Economic analysis of a micro humid air turbine and an internal combustion engine based on hourly demand

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Abstract:

Micro Gas Turbines (mGTs) offer valuable advantages for small-scale Combined Heat and Power (CHP) production compared to internal combustion engines (ICEs): lower maintenance costs, cleaner exhaust, concentration of the residual heat in a single source (the exhaust gases), etc. Nevertheless, mGTs have lower electrical efficiencies, fact that has prevented them from penetrating in the CHP market. Hot liquid water injection—by means of a saturation tower within the micro Humid Air Turbine (mHAT) cycle—allows both improving the flexibility of heat production and the electrical efficiency of mGTs; two qualities that if enhanced would result in an increased economic feasibility of the technology.

This paper presents a comparison of the economic profitability and the primary energy savings of an mGT, an ICE and an mHAT unit operated in real network conditions. The input to the study consists of (1) hourly heat and electricity demand profiles of two distinctive users and (2) 25 electricity and natural gas price scenarios. Our aim is to investigate whether the increase in flexibility and electrical efficiency achieved when transforming an mGT into an mHAT allows them to outperform ICEs.

Results show that the three technologies are viable in scenarios with high electricity and low natural gas prices. For those cases in which investment is feasible, the revenues with mHAT are the highest. This is due to the fact that mHAT units are able to run all year long thanks to their heat generation flexibility. On the other hand, the greatest primary energy savings are achieved with ICE units—which have the highest overall efficiencies—while mHAT savings are substantially lower.

Keywords:

Distributed Generation, Combined Heat and Power, micro Gas Turbine, micro Humid Air Turbine, Internal Combustion Engine.

1. Introduction

Micro Gas Turbines offer important advantages for small scale (up to 500 kW_e) Combined Heat and Power (CHP) production compared to Internal Combustion Engines (ICEs): low vibration level, a smaller number of moving parts, cleaner exhaust and lower maintenance costs [1]. In addition, the usable heat in mGTs is concentrated in the high temperature exhaust gases, while in ICEs it is distributed between the cooling jacket, the exhaust gases and the lubricant oil, making it much more complicated to collect [2]. Nevertheless, the electrical efficiency of mGTs is limited to 30 %, whereas values for ICE go up to 34-35 % [3]. Hence, whenever the heat demand is low and the overall efficiency of the mGT comprises only the electrical efficiency, operation of the unit may not be economical [4].

An increase in electrical efficiency in moments of low external heat demand could allow boosting the viability of mGTs and promoting their penetration in the micro CHP market. To this end, whenever the heat demand is below the nominal output of the mGT, the heat in the exhaust gases—instead of blown off—can be used to warm up water to then re-inject it back into the cycle, following the same principle as the Humid Air Turbine (HAT) developed by Rao [5]. The layout of the micro humid air turbine (mHAT) concept is shown in Fig. 1. On the one hand, the air in the exhaust gases heats up water in the water heater; subsequently, this water is directed towards the saturation tower. On the other hand, after the compressor, the airflow is also passed through the saturation tower, where energy and mass transfer between air and water takes place. Water injection in mHATs therefore enables recuperating part of the energy in the exhaust gases—that would otherwise be lost—as well as augmenting the mass flow through the turbine for a given compressor input (due to the water that evaporates in the saturator). This, in turn, translates to an increase in electrical efficiency that can range from 2 to 4%, depending on the configuration [6, 7].

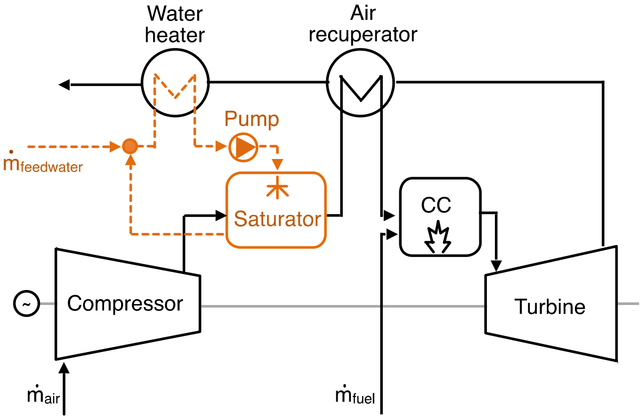


Fig. 1. In black, the typical components of an mGT. In orange, the saturation tower, pump and additional piping required to transform the cycle into an mHAT.

