Annals of the University of Craiova, Electrical Engineering series, No. 32, 2008; ISSN 1842-4805

# SOME EFFECTS OF DISTRICT HEATING SYSTEMS REHABILITATION MEASURES

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*Abstract* – **The paper presents a few rehabilitations methods that might be used for CHP systems or district heating systems based on cogeneration. The mathematical model is based on several optimisation factors that allow a faster simulation of the rehabilitation results**.

**Keywords: CHP, cogeneration, district heating**

## 1. INTRODUCTION

The paper is based by a new approach on CHP systems analysis based on the competitiveness of these systems at the end consumers.
Any financial analysis is based on assuming the incomes resulted from heat and electricity sales. This type analysis involves a high risk because the increase of energy price is not compared with the one obtained by different types of technologies. Under these circumstances even if the investment is feasible from a financial point of view, the increased price of electricity and/or heat might determine the loss of consumers.
The proposed method represents a comparison between the behaviour of the CHP system after the rehabilitation and different alternative solutions, in terms of end consumer's prices. In this way it's possible to select the best rehabilitation solution for the CHP system.

## 2. HEAT LOSSES RATIOS CALCULATION

The first part of the paper establishes a series of relations between the subsystem losses and the global transport and distribution losses.

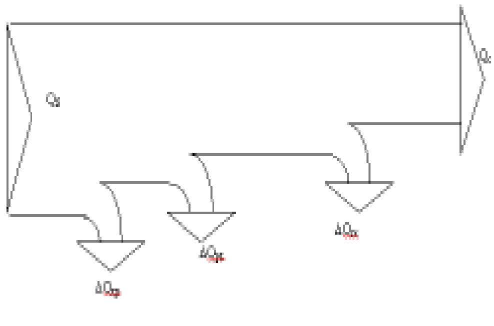

Figure 1. Heat transport and distribution losses

Where:

- $\Delta Q_{rp}$ – heat losses in the main thermal network;
- $\Delta Q_{pt}$ – heat losses in thermal substations;
- $\Delta Q_{rs}$ – heat losses in the secondary thermal network;
- $Q_c$ – consumers heat demand;
- Qs – heat produced by the CHP plant.

The overall efficiency for the transport and distribution of heat with respect to a relative heat loss for the district heating system is:

$$\eta_{qtd} = \frac{Qc}{Q_S} = \frac{Qc}{Qc + \Delta Qtd} = \frac{1}{1 + \frac{\Delta Qtd}{Qc}} = \frac{1}{1 + r_{Qtd}} \quad (1)$$

$\Delta Qtd$ - relative heat loss for the whole district system;

$r_{Qtd}$ - system heat loss ratio;

The advantage of this approach consists of expressing all the losses with respect to the consumers heat demand that might be considered constant before and after the implementation of the rehabilitation measures.
The system heat loss ratio might have three components with respect to the type of system:

- Primary network heat loss ratio:

$$r_{Qrp} = \frac{\Delta Qrp}{Qc} \quad (2)$$

- Secondary network heat loss ratio:

$$r_{Qrs} = \frac{\Delta Qrs}{Qc} \quad (3)$$

- Thermal stations heat loss ratio:

$$r_{Qpt} = \frac{\Delta Qpt}{Qc} \quad (4)$$

The system heat loss ratio is a sum of the subsidiary ratios:

$$r_{Qtd} = r_{Qrp} + r_{Qpt} + r_{Qrs} \quad (5)$$

The last equation allows the analysis of certain district heating rehabilitation methods:

- Rehabilitation of the existing district heating maintaining it's structure ($r_{Qrp}, r_{Qpt}, r_{Qrs} \neq 1$);
- The use of thermal substations within the consumers buildings ($r_{Qpt}, r_{Qrs} = 1, r_{Qrp} \neq 1$), with corresponding increase of the of the primary network heat loss ratio with respect to the increase of the transport distance;
- The decrease of the transport distances by the use of smaller CHP plants closer to the consumers ($r_{Qpt}, r_{Qrs} = 1, r_{Qrp} \neq 1$, if building substations are used).

