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Optimization of Small-Scale Trigeneration Systems in Terms of Levelized Total Costs and Carbon Tax Using a Matrix Modeling Approach

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A B S T R A C T

Combined Heat and Power (CHP) systems have increasingly drawn attention in recent years due to their higher efficiency and lower Greenhouse Gas (GHG) emission. Input-output matrix modeling was considered here as one of the efficient approaches for optimizing these energy networks. In this approach, power flow and energy conversion through plant components were modeled by an overall efficiency matrix including dispatch factors and plant component efficiencies. The purpose of this paper is to propose a modification of the objective function presented in some previous studies. This procedure was performed by adding the parameters of plant component lifetime and environmental costs to the objective function. Thus, the optimization problem was formulated by minimizing the total system levelized cost instead of simply hourly energy cost. The study results revealed that producing the electricity by the trigeneration system led to achieving 1256 MWh annual electricity savings that otherwise must be purchased from the grid. The results also showed a significant reduction in annual CO_2 emissions (703.31 tons per year). Furthermore, if the price of purchasing CHP electricity was considered three times more than the current ones, payback times would be less than 5 years.

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1. INTRODUCTION

Previous studies demonstrated that when primary energy is converted into electricity, more than half of the energy is lost as waste heat [1]. This amount of energy can be used to meet a portion of demands for heating in residential and commercial buildings. In addition, Transmission and Distribution (T&D) of the electricity from central power plants lead to excess losses of net generation (it is around 9 %) [2]. A significant part of total primary energy is consumed in cities [3]. Distributed generation is one of the strategies to meet the rising energy demand [4]. Locally collected and locally utilized renewable energies can significantly improve the local economy if they are properly planned and implemented [5].

CHP systems with district heating offer an alternative energy production mechanism with higher efficiency and greater energy security than many conventional alternatives [6]. When cooling is generated by waste heat in a CHP plant, a process known either as trigeneration (3 products from one fuel source) or Combined Cooling, Heating and Power (CCHP) can result in higher heat recovery and shorter payback time than comparable cogeneration approaches [7].

According to IEA, a significant source of CO_2 emissions is buildings that account for about one-third of global final energy consumption. The International Energy Administration has proposed cogeneration as part of a strategy for reducing GHG emissions [8].

In [9], the effect of micro CHP systems on the GHG emissions in the domestic sector was evaluated. In the optimized case, level of CO_2 emissions was substantially lower than that in the reference case, i.e., with a separate generation of heat and electricity from the grid. In [10], the results demonstrated that the utilization of a CHP system led to the reduction of CO_2, NO_x, and CH_4 emissions in all of the studied buildings.

The concept of cogeneration can be extended to include more outputs. Increase in use of distributed generation technologies has led to the emergence of the terms like “multiple energy carrier systems” [11]. These systems are known as Multi-Source Multi-Product (MSMP) energy systems. The term ‘hybrid energy system’ is used for introducing an energy system in which its inputs include two or more energy sources. This type of system leads to the improvement of system efficiency [12].

Fossil fuels or renewable energies can be considered as inputs to MSMP systems. The system inputs comprise coal, biomass, natural gas and nuclear, and solar or geothermal energy. Outputs may also include electricity, heating/cooling power, and so on [13]. In [14], authors studied the chemical conversion, energy utilization, and pollution reductions in Multifunctional Energy Systems (MESs). In [15], an appropriate example was developed to present the advantages of hybrid energy systems in the building sector.

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There are several approaches to formulating these types of systems including "the so-called hybrid energy hubs" [16]. Finally, in [17], the term "multi-objective systems" was employed that refers to the energy hub concept. The definitions begin by characterizing the energy hub approach, which can provide an interface among energy producers, consumers, and transportation sectors [8]. In other words, energy hub introduces an interface between the energy networks and loads [19]. In terms of the system, an energy hub represents some functions for conversion and storage of multiple energy carriers. The energy hub approach was developed as part of the project "Vision of Future Energy Networks - VoFEN" at ETH Zurich. VoFEN project aimed to organize the optimum configuration of energy systems in the future [20]. An energy hub is considered as a unit for conversion and, sometimes, it represents storage of multiple energy carriers [21].

The energy hub is defined by its conversion matrix. Indeed, it is a matrix that represents the conversion efficiency of one input into one output. In [22], an operational analysis was conducted for multifunctional energy systems at a district level. The analysis consists of electricity, heat, and gas distribution networks. In this case, an efficiency matrix was utilized to model their interrelationships.

In [23], the matrix modeling method was formulated based on the energy hub concept. The authors modeled energy flows among trigeneration components through construction of the overall efficiency matrix, which represents the whole plant. This matrix formulation suggests an appropriate model for optimizing the operational cogeneration problems. An optimal strategy was determined for a case study and its objective function was to minimize the hourly energy cost. The achieved results demonstrate the effectiveness of the proposed matrix formulation.

In the optimization approach proposed by [23], the minimization of hourly energy costs was an operational optimization criterion. However, the investment costs were not considered for the equipment in the objective function. This simplification leads to less accurate solutions, especially in the case of hybrid networks. Given that energy costs of renewable energies such as solar and wind are zero, ignoring their convertor investment costs will make them the optimum choice among other forms of energies. The innovation of this paper is to propose a modification to the objective function presented in some previous studies. In this paper, the minimization problem was redefined by adding the investment costs of subsystems and applying levelized cost analysis. This procedure leads to the improvement of accuracy, which is necessary to see the coupling between the initial costs of equipment and long-term economic performance and quantify long-term outlook. Finally, environmental cost was added to the total cost by assigning the carbon tax to the GHG emissions. It was accomplished to quantify the benefits of reducing GHG emission, reached by applying the trigeneration system. Thus, the optimization problem was formulated by minimizing the total system levelized cost instead of simply hourly energy cost. Applying the optimal strategy determines which components to use per hour and how much each of these components is used to supply electricity, heating, and cooling.