Several authors have studied the economics of mGT and ICE cycles for CHP applications [4, 8, 9]. However, these studies assume a certain amount or running hours for the technology and base the economic analysis on the market conditions of a specific country—with a given natural gas and electricity price. In previous publications [10, 11], the authors of this paper have reported the results of an economic analysis of mGT and mHAT cycles considering the hourly heat and electricity demands of several users—and therefore accounting for power and electricity peaks. In addition, we took into consideration a wide range of scenarios with different electricity and natural gas prices. In the present paper, the economic analysis is extended to ICEs: the main competitor of mGTs in the micro CHP market. The goal of this study is to compare the profitability of mGT, mHAT and CHP technologies and to proof whether the enhanced electrical efficiency and flexibility of heat production of mHATs (at an increased cost) allows them to economically outperform ICEs.

2. Methodology

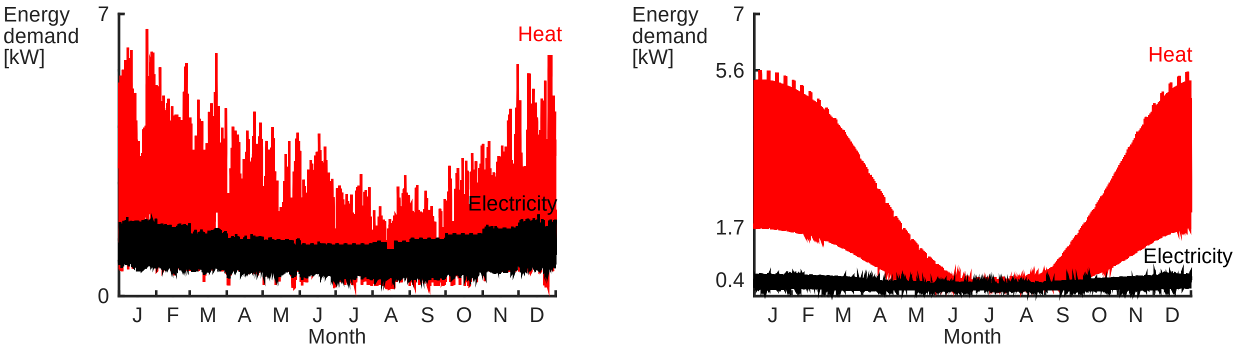
The economic performance of a CHP unit (either based on an mGT or an ICE) depends on the electricity and natural gas prices of the market in which the engine operates. These two variables greatly fluctuate per country and per year. In order to ensure the applicability of this study, we have considered 25 electricity and natural gas price scenarios, with values based on European data from 2002 till 2013 [12, 13]. The prices range from 0.1 to 0.3 €/kWh for electricity and 0.02 to 0.06 €/kWh for natural gas.

The technical specifications of the three evaluated technologies are included in Table 1. The studied ICE is the 2G Cenergy Patruus Series, an engine run on natural gas with an electrical power output of 100 kW_e and a heat output of 143 kW_{th}. The mGT is the Turbec T100, which has the same electrical power (100 kW_e) but a thermal output of 165 kW_{th}. Both of the studied units—the ICE and the mGT—are representative of the current technologies for their specific cycle. The mHAT cycle is based on the Turbec T100 mGT, assuming that it has been equipped with a spray saturation tower as described in [14]. This mHAT facility has been built and tested at Vrije Universiteit Brussel [15]. Simulations in Aspen Plus show that with full water injection, the T100 mHAT can achieve an electrical efficiency increase of 3.8 % [6]. The mHAT can either operate as a CHP unit (in dry operation mode) or with water injection (wet operation mode) when there is no heat demand. Intermediate operation modes (generating external heat while injecting water), when the heat demand is below the nominal heat output of the T100 mGT are also possible and have been included in this study. The lifetime of all the units, as indicated in their technical specifications, is 60 000 h of operation. Therefore, the lifetime in years of each technology depends on the yearly amount of running hours of the specific scenario.

Table 1 Technical specifications of the three evaluated technologies. mHAT can operate in dry operation mode (as a CHP unit), with water injection or in intermediate operation modes. Sources:[16, 17].

		mGT Turbec T100	mHAT Turbec T100		ICE 2G Cenergy Patruus-series
			Dry operation	*Full water injection*	
Nominal P_e	[kW]	100	100	100	100
Nominal P_{th}	[kW]	165	165	0	143
Nominal η_e	[%]	30	30	33.8	34.8
Nominal η_{th}	[%]	50	50	-	50
Lifetime	[h]	60 000	60 000	60 000	60 000

