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A HOLISTIC METHODOLOGY TO QUANTIFY PRODUCT COMPETITIVENESS AND DEFINE INNOVATION REQUIREMENTS FOR MICRO GAS TURBINE SYSTEMS IN HYDROGEN-BASED ENERGY STORAGE APPLICATIONS

Giuseppe Tilocca[1,*], **D. Sánchez**[1], **M. Torres García**[1], **A. Escamilla Perejón**[1], **S. Minett**[2]
[1]Department of Energy Engineering, University of Seville, Camino de los descubrimientos s/n, 41092 Seville, Spain
[2]Challoch Energy Rue Eugène Castaigne 29, 1310 La Hulpe, Belgium

ABSTRACT

Micro gas turbines are an on-site power and heat generation technology with a small footprint, low gaseous (NOx) and acoustic emissions, low maintenance and high-grade heat. They entered the market at the dawn of the twentieth century; nevertheless, they achieved minimal success and a marginal role in the microgeneration market. Reciprocating internal combustion engines raised considerable barriers hindering their market deployment, and Fuel Cells are also set to compete in this segment.

In this scenario, this work presents an analysis of competitiveness grounded in the Theory of Constraints. To this end, a specific Key Performance Indicator has been produced, which combines technical, economic, and operational factors according to the end-user requirement. This indicator is a function of several penalty factors representing technology and market barriers, which aims to yield a unique insight into the most competitive technology for a given application, accounting for the uncertainty deriving from technical and economic elements.

This novel methodology is applied to a new potential niche market: Power-to-Hydrogen-to-Power for remote applications. The methodology is applied to an independent rural community in South Wales, for which a backup power system is assessed. Four technologies are considered in the analysis: reciprocating engines, fuel cells and two different microturbines layouts.

Finally, this work provides an overview of the possible R&D&I paths necessary to increase the competitiveness of micro gas turbines in certain markets.

Nomenclature

$-R, -ICR$	Recuperated, Intercooled-Recuperated
η	Electric Efficiency
C	Cost
COP	Coefficient of Performance
$DALY$	loss of Disability Adjusted Life Year
FC	Fuel Cell
HC	Heat Consumption
ICE	Internal Combustion Engine
k, K	Preference range Index, Preference ranges count
KPI	Key Performance Indicator
LB, lb	Lower Bound
$LCoE$	Levelised Cost of Electricity
$LoLE$	Loss of Load Expectation

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[*] Address all correspondence to this author. Email: g.tilocca@us.es

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MGT	Micro Gas Turbine
$MPMT$	Mean Preventive Maintenance Time
$MTBF$	Mean Time Between Failure
$MTTR$	Mean Time to Repair
n, N	Requirement Index, Total count of requirements
$O\&M$	Operation and Maintenance
OEM	Original Equipment Manufacturer
$P2P$	Power to Power
PC	Power Consumption
$PEM(FC)$	Polymeric Exchange Membrane (Fuel Cell)
$R\&D(\&I)$	Research and Development (and Innovation)
$RAMS$	Reliability Availability Maintainability & Safety
SD	Standard Deviation
SI	Service Interval
TIT	Turbine Inlet Temperature
TOC	Theory of Constraints
UA	Unavailability
UB, ub	Upper Bound
UQ	Uncertainty Quantification

INTRODUCTION

Microturbines or Micro Gas Turbines are small on-site power and heat generators. Their small scale and modularity make them eligible as a technology to help the transition from centralised to distributed energy systems, thereby contributing to a low-carbon economy [1]. Their contribution might be relevant to achieve the ambitious objectives of the European Union, whose Green Deal plans to make Europe the first climate-neutral region in the world by 2050 [2].

MGTs have been in the market for over two decades. Nonetheless, their deployment could not match the expectations of the market (end-users) and the industry (technology providers) for this promising technology inasmuch as the long-lasting presence of reciprocating internal combustion engines (ICE), the established technology in the energy and transportation sector, raised substantial barriers against MGT commercialisation. This paper is part of a corrective actions scheme [3] that aims to identify the root causes of this experience and propose some remedial actions to enable the successful market deployment of microturbines. In particular, rather than relying on a speculative methodology only, as it is usually the case for this type of action, it aims to create a numerical approach that can mimic the Root Cause Analysis process. To this end, it is mandatory to devise a methodology that can model the competitiveness of MGTs compared to other commercial technologies.

In literature, Weighted Decision Matrices are a standard process to select the best candidate amongst a set of different options [4, 5, 6, 7]. In Weighted Decision Matrices, multiple parameters are weighted depending on their importance. Nevertheless, they are specific to their application and only provide information about that individual decision; for instance, Sanchez *et al.* created a compound indicator to identify potential markets for small-scale Concentrating Solar Power systems based on hybrid microturbine and parabolic dish arrangements [8]. Then, Tilocca *and al.* combined the fitness indicator of Sanchez *et al.* and a traditional Weighted Decision Matrices [9]. The resulting methodology assessed the competitiveness of an extensive range of commercial prime movers for several cogeneration applications.

This work builds on Tilocca *et al.*'s approach by introducing a penalty factor based on the Theory of Constraints. The authors seek to improve the previous work by creating a flexible tool for technology innovation that removes arbitrariness and helps drive engineering according to market demand. The tool identifies and quantifies factors necessary for competitiveness in a specific market segment and provides guidance on areas where innovation is needed. Lastly, it serves as a multi-purpose means to advise industry and academia on how to target market needs.

The paper's first section presents the *Theory of Constraint* problem-solving technique. The next part introduces the three competing technologies under analysis: Micro Gas Turbines, reciprocating Internal Combustion Engines and Fuel Cells. Once the context of the paper is set, the following section presents the methodology that defines the Key Performance Indicators. After that, the models used to simulate the performance of Power-to-Power systems accounting for boundary conditions like weather and microgrid for the case study are presented. Then, the following section introduces the approach to uncertainty quantification adopted, including the definition of the methodology and the range of uncertainty of the parameters used. The last two sections discuss the results and provide an overview of the necessary technological improvements and innovation. The conclusive remarks also mention the prospects for future related studies.

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METHODOLOGY

Theory of Constraints

The Theory of Constraints (TOC) was initially drafted by Goldratt [10] and then grew into an effective problem-solving process holistically integrating intuitive and analytical thinking [11]. The approach followed in this work is mainly inspired by the work by Dettmer [12]. The Theory of Constraints aims to improve systems: a set of processes or entities co-acting to achieve a goal. Therefore, defying a problem only makes sense when comparing the system's performance to its expectations.

The principle at the core of the TOC is that "*a chain is no stronger than its weakest link*"; i.e., each system is affected by its constraint, suggesting that the weakest component does negatively affect the entire system [11].