2. METHOD

2.1. Matrix modeling procedure in trigeneration systems

A detailed technical, economic, and environmental evaluation is required for successful implementation of cogeneration projects [24].

In the MSMP energy system, matrix modeling defines the system using an overall efficiency matrix, which is composed of the conversion efficiencies of the inputs to outputs. Inputs and outputs were presented for the system in the matrix form. All of the elements in the input and output matrices are considered with the same order. In this study, energy vectors include fuel (F, input), electricity (E, both input from the grid and output to the load), heat (Q, output), and cooling (C, output). Then, the input and output vectors are considered as follows:

$$\mathbf{V_i} = [F_i, E_i, Q_i, C_i]^T \quad (1)$$

$$\mathbf{V_o} = [F_o, E_o, Q_o, C_o]^T \quad (2)$$

Similar to the study presented in [23], a trigeneration system was considered with the following specifications: 3 micro gas turbines as the prime mover, 6 auxiliary boiler units fueled by natural gas and sized to the maximum heating load, 2 water absorption units, and 2 compression electric chiller units. Figure 1 shows the links between the system components:

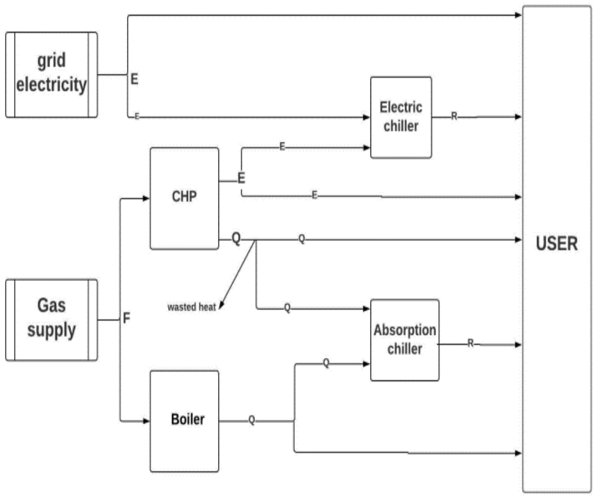


Figure 1. Input-output diagram of the case study trigeneration system.

First, an efficiency matrix is individually constructed for each converter [23]. Afterward, the interconnection matrices are built and dispatch factors are also considered. Dispatch factors are used when an input goes to more than one component. Dispatch factor can take a value between 0 and 1 [4].

In this study, the interconnection matrix is a diagonal 4×4 matrix that represents the connections between the plant components including inputs and outputs. For example, the $T^{M,\ N}$ interconnection matrix defines the direct connection between component M and component N. In the interconnection matrix, the elements in the main diagonal are either unity or dispatch factors. This is dependent on the ratio of the input energy for a given component. For the understudied system, the elements in the main diagonal of the interconnection matrix are denoted by D as follows:

$$\mathbf{D}^{O,B} = [0, 0, \alpha_{QQ}^{B}, 0] \quad (3)$$

$$\mathbf{D}^{O,GT} = [0, \alpha_{EE}^{GT}, \alpha_{QQ}^{GT}, 0] \quad (4)$$

$$\mathbf{D}^{O,ECh} = [0, 0, 0, 1] \quad (5)$$

$$\mathbf{D}^{O,ACh} = [0, 0, 0, 1] \quad (6)$$

$$\mathbf{D}^{O,GE} = [0, \alpha_{EE}^{GE}, 0, 0] \quad (7)$$

$$\mathbf{D}^{B,I} = [1- \alpha_{YF}^{GS}, 0, 0, 0] \quad (8)$$

$$\mathbf{D}^{GT,I} = [\alpha_{YF}^{GS}, 0, 0, 0] \quad (9)$$

$$\mathbf{D}^{ECh,GT} = [0, 1- \alpha_{EE}^{GT}, 0, 0] \quad (10)$$

$$\mathbf{D}^{ECh,I} = [0, 1- \alpha_{EE}^{GE}, 0, 0] \quad (11)$$

$$\mathbf{D}^{ACh,B} = [0, 0, 1- \alpha_{QQ}^{B}, 0] \quad (12)$$

$$\mathbf{D}^{ACh, GT} = [0, 0, \alpha_{CQ}^{GT}, 0] \quad (13)$$

The general approach to constructing the overall efficiency matrix is as follows: there is a backward movement from the outputs to the inputs. This process initiates by the first output and moves backward to the input. We should follow the path by multiplying each individual component efficiency matrix by its relevant interconnection matrix. There are subdivisions and junctions on the path. In a subdivision, the input from one component is split into two or more components or loads. In a junction, the input energy to one component stems from multiple components. If a junction is found in an output toward input path, we should summate the terms found in the paths from the junction point to the inputs. By getting at the input, the scanning procedure will restart from the last saved junction point. When all of the junctions are traced, the procedure is completed.

In the above procedure, the final expression will be configured for the overall efficiency matrix of the system as follows:

$$\mathbf{R} = \mathbf{T}^{O,i}\,\mathbf{I} + \mathbf{T}^{O,B}\mathbf{R}^{B}\,\mathbf{T}^{B,i}\,\mathbf{I} + \mathbf{T}^{O,GT}\mathbf{R}^{GT}\,\mathbf{T}^{GT,i}\,\mathbf{I} + \mathbf{T}^{O,ECh}\mathbf{R}^{ECh}\,(\mathbf{T}^{ECh,i}\,\mathbf{I} + \mathbf{T}^{ECh,GT}\mathbf{R}^{GT}\,\mathbf{T}^{GT,i}\,\mathbf{I}) + \mathbf{T}^{O,ACh}\mathbf{R}^{Ach}\,(\mathbf{T}^{ACh,B}\mathbf{R}^{B}\,\mathbf{T}^{B,i}\,\mathbf{I} + \mathbf{T}^{ACh,GT}\mathbf{R}^{GT}\,\mathbf{T}^{GT,i}\,\mathbf{I}) \quad (14)$$

In this trigeneration system, the efficiency entries are assumed to be constant for each component (its rated values) [23].

