QUALITY ENGINEERING PROCEDURES APPLIED TO DETERMINE THE WEIGHT OF INFLUENCE OF FACTORS ON MICROTRIGENERATION SYSTEMS (mCCHP)

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ABSTRACT

Microtrigeneration systems are characterized by simultaneous generation of power, heat and cold for small applications (<50kW) and are designed for reducing GHG and other emission degreases. The cooling generation by absorption or adsorptions of heat is the most sensible stage of mCCHP systems.The paper si based on the global mathematical model for a mCCHP system with thermal prime mover. The conceptual design of an mCCHP and was estabilished the influenece factors over the global efficiency of the system. The weight of influence factors was made using a Quality Engineering procedure (typised orthogonal array. An adequate mathematic model (ANOVA) was used for weight of factor influence prediction, with a view to global efficiency maximization. The simulation results showing signal and noise factors and these results are important for system design, selection of subsystem, selection of materials and optimal regime settings.

KEYWORDS: microtrigenerations, mCCHP, quality engineering, simulation

1. Introduction

Microtrigeneration systems (mCCHP) are characterized by simultaneous generation of power, heat and cooling for small applications (<50kW) [2, 3]. According to this, the overall efficiency of fossil fuels is increasing and also the emissions of greenhouse gases and other emissions decrease. A great diversity of mCCHP structures are under study and experimental stages. mCCHP systems are in direct dependency on prime mover (thermal stage) of energy conversion. The conceptual structures and designed mCCHP systems are over direct influences of the prime mover or thermal conversion. Usual thermal motor are Diesel engine, Otto engine, Stirling engine, fuel cells etc. The Diesel engines applications for prime movers is considered a classical, but the mCCHP systems follow the continuous evolutions of this thermal motor.

The prime movers (thermal stage) introduced some limitations regarding the fuel and the posibility to use the renewable energy [6,7]. Based on this fact the Stirling engine offers a large spectrum of fuels because the system is characterised by external burning. Trigeneration is usually based on the same initial fuel like an energy source. The trigenereation system structure is in direct dependency with fuel and the thermal initial conversion (prime mover). A schematic principle for mCCHP is showed in figure 1.
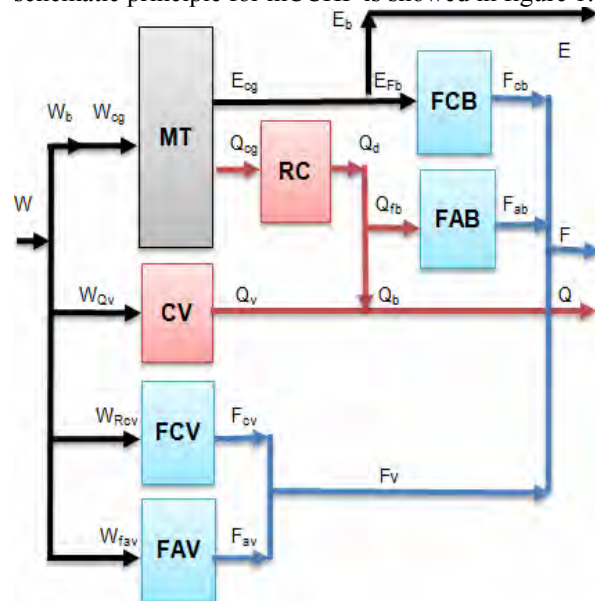

Fig. 1. Schematic representation of a trigeneration system (mCCHP) to cover peak energy demand

The maximum uses of fuel energy are correlated with the heat of the burning system, heat is recovered and converted into heat or cooling and then delivered. Aditional subsystems are presented for the peak values of heat and cooling consumption.
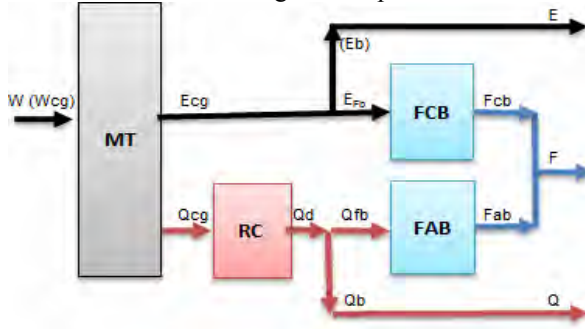

Fig. 2. *Simplified mCCHP.*

Diagram in Figure 1 is a general scheme in which the coverage requirements of electricity, heat and cold are the main design criterions. Cover peak demand for heat and cold is in this case, with additional subsystems dedicated. If the criterion has the economics of resources, the scheme becomes like in figure 2.