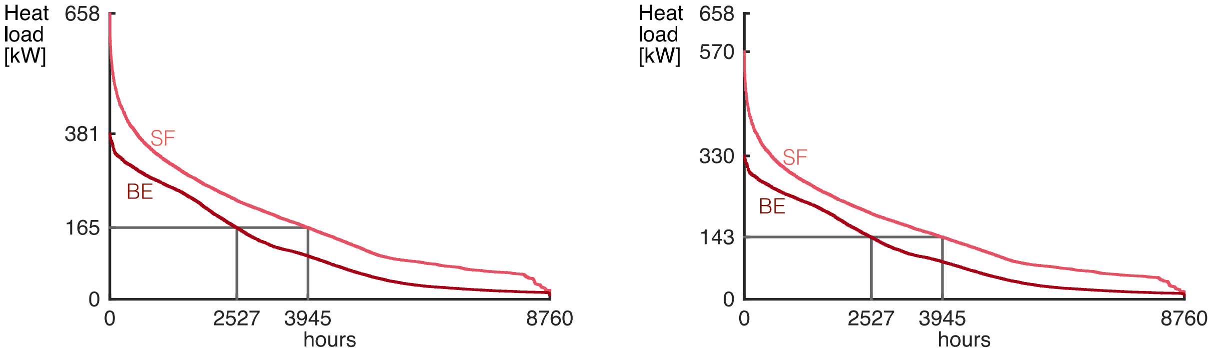
In order to compare how mGT, mHAT and ICE technologies would perform in real market conditions, we have investigated two users exposed to two different climates: one located in Brussels (Belgium) and the other one in San Francisco (USA). It is important to note that the aim of this study is not to compare the demands of users in different parts of the world but to evaluate the performance of the aforementioned technologies for users with distinctive demand profiles. While the data available for San Francisco (illustrated in Fig. 2a) corresponds to the hourly heat and electricity demand of an average dwelling [18], Belgian data tallies to synthetic load profiles: standardised load profiles assigned to small consumers and generally used by system operators to forecast and balance energy demand [19]. Given that load profiles do not represent actual meter readings, they are composed of smooth curves, without peaks; however, we considered them suitable for this study since they reproduce well demand fluctuations during the day and over the year. The values corresponding to the overall yearly heat and electricity consumption for an average European dwelling were taken from [20, 21], resulting in the demand shown in Fig. 2b.



(a) San Francisco (b) Brussels

Fig. 2. The electricity and heat demand profiles of the user in Brussels are based on synthetic load profiles and therefore follow a smooth trend. On the contrary, the demand of the San Francisco user is based on real meter readings.

Among the different options for sizing the demand of CHP units, some of them described in [11, 22-24], the chosen method is the one presented in [11] for which the maximum rectangle area under the heat load curve has a height equal to the heat output of the unit (see Fig. 3). This methodology maximises the amount of heat provided by the CHP unit—and therefore minimises the heat provided by the additional boiler—for the user's demand. The three evaluated technologies have the same electrical output (100 kW_e); however, the nominal heat output of the mGT and mHAT cycles is 165 kW_{th}, whereas the ICE heat output is 143 kW_{th}. Thus, according to this method, the number of dwellings for which the mHAT and mGT provide energy is 99 for the San Francisco case and 68 for the Belgian case. On the other hand, the ICE unit supplies energy to 86 dwellings in San Francisco and 59 in Belgium.



(a) Heat load curve for mGT and mHAT cycles

(b) Heat load curve for ICE cycle

Fig. 3. The demand of the San Francisco and Brussels users is sized so that the maximum rectangle area under the heat load curve corresponds to the heat output of the mGT T100 (165 kW_{th}, left) or to the ICE cycle (143 kW_{th}, right).

The three engines (mGT, mHAT and ICE) run following the hourly heat demand. When the demand is above the nominal heat output of the unit, the engine operates at full load and a boiler provides the extra-required heat. For the mGT and ICE cases, when the demand is between full and 50 % load, the unit runs at part load according to the required heat and at the corresponding reduced electrical and thermal efficiencies. When the demand is below the 50 % load threshold the engine is shut down and the boiler fulfils the heat requirements. In terms of electricity, the unit supplies the demand whenever possible and the missing/extra electricity is purchased/sold to the electricity network.

Contrarily to the mGT and ICE units, the mHAT cycle is able to follow the heat demand while maintaining a high efficiency and without rejecting heat to the environment. Therefore, it can run all year long: when the heat demand is below the nominal T100 heat output, the water warmed up in the water heater is first used to fulfil the heat demand and then injected in the saturation tower. The obtained efficiency increase with water injection depends on the temperature at which the water enters the saturation tower, which is in turn based on the external heat demand. When the heat demand is between 165 and 134 kW_{th}, the water temperature after the water heater is too low to be introduced in the saturation tower. If injected, energy transfer takes pace from air to water instead of from water to air. For this reason, when the demand is between the aforementioned values, the mHAT runs in dry operation mode at part load [11]. When the heat demand is below 134 kW_{th}, the unit runs at full load with water injection.

2.1. Costs and benefits

We have evaluated the profitability of the technologies using Net Present Value (NPV) and Internal Rate of Return (IRR) methodologies. The costs and benefits taken into account for both NPV and IRR calculations are described in Tables 2 and 3.