According to Dettmer [12], the most undesirable effects within a system result from one or a few root causes. These high-level causes are hidden at the end of the cause-effect chain and are usually hard to detect. They result in several undesirable effects connected by an intricate network of cause-effect relationships. Removing them individually (i.e. the symptoms or the low-level causes) delivers a short-term solution that cannot resolve the issue. On the contrary, targeting the root causes eliminates the undesired effects along their cause-effect chain.

A penalty-based approach to quantify competitiveness

Tilocca *et al.*'s work defined a KPI to monitor competitiveness under the name of Global Penalty Factor [9]. The indicator is the weighted sum of single linear penalty functions and enables a model of the competitiveness of different technologies for specific applications. The cited work evaluated the effectiveness of this KPI to compare an extensive range of commercial engines.

Their definition of weights models the importance of each feature monitored by the linear penalty functions, yet, it can introduce some arbitrariness. Moreover, ranking the objectives and determining the weights is a simplified representation of more complex problems and system dynamics. From this observation and experience, the methodology in this paper translates the principle of the TOC into a mathematical formula, making the utilisation of arbitrary weights and parameter ranking unnecessary. The principle behind the TOC is that each system is affected by its constraints, the chain's weakest link, so it does not matter how strong all the other links are.

Following this principle and the overarching objective of this paper, as put forward in the Introduction, the following requirements that the new numerical method should follow are set:

- The KPI monitoring user/market perception should be a maximising function taking values between [0,1]. The KPI should be easy to read and compare.
- The contributions to the KPI are penalty factors. Each penalty simulates the addition of a cause to the effect. Following the TOC problem-definition scheme, they are computed by comparing the system performance against the user's requirements.
- The KPI must lie in a range which is not better than the worse single penalty, according to the TOC principle.
- The KPI and the penalties should be continuous functions to create a valuable numerical tool suitable for optimisations, uncertainty and sensitivity studies.

The mathematical function that satisfies the aforementioned requirements for a minimisation problem is the exponential function defined as:

$$penalty_n = \begin{cases} 1 & \text{if } x < x_{ideal} \\ N^{k+\left|\frac{x-lb_k}{ub_k-lb_k}\right|} & \text{if } x_{ideal} < x < x_{unfeasible} \\ N^K & \text{if } x > x_{unfeasible} \end{cases} \tag{1}$$

where K is the number of preference intervals, lb_k and ub_k are the lower and upper bound for each sub-range k respectively, and N is the number of user requirements (i.e. penalties) of the problem considered. The global penalty and the competitiveness KPI are then defined as:

$$GlobalPenalty = \sum_{n=1}^{N} penalty_n \tag{2}$$

$$KPI = 1 - \frac{log_N(GlobalPenalty) - 1}{K} \tag{3}$$

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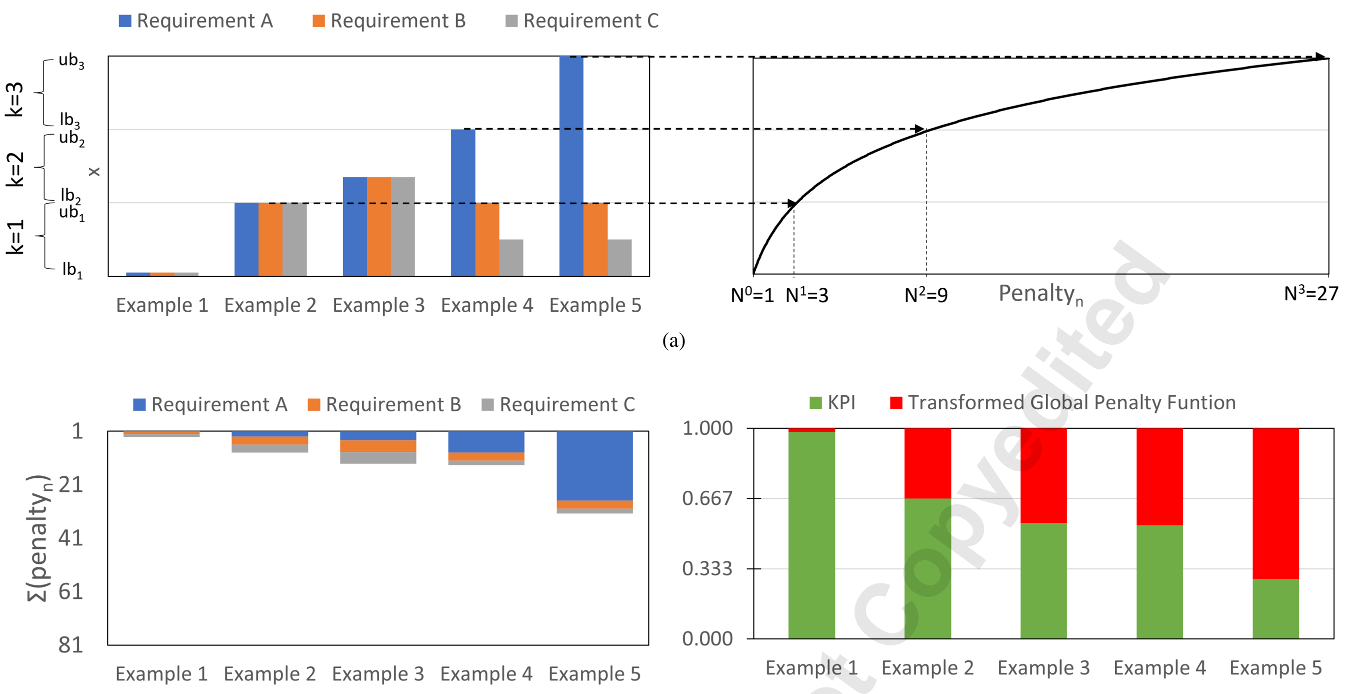

(a)

(b)

(c)

FIGURE 1: This case involves assigning penalties and calculating the Key Performance Indicator (KPI) for K=3 user preference intervals and N=3 user requirements. Five examples are given on the left-hand side of subfigure a) to show the score (x) against the user requirements. The right-hand side of a) displays the conversion to a single penalty factor (Eq. 1). The penalties are then added in subfigure c) using Eq. 2. Subfigure d) exemplifies the calculation of the KPI using Eq. 3. The five examples demonstrate different scenarios, with Example 5 showing that the highest penalty for Requirement A brings the solution to an unfeasible region (Eq. 4) according to the TOC principle, regardless of the x score against Requirements B and C.

User requirements

The present work considers three different user requirements: $N = 3$. They are relative to economic performance, energy system availability and reliability, and the impact of emissions on human health.

