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Economic Analysis of a Micro Humid Air Turbine for Domestic Applications

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Abstract

Micro Gas Turbines (mGT) appear as a promising technology for small-scale (up to 500 kW) Combined Heat and Power (CHP) production. However, their rather low electric efficiency limits their profitability when the heat demand decreases. Hot liquid water injection in mGTs –particularly within the micro Humid Air Turbine (mHAT) cycle– allows increasing electric efficiency by making use of the flue gas residual heat in moments of low heat demand.

Based on simulations performed on a Turbec T100 mGT –modified to operate as an mHAT– installed at the VUB, this paper presents an analysis of the economic profitability of such facility running on real network conditions. The study is performed assuming typical electricity and heat demand profiles for a domestic consumer. 25 natural gas and electricity price combinations have been taken into consideration, along with two types of domestic customers –with higher and lower heat demands. Results show that the profitability of the mHAT with respect to the equivalent CHP facility increases with higher electricity and lower natural gas prices. In particular, given a certain number of CHP running hours and a natural gas price, there is a threshold for the electricity price above which the net income of the mHAT unit is always higher than that of the corresponding CHP unit. In addition, water-cleaning costs for the mHAT case appear to constitute only 1 to 2.5% of total running costs.

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Keywords: micro Gas Turbine; mico Humid Air Turbine; economic analysis; distributed generation

Nomenclature

CHP	Combined Heat and Power
NPV	Net Present Value
mGT	micro Gas Turbine
mHAT	micro Humid Air Turbine

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1. Introduction

Micro Gas Turbines (mGTs) have aroused as a promising technology for decentralised Combined Heat and Power (CHP) operation, with overall energy efficiencies amounting up to 80%. Nevertheless, mGTs' rather low electric efficiency (around 30%) implies that their operation is heat-demand driven. Hence, when the heat demand is low, running the plant may not be economical eventually leading to shutdown. To address this issue, the residual heat in the flue gas can be utilised to warm up water which is re-injected in the cycle –at the back of the compressor– instead of being used for external heating purposes. Such type of facility, known as micro Humid Air Turbine (mHAT), would allow increasing the electric efficiency of the mGT when the heat demand drops, thus also incrementing the number of yearly running hours. At VUB, the Turbec T100 mGT (with an output of 100 kW_e and 166 kW_{th}) has been modified –by adding a spray saturation tower– to operate as an mHAT. Fig. 1 shows the layout of this first-of-a-kind facility. Humid simulations carried out by De Paepe et al. on the T100 working as an mHAT show that for a water injection rate of 36 g/s, the electric efficiency of the facility increases from 30 to 33.8% [1]. Recent experimental tests have proven the stable operation of VUB's T100 mHAT [2].

In the present paper, an economic feasibility analysis of the mGT T100 for domestic applications is presented. Two cases are studied: 1) the facility is operated as a CHP unit running the necessary number of hours to cover the heat demand and 2) the T100 is transformed into an mHAT which runs in CHP mode (dry operation) the number of hours required to cover the heat demand and the rest of the time as an mHAT (i.e., with water injection, wet operation) up to 8040h per year. The aim of this analysis is to find out under which conditions the installation of the water cycle –with the consequent increase of electric efficiency in wet operation mode– compensates for the additional capital, water and maintenance costs. That is, the circumstances under which the mHAT cycle is more profitable than the T100 working only as a CHP unit.

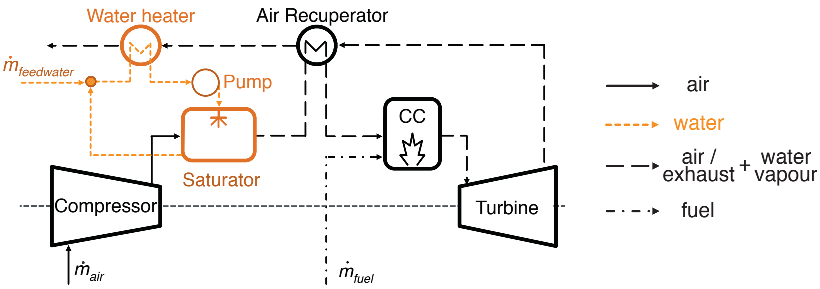

Fig. 1 Layout of the Turbec T100 present at the VUB transformed into an mHAT [3].

