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MODELLING, SIMULATION AND OPTIMIZATION OF SMALL-SCALE CCHP ENERGY SYSTEMS

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Abstract
The article defines and discusses techno-economic models of CCHP system based on a power system with an internal combustion engine or a gas turbine with electric power of 0,2–1 MW including an absorption or vapour-compression refrigeration unit. The thermodynamic, ecological and economical features of the CCHP system under different load situations are analysed in relation to the basic model of energy generation with boiler and vapour-compression refrigeration unit. Based on the data of the equipment manufacturer, functional dependency curves of individual components are created in dependency to the load, which enables the construction of a system model composed of a power system (internal combustion engine or a gas turbine), single-stage or two-stage absorption refrigeration unit and boiler. A program solution has been developed applying the object-oriented programming language *Modelica* that enables the insight into the behaviour and techno-economic validity of usage of the analysed systems in transformable operating conditions. The article examines various energetic models, defining for the influential parameters (electric energy and fuel prices, investment costs and the level of heat recovery) the value of total energy efficiency, the return period on investment costs and the environmental impact concerns.
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Key Words: Small-Scale CCHP, Trigeneration, Optimization, Energy Efficiency, Modelica, SimulationX

1. INTRODUCTION

Greater efficiency of power production plants can be achieved with usage of heating energy of the power system such as internal combustion engine and gas turbine. Heating demands are one way of using the heating energy. This model of power usage is named cogeneration (combined heat and power, CHP) [1], implying simultaneous production of two types of energy (electric and heating energy) in a unique process. The systems in which by the produced electric energy, cogenerate heating energy is used in the process of cooling are called trigeneration facilities (Combined cooling, heating and power, CCHP). CCHP systems are a good way of using the fuel energy in the heating and air-conditioning systems, where the released heating energy is used for heating demands in winter and for the need of the absorption refrigeration unit in the summertime. Electric energy can be utilized for covering the needs of the user or it can be delivered to the external system. The production of electric and heating energy brings up a question of the optimal conducting of the process. The process itself can be conducted following the electric or heating load, or with full electric load. Different strategies of conducting the processes result in different values of system optimization in function of energy efficiency, reduction of greenhouse gases (GHG) and investment payback period.

Different system components of power systems such as internal combustion engine (ICE) and gas turbine (GT), heating energy carriers (steam, hot water) and different refrigeration units (ARU, CRU), lead to different kind of CCHP system. Various systems can have varying energetic and economic efficiency and environmental impact.

Based on the data of the equipment manufacturer for the different components of CCHP systems, it is possible to create models of certain components upon which it is possible to form system models. Developed models enable an insight into the behaviour of CCHP system with variable operating conditions. At the same time, it will enable the choice of optimal configuration of the CCHP system considering the energetic, economic and ecological efficiency in relation to the basic model of heating energy production from its own system, by which the need for electric energy is obtained from the external electrical grid and the cooling energy is obtained through the vapour-compression refrigeration unit (CRU) powered by the external electrical grid.

The problem of techno-economic analysis and optimization of CCHP systems is elaborated on many works [2-10]. These articles present modelling, simulation and optimization of CCHP systems in function of energy efficiency, the decrease of emission of greenhouse gas, and the investment return period based on object-oriented modelling with application of the *Modelica* programming language.

2. PLANT MODELS

Depending on the kind of power system the CCHP system can be divided into a system with an internal combustion engine (ICE) and gas turbine (GT). The focus of this article are the internal combustion engines and gas turbines with the installed power of 0,2–1 MW. This segment corresponds to a small-scale CCHP system. For the purpose of analysis of the CCHP system the energetic models are defined. The models are based on fuel energy transformation. The fuel energy of Q_f transforms into various types of energy such as heating energy Q_h, electric energy Q_e, and cooling energy Q_c. Based on that classification the following system models are formed:

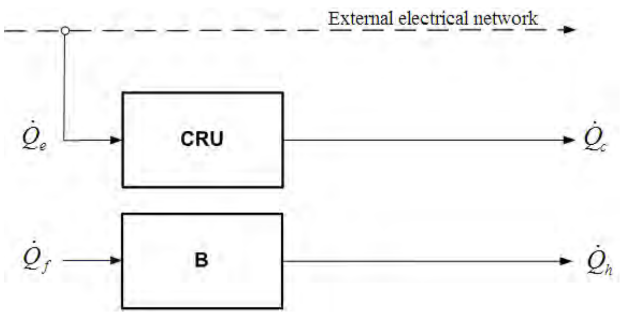

Figure 1: Model M0: B-CRU.

M0: B-CRU, the basic system model shown in Fig. 1 implies the production of heating energy from the boiler (B), while the electric energy demand is generated out of the external electrical grid. The cooling energy is obtained from vapour-compression refrigeration units (CRU) powered by electric energy from the external electrical grid.

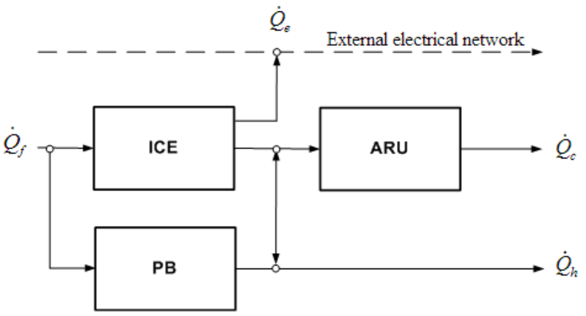

Figure 2: Model M1: ICE-ARU.

