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Energy and economic assessment of small CHP in China: comparison between internal combustion engine and gas turbine

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***Abstract*:**
China is the world's leading consumer of energy. Co-generation is considered an effective way to reduce energy consumption and environmental pollution. Small Combined Heat and Power (CHP) systems can fulfill the electrical and thermal consumption of large facilities that require high demands of heating and power. Internal combustion engine (ICE) is the most established and widespread technology for the combined production of heating and power. Gas turbines (GT) are a relatively new technology for CHP. These two technologies differ in regards to energy efficiency, annual availability, and investment, operating, and maintenance costs. A detailed study was conducted in order to compare the main features of ICE and GT technologies for models below 1MWe. This paper is intended to provide a comparison between ICE and GT technologies and to analyze the energy production, operating and maintenance costs.

Keywords—Cap-and-trade, Health impacts, Mortality, NOx, NOx emissions, Point sources

I. INTODUCTION

In recent years, the rapid economic growth of China has led to a growing energy demand from 603 million tons of standard coal equivalent in 1980 to 3055 million tons of standard coal equivalent in 2009, which accounts for about 19% of the world's total energy consumption [1]. The largest energy source in China is coal. It accounts for about 75% of the overall energy consumption of the country and is the primary reason for the increase of air pollution. Nevertheless, the government officials are striving to reduce environmental pollution but not at the expense of economic growth. Local air pollution conditions in many areas often exceed both daily and annual international air quality standards [2].

Co-generation can meet these two criteria, promoting environmental improvement and economic growth.

According to the definition given by the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE), co-generation, also called CHP (Combined Heat and Power), is the simultaneous production of electrical or mechanical energy and useful thermal energy from a single energy stream [3]. The concept of cogeneration can be related to power plants of various sizes ranging from small scale residential buildings to large CHP systems for industrial purposes. End-users that can benefit most from cogeneration are those that can fully use

May – June 2020
ISSN: 0193-4120 Page No. 7708 - 7716

both the electricity and heating that is being produced by the system.
In this framework, cogeneration con provide several benefits:

- Reduced fuel consumption as a result of increased efficiency
- Lower emissions of pollutant gases
- Reduced energy loss during the transmission and distribution of electricity
- Alleviates electrical supply shortages and improves the urban environment

Small CHP systems below 1000 kWel can meet the electrical and thermal demands from hotels, shopping malls, hospitals, and sports centers to residential domestic use. Typically, small-sized plants working within the power range between 1 to 1000 kWel are designed to produce heat, thus the electrical energy is a collateral benefit [4]. The system must be connected to the grid in order to provide energy for the additional electrical demand. Different technology has been proposed in recent years in order to implement gas-combustion for CHP solutions such as internal combustion engine [5,6,7], gas turbine [8,9], fuel cell [10,11], Stirling engine [12,13], organic Rankine cycle [14,15,16], and thermo-photovoltaic system [17,18]. Some of these technologies are well established and have demonstrated their potential performance and production costs, whereas others are at the early stages of entering the market. Currently, the two most established technologies are internal combustion engine (ICE) and gas turbine (GT).

ICE is the most common and widespread technology for small CHP applications because of their robust nature, reliability and reasonable cost. However, it requires regular maintenance and servicing to ensure availability. The other commercially available co-generator that can be potentially be used for small-scale CHP applications is gas turbine (GT). Compared to ICE solutions, GT presents several advantages, such as reduced maintenance costs, significantly lower emissions (CO_2 and NOx), as well as fuel flexibility [19].

The aim of this paper is to present a comparative study between the two major technologies that can be used for a small CHP energy plant: ICE and GT.

The economic viability of these technologies are strictly related to:

- installation costs
- system maintenance costs
- retail prices for the co-generation system fuel
- electricity costs

II. Development of Co-generation in China

The political, economical, geographical and technological conditions for co-generation developed in China are unique [20]. The history of co-generation in China started in 1953 when the first co-generation plant was imported from the Soviet Union. From 1953 to 1965 the growth rate of co-generation was relatively high, almost 2,4 GW. During this period co-generation plants were typically large (>100 MW) and municipally controlled. The capacity of the turbines was between 25 and 50 MW, with medium levels of steam temperature and pressure. Subsequently, from 1965 to 1980 the growth rate was slow compared to the overall progress, with an increase of less than 2 GW of additional capacity. The situation drastically changed from1980 to 1990 due to the rapid development of co-generation in China which led to the construction of 300 new co-generation plants with a total capacity of 7,96 GW and an average plant size of 27 MW.