Table 2 Costs taken into consideration in the analysis

Costs	*mGT*	*mHAT*	*ICE*	*Comments and references*
Capital cost of the unit	€180 000	€198 000	€135 000	The estimated price of a commercial version of the water cycle installed at VUB's mHAT is €18 000 (i.e. 10 % of the mGT capital cost). The ICE price is based on current market values.
Boiler capital cost	€15 000	€15 000	€15 000	Source: [25]
Operation & maintenance costs	0.015 €/kWh$_e$	0.0165 €/kWh$_e$	0.026 €/kWh$_e$	O&M costs of the T100 mGT have been taken from [26]. O&M costs for mHAT are assumed to increase by the same proportion as capital costs do, i.e. by 10 %. ICE costs are based on current market values.
Consumed natural gas		$\left(\text{Boiler} + \text{unit}\right)_{\text{gas cons.}} \times \text{price}_{\text{gas}}$		Natural gas consumption of the unit and of the additional required boiler.
Water cleaning costs	N.A.	2.35 €/m^3	N.A.	Water costs are based on data from [27]. We have chosen the most conservative rates for treatment plants using ion exchange technology to produce de-mineralized water from tap water to be fed to boilers. Values for surface water would only amount to a few €cents/m^3.

Table 3 Benefits taken into consideration in the economic analysis

Benefits	*mGT*	*mHAT*	*ICE*	*Comments and references*
Avoided natural gas		$\frac{\text{Total heat by the unit}}{\eta_{\text{boiler}}} \times \text{price}_{\text{gas}}$		By simultaneously generating electricity and heat, the natural gas costs associated to producing heat by traditional means (i.e. with a natural gas boiler) are avoided.
Avoided electricity		$\text{Electricity}_{\text{cons.}} \times \text{price}_{\text{electricity}}$		By consuming the electricity produced by the CHP or mHAT unit, the cost of buying this electricity from the grid is avoided
Sold electricity		$\text{Electricity}_{\text{sold}} \times \frac{\text{price}_{\text{electricity}}}{2}$		The electricity produced by the units that is not consumed by the user is sold to the grid at half of the electricity price. Given that this is a strong assumption, we have performed a sensitivity analysis on this price (see Section 3.4).

2.2. Primary Energy Savings

A primary energy savings study allows comparing the performance of CHP systems with respect to a reference scenario. In this analysis, we have considered a reference system in which heat is provided by a boiler with an overall energy efficiency of 90 %, and electricity is generated by a combined cycle with an efficiency of 50 %.

For each technology, we have compared the unit's primary energy, required to achieve its yearly heat and electricity production, to that consumed by a reference system that would generate the same power and heat output.

3. Results

In this section we will first introduce the results concerning the primary energy savings study. Subsequently, we present the NPV and the IRR results for the values introduced in Section 2. Finally we show the outcome of a sensitivity analysis in which demand, O&M costs and the price of electricity sold to the grid fluctuate with respect to their base value.

3.1. Primary Energy Savings

All the three evaluated technologies (ICE, mGT and mHAT) offer energy savings with respect to the reference scenario, as shown in Fig. 4. Primary energy savings have been expressed as a percentage relative to the total consumption of the reference scenario.

The technology with higher primary energy savings is the ICE, fact that is explained by its high electrical and thermal efficiencies. Both ICE and mGT always operate in CHP mode, i.e. simultaneously generating electricity and heat and with overall energy efficiencies of 70-80 %. If the heat demand drops below the unit's 50 % load threshold, the engine is shut down. On the contrary, mHATs are run all year long: in CHP mode when the heat demand is above 134 kW, and in wet operation mode the rest of the time. Water injection allows increasing the electrical efficiency by 3.8 %. Nonetheless, this still means that during wet operation the overall efficiency of the cycle is reduced to the electrical efficiency (33.8 %). Therefore, mHAT is the technology that provides the lowest energy savings. The reason why mHAT primary energy savings are much lower in Brussels than in San Francisco relates to the heat demand: while in San Francisco the mHAT runs 4630h in dry operation (as a CHP unit), in Brussels it only operates as CHP for 2990h.