2.2. Formulation of trigeneration optimization problem

Overall trigeneration system optimization is involved in optimizing dispatch factors, energy sources, and components capacities. To minimize the total costs, the outcome would be to meet the building energy demands by purchasing a rational amount of electricity and fuel to run the trigeneration system.

The energy demand vector (V_d), the amounts of input energies, and the share of energy flows correspond to different ratios of dispatch factors. When these dispatch factors are multiplied by the component efficiencies, the elements will be constructed for the overall efficiency matrix. Given that the dispatch factors are dependent variables, they can be reduced to independent ones. The obtained degrees of freedom provide the basis for developing a nonlinear optimization problem. Thus, the independent dispatch factor vector is presented as follows:

$$\boldsymbol{\alpha} = [\alpha_{EE}^{GE}, \alpha_{YF}^{GS}, \alpha_{EE}^{GT}, \alpha_{QQ}^{GT}, \alpha_{CQ}^{GT}, \alpha_{QQ}^{B}]^{T} \quad (15)$$

2.2.1. Objective function

To evaluate an energy system, the most important issues comprise energy demands, total cost, and GHG emissions [25]. Environmental costs can be considered as a cost category [26]. GHG emissions are estimated by multiplying either the fuel consumption or landfill gas potential by the GHG emission factor. In some jurisdictions, GHG emission factors might be calculated for electricity generation through an aggregate basis to facilitate the preparation of GHG calculations. This value is multiplied by T&D losses (%) and GHG emission factor for the base case electricity system. It is performed to calculate the GHG emissions associated with the T&D losses for the proposed case power system [27].

Here, emission costs of natural gas and the central electricity mix are estimated through the following Equation [27]:

$$C_{emiss} = (GEF_F\, F + GEF_E\, E)\, Ctx \quad (16)$$

Finally the objective function can be rewritten as follows:

$$\text{Total cost} = C_{inv}^{GT} + C_{inv}^{B} + C_{inv}^{ACh} + C_{inv}^{ECh} + C_{O\&M}^{GT} + C_{O\&M}^{B} + C_{O\&M}^{ACh} + C_{O\&M}^{ECh} + C_{F}^{GS}Fi + C_{Ei}^{GE}Ei\_C_{Eo}^{GE}(Ei\_Eo) + C_{emiss} \quad (17)$$

where $C_{inv}^{GT}, C_{inv}^{B}, C_{inv}^{ACh}$, and C_{inv}^{ECh} are the hourly equivalent investment costs for each sub-system of producers, primary converters, and secondary converters, respectively. $C_{O\&M}^{GT}, C_{O\&M}^{B}, C_{O\&M}^{ACh}$, and $C_{O\&M}^{ECh}$ are the hourly equivalent operation and maintenance costs for each sub-system that regularly occur and they are considered for preserving the mentioned sub-system. C_{F}^{GS} and C_{Ei}^{GE} are the hourly prices of purchasing input energies (natural gas and grid electricity). C_{Eo}^{GE} is the hourly price of selling the surplus electricity to the grid. Cemiss is GHG emission cost of consuming input energies. Here, this study has addressed the impact of such tax on the economics of the studied trigeneration system.

As the series of costs are not uniform, the levelized value should be computed. Therefore, it is essential to apply the capital recovery factor to estimate all of the costs for each year throughout the entire economic life of the plant. It is assumed that all prices are escalated at the same rate throughout the project life cycle. The hourly capital recovery factor can be calculated through the following equation [28]:

$$CRF = \frac{1}{8760}\left(\frac{I(1+I)^n}{(1+I)^n-1}\right) \quad (18)$$

where I is the interest rate and n is the lifetime (Yr) of each sub-system.

Table 1 summarizes the rated capacities of the used relevant equipment as well as their investment and operation costs. Similar to [23], the current trigeneration system consists of three micro gas turbines of 100 kW_E and six auxiliary boilers of 150 kWt capacity. Two chillers are also sized to the cooling load peak.

Table 1. The rated capacities of the used relevant equipment.

Equipment	Capacity (kW)	Efficiency (%)	Investment Cost (€/kW)	Annual cost (€/kWh)	Life cycle (yr)
Trigeneration system (3 micro-turbines)	300 (electrical) 450 (thermal)	$\eta_E = 0.3$ $\eta_Q = 0.45$	2000	0.02	15
Boiler (6 units)	900	$\eta_t = 0.8$	200	0.01	25
Electric Chiller (2 units)	400	$COP_{ECh}=3$	400	0.04	25
Absorption Chiller (2 units)	400	$COP_{ACh} = 0.7$	250	0.02	15

2.2.2. Constraints

The equality constraints express energy balances for each energy carrier at the inputs and outputs of plant components and the whole system. Therefore, we have:

$$\mathbf{R}^X\mathbf{V}_i^X - \mathbf{V}_o^X = 0 \quad \text{for } X \in \mathbf{X} \tag{19}$$

$$\mathbf{RV}_i - \mathbf{V}_o = \mathbf{0} \tag{20}$$

$$E_i \,.\, (E_o - E_d) = 0 \tag{21}$$

Eq. (21) suggests a condition in which electricity is either sold to or bought from the grid. It is associated with the inequality constraint Ed≤ Eo. When one energy carrier is split into a number of components at a subdivision, the input energy of each component represents the ratio of total energy flow. Thus, dispatch factors should be greater than or equal to zero and no more than one (Eqs. 22 and 23). The sum of all the divided energy carriers must be identical to the initial energy carrier. Furthermore, input fuel, purchased electricity from the grid, and electricity sold back to the grid must be positive.

$$-\boldsymbol{\alpha} \le 0 \tag{22}$$

$$\boldsymbol{\alpha} - 1 \le 0 \tag{23}$$

$$-E_i \le 0 \tag{24}$$

$$-F_i \le 0 \tag{25}$$

Each plant convertor may have thresholds such that the convertor would be cut down for outputs below a certain threshold. The lower bounds are set to zero for boilers, electric chillers, and absorption chillers. For the micro gas turbine, the technical lower limit is equal to 50 % of its rated output. The GT is switched off below this threshold. The maximum limits of the equipment are equal to the rated capacities of them.