In the late 1990s the proliferation of co-generation in China faced another setback due to a lower loan repayment capability and the difficulty of obtaining project financing resulted in a drastic reduction in the number of small and medium size co-generation plants being started. From the year 2000, co-generation was finally recognized as a national priority by the Chinese government, thus leading to new growth in the market for this type of technology. Starting in 2001, the installed capacity of co-generation in China increased by at least 3000 MW per year while the size of the new plants has been reduced as a result of technological advancements in gas turbines and internal combustion engines used for CHP. In the recent years, environmental policies encouraged the development of small co-generation [21] and some larger cities like Beijing and Shanghai promulgated local energy laws for environmental protection and energy savings. A typical example is the construction of no-coal districts. The government encourages these types of districts within the city where no coal can be burned, thus leading to reduced emissions. According to a report from GCiS China Strategic Research [22], at the end of 2011 the CHP market in China has been estimated at about 28 billion RMB, an increase of 20%.

Imported products from foreign companies play a significant role in the market, valued at about 3.6 billion RMB, most of which are gas turbines and internal combustion engines for small CHP plants.
In October 2011, the National Energy Administration (NEA) suggested the installation of approximately 1000 small co-generation units over a period of five years (2011 to 2015) in order to increase the total capacity of Distributed Generation (DG) to 50 GW by

May – June 2020
ISSN: 0193-4120 Page No. 7708 - 7716

2020. A large number of CHP plants for demonstration purposes have been started in different areas of China, as reported in Table 1 [23]. Moreover, as a result of the laws and regulations promulgated by the Chinese government, it is expected that co-generation in China can continue to further develop in the near future [24].

Table 1 - Demonstration projects of CHP system in China

No.	Location	Technologies
1	*Pudong International Airport, Shanghai*	*Gas turbine*
2	*Huangpu Central Hospital, Shanghai*	*Gas turbine*
3	*Minhang Central Hospital, Shanghai*	*Gas turbine*
4	*Shanghai Institute of Technology, Shanghai*	*Gas turbine*
5	*Shuya Liangzi Ministry of Health, Shanghai*	*Diesel engine*
6	*Zizhu Science-based Industrial Park, Shanghai*	*Gas turbine*
7	*Shanghai Jinqiao Sports Center, Shanghai*	*Gas engine*
8	*Shanghai Global Financial Hub, Shanghai*	*Gas engine*
9	*Beijing Gas Group Monitoring, Beijing*	*Gas engine*
10	*Ciqumen Station Building, Beijing*	*Gas turbine*
11	*Zhongguancun Software Square, Beijing*	*Gas turbine*
12	*International Trade Center, Beijing*	*Gas turbine*
13	*International Business Center, Beijing*	*Gas turbine*
14	*Olympic Energy Exibit Center, Beijing*	*Gas turbine*

III. Comparison of Internal Combustion Engine (ICE) and Gas Turbine (GT) technologies

The two major types of technology for small CHP applications are internal combustion engine (ICE) and gas turbine (GT). The fuel combustion inside ICE produces mechanical energy, converted by an alternator into electricity. Heat production by ICE is recoverable from different sources. The emissions produced by ICE are at 400÷500°C, thus it is possible to recover 40÷50% of the thermal energy. In addition, heat can be recovered from other points of the ICE such as the jacket piston cooling water system, the intercooler system, the electric generator cooling system and the engine lubricant.

GT converts chemical energy into mechanical energy using the Brayton cycle. The flue gases produced by a GT are the only source of heat for CHP applications and the temperature is 250÷300°C, thus lower than ICE.

Regarding the fuel that can be used in a CHP plant, ICE is typically able to use a wide variety of fuel in accordance with the combustion cycle used. For example, Otto cycle engines used in stationary applications are fueled with natural gas, LPG, syngas and biogas. Diesel cycle engines can be fueled with diesel, biodiesel and vegetaboils. The main fuel used in GT is natural gas (even though many manufacturers provide models powered by LPG, biogas, diesel, propane and kerosene.)

Both ICE and GT allow wide flexibility of operation. The automation of these systems follows sudden load variations which maintain a satisfactory efficiency level even during partial load operation.

