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Application of the theory of constraints to unveil the root causes of the limited market penetration 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

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ABSTRACT

Micro Gas Turbines are small devices for on-site power and heat generation. Their high maintainability and fuel flexibility make them a suitable technology for transitioning to a greener economy. However, their commercialisation did not match the stakeholders' expectations. The authors applied the Theory of Constraints – a methodology for the continuous improvement of systems – to the MGT industry introducing a structured and rigorous representation. The constraint – i.e. Root Cause – Analysis identified which entities sustain the cause–effect chain, eventually generating the Undesired Effects. The system constraints link to the specificity and effectiveness of commercialisation strategies and product innovation in agreement with evolutionary market theories. Moreover, the Theory of Constraints emphasises the presence of reinforcement loops that make targeting entities like high product costs ineffective. The missing piece to complete the puzzle is solving a logic block representing the product's market competitiveness depending on economic and technical factors. This study suggests that combining market-driven innovation and commercialisation is likely the only long-term solution to the lack of commercial success of the technology. However, the work also highlights limitations in the proposed methodology and solutions. To tackle these, the authors suggest and introduce numerical frameworks based on the Theory of Constraint.

1. Introduction

Micro gas turbines (MGTs) – or microturbines – are small, decentralised power and heat generation systems which are suitable for decentralised energy systems applications, thanks to their scalability. Recent research proved their capability to run on alternative carbon-free fuels like hydrogen without a noticeable increase in performance and other contaminants [1]. Therefore, MGT could potentially facilitate transitioning from the current centralised generation to a decentralised one, thus contributing to a low-carbon economy by 2030 and to carbon neutrality by 2050 [2].

Most microturbine products entered the market between the late 1990s and early 2000s. However, their deployment did not match the high expectations of the market and investors. This letdown was arguably due to the lack of cost-competitiveness against the established technology, i.e. reciprocating Internal Combustion Engines (ICE).

This paper presents a comprehensive work within the NextMGT project[1] to propose some corrective actions for the deployment of MGTs to the market. The corrective actions scheme implies identifying the root causes, evaluating the solutions and taking remedial actions [3].

1.1. Background and literature review

The deployment of microturbines has always been limited to niche applications [4] despite the claimed winning features of this technology. Often, stakeholders designate the higher equipment cost than established technologies to be the root cause for this limited market volume. However, the authors believe that this statement is tautological and lacks logical validity. The deficiency of sale volumes yields higher costs and overheads which, in turn, are the reasons for the low sales. This fact also emerged from the interviews with OEMs and other major stakeholders carried out by the authors and from an extensive literature search.

This paper introduces the application of a methodical, replicable and rigorous process to identify the actual root causes of the problem

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

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Nomenclature

$CapEx$	Capital Expenditure
CHP	Combined Heat and Power
CLR	Categories of Legitimate Reservation
CRT	Current Reality Tree
CSF	Critical Success Factor
GHG	Green House Gas
ICE	Internal Combustion Engine
IO	Intermediate Objective
MGT	Micro Gas Turbine
NC	Necessary Condition
OEM	Original Equipment Manufacturer
$OpEx$	Operating Expenditure
$R\&D$	Research and Development
RCA	Root Cause Analysis
RCI	Root Cause Identification
SOA	State of the Art
TOC	Theory of Constraints
UDE	Undesired Effect
USD	United States Dollars

and to provide objective conclusions to this long-lasting debate. To this end, the authors chose the Theory of Constraints (TOC) as the methodology to uncover the root causes of the unsuccessful development and commercialisation of MGTs; unfortunately, the academic literature on Root Cause Analysis as intended per Okes [3] and TOC for business(trade)-related processes is small.

Zulbainarni and Khumaera adopted RCA to identify gaps and barriers in developing Sustainable Fisheries Business in Indonesia, applying the "five why's" logic tree to map the cause–effect relationships [5]. Heravizadeh et al. describe a systematic methodology to detect and document the quality dimension of a business process [6] based on the traditional RCA to model the elements of a business process and its related goals, metrics, and issues for a particular case. Harich et al. apply the traditional RCA to sustainability-related problems [7]. Although this is not a strictly business case, it still is an example of dealing with very complex problems depending on policies, regulations, macro and microeconomics, and their impact on local communities. Da Costa et al. published a novel diagnostic technique for the New Product Development based on recurring Current Reality Trees (the Root Cause Analysis tool from the TOC) [8] called *diagile method*. In their experience, Goldratt's CRT [9] struggles to identify multiple root causes, a limitation unsuited for heterogeneous business processes like New Product Design. Finally, Dogget presented a statistical comparison [10] and a framework for the selection [11] of RCA tools, including the cause–effect-diagram and Current Reality Tree (Theory of Constraint). Both works concluded that each tree presents benefits and drawbacks.

These works found ground in the literature and focused on the Root Cause Identification diagrams. In comparison, the paper presented here comprises a broader approach to RCA which, besides the root cause identification, includes the definition of the problem through a Gap Analysis (IO Map) and the analysis of the cause–effect chain. Furthermore, it sets the work for corrective actions, applying the methodology to an open problem.

1.2. Novelty and aim of the work

Since their arrival in the market, MGTs have faced limited success. All the efforts to analyse and solve this situation proved ineffective with time. Most studies on MGT focus on cost reduction, techno-economic analysis or performance improvement alone. The literature on MGT does not include any holistic study that gives an objective and pondered analysis of the problem, followed by a long-term solution. This paper aims to fill this gap. The authors hypothesise that there is a problem in the MGT market, which is not entirely relatable to cost. The methodology used in this work will validate this hypothesis and carry on the logical cause–effect analysis.

According to the results shown in the document, using a systematic, replicable approach to this precise problem is believed to deliver the MGT industry with a valuable tool to reach market deployment in a more technically-driven and rigorous manner, free of speculations. The authors hope this can guide the industry to join the quickly changing energy market in supporting the energy transition.

2. Micro gas turbines

2.1. Technology

Literature defines microturbines as miniature gas turbines with rated power between 30 and 400 kW_e [12]. Commercial microturbines range from 2 to 400 kW_e, with pre-packaged systems comprising several parallel units surpassing 1 MW_e of total installed electrical power [13,14].

Micro gas turbines operate on the same thermodynamic cycle as larger gas turbines; nevertheless, some distinctions set them apart from them. Due to the low volumetric flow, MGTs primarily use single-stage centrifugal/radial turbomachinery for compression and expansion. This setup generates low-pressure ratios below 4.5:1. Additionally, being impossible to cool radial turbines – due to manufacturing limitations –, these machines feature low Turbine Inlet Temperature, around 950 °C. Conversely, larger turbines achieve pressure ratios higher than 20:1, and turbine inlet temperatures above 1600° [15].

These low-pressure ratios and turbine inlet temperatures limit the maximum thermal efficiency engines can practically achieve with a simple cycle configuration. Additionally, the smaller dimensions negatively impact turbomachinery efficiency [16], heat losses [17], and internal leakages [18], yielding a globally detrimental effect on engine performance. Consequently, MGTs always use a recuperative cycle to increase engine performance, even if this comes at the cost of a pricey and bulky recuperator to preheat combustion air. Additionally, microturbines operate at variable, high shaft speeds; this means that a permanent-magnet synchronous generator is needed to produce electricity at a variable frequency. Downstream, power electronics accommodate the power output to the grid requirements.

In addition to the foregoing considerations, control systems MGTs limit the maximum rotational speed to ensure constant Turbine Outlet Temperature (rather than Turbine Inlet Temperature) to ensure that the recuperator downstream of the turbine is not overheated. This control strategy generates a higher decline in electrical efficiency with higher ambient temperature compared to bigger gas turbines [19].

2.2. Data sourcing

The analysis presented in this work is supported by a comprehensive literature review, market research and communication with stakeholders. The study of the technical aspect relies on the specifications of a broad list of engines for on-site generation; thus, specifications of microturbines come from Ansaldo Energia, Bladon Turbines, Aurelia Turbines, MITIS, MTT, Flex Energy Systems, and Capstone Green Energy [13,14,20–24] whilst the sources for Internal Combustion Engines (ICEs) correspond to Adveco, MTU, Cummins and CAT [25–28].

Cost data found in the literature are used to derive cost functions that are assumed to depend on the engine's electric output. These functions are of the logarithmic type since these realistically match the scaling effect of power on the specific cost.

