Applied Energy 360 (2024) 122717

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Applying the root cause analysis methodology to study the lack of market success of micro gas turbine systems

Giuseppe Tilocca *, David Sánchez, Miguel Torres-García

Department of Energy Engineering, University of Seville, Camino de los descubrimientos s/n, Seville, 41092, Spain

ARTICLE INFO

Keywords:
Microturbine
Micro-gas-turbine
Cogeneration
Microgeneration
RCA
ToC

ABSTRACT

Micro Gas Turbines are on-site generators with the potential to help the transition to a greener economy. However, their deployment into the market did not match the expectations. The Root Cause Analysis (RCA) is the methodology to uncover the highest-level causes before identifying possible solutions. This work applies the traditional approach to problem-solving, which originated as a methodology to find faults in processes. The methodology leads to an in-depth exploration of the problem and the cause–effect relationships within the microturbine and energy market. Specifically, the traditional RCA allowed for a creative and extensive approach. This study highlights the difficulty of targeting the problem from a general perspective with such tools. The process-based tools of the RCA make it challenging to represent such complex systems effectively. In this regard, the authors compare the present methodology with the Theory of Constraints, analysing benefits and obstacles. Eventually, the present methodology systematically isolated several root causes of the problem.

1. Introduction

Micro gas turbines (MGTs) or simply microturbines are decentralised power (and heat) generation systems whose small size (between 30 kW and 400 kW [1]) and power output set them in the so-called microgeneration sector. Thanks to their scalability, they are good fits for distributed generation applications. Thereby, MGTs could potentially facilitate transitioning from the current centralised paradigm to a decentralised one, contributing to a low-carbon economy by 2030 and to carbon neutrality by 2050 [2].

Microturbines entered the market in the late 1990s, but, despite being a promising technology, they failed to succeed, arguably due to the lack of cost-effectiveness against reciprocating Internal Combustion Engines (ICE).

This paper presents a comprehensive methodology, carried out within the NextMGT project,[1] with the aim to (i) identify the underpinning (root) reasons behind this failed deployment to the market, and (ii) propose corrective (remedial) actions to revert this situation and succeed at introducing the technology in certain niche markets for the deployment of MGTs to the market [3]. The next section provides a more detailed description of the innovative elements of this work.

1.1. Novelty, scientific and industrial contribution

As stated in the introduction, despite the claimed winning features of micro gas turbines, these systems have always been relegated to niche applications like Auxiliary Power Units in aircraft [4], burning of flare gas in oil and gas installations [5] and others. This marginal market penetration has most often been blamed on the higher costs of micro gas turbines compared to internal combustion reciprocating engines, which would be at the heart of a classical chicken-and-egg problem. The lack of volume production yields higher costs which, in turn, are the reasons for the low sales. This fact also emerged from a series of interviews with original equipment manufacturers, energy service providers, and end-users carried out by the authors and an extensive literature search.

Without disregarding the known link between sales volume and system cost, the authors believe this interpretation of the market is simplistic. Moreover, the only solution for a higher market penetration would be to have more early adopters willing to take the higher cost and risk of these engines, which would also be why the technology has hardly evolved in the last twenty-five years. In other words, low sales seem to be an exogenous problem for the MGT industry.

* Corresponding author.
E-mail address: g.tilocca@us.es (G. Tilocca).

[1] *Next Generation of Micro Gas Turbines for High Efficiency, Low Emissions and Fuel Flexibility -NextMGT* project, a Marie Sklodowska-Curie - Innovative Training Network funded by the Horizon 2020 Programme of the European Commission under Gran Agreement No. 861079. NextMGT is a consortium of universities, research institutions and companies across Europe with complementary expertise in the area of micro gas turbines and related topics and a common will to unleash the potential of this flexible and versatile polygeneration system.

https://doi.org/10.1016/j.apenergy.2024.122717
Received 10 October 2022; Received in revised form 6 December 2023; Accepted 21 January 2024
Available online 20 February 2024

Nomenclature

$CapEx$	Capital Expenditure
CHP	Combined Heat and Power
CLR	Category of Legitimate Reservation
CO	Carbon Monoxide
CO2	Carbon Dioxide
CRT	Current Reality Tree
FC	Fuel Cell
GHG	Green House Gas
GT	Gas Turbine
HCl	Hydrogen Chloride
HR_{el}	Electric Heat Rate
ICE	Internal Combustion Engine
MGT	Micro Gas Turbine
NOx	Nitrogen Oxides
OEM	Original Equipment Manufacturer
$OpEx$	Operating Expenditure
P_f	Price of Fuel
P_{el}	Price of Electricity
$PERT$	Program Evaluation Review Technique
PM	Particulate Matter
RCA	Root Cause Analysis
SOA	State of the Art
SOx	Sulphur Oxides
SS	Spark Spread
TOC	Total Organic Carbon
ToC	Theory of Constraints

In order to shed light on this long-lasting debate, this paper introduces the application of a systematic, engineering-based methodology to identify the root causes for the said lack of market success. The methodology is not new, as it has been applied profusely in areas of engineering where faults and failures can seriously impact safety and security. In the nuclear industry, it has been used since the late 1980s to investigate events [6] and to reduce alarms [7,8] and errors during maintenance [9]. In the aviation sector, methods like the Fault Tree Analysis are common to source root causes [10] and to investigate the causation chain of accidents and incidents [11]. More recently, the healthcare sector recognised RCA as an effective tool to identify root causes [12–14]. Another use for RCA is in processes where errors and faults mine productivity, like manufacturing and industrial processes and operations [15–18]. Nevertheless, RCA has never been applied to assess the deployment barriers of the micro gas turbine market. In fact, there is no literature on RCA for multidisciplinary problems involving business(trade)-related processes and technology simultaneously. The only relatable works in the literature are listed below.

Zulbainarni and Khumaera use RCA to identify gaps and barriers in developing Sustainable Fisheries Business in Indonesia, applying the "five whys" logic tree to map the cause–effect relationships [19]. Heravizadeh et al. describe a systematic methodology to detect and document the quality dimension of a business process [20] based on the application of RCA to model the elements of a business process and its related soft goals, metrics, and issues for a particular case. Harich et al. apply RCA to sustainability-related problems [21]. Although this is not a business case, it is still an example of dealing with complex problems depending on policies' and regulations' impact on local communities.

Moreover, this work does not limit to applying RCA to the afore-described problem. It also comprises a broader approach to RCA, which, besides the root cause identification, includes the problem definition and review and representation of the system from the market, policy, regulation and technological perspectives. According to the results shown in the paper, applying a systematic, replicable methodology to this particular problem is deemed to provide the MGT industry with a valuable tool to approach market penetration in a more rigorous, technically driven, less speculative manner. The authors hope this can lead the industry to leap into the rapidly transforming market to support the energy transition.

2. Micro Gas Turbines

Microturbines are defined in literature as small gas turbines with output between 30 and 400 kW_e [1], but these boundaries are not standardised. In practice, commercial microturbines range from 2 to 400 kW_e, with pre-packaged systems comprising several modular units arranged together exceeding 1 MW_e in total [22,23].

Micro Gas Turbines share the same thermodynamic principles as larger gas turbines. However, there are some very relevant differences in MGTs that set them apart from bigger turbines. For instance, due to the low volumetric flow, micro gas turbines mostly use single-stage centrifugal/radial turbomachinery for compression and expansion, yielding moderate pressure ratios in the order of 3–4.5:1. Additionally, since it is not possible to cool radial turbines, these engines feature lower turbine inlet temperatures of about 950 °C. These specifications are in contrast with pressure ratios higher than 20:1 and turbine inlet temperatures above 1600 °C of larger turbines.[2]

The combination of lower pressure ratios and moderate turbine inlet temperatures limits the thermal efficiency that can be achieved by engines running on simple cycle configurations. Moreover, the lower dimensions negatively affect the turbomachinery performance [26], heat losses [27], and internal leakages [28]. Therefore, micro gas turbines often adopt recuperative layouts to enhance thermal performance; this raises efficiency but also implies using a recuperator to preheat combustion air, which is a bulky and expensive piece of equipment. Micro gas turbines operate at high, variable shaft speeds; therefore, electricity is generated at a variable frequency by a permanent-magnet synchronous generator, downstream of which power electronics condition the power output to meet the requirements of the grid.

The listed differences, together with the control system based on limiting the maximum rotational speed at constant TOT (rather than TIT), reportedly generate a higher drop in electrical performance with ambient temperature when compared with larger GTs [29].

3. Data sourcing

The information, data and charts presented in this paper result from an extensive literature review, market research and direct contact with the industry stakeholders. The analysis of the technical aspect relies on the specifications of a broad list of engines for on-site generation. The microturbine engines specifications come from the Ansaldo Energia, Bladon Turbines, Aurelia Turbines, MITIS, MTT, Flex Energy Systems, and Capstone Green Energy [22,23,30–34] whilst the sources for ICEs are Adveco, MTU, Cummins and CAT [35–38]. The study results have been validated and reinforced by interviews with most Original Equipment Manufacturers (OEMs) of microturbines, and additionally, the authors have carried out interviews with people representing distributors, institutions, regulators and Universities.

[2] Values estimated from Siemens heavy-duty gas turbines [24], assuming polytropic expansion efficiencies taken from [25].

3.1. Cost breakdown

This high-level study uses data found in the literature to derive cost functions that are assumed to depend on the installed electrical output. A logarithmic regression of the data approximates a cost function. The logarithmic function realistically matches the scaling effect of power on the specific cost.

For ICEs, cost data come from several databases of the Environmental Protection Agency and Energy Information Administration of the US Government reporting the cost for a representative range of installed power, and then normalised to USD_{2021} [39–42]. In particular, installation and service costs have been estimated according to [39–41], whereas the equipment cost functions for genset, heat recovery and interconnect/electrical have been derived from [39,40]. Exhaust gas-treatment data are taken from the International Council on Clean Transportation for emission Stage V [43].

For MGTs, the equipment cost data have been taken from several references also, including some of the aforesaid and also others from Electric Power Research Institute [39–42,44] , as well as from private communications with different OEMs. The cost of the fuel compressor has been estimated according to several sources [39,40,44] and that of the heat recovery has been derived from [39]. Contrary to ICEs, the interconnect/electrical component for MGTs is included in the cost of the generator set [39]. Installation and service costs have been estimated according to [34,39–41]. Fig. 1 reports the cost function for MGTs and ICEs.

Fig. 2 shows a representative case of the cost distribution over an MGT and ICE operating life. Reportedly, energy costs tend to be the dominant contribution throughout the equipment's life. They are considerably higher for MGTs due to their lower electrical efficiency. Furthermore, this represents an ideal scenario based on the design point performance. The fuel cost gap can further spread with the effect of ambient temperature [29] and considering part load operations [45]. On average, the capital cost is higher for microturbines than for reciprocating engines, resulting from the higher equipment costs. On the contrary, maintenance and service costs are –on average– lower for MGTs than ICEs.

3.2. Interview with stakeholders

The interview with stakeholders added a meaningful impact and guidance to this work. The interviewee's sample comprises seven OEMs, two MGT distributors, three R&D companies directly involved in MGT development, ten MGT or energy framework experts (four belonging to academia), one regulator, and one system operator. The questions are listed below:

- **Question 1:** Which are MGTs' strengths, weaknesses, threats and opportunities?
- **Question 2:** How is the MGT market structure, and which are the targeted applications?
- **Question 3:** Which factors mainly hindered the success of MGTs?
- **Question 4:** Were/Are commercialisation strategies suited for product and market?
- **Question 5:** What is the role of innovation in product development?
- **Question 6:** How will the product evolve, and new trends (e.g. ICR and H2 MGTs) impact market penetration?
- **Question 7:** How do MGTs fit into the current policies and regulations? What are the main regulative barriers?
- **Question 8:** How will MGTs and competing technologies fit into the route to 2030 and 2050 policies?
- **Question 9:** What is the role of MGTs in emerging economies?