An important difference between ICE and GT are pollutant emissions. ICE needs an additional exhaust system to reduce pollution in order to reach emission levels comparable with GT. In fact, the high levels of pollutant emissions are due to the combustion reactions inside the cylinder of the motor. They depend on the reaction velocity (typically very quick), extremely high temperatures and the gases being in contact with the relatively cold walls of the engine which cannot be completely combusted.

On the other hand, GT technology can assure low levels of CO and NOx from premixed combustion, thus ensuring that emission levels are maintained below 50÷60% of the load. Beyond that load value, the amount of emissions increases drastically.

Additional advantages of GT are minimal noise and vibration, lighter weight and smaller dimensions with respect to analogous ICE plants. To summarize the differences between ICE and GT technology, ICE is more efficient, lower specific fuel consumption and lower investment costs than GT. However, GT has longer operating time between scheduled maintenance, i.e. GT can assure a greater annual availability and lower maintenance costs, while keeping the pollutant emissions at reasonable levels.

IV. ICE and GT on the Chinese market

For the evaluation of specific technical and economical parameters of ICE and GT, the products available on the Chinese market were extensively investigated. The comparative analysis has considered some of the key parameters as references to compare the two CHP technologies analyzed in this paper. In particular, the research focused on:

- Electrical and thermal power
- Electrical and thermal efficiency
- Annual availability
- Emissions
- Costs

V. Internal Combustion Engine (ICE)

The following manufacturers of ICE in CHP configuration were analyzed : Aisin Seiki [25], Caterpillar [26], Cummins [27], Energifera [28], Ge Jenbacher [29], Honda [30], Man [31], MWM [32], Schmitt Enertec [33], Senertec [34], Tecogen [35],

May – June 2020
ISSN: 0193-4120 Page No. 7708 - 7716

Waukesha [36], Yanmar [37] with power up to 1000 kWel .

In Fig. 1 the thermal power as a function of the electrical power is shown and it can be clearly seen that an increase of electrical power involves an increase of thermal power. In Fig. 2 and 3 the electrical efficiency and the thermal efficiency as functions of the electrical power are depicted respectively. In general, the thermal and electrical efficiency are changing values with the electrical power demand. By clustering the ICE into four groups according to the size of the plants, it is possible to find the mean efficiency, as reported in Tab. 2 where it can be seen in general that electrical efficiency increases with the increase of electrical power, while thermal efficiency decreases.

Table 2 - Electrical and thermal efficiency for ICE

		Group 1 0÷25 kW$_e$	Group 2 26÷50 kW$_e$	Group 3 51÷100 kW$_e$	Group 4 101÷1000 kW$_e$
η_e	[-]	0,29	0,31	0,33	0,37
η_t	[-]	0,60	0,59	0,57	0,53

The annual availability, taking into account the maintenance required for ICE operation is 92% of the year. Regarding the specific emissions of ICE, it was not possible to estimate a relationship between the size of the plant and the amount of CO and NOx emitted. The average of the data found during the research among the ICE available on the market is:

$\dot{m}_{CO}$ = 475 mg/Nm^3
$\dot{m}_{NO_x}$ = 375 mg/Nm^3

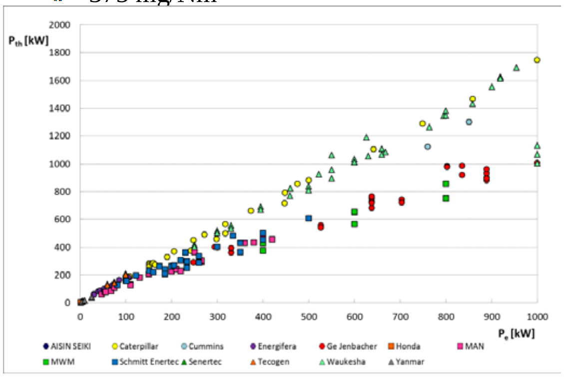

FIG.1.THERMAL POWER AND ELECTRICAL POWER FOR ICE
TECHNOLOGY (1÷1000 KWEL)