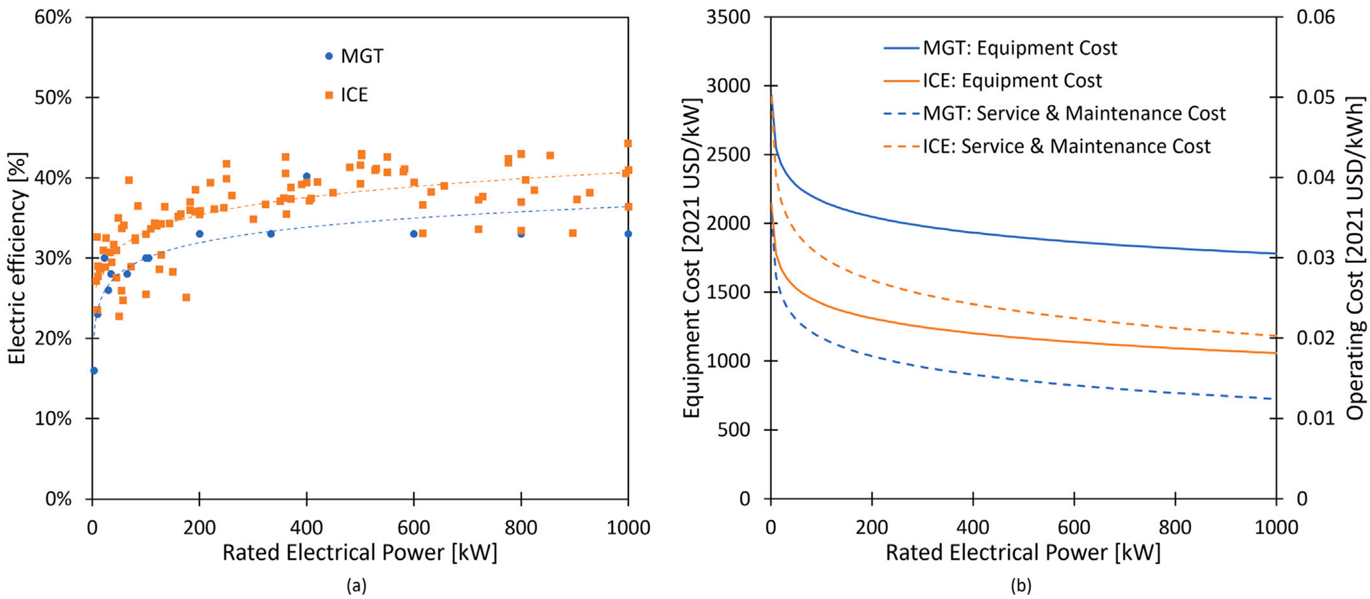

Fig. 1. Comparison of the data gathered for micro gas turbines and reciprocating engines. Figure (a) plots the rated electrical efficiency declared by OEM, representing fuel costs. Figure (b) shows the equipment and service cost functions for both technologies.

- For ICEs, cost data come from several databases of the Environmental Protection Agency and the Energy Information Administration of the US Government, reporting the cost for a representative range of installed power; these data are then normalised to USD_{2022} [29–32]. More specifically, installation and service costs have been estimated according to [29–31], whereas the equipment cost functions for genset, heat recovery and interconnect/electrical have been derived from [29,30]. Exhaust gas-treatment data from the International Council on Clean Transportation for emission Stage V [33].
- For MGTs, equipment cost data have been taken from several references also, including some of the aforesaid and others from the Electric Power Research Institute [29–32,34] , as well as from private communications with different OEMs. The cost of the fuel compressor has also been estimated according to several sources [29,30,34], and that of the heat recovery has been derived from [29]. Contrary to ICEs, the interconnect/electrical parts of MGTs are included in the cost of the generator set [29]. This information is complemented by the specific cost functions developed by Galanti and Massardo for each MGT component [16]. Finally, service costs have been estimated according to [24,29–31].

The resulting cost functions for equipment and service are plotted in Fig. 1 and will be used as a reference in this study. This global representation of equipment and service cost functions is deemed sufficient for the general analysis provided in this work, despite the unavoidable scattering of source data. In this regard, estimates of installation costs are less reliable inasmuch as they are case-specific to a large extent. Some estimates of these installation costs could also be found by comparing [24,29–31].

The interview with stakeholders guided and impacted this work significantly in applying the TOC principles. The list of interviewees includes different stakeholders, including OEMS, Distributors, Service Providers, companies and consortiums specialising in MGT R&D, Gas Turbines associations focusing on decentralised energy systems and micro gas turbines, experts (companies or individuals) on Energy markets and microgeneration; this information is presented in Table 1. The OEM list includes almost all that are active in the Micro Gas Turbines market, where Capstone Green Energy has the largest share. Institutions previously involved in MGT design or developing a new product are also included. Gas turbine associations include the European Turbine Network (ETN Global), an international association with over 120 members worldwide and covering the entire gas turbine supply chain; within ETN Global, the former *Microturbine Working Group* has been converted into the *Decentralised Energy Working Group*, de facto including the integration of micro and small gas turbines into complex energy systems for low-carbon applications. The European Micro Gas Turbine Forum is an association that unites many MGT manufacturers and distributors, mostly in Europe but not only. Finally, the experts' interviews covered different aspects of microturbines' current and potential deployment, including emerging markets, naval and special applications, regulatory framework and investment opportunities.

2.3. Market analysis summary

Micro Gas turbines were introduced to the market between the late 1990s and early 2000s. Despite the initially high expectations and numerous orders, the interest in this product soon declined. Eventually, micro gas turbines found space mostly in small niche markets such as heat-driven cogeneration applications and microgeneration using fuels with reduced and variable low heating values, like sewage and flare gases [4]. This decline was arguably due to higher MGT capital and fuel costs, which were not offset by low maintenance costs. Fig. 1 compares micro gas turbines' technical and economic features with those of reciprocating engines obtained in Section 2.2. The plot shows that reciprocating engines achieve higher electric performance at significantly lower equipment costs than MGTs; the only advantage of the latter systems is lower service and maintenance costs.

Capstone was one of the first companies to launch its microturbines product, leading the market from the beginning. Despite the high expectations, denoted by a record market capitalisation in 2001, the company has yet to reach profitability due to the large overheads; similar trends were observed for other companies in the market. This trend can be observed in Fig. 2, which shows cumulative installations for cogeneration applications below 1 MW in the USA. The initial interest in MGTs soon ceased, giving way to a slow increase in the number of units installed (flatter curve) while the contrary occurred for reciprocating engines: the increasing number of annual installations (slope of the curve) in the last two decades.

Table 1
Details of the stakeholders' interviews.

(a) List of people and institutions involved in the interviews.

Categories	Interviews
MGT OEMS	Capstone Green Energy Ansaldo Green Tech Bladon Jets Aurelia Turbines ICR tech Elliot Power Systems MITIS
Distributors and Service Providers	Pure World Energy (MGT) Capstone Power Systems (MGT) TED Energy (ICE) Challoch Energy (Decentralised Energy Systems)
R&D institutions and consortiums	Brayton Energy (MGT design) Softinway (Turbomachinery design) NextMGT (MGT research)
(Micro) Gas Turbines Associations	European Turbine Network - Decentralised Energy System Working Group ASME Turbo Expo - Cycle Innovation Committee European Micro Gas Turbine Forum
Governmental Agencies	UK BEIS
Experts on Energy markets and microgeneration	Tirreno Power (Centralised generation, energy market, ancillary services) Engineering For Change (Microgeneration in emerging markets) Professor at City University (Microgeneration in emerging markets) Professor at Universidad Adolfo Ibáñez (Microgeneration in emerging markets) Marine Consultant (MGT for naval applications) Senior Research Fellow at NTU Singapore (MGT for special applications) MGT Consultant (MGT Commercialisation and Product Development) Fund Manager (Investments Specialists in Energy Systems)

(b) List of questions for interviewees.

Question	
1	Which are the strengths, weaknesses, threats and opportunities (SWATs) of MGTs?
2	How is the MGT market structured? Which are the targeted applications?
3	Which factors hindered the successful commercialisation of MGTs the most?
4	Are commercialisation strategies suited for product and market?
5	What is the role of innovation in product development?
6	How will the product evolve in the following years?
7	How can new technological trends[a] affect market penetration?
8	Do MGTs fit into the current policy and regulatory framework?
9	Which are the main regulative barriers?
10	Will microgeneration technologies fit into the route to 2030 and 2050 policies?
11	What is the role of MGTs in emerging economies?

[a]For technological trends, the authors intend new or alternative cycle configurations, innovative material or manufacturing methods, and novel combustion technology adopted for conventional or alternative fuels.

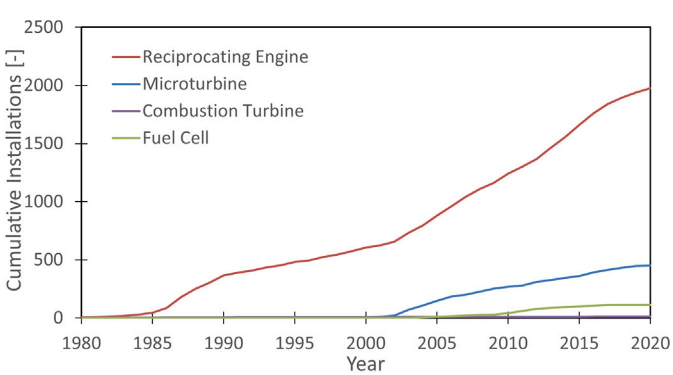

Fig. 2. Cumulative installations for cogeneration applications below 1 MW over the last four decades (United States market).

