THE ANALYSIS OF TRIGENERATION ENERGY SYSTEMS AND SELECTION OF THE BEST OPTION BASED ON CRITERIA OF GHG EMISSION, COST AND EFFICIENCY

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ARTICLE INFO

***Article history*:**
Received 8.5.2012.
Received in revised form 16.7.2012.
Accepted 20.7.2012.

Keywords:
Greenhouse gases
Trigeneration
Optimization

Abstract:

The aim of this paper is to describe various models and optimisation procedures of the trigeneration systems in order to establish their advantages in terms of efficient and ecologically acceptable modes of energy transformation. Five energy models of 4 MW_e are described and analysed, of which the gas engine, combined with the absorption refrigeration unit, has been found out as an optimum. The analysis showed that such a system provides the best payback period and in the same time it has the least possible environment impact. The analysis and optimisation was performed with the use of RETScreen software package.

1 Introduction

The growing need for electric energy, especially during the summer period when numerous cooling devices are connected to the power system, requires at the same time a greater need for the operation of thermo-power facilities that increase CO_2 emission significantly.

As the signatory of Kyoto Protocol, Croatia has agreed to decrease greenhouse gas emission. Therefore, a need has been arisen to find acceptable solutions in order to meet demands of electric energy consumption with the lowest greenhouse gas emission.

One of the solutions, presented here, is the introduction of trigeneration plants which meet the need for power and heating / cooling and at the same time offer decreased greenhouse gas emissions. The trigeneration system can be comprised of different basic components. These components make up different models of energy systems with the possibility to be optimized from the technical, economical and ecological point of view.

The problems of analysis and optimization of trigeneration energy systems have been treated in many books [1-3] and papers [4-8]. This paper presents a model for analysis of a trigeneration energy system and selection of the best option on criteria of GHG emission, cost and efficiency.

2 Greenhouse gases and their equivalent to the potential global warming

Gases that mostly increase the greenhouse effects are carbon dioxide (CO_2) methane (CH_4) and nitrogen oxide (NO_X).

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The share of each gas contribution to greenhouse effects depends on its relative greenhouse potential. The relative greenhouse potential depends on the capacity to absorb heating energy in relation to carbon dioxide. The equivalent global warming potentials of the most influent gases are presented in Table 1. The detailed calculated presentation of the equivalent relative greenhouse potential can be found in IPCC Third Assessment Report: Climate Change 2001, which shows that CO_2 participates with 61% [9] compared to other gases. Therefore, it is the referential basis for the calculation of other greenhouse gas emissions.

Croatian Parliament ratified Kyoto Protocol on April 27th 2007. Thus, Croatia was included as the 170th country to have accepted this document. With the ratification Croatia accepted the obligation to reduce greenhouse gas emissions for 5% until 2012, referring to the year 1990, when the emission of 34.62 million tons of carbon dioxide was reached.

3 Trigeneration plants

Energy plants that apart from power produce also energy for heating and/or cooling are known as trigeneration plants (Fig. 1). In fact, they are cogeneration plants having refrigeration unit run by heat. Refrigeration units, using heat for the cooling process, are named absorption refrigeration units (ARU). The application of trigeneration plants offers a significant decrease of the electric system load during the peak summer season. Besides, trigeneration plants enable a favourable mode of the distribution of power and heating / cooling energy to medium size consumers such as hospitals, university campuses, retirement homes, hotels, shopping centres and different industrial facilities.

