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861079 – NextMGT

(Next Generation of Micro Gas Turbines for High Efficiency, Low Emissions and F

Report on path to MGT commercialisation

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Contents

1. Executive Summary

Micro Gas turbines are on-site prime movers based on the Brayton thermodynamic cycle; this terminology often refers to machines generating below 500 kW of electric power.
Micro gas turbine development started in the 1980s and extended throughout the 1990s. Currently, most of the commercial products are derived from that early development.

Because of the low volumetric flow, micro gas turbines (MGT) mainly adopt centrifugal/radial turbomachinery. This layout and the reduced dimension have some direct and indirect limitations that strongly bind their thermodynamics performance. As a result, MGTs always run on a recuperative cycle which, on the one hand, enhances performance significantly but, on the other, also has a strong negative impact on capital costs.

Microturbines are suitable for different decentralised applications, namely:

- Primary generation.
- Backup power.
- Ancillary services.
- Combined heat and power (CHP).

Considering the features of MGTs and how they compare to competing technologies (reciprocating internal combustion engines and fuel cells), they compete in small niche markets:

- CHP in heat-driven applications: industrial processes requiring high-grade heat, commercial (hotels, wellness centres) and -to a lesser extent–residential applications.
- Waste fuel with low and variable LHV: flare and sewage gases (O&G), and biofuels
- Primary generation for remote applications where reliability and low maintenance is of primary importance, such as telecom towers.

From the Intellectual Property (IP) perspective, many inventions can be tracked in the late 1990s, just before the commercialisation of MGTs, followed by a big reduction after this initial surge in patent families. MGT patent filings have recovered in the last few years, and WP4 has spotlighted several new product development activities.

Lastly, WP4 has identified some barriers hindering commercialisation and market deployment of MGTs, such as:

- Underdeveloped renewable fuel network and inadequate renewable policy framework.
- Lack of market-driven innovation.
- Wrong commercialisation strategies and Business Models.
- Availability of data and market perception.

The authors advise commercialisation and innovation strategies to be more targeted to specific market segments. This trend has been observed recently in the development and commercialisation of new products, in opposition to the more generalistic approach observed in the earliest development and commercialisation phases.

Finally, the report highlights the need for increased industrial cooperation among different OEMs and stakeholders in order to facilitate the availability of operational data that could support potential new MGT business cases. In addition, an extensive and strategic dissemination activity will be crucial to positively affect market perception and policy alignment for Micro Gas Turbine technology. In this framework, the contribution of WP4 within the NextMGT project is recognised to be crucial in order to obtain, facilitate and disseminate such results.

2. Introduction to NextMGT and the role of WP4

Gas turbines are prime movers based on the Brayton thermodynamic cycle where the working fluid (air) is compressed initially, thermal energy is then added, before expansion in a turbine to produce power that is used to drive the compressor and to produce useful shaft power. The term micro gas turbine (MGT) refers to units producing shaft powers below ~500 kW. MGTs can achieve high power density and efficiency and have the advantage of better fuel and operational flexibility compared to other prime movers of similar power rating. They require less maintenance and the noise level brought about by combustion is lower and easier to attenuate than in competing technologies. Despite previous research and development, MGTs still have a low market share. Full technical potential has not been achieved due to insufficient investment in research and development and the absence of suitable coordination and innovation sharing mechanisms among stakeholders. The proposed multidisciplinary training and research programme in NextMGT aims at the development of the technical expertise and scientific knowledge that will enable a significantly improved understanding of the fundamental design and operational aspects of MGT technology, which involves the development of analytical and numerical multi-physics models that will be validated using experimental data to enable a significantly improved understanding of the fundamental design and operational aspects. Component level technology and its integration in an optimal manner will be addressed. An insight into the main features of the incipient MGT community and the existing structures for collaborative research and technology transfer between research institutions and industry will provide valuable information to pave the way to establishing an important European industry. This will lead the way in distributed power generation and link to renewables utilisation. The outcome of NextMGT is therefore significant contributions to researchers with up-to-date knowledge and skills in this field.

2.1 Objectives of WP4 and interactions with other WPs in NextMGT

The primary objective of this four-year work programme is to undertake cutting edge multidisciplinary research and development to make a step change in the understanding of MGT systems' technology and commercialisation aspects to enable large increase in their share in the energy market and contribution to the low carbon economy, while providing specialised training for researchers to help establish the backbone of an important industry. More specifically, the overarching aim of the work addressed in Work Package (WP) 4 is to investigate the enabling measures to commercialisation of the technology focusing on the impact of innovation on industry growth and also the effects of on intellectual/industrial property management, energy policy and regulatory framework and standardisation requirements.