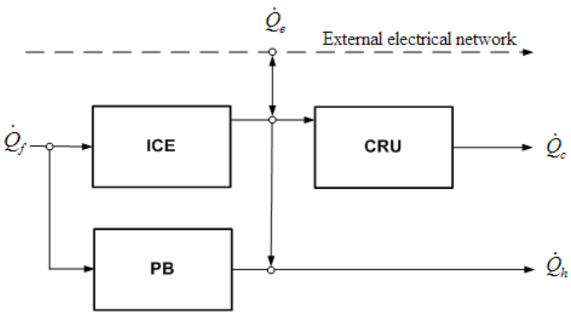

Figure 3: Model M2: ICE-CRU.

M1: ICE-ARU, shown in Fig. 2 implies the production of electric and heating energy from the ICE. The cooling energy is obtained out of ARU powered by the heat from the power system and peak boiler (PB) for covering the peak heating load.

M2: ICE-CRU, shown in Fig.3 implies the production of electric and heating energy from the ICE. The cooling energy is obtained out of CRU powered by self-produced electric energy, or by an external electrical grid.

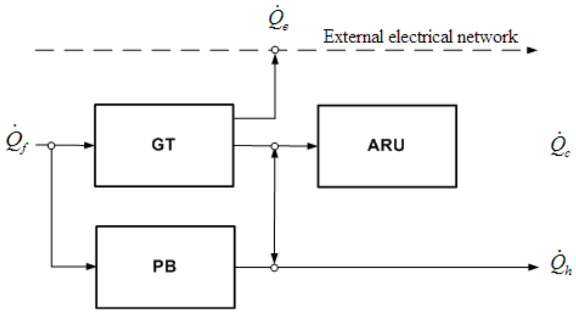

Figure 4: Model M3: GT-ARU.

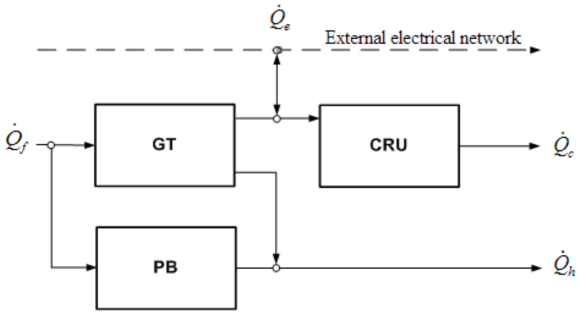

Figure 5: Model M4: GT-CRU.

M3: GT-ARU, shown in Fig. 4 implies the production of electric and heating energy from the GT. The cooling energy is obtained out of ARU powered by the heat from the power system and peak boiler (PB) is used for covering the peak heating load.

M4: GT-CRU, shown in Fig. 5 implies the production of electric energy and heating energy out of GT and peak boiler (PB) for covering the peak heating load. The cooling energy is obtained out of CRU powered by self-produced electric energy or by an external electrical grid.

3. TECHNICAL CHARACTERISTICS

Based on the equipment manufacturer's data the functional dependencies of various sizes are elaborated on behalf of the load rate (X_e, X_h, X_c), which enable the system model production created out of sub-type models: power system (ICE, GT), absorption refrigeration unit (ARU single-stage, ARU two-stage), boiler (B), peak boiler (PB) for covering the peak heating load $\dot{Q}_{h,PB}$. The individual components of the system can be described through static and dynamic characteristics. The mathematic expression for the static characteristics, which can be linear or non-linear, in its general form is $y = f(x)$. The dynamic characteristics indicate a time dependency of the output amount on the time-varying entry amount. This dependency is mathematically presented in the following way $y(t) = f[x(t)]$ for the largest number of practical examples this expression is a differential equation [11].

In a CCHP system this could represent the dynamic characteristic of a heat accumulator that was not used for this variant. In regard to the more elevated speed of the process within the components in comparison to the speed of the process within the system, and in order to simplify the description of the system model, the analysis uses the static characteristics of each individual component of the system, with the condition that the components with an adequate precision present the appearance of a real system.

3.1 Basic system characteristics

Based on the main characteristics it is possible to analyse and compare the energetic efficiency of CCHP systems as it is shown in Eqs. (1-11). The electric degree of fuel energy conversion of CHP system presents the relation of produced electric energy and used fuel energy:

$$\eta_e = \frac{Q_e}{Q_f} \tag{1}$$

Heat degree of fuel energy conversion presents the relation of recovered heat energy and used fuel energy:

$$\eta_h = \frac{Q_h}{Q_f} \tag{2}$$

Total energy efficiency:

$$\eta_{tot} = \frac{Q_e + Q_h}{Q_g} \tag{3}$$

The consumption of fuel energy by produced electric energy unit *HR* (*Heat Rate*):

$$HR = \frac{1}{\eta_e} \tag{4}$$

Immanent energy in fuel Q_f is a product of fuel mass and lower heating value of fuel:

$$Q_f = m_f \, LHV \tag{5}$$

The energy of fuel $\dot{Q}_f$ is a product of mass flow $\dot{m}_f$ and lower heating value of fuel:

$$\dot{Q}_f = \dot{m}_f LHV \tag{6}$$

The rate of electric load X_e is a ratio of generated electric power and maximal electric power of the power system:

$$X_e = \frac{\dot{Q}_e}{\dot{Q}_{e,max}} \tag{7}$$

The rate of heating load X_h is a ratio of cooling power and maximal cooling power of the refrigeration unit:

$$X_e = \frac{\dot{Q}_h}{\dot{Q}_{h,max}} \tag{8}$$

The rate of cooling load X_c is a ratio of cooling power and maximal cooling power of the refrigeration unit:

$$X_c = \frac{\dot{Q}_c}{\dot{Q}_{c,max}} \tag{9}$$

Heating energy Q_h which is usable in the process of cogeneration/trigeneration, can be collected by flue gas recovery and coolant used for cooling the power system:

$$Q_h = Q_{eh} + Q_{ch} \tag{10}$$

The rate of used heating energy towards maximal available heating energy of the power system is called degree of heat recovery:

$$\eta_r = \frac{Q_h}{Q_{h,max}} \tag{11}$$

3.2 Power system characteristics

The article presents the characteristics of power systems supplied by different producers [12-14] in electric power range 0,2 do 1 MW. The elaborated curves are the electric power dependency curves $\dot{Q}_e$ total outcome heating power $\dot{Q}_h$, heating power immanent in exhaust smoke gases $\dot{Q}_{eh}$, heating power of cooling internal combustion engine $\dot{Q}_{ch}$, fuel energy $\dot{Q}_f$, and heat rate *HR* depending on the ratio of electric load X_e and the ambient temperature T_a are described with the polynomial functions Eqs. (12-16):

$$f(X_e) = a_2 X_e^2 + a_1 X_e + a_o \quad (12)$$

$$f(T_a) = b_2 T_a^2 + b_1 T_a + b_o \quad (13)$$

$$f(X_e, T_a) = f(X_e) - \Delta f \quad (14)$$

$$\Delta f = f(100, 15) - f(T_a) \quad (15)$$

where the function f stands for power system characteristics $\dot{Q}_e, \dot{Q}_h, \dot{Q}_{ch}, \dot{Q}_f, HR$ depending on variables X_e and T_a. The equation $f(X_e, T_a)$ presents the value of function depending on the electric load rate and ambient temperature. The equation $f(100, 15)$ presents the value of function for electric load rate of 100 % and ambient temperature of 15 ˚C (ISO standard conditions) because the effect of ambient temperature changes by the engine is negligible. Function f, with two variables describes a curve shifted for value of Δf. Value of Δf stands for the difference of value of two functions by the load of 100 % and various ambient temperatures, namely 15 ˚C and T_a:

$$\Delta f = f(100, 15) - f(100, T_a) \quad (16)$$

Based on equipment manufacturer's data function curves of individual components are created depending on the section of load X_e, X_h *i* X_c and ambient temperature T_a. Function curves for the gas turbine are created depending on the ambient temperature for the location of Zadar and Zagreb [15].

3.3 Refrigeration unit characteristics

The absorption refrigeration unit (ARU) is a key component of the CCHP system. If the CCHP is considered as the system that needs to minimally affect the environment, then for the functioning of that kind of system it is necessary to choose the components that are ecologically acceptable. One solution is to choose the absorption refrigeration unit which functions with a binary composition LiBr-H_2O.

The efficiency of ARU is defined by the coefficient of performance according to:

$$COP_{ARU} = \frac{Q_c}{Q_h} \quad (17)$$

where the cooling energy Q_c, heating energy brought to the heat generator of the absorption refrigerating unit Q_h.

The efficiency of CRU is defined by:

$$COP_{CRU} = \frac{Q_c}{Q_e} \quad (18)$$

where the cooling energy Q_c and electric energy necessary for the function of vapour-compression refrigeration unit Q_e.

In the article the characteristics of refrigeration units manufactured by several producers [16-17] are used. Based on the analysis the curves of the heat ratio of cooling the *COP* are created in relation to load of X_c, which is described by the polynomial function:

$$COP(X_c) = c_3 T_c^3 + c_2 T_c^2 c_1 X_c + c_o \quad (19)$$

3.4 Total energy efficiency

Based on the Eq. (3) it is possible to define the total efficiency of the basic system model (BS), which includes a boiler (B) for the coverage of the heating load, and a vapour-compression refrigeration unit (CRU) for the coverage of the cooling load, powered by electric energy from the external electrical grid, which equals:

$$\eta_{tot} = \frac{Q_e + Q_h}{Q_f} = \frac{Q_{e,CRU} + Q_{h,B}}{\frac{Q_{e,CRU}}{\eta_e} + \frac{Q_{h,B}}{\eta_B}} \tag{20}$$

where $Q_{e,CRU}$ stands for the electric energy from the external electrical grid produced at a power plant with electric grade of conversion η_e while $Q_{h,B}$ stands for heat energy produced in boiler which functions with efficiency of η_B.

The total energy efficiency for the CCHP system, which in its system has an absorption refrigerating unit and a peak boiler (PB) for covering the peak heat level equals:

$$\eta_{tot} = \frac{Q_{e,PS} + Q_{h,PS}\eta_r + Q_{h,PB}}{Q_{f,PS} + \frac{Q_{h,PB}}{\eta_B}} \tag{21}$$

where $Q_{e,PS}$ stands for electric energy produced from the power system. Heating energy is produced in the boiler $Q_{h,PB}$ for covering the peak heating load which functions with the efficiency level η_B The equation $Q_{(t,PS)\eta_r}$ stands for the value of recuperated heating energy from the power system. Based on the Eq. (21) for the CCHP system, which has a vapour-compression refrigeration unit the total energy efficiency level is:

$$\eta_{tot,CCHP} = \frac{Q_{e,PS} - Q_{e,CRU} + Q_{h,PS}\eta_r + Q_{h,PB}}{Q_{f,PS} + \frac{Q_{h,PB}}{\eta_B}} \tag{22}$$