According to the output upper and lower bounds for the components, we can have the corresponding inequality constraints as follows:

$$\mathbf{RV}_i^X - \bar{\mathbf{V}}^X \le 0 \quad \text{for } X \in \mathbf{X} \tag{26}$$

$$\underline{\mathbf{V}}^X - \mathbf{R}^X\mathbf{V}_i^X \le 0 \quad \text{for } X \in \mathbf{X} \tag{27}$$

2.2.3. Optimization algorithm

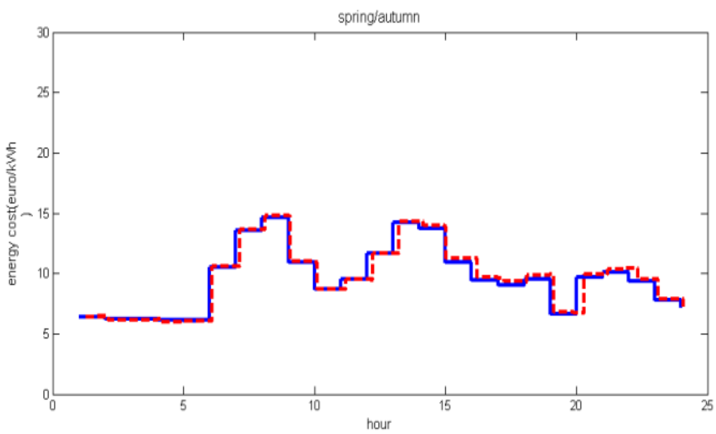
These types of optimization problems can be solved by applying several methods such as penalty and barrier functions, gradient projection algorithm, sequential quadratic programming, and Genetic algorithm [19].

The optimization function chosen here is fmincon.m, in MATLAB, whose algorithm is set to be ‘sqp’ (sequential quadratic programming).

2.3. Case study

First, the optimization was run with respect to the same input datasets as those used in Gianfranco Chicco and Pierluigi Mancarella [23]. This procedure was employed to validate the results. For example, the gas price was set to 20 €/MWh$_t$ and it was assumed that this price would remain constant throughout the analysis. For the sake of simplicity, buying and selling electricity prices were assumed to be the same. Second, the optimization problem was solved by setting the equipment investment and O&M costs to zero and ignoring the greenhouse gas emissions. Therefore, the required conditions presented in [23] were stimulated. Figure 2 shows the results.

The simulation results are consistent with the results obtained in [23]. There was no significant difference between the results. The errors were associated with digitizing the diagrams of load patterns to obtain the load data of the mentioned paper.



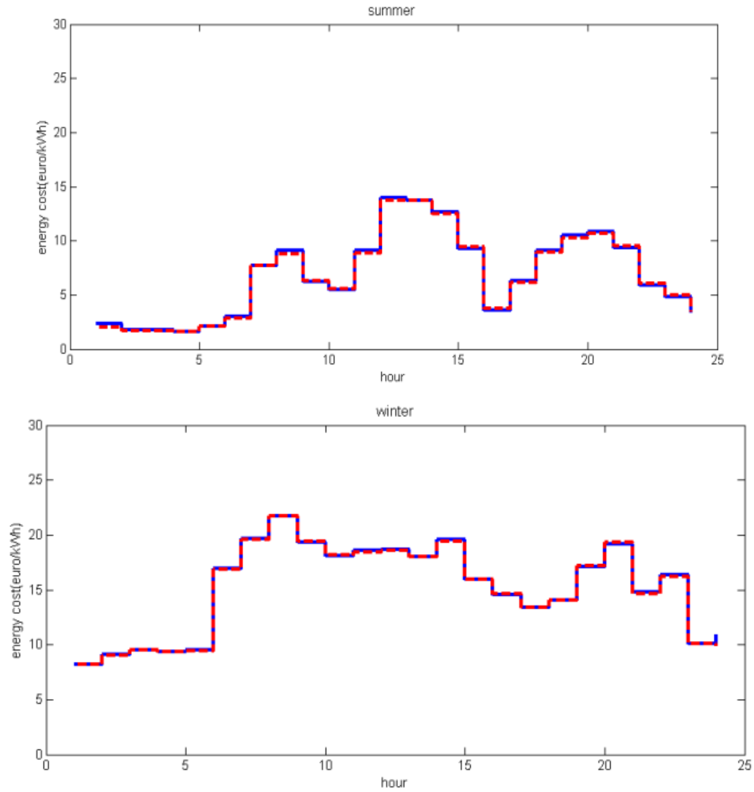
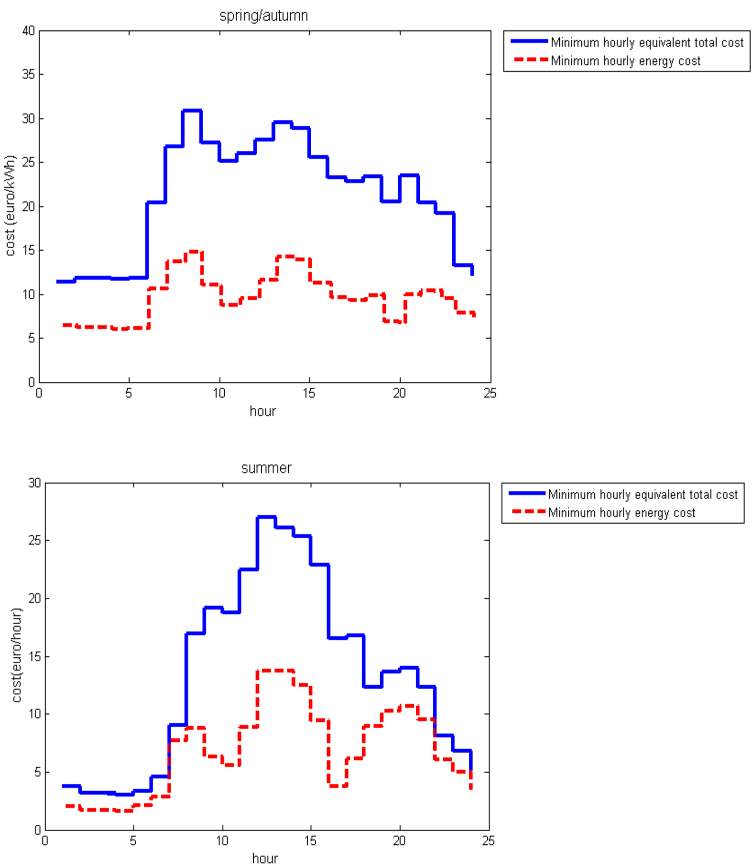