Table 1. The equivalent potentials of global warming

GHG	GWP*
CO_2	1
CH_4	21
N_2O	310

**Values of GWPs are for 100 years GWP*

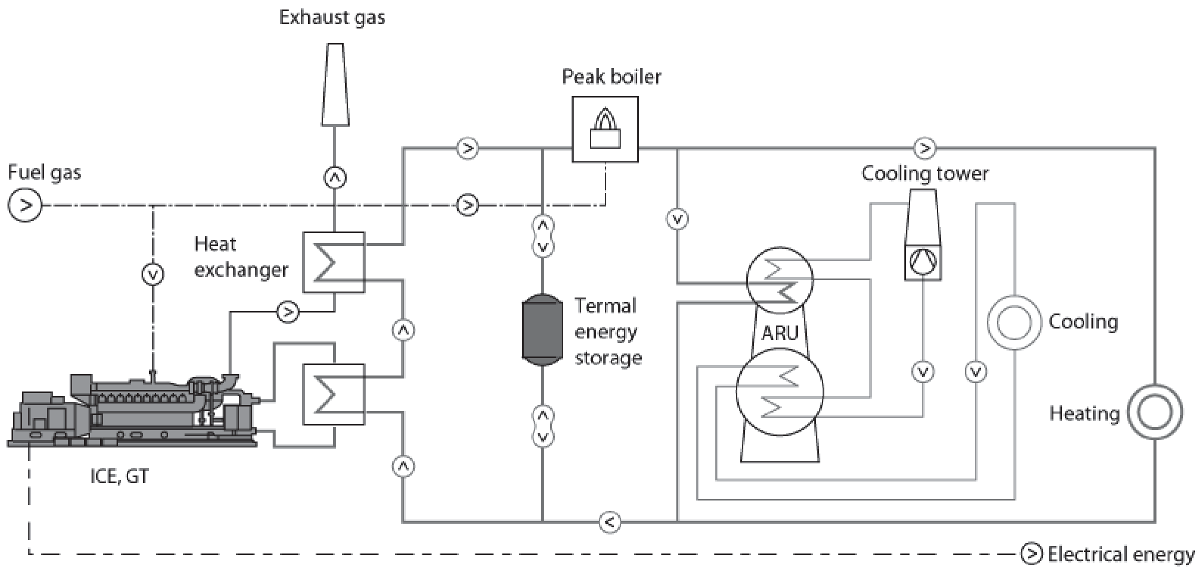

Figure1. Scheme of a trigeneration plant

4 The approach to the optimization of trigeneration systems

This paper presents a techno-economic analysis of a 4 MW_e trigeneration plant. It has been performed by using RETScreen software package [10].
The RETScreen software package was developed by the collaboration of numerous experts of state administration, industry and academic community. It can be used for calculations of energy production costs, flue gas emissions, and cost-effectiveness but also for the possible use of different forms of renewable energy. Four models of energy systems of trigeneration plants have been analysed in this work and compared to the basic model with separate heat and power production. For each model, a detailed techno-economic analysis and ecological analysis has been performed and compared to the basic model.

- **Model 0** (*Basic model*) is shown in Fig. 2. It includes the production of heating energy from the own boiler plant with the power provided from the external power network. The cooling energy is obtained from the compressor refrigeration unit powered by the electric energy from the external network.

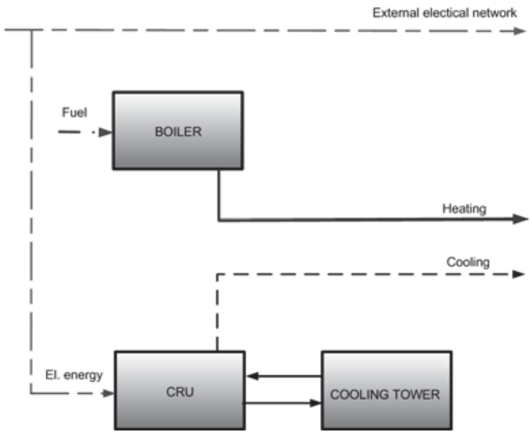

Figure2. Basic model

- **Model 1** (ICE-ARU), shown in Fig. 3, includes the production of power and heating energy from the own plant. The cooling is obtained from one-stage absorption refrigeration unit (with COP 0,75) using the heat recovered from the internal combustion engine driving the electric generator.

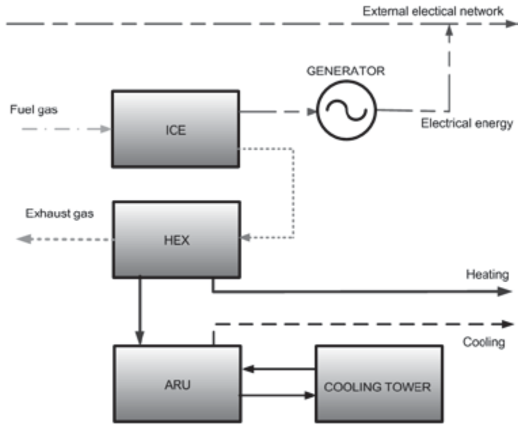

Figure 3. Model 1

- **Model 2** (ICE-CRU), shown in Fig. 4, includes the production of own power by internal combustion engine as in model 1. The cooling is obtained from the compressor refrigeration unit driven by power from the own production or from the external power network.