For each requirement, three preference intervals are defined ($K = 3$). In this case, the final KPI could be interpreted as:

$$\begin{cases} 1.00 < KPI < 0.67 => best\ range \\ 0.67 < KPI < 0.33 => feasible\ range \\ 0.33 < KPI < 0.00 => unfeasible\ range \end{cases} \tag{4}$$

Where $KPI = 1$ represents the ideal solution. Figure 1 demonstrates the framework for a case having N=3 and K=3.

The figure of merit for the system's economic performance is the Levelised Cost of Electricity (LCoE), according to the definition by the International Energy Agency [13]. The wholesale price of electricity predicted for 2030 sets the ideal range threshold [14] whilst the preferred, acceptable and feasibility thresholds correspond to the 2030 projection of LCoE for Secondary Response, Peaker, and Seasonal Storage [15].

The authors selected the Loss of Load Expectation (LoLE) to represent the reliability of the independent microgrid. LoLE is a commonly adopted approach in generation planning studies. It assesses the need for generation reserves as a function of load magnitude, factor and shape, generation availability, and the size and number of generating units [16]. LoLE is computed following the scheme provided by Vijayamohanan Pilla [17]:

$$LOLE = \sum_i P_i t_i \tag{5}$$

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The probability of an event taking place (event occurrence probability, P_i) derives from the achieved availability, including forced (MTBF and MTTR) and planned outages (SI, MPMT). In contrast, the event duration (t_i) is calculated based on the yearly load profile. It represents the number of load hours a specific outage would potentially affect in a year; in other words, given a yearly load profile and a capacity outage scenario, the number of hours with a load demand greater than the leftover system capacity. LoLE's preference ranges are taken from techno-economic, and reliability studies on microturbines by Davis [16]. The ideal LoLE is 0 (i.e., the system operates without interruption). The preferred value is the usual requirement for electric grids, equivalent to 0.1 days per year (2.4 h). The acceptable range is marked by a loss of load expectation of 1 day (24 h), and more than 3 days is deemed unacceptable.

The impact of the calculated emissions of the prime movers follows the *damage assessment* scheme adopted by Macor and Bennato [18]. This procedure aims to estimate the damage caused by each emitter by evaluating it in DALY units[1]. This work considers NOx emissions only, given that the stacks run on pure hydrogen, so the cited emission assessment is qualified for the Respiratory Inorganics damage category. Nonetheless, this parameter can holistically estimate the impact of contaminants for conventional and unconventional fuels other than H_2. Effectively, it can integrate the impact of different contaminants based on the effects on human health for several damage categories. This technique does not need further weighting factors.

The *characterisation* is computed as follows:

$$DALY = s_d \sum_i Cf_i x_i \tag{6}$$

where x is the mass of each contaminant, C_f is its characterisation factor, and s_d is the specific damage in kg_{eq}^{-1} for each impact category. The values are taken from [18]. Since there is no aggregate emission regulatory requirement based on health assessment, the DALY preference ranges are taken from the natural gas and biogas measurements provided by Macor and Bennato.

TABLE 1: Preference ranges for the considered user requirements.

n	Requirement	k=1		k=2		k=3		Reference
		LB	UB	LB	UB	LB	UB	
1	LCoE	0.074	0.2		0.8		2.0	[14, 15]
2	LoLE	0.0	2.4		24		72	[16]
3	DALY	0.0	6.80E-5		2.34E-4		4.68E-4	[18]
	Description	Ideal	Preferred		Acceptable		Unfeasible	

Rural Community Power-to-Power model

This work takes over a feasibility study by Challoch Energy, aimed at investigating the potential supply of green hydrogen to a rural energy community under the '*Hydrogen in Rural Energy Systems* (HyRES)' project. The reference is a local community in South Cornelly, Bridgend County Borough (South Wales). In the same village, a *Whole System Business Research Innovation for Decarbonisation* (WBRID) demonstration project also investigates how to organise low-carbon communities forming local energy markets (LEM), which trade in locally produced and consumed renewable energy. The concept combines locally produced hydrogen with a portfolio of renewables, including wind, photovoltaic and batteries. The analysis presented herein applies to the backup power sub-system only.

The village is comprised of 220 family houses and a nursing house. The residential power demand is estimated from the readings taken by the authors from nine houses between February and May 2022. In this period, consumption profiles proved uniform. Natural gas boilers provide heating to all the sampled houses; hence, the demand for electric power registered is only due to lighting and appliances. These considerations are assumed to be representative of the whole village. Therefore, the final consumption profile is the average measured profile for the nine houses multiplied by the total number of places.

In the current scenario, the residential houses rely on natural gas boilers, and the nursing house has a heat pump installed for heating. For this study, the authors assume the whole village is electrified, and both residential and nursing houses have installed heat pumps. The

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[1] DALY: disability-adjusted life year. One DALY represents the loss of the equivalent of one year of full health.

residential heat demand model considers three different heat profiles based on the house layout. These layouts are assigned following an on-site assessment:

- Terraced houses 10000kWh/year: 66 houses
- Semi-detached house 13000kWh/year: 121 houses
- Detached house 16000kWh/year: 33 houses

The 2.77 GWh/year residential heat demand closely agrees with the gas provider readings. The care home hourly heat consumption is computed from literature by combining a monthly consumption [19] and the hourly normalised profile [20]. The nursing house's electricity profile is the sum of the heat pump power demand and the electricity consumption for lighting and appliances $PP_{carehome}$. The latter is derived from the elderly care wards' power profile per m^2 reported in [21]. $PP_{carehome}$ is assumed constant throughout the year following the same assumption as for the residential houses.

The overall power consumption is then computed as follows:

$$PC_{tot} = PC_{houses} + PC_{carehome} + (HC_{carehome} + HC_{houses})/COP \tag{7}$$

The effective monthly COP as a function of the ambient temperature is assumed according to the values reported by Staffell *et al.* in their review of domestic heat pumps [22].

The Power-to-Power (P2P) model, which ultimately calculates the levelised cost of hydrogen, is an in-house software developed by Escamilla *et al.* at the University of Seville [23]. Weather data and models for renewable energy technologies are taken from the System Advisor Model (SAM) of The National Renewable Energy Laboratory (NREL) [24], using irradiation data from the Photovoltaic Geographical Information System (PVGIS) of the European Commission's Joint Research Centre [25] and wind data from NREL's National Solar Radiation Database [26], all for a geographic location near South Cornelly in Bridgend County Borough (South Wales). Costs relative to the P2P sub-system are gauged from vendors' data, as listed in Table 2. The model accounts for the hourly RES generation and power demand, after which the hydrogen production and the residual power demand to the prime mover are computed.