2. Methodology

The feasibility of a particular CHP or mHAT unit depends on specific market conditions, particularly on natural gas and electricity prices. These two variables substantially fluctuate per country and per year. In order to cover a wide range of scenarios, five different electricity (from 0.1 to 0.3 €/kWh) and natural gas (from 0.02 to 0.06 €/kWh) prices have been considered. These values are based on European data from 2002 till 2013 [4, 5]. The arising 25 price combinations used as an input for the economic analysis are shown in Fig. 2.

Electricity price (€/kWh) (- → +); *Natural gas price* (€/kWh) (- → +)

0.1 *0.02*	**0.15** *0.02*	**0.2** *0.02*	**0.25** *0.02*	**0.3** *0.02*
0.1 *0.03*	**0.15** *0.03*	**0.2** *0.03*	**0.25** *0.03*	**0.3** *0.03*
0.1 *0.04*	**0.15** *0.04*	**0.2** *0.04*	**0.25** *0.04*	**0.3** *0.04*
0.1 *0.05*	**0.15** *0.05*	**0.2** *0.05*	**0.25** *0.05*	**0.3** *0.05*
0.1 *0.06*	**0.15** *0.06*	**0.2** *0.06*	**0.25** *0.06*	**0.3** *0.06*

Fig. 2 25 combinations of electricity (in bold) and natural gas (in italics) prices.

The feasibility of the different cases is evaluated using the Net Present Value (NPV) of the costs and benefits during the lifetime of the facility. Capital, operation and maintenance, water cleaning and electricity costs taken into consideration are presented in Table 1.

Table 1 Value of the costs used in the feasibility study

Costs	CHP unit (dry operation)	mHAT mode (wet operation)	Comments and references
Capital costs	€180,000	€198,000	The estimated price of a commercial version of the water cycle currently installed at VUB's mHAT is 18,000 € (i.e. 10% of the mGT's capital cost).
Operation and maintenance costs	0,015 €/kWh	0,0165 €/kWh	O&Ms costs of the T100 operated as a CHP unit have been taken from [6]. mHAT O&Ms costs are assumed to increase by the same proportion as capital costs do, i.e. by 10%.
Water cleaning costs	-	2.35 €/m^3	Water costs are based on data from [7]. The values taken into consideration correspond to the most conservative rates for treatment plants using ion exchange technology to produce demineralized water from tap water to be fed to boilers. Figures for surface water would only amount to a few cents/m^3.
Purchased electricity costs	Case-dependent	-	CHP units are run the number of hours per month required to match the heat demand. Hence, during those months when the heat demand is especially low electricity production from the T100 is not enough to match the consumer's electricity demand and has to be purchased from the grid.

The benefits of making use of a CHP unit to simultaneously produce heat and electricity –instead of buying electricity from the grid and generating heat in a boiler– have been included in the analysis for both the CHP and mHAT modes. To this end, fuel costs associated to a natural gas boiler with an efficiency of 90% have been introduced as benefits. Adopting a conservative approach, capital costs for such boiler have not been considered. Furthermore, the analysis does not include any financial incentives from the authorities for CHP production. The excess of electricity generated by the facilities and not consumed by the customer is assumed to be sold to the grid at the same price as the cost of electricity. This factor represents a benefit for the mHAT units during all the months; however, this is not the case for the CHP facilities which are run to match the heat demand and therefore produce very little electricity during the summer months (see Fig. 3).

According to the T100 manual, the lifetime of the mGT corresponds to 60,000h of operation [8]. The lifetime in years has been calculated based on hours of yearly operation and this figure. A discount rate of 10% has been fixed for this analysis.