In order to simplify the simulation process the use of a series of optimisation factors allows a significant decrease of the calculations volume.

| Optimisation factor | Calculation relation |
|---|---|
| For the primary thermal network | $f_{optrpi} = \frac{\left(R^{in}_{trpi}\right)}{\left(R^{f}_{trpi}\right)} * \frac{\left(t^{f}_{frpi} - to\right)}{\left(t^{in}_{frpi} - to\right)} * \frac{\left(L^{f}_{echrpi}\right)}{\left(L^{in}_{echrpi}\right)}$ |
| For the secondary thermal network | $f_{optrsi} = \frac{\left(R^{in}_{trsi}\right)}{\left(R^{f}_{trsi}\right)} * \frac{\left(t^{f}_{frsi} - to\right)}{\left(t^{in}_{frsi} - to\right)} * \frac{\left(L^{f}_{echsi}\right)}{\left(L^{in}_{echsi}\right)}$ |
| For the replacement of a heat exchanger within the thermal substation | $f_{optsci} = \frac{\eta^{in}_{sci}}{(1-\eta^{in}_{sci})}\left(\frac{1}{\eta^{f}_{sci}} - 1\right)$ |
| For the replacement of the pipes | $f_{optci} = \frac{\left(R^{in}_{tpti}\right)}{\left(R^{f}_{tpti}\right)}$ |

Table 1. Optimisation factors for the district heating system

Where:

$t_{frpi}$, $t_{frsi}$ - the average flow temperature within the primary, secondary network pipe „i";

$to$ - environmental temperature;

$R_{trpi}, R_{trsi}, R_{tpti}$ - thermal resistance of the primary, secondary network pipe „i" or of the thermal substation pipe „i";

$L_{echrpi}, L_{echrsi}$ - primary or secondary network pipe „i" length;

$value^{f}$ – value after the rehabilitation

$value^{in}$ – initial value (before the implementation of the rehabilitation measure).

The determination of the total annual loss for each subsystem of the district heating system consists in a two calculation as presented forward in the next table.

| | Partial annual heat loss for the replacement of the equipment „i" | Total annual loss |
|---|---|---|
| PN | $\Delta Q^{f}_{Qcrpi} = Qc * r^{in}_{Qcrpi} * f_{optrp}$ | $\Delta Q^{f}_{Qrp} = \sum_{i=1}^{n} \Delta Q^{f}_{Qcrpi} + \Delta Q^{f}_{ntrp}$ |
| SN | $\Delta Q^{f}_{Qcrsi} = Qc * r^{in}_{Qcrsi} * f_{optrs}$ | $\Delta Q^{f}_{Qrs} = \sum_{i=1}^{n} \Delta Q^{f}_{Qcrsi} + \Delta Q^{f}_{ntrs}$ |
| Sb | $\Delta Q^{f}_{sci} = Qc * r^{in}_{sci} * f_{optsc}$<br>$\Delta Q^{f}_{Qcpti} = Qc * r^{in}_{Qcpti} * f_{optc}$ | $\Delta Qpt = \sum_{i=1}^{n} \Delta Q^{f}_{sci} + \sum_{i=1}^{n} \Delta Q^{f}_{Qcpti}$ |

Table 2 Calculation of the total annual heat losses

Where:

PN- primary thermal network;

SN- Secondary thermal network;

Sb- thermal substations;

$\Delta Q^{f}_{Qcrpi}$ - heat loss for the primary network pipe „i", after replacement;

$\Delta Q^{f}_{Qcrsi}$ - heat loss the secondary network pipe „i" , after replacement;

$\Delta Q^{f}_{sci}$ - heat loss for the heat exchanger „i" , after replacement;

$\Delta Q^{f}_{Qcpti}$ - heat loss for the pipe „i", after replacement;

$r^{in}_{Qcrpi}$ - initial heat loss ratio for the primary network;

$r^{in}_{Qcrsi}$ - initial heat loss ratio for the secondary network;

$r^{in}_{sci}$ - initial heat loss ratio for the heat exchangers;

$r^{in}_{Qcpti}$ - initial heat loss ratio for the thermal substation pipes;

With the relations presented above it is possible to determine the losses for heat transport and distribution system and the global efficiency of the district heating system. The method presented above does not exclude the possibility to calculate individual subsystems efficiencies, used in engineering literature: global efficiency for the secondary/primary thermal network [6], the global efficiency of thermal substations [6].