3.5 Ecological characteristics

The emission of greenhouse gases of the BS model system is a sum of emissions created by the burnout of gases in the boiler and emissions created by the production of electric energy in a power plant, which is:

$$GHG_{BS} = GHG_{f,BS} + GHG_{e,BS} \tag{23}$$

The difference of emission of the basic system model (BS) and CCHP model equals:

$$GHG_{CCHP} = GHG_{f,BS} - GHG_{CCHP} \tag{24}$$

The specific decrease of greenhouse gas emission presents a difference of greenhouse gases emission of the basic model (24) on the used fuel energy:

$$\left(\frac{\Delta GHG_{CCHP}}{Q_f}\right) \tag{25}$$

The greenhouse gasses emission of the CCHP system depends on the refrigeration unit (CRU, ARU). For the CCHP system with ARU, the difference of the greenhouse gases emission is:

$$\Delta GHG_{CCHP,ARU} = GHG_{f,BS} + GHG_{e,BS} - GHG_{f,CCHP} + GHG_{e,CCHP} \tag{26}$$

The values of emission factors $f_{GHG,}$ tCO_2/MWh are given in the Table I [18]. The values of the emission factors for the electrical energy depend on the method of production of the energy (hydro power plant, thermal power plant, co-generation). The segment of electrical energy consumed in Croatia, and derived from the emission of CO_2 amounts to only 30 %. In the presented case, the emission factor for electric energy $f_{GHG,e}$ is calculated based on the electric conversion level η_e which equals 35 % for the assumed efficiency of the energy produced in a coal thermal power plant, considering the loss in the electrical grid of 12.7 %.

Table I: Emission factors of the energy-generating products f_{GHG}.

Energy source	t CO_2/MWh
Coal	0.350
Diesel oil	0.266
Natural gas	0.197
Power	1.144

3.6 Economic characteristics

The expense of power system fuel in a continuous time period $t_o - t_1$ is:

$$E_{f,PS} = C_f \int_{to}^{t1} \dot{m}_{f,PS}\, dt \tag{27}$$

where the cost of fuel is C_f, US$/kg. Based on the Eqs. (4-6) the mass flow of power system fuel $\dot{m}_{f,PS}$, kg/s, is calculated by:

$$\dot{m}_{f,PS} = \frac{HR(X_e, T_a)\, \dot{Q}_e(X_e, T_a)}{3600LHV} \tag{28}$$

The expense of electric energy of the vapour-compression refrigerating unit in time period $t_o - t_1$ is calculated by:

$$E_{e,CRU} = C_e \int_{to}^{t1} \frac{\dot{Q}_C}{COP_{CRU} dt} \tag{29}$$

The total expenses of investment and maintenance E_{tot}, US$, is a sum of individual equipment investment expenses and operation and maintenance expenses. These cost rates are calculated based on the price of equipment and installation C_{PS}, C_{RU}, C_{PB}, US$/kW and operating and maintenance costs $C_{O\&M}$, US$/kWh [19], depending on the type of power system (ICE, GT) and its installed electric power $\dot{Q}_e$, kW, type of refrigeration unit (CRU, ARU) installed cooling power of the refrigerating device $\dot{Q}_c$, kW, and installed heating power of boiler $\dot{Q}_h$, kW. The complete expenses of investment and maintenance are calculated by:

$$E_{tot} = E_{I,PS} + E_{I,RU} + E_{I,B} + E_{O\&M} \tag{30}$$

that is:

$$E_{tot} = \dot{Q}_e C_{PS}(\dot{Q}_e) + \dot{Q}_c C_{RU}(\dot{Q}_c) + Q_h\ C_{PB}\,(\dot{Q}_h) + \dot{Q}_e C_{O\&M}(Q_e) \tag{31}$$

The income in certain energetic models is based on the generated income created from the sold electric energy I_e and the income reached by lowering the emission of the greenhouse gases $I_{\Delta SP}$.

Sold electric energy income I_e is:

$$I_e = Q_e C_e \tag{32}$$

The time period income is calculated by the equation:

$$I_e = C_e \int_{to}^{t1} \dot{Q}_e\, dt \tag{33}$$

where C_e, US$/kWh is the cost rate of electric energy depending on tariff system.

The income $I_{\Delta SP}$ realized by lowering the emission of CO_2 equals:

$$I_{\Delta GHG} = \Delta GHG C_{CO_2} \tag{34}$$

where C_{CO_2} is greenhouse gas emission cost C_{CO_2}, US$/t$CO_2$.

The income (I) generated in certain CCHP models, is a profit obtained by decreasing the greenhouse gas emission ΔGHG. The expenses generated in certain models are the fuel expenses E_f, of electric energy equipped from the external electrical grid E_e.

The total profit of the CCHP system in general is:

$$P_{tot} = \left(E_{f,BS} + E_{e,BS}\right) - \left(E_{f,CCHP} - I_{e,CCHP} - I_{\Delta GHG}\right) \tag{35}$$

The payback period for certain energetic model represents the rate of investment costs of certain models in relation to the annual profit that is:

$$BP = \frac{E_{tot}}{P_{tot}} \tag{36}$$

The investment payback period of CCHP model with ARU equals:

$$BP_{CCHP} = \frac{E_{tot}}{\left(E_{f,B} + E_{e,CRU}\right) - \left(E_{f,PS} + E_{f,PB} - I_{e,PS} - I_{\Delta GHG}\right)} \tag{37}$$

The investment payback of CCHP model with CRU equals:

$$BPBP_{CCHP} = \frac{E_{tot}}{E_{f,B} - \left(E_{f,PS} + E_{f,PB} - I_{e,PS} - I_{\Delta GHG}\right)} \tag{38}$$

The calculation of the economic index facility is based on the redemption and costs of electric energy C_e, for fuel costs (diesel oil, natural gas) C_f and the complete investment expenses E_{tot}.