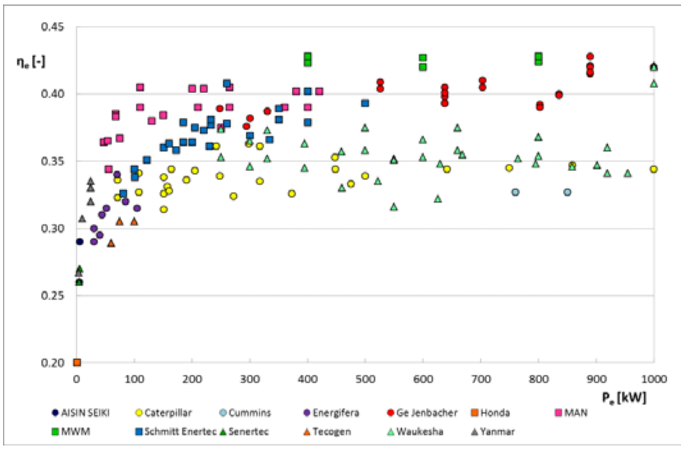

FIG.2ELECTRICAL EFFICIENCY AND ELECTRICAL POWER FOR ICE TECHNOLOGY (1÷1000 KWEL)

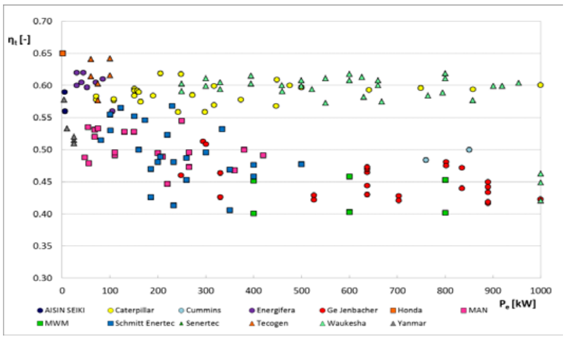

FIG.3THERMAL EFFICIENCY AND ELECTRICAL POWER FOR ICE TECHNOLOGY (1÷1000 KWEL)

During the analysis of the CHP market in China, information about the specific costs was also collected. In particular, as summarized in Table 3, two different sets of parameters have been taken into account. The first set-collecting information about the specific product costs (c_{pr}), equipment costs (c_{eq}), installation costs (c_{in}) as functions of the electrical power installed. The second set of collected data focuses on the specific maintenance costs (c_{ma}) and the specific lube oil costs (c_{lu}) as functions of the electrical energy produced.

Table 3 - Specific costs for ICE

		Group 1 0÷25 kWe	Group 2 26÷50 kWe	Group 3 51÷100 kWe	Group 4 101÷1000 kWe
c_{pr}	[RMB/kW$_{el}$]	4000	2200	1700	900
c_{eq}	[RMB/kW$_{el}$]	1200	660	500	250
c_{in}	[RMB/kW$_{el}$]	940	520	400	200
c_{ma}	[RMB/kWh$_{el}$]	0,191	0,152	0,152	0,114
c_{lu}	[RMB/kWh$_{el}$]	0,015	0,015	0,015	0,015

V.1 GAS TURBINE (GT) Among manufacturers of GT systems used for CHP purposes, the products with power up to 1000 kWel produced by Capstone [38], Flex Energy [39], Kawasaki Heavy Ind. [40], Turbec [41] and Vericor [42] have been analyzed. GT is an innovative technology and therefore is not yet as widespread as ICE, the number of GT plants on the market is significantly lower. The main characteristics of GT technology available on the market are compared in Fig. 4, Fig. 5 and Fig. 6.

In Fig. 4 the thermal power as a function of the electrical power is reported (where it can be seen that an increase of electrical power involves an increase of thermal power) while in Fig. 5 and 6 depicts the electrical efficiency and the thermal efficiency as a function of the electrical power respectively. As for ICE, even in the case of GT the thermal and electrical efficiencies increase with the size of the plant. In Table 4, the GT plants available on the market have been divided into four sets depending on the size and the mean efficiency of each group.