Analyzing Figure 1, one can say that the trigeneration plant in the most general case, is composed of a cogeneration plant plus compression and absorption refrigeration plants that produce cold in the basic.

2. Mathematical model for microtrigeneration system (mCCHP)

Cogeneration index is also based trigeneration systems, which is defined by:

$$y = \frac{E}{Q} \tag{1}$$

The first indicator required to characterize the mCCHP systems is the overall efficiency:

$$\eta_{gI} = \frac{E + Q + F}{W} \tag{2}$$

For the trigeneration system, the overall efficiency of energy production, in some cases, exceed unity, on account of this facility to generate cold (contradiction of the first law of thermodynamics or the law of conservation of energy). In the latter, the energy consumed is less than the amount of cold produced (especially, in compression refrigeration). For these reasons, it uses the *primary energy ratio* (PER) defined by the relationship:

$$PER = \frac{E + Q + F}{W} \tag{3}$$

In order to do an energy analysis it is necessary to define a number of technical indicators that help to express energy consumption by delivered energy:

Trigeneration coefficient for each of the three forms of energy produced a ratio between the amount of energy produced in cogeration system and all the energy produced and delivered to customers:

$$\alpha_E = \frac{E_b}{E}; \quad \alpha_Q = \frac{Q_b}{Q}; \quad \alpha_F = \frac{F_b}{F} \tag{4}$$

All these three factors can be defined for an entire group or trigeneration system and have values between 0 and 1.

The production structure of the three forms of energy is characterized by *structural indices of energy production:*

$$\gamma_E = \frac{E}{E+Q+F}; \quad \gamma_Q = \frac{Q}{E+Q+F}; \quad \gamma_F = \frac{F}{E+Q+F} \tag{5}$$

The link between the structural indices of production of electricity, heat and cold is::

$$\gamma_E + \gamma_Q + \gamma_F = 1 \tag{6}$$

Frigorific indice is the ratio between the amount of cold produced by refrigeration compression and the total quantity of cold and is defined by the relations:

$$\beta_b = \frac{F_{cb}}{F_b}; \quad \beta_v = \frac{F_{cv}}{F_v} \tag{7}$$

According to Figure 1, the total fuel used in a plant of trigeneration can be written as following:

$$W = W_{cg} + W_{Qv} + W_{Fcv} + W_{Fav} \tag{8}$$

$$EET = \frac{E+Q+F}{W_{cg}+W_{Qv}+W_{Fcv}+W_{Fav}} \tag{9}$$

For explicit input energy components is taken into account the local energy conversion efficiency of the system:

$$W_{Fcv} = \frac{E_{Fv}}{\eta_{ZEN}}; \quad W_{Fav} = \frac{E_{Fv}}{\eta_{QFv}}; \tag{10}$$

Also cold generation processes, involved in Figure 1, are energy-dependent on coefficients of performance (COP) for compression and absorption refrigeration:

$$COP_{cv} = \frac{F_{cv}}{E_{Fv}}; \quad COP_{av} = \frac{F_{av}}{Q_{Fv}} \tag{11}$$

$$COP_{cb} = \frac{F_{cb}}{E_{Fb}};.. \quad COP_{ab} = \frac{F_{ab}}{E_{Fb}} \tag{12}$$

Energy needed to produce cold in the peak regime can be written:

$$W_{Fcv} = \frac{F_{cv}}{COP_{cv}\eta_{ZEN}}; \quad W_{Fav} = \frac{F_{av}}{COP_{av}\eta_{QFv}} \tag{13}$$