The global efficiency for the secondary thermal network might be expressed in terms of the heat loss ratio for the secondary network:

$$\eta_{rs} = \frac{Qc}{Qc + \Delta Qrs} = \frac{1}{1 + r_{Qrs}} \qquad (6)$$

For the thermal substations the global efficiency depends both the heat loss ratio for the secondary network and heat loss ration for the thermal stations:

$$\eta_{PT} = \frac{Qc + \Delta Qrs}{Qc + \Delta Qrs + \Delta Qpt} = \frac{1 + r_{Qrs}}{1 + r_{Qrs} + r_{Qpt}} \qquad (7)$$

Finally the global efficiency for the primary network might be calculated as follows:

$$\eta_{rp} = \frac{Qc + \Delta Qrs + \Delta Qpt}{Qc + \Delta Qrs + \Delta Qpt + \Delta Qrp} = \frac{1 + r_{Qrs} + r_{Qpt}}{1 + r_{Qrs} + r_{Qpt} + + r_{Qrp}} \qquad (8)$$

The use of these subsystem efficiencies might be useful when the available funds for the rehabilitation of the district heating system are limited and it's necessary to establish a particular order for the specific rehabilitation measures.

## 3. THE INFLUENCE OF DISTRICT HEATING SYSTEM LOSSES OVER THE GLOBAL EFFICIENCY OF THE CHP SYSTEM

For the elaboration of the method presented within this paper was preferred the global efficiency of the CHP system [6] instead of the overall efficiency of the CHP plant as in Directive 2004//EC [7] due to the possibility of evaluation of heat and electricity transport losses. For the purpose of the calculations presented within this paper we have used a modified form of the global efficiency of the CHP system with the following calculation relation:

$$\eta^{f}_{gcg} = \frac{E_S \eta_{etd} + Q_{cg} \eta_{qtd} + Qv\, \eta_{qtd}}{Q_{ep} \dfrac{\eta_{cz}}{\eta^{f}_{cz}} + Q^{v}_{ep} \dfrac{\eta^{v}_{cz}}{\eta^{vf}_{cz}}} \qquad (9)$$

where:

$E_S$ - electricity produced by the CHP plant

$\eta_{etd}$ - electricity transport and distribution efficiency;

$Q_{cg}$ - heat produced by the CHP plant;

$Qv$ - heat produced with peak boilers;

$\eta_{cz}$ - boilers average initial efficiency;

$\eta^{f}_{cz}$ - boilers efficiency after rehabilitation.

The graphs presented bellow show the influence of different rehabilitation over the global efficiency of the CHP system.

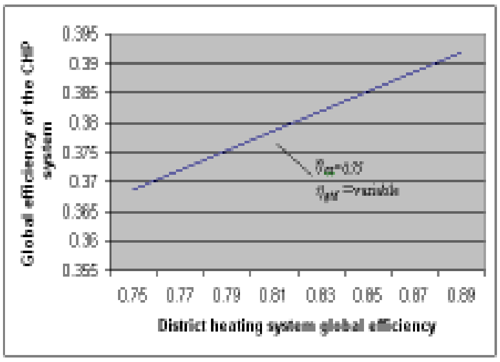


Figure 2. The effect of rehabilitation measures for the district heating system

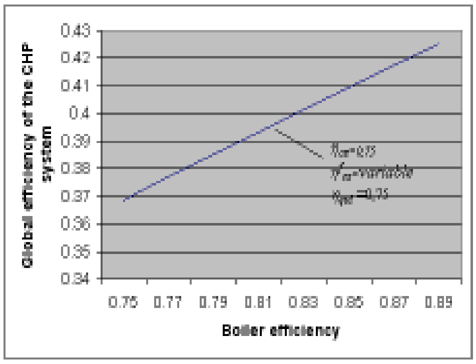


Figure 3. The effect of boiler rehabilitation

The variation curves plotted in the graphs presented above show a rather small influence of the increase of the district heating system. The second picture shows that for the analysed example the rehabilitation of the CHP plants boilers might bring a higher increase of the global efficiency of the CHP system with significantly smaller costs. This observation underlines the importance of analysing different rehabilitation measures for the CHP systems, especially when the available funds are limited.

This type of analysis imposes the use of criteria that takes into account the influence of different rehabilitation measures over the competitiveness of the CHP system. The proposed criteria is the financial savings ratio first proposed by the authors of this article at WESC 2006 [4], with the following calculation relation:

$$FSR = \frac{c_{fEualt} - c_{fEucg}}{c_{fEualt}} = 1 - \frac{c_{fEucg}}{c_{fEualt}} \qquad (10)$$

where:

$c_{fEucg}$- the specific cost of the energy delivered to the consumer for the analysed solution (CHP plant or separate production);

$c_{fEualt}$- the specific cost of the delivered energy for the alternative solution.