Several companies, such as Capstone Green Energy, Ansaldo Green Tech, Aurelia Turbines, MTT, and Flex Energy, offer commercial MGTs; this information is compiled in the micro gas turbine market report issued by Gonzalez et al. [35]. Nevertheless, the current market size estimation is still uncertain, and despite several market reports being online, their reliability is questionable, and their predictions span over two orders of magnitude. As a means to compensate for the scattering of this market volume estimates, the authors also utilised the information from public financial statements, the available revenues and MGT orders data, and the stakeholder's interviews to estimate the MGT market size based on the OEM's revenue. Fig. 3 presents this data.

3. Theory of constraints

3.1. The history and principles of TOC

The Theory of Constraints was initially formulated by Goldratt [9] and then expanded into an effective problem-solving methodology holistically combining intuitive and analytical thinking [36]. The approach followed in this work is mainly inspired by the work by Dettmer [37].

The Theory of Constraints (TOC) is a specific methodology for improving systems, understood as a set of processes or components acting together to achieve a goal [37], often by taking inputs and transforming them into outputs. The goal of the system constitutes the benchmark for its performance. Performing a gap analysis between the expected output and the current reality indicates the system's performance. In other words, the definition of the goal only makes sense when comparing the system to the expectations.

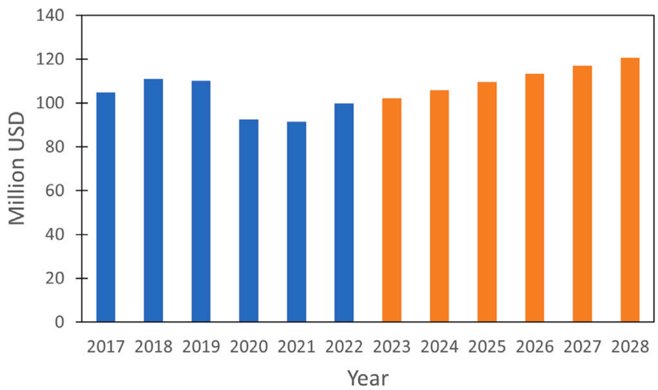

Fig. 3. Evaluation of the market size from the OEM's revenue. The prediction (orange) is based on a linear regression of each company's last 3-year trend.

On the one hand, the principle at the heart of the TOC is that "*a chain is no stronger than its weakest link*"; i.e. each system is affected by at least one constraint, meaning that the weakest part can negatively affect the outcome of the system [36]. On the other, the TOC converges with Okes' RCA philosophy. Indeed, according to Dettmer [37,38], the most undesirable effects inside a system originate from one or a few root causes which are – almost – never clearly visible. They often manifest themselves with several undesirable effects (UDEs), linked by a complex network of cause–effect relationships whose elimination (of the UDEs) provides a short-term solution but does not resolve the issue. In opposition, targeting the critical root cause eliminates all resulting Undesirable Effects within its cause–effect chain.

3.2. The logical thinking process and Goldrat's logic trees

Goldratt's Theory of Constraints is a logical process by definition. It finds its practical execution in a tool representing the logic of the TOC: the Logical Thinking Process. It comprises six different logic trees and their rules-of-logic, even if Goldratt enunciated only five of these tools initially [9], and it was only later that he mentioned the idea of another logic tree, called Intermediate Objective (IO) Map. This tool was first briefly introduced by Dettmer in [39], then presented in all detail in [37].

3.3. The categories of legitimate reservation

The categories of legitimate reservation (CRL) (Table 2) are the rules that govern the thinking process, differentiating the thinking process from other problem-solving and analysis tools. Effectively, this set of rules 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.

Table 2
Summary of the six categories of legitimate reservation according to Dettmer [37].

Category	Implications
Clarity	It clears any possible misunderstanding due to communication before even addressing the logical side. The following questions help verify this category: is any additional explanation required for the cause or effect? Is the connection between cause and effect convincing without the need to look deeper for hidden meanings or logical validity? Are intermediate effects missing (also called "long arrow")?
Entity existence	We can raise a reservation of entity existence when (i) a statement is not grammatically correct or a complete sentence, (ii) there is an embedded logic statement, (iii) the entity does not represent a true statement, it does not exist in reality, or its existence cannot be proved.
Causality existence	The Causality Existence challenges the validity of the logical connections between entities.
Cause sufficiency	The Cause Insufficiency reservation is raised when a cause is too small to produce the effect.
Additional cause	If two or more independent causes lead to the same effect, the additional cause reservation is raised. If a causal relationship falls in this category, all the additional causes must be removed to break the cause–effect chain.[a]
Cause–effect reversal	The reservation of cause–effect reversal is based on a distinction that sometimes can be very misleading: why an effect exists versus how we know it exists.
Predicted effect existence	The reservation of the predicted effect existence aims to test and validate a cause–effect relationship. Effectively, the existence of a hypothetical expected effect can be used to verify a cause–effect relationship.
Tautology	Tautology is a synonym of circular logic. It indicates a statement that is always true and thus of no logical validity. In this category, the effect is often a justification for the existence of the cause. Tautology, like the previous reservation, should never stand alone.

[a]This category of legitimate reservation does not contest the validity of a stated cause. It only adds another entity that, by itself, can generate the same – or a similar – effect.

4. Problem definition: the IO map and the undesired effects

The IO Map lays down the foundation of gap analysis and problem-solving methodology in the TOC. It sets the benchmark for measuring the deviation between the goal and the current reality. That deviation, defined practically in terms of the undesired effect, is the base of the current reality tree (CRT), the ultimate root cause analysis tool.

Firstly, the sphere of influence of this study is the microturbine R&D sector, including all stakeholders. The second step is to determine the System Goal: the successful deployment of microturbine technology and fostering of the associated industry. The Critical Success Factors measure to what extent the system succeeds in its goal: the size of the industry and its long-term economic sustainability. A successful industry holds a sensible market share, continues to grow, and is self-sustainable. Therefore, CSF#1 is the size of the microturbine market, and CSF#2 is that the MGT business needs to be remunerative. The next step is determining the Necessary Conditions (NC) to achieve each Critical Success Factor. Then, once all Critical Success Factors and Necessary Conditions are defined, they must be arranged on the map.

Micro gas turbines are units for on-site power and heat generation. As previously discussed, the product can achieve high sales if it represents a profitable investment or its technical features satisfy a specific market requirement or need. The MGTs must therefore be competitive from technological and financial standpoints. Additionally, an active regulatory push towards distributed generation technologies would become an additional market driver. On the other hand, high margins and reduced costs are conditions for companies to be profitable. In addition, distribution channels must be well developed/established, with commercialisation strategies and business models optimised for the product and its market. Fig. 4 integrates this information with all the items arranged in the tree.

The analysis of the Necessary Conditions within the sphere of influence yields the following:

- **CSF# 1 The market size is comparable with competing or similar industries**: the global MGT market estimates are around USD 200 Million [40], which is very small compared to other sectors. For instance, the market for reciprocating ICE for energy applications [41] is estimated at around USD 20 Billion.
- **CSF# 2 MGTs companies are profitable**: to date, Capstone Green Energy, which owns the largest market share, has never been profitable [42]. According to the company filings, this is due to insufficient units sold (CSF#1) and an inadequate cost structure (NC#7). This characteristic is assumed to represent the entire industry.

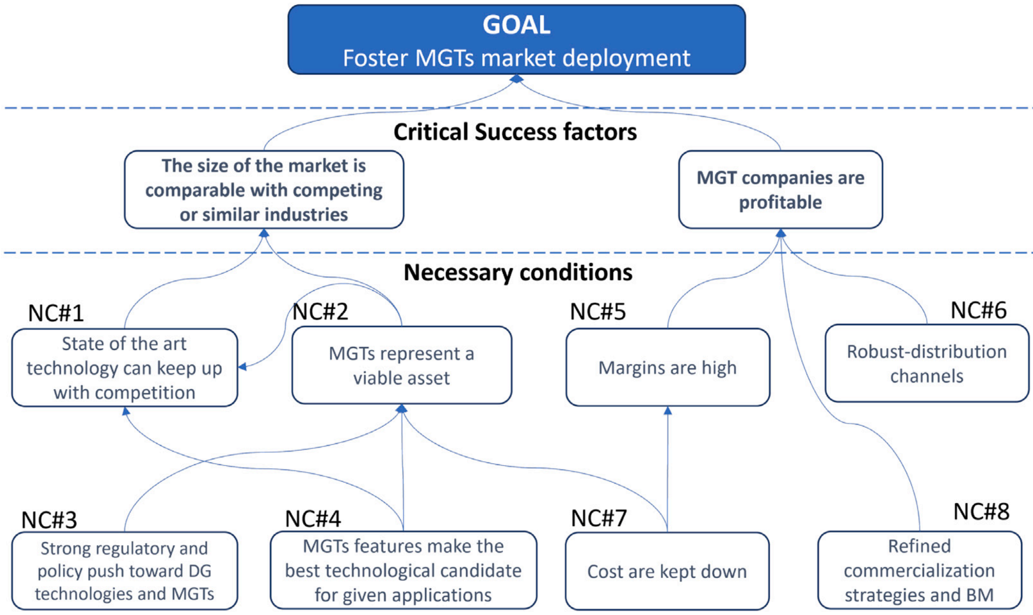

Fig. 4. Intermediate Objective map.