4. A process-focused approach to Root Cause Analsysis

A cause sits behind every problem. Identifying the cause and removing it is the only way to resolve the undesired effect. Root Cause Analysis is a methodology that allows for finding the root cause of a process. Its invention is credited to Sakichi Toyoda [46], founder of Toyota, who invented the "The Five Whys" methodology, a tool that helps dig into higher-level causes. Currently, it is a widespread tool for root cause identification, which is only a part of modern RCA methodologies.

In the literature, there is no unified definition of root cause analysis. According to Andersen, RCA is a structured approach aimed at investigating and identifying the actual cause of a problem and the actions that are needed to eradicate it [47]. This author warns that RCA comprises different tools and methods used solely or in combination to investigate the root causes of a problem.

The root cause is the highest-level cause, or the cause responsible for the cause-and-effect relationships that eventually end up creating the problem [47]. Conversely, lower-level -or first-level- causes are the ones that directly cause it, and symptoms are only manifestations of the problem. Solving problems requires an in-depth analysis, a structured methodology and often a combination of time and resources. For this reason, people and organisations tend to take remedial actions to tackle symptoms or lower-level causes, mainly to make the issue less visible. This approach does not have a long-term effect on the problem, which will likely reoccur cyclically [3].

This paper follows the approach to problem-solving proposed by Okes [3]. The workflow and stream of information are presented in Fig. 3. The first step is to define the problem, starting with a basic understanding of it and its symptoms. It provides the input for the core loop of Root Cause Analysis, represented by Okes with a diverging and a converging cone. The diverging cone represents the creative part of the block, which requires open-minded thinking and brainstorming sessions. In this case, a good understanding of the process involves several steps, including *researching* the technology (MGT), *reviewing* the existing literature on microturbines, *studying* the market and *having interviews* with stakeholders. The collection of preliminary causes is the input to steps 4 and 5. The purpose of this block is to process a substantial set of unordered data and converge to the root cause of the problem. This paper focuses on the logic-driven approach (Root Cause Identification), leaving the data-driven one for future work.

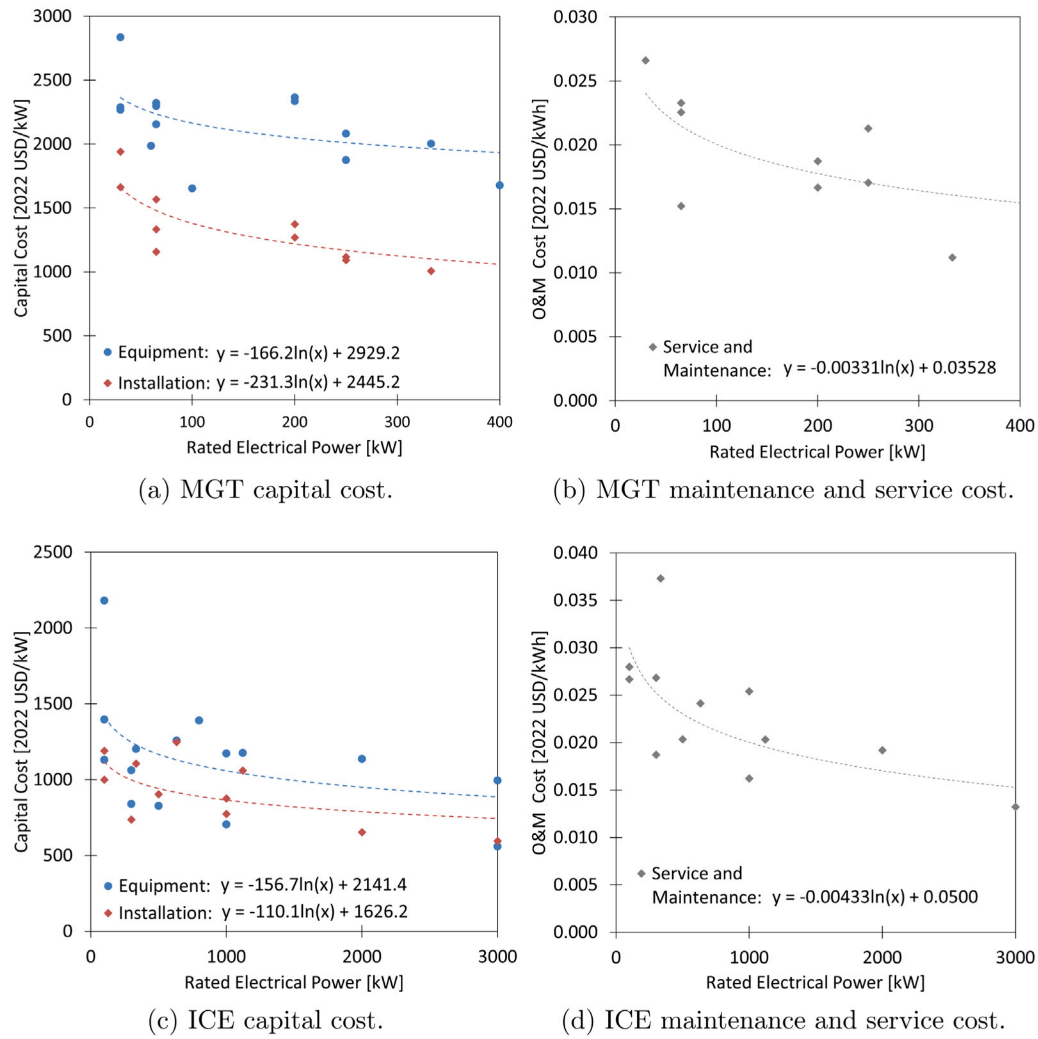
4.1. Define the problem

The methodology proposed by Okes starts with a clear and concise problem statement called *"what, when, who, where, how much"*.

What. Despite being considered a promising technology, Micro Gas Turbines have never met initial expectations.

When. Micro gas turbines for the generation of power and heat have been in the market for more than two decades. Capstone Green Energy pioneered the technology and has been leading the market ever since. Initially called NoMac Energy Systems, the company was founded in 1988 with a product initially meant to overcome Californian brownouts. The first commercial unit was sold in 1998, and the company has experienced several spikes since then. Capstone market capitalisation in the 2000s exceeded USD 7 billion, but in spite of this, Capstone has never reached profitability and has relied on investors' money to continue operations [48].

Who. Together with Capstone, other companies listed in Fig. 4 entered the MGT market in the early 2000s. None of these companies, aside from Capstone, is currently active though newcomers have replaced them in recent years. The root cause analysis methodology will be used to see what went wrong in the last 20 years for the said companies to quit the market and to compare it to the current situation and market conditions.



(a) MGT capital cost. (b) MGT maintenance and service cost.

(c) ICE capital cost. (d) ICE maintenance and service cost.

Fig. 1. Cost functions and the data gathered for micro gas turbines, (a) and (b), and internal combustion engines, (c) and (d). Figure (a) and (c) shows the equipment and installation cost functions. Figure (b) and (d) shows the maintenance and service cost function. The shown data is representative of CHP applications only.

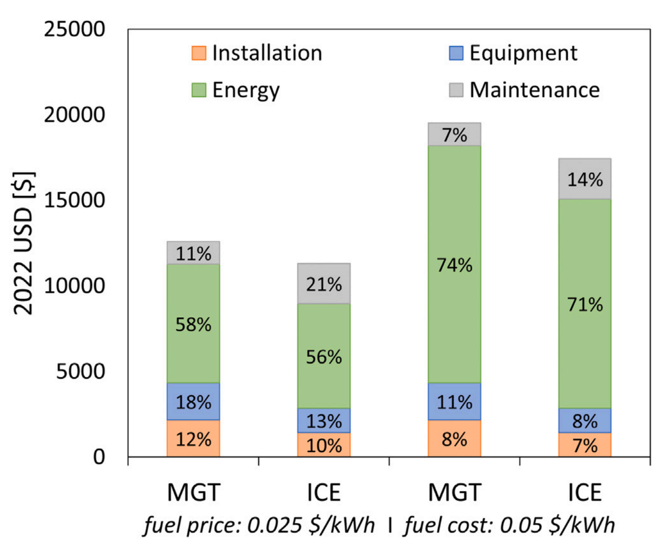


Fig. 2. Comparison of lifecycle cost for MGT and ICEs. The assessment considered a 100 kW installation with ten years of assumed working life. This bar chart analyses two fuel prices: 0.025 $/kWh to 0.075 $/kWh with an operational availability of 95%.

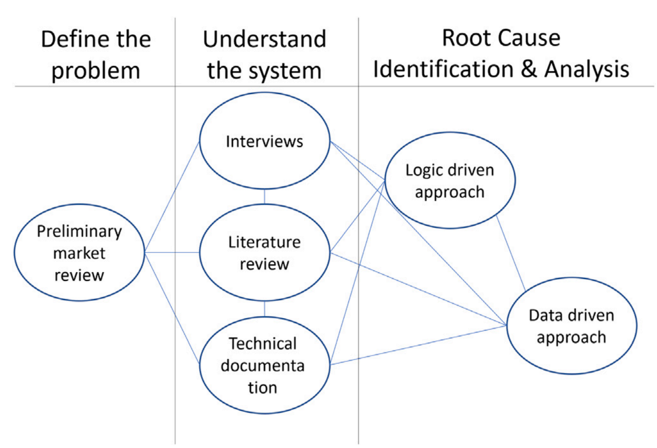


Fig. 3. Program Evaluation and Review Technique (PERT) diagram representing the flow of work and information in this paper.