Work Package 4 has a strong interaction with all other work packages with topics listed below:

1. Examine cycle innovations required to achieve high overall MGT efficiency to match other prime movers of similar power range and develop advanced methods to optimise micro gas turbine systems for several applications based on a standard core technology as well as smart integration with energy systems (WP1).
2. Investigation of advanced combustion technologies for achieving low emissions and fuel flexibility including biofuels in solid, liquid and gaseous forms and combustible industrial residues (WP2).
3. Develop innovative methods to enhance aerodynamic, mechanical and electrical aspects of MGTs and utilisation of new materials and to develop suitable storage systems to enable effective operation (WP3).
4. To train ESRs using a structured programme which covers: individual personalised research projects that lead to their PhDs; specialised training courses offered by the participating institutions; network-wide training activities in the format of seminar, workshop, conference and summer schools, and knowledge exchange with the members of the network through activities such as secondments and events (WP5).
5. To create wider impact in the relevant scientific arena and applications fields that come together in energy systems through wide communications dissemination of results including the general public (WP6).

6. To manage the proposed programme according to the guidelines of the Marie-Skłodowska Curie Action and disseminate the knowledge that it acquires through international publications (WP7).

2.2 Impact of the Project

The outcome of the NextMGT project will inevitably have (1) technological/ economical/ societal impact on the scientific fields and on the general public, and (2) individual impact on the ESRs' employability and development

1. Technological/economical/societal impact:
    - Research output that will be disseminated widely through a well-defined plan.
    - Highly trained ESRs ready to join a workforce the implements the EU principles including clean, affordable and secure energy through increased innovation capacity.
    - The wide-ranging involvement of industry and the commercial dimension of the programme will facilitate bringing ideas to market.
    - NextMGT emphasises the link to EU research/policy goals e.g., Horizon 2020 Societal Challenges or Industrial Leadership Pillar, Research Roadmaps, EU sectoral policies and the transferrable skills training programme as well as secondments at specialist associations.
2. Individual impact:
   The aim of this project is to contribute to the EU agenda on European Research Area by training "*a new generation of creative, entrepreneurial and innovative early-stage researchers*", who can face future challenges and to "*convert knowledge and ideas into products and services for economic and social benefit*". In addition, support to and compliance with the United Nation's Sustainable Development Goals (SGDs) will be at the heart of the training of ESRs and of the scientific and economic outcomes of this research. This will be achieved through the extensive nature of the training programme offered which includes:
    - Secondments at leading institutions and industrial organisation.
    - Wide range of scientific courses.
    - Training in transferrable skills (communication, presentation, employability…).
    - Opportunities to attend seminars, conferences, and events across different countries.
    - Opportunity to live in various countries either at host institutions or in secondment institutions.
    - Workshops and summer/ winter schools.

2.3 Work Package 4 description

Work Package 4 is comprised of three complementary projects, covered by ESR13, ESR14 and ESR15. These are developed at University of Seville (Spain), University of Stavanger (Norway) and City, University of London (United Kingdom). The lead participants in WP4 are listed in Table 1, showing the early-stage researchers involved along with their supervisors and co-supervisors.

Table 1 Participants in WP4

Name	Role	Beneficiary
David Sánchez	WP Leader	USE
Giuseppe Tilocca	ESR13	USE
-	ESR14	UIS
Kirti Sharma	ESR15	CITY

The rationale of the work package is shown schematically in Figure 1. Early-Stage Researchers 1 to 12 are organised in three work packages within NextMGT:

- WP1: Cycle Innovations and Optimisation.
- WP2: Combustion and Emissions.
- WP3: System Component Innovations.

These three WPs develop either concepts for the integration and application of micro gas turbine systems or their constituent components. This is expected to yield several potentially exploitable results that will be of interest for a large portfolio of end-users: combined heat and power, backup power, energy storage, propulsion, etc. Nevertheless, the technical interest of a technology does not suffice to make it commercially viable. It is mandatory to also:

1. Assess the economic performance of the system to make sure that it is also economically interesting.
2. Make sure that the appropriate measures to guarantee the safe commercial/ industrial exploitation of the technology are in place.
3. Ensure that the combination of energy policies and legislation in the short and long terms are coordinated to guarantee a fair and sustainable market for the future generations.

These are the three pillars supporting market deployment of micro gas turbine technology and they are, therefore, dealt with specifically in WP4. Thus, it could be stated that WP4 acts as a sort of catalyst for the rest of WPs, paving the way for the future industrialisation of the technology. In particular:

a. ESR13 (USE) will identify the underpinning causes hindering the successful commercialisation of the technology. This will provide feedback to the other ESRs in WP4 to allow them to focus on those features of the technology that are impeding its further development. At the same time, ESR13 will also evaluate the framework that is needed to nurture the successful collaboration between industry and R&D as this is acknowledged to be a key pillar of technology development.
b. ESR14 (UIS) aims at developing innovative techno-economic analysis procedures for micro gas turbine systems with strong links to the technology development aspects of WPs 1–3. This is a critical step towards the commercial deployment of the technology in as much as it will enable overcoming not only the technical hurdles identified by ESR13, but also potential economic limitations to be tackled in the future (for instance, installation or maintenance costs).
c. ESR15 (CITY) will explore and characterise the stage where micro gas turbines will play their role in a future decentralised energy scenario. This implies current and future energy policies and also standardisation and regulation, as these are cornerstones of a fair and sustainable future energy market where all technologies are treated equally for the sake of the end-users and the environment.