In these conditions, *PER* may be expressed:

$$PER = \frac{E+Q+F}{\frac{E_{cg}}{\eta_{Ecg}}+\frac{Q_v}{\eta_{Qv}}+\frac{F_{cv}}{COP_{cv}\eta_{ZEN}}+\frac{F_{av}}{COP_{av}\eta_{QFv}}} \tag{14}$$

To build energy dependence of the input/output, one can specify these equations among the flows of energy from the scheme in Figure 1:

$$E = E_b + E_{ncg}; \quad E_{cg} = E_b + E_{Fb} \tag{15}$$

$$Q = Q_b + Q_v; \quad Q_{cg} = Q_b + Q_{Fb} \tag{16}$$

$$F_b = F_{cb} + F_{ab}; \quad F_v = F_{cv} + F_{av}; \quad F = F_b + F_v \tag{17}$$

The four components of the input energy can be expressed in terms of energy required to exit and indices and factors previously defined:

$$\frac{E_{cg}}{\eta_{Ecg}} = \frac{\gamma_E\left[Q_b + Q_v + \frac{F_b(1-\beta_b)}{COP_{ab}}\right]}{\gamma_V\eta_{Ecg}} \tag{18}$$

$$\frac{\dot{E}_{tv}}{\eta_{QFv}} = \frac{\dot{Q}(1-\theta_s)}{\eta_{QFv}} \qquad (19)$$

$$\frac{\dot{E}_{tv}}{COP_{tv}\eta_{SENv}} = \frac{\dot{E}\,\theta_s(1-\theta_s)}{COP_{tv}\,\eta_{SENv}} \qquad (20)$$

$$\frac{\dot{E}_{tv}}{COP_{tv}\eta_{QFv}} = \frac{\dot{E}(1-\theta_s)(1-\theta_s)}{COP_{tv}\eta_{QFv}} \qquad (21)$$

PER can be expressed as a function of:

$$PER = PER(\dot{E},\dot{Q},\dot{F},\alpha_E,\alpha_Q,\alpha_F,\theta_s,\beta_v,COP_{Cv},$$
$$COP_{Ch},COP_{Tv},COP_{Av},\eta_{ETg},\eta_{Qv},\eta_{SENv},\eta_{QFv})..... (22)$$

3. Quality engineering procedure aplied on trigeneration unit

The influence over *PER*, in this case is complex, being dependent on a large number of factors (22). Quality engineering offers an analysis method of those dependencies, both theoretical and practical. For n=23 factors lenght into evidence, as wells for a minimun of 3 values measured for each factor, the number of runs is:

$$r = k^n \qquad (24)$$

Experimental/simulation procedure involves choosing a quality engineering of a typical orthogonal array [1]. This type of matrix drastically reduces the number of runs in the experiments / simulations (partial factorial procedure). mCCHP system was to simulate a total of 6 chosen as the most significant factors (Table 1) and an L18 Orthogonal Array -3⁶ (table 2) [1].

Table 1. *Selected factors and selected levels*

	FACTORS		Levels		
		UM	1	2	3
A	delivered power	J	1000	2000	3000
B	delivered heat	J	3000	10000	15000
C	delivered cooling	J	12000	6000	0
D	COP absorbtion	-	0,5	0,6	0,8
E	heat recovery eficiency	-	0,4	0,5	0,6
F	power efficiency	-	0,1	0,12	0,15

The chosen values for the six factors and obtain complete orthogonal array matrix experiment (Table 3). The mathematical model of the trigeneration unit (23) is built on energy balance equations and the indices and coefficients defined.

Table 2. *Orthogonal array L18 (3⁶)*

Experiment	Specified Factors							
	1	2	3	4	5	6	7	8
	e	A	B	C	D	E	e	F
1	1	1	1	1	1	1	1	1
2	1	1	2	2	2	2	2	2
3	1	1	3	3	3	3	3	3
4	1	2	1	1	2	2	3	3
5	1	2	2	2	3	3	1	1
6	1	2	3	3	1	1	2	2
7	1	3	1	2	1	3	2	3
8	1	3	2	3	2	1	3	1
9	1	3	3	1	3	2	1	2
10	2	1	1	3	3	2	2	1
11	2	1	2	1	1	3	3	2
12	2	1	3	2	2	1	1	3
13	2	2	1	2	3	1	3	2
14	2	2	2	3	1	2	1	3
15	2	2	3	1	2	3	2	1
16	2	3	1	3	2	3	1	2
17	2	3	2	1	3	1	2	3
18	2	3	3	2	1	2	3	1