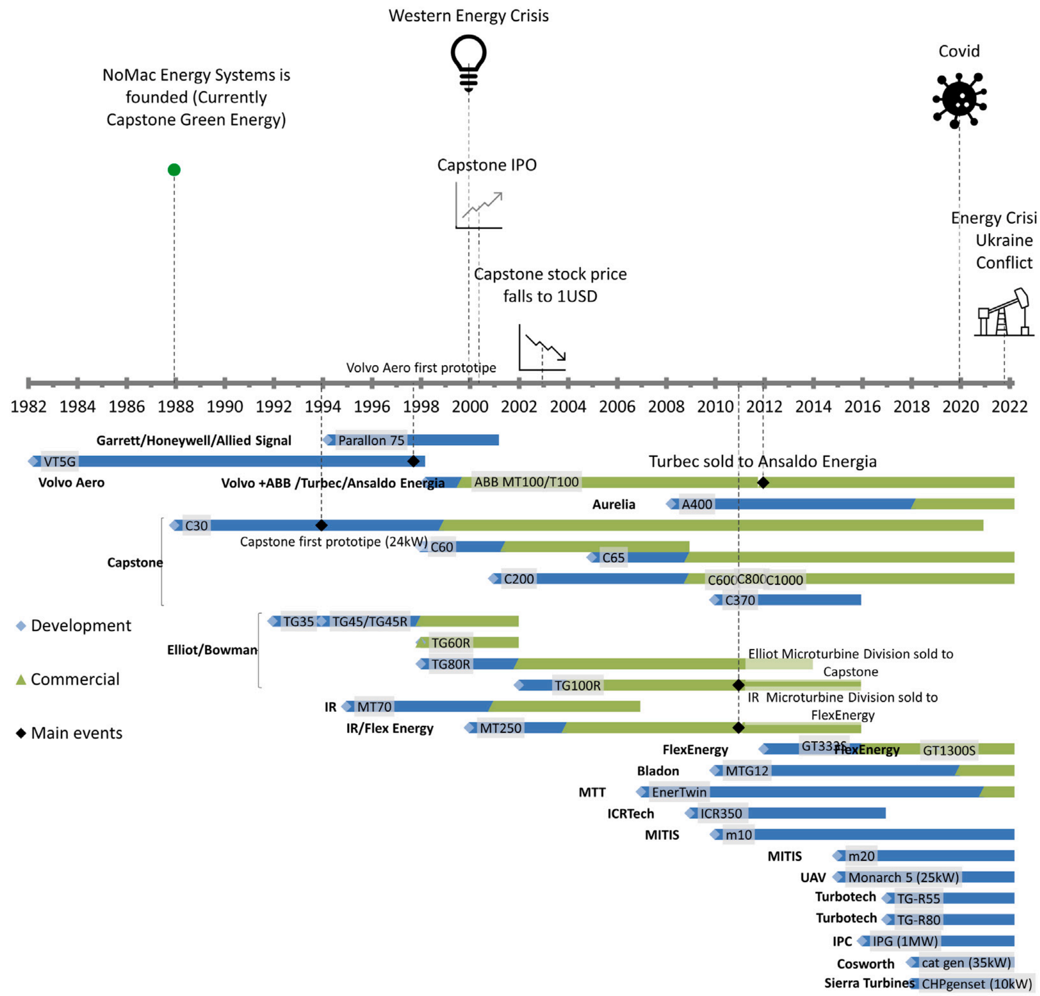


Fig. 4. Representation of the development and commercial of MGT. Information sourced from OEMs website, complemented and validated by the interviews with stakeholders (Section 3).

Where. Most of the MGT developers were/are located in Europe (e.g., Ansaldo, Aurelia, MTT, etc.), the USA (e.g. Capstone, Flex Energy etc.) and Japan (Elliot as part of Ebara Corporation). The website of Capstone [22] and the database of the US Department of Energy [49] show some representation of MGT installations worldwide and in the US, respectively.

How much. Capstone Green Energy, the only public company, maximum market capitalisation is roughly 1/100 of its maximum level.[3] For the latter, the size of the global MGT market is estimated to be around USD 200 million [50], but, again, this value is way lower than Capstone's maximum market cap (several billion). Moreover, the current MGT market is orders of magnitude below the size of similar and competing industries. The market for reciprocating ICE for energy applications [51] is estimated to be around USD 20 billion (around 100 times larger).

Table 1 summarises the problem statement with the *"what, when, who, where, how much"* method.

Table 1
Breakdown of the problem statement.

	Problem definition
What	MGT market is not successful
Where	US, Europe and worldwide
Who	O&M, Legislators, Universities and R&D institutions
When	From the '80s (PD), through the late '90s (early commercialisation) until today
How much	The market size is orders of magnitude lower compared to expectations

4.2. Understand the system: technical and economic features of commercial micro gas turbines

Understanding the process implies stepping back and taking a broad view of the problem before jumping to its possible causes.

The MGT industry is not just a process but a complex system, including companies, legislators, end-users, etc. To simplify the analysis, the system is split into:

- Offer: commercial products that are –or were– in the market and those that are under development.
- Demand: market needs, divided into sectors and niches.
- Context in which they operate, comprised of macro and micro sides. The macro side includes global policies and markets (energy spot prices, interest rates). The micro side is more about local regulations, social acceptance, and impact on local communities.

4.3. Root cause identification

Root cause identification aims to break down the problem and identify possible causes expansively and creatively. This work utilises a

[3] Value subject to the volatility of the share price.

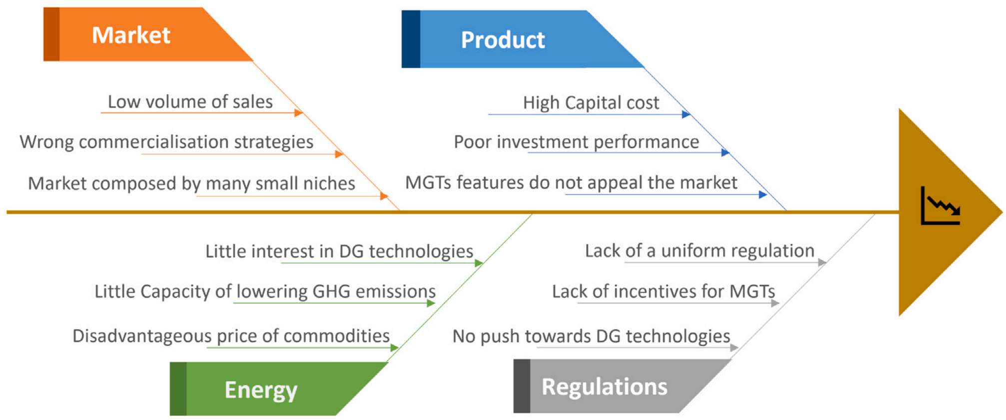


Fig. 5. Fishbone diagram.

combination of the fishbone chart and logic tree. The fishbone chart or cause–effect diagram serves to break down the problem. It is simple to implement, and it efficiently splits the problem into multiple categories and triggers thoughts during brainstorming sessions [3,47]. The main branches –or fish bones– represent the categories. The causes expand from there like branches. The configuration follows a cause–effect relationship, like in the logic tree. However, a few limitations come with its simplicity, like the lack of room to dig deep into higher-level causes very far.[4] Following the concept described in the previous section, the categories are *product*, **market** and context. In turn, the context is divided into the macro -**Energy framework and macroeconomics**- and micro -**Regulations**- categories. The cause–effect diagram in Fig. 5 shows the category breakdown with the low-level causes, which will be the starting point of the RCI process. For each category, a logic tree will expand the causal chain. The logic tree is also named a why-why or five-whys diagram since, for each step, the user asks the question: "*why?*". The logic tree breaks down the system, starting to form the problems to the lower-level causes and up to the higher-level causes. The system analysis follows an incremental cause-and-effect perspective.

4.3.1. *The microturbine market*

The low volume of sales might be considered one of the biggest symptoms of the problem. It combines many different factors. First, **the market structure:** micro-cogeneration generation is a relatively small market, with a moderate growth.[5] Microturbines currently target the energy sector. MGTs abandoned the automotive industry after a few unsuccessful attempts [53–55]. In the marine sector, only a few examples are present in history [56,57]. In aviation, UAV Turbines [58], Sentientblue [59], and Turbotech [60] are currently developing propulsion systems for small and unmanned applications.

MGT and ICEs have similar inputs and outputs and target similar applications. Markets based on established technologies that hold a vast market share –like ICEs in this case– tend to raise barriers like collective preferences, policy alignment, technical performance, and effective supply chain. Technological niches could push to become an established part of the market environment, or they could also create a new one [61]. Overcoming these barriers or forcing them to adapt represents the main effort.

When competing with ICEs, MGTs have longer payback periods and higher capital costs. Moreover, they do not provide any practical advantage (see Section 4.3.4), making them more competitive than other technologies. The targeted market is, therefore, fragmented and composed of many small niches [62] comprising several applications with specific requirements, such as O&G, industrial and commercial mid-grade heat, biogas and biofuels with low and variable LHV. Still, their penetration was insufficient to lead to a significant expansion. Their technical characteristics were inadequate or ineffectively exploited to lead to more substantial market penetration.

Inadequate commercialisation strategies waste precious resources by targeting areas where the product is weak. They are often due to the lack of knowledge of the product itself and its potential markets. The interviews with stakeholders confirmed that MGTs initially had a volume-based approach to the market rather than the market-niche one illustrated by Schot in [61]. They agreed that ineffective strategies hindered the commercialisation at the early stages of the MGT market deployment.

The unwillingness to invest in energy technologies is another factor limiting sales. Cutting energy costs requires a big commitment and does not yield significant economic benefits. A study for domestic microgeneration in the UK [63] found that high costs with long payback periods, lack of trustworthy information, and installation concerns are the main barriers, according to rejecters of the technology. For microgeneration, the same concept applies to the commercial and industrial sectors. According to the MGT and ICE operators interviewed, companies tend to be reluctant to operate actively in energy since it is not their core business. They are discouraged by the long payback periods, installation and integration hurdles, and contractual and regulatory implications. Additionally, according to the interviewees, there is a distorted perception of the energy market by many end-users who generally do not consider MGTs a green technology. Currently, MGTs running on renewable fuels represent the minority of the total applications due to an undeveloped framework of renewable resources. These conclusions align with the EC "*An EU Strategy for Energy System Integration*" [64] for local energy sources not being efficiently and sufficiently exploited because of:

> "*Insufficient awareness and knowledge about these solutions, the reluctance of companies to enter into a new business that is not their core activity, lack of regulatory and contractual frameworks to share the costs and benefits of new investments, and barriers related to planning, transaction costs, and pricing signals*".

Moreover, especially for CHP applications, all installations are complex and different. They often imply even higher installation costs than primary power ones, significant commitment, indoor/outdoor space occupation, and new interconnections/pipings.

Fig. 6 shows the resulting logic tree for the market, which integrates all the information above.

[4] This is the exact reason why the authors decided to use a combination of fishbone diagram and logic tree.

[5] Micro CHP is considered a fraction of the whole CHP market whose global share, as reported by Cogen Europe, has been constant in Europe in the last years [52].

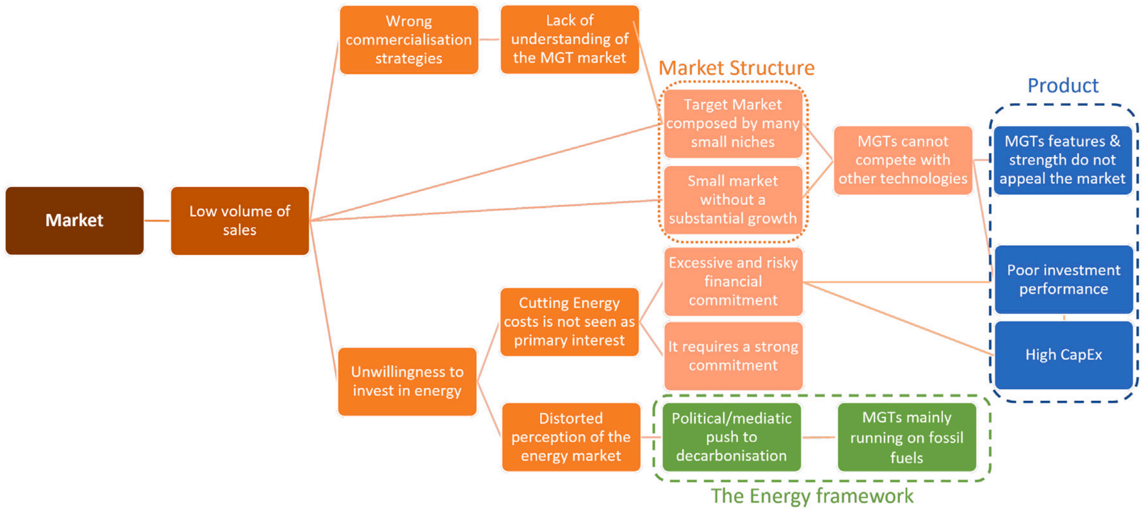


Fig. 6. Logic tree for the market. Items for these three are highlighted in orange. Items from other trees are represented in blue (product), green (energy), and grey (regulations).

