

- lignite price: 0.06690 €/kg
- heat pump investment: 142907.5 €/1 MW, and
- hot water boiler room investment: 43125 €/1 MW

Investment costs

A. Total investment costs for separate production of heat in a boiler-room are $3.130875 \cdot 10^6 \text{ €}$.

B. Investment costs for combined system (example presented for system with R134a and $\Delta t_c = 5 \text{ K}$):

- heat pumps: $5.187542 \cdot 10^6 \text{ €}$, and
- hot water boiler room: $1.565437 \cdot 10^6 \text{ €}$.

Exploitation costs

– Fuel

A. Separate production of heat in boiler room: $4.7314 \cdot 10^6 \text{ € per year}$.

B. Combined system: $2.0052 \cdot 10^6 \text{ € per year}$.

– Maintenance costs (adopted as 6% of annual fuel cost).

A. Separate production of heat in boiler room: $0.2839 \cdot 10^6 \text{ € per year}$.

B. Combined system: $0.1203 \cdot 10^6 \text{ € per year}$.

Total annual costs

A. Investment costs for estimated lifespan of eight years are: $0.3914 \cdot 10^6 \text{ € per year}$:

- fuel costs: $4.7314 \cdot 10^6 \text{ € per year}$, and
- maintenance costs: $0.2839 \cdot 10^6 \text{ € per year}$.

Total annual costs for purely hot water boiler-room system:

$$\Sigma T_A = 5.4067 \cdot 10^6 \text{ € per year} \quad (14)$$

B. Investment costs for estimated lifespan of eight years are: $0.8441 \cdot 10^6$ € per year:

- fuel costs: $2.0052 \cdot 10^6$ € per year, and
- maintenance costs: $0.1203 \cdot 10^6$ € per year.

Total annual costs for the combined system are:

$$\Sigma T_{B,com} = 2.9696 \cdot 10^6 \text{ € per year} \quad (15)$$

Energy unit (specific) price:

$$C_A = \frac{5.4067 \cdot 10^6}{132,5 \cdot 10^3} = 40.81 \text{ €/MWh} \quad C_B = \frac{2.9696 \cdot 10^6}{132,5 \cdot 10^3} = 22.41 \text{ €/MWh}$$

The rest or *the savings* are:

$$(5.4067 - 2.9696) \cdot 10^6 = 2.4371 \cdot 10^6 \text{ € per year}$$

Investment payback period:

$$\tau = \frac{5.1875 + 1.5654}{2.4371} = 2.77 \text{ years} \quad (16)$$

Techno-economic analysis is performed under equal energy efficiency of both systems. Results from the techno-economic analysis are summarized in tab. 3.

Conclusions

Proposed modernisations of power units in order to utilize the waste heat energy of flue gases offers many advantages. They also draw costs that should be also considered.

Table 3. Comparison of the total annual costs for both systems

System type	Energy unit price [€/MWh ⁻¹]	Total annual costs [€ per year] (in millions)	Savings [€ per year] (in millions)	Investment return period [years]
System A	40.81	5.4067	–	–
System B: R134a; $\Delta t_c = 5$ K	22.41	2.9693	2.4371	2.77
System B: R134a; $\Delta t_c = 3$ K	22.45	2.9746	2.4321	2.78
System B: R410A; $\Delta t_c = 5$ K	22.52	2.9840	2.4227	2.79
System B: R410A; $\Delta t_c = 3$ K	22.77	3.0172	2.3895	2.83

First of all, the cost of a TUE with a total estimated weight of 190 tons (per block), cost for its installment and for raising the capacity of air unit heaters must be considered. On the world market, building of a new power plant using coal as energy costs around 1500 \$/kW, while the modernisation with TUE would cost roughly 500 \$/kW. These costs are incomparable to the newly gained effects.

Installation of HTE in the three blocks of TPP *Bitola*, with a total heat gain of 135 MW, results in great savings on *not* building large water-heating boiler room for district heating of Bitola. The HTE is an installed water-heating surface with no need for special room, or

equipment for the flue gas or servicing personal. Heat energy production in HTE needs 1.8 times smaller specific fuel consumption compared to conventional water-heating boilers. Heat energy production with HTE installation is accompanied by much smaller environmental impact compared to water heating boilers using heavy oil as fuel. It is achieved by using cheap lignite, instead of expensive heavy oil. The HTE installment is a lot cheaper than water-heating boilers installation. In a case when there is no need for heat energy produced by the HTE, the circulation of district heating water is turned off and the block works in basic regime with its parameters.

Proposed rationalisation by installing heat exchanger in the recirculation duct of TPP *Bitola* has its advantages as well as disadvantages. The *good* side of the rationalisation comprises: flexibility in the heat flow regulation, possibility to operate at any temperature of the return water, better usage of the utilisation heat, and lowering of the unit air heating. Main disadvantages of this scheme include: relatively small amount of heat extracted by the exchanger ($Q_{H,RRK} = 17.44$ MW), necessity to install additional recirculation ventilator (it is very difficult to estimate whether the reserves of the fresh air fan are sufficient to meet new requirements).

Compared to HTE rationalisation proposal, efficiency of flue gas heat energy usage in this case is much higher: 66% of the heat energy is acquired without additional fuel consumption.

For the defined optimal greenhouse complex comprised of 21 modules, each having 1.5 ha or 31.5 ha in total, and heat energy demand of 72.6 MW for heating up the complex, two systems are proposed:

A. *Separate system*, comprised of boiler room for production of hot water which meets the total requirements for heating of the complex (72.6 MW, system 75/35 °C).

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 boiler room with capacity of 36.3 MW that will cover the remaining 25% of the annual heat energy needs. Calculations are done for cooling fluid R134a and R410A at condensation temperature difference of $\Delta t_c = 5$ K.

Fuel used in the boiler room is lignite from the *Suvodol* basin (fuel used by the TPP) with average lower heating value of $H_d = 7494$ kJ/kg.

From the analysis presented in the article we can conclude that the combined (merged) system, that is the system that uses R134a as a cooling fluid, and $\Delta t_c = 5$ K is the most favorable in terms of savings and investment payback period.

Exploitation effects from the substantial reduction of fuel consumption, lower environmental impact through lower NO_x emission, are also benefits that should not be neglected while considering all these modernisations.

Nomenclature

B – fuel consumption, [kg h^{-1}] or [th $^{-1}$]
 b – specific fuel consumption, [kgkWh $^{-1}$]
 C – energy specific price, [€MWh $^{-1}$]
 COP – coefficient of performance, [–]
 H_d – lower heating value, [kJkg $^{-1}$]
 l_i – engaged specific energy for compressor's operation, [kJkg $^{-1}$]
 m_f – mass flow of refrigerant, [kgs $^{-1}$]
 N, N_e – engaged power, installed power, [kW] or [MW]
 Q_k, Q_{kal} – heat energy, heat load, [kW]

q_c – specific heat load on the condenser, [kJkg $^{-1}$]
 t_a – ambient air temperature, [°C]
 t_{min} – minimum metal temperature at RAH wall, [°C]
 ΣT – total annual costs, [€]

Greek symbols

β_c – coefficient of air recirculation, [–]
 η – coefficient of efficiency, [–]
 τ – investment payback period, [year]

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