The yearly electricity and heat demand profiles for a typical domestic customer have been taken from Synergrid's Synthetic Load Profiles (SLP) for 2013 [9]. Overall heat demand over the year has been considered 4 times greater than the overall electricity demand, based on data on electricity and heat consumption by an average European dwelling [10, 11]. The demand is presumed to be smooth, with no peaks. For the case of the reference customer, it has been assumed that in January –which is the month in the year with the highest heat demand– the mGT is working at full load to provide heat during 31 days. During the rest of the year, the mGT works at full load the necessary time to match the corresponding monthly heat demand. As a result, in order to fulfill the yearly heat demand of the reference customer (which amounts to 679.6MWh), the mGT needs to operate as a CHP unit (i.e. in dry operation mode, without water injection) a total of 4118h per year. This heat demand corresponds to a group of 61 average European dwellings, according to data from the Odyssee project [11]. An economic analysis for a customer with a lower heat demand, which only requires a total of 2500 dry running hours per year, has also been conducted. In this case, the demand corresponds to a group of 37 dwellings. It has been assumed that the heating and electricity demand profiles change according to the SLP and Odyssee indicators. Fig. 3 shows the monthly heat and electricity demand for both the reference and the low heat demand consumers.

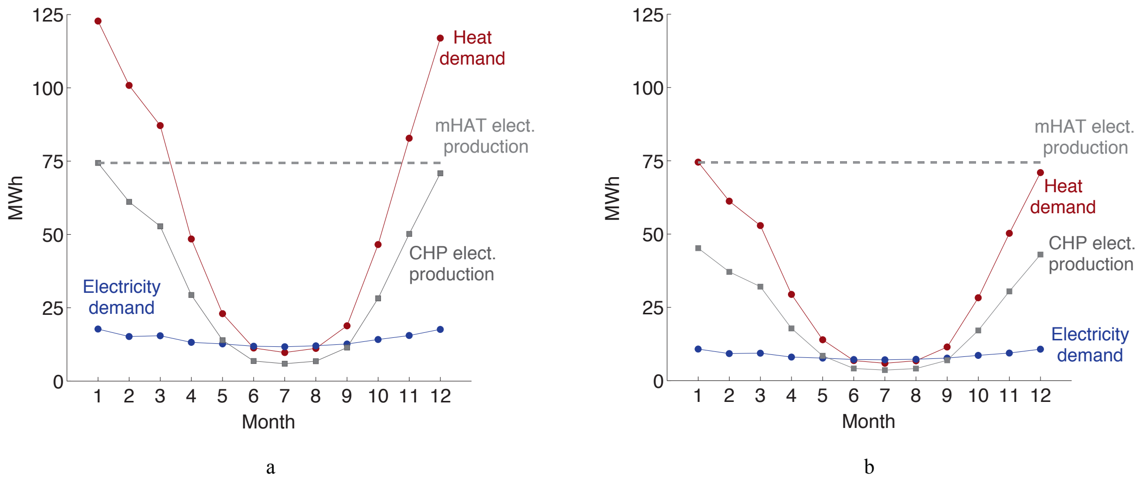

Fig. 3 Domestic monthly heat (in red) and electricity (in blue) demand for the (a) reference customer and (b) low-heat-demand consumer. mHAT and CHP electricity production are displayed in grey. Since heat demand is very low during the summer, the electricity produced by the CHP units during these months is not enough to match the demand; hence, additional electricity has to be bought from the grid. mHAT units are run all year long, producing extra electricity (which is sold to the grid) all the months.

3. Results and discussion

Fig. 4 shows the resulting NPV for both the reference and the low-heat demand consumers for a discount rate of 10%. The economic feasibility of both types of consumers strongly depends on the natural gas and electricity prices and on the relationship between these two variables. Increasing natural gas prices yield lower NPV values, while increasing electricity prices result in higher NPVs. For more expensive natural gas, higher electricity prices are required to make the facilities economically feasible (i.e. with positive NPV values). As expected, a higher number of dry running hours substantially increases the NPV of the CHP cases, which are shut down if not operating dry. For the mHAT cases this increase is not as acute since these facilities are assumed to run all year long (in wet mode when there is no heat demand).

The competitive advantage of transforming the mGT into an mHAT is more obvious for a reduced number of dry running hours. This translates to lower electricity prices required for the mHAT cases to become more profitable than the CHP cases (for a given natural gas price).