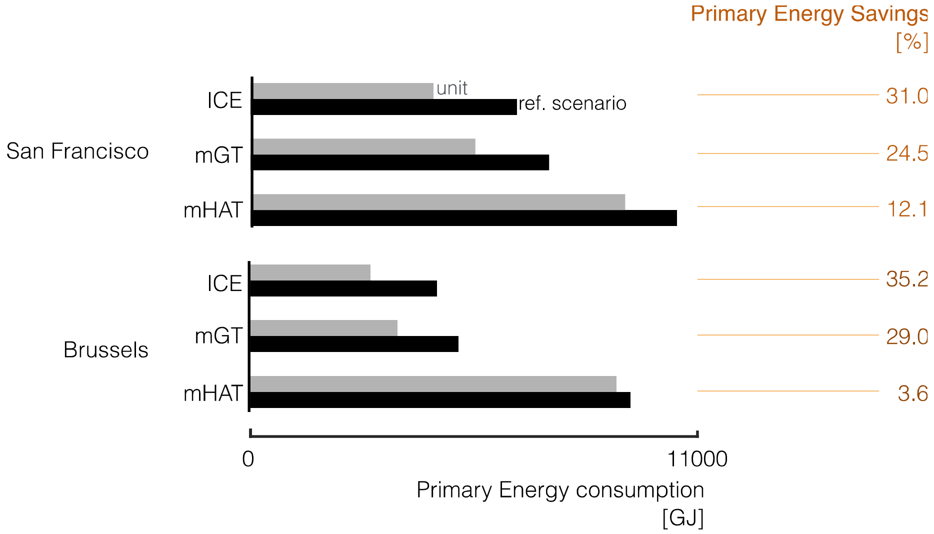


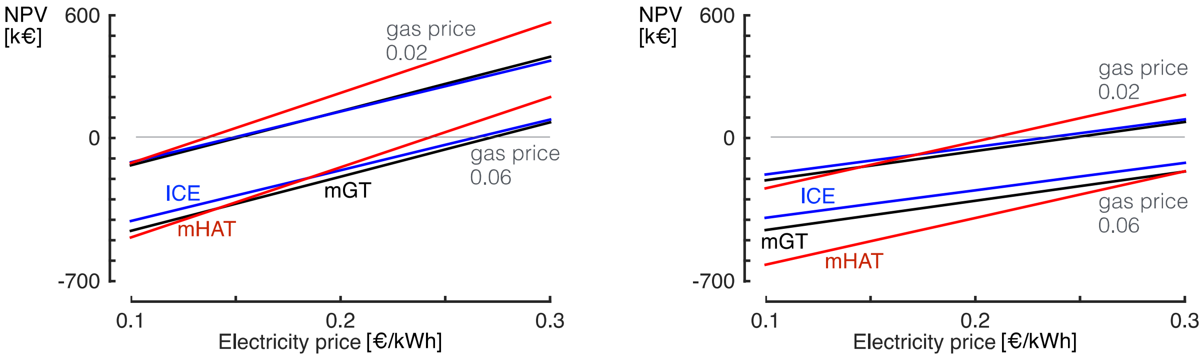
Fig. 4. The technology that provides the greatest primary energy savings is the ICE, given that it has the highest energy efficiencies. mHAT energy savings are considerably lower due to the fact that, when operating with water injection, the overall efficiency is reduced to the electrical efficiency of the unit.

3.2. NPV results

The NPV results for the mGT, mHAT and ICE technologies for all the electricity price range and for the lowest and highest gas prices are shown in *(a) San Francisco*

(b) Brussels

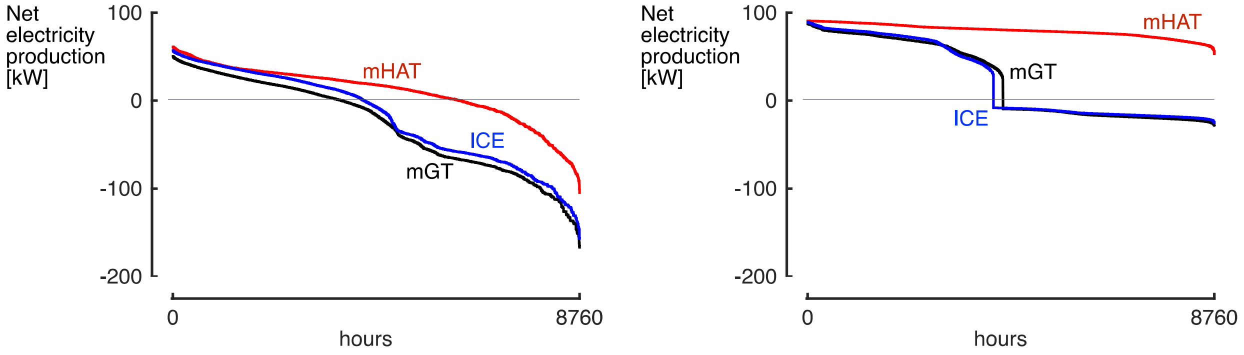
Fig. 5, assuming a discount rate of 10 %. As expected, the NPV of all three technologies increases as the electricity price rises and the gas price diminishes. For all the viable scenarios, i.e. those that have an NPV greater than zero, the mHAT unit is the most profitable technology since it offers the highest NPV value. ICE and mGT technologies present, in comparison to mHAT, a similar economic performance in most of the scenarios: the savings corresponding to the increased electrical and thermal efficiency of ICEs are compensated by their higher O&M costs compared to mGTs. The superior performance of mHAT technology is linked to the operational flexibility that this cycle provides: it is able to operate all year long and therefore capable of fulfilling all the heat demand (except the heat peaks) as well as a greater part of the electricity demand.