Table 4 - Electrical and thermal efficiency for GT

		Group 1 0÷25 kW$_e$	Group 2 26÷50 kW$_e$	Group 3 51÷100 kW$_e$	Group 4 101÷1000 kW$_e$
η_e	[-]	0,23	0,24	0,27	0,28
η_t	[-]	0,52	0,51	0,53	0,48

The annual availability, taking into account the maintenance required for GT operation is 97% of the year. The average of the specific emissions of GT found during the research of the equipment available on the market is:

$\dot{m}_{CO} = 33$

$\dot{m}_{NO_x} = 17$ 3

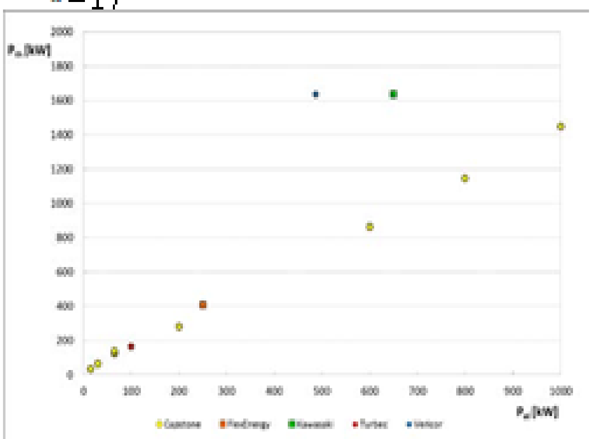

Fig. 4 Thermal power and electrical power for ICE technology (1÷1000 kWel)

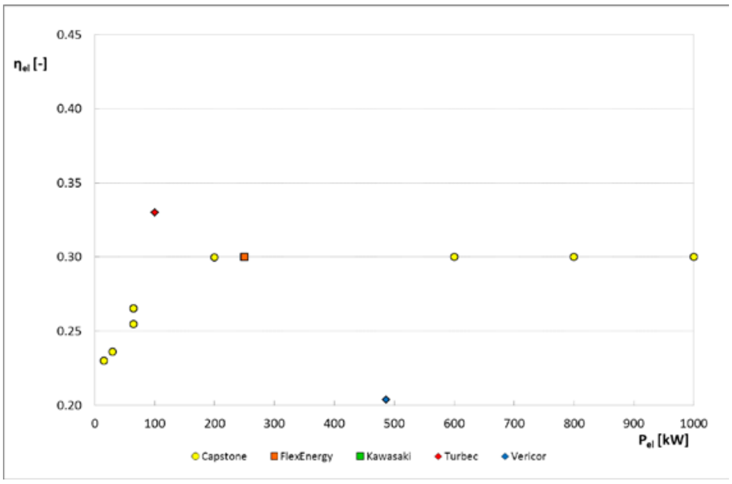

Fig. 5 Electrical efficiency and electrical power for GT technology (1÷1000 kWel)

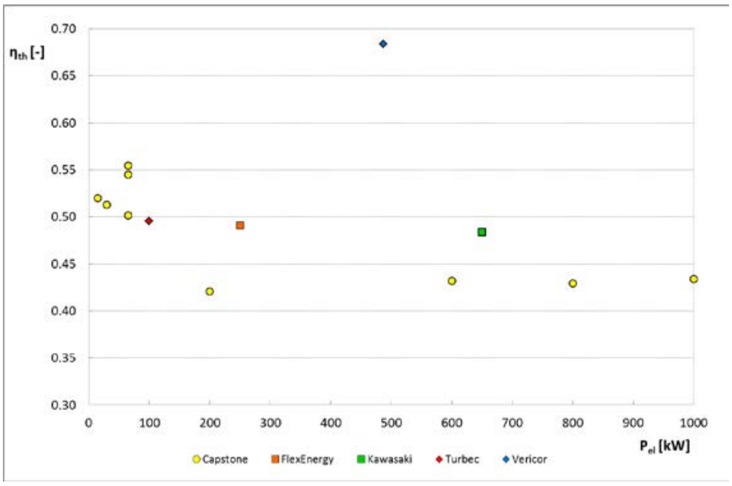

Fig. 6 Thermal efficiency and electrical power for GT technology (1÷1000 kWel)

Table 5 - Specific costs for GT

		Group 1 0÷25 kWel	Group 2 26÷50 kWel	Group 3 51÷100 kWel	Group 4 101÷1000 kWel
c_{pr}	[RMB/kW$_{el}$]	18500	7600	7600	6300
c_{eq}	[RMB/kW$_{el}$]	0	0	0	0
c_{in}	[RMB/kW$_{el}$]	800	440	340	170
c_{ma}	[RMB/kWh$_{el}$]	0,095	0,076	0,076	0,051
c_{lu}	[RMB/kWh$_{el}$]	0	0	0	0

In Table 5, the analysis of the mean values of the main parameters (c_{pr}, c_{eq} and c_{in} c_{ma} c_{lu}) characterizing the costs of CHP by using GT is reported. It is worth noting that for all GT plants within these groups some parameters are null. In fact, due to its compactness and mechanical design that includes all the parts required to produce heat and electrical power simultaneously, the specific cost c_{eq} is practically null. Moreover, as a result of the mechanical design of GT systems, the

May – June 2020
ISSN: 0193-4120 Page No. 7708 - 7716

amount of lubricant oil required can be disregarded, thus the value of the specific lubricant oil c_{lu} is relatively null.