Fig. 5 illustrates how sufficiently high electricity prices with respect to natural gas prices lead to mHAT net incomes high enough to compensate for its overheads. For a given number of running hours, there is a limit for the electricity price in relationship to the gas price above which turning the T100 into an mHAT yields higher profits than leaving the mGT operating as a CHP unit only. It is important to note that this limit is very close to the threshold of positive NPV, especially for the low-heat demand consumer.

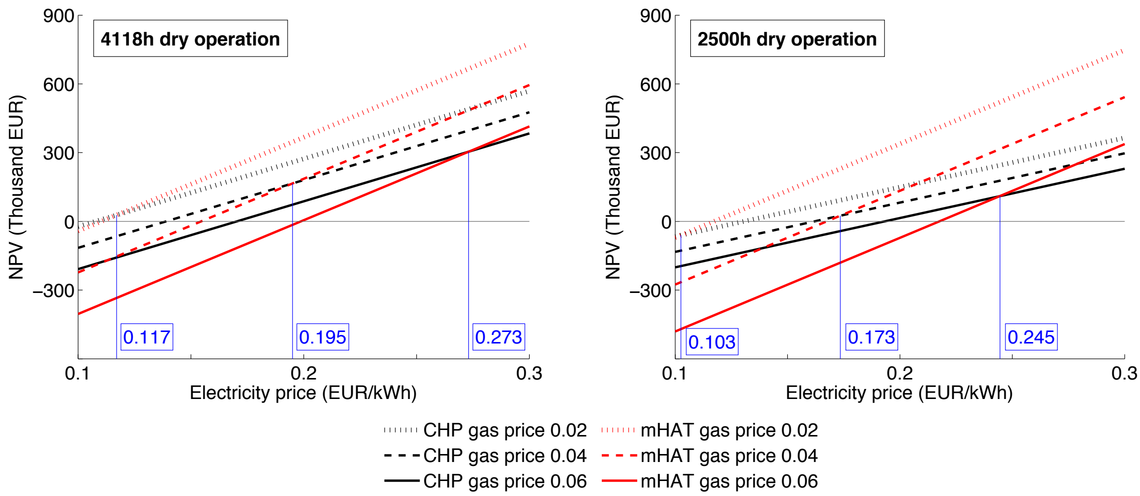

Fig. 4 NPV for varying electricity and natural gas prices for a discount rate of 10%. All prices are expressed in EUR/MWh. For a given natural gas price, the electricity price at with the mHAT facility is more economical than the corresponding mGT working as a CHP unit is marked in blue. Higher dry running hours lead to higher NPV values; however, the profitability of the mHAT cases with respect tot the CHP cases is greater for users with a lower number of dry running hours.

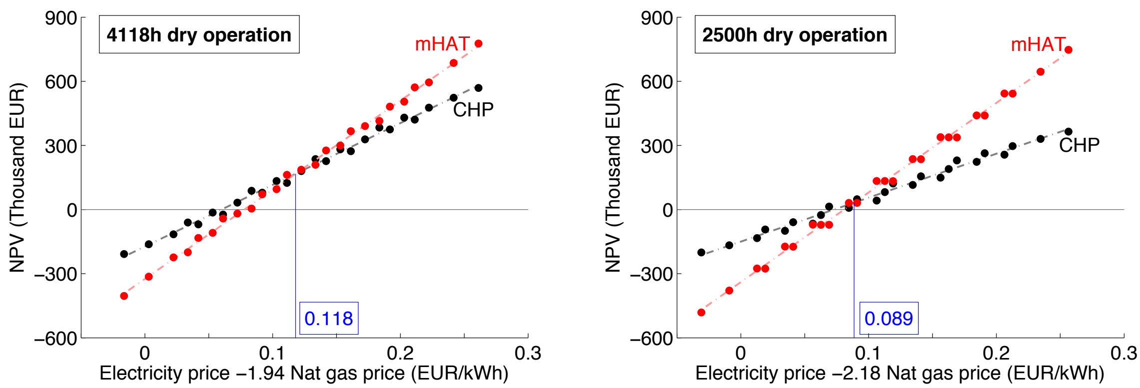

Fig. 5 NPVs expressed as a linear relationship between electricity and natural gas prices for the 25 price combinations for the reference consumer (4118h dry operation) and the low heat demand consumer (2500h dry operation). For the reference customer an electricity price equivalent to 0.118+0.194*nat gas price constitutes the threshold above which mHAT cases are more profitable than the mGT working as a CHP unit only. The threshold for the low heat demand consumer corresponds to 0.089+2.18*nat gas price.