Table 3. *Experimental/simulation matrix*

Experiment	Specified levels					
	1	2	3	4	5	6
	delivered power	delivered heat	delivered cooling	COP absorbtion	heat recovery eficiency	power efficiency
	A	B	C	D	E	F
m.u.	J	J	J	-	-	-
1	1000	3000	12000	0,50	0,40	0,10
2	1000	10000	6000	0,60	0,50	0,12
3	1000	15000	0	0,80	0,60	0,15
4	2000	3000	12000	0,60	0,50	0,15
5	2000	10000	6000	0,80	0,60	0,10
6	2000	15000	0	0,50	0,40	0,12
7	3000	3000	6000	0,50	0,60	0,15
8	3000	10000	0	0,60	0,40	0,10
9	3000	15000	12000	0,80	0,50	0,12
10	1000	3000	0	0,80	0,50	0,10
11	1000	10000	12000	0,50	0,60	0,12
12	1000	15000	6000	0,60	0,40	0,15
13	2000	3000	6000	0,80	0,40	0,12
14	2000	10000	0	0,50	0,50	0,15
15	2000	15000	12000	0,60	0,60	0,10
16	3000	3000	0	0,60	0,60	0,12
17	3000	10000	12000	0,80	0,40	0,15
18	3000	15000	6000	0,50	0,50	0,10

Making the 18 runs experimental/simulations of mCCHP operation, shows values 18 *PER* (Table 4).

The mathematical simulation mCCHP operation using QE procedure involves the conversion of EET (dimensionless) depending on the target with the relationship:

$$t_{EET} = -10 \log (EET) \text{, dB} \tag{24}$$

Table 4. Target funtions based on EET for each simulated experiment

Experiment	EET	Target function
UM	-	dB
1	0,20	7,01
2	0,72	1,42
3	1,02	-0,10
4	0,20	7,02
5	0,44	3,60
6	0,46	3,38
7	0,18	7,38
8	0,23	6,48
9	0,44	3,57
10	0,26	5,90
11	0,87	0,58
12	0,91	0,42
13	0,14	8,69
14	0,50	3,00
15	0,60	2,24
16	0,20	7,10
17	0,32	4,92
18	0,37	4,32

4. Results and discusions

Depending on the target function value, for each experiment simulated, we can calculate the share accounted for the level of each factor considered. The results are shown in Table 5. The higher value of the target function is a value close to the optimum desired. In a first run, the mean is 4,27dB and the best setting factors are A1B3C1D2E3F3.

Table 5. Optimal configuration

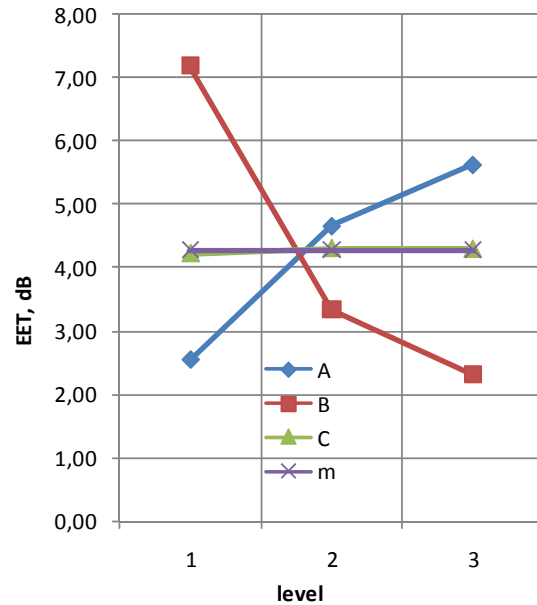| FACTOR		Level (dB)		
		1	2	3
A	delivered power	2,54	4,65	5,63
B	delivered heat	7,18	3,33	2,31
C	delivered cooling	4,22	4,30	4,29
D	COP absorbtion	4,28	4,11	4,43
E	heat recovery eficiency	5,15	4,20	3,47
F	power efficiency	4,93	4,12	3,77
			m	4,27