As shown in in Figure 1, the information produced by ESR14 and ESR15 is then processed by ESR13 which will take the last step towards commercialisation.

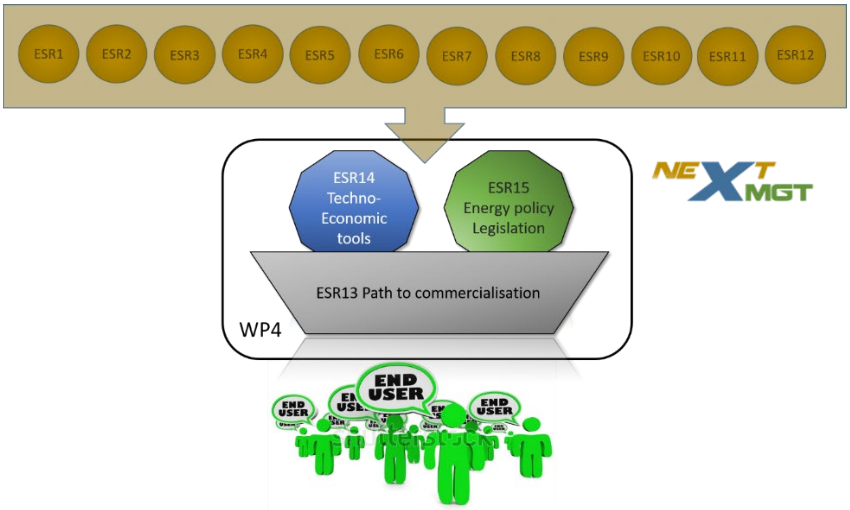

Figure 1. Rationale of Work Package 4

3. Micro gas turbine technology

3.1 Intrinsic limitations of small GTs

As said, micro gas turbines refer to small gas turbine units delivering shaft power below ~500 kWe [1]. In practice, commercial microturbines span from as little as 2kWe to 400 kWe, with some pre-packaged, parallel units exceed 1 MWe of total installed electrical power. However, the MGTs composing these latter units are a fraction of the total installed power. A thorough review of the State-of-the-Art technology is provided by the European Turbine Network Report [2].

Microturbines run on the Brayton thermodynamic cycle, just like bigger GTs. Nonetheless, their reduced size, hence volumetric flow, led to some substantial differences that set them apart from the larger sisters technologically.

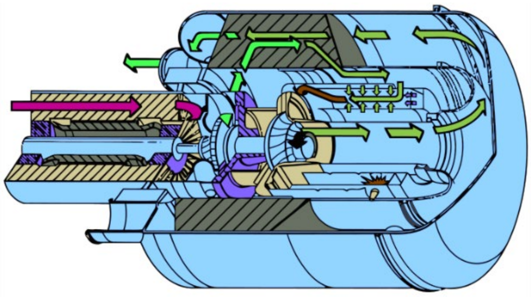

Figure 2: MGT layout. Source: Wikimedia Commons.

Because of the low volumetric flow, microturbines mainly adopt centrifugal/radial turbomachinery.This brings about the following practical limitations to cycle performance:

1. In radial turbines, cooling is not currently technically feasible and, therefore, MGTs feature a low Turbine Inlet Temperature (TIT) of around 950˚C (*vis a vis* 1600˚C of larger turbines). As known, the maximum thermal efficiency attainable by a simple Brayton cycle is limited by TIT and this explains why micro gas turbines do not typically feature very high efficiencies.
2. The utilisation of small radial turbomachinery sets, in practice, another limit on cycle pressure ratio:
    - Stage pressure ratio of centrifugal compressors is typically limited to ~5:1. High cycle pressure ratios require multiple stages, with globally worse performance than large axial multi-stage machines due to pressure drops across the return channel between stages.

    - In smaller machines, higher pressure ratios imply lower volumetric flows which enhance the negative impact of leakage flows and low Reynolds number on stage efficiency.
    - Small compressors and turbines are less adiabatic than larger machines. This implies higher compressor work and lower expansion work than in large turbomachinery.
3. The unaffordability of high-pressure ratios and turbine inlet temperatures explains why virtually all micro gas turbines make use of recuperative (or recuperated) Brayton cycles. In a recuperative cycle, the exhaust heat from the turbine is used to preheat the air stream delivered by the compressor prior to the combustion process. This reduces the fuel flow rate for a given output power and also the amount of energy released to the environment, thereby increasing efficiency.