Figure 2. Verification of the written optimization code by simulating the conditions of Mancarella et al. [23]. The results achieved with minimum hourly energy cost over the 3 seasonal days (blue) show good consistency with those of the mentioned study (red).

3. RESULTS AND DISCUSSION

The true value of CHP over its lifetime was reached by analyzing several items including capital and maintenance costs and financial and environmental benefits. To this end, the optimization was repeated by considering the levelized costs of plant components and evaluating the environmental costs due to the electricity generated and fuel consumption. Figure 3 shows the optimal total cost in comparison with the energy cost on three seasonal days.



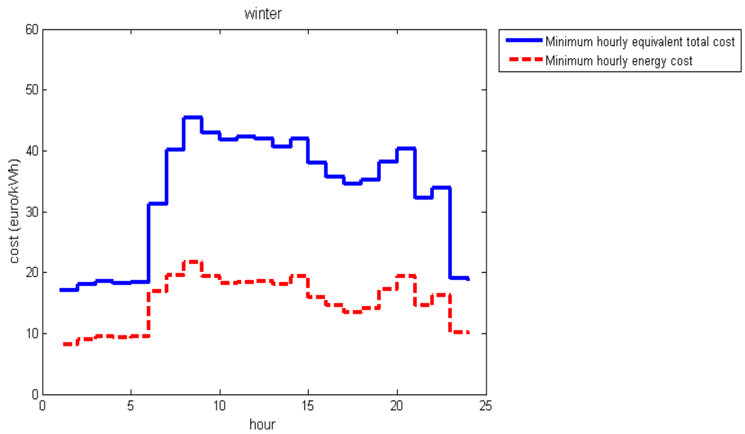
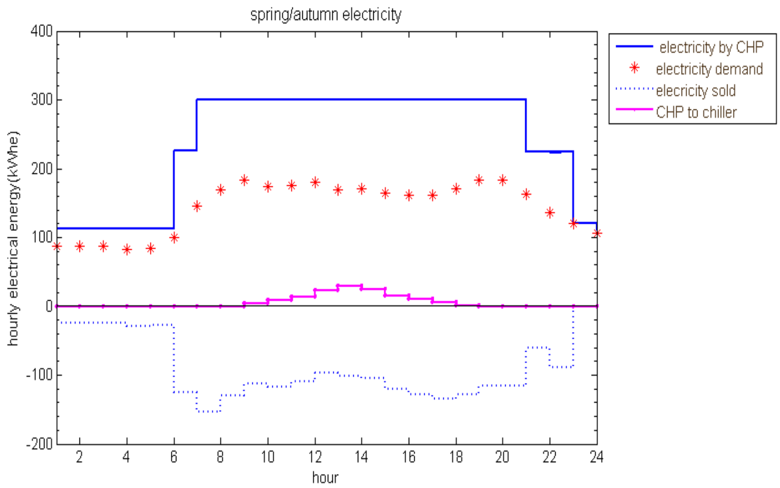


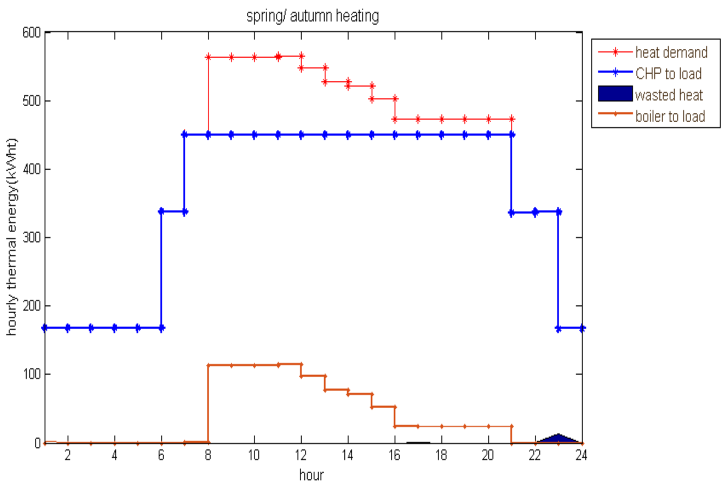
Figure 3. Minimum hourly equivalent levelized total cost (blue) compared to minimum hourly energy cost on the 3 seasonal days.

The blue line represents the total costs of the studied trigeneration system. These costs are included in investment costs, energy costs, operation and maintenance costs, and GHG emission taxes on the fuel consumption and grid electricity generation. The total costs are plotted against the hourly energy costs. The minimum differences between the two lines were observed during the first hours of the summer, because the electricity demand in the optimum case was totally supplied through grid electricity during these hours. Thus, the cost of the micro turbines has no contribution to the total cost in these hours. Therefore, GHG emission costs were added only to the base case. It should be mentioned that the equipment investment costs are converted to equivalent levelized costs. Then, the costs were calculated according to the hours, resulting in the optimum case. Thus, the levelized equipment cost was set to zero during non-use hours.