TABLE 2: Economic assumptions of the P2P model.

Item	Capital Cost		O&M Cost	
Wind Turbine	1695	€/kW	51	€/kWyear
PV	1000	€/kW	9	€/kWyear
Electrolyser	1500	€/kW	20	€/kWyear
Water	-	-	4.9	€/m^3
HP Vessel	70	€/Nm^3	-	-
Compressor	4000	€/kW	240	€/kWyear

The model simulates each hour of the year for the total lifespan of the equipment. If renewable power production exceeds the electric demand, surplus energy drives the electrolyser, producing hydrogen stored in high-pressure tanks. Contrariwise, if the demand exceeds the available renewable power, the prime mover (MGT, ICE or FC) runs on stored H_2 to fill the energy gap.

This work considers an arrangement comprised of two parallel 400 kW_e prime movers to satisfy the LoLE feasibility requirement inasmuch as an arrangement with one engine only would not provide sufficient availability, as observed in an early study by Davis [16]. Figure 2 displays the installed capacity and power demand profiles for the characteristic year considered. With this configuration, the systems operate with a 12% reserve margin.

Technical specifications under Uncertainty

In many engineering problems, the uncertainty of input data and parameters is a significant and critical concern. The analysis of complex energy systems commonly assumes a series of deterministic input parameters. Nevertheless, many of these variables are subject to uncertainty since they may not be measured, determined or predicted with enough precision, and they can strongly affect the final output. The evaluation of competitiveness based on a techno-economic analysis is no exception, and, therefore, the assessment of market competitiveness through the KPI presented in this work incorporates Uncertainty Quantification. Given the relatively quick KPI

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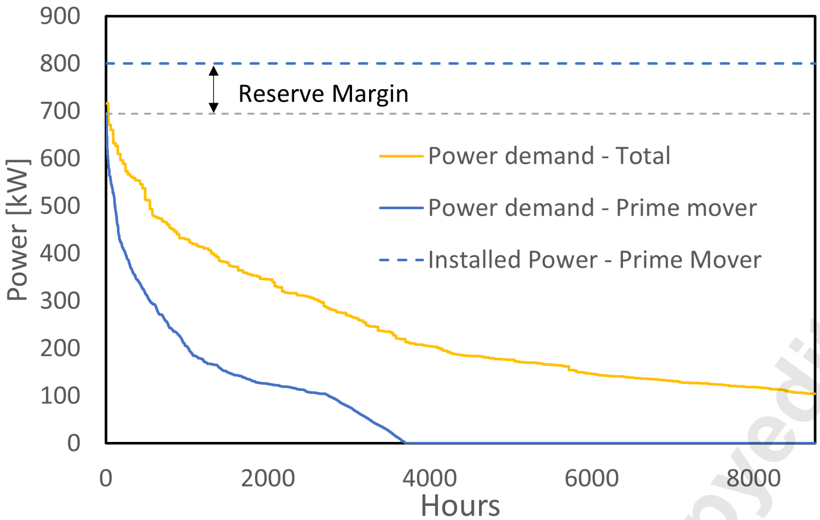

FIGURE 2: Annual power demand profile and reserve margin. The power demand for the prime mover is the total demand minus the available renewable power.

evaluation (around 0.25s in an average i7 laptop) and the level of accuracy needed, the authors opted for a direct application of the Monte Carlo Method.

Table 3 summarises the information about Uncertainty Quantification. The installation cost is assumed to be a normal distribution with a mean value of 830€/kW and 20% standard deviation (*SD*) for all technologies. The microgrid failure rate of 0.2 failures per year and the Mean Time to Repair (*MTTR*) of 12 h is taken from Kumar *et al.* [27].

Micro Gas Turbines Micro Gas Turbines are miniature gas turbines with rated electric output between 1 and 500 kW_e approximately [28].

Due to their reduced volumetric flow, MGTs primarily use single-stage radial turbomachinery for compression and expansion. Since radial turbine cooling is not commercially available, microturbines feature low TITs of around 950ºC. Also, given the adoption of single-stage turbomachinery, pressure ratios do not exceed 4-5:1). These are different specifications to larger gas turbines, which feature TITs higher than $1500°C$ [29] and pressure ratios higher than 20:1. The low TITs and pressure ratios of micro gas turbines limit the maximum thermal efficiency of a simple Brayton cycle, whose low performance is further exacerbated by the small scale of turbomachinery [30, 31, 32]. Accordingly, the most widespread solution is the recuperated MGT (MGT-R) which uses an internal heat exchanger to enhance its thermal performance substantially. However, this is at the expense of a costly and bulky component. Another configuration that could enhance the performance of the microturbine further is the intercooled and recuperated MGT (MGT-ICR). This combines intercooling between two compressor stages and internal heat recovery, further increasing electrical efficiency [33].

The performances of the micro gas turbines are taken from representative commercial products; Capstone's C200 [34] and Ansaldo Green Tech's AE100 [35] for MGT-R and Aurelia Turbine's A400 [36] for MGT-ICR.

The R&D community is exploring the possibility of burning hydrogen on MGTs, which is currently not commercial. In a recent study, Banihabib and Assadi [37] declared to have operated a T100 (100 kW_e) MGT on pure H_2 and NG-H_2 blends, making use of a FLOX$^{®}$ combustor designed by the German Aerospace Centre (DLR). The measurements reveal that NOx emissions did not grow significantly, certainly not exceeding the regulated levels, nor was any significant shift in performance experienced when running on pure H_2. Based on this experience, the authors of this paper assume that both (C200 and T100) MGTs can operate on hydrogen without significant changes to emissions because the working cycle (TIT, pressure ratio, layout) of both engines are similar.

The A400 engine operates with slightly higher TIT (around 1070ºC [33, 38]) and, according to a conversation between representatives of Aurelia Turbines and the authors of this paper, the engine is also being tested with a similar FLOX$^{®}$ combustor developed by DLR. Accordingly, the authors assume that the specifications of the engine running on hydrogen are similar to those of the factory engine running on NG, though with a higher degree of uncertainty due to the different cycles and TIT to the T100 engine.

Following these considerations, the efficiency curve for the recuperated MGT is taken from the specifications of the C200 engine [34]. A normal probability density distribution is applied to the peak efficiency value for UQ, with the efficiency corrections developed

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by Galanti and Massardo to upscale from 200kW$_e$ to 400 kW$_e$ [30]. The efficiency curve for the intercooled-recuperated MGT is taken from the specifications of the A400 engine [36], with a standard deviation of $SD = 0.01$ applied to peak efficiency. For both MGTs, the standard deviation is a cubic polynomial with an equivalent $SD = 0$ at 100% power and $SD = 0.1$ at 10% power.