4.3.2. Energy sector and macroeconomics

This section analyses the energy sector as a whole. The breakdown includes the energy market, long-term policy framework, and macroeconomics. In this scenario, the interest in DG technologies, particularly MGTs, has been characterised by short spikes. However, it never took off except for "renewable" microgeneration systems like solar and wind.

For micro-thermal generation and microturbine applications, three main drivers for the adoption of microturbines can be identified at the macro level:

- Value of the investment.
- Necessity.
- Lowering greenhouse gases and other emissions.

The single decision, i.e. at the micro-level, depends on the balance of these three drivers and on how that solution compares to other technologies (more deeply analysed in Sections 4.3.4 and 4.3.1). Effectively, the value of the investment combines the capital (CapEx) and operating (OpEx) costs of the product (Fig. 2). This combination bounds the savings/profits compared to the separate heat and power production.

For large gas turbines –like CCGT plants–, the metric to assess the economic feasibility in terms of energy costs is called Spark Spread (SS), the difference between the electricity price P_{El} and the fuel price P_F, multiplied by the heat rate of the engine HR_{El} [65–67]. The higher the SS, the larger the margin for additional operational expenses (e.g., service) and the room for profits. For a CHP system, the conceptual approach remains with few additional considerations. A review of CHP economics, including spark spread and payback period, is given by Smith et al. [68]. The payback period evaluates the investment feasibility. It indicates the time needed to repay the initial investment by the overall profits or savings [69].

Many companies started the MGT business in the 1990s and 2000s (Fig. 4). At that time, the oil price was about USD 20 per barrel, and in the next decade, prices rose to over USD 140 (July 2008)., Fig. 7, The price of NG increased by a factor of four in the same period. The rise in electricity prices in many countries could not compensate for the surge in NG price, having their price ratio and spread going down. From a macro perspective, this did not favour on-site generation solutions. More specifically, this brings back to the product characteristics and the market needs.

The second "macro" item is *necessity*. The need for such technology can depend on indirect financial or social benefits. Alternatively, the unicity of a product feature can make it the only possible solution. An

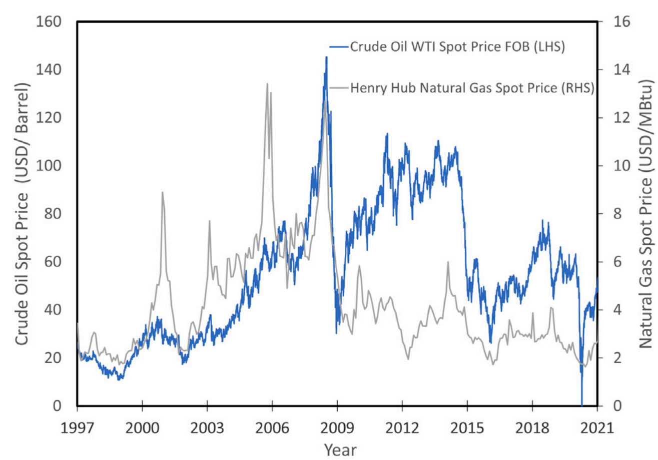


Fig. 7. Spot price history of Crude oil (WTI) and Natural gas (Henry Hub) [70].

example of an indirect benefit is the drive to install DG technology to avoid production stops due to blackouts and brownouts resulting from an unreliable grid. This perception of necessity can be triggered by big events with a large mediatic resonance, such as the Oil Crisis in the '70s [71], or the Western Energy crisis of the 2000s [72]. Nevertheless, the actual quality of the power grid in the EU and USA through these last two decades has been good overall –for countries targeted by microturbines– according to The World Bank's Quality of Electricity Supply index, [73]. Moreover, in many cases, their integration requires and depends on external frameworks and technologies of inherently slow adoption, like smart grids [74]. The DG contribution to grid stability, reliability and power quality [75–77], and the capacity to shave peak loads [76,77] may play a bigger role in the future. Indeed, a "*fast-moving energy framework*" [74,78] with increased production of renewables can create new drivers of necessity.

The last macro driver is the reduction of GHG and other emissions. Several countries and regions, like the EU, are pushing for a drastic cut in GHG emissions. In particular, the European Green Deal [2] aims to reduce GHG emissions by 55% by 2030 (compared to the 1990s emissions) to become carbon neutral by 2050. The UK and US emission reduction plans have similar targets to that of the EU [79,80].

In line with the aforementioned objectives, the average GHG intensity of EU countries is steadily decreasing. Above 500 g_{CO_2}/kWh in 1990, it is currently below 300 g_{CO_2}/kWh with the target of 100

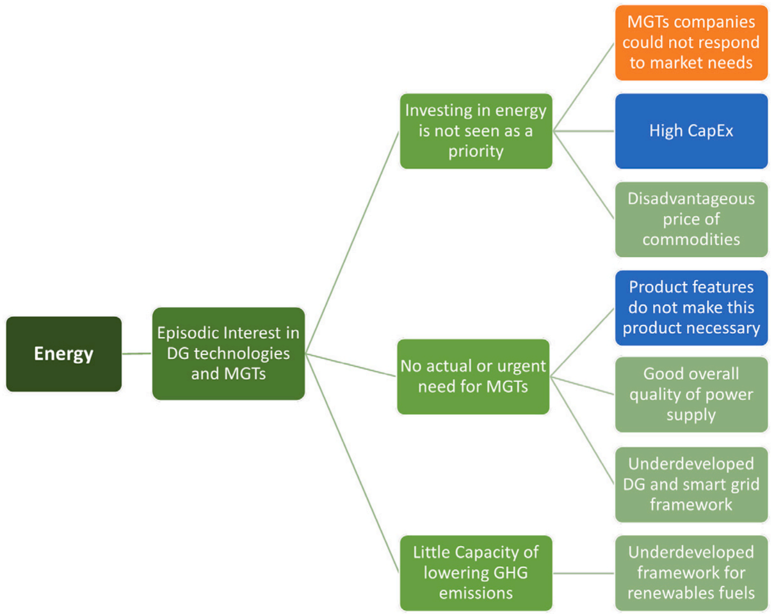


Fig. 8. Logic tree energy. Items for this tree are highlighted in green. Items from other trees are represented in: orange (market), blue (product), and grey (regulations).

g_{CO_2}/kWh for 2030 [81]. Tilocca et al. [82] compared the grid emission of European countries against a few sample CHP configurations recovering all the heat available. Even in this favourable case, there is no apparent reduction in GHG emission compared to most countries' grids.[6]

Fig. 8 presents the resulting logic tree for the energy sector and macroeconomics.

4.3.3. Regulations

This section looks into legislation, regulations and standardisation. The low-level causes from which to develop the logic tree are:

- Lack of uniform regulations and standards.
- Insufficient incentives towards DG technologies and MGTs in particular.

The first cause is the lack of uniformity within the EU and worldwide. This element quickly emerged during the private interviews with OEMs carried out by the authors, which is in agreement with the hurdles recognised by the European Commission:

> "*New or changing technical regulations in different countries can create unnecessary and unjustified technical barriers to trade. Discrepancies between product rules can impose additional costs on exporting enterprises and restrict inter-EU trade [83]*".

Internationally, the only standard that applies to MGTs is standard ISO 19372:2015 [84] (most recent update in 2020). In Europe, manufacturers must make sure that their products are compliant with the applicable directives[7] and harmonised standards[8] [87].

The EU harmonised standards relative to MGTs are mainly the Low Voltage Directive 2014/35/EU [88], the Electromagnetic Compatibility Directive 2014/30/EU [89], and the Machinery Directive 2006/42/EC [90]. This last one, dating from 2006 originally, is in the process of being replaced by a new one [91] given the following problems identified by the impact assessment carried out by the European Commission [92]: (i) it does not sufficiently cover new risks originating from emerging technologies; (ii) legal uncertainty due to a lack of clarity on the scope and definitions and possible safety gaps in traditional technologies; (iii) insufficient provisions for high-risk machines; (iv) monetary and environmental costs due to extensive paper-based documentation; (v) inconsistencies with other pieces of Union product-safety legislation; (vi) divergences in interpretation due to transposition.

Additionally, the equipment and processes for on-site generation in different countries must comply with local regulations regarding emissions, noise, and fire prevention. These may differ at a national, regional, and community level. These discrepancies may harm product development costs since adapting products and processes to different regulations is necessary. It also increases the complexity of distribution strategies through a heterogeneous territory. Concerning grid codes, Bründlinger reported some differences between the national requirements of different countries and the uncertainty concerning the implementation, testing, and certification procedures [93]. This barrier is particularly relevant for emerging technologies (such as

[6] The emission levels are average values. In practice, there are daily and hourly variations due to the change in the energy mix necessary to follow the power load. There could be times when adopting CHP and on-site thermal generation would have more or less GHG emissions than the baseline.

[7] A directive is a legislative act of the European Union setting out a goal that all EU countries must achieve. However, it is up to the individual member states to devise their laws on how to reach these goals [85]. Directives usually intend to control the effect of products and processes on people, for instance, laying down the requirements or Essential Health and Safety Requirements (EHSR) for OEMs and operators willing to commercialise their products in the EU.

[8] A harmonised standard (HS) is a European standard developed by a recognised European Standards Organisation. Manufacturers, assessment bodies and operators can use HS to prove that products, services, or processes are compliant with the respective EU legislation [86].

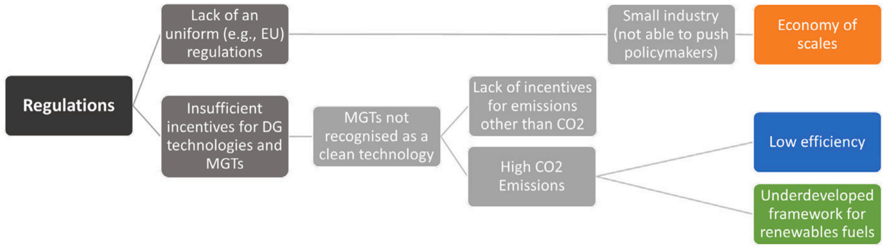


Fig. 9. Logic tree for the regulations. Items for this tree are highlighted in grey. Items from other trees are represented in: orange (market), green (energy), blue (product).

MGTs). Robinson, an EU Horizon 2020 project integrating local energy sources in industrialised islands, has recently highlighted that the policies for getting operation permits throughout Europe are not uniform. This nonuniformity tends to raise barriers to the adoption of decentralised systems. Moreover, the framework for the definition of non-exclusive requirements[9] is not sufficiently inclusive for the deployment of decentralised energy systems.

Other industries like solar and wind might contribute to conforming grid standards, for which talks are already in progress [93].

Regarding the second branch of the tree, **insufficient incentives**, investing in micro-cogeneration is generally not attractive within the current policies and regulations, as highlighted by Carrero et al. in [97].