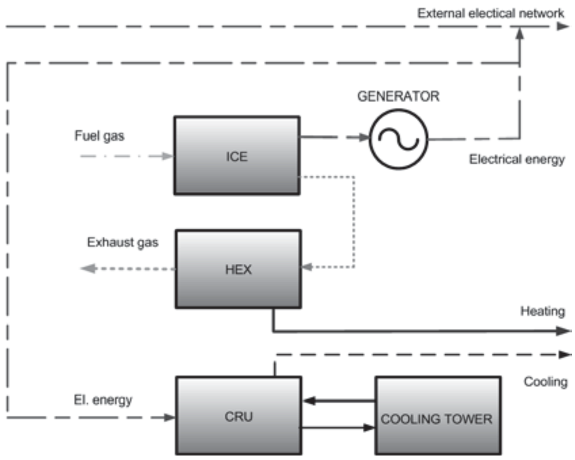

Figure 4. Model 2

- **Model 3** (GT-ARU), shown in Fig. 5, includes the production of power from the own plant and heat recovered from exit flue gases of the gas turbine. The cooling is obtained from two-stage absorption refrigeration unit (with COP 1,3) using the heat recovered from the gas turbine.
- **Model 4** (GT-CRU), shown in Fig. 6, includes the production of own power by gas turbine as in model 3. The cooling is obtained from the compressor refrigeration unit run by power from the own production or from the external power network.

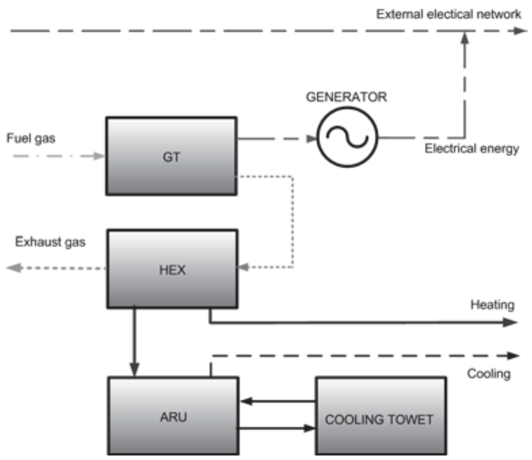

Figure 5. Model 3

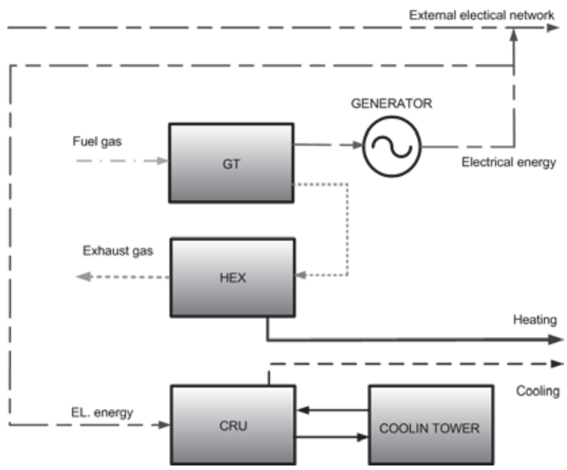

Figure 6. Model 4

5 The analysis of energy load

Before proceeding to the analysis of a trigeneration system, it is necessary to conduct a detailed analysis of the energy consumption during one year period. The key criterion must be the consumption of heating energy, while the power surplus can be delivered to the external network or imported from it in case of its shortage. The parameters of heating energy are important factors for the selection of a trigeneration process. It is necessary to establish the yearly level of needed energy, the total load and the consumption period during the year. The trigeneration process is the most efficient when it covers heating and electrical load by maximum number of working hours. In order to determine the load curve, it is necessary to know the climate data for the referential location. The referential location for Zadar / Zemunik is applied in this work, as shown in Table 2.

In order to select the size of a trigeneration plant it is necessary to determine the curve of heating load during the year. Besides for space heating and cooling, the necessary energy for domestic hot water heating is also included in the analysis. The supposed size of the analysed buildings is 200.000 m^2, which, as an example, could be the size of a university campus. The structure of heating and electric load is presented in Table 3.