The method demands the calculation of the financial saving ratio for different rehabilitation methods with respect to the same alternative solution. In this way might be considered eligible the rehabilitation measures that are leading to positive financial saving ratio, the best rehabilitation measures having higher values of this coefficient.

## 4. CASE STUDY FOR AN EXISTING CHP SYSTEM

In order to demonstrate the flexibility of our model we present the results for a case study.

The existing solution is an CHP system consisting in a large scale cogeneration plant with two groups of 150 MW installed power and a district heating system with 94 thermal stations.

In table 3 we present the main data regarding the primary energy consumption and the production of electricity and heat.

The efficiency of the CHP plant is negatively influenced by the competition on electricity market that causes an operation for long periods of time with a very small electricity production.

A direct consequence of this fact it's the use of peak boilers for heat production that lead to an efficiency of only 44.3 % for the last year.

The losses for the district heating system aggravate the situation leading to global efficiency for the CHP system of only 37.4 %.

| | Value |
|---|---|
| Heat produced with heat exchangers [TWh/year] | 0,73 |
| Heat production with peak boilers [TWh/year] | 0,25 |
| Electricity production in cogeneration regime [TWh/year] | 0,3 |
| Separate production of electricity [TWh/year] | 1,14 |
| Primary energy consumption for coal [TWh/year] | 5 |
| Primary energy consumption for natural gas (used as support fuel) [TWh/year] | 0,5 |
| Power to heat ratio for the delivered energy | 1.59 |
| Efficiency of the CHP plant [%] | 0.443 |
| Efficiency of the district heating system [%] | 0.77 |
| Efficiency for the electricity transport [%] | 0.85 |
| Global efficiency of the CHP System [%] | 0.374 |

Table 3. System operation

All the rehabilitation measures would be analysed with respect to an alternative solution consisting of the CHP plant operating in a condensing regime (thus producing only electricity) and local boilers at the consumers for heat production.

### 4.1. The analysis of the rehabilitation of the existing district heating system

The rehabilitation measures for the heat transport and distribution system maintaining it's structure are:

- replacement of the underground pipes with pre-insulated pipes;
- replacement of the thermal insulation for aerial pipes;
- replacement of the heat exchangers from the substations;

| Investment | Value (mil €) |
|---|---|
| Total investment for the primary thermal network | 57,87 |
| Thermal substation<br>TOTAL<br>Plates heat exchangers cost<br>AMC<br>Automation equipment | <br>3,789<br>1,551<br>0,601<br>1,637 |
| Cost for the secondary network rehabilitation | 101,27 |
| TOTAL INVESTMENT COST | 162,93 |

Table 4. Investment structure

| | | |
|---|---|---|
| Annual reduction of heat losses | TWh/year | 0,28 |
| Global efficiency of the CHP system after rehabilitation | % | 38 |
| Yearly investment recovery | Mil. € | 2,14 |
| Yearly increase of the total heat production, transport and distribution cost | Mil € | 11,38 |

Table 5 Effect of the rehabilitation measures

Table 5 indicates a smaller competitivity of the CHP system after rehabilitation. The direct effect of the rehabilitation measures consists in an increase of 10,49 % of the cost for the heat production, transport and distribution.

| Indicator | Before rehabilitation | After rehabilitation |
|---|---|---|
| Heat specific cost (at the consumer) (€/MWh) | 58,39 | 64,51 |
| FSR | -0,169 | -0,29 |

Table 6. Comparative analysis of the CHP system competitiveness before and after rehabilitation

### 4.2. Passing to thermal modules within the consumers buildings

Due to a higher efficiency of the primary thermal network for this measures we have considered only:

- the cost of the thermal modules;
- the cost for the extension of the primary network (necessary to replace the secondary thermal network).

| Investment | Value Mil. € |
|---|---|
| Investment for the thermal modules | 38,508 |
| Investment for the primary network extension | 60,45 |
| TOTAL INVESTMENT | 95,96 |

Table 7. Investment structure

| | | |
|---|---|---|
| Annual reduction of heat losses | TWh/year | 0,259 |
| Global efficiency of the CHP system after rehabilitation | % | 38,8 |
| Yearly investment recovery | Mil. € | 8 |
| Yearly increase of the total heat production, transport and distribution cost | Mil € | 4,6 |

Table 8 Effect of the rehabilitation measures

The calculations indicate an important increase of the total heat production, transport and distribution cost for a relative modest increase of the CHP system global efficiency. In parallel with the proposed measures we have also analysed the possibility to increase the global efficiency of the CHP system by a reduction of electricity production.