None of the critical success factors listed above is therefore satisfied. Hence, the analysis of the Necessary Conditions follows, and wherever the conditions are unsatisfied, the Undesirable Effect replaces their respective Critical Success Factors and Necessary Conditions.

- **NC#3 Strong regulatory and policy push towards DG technologies and MGTs**: a study from Carrero et al. [43] finds that investing in micro-cogeneration is not attractive within the existing regulatory framework and policies. This is mostly because current policies do not support the deployment of DG technologies sufficiently, particularly MGTs.
- **NC#2 MGTs represent a viable asset**: product costs are high compared to competing technologies (**NC#7**) and reflect into the equipments costs. Moreover, the electrical efficiency of most MGTs in the market tends to be lower than that of typical ICEs, which raises the cost of fuel over the operating life of the equipment (Fig. 5). Finally, in conventional applications, MGTs' lower maintenance costs than ICEs cannot compensate for the high capital and energy costs. As a result, in most cases, MGTs may not represent a good investment compared to ICEs.
- **NC#4 The features of MGTs make them the best technological candidate for given applications**: MGTs feature some benefits like low maintenance, high-grade heat available and high heat-to-power ratio, low emissions, fuel flexibility and compactness. However, they only allowed them to conquer small niches during the last two decades [44]. Specifically, high-grade heat and high heat-to-power ratios appeal only to selected applications: in reality, less than a fourth of industrial applications require mid-to-high grade heat [45], and most commercial and residential applications require low-temperature heat only. In most cases, ICEs maximise the profits for CHP applications [46].

  As previously discussed, low emissions cannot become a true market advantage under the current regulatory framework. Concerning fuel flexibility, it is true that MGTs can run on many fuels, even with relatively low heating values but, despite this, most biofuel installations are still running on ICEs [47–49], whilst the cost-effectiveness of MGT running on hydrogen is yet to be proven. On this last point, Escamilla et al. [50] assessed Power-to-Power solutions adopting hydrogen and MGT, concluding that increasing the performance of MGT will be essential to attain acceptable round-trip efficiencies.

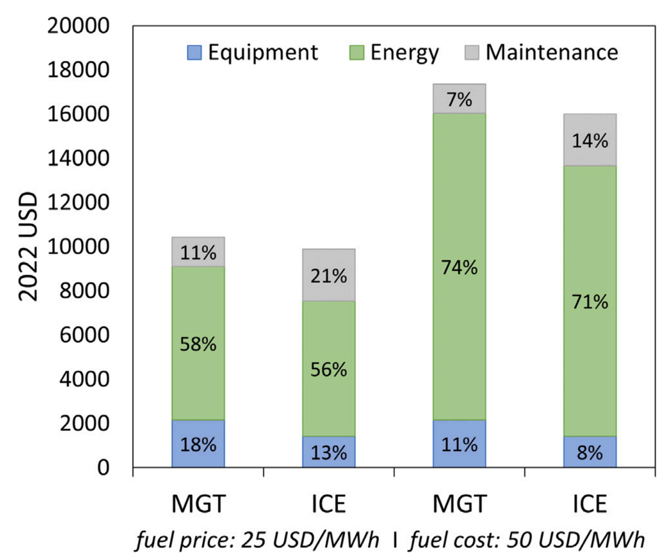

Fig. 5. Lifecycle cost for two representative power applications. The assessment considered a 100 kW MGT and a 100 kW ICE. The assumed working life is ten years with an operational availability of 95%. The equipment and maintenance/service cost functions are from Fig. 1; installation costs are from Section 2.2. The fuel prices considered are 25 and 50 USD/MWh, respectively.

  Compactness is often considered a Gas Turbine benefit. However, this does not scale as well for microgeneration applications since, in practice, the cost and volume of recuperators and other bulky components can easily overcome this advantage. The authors found that, based on the specifications provided by OEMs, the size and weight of MGTs and ICEs are similar. Given these considerations, **NC#4** is unsatisfied.
- **NC#1 MGTs State of the art technology can keep up with competition**: this Necessary Condition is not satisfied, considering the conclusions for **NC#2** and **NC#4**. Their causal relationship is further discussed in the next section.
- **NC#5 Margin:** retail margins are estimated to be 20% in case of direct sale, 25% in case of a 5-year Firm Fixed Price sale and going up to 60% for a 5-year rental (this latter solution is being adopted

by many MGT companies recently). These data correspond to the Capstone C1000 system [51], but it is assumed to represent most commercial products. Following the consideration for CSF#2, the cost structure and the number of sales seem to be the issue. Achieving high retail margins is possible, but this depends on how much customers are willing to pay and how many customers are willing to take the technology. In fact, retail margins depend on the expected units sold. In this case, the margins cannot guarantee profitability. For instance, for Capstone Turbine, gross margins were about 10%, way below the average levels from the industry.[2] According to their Fiscal report [42], this is due to manufacturing overheads and direct material costs.

- **NC#6 Robust distribution channels:** the RCI did not yield any correlation on poor distribution channels leading to undesired effects. The stakeholder interviews confirmed that distribution channels had expanded significantly during the last 20 years. From the website of the companies listed in Section 2.2, it also emerged that their distributors now extend to many regions worldwide. Moreover, distribution channels tend to scale with the industry, so comparing them with those of established technologies would be unfair.
- **NC#8 Commercialisation strategies and business models are optimised:** the interviews confirmed that commercialisation strategies were sometimes not aligned with the product characteristics, particularly targeting a general market and aiming for volume proved to be a wrong long-term strategy. As a lesson learnt, current MGT distributors and OEMs acknowledge the value of focusing on specific niches.

5. Root cause identification and analysis: the current reality tree

The current reality tree is one of the initial five thinking process tools for implementing the Theory of Constraints [10]. In the TOC, the CRT, also called the effect-cause–effect diagram [10], is a tool that helps the user find the cause–effect link between the problems and the so-called undesirable effects of the core problem.

Doggett summarised different thoughts previously expressed in literature [38,53,54] by saying that the CRT aims to represent the current state of reality as it exists in a system [10]. The representation follows the most probable chain of cause–effect links, and, ultimately, it serves to identify a core driver, hence a shared cause, common to several symptoms.

The CRT diagram can look very similar to Okes's logic tree, but whilst the latter is based on general causality (question *why?*), CRT follows the CLRs (see Table 2); in particular, the cause sufficiency marks the major difference between the two diagrams. The CRT is created top-down, although it is read from bottom to top [55] using the following construction: *"If [cause], then [effect]"*.

5.1. Symbols

According to the categories of legitimate reservation in Section 3.3, the CRT – like many other Goldratt's logic trees – presents a proper symbology (CLR: *Clarity*) which is summarised in Fig Fig. 6. Rectangles with rounded corners represent *Entities*. Undesirable Effects are considered special entities (coloured boxes). Arrows connect entities: the tail points to the cause, whilst the tip points to the effect. Another difference with other RCA tools is the elliptic "*and*" connector [38,54,55]. It represents interdependent causes according to its relative reservation category (cause sufficiency in Table 2). It is equivalent to a logic "*and*" operator, meaning that the causes must all be present to

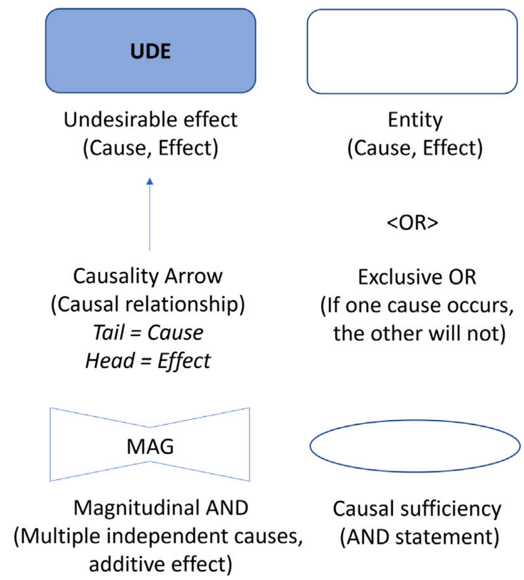

Fig. 6. Legend of the symbols in a CRT.

generate the effect. As stand-alone causes, they are insufficient to cause any consequence.