Table 2. Climate data for referential location Zadar / Zemunik [10]

Month	Air temperature	Relative humidity	Daily solar radiation	Atmospheric pressure	Wind speed	Heating degree-days	Cooling degree-days
	°C	%	kWh/(m²d)	kPa	m/s	°C-d	°C-d
January	4,8	76,8	1,30	98,1	2,4	409	0
February	5,5	75,1	2,14	97,9	2,5	350	0
March	8,2	71,8	3,27	97,8	3,0	304	0
April	12,5	72,7	4,06	97,5	3,0	165	75
May	16,8	73,0	5,29	97,6	2,4	37	211
June	20,5	68,9	6,01	97,7	2,3	0	315
July	23,9	63,1	6,21	97,7	2,4	0	431
August	23,4	65,7	5,39	97,7	2,3	0	415
September	19,4	74,2	3,88	97,8	2,3	0	282
October	14,8	79,1	2,35	98,0	2,3	99	149
November	9,5	79,4	1,33	97,9	2,6	255	0
December	6,6	79,2	1,05	98,0	2,5	353	0
Average	13,9	73,2	3,53	97,8	2,5		
Sum						1.973	1.878

Table 3. The values of the energy load

	Mark	Units	Value
Floor area of building	A	m^2	200.000
Heating load	q_h	W/m^2	70
Cooling load	q_0	W/m^2	40
Domestic water heating	Q_{hw}	MWh	2.300
Peak heating load	$\dot{Q}_h$	MW	7
Peak cooling load	$\dot{Q}_c$	MW	4
Peak electric load	$\dot{Q}_e$	MW	4

The curve of energy load of the basic model with separate production of energy is shown in Fig. 7. In this case, the electric energy corresponds to the energy taken from the external network. The heating load of the model 2 and 4 is shown in Fig. 7. The electric energy, in all cases, comes from the own production or from the external network.

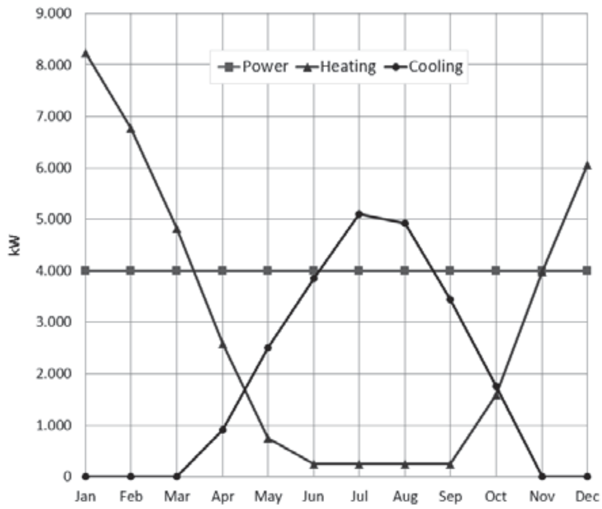

Figure 7. Energy load curve during the year for the basic model and for models 2 and 4

The load of system according to models 1 and 3 is presented in Fig. 8. In this case, electric energy is provided completely from the own production. During the winter period, the heating presents the energy needed for heating, while during the summer period it is used by ARU to produce cooling. In the analysed case, there is less power in the summer season because it is not needed to drive the compressor refrigeration unit.

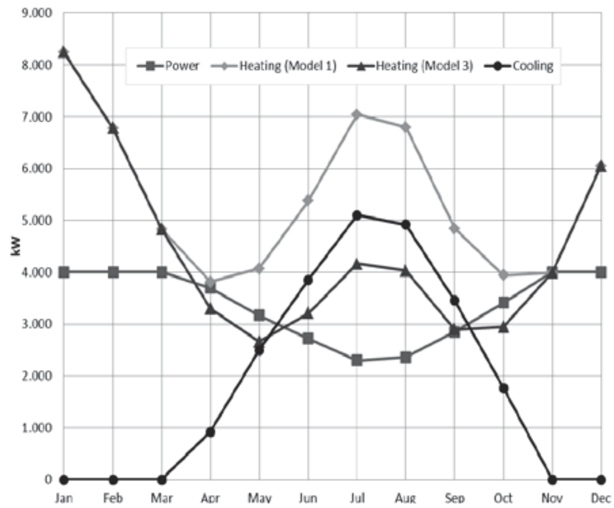

Figure 8. Energy load curve during the year for models 1 and 3

In order to achieve the heat recovery from the system with the internal combustion engine, one-stage ARU is used, while in the system with gas turbine, two-stage ARU is incorporated.