Planned maintenance data are taken from Capstone's and Aurelia's product maintenance schedules. UQ is applied to the Mean Preventive Maintenance Time ($MPMT$) only, through a log-normal distribution such that the $MPMT$ is higher than $0.8 \cdot MPMT_{average}$ and 80% lower than $1.2 \cdot MPMT_{average}$ 95% of the time. The logarithmic failure rate distribution for both MGTs is taken from Robinson *et al.*'s assessment of the reliability of distributed energy resources [39]. Given the very low failure rate, the results turn out to be weakly affected by $MTTR$.

Equipment and O&M costs are taken from the MGT cost functions presented previously by Tilocca *et al.* for a 400kW engine [9]. The Gaussian standard deviation distribution is equal to 10% of the mean value. For the MGT-ICR, equipment cost is the sum of the OEM ex-works price plus the fuel compression cost function for the NG engine, according to Tilocca *et al.*'s study. O&M cost is assumed to be the same as for MGT-R.

Reciprocating Internal Combustion Engines ICEs are the most widespread technology for distributed (thermal) power generation, cogeneration and biofuel applications [40]. Their superiority relies on their high versatility, flexibility, availability, cost-effectiveness and efficiency.

The mean value and standard deviation of the performance of ICEs working at rated conditions derive from a normal regression of the Natural Gas engines used in the study by Tilocca *et al.* [9], for units with rated electric output between 250 kW$_e$ and 550 kW$_e$. According to recent assessments, the performance of ICEs running on hydrogen should not experience relevant deviations from that of conventional fuels [41].

The normalised part-load efficiency curve is taken from literature, both for the mean value and standard deviation [42, 43], which is deemed representative of a broad spectrum of ICEs.

ICEs already utilise after-treatment of the exhaust gases to meet the stringent NOx limits set by regulations. As a result, their mean NOx emissions are equivalent to the threshold set by the European Commission's Stage V. In this case, the uncertainty applies to the current post-exhaust treatment costs [44].

The service interval of reciprocating engines is set to 2000 h, following the maintenance schedules of most OEMs. The upper and lower bounds of $MPMT$ are estimated at 47.8 h and 17.8 h, respectively. The author's assessments lead to a log-normal distribution such that the cumulative probability of $MPMT$ values being lower than 17.8 h is 5%, and that of being greater than 47.8 h is 85%. The uncertainties applicable to failure rate and $MTTR$ are quantified according to NREL's measurements for well-maintained engines [45]. Equipment and O&M costs are from the cost function of ICEs developed by Tilocca *et al.* for a 400kW engine [9], with a 10% standard deviation.

Fuel Cells FCs generate electric power through electrochemical reactions; thus, the Second Law of Thermodynamics does not limit their performance [46]. Fuel cells consume fuel -typically hydrogen- and an oxidiser, with water being the end product. FCs are a clean technology and do not rely on combustion [47]. A study from Napoli *et al.* [48] demonstrated that PEMFC is the most suitable FC technology for load-following operations, thanks to their quick-response capability and steep ramp rates. For this reason, this work considers PEMFC only.

For FCs, the total cost of ownership is -likely- the most decisive system constraint. Yet, it presents a very high uncertainty due to the low availability of price data for stationary applications of PEMs and to the erratic price trends owing to a fast-evolving market and supply chain. The capital cost is taken from the European Scenario for stationary FCs of Hydrogen Europe for large PEMFC [49]. The reference values are those provided for State-of-Art (1900€/kW$_e$) and the 2030 prediction (900€/kW), values that do not include power conversion systems and margins. The cost of power electronics is set according to the *FC manufacturing Cost Analysis* of the Department of Energy [50], whose maximum and minimum values based on production volumes are taken as worse and best-case scenarios, respectively. The gross sales margin is set to 30%. The logarithmic distribution used to quantify the high uncertainty is defined such that the cumulative probability of the equipment cost being lower than the minimum value (1569€/kW) is 5%, that of being lower than the maximum value (3259€/kW) is 85%. Uncertainty Quantification for the O&M cost[2], electrical efficiency[3] and degradation profile are defined similarly, taking the State of the Art and 2030 values from Hydrogen Europe's report [49]. The standard deviation function for part-load performance is a polynomial regression of the standard deviation from the normalised part-load efficiency reported

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[2] O&M costs include the potential stack replacement.

[3] DC/AC Conversion efficiency is assumed to be 93%.

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TABLE 3: Uncertainty distribution of input parameters. The Probability Density Functions (PDF) are marked as D (deterministic), N (normal) and LOG (log-normal). The PDFs that use variable mean and Standard Deviation (SD) functions are marked with V. For the LOG category, the reported mean and standard deviation are those of the logarithm of the normal distribution; the corresponding mean is computed as: $MEAN = exp(MEAN_{LOG} + SD^2)$.

Product	Parameter	Units	PDF	Mean	SD	Ref.
MGT ICR	$\eta_{el(Rated)}$	[-]	N	0.4056	0.005	[36]
	$\eta_{el(PartLoad)}$	[-]	N-V	-	-	[36]
	$NOx_{(Rated)}$	g/kWh	N	0.99	0.0382	[37]
	$MTBF$	h	LOG	9.267	0.324	[39]
	$MTTR$	h	LOG	2.47	1.59	[-]
	SI	h	D	1904	-	[36]
	$MPMT$	h	LOG	-0.130	0.171	[36]
	$C_{Equipment}$	€/kW	N	1148	115	[36]
	$C_{O\&M}$	€/MWh	N	17.3	1.73	[9]
MGT R	$\eta_{el(Rated)}$	[-]	N	0.3336	0.005	[34]
	$\eta_{el(PartLoad)}$	[-]	N-V	-	-	[34]
	$NOx_{(Rated)}$	g/kWh	N	0.99	0.0191	[37]
	$MTBF$	h	LOG	9.267	0.324	[39]
	$MTTR$	h	LOG	2.47	1.59	[-]
	SI	h	D	4000	-	[34]
	$MPMT$	h	LOG	0.513	0.162	[34]
	$C_{Equipment}$	€/kW	N	1448	145	[9]
	$C_{O\&M}$	€/MWh	N	17.3	1.73	[9]
ICE	$\eta_{el(Rated)}$	[-]	N	0.4027	0.022	[9]
	$\eta_{el(PartLoad)}$	[-]	N-V	-	-	[42, 43]
	NOx	g/kWh	N	0.607	0.051	[-]
	$MTBF$	h	LOG	7.389	0.312	[45]
	$MTTR$	h	LOG	2.47	1.59	[45]
	SI	h	D	2000	-	[9]
	$MPMT$	h	LOG	3.53	0.396	[-]
	$C_{Equipment}$	€/kW	N	680	68	[9]
	$C_{Exhaust}$	€/kW	LOG	3.29	0.274	[44]
	$C_{O\&M}$	€/MWh	N	26.0	2.60	[9]
FC	$\eta_{el(Rated)}$	[-]	LOG	-0.708	0.0548	[49]
	$\eta_{el(PartLoad)}$	[-]	N-V	-	-	[51]
	$d\eta_{el}/dt$	[%/1000h]	LOG	-5.79	0.259	[49]
	UA	[-]	LOG	-4.10	0.285	[51]
	$C_{Equipment}$	€/kW	LOG	7.87	0.316	[49, 50]
	$C_{O\&M}$	€/kWh	LOG	-3.35	0.342	[49]
General	$C_{Installation}$	€/kW	N	830	166	[9]