VI. Case Study

In order to highlight the differences between the two technologies used for CHP, a case study based on the comparison between the results obtained by using ICE rather than GT technology is analyzed.

In particular, the energy demands in terms of annual thermal demand and annual electricity demand for a hotel located in Shanghai are met using both GT and ICE. In Table 6 the energy demands, the base-load and the specific costs used during the analysis are reported. Table 6 - Boundary condition for the case study

	Yearly Hours	[hr/yr]	8,760
D_t	*Annual Thermal Demand*	[kWh_t/yr]	9,200,000
D_e	*Annual Electricity Demand*	[kWh_e/yr]	8,000,000
	Thermal base-load	[kW]	617
	Electricity base-load	[kW]	426
c_f	*Fuel Cost*	[RMB/Nm^3]	2.8
LHV_f	*LHV Fuel (natural gas)*	[kWh_f/Nm^3]	9.59
c_e	*Electricity Cost*	[RMB/kWh_e]	0.8
c_t	*Thermal Energy Cost*	[RMB/kWh_t]	0.4
d	*Discount rate*	%	5%

Four different case studies are evaluated:

1) ICE and GT produce the same annual thermal energy (E_t), equal to the annual thermal energy demand of the hotel (D_t).
2) ICE and GT have the same thermal power (P_t), set to the thermal base-load of the hotel.
3) ICE and GT produce the same annual electrical energy (E_e) equal to the annual electrical demand of the hotel (D_e).

ICE and GT have the same electrical power (P_e) set to the electrical base-load of the hotel.In all four cases, we assumed that when the electrical demand or the thermal demand is not satisfied by CHP then they are provided at a specific cost (ce and ct respectively) from external sources, e.g. the electrical state grid or the city's district heating.

For each case, the different results coming from the use of
ICE or GT are evaluated after ten years with the Net Present Cost (NPC). As reported in Eq.1, the calculations of the NPC index involves the use of fixed and variable costs:

$$NPC_i = -I_0 + \sum_{k=1}^{i} \frac{F_i}{(1+d)^k} \qquad 1 \le i \le 10$$

where I_0 represents the sum of the fixed costs and F_i represents the sum of the variable costs. In particular, the two terms are defined by the following equations:

$$I_0 = C_{pr} + C_{eq} + C_{in}$$

$$F_i = C_{ma} + C_f + C_{lu} + C_e + C_t$$

For a given CHP system, C_{pr} is the production cost, C_{eq} is the equipment cost and C_{in} is the installation cost of the
CHP. The variable terms in Eq. 3 are the maintenance cost
C_{ma}, the fuel cost C_f, the lubricant cost C_{lu}, cost of electricity C_e and the thermal cost C_t of the electrical and thermal energy that have to be provided to the hotel from external sources if the CHP system cannot satisfy the demand.
The data collected for all four case studies analyzed are reported in Table 7.

As it can be seen, after ten years "case 1" has a minimum NPC for both ICE and GT. The choice of the CHP size is determined by the annual demand of thermal energy. This proves that sizing the CHP system by considering the required thermal base-load does not guarantee higher economic benefits. For "case 2" and "case 4", the size of the CHP system was chosen respectively to satisfy the thermal base-load and the electrical base-load of the hotel. The CHP systems were quite similar, providing that the NPC indexes were almost the same. To conclude, in "case 3" both CHP technologies were chosen to fulfill the annual electrical demands. However, this approach led to a surplus of heat production resulting in a waste of energy as the excess heat has to be dissipated.