(a) San Francisco *(b) Brussels*

Fig. 5. NPV rises as the electricity price increases and the natural gas price decreases. In scenarios with high electricity and low natural gas prices, investment in the three technologies is profitable. In these cases, mHAT always offers the highest NPV values.

As observed in Fig. 5, NPVs of the San Francisco units are higher than those of Belgium. This is due to the fact that, as previously shown in Fig. 2, the electricity use per dwelling in San Francisco is much larger than in Brussels: in fact, the average electricity demand over the year for the mGT and mHAT users in San Francisco is 90 kW, whereas the average in Brussels amounts only to 20 kW. Hence, in San Francisco the users consume most of the electricity generated by the units (i.e. the net electricity production is low, see Fig. 6a), while in Brussels most of the electricity produced is sold to the grid (see Fig. 6b). In San Francisco there are moments when the electricity produced by the mHAT unit is lower than the demanded electricity, which means that the extra-required electricity has to be purchased from the grid and which translates into a negative net electricity production in Fig. 6.



(a) San Francisco *(b) Brussels*

Fig. 6. The net electricity production (i.e. electricity production of the unit minus the user's consumption) in San Francisco is much smaller in Brussels.

3.3. IRR results

NPV methodology requires the assumption of an arbitrary discount rate. A complementary analysis of the NPV method is the Internal Rate of Return (IRR), defined as the interest rate that produces a NPV of zero for the cash flow stream. The IRR of the mGT, mHAT and ICE units for the two studied users (located in San Francisco and in Brussels) are presented in Table 4.

Table 4. IRRs (in percentage) for the mGT, mHAT and ICE cases in Belgium and San Francisco. Dashes are inserted when no result was obtained when equalising the NPV to zero. No result or a negative number indicates that the project is not economically feasible.

(a) mGT, San Francisco

		Electricity prices [€/kWh]				
		0.1	**0.15**	**0.2**	**0.25**	**0.3**
Gas prices [€/kWh]	**0.02**	-10.4	9.9	23.9	36.3	47.9
	0.03	-	-0.8	15.8	28.9	40.9
	0.04	-	-17.8	6.5	21.2	33.8
	0.05	-	-	-5.4	12.7	26.3
	0.06	-	-	-34.1	2.8	18.4

(b) mGT, Brussels

		Electricity prices [€/kWh]				
		0.1	**0.15**	**0.2**	**0.25**	**0.3**
Gas prices [€/kWh]	**0.02**	-	-6.4	3.5	10.7	16.8
	0.03	-	-	-4.5	4.7	11.7
	0.04	-	-	-22.1	-2.9	5.8
	0.05	-	-	-	-16.3	-1.3
	0.06	-	-	-	-	-12.7

(c) MHAT, San Francisco

		Electricity prices [€/kWh]				
		0.1	**0.15**	**0.2**	**0.25**	**0.3**
Gas prices [€/kWh]	**0.02**	-11.3	16.8	37.8	56.6	74.4
	0.03	-	3.6	27.1	46.7	65.0
	0.04	-	-13.8	15.4	36.6	55.4
	0.05	-	-	1.9	25.8	45.6
	0.06	-	-	-16.4	14.0	35.4

(d) MHAT, Brussels

		Electricity prices [€/kWh]				
		0.1	**0.15**	**0.2**	**0.25**	**0.3**
Gas prices [€/kWh]	**0.02**	-	-13.4	7.43	23.0	36.6
	0.03	-	-	-8.8	10.5	25.6
	0.04	-	-	-44.0	-4.7	13.4
	0.05	-	-	-	-29.8	-0.9
	0.06	-	-	-	-	-22.0

(e) ICE, San Francisco

		Electricity prices [€/kWh]				
		0.1	**0.15**	**0.2**	**0.25**	**0.3**
Gas prices [€/kWh]	**0.02**	-14.5	10.7	26.6	40.5	53.8
	0.03	-	-1.1	17.8	32.5	46.2
	0.04	-	-	-22.1	-2.9	5.8
	0.05	-	-	-5.1	15.3	30.4
	0.06	-	-	-	4.8	21.9