Figure 3 shows the performance of a non-recuperative cycle against a recuperated cycle. In this example, the adoption of internal heat recovery brings about a twofold positive effect on cycle efficiency: the efficiency is twice as high as for the non-recuperated cycle at low TIT (for the same turbine inlet temperature); the pressure ratio at which efficiency is optimised is much lower for the recuperated cycle. Nevertheless, despite the recuperated layout having a considerable advantage in terms of performance and low compression requirements, the recuperator needed to preheat combustion air is a bulky (hence costly) component which also sets constraints on turbine exhaust temperature. Indeed, the control system of a MGTs sets a limit on maximum rotational speed whilst keeping turbine exhaust temperature constant. As opposed to this, larger gas turbines can either work off-design at constant turbine inlet temperature (simple cycle gas turbines) or at constant turbine exhaust temperature (combined cycle gas turbines).

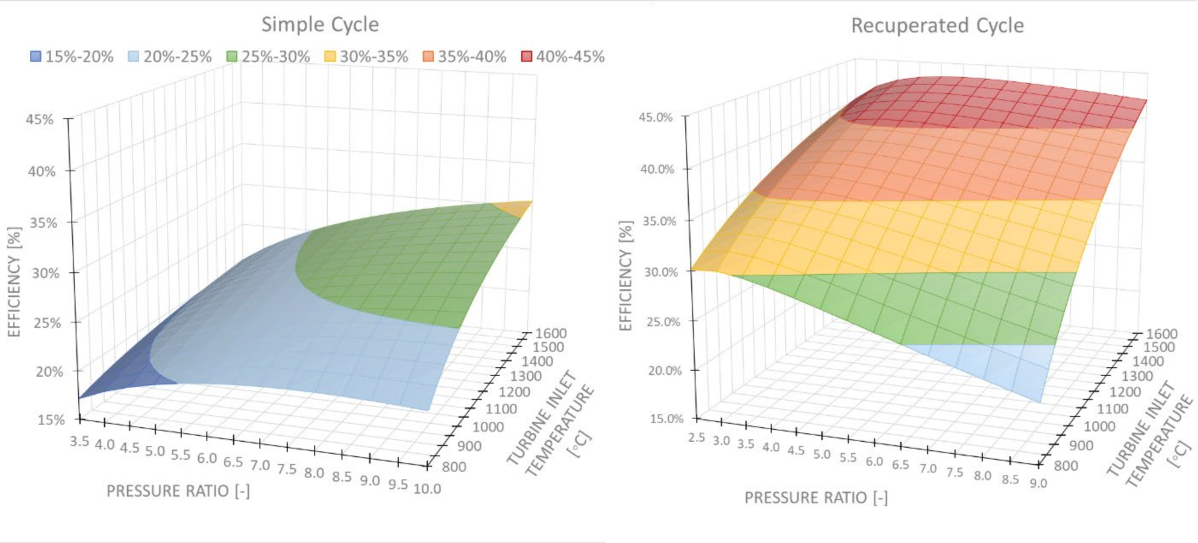

Figure 3: Surface chart of predicted MGT electrical efficiency for a simple and a recuperated cycle.

Finally, microturbines work at variable, high shaft speeds; thus, they drive a permanent-magnet synchronous generator at variable frequency. Downstream, power electronics adjust the power output to the requirements of the grid.

3.2 Comparison with other technologies

Microturbines are on-site power (and heat generators). From a technical standpoint, they compete agaisnt reciprocating internal combustion engines (ICE), the established technology for small-scale power and transportation, and fuel cells. The latter joined the market more recently and they are gaining momentum despite the very high costs, mostly thanks to the strong push for decarbonisation. Table 2 provides an overview of some techno-economics key performance indicators for the three technologies.

Table 2: Commercial MGTs and OEMs.

	MGTs	*ICEs*	*FCs*
Capital cost	Mid	Low	High
Maintenance Cost	Low	Mid	High
Fuel Cost	Mid	Low	Low
Waste Heat Grade	Mid-High	Low-Mid	Low-High
Heat to Power Ratio	High	Low-Mid	Low-Mid
Emissions	Low	High	None
Mechanical power	Less Suitable	Suitable	None
Fuel Flexibility	High	Mid-high	Low
Load Responsiveness	High	High	Mid-high
Availability	>95%	85%-95%	

Fuel Cells are still not competitive in terms of costs, although this can arguably change rapidly given the increased production rate that can lead to a sharp decrease in manufacturing costs; this is uncertain though, and more time is needed to confirm the better economic performance of the technology in the coming years. ICEs are by far the cheapest technology, whereas MGTs tend to be slightly more expensive (Figure 4). Maintenance costs tend to be to be lower for MGTs thanks to their long maintenance intervals (around 8000h, against the 1000h for ICEs) and high reliability. This is especially relevant for remote applications, like rural communities, telecom towers and off-shore applications when the cost of corrective and planned maintenance tends to increase dramatically. Thanks to the long maintenance intervals and high reliability MGTs have operational availability over 95%, on average, slightly higher than ICEs.