The "*magnitudinal and*", represented by a bow tie, is another example of insufficient cause. In these cases, the connected entities accumulate to worsen the effect [37], with the relative contribution of each cause – if known – often written as a percentage close to its relative arrow. The logical "*or*" with additional cause reservation is represented in CRT with multiple arrows without the ellipse. If the additional causes are self-excluding, i.e. they cannot be present simultaneously, they are marked with an "*or*".

Finally, the CRT also qualifies reinforcement loops. These can either positively or negatively magnify the effect of a cause. A thicker arrow that goes from one effect down to one of the deeper causes represents a reinforcement loop (see Figs. 6, 10 and 12).

5.2. Building the current reality tree

Building the current reality tree is a top-down approach comprised of the following steps:

1. Placing the Undesirable Effects (UDE) and establishing the first cause–effect connections.
2. Ordering the entities following the correct cause–effect relationship.
3. Appending additional causes.
4. Defining the causal relationships according to the CLRs.

The main reasons for not reaching the goal are the two Critical Success Factors. The UDE corresponding to CSF#1 (market size) becomes "*The number of sold units is insufficient*" since, in practice, CSF#1 corresponds to the revenue of the units sold. The UDE corresponding to CSF#2 (profitability) is "*MGT companies are not profitable*" owing to gross margins not being sufficient. Indeed, the previous section highlighted that the fraction of revenue going into gross margin is below average in the distributed power generation sector, concluding that manufacturing overheads, direct material costs and low sales yield low gross margins. The manufacturing overheads are the costs incurred to run production facilities that are not linked directly to a product. Direct material costs are high because microturbines need expensive materials and components to achieve acceptable performance [56,57]. This factor results from the high operating temperatures needed to increase the thermal efficiency of a Brayton cycle and from the need to adopt a

[2] Average gross margins are 41% of revenue for the Power sector, 35% for the Machinery sector and 34% for the Electrical Equipment sector [52].

recuperative cycle to enhance efficiency (the cost of the recuperator is a large contribution to capital cost). The other factor impacting gross margins is production volume to achieve economies of scale. Accordingly, the number of sales affects gross margins in relative (by affecting cost overhead, material and components costs) and absolute terms by reducing the actual values of revenue and margins. A report from the European Turbine Network [44] reveals the impact of sales volume on equipment cost for MGTs. In this case, an additional cause reservation is the most suitable way to represent these effects since each cause is sufficient to create the effect; nevertheless, the same entities are present in the bottom part of the tree. Their causal relationship will be rediscussed further in this section.

The poor sales result from two independent causes: wrong commercialisation strategies and an atomised market comprised of many niches. Even targeting a large market, inappropriate commercialisation strategies still hinder market penetration and conversely, companies may improve sales by appropriately targeting small niche markets. Nevertheless, if the niches are small and have little growth potential, better strategies will not substantially increase sales; this becomes even more so if the market is fragmented and heterogeneous. This last entity explains the lack of success of general volume-based market strategies used in the early years of MGTs commercialisation and also the challenges experienced in the recent shift towards more focused commercialisation.

Following the cause–effect relationship, the market is small and comprises many niches because of two insufficient causes. Investing in energy for on-site generation is not a primary interest, AND the state-of-the-art technology cannot keep up with the competition (Undesirable Effect of NC#1). The first item, influenced by **macro** drivers and barriers, relates to the market size. The latter depends on the ability of the product to penetrate the market, so it belongs to the **micro** world. The chain would break if (i) the on-site generation market expanded, with MGT being able to keep its market share, or (ii) MGTs increased the market share against the competition without a global market expansion.

Following the branch on the left-hand side, the low interest for energy investment has two independent causes. One is the inadequate regulatory push towards distributed generation technologies (this entity is the Undesirable Effect of NC#3). The second factor is that investing in energy requires longer-term commitment, economically or practically (i.e., utilisation-wise). This lack of push towards DG technologies and MGTs is a combination of insufficient causes. The existing regulatory frameworks are heterogeneous and do not promote reducing emissions below certain levels, except for CO_2 [47]. Such is the case of NOx, widely recognised as a dangerous emission [58], that yields about 90% of the damage to human health amongst all emissions of ICEs [59,60]. This explains why the consequences of using biogas are three times stronger than NG, given their higher NOx emissions, and this effect on human health is particularly relevant in urban areas [61]. Unfortunately, most regulatory schemes give no competitive advantage in having the lowest emissions.

From the considerations in the previous paragraph, it becomes evident that encouraging the adoption of the cleanest technology overall could see MGTs improving their competitiveness [62], since these engines help reduce the emissions of NOx and other harmful contaminants thanks to lean premixed or flameless combustion technologies both for conventional [63] and biofuels [64].

On the other hand, the unwillingness to invest in energy constitutes a substantial barrier since reducing energy costs requires a strong commitment that might not yield significant economic benefits. For instance, a study carried out in the UK found that potential users of microgeneration rejecting the adoption of these technologies were pushed back by high capital costs, long payback periods, scarcity of trustworthy information, and operational concerns [65]. These conclusions align with "*An EU Strategy for Energy System Integration*" issued by the European Commission [66] for local energy sources not being efficiently and sufficiently exploited because of: low market awareness, hesitation of businesses to enter a company outside their core activity, absence of appropriate regulatory and contractual frameworks to manage pricing, cost management, and planning. Indeed, companies tend to be reluctant to cut energy costs since it is not their core business and does not yield significant economic benefits if they do not translate into higher margins (i.e. if they come at the expense of higher capital costs or lower reliability). For electricity generation, Spark Spread (SS) is a metric commonly used to evaluate the economic feasibility of energy costs [67–69]: a higher SS implies more extensive operational costs and profit margin (an alternative though equivalent definition for CHP has been derived by Smith et al. [70]).

Low Carbon Dioxide emissions are also critical for market deployment. If MGTs had the lowest CO_2 emissions, they could become the preferred choice in a market pushing strongly to reduce CO_2. Unfortunately, the carbon footprint is directly linked to efficiency. For the aforementioned reasons, state-of-the-art MGTs cannot inherently contribute to decarbonising the grid in most EU countries, as shown in Fig. 7, neither for power-only or CHP applications. In this plot, GHG savings for CHP applications are relative to the separate electricity and heat production, taking electricity from the grid and using a natural gas boiler to produce heat:

$$(GHG_{Intensity})_{MGT} = (GHG_{Intensity})_{NG} \left(\frac{1}{\eta_{el}} - \frac{HP}{\eta_{boiler}} \right) \tag{1}$$

Where the GHG intensity of natural gas is $(GHG_{Intensity})_{NG}$=180 g_{CO_2}/MWh, and the Boiler efficiency is $\eta_{bolier} = 90\%$. The electrical efficiency of MGTs η_{el} is taken from two engines in the market [20,22] and the heat-to-power ratio HP is computed as the rated thermal power divided by the rated electric output. The authors assumed that the application could recover all the heat available for each configuration, representing the best-case scenario. Even in this favourable case, there is no apparent reduction in GHG emission compared to the independent production of power and heat in most countries and the EU27 average.[3]

Again, this is due to two insufficient causes: most applications run on conventional fuels, AND MGTs have lower electric efficiency than other technologies (ICEs and Fuel Cells). This block is an example of negative reinforcement: if most applications run on carbon-rich fuels and have low electric efficiency, CO_2 emissions are higher. This entity leads to the Undesirable Effect of NC#3: the small MGT market cannot lobby and push towards more fair and convenient regulatory frameworks, which often align with the established technologies [71].

The Undesirable Effect of NC#1 "*SOA technology cannot keep up with the competition*" is a direct consequence of "*MGTs do not represent a viable asset*", which is a sufficient cause to generate the effect. In turn, this is because the "*MGTs features do not meet the needs of the applications*". However, this is not a sufficient cause. The entity "*MGTs do not represent a viable asset*" does not only depend on the product features for the application needs, but it is also a function of economic and financial parameters. The main factors influencing economic and financial performance are "*Capital Costs (CapEx) are high*" and "*Operating costs (OpEx) are high*". The combination of capital and operating costs generates savings and profits; it impacts all economic indicators.

In this case, the standard logical connectors like the cause sufficiency and additional cause cannot be used. The so-called "*magnitudinal AND*", defined in Section 5.1, is the most appropriate connector instead. Here, the contributions of the connected causes accumulate to create and worsen the effect. A bow tie represents the "*magnitudinal AND*" (Fig. 9); in addition, the relative contribution of each cause – if known – is often written as a percentage close to its relative arrow crossing the

[3] 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 variable demand. There could be times when adopting CHP and on-site thermal generation would reduce CO_2 emission.