To use the important, still unused cogeneration and trigeneration potential of the renewable energy sources, a legal framework has been established in the Republic of Croatia, as well as the regulation of conditions for gained earning's from these kind of projects, which anticipates stimulating prices for the supplied electrical energy [20-21]. The electric energy needs to be produced within a cogeneration/trigeneration process based on a system defined by the regulation for the acquiring of the status of preferential producer [22]. In this analysis valid tariff values are applied for production, transfer, distribution and electric energy supply, the greenhouse gases emission charges [23] and energy-generating products for cogeneration/trigeneration shown in Table II, together with the investment expenses of internal combustion engine or gas turbine plants [19].

Table II: Energy prices included in calculations.

Energy type	**Mark**	**Unit**	**Price**
Natural gas [24]	$C_{f,G}$	US$/m^3	0.42
Diesel oil [25]	$C_{f,FO}$	US$/l	1.10
Power (HT) [26]	$C_{e,HT}$	US$/kWh	0.14
Power (LT) [26]	$C_{e,LT}$	US$/kWh	0.07

4. OPERATING STRATEGY

The strategies of operating process (OS) are analysed in the article with the goal of defining the optimal power efficiency: Heat load following (HLF), Full power loading (FPL).

The need for heating energy in most cases varies, which has for a consequence the work of power system with a varying load rate. The work of the power system under various loads results in a total efficiency decrease of the power system. In the system with the absorption refrigeration units the heat load monitoring strategy implies the monitoring of the consumption of heat energy Q_h, where the heating energy is used for production of cooling energy Q_c, and in this case the heat load monitoring strategy indirectly presents the cooling load monitoring Q_c.

In the CCHP system with a vapour-compression refrigeration unit the heat load monitoring strategy implies the cooling load monitoring, which in the end implies the electric load monitoring Q_e needed for the operation of the vapour-compression refrigeration unit. The strategy for full electrical power loading implies the maximized work of a power generator for the maximal production electric energy.

5. COMPUTER MODEL OF CCHP SYSTEMS

Analysing the existing program solution [25] and noting the disadvantages and sensitivities in varying operating conditions of the facility, in this article, for the purpose of simulation and optimization of the CCHP system, a personal program solution called the CCHP_mo was developed applying the object-oriented programming language *Modelica* [27-30]. *Modelica* is an object-oriented programming language used for the description of physical models and its components, adequate for description of complex physical systems from domains such as mechanics, electrical engineering, electronics, hydraulics and thermodynamics.

Fig. 6 indicates the changes in values of the variables of the model system, which change continuously or discretely in relation to time changes. Fig. 7 shows a model of a system with inbound (endogen) variables, internal variables, and the connections between the individual elements of the system and the outbound (exogen) variables of the system. In this analysis the elements of the system represent the objects of individual system components [31]. Each object is described through equations. The equations can be algebraic or differential.

The developed CCHP program solution is purposed for a dynamic simulation and the optimization of a three-generational system with discreet sizes, in accordance to which the time frame can be selected to be a second, an hour, a day, a month or a year. With the selection of smaller time steps a more real system simulation is achieved.

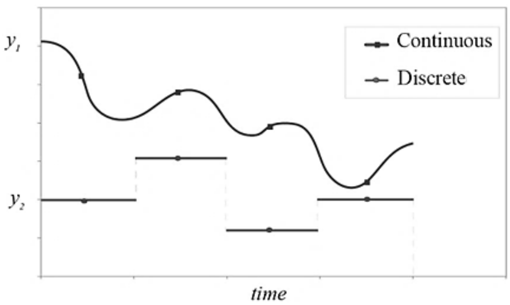

Figure 6: Showing continuous and discrete time changes [29].

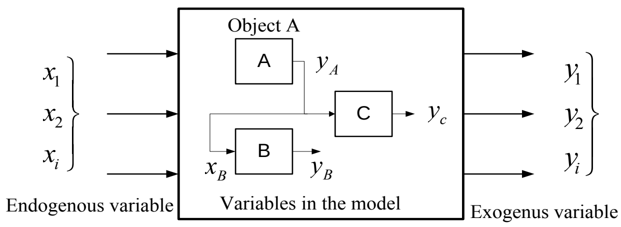

Figure 7: System model schematics.

6. OPTIMIZATION

The optimization process retrieve's the most favourable solution of a certain issue. It gives the answer to the question what needs to be done, with the goal of reaching the best solution, as opposed to the simulation, which is a process of imitating the system under implied conditions [15].

In the article, for the needs of optimization of the CCHP energy systems, the goal function is set with the shortest payback period *PBP*, highest total energy efficiency η_{tot} and highest specific greenhouse gases emission decrease ($\Delta GHG/Q_f$) is:

$$U = f\left[(PBP)_{min},\ (\eta_{tot})_{max},\left(\frac{\Delta GHG}{Q_f}\right)_{max}\right] \tag{39}$$

The searching process for the optimum model of the CCHP energy system shown in Fig. 8 is based on the input values of the outer load ($\dot{Q}_h$, $\dot{Q}_c$) the set limits such as the minimal electrical load ratio $X_{e,min}$ and the choice of process operation strategies (HLF, FPL). Based on the mathematical model of the system the simulation is performed after which the goal function parameters are memorized and the simulation process is continued on the next model. The optimization process is conducted on the basis of the saved data provided by the simulation, more precisely the search method [32] is used in order to obtain the optimal solution for the CCHP power system for the given external load and set restrictions.