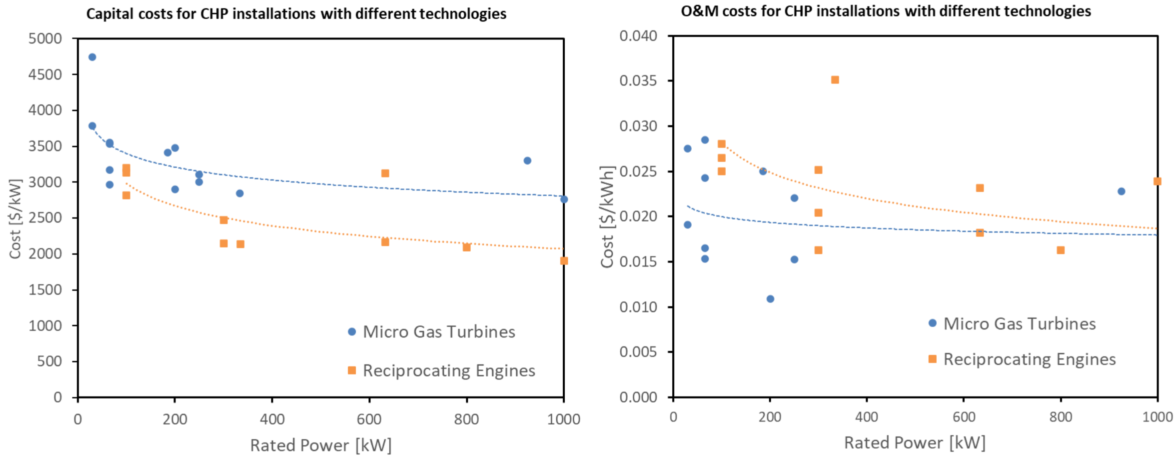

Figure 4: Capital and O&M (excluding fuel) cost for Micro Gas Turbines and Reciprocating Engines versus rated electrical power. Sources [13] [14] [15] [16].

Fuel costs tend to be lower for ICEs and FCs, whereas MGTs –due to their lower electrical efficiency- tend to have the highest fuel costs. However, thanks to the slightly lower efficiency and to the fact that all the waste heat is contained in a single gas stream (as opposed to ICEs, for which waste heat is carried by both the exhaust gases and cooling water, they are very suitable for heat driven CHP applications rather than primary power. Indeed, MGTs can reach higher heat to power ratios in applications demanding medium-grade heat (around 300˚C), for instance small industries demanding CHP energy. In addition, the high content of oxygen enables duct-firing downstream the exhaust to further increase the temperature and energy content of waste heat [3].

For high-efficiency MGTs using intercooled-recuperated cycles, the available exhaust heat and heat-grade are lower and comparable to reciprocating engines, mainly because of the higher conversion efficiency. Nevertheless, reciprocating engines still have the available waste heat divided in three different streams: exhaust gases, cooling water and lube-oil lubrication cooling. Having several heat exchangers to recover this heat to achieve higher heat outputs is often not economically feasible; moreover, the intermediate-grade heat only comes from the exhaust, the other two sources provide low temperature heat (80˚-100˚C). The temperature at which waste heat from fuel cells is available depends on the type of fuel cell considered: Proton Exchange Membrane Fuel Cells (PEMGC) deliver low grade heat (80˚C) whereas Solid Oxide Fuel Cell (SOFC) deliver high-grade heat (>700ºC), which could also be fed into bottoming cycles to form hybrid power generation systems.