by NREL's statistical measurements for stationary FCs above 100 kW$_e$ [51]. The uncertainty of *Reliability, Availability, Maintainability and Safety* (RAMS) is quantifiable from the same NREL's statistical assessment measuring the operational availability of stationary FCs above 100 kW$_e$.

RESULTS

Discussion of results

The convergence study highlighted in Fig. 4 shows that 1000 evaluations are enough to achieve an accuracy of 10^{-3} for MGT-R, MGT-ICR and ICEs, whereas FCs need 10000 evaluations to reach a 10^{-3} precision. Within the scope of the analysis in this work, the 1000 seed's accuracy is deemed sufficient.

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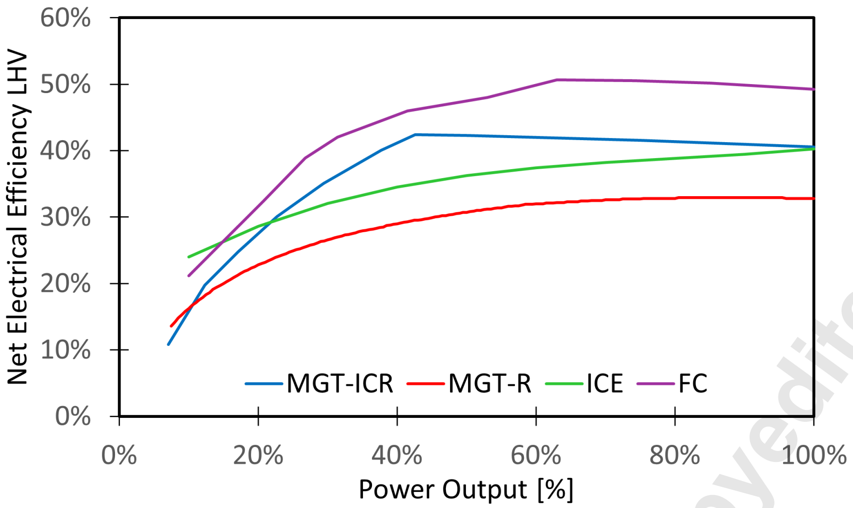

FIGURE 3: Mean part load net electrical efficiency of the four considered technologies.

Figure 5 presents the simulation results. Overall, the analysis shows a fair comparison of MGT-ICR and ICE. From an economic perspective, the vast majority of the result scored between the acceptable and the unfeasible bounds, thus remaining in the feasible domain, aside from a few exceptions. Moreover, a small subset of ICEs and MGT-ICRs scored more than acceptable. Therefore, according to the model, the mean and median LCoE for decentralised hydrogen P2P are way above the expected wholesale price of electricity but still below the projected price of seasonal storage.

Considering the median values, MGT-ICR exhibit the best LCoE, followed closely by ICEs. In the case analysed, the median MGT-ICR has a better LCoE than 55% of ICEs. MGT-Rs are the third technology in terms of economic competitiveness, with a substantial gap from both MGT-ICR and ICEs due to a low electrical performance which cannot compensate for the relatively high capital costs. Tilocca *et al.* already assessed that MGT-Rs are competitive in heat-driven cogeneration applications. Still, they also observed that MGT-Rs' competitiveness decreases for heat demands featuring either lower amounts of heat or lower heat grades. On the other hand, modern MGT-ICRs present enhanced rated and part-load performances, bridging the economic competitiveness gap with ICEs.

Despite the highest rated and part-load efficiencies, Fuel Cells present the worse median LCoE, due to their extremely high capital cost. Furthermore, their LCoE penalty presents a very high variance, primarily due to the high variability in their cost and performance data (Table 3) deriving from their fast-evolving market deployment and technological development.

It is interesting to note that MGT-ICRs have lower LCoE than FCs, with a 99.9% confidence. This datum implies that even in the FC 2030 scenario for cost and performance -accounted for in the Uncertainty Quantification- MGT-ICRs would still be more economically viable than FCs.

Considering RAMS, MGTs generally provide the best LoLE thanks to extended maintenance intervals and higher reliability. Well-maintained ICEs perform slightly worse but still fall in the preferred range when two engines in parallel are considered. NREL's recorded availability data indicates that the availability of Fuel Cells would lie between those of ICEs and MGTs [51].

The damages of MGT and ICE relative to emissions are comparable to those of current systems running on natural gas. The potentially higher NOx is partly compensated for by the lack of other emissions when running on pure H_2. However, the pending combustion performance and the evolving regulations induce intrinsic uncertainty. New regulations setting more stringent requirements on NOx emissions would substantially impact technological competitiveness. In this field, Fuel Cells all score the minimum penalty ($penalty = -1$) since they are assumed not to emit any contaminant.

Thanks to the optimal compromise between capital cost, part-load performance, reliability and emissions, the median MGT-ICR is better than 86% of ICEs, 95% of FCs and 100% of MGT-R. Finally, the competitiveness KPI indicates that MGT-ICRs are the best technology for the application considered, with a median KPI of 0.517. ICEs follow closely with a median KPI of 0.502. The median KPI of FCs stands at 0.459; lastly, it has a value of 0.450 for MGT-Rs. MGT-Rs proved to be the least competitive technology as far as median values are concerned.

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Remarks on competitiveness and innovation

Based on the current state of MGT R&D, burning pure H_2 does not seem to affect the performance of engines, which could hence be retrofitted with H_2 combustion systems. Nevertheless, further research is required to clarify the effect that running the engines on H_2 would have on performance, emissions, RAMS and overall costs. In this section, the authors discuss the progress needed to improve MGTs' competitiveness based on the discussed results.