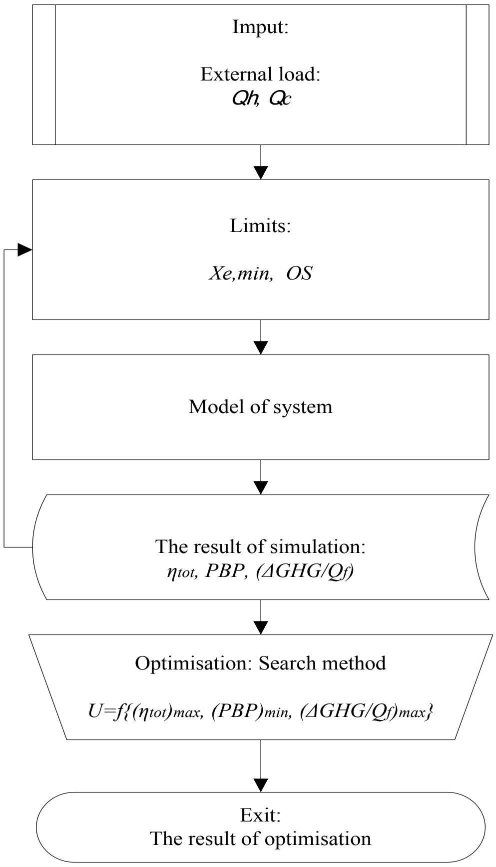

Figure 8: Flowchart of simulation and optimization.

7. CASE STUDY

Investment expenses, fuel and electricity costs and seminal costs of electrical energy produced out of renewable resources and cogeneration affect the choice of optimal power system and refrigerating unit with various loads and operating strategy processes. In the recovery phase of the heating and cooling system based on the BS model it is required to define the optimal alternative CCHP system. The alternative solution has to satisfy the adequacy of system application for the period of 5,110 hours corresponding to the annual operation of the system during the higher-tariff period.

Based on the elaborated CCHP_mo program solution a techno-economic analysis was conducted together with the optimization process of the small-scale CCHP system for the location of Zadar/Croatia and the assumed object size of total 10,000 m^2. The values of heating and cooling load shown in Fig. 8 used as input values in the CCHP_mo program solution were obtained based on the values out of Table III and the application of the program solution [18] with its output values shown in Fig. 9. In the analysis the value of the heating energy was additionally increased for 10 % due to the needs of production of hot water use.

Table III: The values of the energy load.

	Mark	Units	Value
Object size	A	m^2	10,000
Unit heating loss (heating)	$\dot{q}_h$	W/m^2	70
Unit heating profit (cooling)	$\dot{q}_c$	W/m^2	40

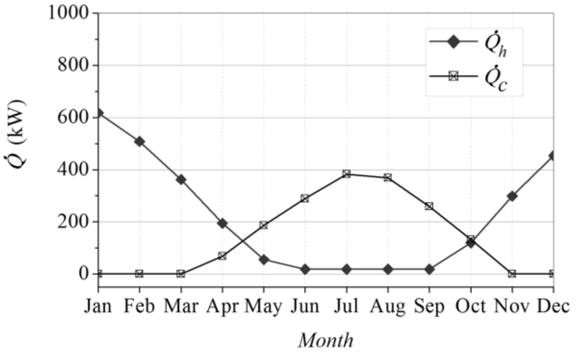

Figure 8: External cooling and heating loads.

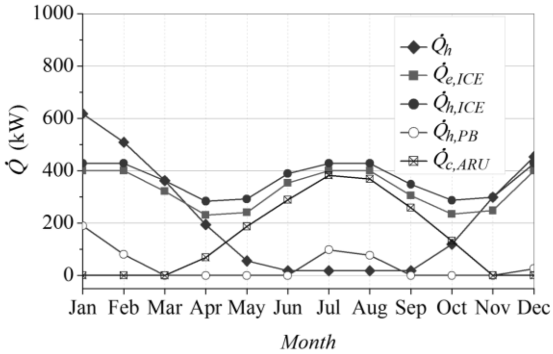

Figure 9: Small-scale CCHP loads, M1: ICE-ARU.

8. RESULTS OF TECHNO-ECONOMIC ANALYSIS

From the optimization process results (see Fig. 10) it is possible to draw a conclusion that the power system with the internal combustion engine and with the absorption refrigeration unit is optimal. That system results in the shortest investment payback period in the case of a full electric energy load strategy (M1: ICE-ARU, FPO). During the conducting of a strategy operation and following the heating load (M1: ICE-ARU, HLF) it shows a slightly longer investment payback period for the highest total energy efficiency level η_{tot} and highest specific decrease of greenhouse gases emission *(ΔGHG/Q_f)*.

Table IV: Technical characteristics of optimized system.

	Mark	Unit	M1: ICE-ARU	M2: ICE-CRU	M3: GT-ARU	M4: GT-CRU
Power system	*PS*	-	ICE	ICE	GT	GT
Fuel type	*f*	-	NG	NG	NG	NG
Availability	τ	h/year	5,110	5,110	5,110	5,110
Installed electrical power	$\dot{Q}_e$	kW	400	400	400	400
Minimal ratio of the electric load	$X_{e,min}$	%	50	50	50	50
Type	-	-	TCG 2016V08C	TCG 2016V08C	Capstone C400	Capstone C400
Heat rate	*HR*	kJ/kWh	8,514	8,514	9,010	9,010
Efficiency of electric energy production	η_e	%	42.3	42.3	33.0	33.0
Heat power	$\dot{Q}_h$	kW	428	428	423	423
Heat power of peak boiler	$\dot{Q}_{h,PB}$	kW	190	194	195	195
Refrigeration unit	*RU*	-	ARU	CRU	ARU	CRU
ARU type	*st*	-	single-stage	-	two-stage	-
Coefficient of performance	*COP*	-	0.76	4.0	1.41	4.0

Table V: The results of techno-economic analysis optimal small-scale CCHP, ICE.