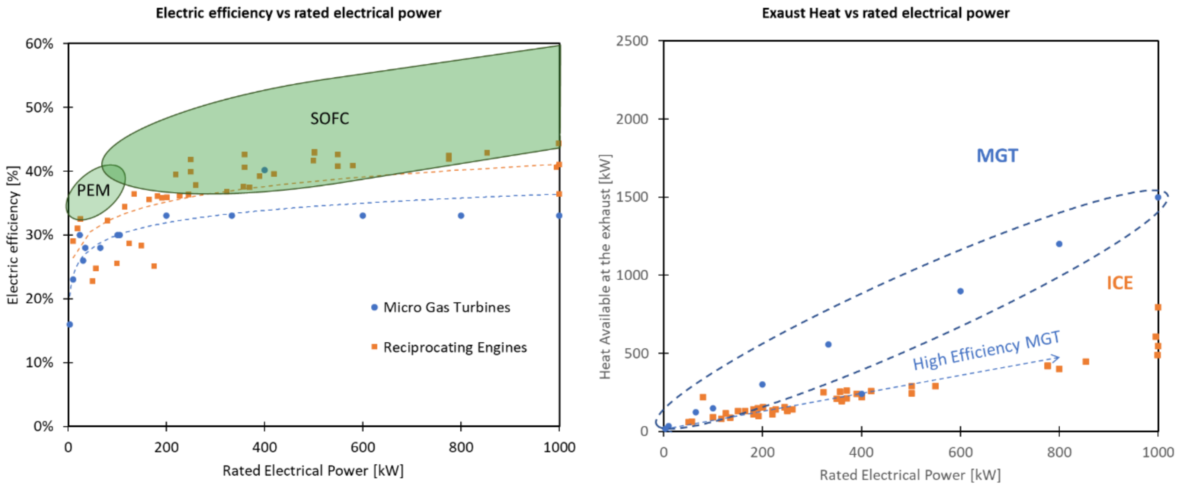

Figure 5: On the left hand side, a comparison of the electrical efficiency for different technologies. For ICE and MGTs the data is from actual products, according to OEMs specifications. For fuel cells, the range of the electrical efficiency has been estimated according to [4]. *On the right-hand side, a representation of the available exhaust heat for different power output.*

MGTs are less appropriate for producing mechanical power because of the low torque and inertia. In terms of emissions, FC clearly perform better for all type of fuels as no combustion takes place internally. Conversely ICEs need to make use of exhaust gas treatment to reduce the emissions of NO_x, Particulate Matter (PM), SO_x and hydrocarbons. MGTs, thanks to lean combustion and low firing temperatures, do not need exhaust gas treatment. Both ICEs and MGTs are very fuel flexible, although MGTs reportedly perform better with fuels having very low variable Low Heating Value (LHV) such as sewage and flare gases.

4. Market and applications

4.1 Primary applications

Microturbines are suitable for different decentralised applications:

- Primary generation.
- Backup power.
- Ancillary services.
- Combined heat and power (CHP).

Primary power generators produce electric power following the end-user or microgrid demand. These units are likely to operate for long time intervals under variable loads; therefore, operating (i.e., fuel) costs are a primary concern in these applications.

Backup units are secondary power generators expected to come online when the primary generator is unavailable or if this cannot meet the power demand on its own. Low capital costs, fast response, and reliability are the main drivers for these units.

Ancillary power is somewhat similar to the previous case but, now, the system comes online to fulfil the grid's power balance only: load balancing, voltage and frequency control. These ancillary services are usually highly paid and constitute an opportunity for fast-reacting power generators, which can come online shortly after receiving the request to do so. Therefore, the primary cost driver is low capital cost, whereas operating costs are less relevant.

Ultimately, *CHP* refers to the simultaneous production of electricity and heat. In a centralised scheme, waste heat is inevitably rejected to the environment and lost. In decentralised systems, such heat can be used effectively, either in the form of heat at the same temperature in a different process, upgraded heat or converted into useful mechanical/electric power. Some examples are process heat, steam, hot water or even cooling power through an absorption chiller (Combined Heat, Cooling and Power CCHP or trigeneration).

4.2 Companies and products

The global MGTs market is estimated to oscillate between USD 62 and 200 Million [5] [6]. Capstone Green Energy owns the largest share, with yearly revenues between USD 60-80 Million, which is still a small amount compared to other sectors. For instance, the market for reciprocating ICE for energy applications is estimated at around USD 20 Billion.

The market of Micro Gas turbines has seen some ups and downs in the last two decades. The first commercial units were released between the late 1990s, with an initial success followed by a sharp decrease in units sold due to their lack of techno-economic competitiveness against reciprocating engines, and a worldwide surge in gas price that affected the whole distributed generation framework. For instance, the market leader Capstone Green Energy had its Initial Public Offering (IPO) in the year 2000, close in time to the California brownouts. Back then, the interest in distributed generation (DG) and microturbine had a short surge, and so did Capstone’s share price. However, already in 2003, the stock price reached a minimum after the product did not survive the hype.

Figure 6 shows a similar pattern for the US CHP installations. Effectively, both MGT and ICE installations skyrocketed at the beginning of the 2000s. Soon after, ICEs managed to maintain a steady trend whereas MGTs installations dropped.