A breakdown of the costs taken into consideration in this analysis is presented in Table 2 for two particular price combinations (medium range electricity price and high and low range natural gas prices). Fuel costs constitute, in all cases, the bulk of total costs. Water consumption and purification has been traditionally identified as a major drawback of steam injected and humid air turbines [12]. Nevertheless, the results of this study show that even when taking into consideration very conservative values, water costs only represent 1-2.5% of total costs (or 1-3% of natural gas costs). These values are even lower than the 5% of fuel costs figure suggested by Tuzson in [13] for steam-injected turbines.

Table 2 CHP and mHAT on-going costs (in €) for the reference consumer (4118h dry operation), assuming an electricity price of 0.2 €/kWh and a discount rate of 10%.

	Nat gas price = 0.02 €/kWh				Natural gas price = 0.06 €/kWh			
	CHP	**mHAT**	***CHP***	***mHAT***	**CHP**	**mHAT**	***CHP***	***mHAT***
Natural gas	27,454	50,661	*74.0%*	*78.1%*	82,362	151,982	*89.5%*	*91.4%*
Maintenance	6,177	12,648	*16.7%*	*19.5%*	6,177	12,648	*6.7%*	*7.6%*
Water	-	1,593	-	*2.5%*	-	1,593	-	*1.0%*
Electricity	3,467	-	*9.3%*	-	3,467	-	*3.8%*	-
Total Costs	**37,098**	**64,901**	***100%***	***100%***	**92,006**	**166,222**	***100%***	***100%***

4. Concluding remarks and perspective

This paper presents an economic feasibility analysis for the Turbec T100 mGT working as a CHP unit and as an mHAT. 25 natural gas and electricity price combinations have been taken into account. The analysis has been performed for two types of domestic customer: a 'reference' consumer with a heat demand that requires 4118h of dry operation (i.e. mGT operating as a CHP unit) and a 'low-heat demand' consumer which only requires 2500h of yearly dry operation. CHP facilities are assumed to run only during the above-mentioned hours of dry operation whereas mHATs run the remaining number of hours per year (up to 8040h) with water injection (i.e. in wet mode).

The results of this analysis show that the economic feasibility of the T100 working as a CHP and as an mHAT strongly depends on the market's natural gas and electricity prices and on the relationship between these two variables. Higher NPV values are obtained with higher electricity and lower natural gas prices. For a given number of dry running hours and a natural gas price, there is a threshold for the electricity price above which mHATs become more profitable than the mGT working as a CHP unit. This threshold is very close to the limit of positive NPV, especially for the low-heat demand consumer. As expected, the profitability of the mHAT with respect to the CHP cases becomes more evident for consumers with a reduced number of running hours.

Fuel costs represent the majority (74 to 90%) of the total on-going costs –which include natural gas, operation and maintenance, water and additional electricity. mHAT water cleaning costs, traditionally identified as a handicap of this technology, only represent 1 to 2.5% of the total costs, despite of the fact that conservative values have been considered.

Future work would include considering how mHAT operation affects the lifetime of the cycle (since water injection contributes to enhanced recuperator wearing, for example). The demand will be analysed on a daily basis to confirm whether the mGT is able to cover power peaks. In addition, the economic analysis will be also performed for an industrial consumer with a demand profile very different to that of domestic customers.

Acknowledgements

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Biography

Marina Montero Carrero is PhD candidate at Vrije Universiteit Brussel (VUB). She holds a BSc and MSc in electro-mechanical engineering from Universidad Politécnica de Valencia (Spain) and an MSc in Sustainable Energy Futures from Imperial College London. Prior to starting her PhD, she worked as a researcher on green economy issues at the London School of Economics and Political Science and completed a traineeship at the European Commission.