The abatement of specific harmful contaminants like NOx, CO, HCI, TOC, SOx, and particles is often not regulated and incentivised in the same way as CO_2. Such is the case of NOx, which is widely recognised as a dangerous emission [98], especially in urban areas [99]. For instance, Bennato and Macor in [100] compare the emission limits of Italy and Germany; in all cases, the emissions of NOx, CO, HCI, TOC, SOx, and PM have specific thresholds (depending on fuel, technology and installed power). Assuming that two technologies (e.g., MGTs and ICEs) are below these limits, there is no competitive advantage in having the lowest emissions. Moreover, Macor and Benato found that NOx produces 90% of the damage to human health amongst all emissions of ICEs [101,102]. Consequently, reducing the toxicity of biogas and natural gas emissions requires cutting NOx. Additionally, biogas effects are three times higher than natural gas due to the higher NOx emissions. Nevertheless, most of the biogas installations rely on ICEs [49,100,103]. Microturbines could help reduce NOx emissions and other harmful contaminants thanks to lean premixed or flameless combustion [104]. In a study, Chiaramonti et al. [105] tested a liquid fuel (diesel) micro gas turbine with different first-generation biofuels, such as vegetable oil and biodiesel. They show that MGT can successfully operate with biofuels without significant penalties for emissions. Promoting the cleanest technology overall could raise the competitiveness of MGTs, as shown by Rodriguez et al., who found that NOx incentives could make MGTs more competitive than ICEs [106].

From the information in this section on regulations, this branch of the logic tree redirects to the energy framework. Given that ICEs perform better in terms of CO_2 emissions, these technologies have an advantage for incentive schemes with a premium on tax reductions proportional to CO_2 savings (like the UK CHPQA scheme [107]). Accordingly, the low efficiency of MGTs –a product feature– is the other high-level cause in the regulation tree, which stops here as all highest-level causes redirect to other logic trees. Fig. 9 presents the logic tree for the regulations.

[9] In the Network Code on Requirements for Generators (RfG NC) by the Member States (Commission Regulation (EU) 2016/631) [94], standard N 50549 1/2 [95,96].

4.3.4. The product

This last section of RCI will discuss the cause–effect relationship on the offer side, as shown in the log tree presented in Fig. 10. Three different factors are potentially causing the lack of interest in MGTs:

- High capital cost (CapEx).
- Investing in MGTs is not profitable, feasible, or attractive.
- The features of MGTs do not appeal to the market or satisfy any of its needs or requirements.

High capital cost is –by itself– a considerable barrier. It can put a full stop to many potential projects, especially for private investors and SMEs who cannot invest large sums. In addition, investment feasibility is a relevant decision factor (See Section 4.3.1).

The (equipment) cost of MGTs tends to be higher than other competing technologies like reciprocating internal combustion engines (ICEs), and the potentially lower maintenance does not suffice to total cost keep economic indicators in a competitive range (Fig. 2). Energy and maintenance costs are the main constituents of OpEx. High energy costs are due to the high fuel price combined with the lower efficiency of MGTs. When MGT joined the market, they had already suffered a gap in performance with ICEs. Most of the products that joined the market in the 2000s (see Fig. 4) had little to no evolution and improvement in performance. Conversely, ICEs which already could benefit from decades of development, kept innovating and improving [108–110]. Therefore, fuel costs can be either an absolute problem (competitiveness of decentralised systems versus centralised ones, Section 4.3.2) or a relative one (competitiveness of MGTs versus other decentralised technologies). The other component of the operating expenditure is the cost of service and maintenance. MGTs can benefit from extended maintenance intervals (around 8000 h). These intervals are roughly an order of magnitude larger than ICEs', which lowers maintenance costs. However, they can be negatively affected by two main factors: higher specific costs of maintenance and reliability. The workforce for the service and maintenance of microturbines is highly specialised and typically lies with the OEMs, which negatively impacts service costs despite the longer maintenance intervals. On the contrary, maintenance labour for reciprocating engines is relatively cheap and straightforward and can rely on third parties due to economies of scale. Reportedly, some MGTs did not perform well in terms of reliability [111–113] and availability of spare parts [113], that can lead to lower availability, increased costs, and lower savings.[10] Not only this, but reliability-related problems also may impact the reputation and perception of the technology.

Capital costs are divided into installation and equipment costs (See Fig. 1). The high equipment costs are due to two phases of the product: the design and the supply chain. *Product Design* includes R&D, prototyping, testing, and IP acquisition and management take much time and financial effort. Indicatively, the journey from the initial concept to a commercial product can take over years (Fig. 4), reflected in product

[10] The information found in the cited paper was confirmed in the round of interviews with OEMs and energy system distributors carried out by the authors.

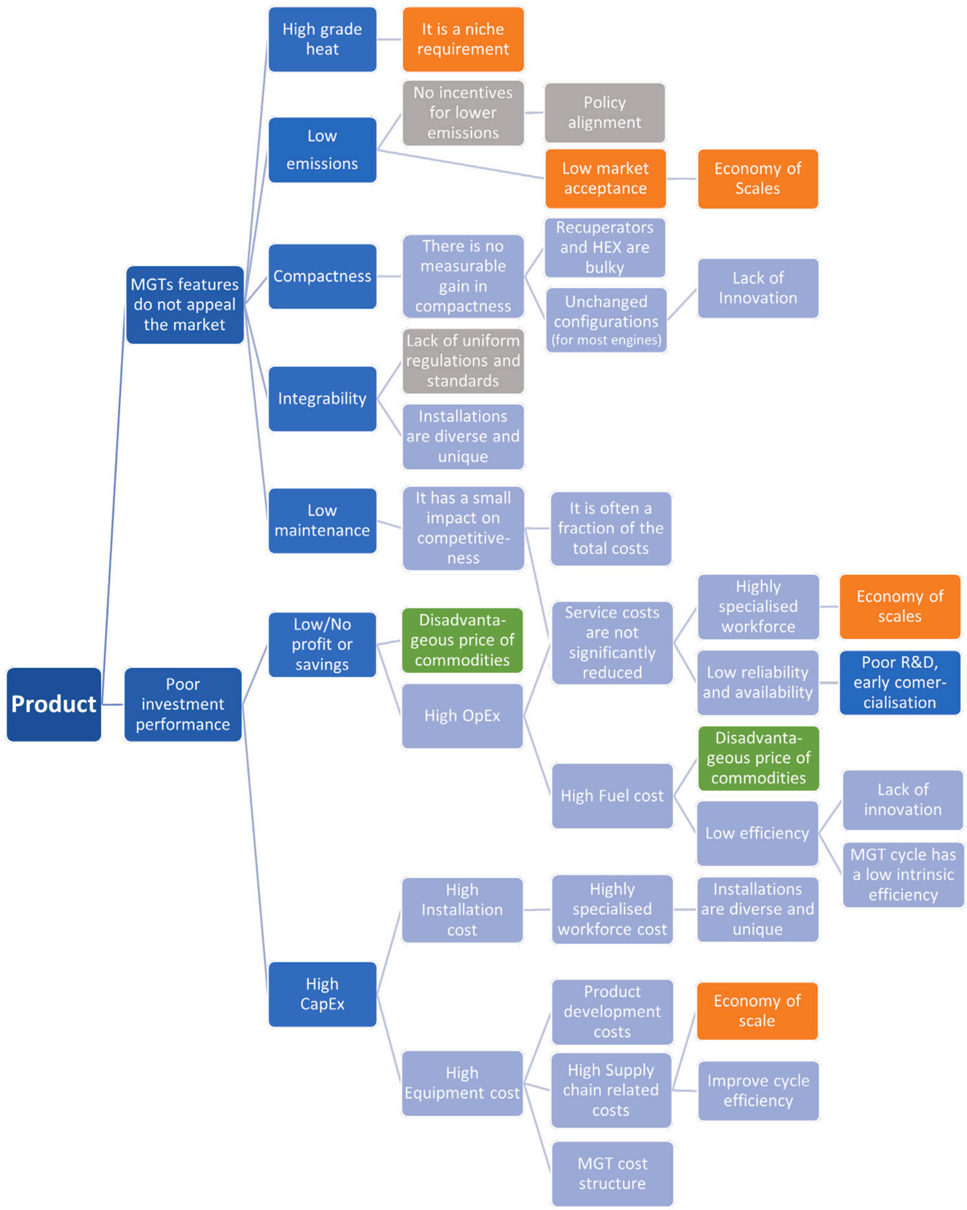


Fig. 10. Logic tree for the product. Items for this tree are highlighted in blue. Items from other trees are represented in: orange (market), green (energy), grey (regulations).

costs. Another aspect to consider is the cost structure of MGT reported by the European Turbine Network [114], where the contribution of the core mover is only a fraction of the total genset cost. OEMs often rely on external companies to provide additional components (i.e., generator, recuperator), which means that manufacturers can profit on a small portion of the equipment cost. The interviews with stakeholders confirmed this structural problem.

High costs within the supply chain relate to expensive components, materials, and manufacturing methods. The reasons for this rely on the economy of scale and the need for expensive components and materials –like recuperators and heat exchangers [115,116]– to improve the engine's efficiency. The impact of sales volume on the cost of equipment is exemplified in a report by the European Turbine Network [114].

High installation expenditures are caused by different factors. Logistics and shipment fees can be significant, but they are inevitable and assumed comparable to ICEs [39]. The workforce needed for the installation is highly specialised and often belongs to the OEMs. Moreover, most applications require *ad hoc* integration, connection, and equipment, and this is especially true for CHP applications where the requirements posed by the process of using heat create unique conditions. A universal plug-in solution is unlikely to exist if not for specific niches. In the analysis of the Capital Cost side of the chart, most elements point to the economy of scale as the reason for high costs. However, the economy of scale directly results from the low volume of sales. It cannot be a cause as it is already a symptom of the problem, leading to a cyclic dependency which cannot be represented in the adopted logic tree. The last part presented in Fig. 10 is the one relative to the product features. For each item, the intended statement in the logic tree would be:

> "*The ITEM does not appeal to the market or it does not act as a strong driver*".

This last paragraph analyses the MGT features identified as possible drivers.

- Low maintenance (longer time between overhauls). This item has already been discussed in this section.
- High-grade and high heat-to-power ratio: microturbines deliver exhaust gas at intermediate temperature and high oxygen content.

This makes them suitable for several applications requiring high-grade heat and high heat-to-power ratios that are not reachable by FCs and ICEs. However, in reality, only 23% of industrial applications are estimated to require heat at 200 °C–300 °C, whereas 66% of them require heat below 200 °C [117]; on the other hand, heating for commercial and residential applications also demands low-temperature heat. In this case, ICEs maximise the profits for power, and CHP distributed generation applications [118], and this is why they tend to be the preferred choice for applications without specific requirements.
- Low emissions: as reported in Section 4.3.3, MGTs can provide considerable advantages in terms of emissions of pollutants (except for CO_2), but it does not convert into a market advantage under the current regulatory framework.
- Fuel flexibility: MGTs can run on many fuels, even with relatively low heating value, and withstand a large variability in fuel composition without experiencing significant issues concerning reliability, availability and maintenance costs. These two factors could make microturbines competitive in low-calorific-value fuels or biogas applications. Despite this and the lower maintenance costs reported in the previous bullet, most biogas and biofuel installations still use ICEs [49,100,103]. For new fuels like hydrogen, MGTs will have to demonstrate the technical feasibility of such solutions and prove their competitiveness inside this new framework. Escamilla et al. [119] assessed the round-trip performance of Power-to-Power solutions adopting MGT and hydrogen. They concluded that improving MGT's performance will be crucial in achieving acceptable levels of round-trip efficiency.
- Compactness [114]. The size and weight of the prime mover in an MGT is just a fraction of the footprint of the whole package for energy applications. In practice, commercial MGTs' footprints are comparable to ICEs' when according to OEM specifications. Recuperators, intercoolers and heat exchangers generally take up plenty of space in MGT packages. During the year, this feature of MGTs, including the packaging configuration, has not really evolved in commercial products (no innovation). This feature opened a new market segment for jet engines in aviation against ICE. The clear difference in size and weight opened up a strong market niche for large aircraft but not for smaller planes. In the latter case, the engine's specific output had a lesser impact than the higher equipment cost. Presently, the potential emerging microturbines market for autonomous aircraft propulsion is in the development stage. On the contrary, most of the attempts to use compact MGTs as a range extender in the ground transportation sector have not reached the market [53–55].
- Integrability and modularity. Complexity and regulative and bureaucratic burdens (see Section 4.3.3) can hinder the commercialisation of micro-generators. In particular, CHP involves complex and specific installations tailored to the requirements and setup of each end-user, meaning that plug-in, pre-packaged and easy-to-install solutions are technically challenging for most niches that MGTs could target.