For decentralised P2P, the penalty analysis showed that LCoE is the TOC system constraint. Improving LCOE needs reducing the prime mover's capital and operating costs. The median composition of the LCoE presented in Fig. 6 reveals that service costs have a negligible effect on LCoE penalty and global KPI. In contrast, fuel costs contribute about 80% of the LCoE for MGTs and ICEs. Capital costs (equipment and installation) follow with an allocation of 15% to 20% of LCoE for MGTs.

Therefore, reducing energy costs will be crucial to achieving competitiveness for decentralised hydrogen applications. The cost of producing hydrogen has a dominant effect on increasing LCoE; however, this depends on external factors since the capital cost of PV, Wind, and Electrolysers sets the hydrogen cost for decentralised applications. Further study is needed to clarify the relative changes in technological competitiveness for different hypothetical hydrogen costs and operating hours. These two factors will likely affect both the magnitude and composition of LCoE.

The paramount importance of reducing energy costs and the secondary impact of equipment costs implies that innovations able to enhance the performance of MGTs would dramatically affect their competitiveness. In this work, two-spool MGT-ICRs featuring a higher TIT has drastically improved MGT technology's competitiveness for hydrogen P2P applications. They have high peak efficiency and an exceptionally flat part-load efficiency curve, a difference that is intrinsic to the machine configuration. Conversely, with the current technology, there is little room for improvement in the case of single-shaft machines, especially considering the standard control methods of MGTs [52].

A techno-economic study of the effect of component performance on LCoE, including price modelling, was performed by Galanti and Massardo in 2011, considering TITs up to 950ºC [30]. These authors predicted the superior performance of MGT-ICRs for pure power generation before any commercial MGT-ICR arose in the market and even identified an optimal cycle performance for a range of rated power outputs. The same study from Galanti and Masardo presented a techno-economic evaluation assessing trade-offs between enhanced component performance and higher manufacturing cost.

Further work could include a combination of the modelling technique by Galanti and the framework to evaluate competitiveness introduced in this paper, considering the technological advancement and changing market conditions experienced in the last decade. In particular, the study should consider the effect of performance enhancement on costs, RAMS and emissions, and it should evaluate several (competitiveness) scenarios; for instance, increasing TIT would likely raise the manufacturing and material costs and could

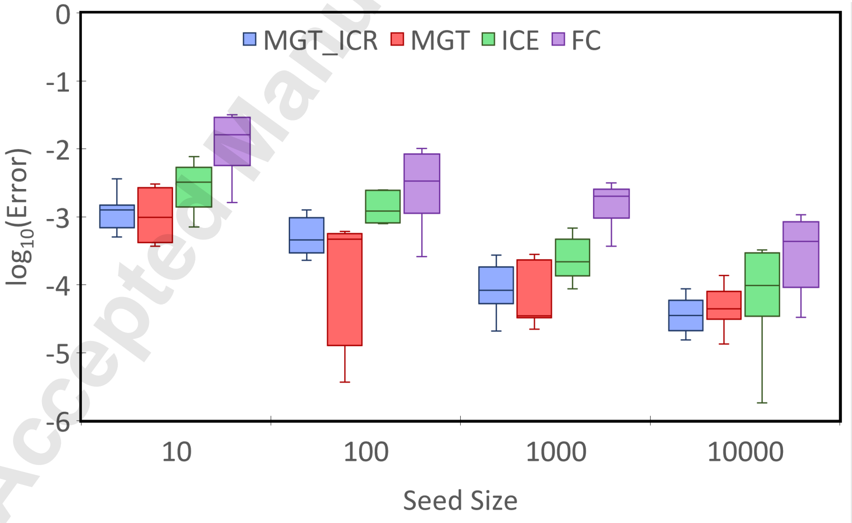

FIGURE 4: Convergence study over the number of evaluations (seed size) of the Monte Carlo method. Four seed sizes (10, 100, 1000 and 10000) are considered; the authors run a pool of 10 simulations for each. The error is measured as the deviation of the median KPI for each simulation to the average median KPI of each pool. The statistical data for each group is represented in the box chart. The ends of the box represent the first and third quartiles, whilst the horizontal line within the box indicates the median.

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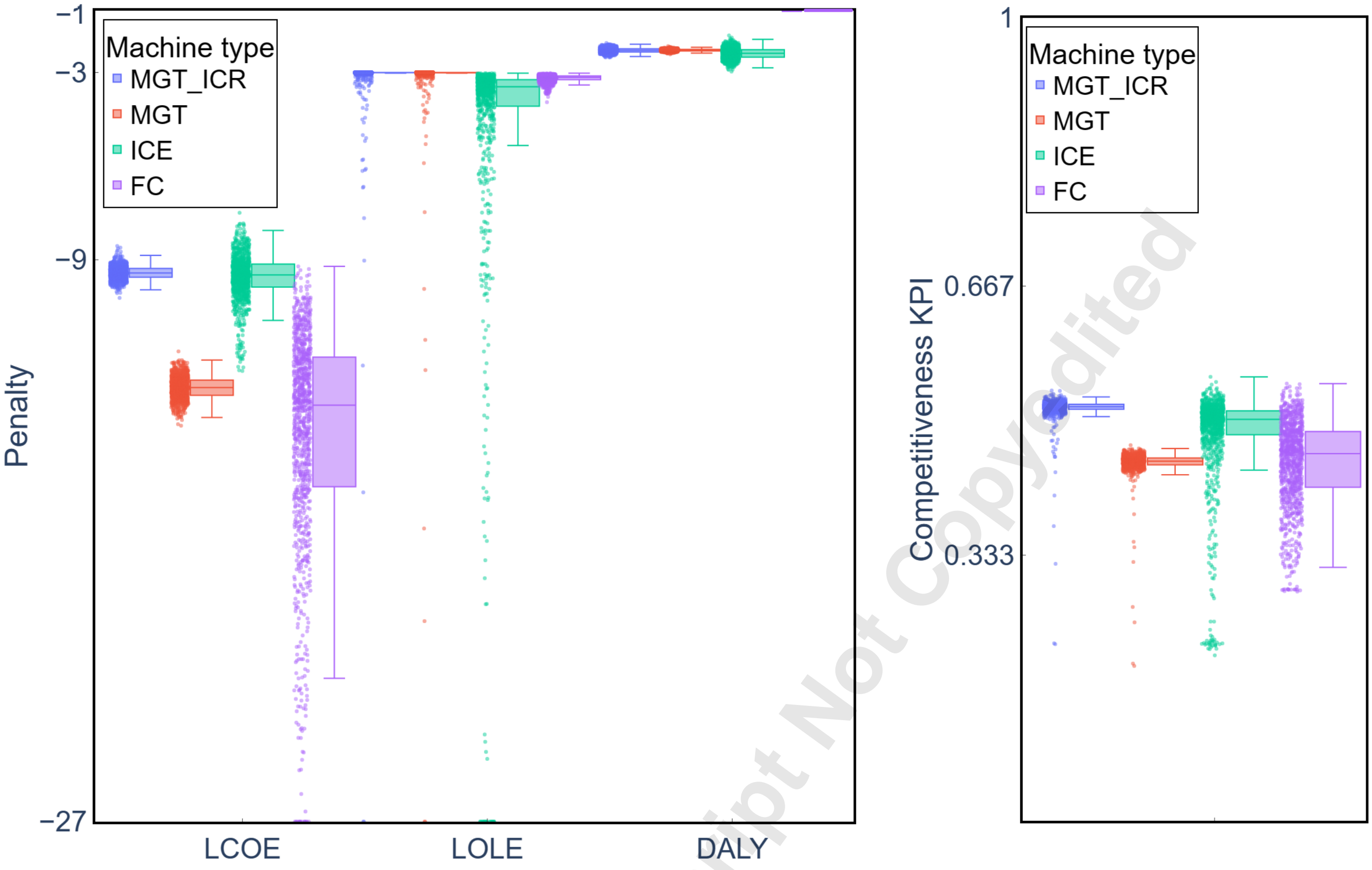