Yearly energy needs of the plants are shown in Table 4.

Table 4. Yearly energy need of the analysed plants

	Unit	Mark	Basic model	Model 1	Model 2	Model 3	Model 4
Power	kW	$\dot{Q}_e$	4.000	4.000	4.000	4.000	4.000
	MWh	Q_e	35.040	29.236	34.936	29.236	34.936
Heating	kW	$\dot{Q}_h$	14.000	21.733	14.000	18.462	14.000
	MWh	Q_h	27.543	50.344	27.543	40.695	27.574
Cooling	kW	$\dot{Q}_c$	8.000	8.000	8.000	8.000	8.000
	MWh	Q_c	17.413	17.413	17.413	17.413	17.413

6 Techno-economical parameters

To calculate expenses and to compare the analysed costs of energy plants for heating and/or cooling, it is necessary to establish:
- energy for heating and/or cooling
- energy prices
- total investment cost.

Other costs are smaller, nearly the same for all analysed energy models, and for this reason have not been taken separately into account.
Based on the heating and electric load, adequate power-generating units (ICE, GT) are chosen and incorporated with cooling device (ARU, CRU).

6.1 Energy prices and tariffs

Current energy tariffs are applied in this analysis. The prices of energy are shown in Table 5. The price of the imported electric energy from the outside grid is 0,11 €/kWh [11]. Prices of electric energy produced in cogeneration plants are presented in Table 5.

Table 5. Energy prices included in calculations

Energy type	Units	Price
Natural gas [13]	€/m^3	0,34
Diesel oil [14]	€/m^3	0,87
Power (daily) [15,17]	€/kWh	0,09
Power (nightly) [15,17]	€/kWh	0,05

6.2 Investment costs and main performances of the analysed plants

In the year 2007, a Decree of rates, i.e. corrective coefficients and scales were issued to determine the rates of compensation for the carbon dioxide (CO_2) emission. According to this Decree, the cost for the greenhouse emission is 2,38 €/t $_{CO2}$ [12].

Table 6. Technical characteristics of analysed plants [10]

	Marks	Units	Model 1	Model 2	Model 3	Model 4
Power system	-	-	ICE	ICE	GT	GT
Availability	-	%	50	50	50	50
Fuel type	-	-	NG	NG	NG	NG
Electric load	$\dot{Q}_e$	kW	4.000	4.000	4.000	4.000
Type	-	-	General Electric J624 GS	General Electric J624 GS	Rolls-Royce 501-KB5	Rolls-Royce 501-KB5
Heat rate	HR	kJ/KWh	7.826	7.826	12.411	12.411
Efficiency of electric energy production	$\eta_e = \dot{Q}_e / \dot{Q}_f$	%	46	46	29	29
Heat recovery efficiency	η_r	%	78	78	78	78
Fuel consumption	$\dot{Q}_f = \dot{Q}_e / \eta_e$	MW	8,69	8,69	13,77	13,77
Available heat rate	$\dot{Q}_h = \dot{Q}_f - \dot{Q}_e$	MW	4,69	4,69	9,79	9,79
Recovered heat rate	$\dot{Q}_r = \eta_r \cdot \dot{Q}_h$	MW	3,66	3,66	7,63	7,63
Refrigeration unit type	-	-	ARU	CRU	ARU	CRU
Type			One-stage ARU		Two-stage ARU	
Coefficient of performance	COP	-	0,75	3	1,3	3

7 The analysis of greenhouse gas emission

The analysis of greenhouse gas emission is conducted for each model and compared to the basic model for the separate production of heat and power. The values of emission factor for fossil fuels were taken in account as shown in Table 7.
The values of the emission factor for coal fired power plants were calculated basing them on the efficiency of power production 35%, with additional transmission loss of 12,7 %.
The same transmission loss is also taken into consideration for the power delivered to the outside network.
The calculated greenhouse gas emission values of the analysed energy models are given in Table 8.