	Mark	Unit	M1: ICE-ARU	M1: ICE-ARU	M2: ICE-KRU	M2: ICE-KRU
Operation strategy	*OS*	-	HLF	FPL	HLF	FPL
Electricity exported	Q_e	MWh	1,674	2,044	567	1,863
Fuel consumption	Q_f	MWh	4,283	5,071	2,160	4,981
Electricity export income	I_e	US$	249,145	304,221	84,341	277,297
GHG reduction income	$I_{\Delta SP}$	US$	5,421	6,299	2,683	5,679
Fuel expense	E_f	US$	207,458	245,783	101,141	240,814
Total expense	E_{tot}	US$	834,592	834,592	838,494	838,417
Payback period	*PBP*	year	3.6	3.4	5.1	3.7
Total energy efficiency	η_{tot}	%	87.5	81.2	78.8	60.2
Specific GHG reduction	$\Delta SP/Q_g$	tCO_2/MWh	0.4	0.4	0.4	0.3

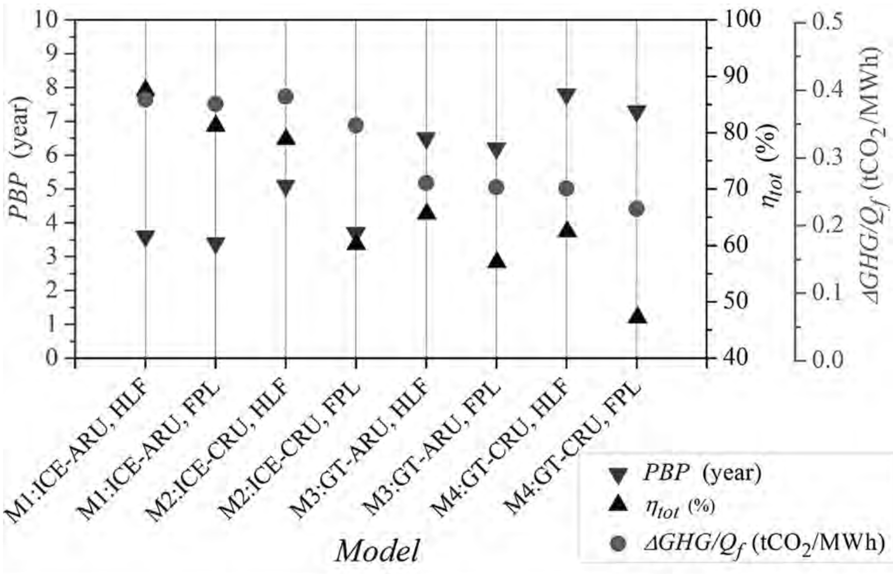

Figure 10: The results of techno-economic analysis small-scale CCHP.

The selection of the optimal solution choice with different strategies of process conducting does not give a single-valued solution. The methodology of choosing the optimal solution leads to two opposed views on the goal of optimization in the selection of the final solution. The first one is concerned with the system operation with the highest total energy efficiency level, whereas the second is a system with the shortest investment payback period. From the investor's point of view, whose goal is choosing the system with highest cost effectiveness, the system with shorter investment payback period is the optimal one (M1: ICE-ARU, FPO). From the techno-economic adequacy point of view the optimal system is the one with the highest total efficiency (M1: ICE-ARU, HLF). To define the optimal solution between those two operating process strategies of the same model it is necessary to express the negative environmental effects in monetary values of the techno-economic model, in other words a legal framework is needed as the basis for penalizing the system with the lower heat recovery level, that is with lower fuel energy efficiency level.

9. CONCLUSION

Techno-economic optimization method of the CCHP system is developed in the function of electric, heating and cooling energy with recovery of the outgoing heat of smoke gases with application of the gas turbine and internal combustion engine as a power system, and an absorption and vapour-compression refrigeration unit. The method is elaborated using the *Modelica* programming language for modelling complex physical systems such as CCHP systems. Based on the elaborated methods, and with the goal of finding the optimal solutions for the CCHP energy system, a program solution CCHP_mo for simulation and optimization is developed implementing the object-oriented programming language *Modelica*. The elaborated CCHP_mo program solution enables a fast insight into behaviour and techno-economic size of CCHP systems in stationary and variable operation conditions.

Applying the CCHP system with the absorption refrigerating unit it is possible to increase the number of operation hours for a facility, and in this way decrease the negative effects of a small number of work hours of the CHP system, which significantly affects the investment payback period. The conducting of the process is important for the system optimization. The conducting of the process strategy of following the heating load shows an advantage in relation to the strategy of full electric energy load. The method for choosing the optimal strategy of conducting the process of CCHP systems is elaborated with regard to the techno-economic and ecological conditions. The results of CCHP system optimization in the range of electric power 0,2–1 MW, shows that in conditions of combined production of heating and cooling energy, the system operated with internal combustion engine and single-stage absorption refrigeration unit presents the optimal solution. That system has an increased efficiency level, increased reduction of greenhouse gases emission, and shorter investment payback period comparing to a power system with a gas turbine.