Fig. 3. Influence of factors A, B and C over the target function

The graphic representation of the influence of factors considered is shown in Figure 3 and Figure 4. Factor A (power delivered) directly affect *PER* after the ascending curve. Factor B (heat delivered) also has an influence in the form of a curve downwards. Representation shows the cumulative effect of these factors and antagonist and extended area of influence on *PER* and the objective function considered. Cogeneration index influence on EET is shown in Figure 7.
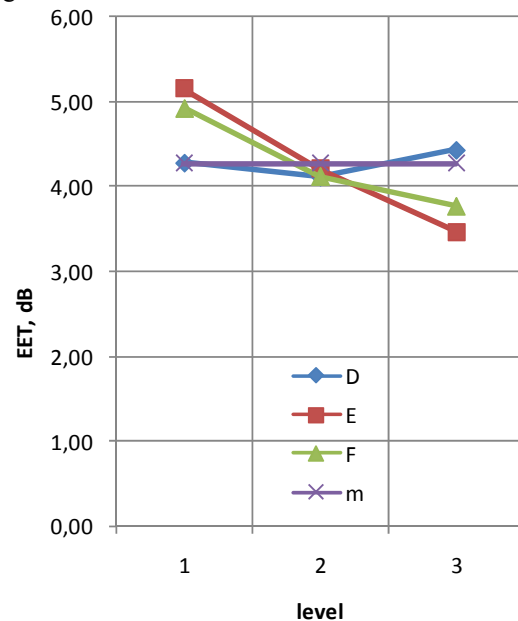

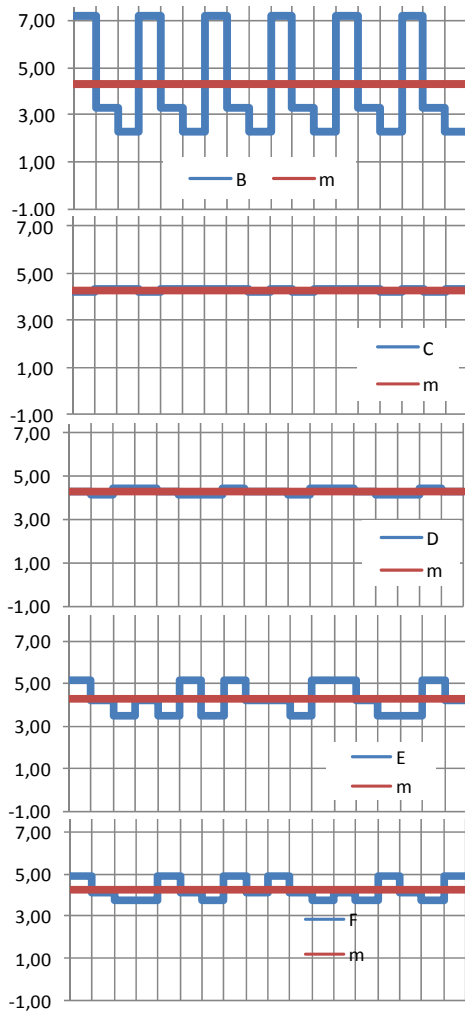*Fig. 4. Influence of factors D, E and F over the target function.*

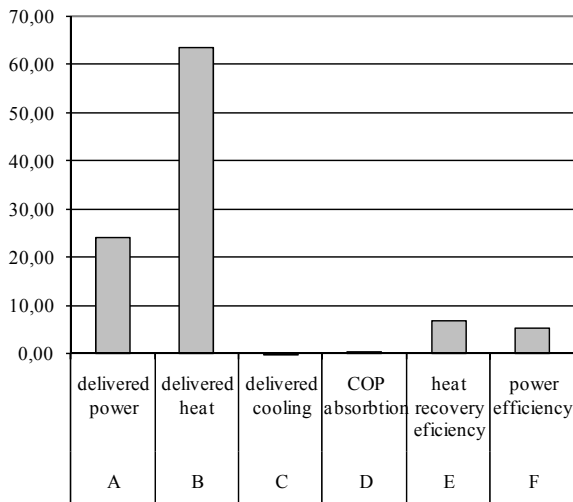**Fig. 5.** *Fourier decomposing for target functions and each factor estimated influence*