(f) ICE, Brussels

		Electricity prices [€/kWh]				
		0.1	**0.15**	**0.2**	**0.25**	**0.3**
Gas prices [€/kWh]	**0.02**	-	-7.4	4.5	12.7	19.7
	0.03	-	-	-4.2	4.7	14.2
	0.04	-	-	-42.7	-1.5	8.2
	0.05	-	-	-	-16.0	0.9
	0.06	-	-	-	-	-10.3

IRR ‘expects’ cash outflows in the earliest years after the investment, eventually overweight by incoming returns so that net cash inflows are obtained towards the end of the lifetime of the project. Whenever the yearly cost exceed the yearly benefits or whenever the capital costs are too high, it may not be possible to find a value for the IRR or the IRR may be negative. In these cases, the IRRs can be difficult to interpret or meaningless [28].

The same message as for the NPV analysis is withdrawn from the results shown in Table 4: high electricity and low natural gas prices yield higher IRRs for all the technologies. The technologies in San Francisco give higher profits than in Brussels. When the IRR has a positive value, mHAT technology is more profitable than ICE and mGT. In addition, there are more scenarios with positive IRRs for mHAT than for mGT and ICE, which means that mHAT is profitable for a wider variety of prices than mGT and ICE are.

3.4. Sensitivity analysis

The economic analysis outlined above strongly depends on different assumption: the sizing method, the user's demand, the costs and benefits, etc. Thus, we have analysed the sensitivity of the results to changes on the three most important parameters: (1) the user's demand, which could change from year to year due to climate variations; (2) O&M costs, which may decrease as the technologies mature and (3) the price at which the electricity is sold to the grid compared to the price at which electricity is purchased (named price factor in this analysis).

Among the 25 electricity and natural gas price scenarios, we have chosen the one with higher electricity (0.3 €/kWh) and lower natural gas prices (0.02 €/kWh) to perform the sensitivity analysis. This is the only case for which IRRs of all the technologies are well above 10 %. Figs. 7 and 8 illustrate the results for the San Francisco and Brussels users. The graphs are normalised in order to more easily identify which technology is more sensitive to a specific change. It is important to mention that in all cases and for all fluctuations, mHAT always arose as the technology with the highest NPV.

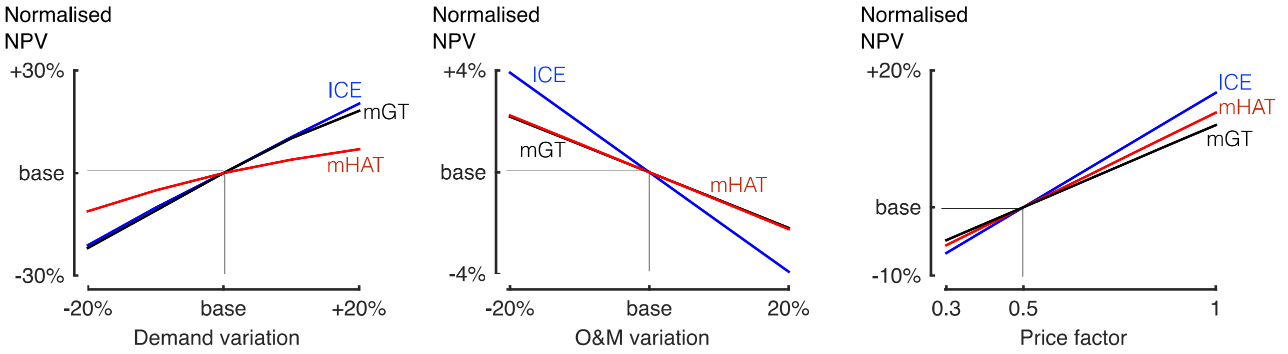


Fig. 7. Sensitivity analysis for the San Francisco user. As anticipated, NPV is higher for increasing demand and lower for increasing O&M costs. The price factor indicates the relationship between the price at which electricity is sold to the grid with respect to the price at which it is purchased. For higher sold electricity prices, the NPVs augment; however, this effect is much more limited for the San Francisco than for the Brussels user.