5. Discussion of results

This last section used a combination of a cause–effect diagram and a "5-whys" logic tree. The former supported the brainstorming and initiated the analysis, whilst the latter looked more deeply into the cause–effect relationships. The information gathered from the literature review, market research, and stakeholder interviews populates the logic trees. RCI effectively decomposes the problem and sheds light on the more obscure areas and cause–effect relationships to achieve a sound knowledge of the system. The logic trees for each subsystem eventually identified many high-level causes. At the same time, they highlighted a high degree of complexity and interdependency amongst the subsystems. This issue makes it very hard to identify and analyse some well-defined root causes. Eventually, though, the four diagrams identified the highest-level causes of the system, i.e. the possible root causes.

Most of the identified causes relate to product and macroeconomics. In the first case, high levels cause range from product features and specs to R&D and product design. Mainly, the low intrinsic efficiency of the Brayton cycle for the MGT configurations is responsible for many lower-level causes. It directly affects operating costs and, indirectly, capital costs and the cost structure (i.e., the need for expensive components and materials). On the other hand, the discontinuous innovation did not improve MGT features and performance at the same pace as the competition and/or did not target the actual market needs. The macroeconomics highlights some of the missing drivers and existing barriers related to the demand for MGTs, the value of investing in on-site generation and the development of an external framework (distribution and renewable fuels infrastructure) on which MGTs can rely. Finally, the market tree highlights a barrier intrinsic to the targeted market as its level of commitment to investing in energy.

6. Comparison of RCA methodologies

This paper has discussed the traditional approach to Root Cause Analysis inspired by Okes. Using the traditional Okes' approach to RCA for such a multidisciplinary problem highlighted several weaknesses. This representation does not clearly resolve the interdependency of many causes — within the same tree and with other trees. In addition, the logic tree does not allow for characterising complex cause relationships and considering each entity's different impact. Lastly, some steps miss a rigorous approach. Despite this increasing creativity and in-depth exploration of the problem, it might lead to a crowded representation of reality. The authors researched alternative methods that can overcome these barriers. The Theory of Constraints [120] has been identified as a methodology that could potentially overcome the cited issues through:

- The **category of legitimate reservation** (CLR) dictates the rigorous and holistic approach to the thinking process, providing it with a scientific value and differentiating a truthful representation of reality from a mere perception of it.
- The **thinking process** comprises six different logic trees and their rules-of-logic [120,121]. Each one represents one step of the problem-solving methodology. The output of one tree is the input of the following one. The Current Reality Tree, the tool for RCI and RCI, defines different types, degrees, and directions of causality (according to the CLR).

The authors adopted the ToC to re-assess the same problem; the results are presented in a separate work [82].

By comparing the present and the cited work, the authors concluded that both approaches aim to identify and address the root causes of a problem. However, they differ in their underlying principles and tools. Table 2 summarises and compares each step of the RCA process for the two methodologies.

RCA-A, the traditional approach, has evolved over the years and comprises various tools and methodologies intended to analyse and correct processes. The problem-solving process in RCA-A begins with problem definition, followed by root cause analysis and solution implementation. Okes presents a general approach that includes several tools and methodologies, and this work selects the most appropriate ones for the purpose at hand.

In contrast, the ToC methodology (RCA-B) is a more general scheme for continuously improving systems. It follows a defined set of rules called the category of legitimate reservation (CLR) and utilises specific tools known as the thinking process (TP). The TP consists of six logic trees and their rules of logic, representing each step of the problem-solving methodology. The Current Reality Tree (CRT), the tool used

Table 2
Comparison of the traditional process-based approach to RCA (RCA-A) and the Theory of Constraints (RCA-B). This table makes a one-by-one comparison of three Root Cause Analysis steps: (1) Define the problem, (2) Understand the system, (3) Identify root causes.

	Traditional (RCA-A)		ToC (RCA-B)	
	Positives	Negatives	Positives	Negatives
1	- break down the problem, identify the stakeholders, the geographic and historical context		- Clear, streamlined approach - Comprises steps (1) and (2) - Provides clear inputs for step (3)	
2	- brings forth the analysis from several perspectives - allows studying the system components and their links			
3	- Breaks down the problem and the system in all its details	- Very dispersive - Does not specify the cause type - Do not quantify causality	- It is clear and concise - Defines several types of causality - Easy to trace the cause–effect chain - Includes reinforcement loops	- The many symbols can confuse the reader - It is not as thorough in analysing the system as the first approach

for root cause analysis in the ToC, defines different types, degrees, and directions of causality according to the CLR.

The first step in both approaches is problem definition. In RCA-A, the problem is defined using the "what, when, who, where, how much" method, breaking down the problem by identifying stakeholders and geographic and historical contexts. However, quantifying the problem ("how much") can be a generic question with multiple possible answers. On the other hand, in RCA-B, the problem is defined through gap analysis using the Input–Output (IO) Map. The IO Map justifies and quantifies the problem, and the Critical Success Factors and Necessary Conditions help uncover the symptoms of the problems, referred to as Undesired Effects (UDEs). This structured approach in RCA-B provides a clear understanding of the system and the problem.

Moving on to the root cause analysis phase, RCA-A divides the system into categories and employs flow charts to analyse the interactions between processes and their linkages. The analysis concludes with the use of logic trees. However, the fault tree used in RCA-A has some limitations. While it effectively breaks down the problem and analyses the cause–effect chain in detail, it can lead to complex and difficult-to-read diagrams due to numerous ramifications. The tree also fails to represent cross-connections and cyclic relations well. Furthermore, it does not differentiate the type of causal relations or quantify the contribution of different causes, making it challenging to determine the primary contributors to the chain of events.

On the other hand, RCA-B addresses many of the limitations of the fault tree through the use of CRT. The CRT, supported by the CLR, provides a well-defined and referenced representation of each entity and considers causes with relevant causality. It defines the type of cause–effect relationship and allows for tracing the impact of root cause removal. By defining the sphere of influence, the CRT focuses only on the relevant areas of the tree, improving the analysis and resolution of the problem.

In summary, both RCA-A and RCA-B present similar steps in problem-solving, starting with problem definition and root cause analysis. However, they differ in their underlying principles and tools. While RCA-A relies on various methodologies and tools, RCA-B follows a structured approach based on the CLR and the TP. The ToC methodology overcomes some of the limitations of the traditional RCA approach by providing a more rigorous and holistic thinking process. It allows for a more accurate representation of complex cause relationships and considers the different impacts of each entity.

Conversely, the traditional RCA process is prone to a first approach to a new or unknown process, of which the causal relationships and component links are unfamiliar. It is instrumental in exploring processes and systems in detail, identifying any entity and uncovering every hidden link.

7. Quantification methodologies based on the Root Cause analysis

The previous RCA analysis indicates that market-driven innovation is likely the most effective way to act. Following the problem-solving workflow implicates the use of data to validate and quantify the logical/qualitative solution obtained. Recent works proposed numerical approaches to continue this RCA-grounded problem-solving process and provide quantitative methods for RCA analysis. Tilocca et al. [122] developed a Key Performance Indicator that combines technical, economic, environmental, and operational factors to compare competing technologies in the same market. The indicator is the sum of weighted penalty factors. Each penalty represents the contribution to each cause in generating the effect. This methodology enables the analysis of market niches and insights into the economic and technological gaps of the micro gas turbine industry. The quantitative methodology confirms the preliminary conclusion of the present study without any substantial computational effort, being the penalties analytically defined mathematical functions.

Moreover, a follow-up work by the same authors [123] builds on the previous methodology to overcome some limitations. The improved methodology uses the Theory of Constraints principle to remove the arbitrariness of penalty weights and include the effect of uncertainty from technical and economic elements, resulting in a probabilistic-based evaluation of the best technology for a given application. The approach was applied to a practical case of a Power-to-Hydrogen-to-Power energy storage system in a rural energy community under the HyRES project, demonstrating the potential of MGTs with innovative features to cost-effectively mitigate global root causes and create new market opportunities for the technology. Such methodologies constitute the bridge between the present root cause analysis and the solution analysis, the following block of the problem-solving and corrective action scheme.

8. Conclusions

MGTs have the potential to contribute significantly to a low-carbon economy. However, they have struggled to gain market success in recent decades. This work aims to find a holistic and objective process for resolving complex business and technology-related problems. It is part of a more comprehensive work to roadmap microturbines' technological and commercial deployment. Through problem-solving, the Corrective Action Scheme is the methodology that allows doing that. The first part is the root cause analysis, which aims to find the high-level causes of MGT's lack of market success in the last decades.

Combining the fishbone diagram and traditional logic tree (the 5-whys method) allowed the authors to extensively break down the problem. The lack of strict rules allowed the exploration of the domain in line with Okes's comprehensive approach. However, it led to a confused and crowded representation of the cause–effect chain and a degree of subjectiveness. Overall, the traditional RCA showed several barriers to resolving complex multidisciplinary problems.

The author considered the Theory of Constraint (ToC) as a candidate to overcome these barriers and achieve a more precise representation of the cause–effect relationships. The presented approach, traditional RCA, has been compared with the ToC methodology applied to the same problem. The ToC proved capable of resolving some limitations of the traditional RCA approach, mainly regarding objectives and replicability. Nevertheless, the traditional RCA approach remains valid for exploring new, unfamiliar, complex problems.

The logic tree identified some possible root causes in several areas of the fishbone diagram. Specifically, MGT's lack of competitiveness can be attributed to several key factors:

1. The equipment costs are higher than the competition; however, the low sales –a low-level cause– further exacerbate the problem. This conflict creates a vicious cycle that is problematic to break.
2. The product's suboptimal performance dampens its competitiveness in the market. Furthermore, although the product does have features that are often considered strengths, they are not practical for larger markets and only serve to target small niches.
3. MGT's products have not kept up with the pace of innovation exhibited by their competitors, resulting in a wider gap in competitiveness between MGT and rival technologies.

Following Okes' problem-solving scheme, these candidates will be the object of data validation in future work. These studies include a more in-depth study with particular applications of MGTs utilising a data-driven approach and confirm the qualitative conclusions reported in this work. Finally, the proposed methodology proved capable of solving complex business and technology-related problems in a more scientific, holistic and objective way with respect to the industry's common practices.

CRediT authorship contribution statement

Giuseppe Tilocca: Writing – review & editing, Writing – original draft, Formal analysis, Conceptualization. **David Sánchez:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Miguel Torres-García:** Supervision, Conceptualization.

Declaration of competing interest

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.

Data availability

Data will be made available on request.

Acknowledgements

NextMGT has received funding from the European Union's Horizon 2020 research and innovation programme under Marie Sklodowska-Curie grant agreement N° 861079 (www.nextmgt.com). The University of Seville is also gratefully acknowledged for supporting this research through its Internal Research Programme (Plan Propio de Investigación), under contract No 2019/00000359.