What emerges from the previous data analysis is that for all four cases, the NPC indexes for GT systems are always higher than the NPC indexes for the analogous ICE systems. Thus, the higher availability and the lower cost of maintenance of GT with regards to ICE are not sufficient to compensate for the higher production costs and the lower efficiency of GT systems when compared to ICE.
Table 7(a) - Analysis results

	CASE 1		**CASE 2**	
	ICE	**GT**	**ICE**	**GT**

P_e	[kW_e]	797	632	431	360
P_t	[kW_t]	1,142	1,083	**617**	**617**
η_e	[-]	0.37	0.28	0.37	0.28
η_t	[-]	0.53	0.48	0.53	0.48
E_e	[kWh_e/yr]	6,422,642	5,366,667	3,471,386	3,058,284
E_t	[kWh_t/yr]	**9,200,000**	**9,200,000**	4,972,526	5,242,772
C_{pr}	[RMB]	717,240	3,978,958	387,662	2,267,475
C_{eq}	[RMB]	199,233	0	107,684	0
C_{in}	[RMB]	159,387	107,369	86,147	61,186
C_{ma}	[RMB/yr]	732,181	273,700	395,738	155,972
C_f	[RMB/yr]	5,068,172	5,596,107	2,739,307	3,189,034
C_{lu}	[RMB/yr]	96,340	0	52,071	0
C_e	[RMB/yr]	1,261,887	2,106,667	3,622,891	3,953,373
C_t	[RMB/yr]	0	0	1,690,989	1,582,891
NPC_{10}	[RMB]	-56,352,516	-65,678,542	-66,223,930	-70,907,479

Table 7(b) - Analysis results

		CASE 3		CASE 4	
		ICE	GT	ICE	GT
Pe	*[kWe]*	993	941	**426**	**426**
Pt	*[kWt]*	1422	1,614	610	730
ηe	*[-]*	0.37	0.28	0.37	0.28
ηt	*[-]*	0.53	0.48	0.53	0.48
Ee	*[kWhe/yr]*	**8,000,000**	**8,000,000**	3,433,219	3,619,807
Et	*[kWht/yr]*	11,459,459	13,714,286	4,917,855	6,205,384
Cpr	*[RMB]*	893,389	5,931,366	383,400	(1)2,683,800
Ceq	*[RMB]*	248,164	0	106,500	0
Cin	*[RMB]*	198,531	160,053	85,200	72,420
C_{ma}	[RMB/yr]	912,000	408,000	391,387	184,610
C_f	[RMB/yr]	6,312,882	8,342,023	2,709,189	3,774,564
C_{lu}	[RMB/yr]	120,000	0	51,498	0
C_e	[RMB/yr]	0	0	3,653,425	(2)3,504,154
C_t	[RMB/yr]	0	0	1,712,858	1,197,846
NPC_{10}	[RMB]	-58,055,317	-73,656,776	-66,351,592	(3) -69,635,519

CONCLUSION

A comparison between the two most established small CHP technologies, namely Internal Combustion Engine (ICE) and Gas Turbine (GT), was presented in this paper.

From the efficiency point-of-view, ICEs presents higher electrical and thermal efficiency and therefore a lower specific fuel consumption w.r.t. GTs. Moreover, ICE has a lower initial investment cost if compared to an equivalent GT system.

On the other hand, GT systems have lower maintenance costs and a longer operating time, thus reducing the number of routine maintenance operations. This implies that a GT system has to be off-line for less time than an ICE system. Moreover, a GT system produces less pollutant emissions such as CO and NOx.

A benchmark research provided the main features of ICE and GT systems currently available on the Chinese market with a size lower than 1 MWe. As the efficiency and the specific cost depend on the size, four groups of systems have been identified depending on the nominal power (0÷25 kWe, 26÷50 kWe, 51÷100 kWe and 101÷1000 kWe).

The availability during the year and the pollutant emission of ICE and GT were compared. The data collected by the benchmark were used to compare ICE and GT by referring to a specific case, i.e. the energy demands for a hotel located in Shanghai. The energy (electrical and thermal) was supplied to the hotel by alternatively using GT and ICE. By exploiting the NPC index defined in Eq.1, it was found that a CHP based on ICE has a lower NPC than using GTs.

Four cases were analyzed; the results show that the choice of the CHP size is related to the fulfillment of the annual thermal energy demand and not only to cover the electrical base-load. To conclude, from our analysis it shows that the production cost of GT is a major factor as to why the widespread use of GT in China is limited.

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May – June 2020
ISSN: 0193-4120 Page No. 7708 - 7716

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