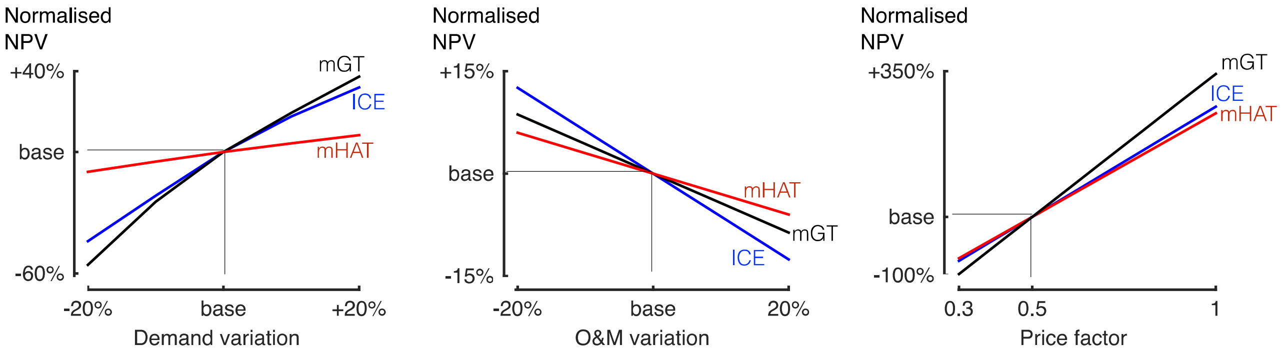


Fig. 8. Sensitivity analysis for the Brussels user. Given the low electricity demand of this customer, most of the electricity produced by the units is sold to the grid. Therefore, the NPV of the technologies is extremely sensitive to the price of sold electricity, which can go up by 350 % if electricity was sold at the same price at which it is purchased from the grid.

As expected, higher heat and electricity demands lead to higher NPVs for all the technologies and for both users. This is deduced from the fact that an increased heat demand entails a larger number of working hours in CHP or dry operation mode, i.e., when the overall efficiency of the cycle is at its maximum. Also for this reason demand fluctuations in Brussels have a greater impact than in San Francisco. While the profitability of ICE and mGT similarly reacts to changes in demand, mHAT is much less sensitive. This is due to the fact that, as opposed to ICE and mGT, mHAT runs all year long. In addition, this also illustrates the flexibility of mHAT in real applications.

A reduction in O&M costs involves an increase in the NPV of the engines: the most sensitive technology to this change is the ICE given that its O&M costs are the highest. Again, Brussels user is more sensitive to variations in this parameter than San Francisco user.

Finally, the economic performance of the user in Brussels would be acutely affected by subsidies on the electricity produced (in this case, these subsidies would be represented by electricity sold prices close to the price of purchased electricity). For a price factor equal to one, i.e., for a price of sold electricity equal to the price of purchased electricity, the NPV of the mGT unit increases by 350 %, with ICE and mHAT NPV also ramping up by 280 %. If electricity were sold at a third of the price of purchased electricity, the three technologies would have an NPV close to zero. In contrast, the San Francisco user is much more insensitive to subsidies: varying the sold electricity between the same ranges only leads to variations of +20 or -10 % in the NPV of the units.

4. Conclusion

In the present paper we have analysed the economic profitability of an mGT, an ICE and an mHAT unit for 25 electricity and natural gas price scenarios and for two types of users with distinctive heat and electricity demand profiles—one located in Brussels and the other one in San Francisco. All the units run following the heat demand, which is evaluated on an hourly basis, and the lack or extra electricity is either purchased or sold to the grid.

Results show that the viability of all three technologies greatly depends on the electricity and natural gas price combination: high electricity and low natural gas prices lead to lucrative investments. For scenarios where the investment is feasible, mHAT technology clearly outperforms mGT and ICE. In addition, mHAT is viable for a wider range of electricity and natural gas prices than both mGT and ICE.

The sensitivity analysis revealed that the Brussels user, with an electricity demand much lower than the nominal production of any of the three units, is extremely sensitive to the price at which electricity is sold to the grid. This price is subject to subsidies in many countries and can be used as a policy mechanism to promote the proliferation of small-scale CHP. If in Brussels electricity is sold at the same price at which it is purchased (instead of at half), the NPVs of the studied units increase by 350 %. Hence, subsidies would certainly contribute to an increased investment in CHP technology.

Finally, the primary energy savings analysis disclosed that mHAT savings are substantially lower than those of ICE. The flexibility of heat production of the mHAT units, which allows for a higher profitability, also means that the technology runs as an electricity-generating facility during a part of the year. The electrical efficiency of mHAT (~34 %) is much lower than the overall CHP efficiencies of ICE and mGT (~70-80 %). Thus, the energy savings are lower. However, if the higher profitability of mHAT attracts more investment in the micro CHP sector, there is a great potential for overall primary energy savings as a consequence of a more widespread adoption of distributed domestic CHP units.

Acknowledgements

The work leading to the results of this study has been supported by Electrabel S.A. under the project FlexiHAT.

Nomenclature

CHP	Combined Heat and Power
ICE	Internal Combustion Engine
IRR	Internal Rate of Return
mGT	micro Gas Turbine
mHAT	micro Humid Air Turbine
NPV	Net Present Value
O&M	Operation and Maintenance
P	Power output

Greek symbols

η	efficiency

Subscripts and superscripts

e	Electrical
th	Thermal

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