Fig. 6. *Weight factors over simulated experiments.*

The trigeneration energy efficiency increases by a logarithmic function with decreasing index of cogeneration. So, to get maximum efficiency, cogeneration index there strive for its lower values (figure 7).
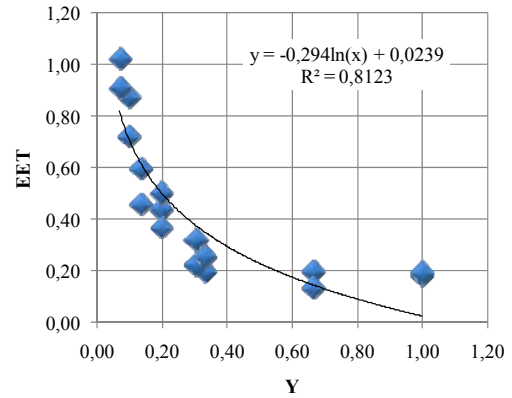

$$y = -0,294\ln(x) + 0,0239$$
$$R^2 = 0,8123$$

Fig. 7. *Dependence on total energy efficiency of cogeneration index*

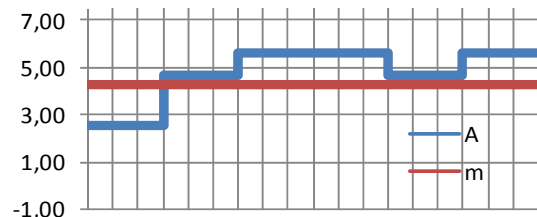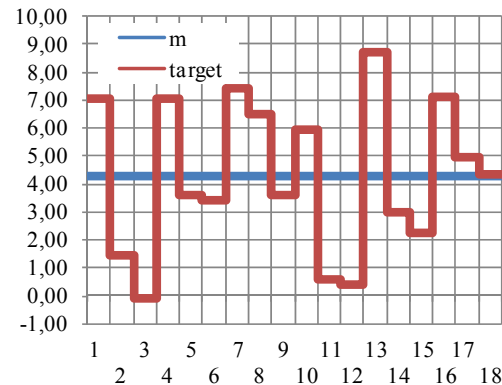$$y = 21156e^{-0,916x}$$
$$R^2 = 0,277$$
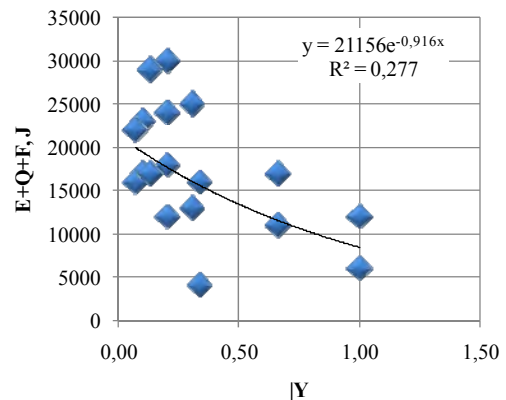
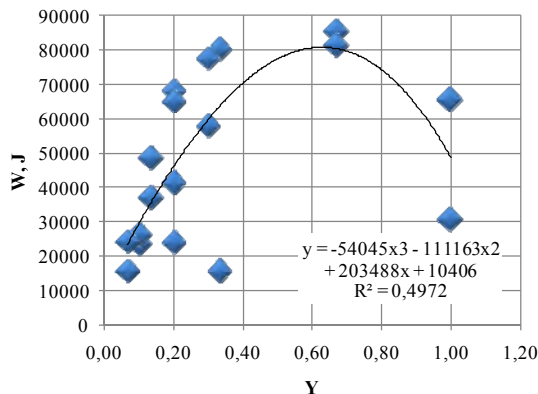**Fig. 8.** *Influence of cogeneration index on total energy delivered*

Figure 9. *Influence of cogeneration
index on total energy entry.*

In figure 8 is shown the dependence of energy over the index of cogeneration. It shows a great dispersion of values which is consistent with the situation in areas where energy demand is variable both in amount and in structure. Influence of energy cogeneration index entry shows a dispersion of the values that can be approximated by a polynomial curve (Figure 9). Representations of Figures 7.8 and 9 are important for determining the installed power trigeneration system and structure of energy delivered to the consumer.