In figure 4 it is presented the increase of the global efficiency of the CHP system for the decrease of electricity production.

In further calculation we have considered the maximum increase of the global CHP system efficiency obtained for a decrease of 50 % of the electricity production.

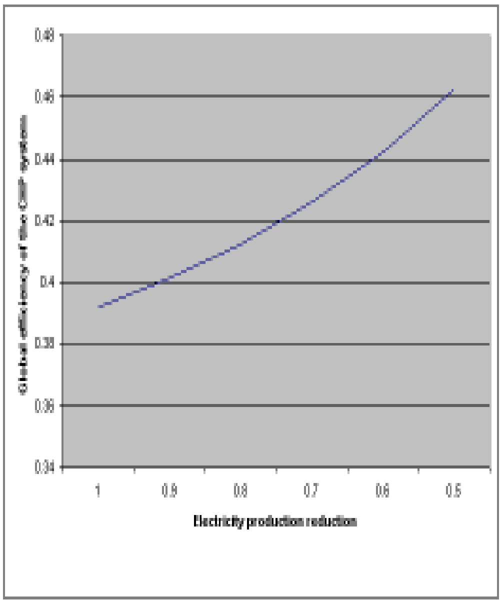


Figure 4. The increase of the global efficiency of the CHP system with the decrease of the electricity production

| | | |
|---|---|---|
| Annual reduction of heat losses | TWh /year | 0,259 |
| Global efficiency of the CHP system after rehabilitation | % | 46,2 |
| Yearly investment recovery | Mil. € | 8 |
| Yearly decrease of the total heat production, transport and distribution cost | Mil € | 4,8 |

Table 9. Effect of the implementation of thermal modules and a decrease of electricity production

| Indicator | Before rehabilitation | After rehabilitation |
|---|---|---|
| Heat specific cost (at the consumer) (€/MWh) | 58,39 | 51,8 |
| FSR | -0,169 | -0,03 |

Table 10. Comparative analysis of the CHP system competitiveness before and after rehabilitation

As one might see in table 9, the effect of all measures consists in small increase of the specific heat cost of 2,5 €/MWh with respect to the separate production of electricity and heat. This small increase of the specific heat cost cannot lead to the loss of an important number of consumers.

### 4.3. The reduction of heat transport distance by the use of smaller CHP plants closer to consumers.

For this rehabilitation solution we have considered the use of several small CHP plants with gas turbines or internal combustion engines running on natural gas mounted at the level of the thermal substations. The secondary thermal network in this case must be replaced. The calculations were carried out for a price of gas of *260 €/ 1000Nm$^3$*

| Investment | CHP plants with gas turbines ($\eta_{TG}$=0,31) | CHP plants with internal combustion engines ($\eta_{MT}$=0,4) |
|---|---|---|
| Investment for the CHP plants [Mil. €] | 93,7 | 121,9 |
| Investment for the thermal modules [Mil. €] | 38,508 | 38,508 |
| Investment for the primary thermal network [Mil. €] | 60,45 | 60,45 |
| TOTAL INVESTMENT [MIL. €] | 189,66 | 217,86 |

Table 11. Investment structure

| Indicator | Unit | Gas turbines CHP plants ($\eta_{TG}$=0,31) | Internal combustion engines CHP plants ($\eta_{MT}$=0,4) |
|---|---|---|---|
| Global system efficiency | % | 73 | 72 |
| Annual investment payback | Mil. € | 7,58 | 12,1 |
| Total cost for the production, transport and distribution | Mil. € | 78,8 | 80,9 |
| Reduction of the total cost for the production, transport and distribution | Mil. € | 29,6 | 27,5 |
| FSR | | 0,231 | 0,2 |

Table 12. Effect of the proposed measures

The calculation indicates for the first time a positive financial savings ratio. This means that in this particular case the specific cost of the useful energy (electricity and heat) would be smaller than the one obtained for separate production.
These results might change however for an important increase of the gas price.

## 5. CONCLUSIONS

The analysis of the calculation shows that the rehabilitation of the heat transport and distribution system implies a very high investment cost.
For the CHP system analysed in this paper, the only possible rehabilitation solution if it's desired to maintain the existing CHP plant consists in thermal modules mounted in consumers buildings. This measure is possible only with a significant decrease of electricity production in order to obtain the necessary increase of the global CHP system efficiency.
The use of smaller CHP plants closer to the consumers **improves** the competitiveness of the CHP system, but involves an important risk factor tacking into account the recent evolution of the natural gas price.

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