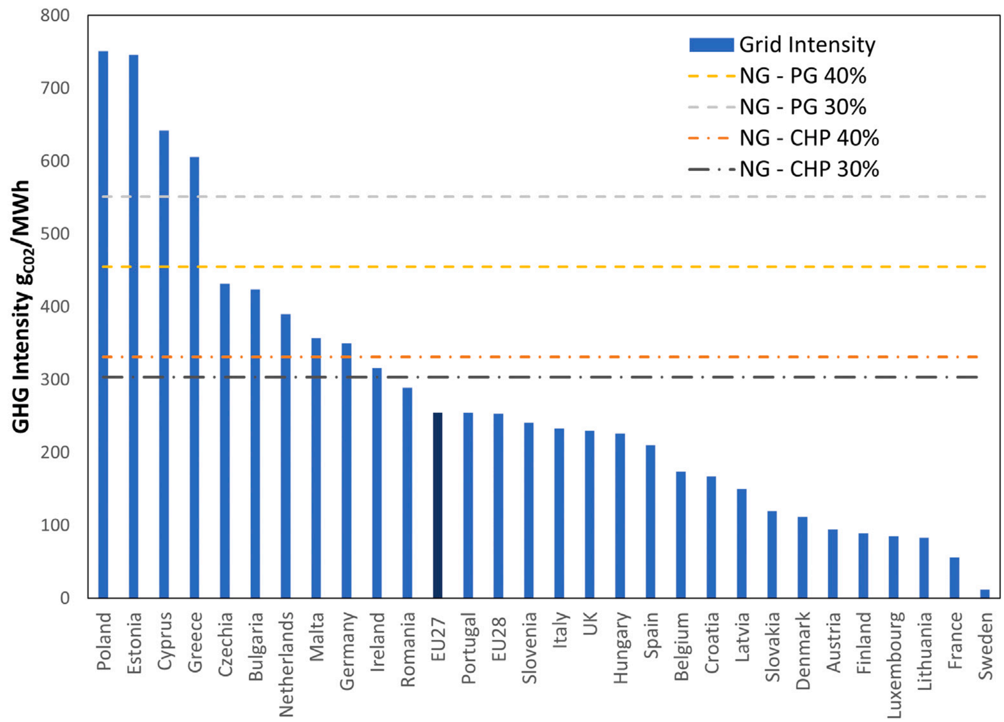

Fig. 7. This chart compares European greenhouse gas (GHG) emissions for Primary Electricity Generation (PG) and CHP burning natural gas (NG) using an MGT. The data is calculated for two MGT models using their rated electrical efficiency (30% and 40% respectively) and the thermal output specified by the original equipment manufacturers (OEMs) [20,22].

bow tie. In this case, the supplement of each cause strictly depends on the specific application and is not known *a priori*. For instance, the high capital cost might be the most relevant component in a particular case, whilst the profitability of the investment (combination of CapEx and OpEx) or the heat requirement could be the ones for other instances. Each case and application is different, and this dependency represents a barrier to resolving the more general Current Reality Tree based on a wide sphere of influence.

The sufficient reason for the high equipment cost is the Undesirable Effect of NC#7: high product costs. In this case, the logical connection combines additional and insufficient causes. The high overhead cost is a sufficient cause. Conversely, the cost structure and cost of components are two insufficient causes; removing one of the two is sufficient to remove the effect. Unfortunately, the cost structure is inherent to MGTs. Trying to remove this cause by having all components designed and manufactured by the OEM could introduce additional expenditures. Furthermore, insufficient sales volume is the principal entity influencing product costs because low sales negatively reinforce overhead, material and components costs. This complex causal relation highlights that pointing at equipment costs as the root cause does not make logical sense. Effectively, the primary way to reduce costs is to sell more and vice versa. These considerations lead to a complex causal relationship, which can be simplified as shown in Fig. 8.

This analysis will start again from the "*OpEx is high*" entity. OpEx is acceptable when it is (i) lower than the saving or profits, (ii) lower than other technologies or (iii) repaying the CapEx in an acceptable timeframe. None of these three predicted effects is generally satisfied. Following this consideration, the high OpEx depends on two insufficient causes. The energy costs are high, AND the larger maintenance intervals do not significantly reduce service costs. This latter entity is possibly trustworthy for most general applications exemplified in Fig. 5. However, it might fail in cases of higher maintenance costs, like in remote and dispersed applications. Generally speaking, service costs depend on the number of services and on their unitary costs; for MGTs, given that the planned maintenance intervals are considerably longer than for competing technologies, the low number of services drives service costs. Unfortunately, despite this inherent advantage, it is also true that some products suffered from low reliability and low availability of spare parts [72–74], which eventually resulted in more frequent maintenance of the engines. Moreover, the unitary service costs for MGTs tend to be higher than for reciprocating engines, a well-known technology, inasmuch as MGTs need to be serviced by a highly specialised workforce directly, often belonging to the OEMs; this last entity is, in addition, negatively reinforced by the low sales volume.

Energy costs are dominant for many applications, which are higher for MGTs than ICEs, given their lower efficiency. Moreover, most commercial MGTs experienced little to no evolution in terms of performance in the last two decades, as opposed to the continuous performance enhancement of ICEs, which widened the gap between these two technologies [75–77].

The last entity to analyse is "*MGTs features do not represent a market requirement*". This case has been discussed thoroughly in a previous section. However, it is not possible to define a representative relation of causality because this configuration is very application-dependent and not subject to generalisation. Further work needs to be done in this regard.

A possible approach could be to apply a data-driven numerical method to estimate the contributions to this entity and the marginal AND. By analysing the MGT niches in the first years of their commercialisation, as reported by Schot et al. [71], and the MGT existing in the market, these did not evolve to improve the penetration in those niches or to open new ones. It is to be acknowledged that a small industry like that of MGTs cannot compete with established technologies in terms of R&D&I due to limited resources. Still, it must develop technological and market niches leveraging its specific strengths. As discussed for dispersed commercialisation strategies aimed at the general market, it can be safely assumed that innovation and product design have followed similar, unfocused (i.e., not targeting a specific niche or application) patterns in the MGT industry. Whether or not this is continued by some new products coming into the market recently remains to be seen.

Fig. 9 presents the complete current reality tree showing all the information.

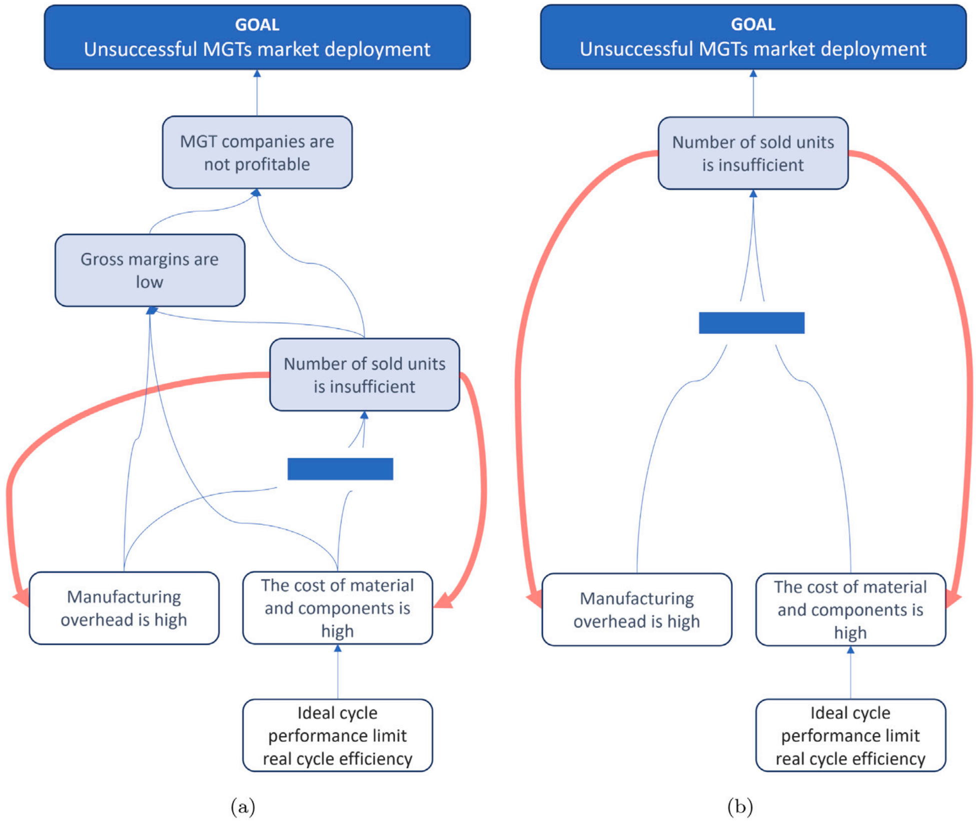

Fig. 8. Simplification of two equivalent causal relationships. Sub-figure (a) shows the original configuration, while the simplified one is shown in sub-figure (b). In this case, the sufficiency of the reinforcement loop ensures equivalence. Removing the reinforcement loop is the only way to fix the Undesirable Effect on low margins effectively.