References

[1] Soares C. Microturbines: applications for distributed energy systems. Elsevier; 2011.
[2] European Commission. The European green deal COM/2019/640 final. Tech. rep., 2019.
[3] Okes D. Root cause analysis: The core of problem solving and corrective action. Quality Press; 2019.
[4] Sforza P. Commercial airplane design principles. Butterworth-Heinemann; 2014.
[5] Capstone Green Energy. Microturbine applications in Oil and Gas, https://www.capstonegreenenergy.com/solutions/oil-gas-other-natural-resources, visited on 2022-10-07.
[6] Paradies M, Busch D. Root cause analysis at Savannah River plant (nuclear power station). In: Conference record for 1988 IEEE fourth conference on human factors and power plants. IEEE; 1988, p. 479–83.
[7] Larsson JE, Öhman B, Nihlwing C, Jokstad H, Iren L, Kvalem J, Lind M. Alarm reduction and root cause analysis for nuclear power plant control rooms. In: Norway proc. enlarged Halden prog. group mtg. 2005.
[8] Larsson JE. On-line root cause analysis for nuclear power plant control rooms. In: International symposium on symbiotic nuclear power systems for the 21st century, ISSNP, Tsuruga, Fukui, Japan. 2007.
[9] Wu T-M, Hwang S-L. Maintenance error reduction strategies in nuclear power plants, using root cause analysis. Appl Ergon 1989;20(2):115–21.
[10] Wong J-T, Yeh W-C. Validation of fault tree analysis in aviation safety management. J Air Transp 2007;12(2).
[11] Rashid H, Place C, Braithwaite GR. Investigating the investigations: a retrospective study in the aviation maintenance error causation. Cogn Technol Work 2013;15(2):171–88.
[12] Taitz J, Genn K, Brooks V, Ross D, Ryan K, Shumack B, Burrell T, Kennedy P. System-wide learning from root cause analysis: a report from the New South Wales Root Cause Analysis Review Committee. Qual Saf Health Care 2010;19(6):e63.
[13] Peerally MF, Carr S, Waring J, Dixon-Woods M. The problem with root cause analysis. BMJ Qual Saf 2017;26(5):417–22. http://dx.doi.org/10.1136/bmjqs-2016-005511, arXiv:https://qualitysafety.bmj.com/content/26/5/417.full.pdf, URL https://qualitysafety.bmj.com/content/26/5/417.
[14] Imach S, Eppich W, Zech A, Kohlmann T, Prückner S, Trentzsch H. Applying principles from aviation safety investigations to root cause analysis of a critical incident during a simulated emergency. Simul Healthc 2020;15(3):193–8.
[15] Mahto D, Kumar A. Application of root cause analysis in improvement of product quality and productivity. J Ind Eng Manag (JIEM) 2008;1(2):16–53. http://dx.doi.org/10.3926/jiem.v1n2.p16-53, URL http://hdl.handle.net/10419/188371.
[16] Hicks BJ, Matthews J. The barriers to realising sustainable process improvement: A root cause analysis of paradigms for manufacturing systems improvement. Int J Comput Integr Manuf 2010;23(7):585–602.
[17] Gattiker TF, Boyd LH. A cause-and-effect approach to analyzing continuous improvement at an electronics manufacturing facility. Prod Inventory Manage J 1999;40(2):26.
[18] Zhong X, Xu Y, Liu Y, Wu X, Zhao D, Zheng Y, Jiang J, Deng Z, Fu X, Li X. Root cause analysis and diagnosis of solid oxide fuel cell system oscillations based on data and topology-based model. Appl Energy 2020;267:114968.
[19] Zulbainarni N, Khumaera NI. Root cause analysis on development of sustainable Fisheries business in Indonesia. J Manaj Agribisnis 2020;17(1):33.
[20] Heravizadeh M, Mendling J, Rosemann M. Root cause analysis in business processes. 2008.
[21] Harich J, Bangerter P, Durlacher S. Solving the sustainability problem with root cause analysis. In: Proceedings of the ecosystem services partnership conference, Portland, OR, USA. 2012, p. 25.
[22] Capstone Turbine Website, https://www.capstoneturbine.com/, visited on 2021-03-23.
[23] Flex Energy Website, https://www.flexenergy.com/, visited on 2021-03-23.
[24] Siemens gas turbines online catalogue. 2021, https://www.siemens-energy.com/global/en/offerings/power-generation/gas-turbines.html, visited on 2021-03-23.
[25] Kotowicz J, Job M, Brzęczek M, Nawrat K, Mędrych J. The methodology of the gas turbine efficiency calculation. Arch Thermodyn 2016;37. http://dx.doi.org/10.1515/aoter-2016-0025.
[26] Galanti L, Massardo AF. Micro gas turbine thermodynamic and economic analysis up to 500 kWe size. Appl Energy 2011;88(12):4795–802.
[27] Verstraete D, Bowkett C. Impact of heat transfer on the performance of micro gas turbines. Appl Energy 2015;138:445–9.
[28] Kim MJ, Kim JH, Kim TS. The effects of internal leakage on the performance of a micro gas turbine. Appl Energy 2018;212:175–84.
[29] Caresana F, Pelagalli L, Comodi G, Renzi M. Microturbogas cogeneration systems for distributed generation: Effects of ambient temperature on global performance and components' behavior. Appl Energy 2014;124:17–27.
[30] Ansaldo Energia website, microturbine division, https://www.ansaldoenergia.com/business-lines/new-units/microturbines, visited on 2021-03-23.
[31] Bladon Jets Website, https://www.bladonmt.com/, visited on 2021-03-23.

[32] Aurelia Turbine Website, https://aureliaturbines.com/, visited on 2021-03-23.
[33] MITIS Website, https://www.mitis.be/, visited on 2021-03-23.
[34] MTT Website, https://www.mtt-eu.com/, visited on 2021-03-23.
[35] Adveco. TOTEM cogeneration (CHP) range, product guide SR400001.r2. 2017, https://adveco.co/wp-content/uploads/2017/03/SR400001.r2-Totem-CHP-Product-Brochure.pdf, accessed on 23/09/2021.
[36] MTU Website. MTU power generation products. 2021, https://www.mtu-solutions.com/eu/en/applications/power-generation/power-generation-products, accessed on 23/09/2021.
[37] Cummins Website. Cummins generator sets. 2021, https://www.cummins.com/generators/, accessed on 15/03/2021.
[38] CAT Website. CAT generator sets). 2021, https://www.cat.com/en_US/products/new/power-systems/electric-power/, accessed on 23/09/2021.
[39] US Environment Protection Agency. Catalogue of CHP technologies. Tech. rep., 2015.
[40] US Environment Protection Agency. Catalogue of CHP technologies. Tech. rep., 2008.
[41] Sentech, Inc. C&I CHP technology cost and performance data analysis for EIA. Tech. rep., 2010.
[42] ICF International, Inc. CHP policy analysis and 2011–2030 market assessment report, Feb 2012 (for California energy commission). Tech. rep., 2010.
[43] Dallmann T, Posada F, Bandivadekar A. Costs of emission reduction technologies for diesel engines used in non-road vehicles and equipment. ICCT Work. Paper 2018-10, 2018.
[44] EPRI. Assessment of leading microturbine technologies. 2003.
[45] Thu K, Saha BB, Chua KJ, Bui TD. Thermodynamic analysis on the part-load performance of a microturbine system for micro/mini-CHP applications. Appl Energy 2016;178:600–8.
[46] thwinkorg. Root cause analysis. 2003, http://www.thwink.org/sustain/publications/brochures/04_RCA_At_Thwink/RCA_At_Thwink_Pages.pdf.
[47] Andersen B, Fagerhaug T. Root cause analysis: simplified tools and techniques. Quality Press; 2006.
[48] Capstone Turbine. Capstone Turbine Corporation FORM 10-K For the fiscal year ended March 31, 2020. 2020, https://www.sec.gov/Archives/edgar/data/1009759/000155837020007825/cpst-20200331x10k.htm#Item15ExhibitsandFinancialStatementSched, visited on 2021-09-27.
[49] U.S. Department of Energy Combined Heat and Power and Microgrid Installation Databases, https://doe.icfwebservices.com/, visited on 2021-02-15.
[50] Imarc. Microturbine market: Global industry trends, share, size, growth, opportunity and forecast 2021–2026. 2020, https://www.imarcgroup.com/microturbine-market, visited on 2021-09-27.
[51] Grand View Research. Reciprocating power generating engine market size, by fuel type (gas-fired, diesel-fired, dual fuel), by rated power (0.5 MW - 1 MW, > 1 MW - 2 MW, > 2 MW - 3.5 MW, > 3.5 MW - 5 MW, > 5 MW - 7.5 MW, > 7.5 MW), by application (industrial, CHP, energy & utility, landfill & biogas), industry analysis report, regional outlook, application potential, competitive market share, & forecast, 2020 – 2026. 2019, https://www.gminsights.com/industry-analysis/reciprocating-power-generating-engine-market?gclid=CjwKCAjw7rWKBhAtEiwAJ3CWLIl1aAvJxaC64OJx3U2TloQR-xZAO3ePEkVxD3lqdb-aOd3_0HCBkxoC-DAQAvD_BwE, visited on 2021-09-27.
[52] Cogen Europe. 2018–2019 COGEN Europe National Snapshot Survey, Preliminary results. 2019, https://www.slideshare.net/COGENEurope/cogen-europe-presentation-microchp-overview-at-eu-level, visited on 2022-01-14.
[53] Reference for Business. Capstone Turbine Corporation - Company Profile, Information, Business Description, History, Background Information on Capstone Turbine Corporation, https://www.referenceforbusiness.com/history2/17/Capstone-Turbine-Corporation.html#ixzz78ypG2A9i, visited on 2021-10-11.
[54] ICR Tec Website, https://www.icrtec.com/, visited on 2021-03-23.
[55] UK Research and Innovation. Ultra lightweight range extender for electric vehicles ("ULRE"). 2010, https://gtr.ukri.org/projects?ref=400138#/tabOverview, visited on 2021-10-15.
[56] Herring MR. Way station to space: A history of the John C. Stennis space center. NASA SP-4310, Chapter 4, https://history.nasa.gov/SP-4310/ch4.htm, from the The NASA History Series, Visited on 2021-09-27.
[57] Bill Bishop. Boating the NASA way. 2011, http://themarineinstallersrant.blogspot.com/2011/07/nasa.html, visited on 2021-09-27.
[58] UAV Turbines website, https://www.uavturbines.com/, visited on 2021-09-27.
[59] Sentientblue website, sentientblue.com, visited on 2021-09-27.
[60] Turbotech Aero website, https://www.turbotech-aero.com/, visited on 2022-09-21.
[61] Schot J, Geels FW. Niches in evolutionary theories of technical change. J Evol Econ 2007;17(5):605–22.
[62] Höök G, Olsson O. Networks and niches for microturbine technology in Europe and US-A strategic niche management analysis of microturbines (Master's thesis), 2007.
[63] Balcombe P, Rigby D, Azapagic A. Investigating the importance of motivations and barriers related to microgeneration uptake in the UK. Appl Energy 2014;130:403–18.
[64] European Commission. An EU strategy for energy system integration. Tech. rep., 2020.
[65] Deng S, Johnson B, Sogomonian A. Spark spread options and the valuation of electricity generation assets. In: Proceedings of the 32nd annual hawaii international conference on systems sciences. 1999. HICSS-32. Abstracts and CD-ROM of full papers. IEEE; 1999, p. 7–pp.
[66] Martínez B, Torró H. Hedging spark spread risk with futures. Energy Policy 2018;113:731–46.
[67] Benth FE, Saltyte-Benth J. Analytical approximation for the price dynamics of spark spread options. Preprint series. Pure mathematics, Matematisk Institutt, Universitetet i Oslo; 2005, http://urn.nb.no/URN:NBN:no-8076.
[68] Smith AD, Fumo N, Mago PJ. Spark spread–A screening parameter for combined heating and power systems. Appl Energy 2011;88(5):1494–9.
[69] Nesreddine H, Dostie M, Millette J, Poulin A, Handfield L. MicroTurbine economics in commercial and institutional buildings. 2006.
[70] US Energy Information Administration, https://www.eia.gov/, visited on 2021-03-23.
[71] The New York Times. Energy crisis: Shortages amid plenty. 1973, https://www.nytimes.com/1973/04/17/archives/energy-crisis-shortages-amid-plenty-energy-crisis-paradox-of.html, Newspaper article, digital version. Visited on 2021-09-27.
[72] Federal Energy Regulatory Commission. The western energy crisis, the enron bankruptcy, and FERC's response. Tech. rep., 2005, Visited on 2021-09-27.
[73] The World Bank. The global competitiveness report 2017–2018. Tech. rep., 2018, Visited on 2021-10-30.
[74] IEA. Technology roadmap - smart grids. Tech. rep., Paris; 2011, https://www.iea.org/reports/technology-roadmap-smart-grids.
[75] El-Khattam W, Salama MM. Distributed generation technologies, definitions and benefits. Electr Power Syst Res 2004;71(2):119–28.
[76] Heinen S, Elzinga D, Kim S, Ikeda Y. Impact of smart grid technologies on peak load to 2050. Tech. rep., International Energy Agency; 2011.
[77] Alvarado FL. Locational aspects of distributed generation. In: 2001 IEEE power engineering society winter meeting. Conference proceedings (Cat. no. 01CH37194). Vol. 1, IEEE; 2001, p. 140–vol.
[78] El-Hawary ME. The smart grid—state-of-the-art and future trends. Electr Power Compon Syst 2014;42(3–4):239–50.
[79] UK Government, Press release. UK enshrines new target in law to slash emissions by 78% by 2035. 2021, https://www.gov.uk/government/news/uk-enshrines-new-target-in-law-to-slash-emissions-by-78-by-2035, visited on 2021-09-27.
[80] The White House, Statements and releases. FACT SHEET: President biden sets 2030 greenhouse gas pollution reduction target aimed at creating good-paying union jobs and securing U.S. leadership on clean energy technologies. 2021, https://www.whitehouse.gov/briefing-room/statements-releases/2021/04/22/fact-sheet-president-biden-sets-2030-greenhouse-gas-pollution-reduction-target-aimed-at-creating-good-paying-union-jobs-and-securing-u-s-leadership-on-clean-energy-technologies/, visited on 2021-09-27.
[81] European Environment agency. Greenhouse gas emission intensity of electricity generation. 2021, https://www.eea.europa.eu/data-and-maps/daviz/co2-emission-intensity-8#tab-googlechartid_googlechartid_googlechartid_googlechartid_chart_11111, visited on 2021-09-27.
[82] Tilocca G, Sánchez D, Torres-García M. Application of the theory of constraints to unveil the root causes of the limited market penetration of micro gas turbine systems. Energy 2023;278:127717.
[83] European Commission. Barriers to trade, https://ec.europa.eu/growth/single-market/barriers-to-trade_en?2nd-language=hr, visited on 2021-09-27.
[84] International Organization for Standardization. ISO 19372:2015 Microturbines applications — Safety. 2015.
[85] European Commision. Regulations, Directives and other acts, https://europa.eu/european-union/law/legal-acts_en, visited on 2021-09-27.
[86] European Commision. Internal Market, Industry, Entrepreneurship and SMEs - Harmonised Standards, https://ec.europa.eu/growth/single-market/european-standards/harmonised-standards_en.
[87] European Commision. Internal Market, Industry, Entrepreneurship and SMEs - Manufacturers, https://ec.europa.eu/growth/single-market/ce-marking/manufacturers_en, visited on 2021-09-27.
[88] Official Journal of the European Union. Directive 2014/35/EU of the European Parliament and of the Council of 26 February 2014 on the harmonisation of the laws of the Member States relating to the making available on the market of electrical equipment designed for use within certain voltage limits. 2014, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32014L0035&from=EN, visited on 2021-09-27.
[89] Official Journal of the European Union. Directive 2014/30/EU of the European Parliament and of the Council of 26 February 2014 on the harmonisation of the laws of the Member States relating to electromagnetic compatibility. 2014, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32014L0030&from=EN, visited on 2021-09-27.
[90] Official Journal of the European Union. Directive 2006/42/EC of The European Parliament and of the Council of 17 May 2006 on machinery, and amending Directive 95/16/EC. 2006, https://euoag.jrc.ec.europa.eu/files/attachments/directive_2006_42_ec.pdf, visited on 2021-09-27.