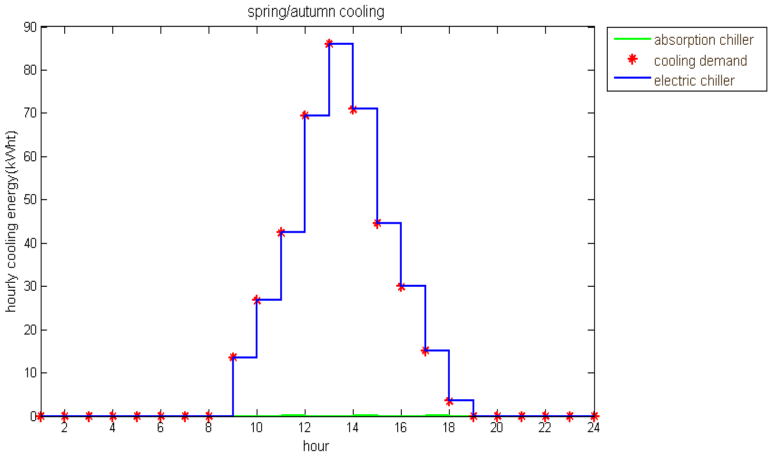
Relevant power flows corresponding to the minimum total levelized cost are shown in Figs. 4, 5, and 6.



a) Spring/Autumn electricity



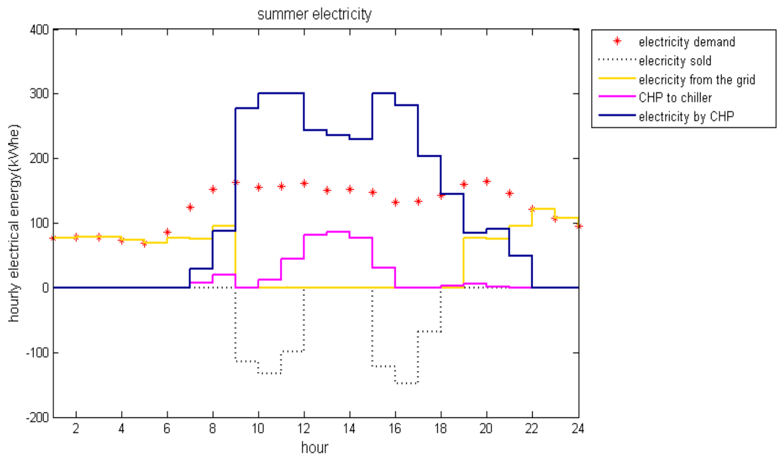
b) Spring/Autumn heating



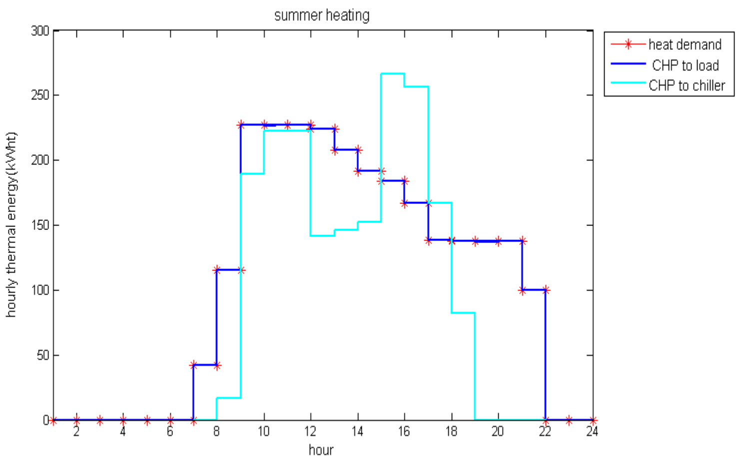
c) Spring/Autumn cooling

Figure 4. Hourly energy flows on a typical day in an intermediate (spring or autumn) season for the optimal operational strategy; a) electricity, b) heating, and c) cooling.

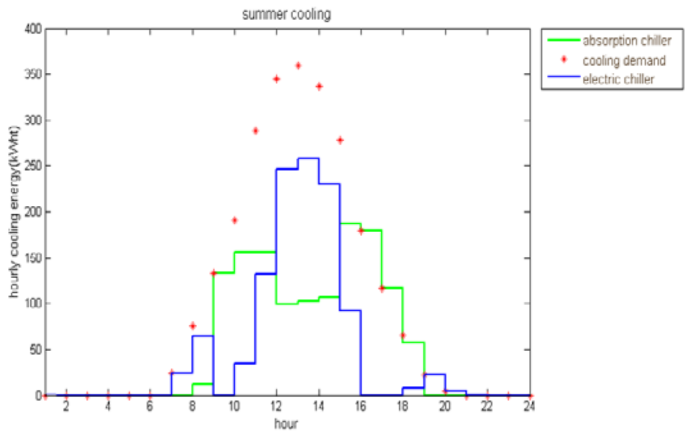
Figure 4a shows that the entire electricity demand is supplied by the CHP during a typical day of an intermediate (spring/autumn) season. Thus, no electricity is purchased from the grid. A part of the electricity generated by CHP goes to the electric chiller. From 7 to 21, the CHP system (3 micro-turbines) operates at its rated capacity (300 kW_E). The surplus electricity is sold to the grid, as shown by the dotted line in Figure 4a. The heat generated by CHP can meet the whole heating demand for the intermediate season, from 21 to 8, except during 8 to 21, although it operates at its rated heating capacity (450 kW_Q), it cannot meet the entire heating demand. Accordingly, the remaining demand is supplied through operation of auxiliary boiler (Figure 4b). The entire cooling demand is met by the electric chiller during a day in the intermediate season. It operates with power supply from the CHP (Figure 4c).