5.Conclusions

Simulations of a trigeneration system useful in sizing the east from the point of view so that the energy of the system be better satisfied east energy demand and structure. Energy application is a characterization of variability in Eastern residential energy demand and its structure. From table 5 it is seen as an optimal structure the factors influence showing that *PER* is best when power is required at the level 1 (1kW), heat is delivered at level 3 (15kW), and cold is delivered at level 1 (12kW). *PER* in this case it is influenced favorably by COP$_{fb}$. The first two factors (power supply and heat delivered) were inverse action (Figure 3) and strongly influence the *PER* (Figure 6). From *ANOVA,* this influence is about 23% respectively 63% and amounted to influence more than 86%. These two factors are considered and related *signal* factors through cogeneration index. The result of simulation is a direct and logical one: *the recovered heat* is the key to a trigeneration system, that takes advantage of the system. A converter of heat into the cold by absorption, which has lower value of COP, 0.8 ... 1, can meet demand from the cold (Table 5 and Figure 3) [9]. The influence factors E (heat recovery efficiency) an F (power efficiency) had reduced for selected levels and these factors will be included in the noise factors category [1]. The selected levers for these factors have normal values

for actual equipments. When efficiency increases (from level 1 to level 3) the global influence over *PER* (dB) for E and F factor are decreased. (figure 3 and 4).

The target function variations over simulated experiments and the elemental influence (simple Fourier decomposed) of each factor (figure 5) showed nominal values and maximum interval of influence.

On the basis of actual efficiency of the thermal stage energy conversion (10%....40%), cogeneration index (Y) is lower than 0,4 and that leads to drawings EET next to 1 (figure 7).

6. Abreviations and notations

mCCHP – microtrigenerations (micro Cooling Combined-Heat and Power)
GHG – greenhouse gases
EET - energy efficiency of trigeneration
ηgl overall efficiency of energy production
E - the total electricity generated in the trigeneration system, which is actually delivered to consumers, J
Q - amount of heat produced in the trigeneration system, which is actually delivered to consumers, J
F - amount of cold produced trigeneration system, J
W - total consumption of fuel used to produce energy in the system of trigeneration, J
α$_E$ – power coefficient of trigeneration
E$_b$-quantity of electricity produced in the system under cogeneration and trigeneration actually delivered to consumers, J
α$_Q$ - thermal coefficient of trigeneration
Q$_b$ - amount of heat produced in the system under cogeneration and trigeneration actually delivered to consumers, J
α$_F$ – cooling coefficient of trigeneration
F$_B$ - the amount of cold produced by the trigeneration system under joint production, J
γ$_E$ - index structure of electricity production
γ$_Q$ - index of heat production structure
γ$_F$ - index structure for cold production
W$_{Fcv}$ - fuel used for cooling in plants with compression regime, J
W$_{Fav}$ - fuel used for cooling the plant absorption peak regime, J
β$_b$ - is the index of the cold (base vs peak)
F$_{cb}$ - the amount of cold produced by the plant trigeneration system with compression based cooling system, J
βv – peak cooling index
F$_{cv}$ – cold in trigeneration system by compression refrigeration plant under peak regime, J
E$_{Fv}$ - electricity in the energy system used for freezing in freezer installations peak, J
η$_{SEN}$ - return of the power generation system
Q$_{Fv}$ - heat peak in plants used in plant freezing peak, J
η$_{QFv}$ - return heat production in non-cogeneration system is used for freezing the plant top
COP$_{cv}$ - coefficient of performance of compression cooling plant operating under peak
COP$_{av}$ - coefficient of performance of absorption cooling plant operating under peak
F$_{av}$ - cold in the trigeneration plant by plant absorption cooling system peak, J
E$_{Fb}$- electricity produced in cogeneration facility and used for cooling in a cold storage facility with basic compression, J

Aknowledgements

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