[91] European Commission. Proposal for a Regulation of the European Parliament and of the Council on machinery products. 2021, https://ec.europa.eu/docsroom/documents/45508/attachments/4/translations/en/renditions/native, visited on 2021-09-27.

[92] European Commission. Commission staff working document.Impact Assessment Accompanying the Proposal for a Regulation of the European Parliament and of the Council on machinery products. 2021, https://ec.europa.eu/docsroom/documents/45508/attachments/4/translations/en/renditions/native, visited on 2021-09-27.

[93] Bründlinger R. Grid Codes in Europe - Overview on the current requirements in European codes and national interconnection standards. 2019, Conference: NEDO / IEA PVPS Task 14 Grid Code and RfG Workshop.

[94] Official Journal of the European Union. Commission regulation (EU) 2016/631. 2016, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32016R0631&from=EN, visited on 2022-02-04.

[95] European Standards. Requirements for generating plants to be connected in parallel with distribution networks - Part 1: Connection to a LV distribution network - Generating plants up to and including Type B. 2019.

[96] European Standards. Requirements for generating plants to be connected in parallel with distribution networks - Part 2: Connection to a MV distribution network - Generating plants up to and including Type B. 2019.

[97] Carrero MM, Sánchez IR, De Paepe W, Parente A, Contino F. Is there a future for small-scale cogeneration in Europe? Economic and policy analysis of the internal combustion engine, micro gas turbine and micro humid air turbine cycles. Energies 2019;12(3):413.

[98] Royal College of Physicians. Every breath we take: the lifelong impact of air pollution. Tech. rep., 2016.

[99] Fu X, Xiang S, Liu Y, Liu J, Yu J, Mauzerall DL, Tao S. High-resolution simulation of local traffic-related NOx dispersion and distribution in a complex urban terrain. Environ Pollut 2020;263:114390. http://dx.doi.org/10.1016/j.envpol.2020.114390, URL https://www.sciencedirect.com/science/article/pii/S0269749119344458.

[100] Benato A, Macor A. Italian biogas plants: Trend, subsidies, cost, biogas composition and engine emissions. Energies 2019;12(6):979.

[101] Macor A, Benato A. A human health toxicity assessment of biogas engines regulated and unregulated emissions. Appl Sci 2020;10(20):7048.

[102] Macor A, Benato A. Regulated emissions of biogas engines—On site experimental measurements and damage assessment on human health. Energies 2020;13(5):1044.

[103] Shen Y, Linville JL, Urgun-Demirtas M, Mintz MM, Snyder SW. An overview of biogas production and utilization at full-scale wastewater treatment plants (WWTPs) in the United States: challenges and opportunities towards energy-neutral WWTPs. Renew Sustain Energy Rev 2015;50:346–62.

[104] Hiramatsu M, Nakashima Y, Adachi S, Yamasaki Y, Kaneko S. Combustion characteristics of small size gas turbine combustor fueled by biomass gas employing flameless combustion. In: Turbo expo: Power for land, sea, and air. Vol. 47918, 2007, p. 463–9.

[105] Chiaramonti D, Rizzo AM, Spadi A, Prussi M, Riccio G, Martelli F. Exhaust emissions from liquid fuel micro gas turbine fed with diesel oil, biodiesel and vegetable oil. Appl Energy 2013;101:349–56.

[106] Aleman ER, Zaili JA, Sayma AI. Techno-economic analysis of small scale CCHP systems focused on emissions performance. In: Proceedings of ETN gas turbines in a carbon-neutral society 10th international gas turbine conference. 2021.

[107] UK Government, Department for Business, Energy & Industrial Strategy. The CHPQA standard,issue 8. 2021, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/968350/CHPQA_Standard_Issue_8.pdf, visited on 2021-09-27.

[108] Chon DM, Heywood JB. Performance scaling of spark-ignition engines: Correlation and historical analysis of production engine data. Tech. rep., SAE Technical Paper; 2000.

[109] Heywood JB, Welling OZ. Trends in performance characteristics of modern automobile SI and diesel engines. SAE Int J Engines 2009;2(1):1650–62.

[110] Sinigaglia T, Martins MES, Siluk JCM. Technological evolution of internal combustion engine vehicle: A patent data analysis. Appl Energy 2022;306:118003.

[111] Staunton R, Ozpineci B. Microturbine power conversion technology review. Tech. rep., United States. Department of Energy; 2003.

[112] Van Holde D, Cler G, Hurley C, Slowe J. Microturbines: Lessons learned from early adopters: An E-source multi-client study. 2003.

[113] Rychkova A, Sokolov V, Naumov S. Analysis of experience of actual operation of gas turbine units capstone C1000. Issues of concern and methods for problem-solving. In: International conference on industrial engineering. Springer; 2021, p. 1358–66.

[114] European Turbine Network. Micro gas turbine technology summary. Tech. rep., 2019.

[115] Xiao G, Yang T, Liu H, Ni D, Ferrari ML, Li M, Luo Z, Cen K, Ni M. Recuperators for micro gas turbines: A review. Appl Energy 2017;197:83–99.

[116] McDonald CF. Low cost recuperator concept for microturbine applications. In: Turbo expo: Power for land, sea, and air. Vol. 78552, American Society of Mechanical Engineers; 2000, V002T04A018.

[117] Haddad C, Périlhon C, Danlos A, François M-X, Descombes G. Some efficient solutions to recover low and medium waste heat: competitiveness of the thermoacoustic technology. Energy Procedia 2014;50:1056–69.

[118] Masoud B, Mohammad NM, Ahad K. Optimal price and quantity determination of retailer electric contract and maximizing social welfare in retail electrical power markets with DG. 2016, arXiv preprint arXiv:1607.08217.

[119] Escamilla A, Sánchez D, García-Rodríguez L. Assessment of power-to-power renewable energy storage based on the smart integration of hydrogen and micro gas turbine technologies. Int J Hydrogen Energy 2022;47(40):17505–25.

[120] Goldratt EM, Cox J. The Goal: a process of on-going improvement. North River, Press. Inc; 1984.

[121] Dettmer WH. Goldratt's theory of constraints: A systems approach to continuous improvement. Asq Pr; 1997.

[122] Tilocca G, Sánchez D, Torres García M. Root cause analysis of the lack of market success of micro gas turbine systems. In: Turbo expo: Power for land, sea, and air. Vol. 86021, American Society of Mechanical Engineers; 2022, V005T09A004.

[123] Tilocca G, Sánchez D, Torres García M, Escamilla Perejón A, Minet S. A methodology to quantify product competitiveness and innovation requirements for micro gas turbine systems in hydrogen backup applications. In: Turbo expo: Power for land, sea, and air. Vol. 102606, American Society of Mechanical Engineers; 2023.