8 Economic analysis of energy system models

The results of technical, economical and environmental analysis of the selected trigeneration energy systems are presented in Tables 6, 8 and 9 with the aim to select the best solution. The capacity and structure of trigeneration systems are defined according to the detailed analysis of the yearly energy need of a university campus. The system for separate power and heat production is chosen as a basic system (Model 0) to which other analysed models are compared. The investment, fuel, power and GHG emission costs are the main values for the final conclusion based on the calculated payback period.
The total energy efficiency of system for separate power and heat production is calculated as follows:

$$\eta_{tot} = \frac{Q_e + Q_h}{\frac{Q_e}{\eta_e} + \frac{Q_h}{\eta_h}} = 0{,}472;$$
$$Q_e = 35.040 MWh; Q_h = 27.543 MWh; \quad (1)$$
$$\eta_e = 0{,}35; \eta_t = 0{,}85$$

The payback period is calculated as follows:

$$P_{m1} = \frac{C_{tot,m1}}{C_{f,m0} - \left(C_{f,m1} - I_{GHG,m1} - I_{e,m1}\right)} = 1.9 \quad (2)$$

Table 7. Emission factors for fossil fuels [10]

Energy source	Emission factor CO_2	Emission factor CH_4	Emission factor NO_2	Power production efficiency	Transmission loss	Emission factor for GHG
	kg/GJ	kg/GJ	kg/GJ	%	%	t_{CO2}/MWh
Coal	95,8	0,015	0,003	-	-	0,35
Diesel Oil	73,3	0,002	0,002	-	-	0,266
Natural gas	54,5	0,004	0,001	-	-	0,197
Power	313,7	0,0491	0,0098	35	12.7	1,144

Table 8. The results of annual greenhouse gas emissions for analysed energy models

	Units	Model 1	Model 2	Model 3	Model 4
Natural gas	MWh	78.438	41.634	52.784	37.310
Electric energy supplied from external network	MWh	0	13.594	0	5.561
GHG emission	tCO2	18.036	15.649	12.157	14.942
GHG emission Model 0	t_{CO2}	34.881	24.184	21.872	21.255
Annual GHG emission reduction	t_{CO2}	16.845	8.536	9.715	6.313

Table 9. The results of techno-economical analysis

	Mark	Unit	Model 0	Model 1	Model 2	Model 3	Model 4
Electricity export income	I_e	€	-	1.634.400	762.300	682.800	523.400
GHG reduction income	I_{GHG}	€	-	40.000	20.300	23.100	15.000
Fuel cost	$C_{f,m}$	€	3.388.800	2.788.500	1.988.800	2.014.660	1.916.300
Total energy efficiency	η_{tot}	%	48	88,1	88,1	84,4	84,4
Total investment cost	$C_{tot,m}$	€	-	4.360.000	4.625.000	5.285.000	5.550.000
Payback period	P_m	year	-	1,9	2,1	2,5	2,8

9 Conclusion

The major aim of this paper is to describe a procedure of finding the best option on a trigeneration energy system, which is used as an efficient and ecologically acceptable way of energy transformation. Five models of energy systems are proposed and analysed in this paper. The model with the gas engine and with the absorption refrigeration unit (Model 1) is derived as an optimum solution. For analysed parameters, this energy system gives the shortest payback period and it has the lowest environment influence. The gas turbine plant showed somewhat worse results because of increasingly high investment costs pertaining to the power-generating unit. In addition to higher energy efficiency, a significant reduction of greenhouse gas emissions, particularly of CO_2, can be achieved with the application of trigeneration systems. In conclusion, when compared to conventional energy systems, the trigeneration systems present the most efficient way of energy conversion from technical, ecological and economical point of view.

10 List of signs

Area	A	m^2
Power	$\dot{Q}$	W
Energy	Q	Wh
Specific power	q	W/m^2
Efficiency	η	%
Heat rate	HR	kJ/kWh
Income	I	€
Payback period	P	*year*

10.1 Indexes

Electric	*e*
Fuel	*f*
Heat	*h*
Cool	*c*
Thermal	*t*
Recuperation	*r*
Hot water	*hw*
Total	*tot*
Model	*m*

10.2 Abbreviations

Internal combustion engine	*ICE*
Gas turbine	*GT*
Natural gas	*NG*
Absorption refrigeration unit	*ARU*
Compressor refrigeration unit	*CRU*
Coefficient of performance	*COP*
Combined heat and power	*CHP*
Internal rate of return	*IRR*
Greenhouse gas	*GHG*
Global warming potential	*GWP*

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