(a) (b)

FIGURE 5: Statistical distribution of penalties (a) and global KPI (b). The coloured boxes show the interquartile range. The ends of the box represent the first and third quartiles, whilst the horizontal line within the box indicates the median. The far bottom line of the chart is the minimum, and the far top is the maximum. The points beyond the minimum and maximum are considered outliers.

increase the risk of incurring heat-related failures, in addition to affecting NOx emissions negatively. The framework presented in this work could conduct an in-depth assessment of optimal innovation paths for specific applications, leveraging on past research, either technical or economic.

From an operational standpoint, this study has also revealed that MGTs already show excellent availability, which increases their competitiveness in load-following applications with stringent LoLE requirements. However, statistical data on the RAMS of MGTs is scarce compared to ICEs, affecting market awareness and perception. Accordingly, the authors advise the MGT community to increase market awareness about the benefits of MGTs in terms of availability by promoting the dissemination of operational data (data sharing between operators, OEMs and potential end-users).

Burning pure hydrogen excludes many contaminants that other fuels could promote. On the contrary, it presents some inherent challenges, such as high flammability and high flame speed and temperature of this fuel, which add to other health and safety concerns related to storage. Academia and industry are very active in finding solutions to accommodate unconventional fuels, including H_2, for both micro and large gas turbines. In particular, two types of combustion technologies are currently considered for H_2: flameless and pre-mixed lean combustion. The latter is the technology currently used for conventional fuels. It has the advantage of having very low NOx at rated conditions. However, a diffusion-type pilot flame is predominant in part load operation, increasing NOx emissions [53]. Conversely, flameless combustion has also proved an effective solution for part-load applications running on pure H_2 [37]. Therefore, the role of R&D&I in combustion technologies is deemed crucial as a technical enabler and a factor of competitiveness, especially in the case of more stringent regulations, as proven in this work. For instance, if MGTs want to be competitive in applications where part-load operations are relevant, they need consistent performance across their operating range without the need for post-combustion treatment,

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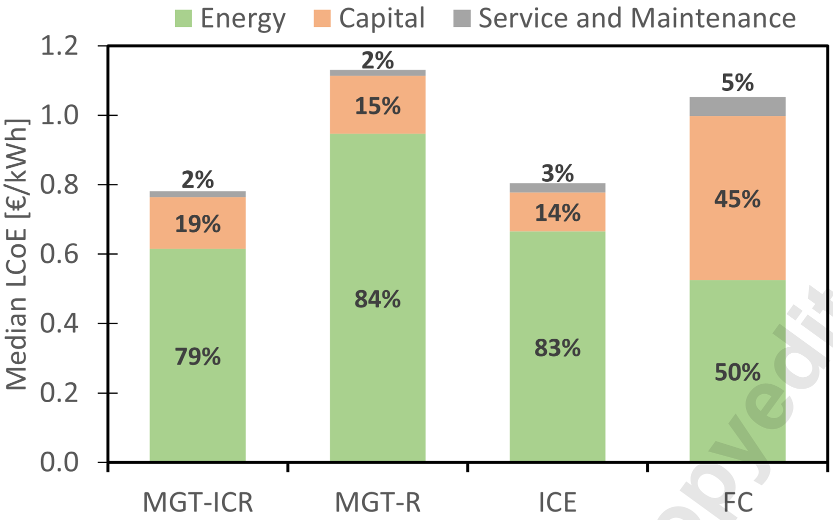

FIGURE 6: Analysis of the median distribution of the constituents of LCoE divided into energy cost (cost of fuel), capital cost, and cost of service and maintenance.

as this would decrease their price competitiveness.

CONCLUSIONS AND FURTHER WORK

This paper studies the competitiveness of a Power-to-Hydrogen-to-Power system considering three possible prime movers: micro gas turbines (with recuperated and intercooled recuperated cycles), reciprocating internal combustion engines, and fuel cells. The assessment is based on an enhanced methodology to asses the technological competitiveness of power and combined heat and power generation systems devised specifically by the authors. Whereas traditional techno-economic studies focus on one side of the problem, the presented framework addresses the analysis holistically through a unique KPI incorporating the energy system performances in terms of economics, reliability, availability and health impact on local communities. The study reveals that the recent advancement in MGT technology, particularly the commercial adoption of two-shaft MGT-ICR engines, is increasing the competitiveness of micro gas turbines for reference applications. The enhanced electrical efficiency, superior availability, and reduced NOx help compensate for having a higher capital cost than internal combustion engines. At the same time, the assessment confirms (once again) the lack of competitiveness of single-shaft MGT-Rs for this application because of their low electrical efficiency, which drives up the cost of energy and, ultimately, LCoE. Finally, reciprocating engines prove to be very competitive thanks to a low capital cost and good electrical performance. Fuel Cells feature high equipment costs, significantly harming the technology's competitiveness; nevertheless, new technology improvements and higher production rates may substantially increase their competitiveness in the route to 2030.

The framework for the assessment of competitiveness presented in this paper proves to be a flexible tool to assess energy systems holistically. Its scope could be extended to other applications targeted by MGTs, such as cogeneration, road transport, aviation and ships. Other cases could see additional combinations of user requirements, including compactness, weight and integrability.

In conclusion, this study suggests that there is great potential for increasing competitiveness through the implementation of innovative strategies. Future research could explore the impact of these strategies on every penalty factor and global KPI, paving the way for a brighter and more sustainable future for applications running on alternative fuels.

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DECLARATION OF CONFLICT OF INTERESTS

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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