a) Summer electricity



b) Summer heating

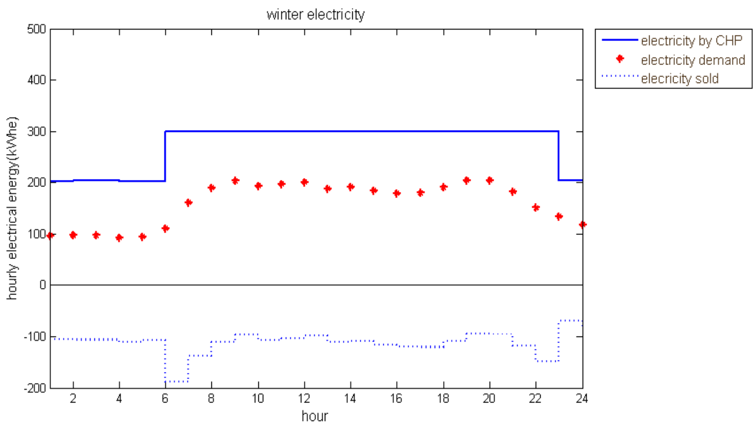


c) Summer cooling

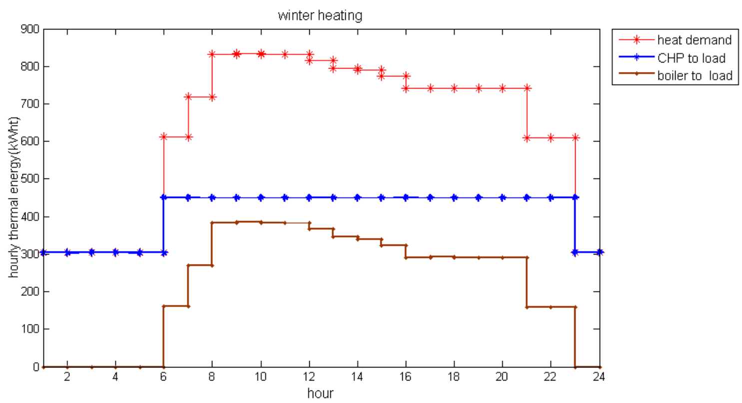
Figure 5. Hourly energy flows on a typical day in summer season for the optimal operational strategy; a) electricity, b) heating, and c) cooling.

On a summer day, due to the increased power demand, applying CHP leads to much more heat. Thus, regarding low heating demand during the night, the CHP is switched off from 22 to 7 in the optimal strategy. Furthermore, selling the surplus of generated electricity to the grid is not profitable during the interval of time. Therefore, the electricity is bought from the grid. From 19 to 22, about half of the electricity demand is supplied by the CHP and the remaining electricity comes from the grid. From 7 to 20, the produced electricity on a summer day can be used to power compressors for the cooling system. The excess electricity is sold to the grid during the interval of time (Figure 5a). From 7 to 22, the entire heating demand is met by the CHP, while the excess heat is used to run the absorption chiller (Figure 5b). The cooling demand on a summer day is covered by both the absorption and electric chillers whose supplies come from the CHP (Figure 5c).

The electricity generated by CHP is sold during the entire winter day. In the optimal strategy, the CHP system (3 micro-turbines) operates at its rated capacity from 6 to 23 (Figure 6a). Although the CHP operates at its rated capacity in these hours, it cannot cover the whole thermal demand. In this case (from 6 to 23), the remaining heating load is provided by the auxiliary boiler. On a winter day, the CHP supplies the total heating demand from 23 to 6. As there is no cooling demand, no energy goes to chillers (Figure 6b).



a) Winter electricity



b) Winter heating

Figure 6. Hourly energy flows on a typical day in winter season for the optimal operational strategy; a) electricity, b) heating.

As it can be seen, despite the added cost of the equipment, the optimal strategy offers the CHP to be switched on for most of the time instead of buying electricity from the grid. One reason is that the hourly equivalent equipment cost is negligible for the CHP system components throughout the lifetime of the plant. This situation makes it still profitable in comparison with the buying electricity from the grid. The second reason is that less carbon tax is levelized on the power generated by the CHP. Since CHP cogenerates electricity and heat, the application of CHP instead of using grid electricity and boiler separately for producing the same amount of electricity and heat reduces GHG emissions.

3.1. Payback time

The current utilization of cogeneration systems is extremely low in the United State residential sector. It is mainly due to their high costs in comparison with conventional energy systems [29]. Therefore, utilization of these types of technologies in the domestic sector requires comprehensive technical and economic analysis and it may also be able to acquire government grants [30].

In the studied system, electricity can be either purchased from or sold to the grid. It is implemented by considering the corresponding electricity prices. In this case study, it was assumed that the remaining electricity was sold back to the grid at the same price with purchasing electricity from the grid. Therefore, the annual profits could not recoup the investment costs as well as annual O&M and energy costs. To make the CHP option profitable, it is essential to sell the surplus electricity of CHP at higher prices.

Therefore, the optimization was [16] performed first with respect to the assumption that the entire electricity demand would be met by the CHP system and no electricity was bought from the grid. The hourly profit was calculated for selling surplus electricity in 3 typical days corresponding to 3 spring/autumn, summer, and winter seasons.

The optimization was repeated with respect to different selling/purchasing electricity rates to/from the grid prices ratios. Based on the achieved results, Figure 7 depicts that payback time decreases by increasing the purchasing price for the electricity generated by the CHP system. If the price of purchasing CHP electricity is considered three times more than the current ones, payback times below 5 years can be achieved.

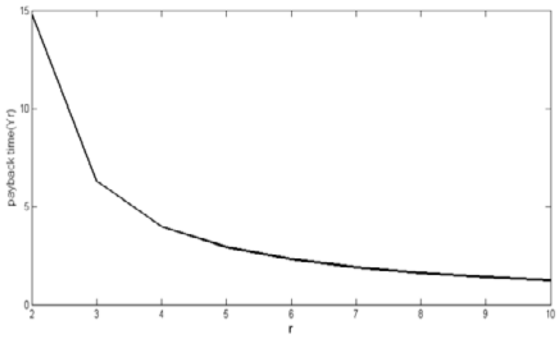


Figure 7. The range of payback periods of the studied CCHP system, calculated for different selling to purchasing electricity prices ratios (r).