5.3. Discussion of results

The authors applied the Theory of Constraints to the MGT market. Thanks to the analysis performed with the IO map, the authors confirmed that the microturbine industry does not meet its Critical Success Factors. Following the IO analysis with the system Necessary Conditions, the Undesired Effects were identified, i.e. problems, symptoms or low-level causes. The Undesirable Effects were the starting brick of the CRT, which was compiled according to the Categories of Legitimate Reservation using data and information from the academic literature, industrial reports and specifications, and stakeholder interviews.

The Negative Reinforcement Loops of the CRT highlighted that acting on costs is unlikely to produce any noticeable positive effect on the system. The insufficient number of sales sufficiently reinforces most cost-related high-level causes. A similar phenomenon exists in the renewable fuel network and in the inconvenient regulatory framework, where there is little space for any injection (i.e. action aimed to eliminate an entity).

Some high-level causes that can potentially break the cause–effect chain are:

- Cause-1: Wrong commercialisation strategies and Business Models.
- Cause-2: The complex cost structure.
- Cause-3: All installations are different.
- Cause-4: Fuel price and external fuel costs are high.
- Cause-5: Ideal cycle performance limits the real cycle efficiency.
- Cause-6: Lack of market-driven innovation.

Despite being an Undesirable Effect at the top of the CRT, Cause-1 proved a substantial constraint, especially in the early stages of MGT commercialisation. It is a sufficient cause directly connected to the main branch leading to the problem, meaning that it must be removed for the cause–effect chain to collapse. Cause-2 sits at the bottom of the CRT; it is an insufficient cause contributing to the entity "Product costs are high". Two more causes generate the effect. One of the two causes is sufficient: acting on the cost structure will not break the cause–effect chain. Causes 3 and 4 additionally contribute to higher installation and energy costs, respectively: the fact that they are additional causes implies that their removal may improve the system, but that would be insufficient to eliminate the effect. Cause-5 contributes insufficiently to the low efficiency of MGTs in the market and sufficiently to the high material costs (and partially to the cost structure); modifying the cycle increases performance (recuperated, intercooled and humidified cycles), but it also increases costs, amplified by the reinforcement loops. Cause-6 is linked to Cause-5 in generating low performance, but it is also responsible for the lack of competitive features of MGTs. The authors recommend a more thorough evaluation of MGT innovation and product design paths through the history of MGT, followed by an evaporation cloud, as discussed in the next Section.

6. From root causes to solutions

6.1. The evaporation cloud

The root cause identification highlights several high-level causes that significantly contribute to generating the problem. The next step involves analysing the CRT to identify possible injections – i.e. solutions – that will break the cause–effect relationships.

Considering the sphere of influence within the R&D community, the main issue is improving the product competitiveness knowing that acting on the CapEx branch is complex and possibly counterproductive; also, the Policy and Regulations branch (on the right-hand side of Fig. 9) is outside the industry sphere of influence as it strongly depends on the wider policy scenario. Acting on market-driven innovation is

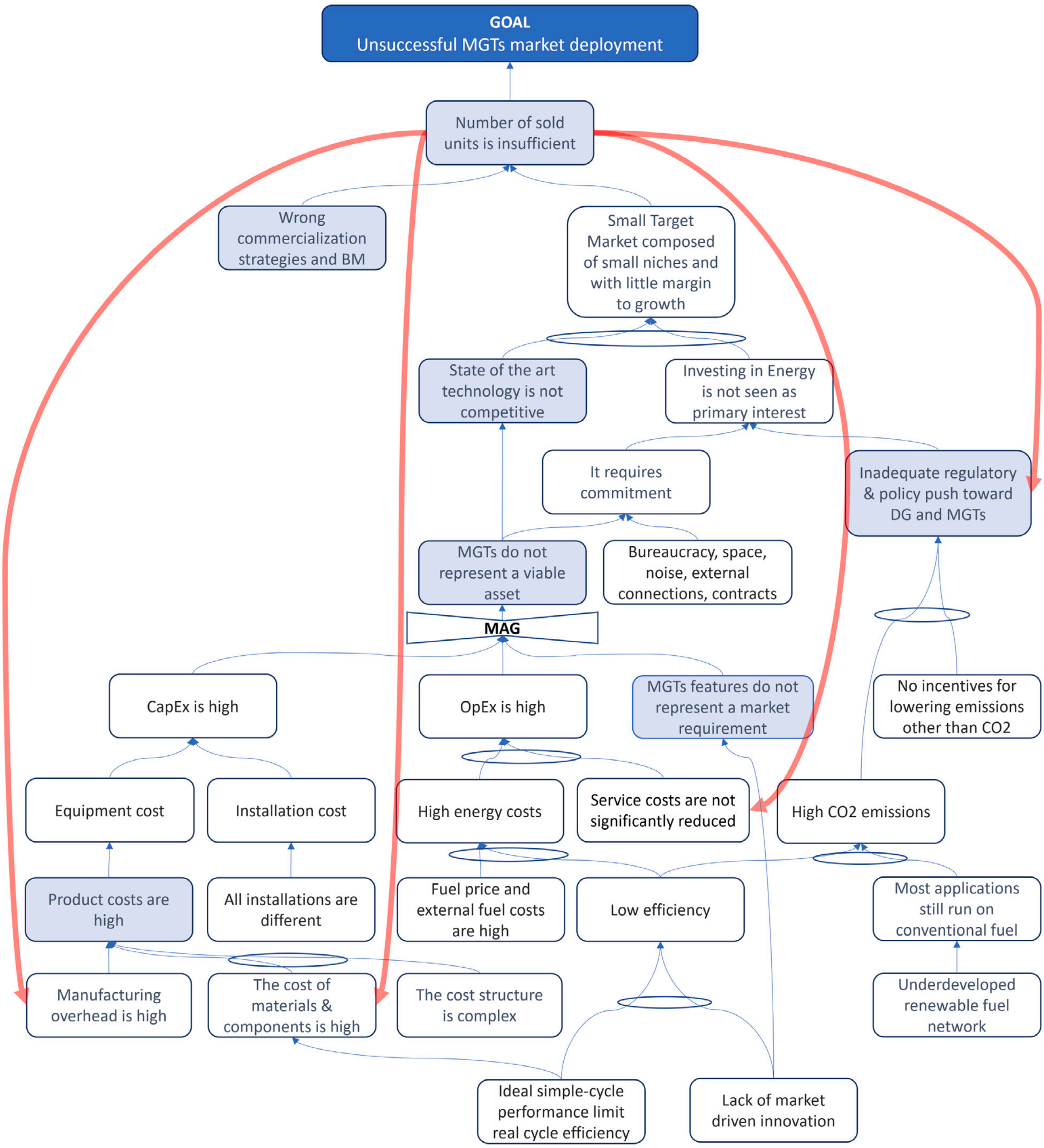

Fig. 9. Complete version of the CRT for the unsuccessful market deployment of MGTs.

potentially the only viable long-term option to break the CRT (Fig. Fig. 10). It implies creating – through specific innovation – the most competitive product for a specific market niche. This strategy is mandatory to pass from an emerging technology into a technological niche and, eventually, into a market niche.

These last considerations are in agreement with the evolutionary market theory, given the current positioning of MGTs as a technological/market niche [4,71]. Assuming that the global market is a network of several niches, the requirements to carry out market-driven innovation are: (i) securing technological and economic competitiveness in a specific niche, (ii) the network of market niches enabled by a specific innovation strategy should yield a large enough market to pay the investment back.

Finally, there are three main limitations to the proposed methods. The injection from market-driven innovation will tear up the cause–effect relationships up to the very top of the tree. However, the entity **"wrong commercialisation strategies"** is by itself sufficient. This means that properly application-oriented commercialisation strategies must follow market-driven innovation.

The second issue is the competing and contrasting nature of some entities. The Evaporating Cloud is the tool to analyse these specific aspects that follow the CRT analysis. The competing nature of the ongoing dilemma of reducing the costs versus improving the product performance with innovation is reflected in Fig. 11, which presents the evaporation cloud.