REFERENCES

[1] ASHRAE (2008). HVAC Systems and Equipment – Chapter 7: Combined Heat and Power Systems, *2008 ASHRAE Handbook,* American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. (ASHRAE), Atlanta

[2] Liu, M.; Shi, Y.; Fang, F. (2014). Combined cooling, heating and power systems: A survey, *Renewable and Sustainable Energy Reviews*, Vol. 35, 1-22, doi:10.1016/j.rser.2014.03.054

[3] Xu, D.; Qu, M. (2013). Energy, environmental, and economic evaluation of a CCHP system for a data center based on operational data, *Energy and Buildings*, Vol. 67, 176-186, doi:10.1016/j.enbuild.2013.08.021

[4] Lozano, M. A.; Ramos, J. C.; Serra, L. M. (2010). Cost optimization of the design of CHCP (combined heat, cooling and power) systems under legal constraints, *Energy*, Vol. 35, No. 2, 794-805, doi:10.1016/j.energy.2009.08.022

[5] Kavvadias, K. C.; Tosios, A. P.; Maroulis, Z. B. (2010). Design of a combined heating, cooling and power system: Sizing, operation strategy selection and parametric analysis, *Energy Conversion and Management*, Vol. 51, No. 4, 833-845, doi:10.1016/j.enconman.2009.11.019

[6] Li, L.; Mu, H.; Gao, W.; Li, M. (2014). Optimization and analysis of CCHP system based on energy loads coupling of residential and office buildings, *Applied Energy*, Vol. 136, 206-216 doi:10.1016/j.apenergy.2014.09.020

[7] Wu, J.-Y.; Wang, J.-L.; Li, S.; (2012). Multi-objective optimal operation strategy study of micro-CCHP system, *Energy*, Vol. 48, No. 1, 472-483 doi:10.1016/j.energy.2012.10.013

[8] Han, G.; You, S.; Ye, T.; Sun, P.; Zhang, H.(2014). Analysis of combined cooling, heating, and power systems under a compromised electric–thermal load strategy, *Energy and Buildings*, Vol. 84, 586-594, doi:10.1016/j.enbuild.2014.09.006

[9] Huicochea, A.; Rivera, W.; Gutiérrez-Urueta, G.; Bruno, J. C.; Coronas, A. (2011). Thermodynamic analysis of a trigeneration system consisting of a micro gas turbine and a double

effect absorption chiller, *Applied Thermal Engineering*, Vol. 31, No. 16, 3347-3353, doi:10.1016/j.applthermaleng.2011.06.016
[10] Jayasekara, S.; Halgamuge, S. K.; Attalage, R. A.; Rajarathne, R. (2014). Optimum sizing and tracking of combined cooling heating and power systems for bulk energy consumers, *Applied Energy*, Vol. 118, 124-134, doi:10.1016/j.apenergy.2013.12.040
[11] Buyruk, E.; Karabulut, K. (2013). Numerical investigation into heat transfer for three-dimensional plate fin heat exchangers with fins placed perpendicular to flow, *Transactions of FAMENA*, Vol. 37, No. 2, 87-102
[12] MWM – Energy, Efficiency, Environment, from *http://www.mwm.net*, accessed on 07-02-2015
[13] MAN – Products & Services, from *http://www.man.eu*, accessed on 07-02-2015
[14] Capstone turbine corporation, from *http://www.capstoneturbine.com*, accessed on 07-02-2015
[15] Wolfram Research – Current & Historical Weather Data, from *http://www.wolfram.com*, accessed on 17-03-2015
[16] Johnson Controls – York Process Systems, from *http://www.johnsoncontrols.com*, accessed on 07-02-2015
[17] Broad Group, from *http://www.broad.com*, accessed on 07-02-2015
[18] RETScreen International – Empowering Cleaner Energy Decisions (Natural Resources Canada), from *http://www.retscreen.net*, accessed on 15-01-2015
[19] Darrow, K.; Tidball, R.; Wang, J.; Hampson, A. (2015). *Catalog of CHP technologies*, ICF Int., funding: U.S. Environmental Protection Agency, Combined Heat and Power Partnership, U. S. Dept. of Energy
[20] EUR-Lex. Directive 2004/8/EC of the European Parliament and of the Council of 11 February 2004 on the promotion of cogeneration based on a useful heat demand in the internal energy market and amending Directive 92/42/EEC, 2004, from *http://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:32004L0008*, accessed on 05-01-2015
[21] IUS-Info. (2012). Energy Act (in Croatian), NN 120-2583
[22] HROTE – Croatian Energy Market Operator. (2012). The tariff system for electric energy produced from renewable sources and cogeneration (in Croatian), NN 63/2012, from *http://files.hrote.hr/files/PDF/Dokumenti/Obnovlj.%20izvori%20energije%20i%20kog/Tarifni_sustav_za_proizvodnju_EE_iz_OIEK_NN_63_12.pdf*, accessed on 05-01-2015
[23] IUS-Info. (2009). Regulation on unit charges, corrective coefficients, criterions and standards for determining the charge for emissions of carbon dioxide into the environment (in Croatian), NN 48-1069
[24] Energo, Production and distribution of gas and heating energy, from *http:/www.energo.hr*, accessed on 17-01-2015
[25] INA Group, from *http://www.ina.hr*, accessed on 17-01-2015
[26] HROTE – Croatian Energy Market Operator, from *http://www.hrote.hr*, accessed on 17-01-2015
[27] Modelica Association – Modelica, from *http://www.modelica.com*, accessed on 15-01-2015
[28] Tiller, M. (2001). *Introduction to Physical Modeling with Modelica*, Kluwer Academic Publishers, Boston
[29] Fritzson, P. (2011*). Introduction to Modeling and Simulation of Technical and Physical Systems with Modelica*, Wiley, Hoboken, IEEE Press, Piscataway
[30] ITI – SimulationX, from *http://www.iti.de*, accessed on 15-01-2015
[31] Sterman, J. D. (1991). A Skeptic's Guide to Computer Models, Barney, G. O.; Kreutzer, W. B.; Garrett, M. J. (Eds.). *Managing a Nation: The Microcomputer Software Catalog*, Westview Press, Boulder, 209-229
[32] Jaluria, Y. (2008). *Design and Optimization of Thermal Systems*, CRC Press, Taylor & Francis Group, Boca Raton