4. CONCLUSIONS

In the studied system, application of CCHP led to saving in the electricity bought from the grid. These savings were computed and the emissions from the fuel consumption were evaluated. Electricity generation by CCHP led to achieving 1256 MWh annual electricity savings that otherwise must be purchased from the grid. The results also showed a significant reduction in annual CO_2 emissions (703.3 tons per year). The environmental impact of this project was assessed by GHG emission analysis. The results showed that applying the trigeneration system reduced CO_2 emission by 10550 tons during the system lifetime (15 Years). If the carbon tax was assigned to GHG emissions, the advantages of GHG emission reduction would be quantified (prices varying from 1 to 100 €/ton of CO_2; an average cost of 30 €/ton CO_2 was set [31]). This process led to 21099 € savings annually.

Increase in purchasing price of the electricity generated by these technologies can be considered as one of the supportive policies to promote the renewable energies as well as CHP systems. The attained results showed that this strategy would make cogeneration energy systems profitable and improve the contribution of these systems for supplying electrical and thermal demands in residential buildings.

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NOMENCLATURE

ACh	Absorption chiller
B	Boiler
C	Cooling (kWh)
C	Cost (€)
Ctx	Carbon tax
D	Main diagonal of the interconnection matrix
d	Demand
E	Electricity(kWh_E)
ECh	Electrical chiller
Emiss	Emission
F	Fuel (kWh_t)
GE	Grid electricity
GEF	Greenhouse gasses emission factor (tons of CO_2 per kWh)
GS	Gas supply
GT	Micro gas turbine
i	Input
I	Interest rate
inv	Investment
M	Number of energy vectors
n	Lifetime
o	Output
Q	Heat (kWh_t)
R	Efficiency matrix
T	Interconnection matrix
v	Array of energy vectors
X	Plant components
Y	Cogenerator
Greek letters	
α	Dispatch factor
η	Efficiency
Abbreviations	
CCHP	Combined cooling, heat and power
COP	Coefficient of performance
CRF	Capital recovery facor
GHG	Greenhouse gasses
IEA	International energy agency
MESs	Multifunctional energy systems
MSMP	Multi-source multi-product
O&M	Operation and maintenance

sqp	Sequential quadratic programming	**Superscript**	
T&D	Transmission and distribution	T	Array or matrix transposition operator
Subscripts			
t	Thermal		

APPENDICES

Appendix A. Hourly electricity, heat and cooling loads for the 3 typical seasonal days used in the case study [23]

Hour	Spring/Autumn load (kWh)			Summer load (kWh)			Winter load (kWh)		
	Electricity	Heating	Cooling	Electricity	Heating	Cooling	Electricity	Heating	Cooling
1.00	87.00	168.00	0.00	77.34	0.00	0.00	96.67	303.39	0.00
2.00	87.00	168.00	0.00	78.32	0.00	0.00	97.48	304.87	0.00
3.00	87.00	168.00	0.00	78.32	0.00	0.00	97.08	304.87	0.00
4.00	83.00	168.00	0.00	74.05	0.00	0.00	92.21	303.39	0.00
5.00	85.00	168.00	0.00	69.79	0.00	0.00	94.64	303.39	0.00
6.00	100.00	338.17	0.00	86.85	0.00	0.00	111.27	610.99	0.00
7.00	146.00	450.43	0.00	125.25	41.70	24.46	161.54	718.95	0.00
8.00	170.00	563.73	0.00	152.82	115.29	76.06	189.92	832.83	0.00
9.00	183.00	563.73	13.57	162.66	226.77	132.73	203.30	834.30	0.00
10.00	174.00	563.73	26.70	155.44	227.40	190.25	193.57	832.83	0.00
11.00	176.00	564.78	42.36	157.09	227.39	288.36	196.81	832.83	0.00
12.00	180.00	547.99	69.39	161.68	224.02	345.04	201.27	816.56	0.00
13.00	170.00	527.01	86.06	150.52	208.14	359.42	188.30	795.85	0.00
14.00	171.00	520.72	70.91	152.82	191.82	336.58	191.54	789.94	0.00
15.00	165.00	502.88	44.64	147.24	183.92	278.21	184.24	773.67	0.00
16.00	161.00	473.51	29.99	133.13	166.99	179.25	179.38	741.14	0.00
17.00	161.00	473.51	15.08	134.44	138.20	116.66	179.78	742.61	0.00
18.00	171.00	473.51	3.46	143.63	137.58	65.06	190.73	741.14	0.00
19.00	184.00	473.51	0.00	160.70	137.58	21.92	204.52	741.14	0.00
20.00	184.00	473.51	0.00	164.96	137.58	5.01	204.52	741.14	0.00
21.00	163.00	336.08	0.00	145.60	99.60	0.00	182.22	609.52	0.00
22.00	136.00	337.12	0.00	121.64	0.00	0.00	151.00	609.52	0.00
23.00	120.00	167.17	0.00	107.20	0.00	0.00	133.97	304.87	0.00
24.00	106.00	167.17	0.00	95.39	0.00	0.00	118.16	304.87	0.00

Appendix B. Hourly grid electricity prices on the 3 seasonal days of the case study [23]

Electricity price (€/MWh)			
Hour	Spring/Autumn	Summer	Winter
1	40	30	50
2	20	20	40
3	20	20	40
4	20	20	40
5	20	30	40
6	40	40	40
7	40	50	50
8	60	70	70
9	110	100	110
10	120	110	110
11	120	110	110
12	110	80	110
13	80	70	100
14	80	80	80
15	90	80	100
16	90	100	110
17	90	80	120
18	90	70	120
19	120	60	110
20	90	60	80
21	70	60	80
22	60	50	50
23	40	50	50
24	40	40	40

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