Finally, the "Magnitudinal AND" connector represents a barrier to solving the general CRT (Fig. Fig. 12). Each niche application has a

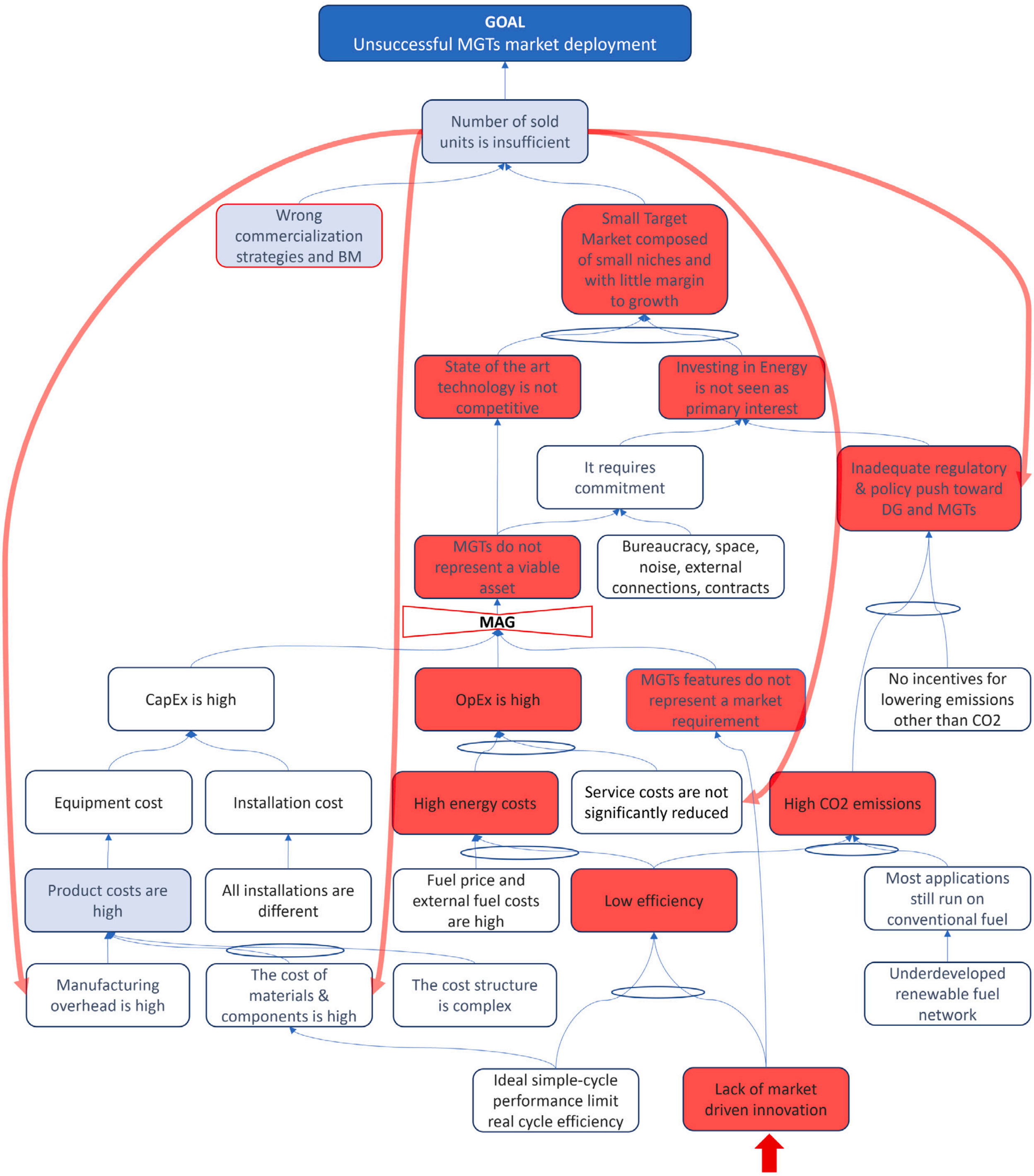

Fig. 10. Cause–effect chain of a possible injection represented using the CRT.

specific combination of capital/operating costs and required features. The way these entities combine – due to higher-level causes – dictates how the technology will compete in specific technological and market niches.

6.2. TOC-based quantification methodologies

The previous section demonstrates that the TOC analysis suggests acting on market-drive innovation is the most effective way to act. Nevertheless, the presence of the magnitudinal AND connector is said to represent a barrier in resolving the general CRT and, thus, in finding a unique solution to the problem. At the same time, investing in innovation to reduce operating costs and improve the product can harm capital costs. Some recent works targeted these two limitations of the TOC study by proposing numerical approaches that aim to resolve the magnitudinal AND connector, evaluate the current status of the technology for specific applications and advice on optimal innovation paths. Such methodologies represent an innovative way to turn the qualitative TOC analysis into a quantitative method.

More specifically, Tilocca et al. recently created a *Key Performance Indicator* to combine technical, economic, environmental, and operational factors into a single figure of merit to benchmark competing technologies in the same market [78]. This *indicator* is the sum of several weighted penalty factors, each representing the contribution

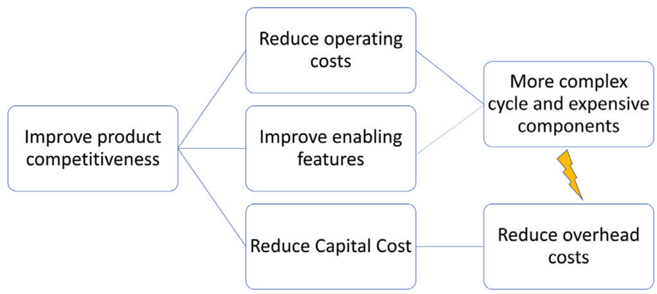

Fig. 11. Representation of evaporating cloud for the micro gas turbine market.

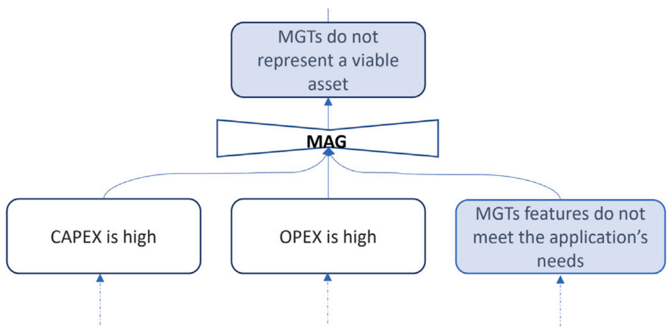

Fig. 12. CRT decision block.

of each cause into the Magnitudinal AND. The work demonstrated the potential of the TOC to identify and analyse particular market niches quantitatively and to provide useful insights on some economic and technological aspects of the micro gas turbine industry. One of the limitations of this approach was the arbitrariness in assigning weights to different entities. In a follow-up work published in 2023, the same core group of authors presented an evolution of the methodology grounded in the Theory of Constraints [79]. This new *Key Performance Indicator* still combines technical, economic, and operational factors according to the end-user requirements. However, this time, the arbitrariness of penalty weights has been removed since the new penalty function emulates the TOC principle of causal sufficiency and additional causality. Moreover, the effect of uncertainty deriving from technical and economic elements has also been included to perform a probabilistic-based evaluation of the best technology for a given application. This has been applied to the practical case of a Power-to-Hydrogen-to-Power energy storage system in a rural energy community under the '*Hydrogen in Rural Energy Systems* (HyRES)' project. The reference location is South Cornelly, Bridgend County (South Wales), a village comprising 220 family houses and a nursing house. The concept combines hydrogen produced locally from a portfolio of renewables (including wind and photovoltaic) and batteries. The analysis presented therein applies to the backup power sub-system only. This study underlines the potential of MGTs incorporating specific innovative features to mitigate global constraints (technical and environmental) cost-effectively, thus opening up new market opportunities for the technology.

7. Conclusions

This paper is part of a broader effort to analyse the deployment of MGTs from technological and commercial standpoints. The authors utilised the Theory of Constraints (TOC) to comprehensively solve complex business and technology-related problems. The first step in this approach is to identify system constraints through root cause analysis, which helps pinpoint the high-level causes of the problem at hand, such as the failure of MGTs to meet market expectations.

The TOC employs a set of strict rules known as the Categories of Legitimate Reservation to maintain objectivity in problem-solving, in contrast to more traditional RCA tools that prioritise creative problem exploration. Through the IO map and Current Reality Tree, the TOC accurately represented causal chains and defined cause–effect relationships, thereby systematising several negative reinforcement loops that have hindered the industry's efforts to improve MGT competitiveness over the past two decades.

After analysing potential solutions, the authors concluded that focusing on market-driven innovation is the most effective approach. Nevertheless, this investment must consider the economic feasibility of opening specific market niches.

It is important to note that there is no one-size-fits-all solution. As the Magnitudinal AND connector inside the Current Reality Tree logical representations indicates, innovation strategies must be tailored to specific markets and not aimed at the global scale. Another limitation is the conflict between improving performance and technological features through innovation, and potentially hindering other entities like the already high capital costs. To address these limitations, the authors developed and presented – in separate works – quantitative models that transform the TOC methodology into a framework for evaluating the impact of innovation strategies on overall product competitiveness. These models confirm the potential of MGTs as an effective mitigation technology for a low-carbon economy, considering their technological, environmental, and economic benefits.

Further work could include specific identification of possible innovation paths combining qualitative and quantitative evaluations and their combination with tailored commercialisation strategies.

CRediT authorship contribution statement

Giuseppe Tilocca: Conceptualization, Methodology, Data curation, Writing – original draft. **David Sánchez:** Conceptualization, Review and editing, Supervision, Project administration. **Miguel Torres-García:** Supervision, Project administration.

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

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