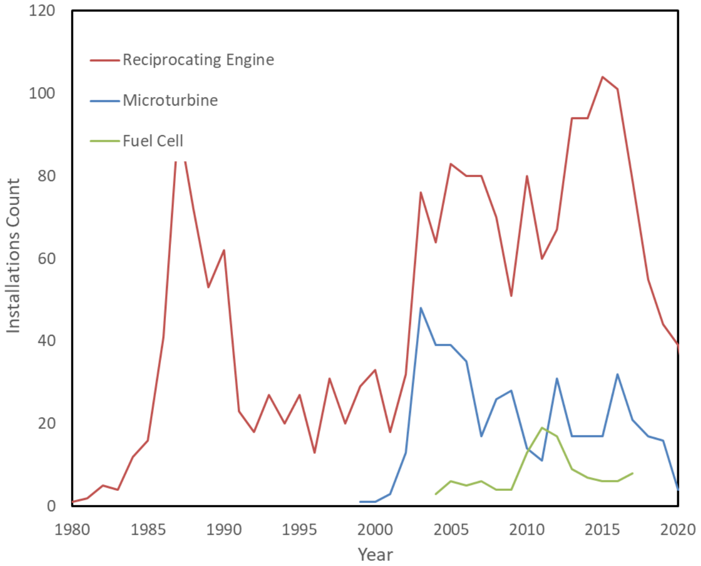

Figure 6: Yearly count of CHP Installation <1MW$_{el}$ in the US for different prime movers. Source [7].

The companies active in the market, and their commercial products, are presented in Table 3.

Table 3: Commercial Micro Gas Turbines products and companies. Products within brackets are pre-packaged modular units of the model in the same cell.

Manufacturer	**Model**	**Rated Output [kWe]**
Capstone Green Energy [3]	C65	65
	C200S (C600S C800S C1000S)	200 (600, 800, 1000)
Flex Energy [4]	GT333S (GT1300S)	333 (1300)
Aurelia [2]	A400	400
Ansaldo [5]	AE-T100NG	100
Bladon [8]	Bladon MGT	12
MTT [9]	EnerTwin	3.2

These products exist in different versions to accommodate various fuels (e.g., high/low pressure natural gas, diesel, propane, biofuels) and configurations (dual mode, grid connected, islanded). In addition, a few units have been adapted to run with external ehat addition, such as Ansaldo'a A100E and B+K'a Clinx50 and Clinx150 based on Capstone C65 and C200 microturbines. Externally fired machines can run on solid fuels like untreated wooden biomass and landfill waste.

4.3 Niche markets

Considering the features of MGTs (Section 3) and how they compare to competing technologies (Section 4.2) for the "primary applications" mentioned earlier, they manage to contend in small niche markets with specific requirements [8]. These are:

- CHP in heat-driven applications such as:
    - Industrial cogeneration requiring mid/high-grade heat (e.g., food processing, paper milling).
    - Industrial, commercial and -to a lesser extent- residential sector cogeneration with a

    - high heat-to-power ratio.
- Waste fuel with low and variable LHV such as:
    - Flare gases, mainly in offshore Oil and Gas applications.
    - Sewage and Biofuels.
- Primary generation/continuous power for remote applications such as:
    - Telecom towers.

On the contrary, it seems difficult that MGTs become competitive in transport applications. Due to their low torque, GTs are not very suitable for delivering mechanical power in directly-driven road and sea transport systems. Several companies tried powertrains based on micro gas turbines in light passenger cars (Chrysler, Rover) and heavy-duty trucks (Chevrolet, Ford, Volvo), but none of these experienced any commercial success despite the proven weight/volume savings. Recently, several companies tried to apply MGT as range extenders -i.e., hybrid electric engines- but experienced the same lack of market success. More recently, some newcomers are working on MGTs for hybrid aerospace propulsion, in this case, they leverage the small size of the GT drives to enter applications where the range is way more relevant than costs (e.g., unmanned military).

These are the niche markets where MGTs hold some advantages against the competition. There are two types of niches: a *technological niche* is an environment based on the expectations of potential prospects, and a market niche is a defined space where the stakeholders recognise the benefits of the technology. Technological niches tend to evolve into market niches [9]. Markets shaped by established technologies tend to raise barriers like market acceptance, policy alignment, technological performance and effective supply chain. One common market strategy when releasing a new product or technology is aiming for technological niches and expanding their network within their protected environment.

It took some time for MGT companies to implement this concept. Effectively, there was a tendency at the sparks of MGT market deployment to commercialise a mainstream product that would "crush" the market. Arguably, the interest in MGT and distributed technologies skyrocketed several times, with certain events linked to grid issues and energy crises. Microturbines could nevertheless not live to their expectations, and many companies abandoned their MGT project and businesses.

Today, all the players acknowledge that MGTs are a niche product. All processes along the supply chain -from product development to commercialisation- should account for this.

5. Policy, regulations, and standardisation

As already discussed, despite being a potential technology for current and future electricity and heat supply, micro gas turbines have achieved very limited market success due to technical, market and policy barriers. Previous research suggests that the adoption of such technologies includes an interplay between incentive policies, technology advancement, and consumer behaviour. The large-scale market penetration of MGT still requires clear and strong policy support to achieve widespread adoption.

As highlighted in Section 4, it is true that MGTs are capturing some market share from ICEs for CHP and are finding some opportunities in distributed energy generation. Indeed, MGT's future within distributed generation systems is promising as an alternative source for renewables due to its reliability, as the trends of policies focused on renewable fuels are providing a better incentive [10]; unfortunately, those are still not enough to bare the initial cost of MGT. There are also several issues related to the policy environment in which the distributed generation operates; energy policy is unique and complicated by the nature of the electricity grid infrastructure. The further step in improving the competitiveness of such small DG technologies should be to allow users to generate their own power and transmit excess to neighbours [2].

Due to the prominent role of policy measures in the development and deployment of low-carbon technologies, it is appropriate to analyse the impact of these measures. In a market economy, there cannot be direct political influence on economic decision-making. Instead, a variety of organisations and policy processes can have an impact on corporate decisions and innovation-related activities. As a result, it is advantageous to have a quantitative assessment of the effects of energy policies on MGT market share so that the precise support required can be easily communicated to policymakers.

The role of regulatory measures is viewed as more nuanced. It is important to recognise that not all technologies are created equal in terms of scale or performance. It is unrealistic to expect them all to perform consistently under the same market and regulatory conditions [11]. Apart from having a direct impact, these regulatory measures can indirectly make markets available for the technology; for example, the minimum efficiency requirement is perceived to be beneficial for CHP because it raises consumer awareness.

Because of the level of technical complexity, it is difficult for final customers to fully understand all exemptions and requirements, prompting some MGT producers to take over approval and accounting processes for their customers, resulting in the development of service innovations. Aside from complex administrative requirements, the technical requirements for grid connection are unclear, and it is reported that response times and collaboration with some grid operators are inadequate.

Product safety, energy efficiency, and grid connections are all areas of regulation that apply to technologies like MGT. This regulation establishes the "essential requirements" that MGTs must meet for a specific application in order to be sold in the European market. These regulations' requirements are formulated at a relatively abstract level and do not prescribe technical details or solutions that must be implemented to meet them. Standards provide critical guidance on how to meet these requirements. The initial absence of key standards has had significant implications for the development of technology, making the elaboration of this standard a priority for the industry, in particular for managing innovation [12]. ESR15 of WP4 is now working towards the impact of policies and regulations on the long-term deployment of MGT and aiming to provide recommendations to decision-makers in order to promote technologies like MGTs, due to their contributions to energy and environmental targets.

6. Innovation and IP Management

6.1 Evolution of MGTs and IP transfer

Qhwn micro gas turbine development started in the 1980s and extended throughout the 1990s, Volvo Aero, NoMac (today Capstone Green Energy) and later Elliot were amongst the first companies to initiate this development. Currently, most of the commercial products in the market derive from that early development. Figure 7 shows the development and commercial status of the more active companies in the market. It also highlights the IP transfer through joint ventures, merges and acquisitions over the history of micro gas turbines.

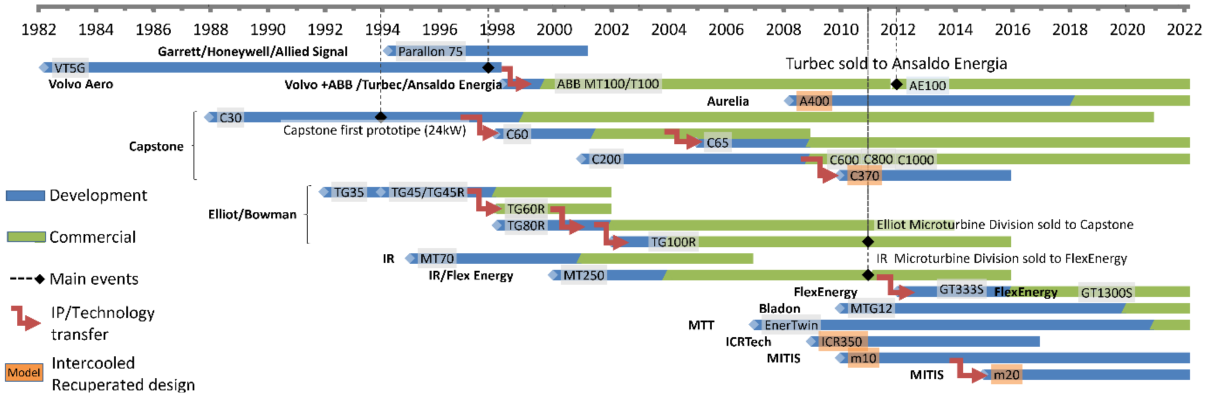

Figure 7: Evolution of products and companies in the MGT industry.

6.2 Patent history

Figure 8 shows a patent analysis of MGTs. The study was carried out using the EPO Patstat database (Spring 2021) searching for the keywords '*microturbine*' and '*micro gas turbine*' in the title and abstract and filtering according to the relevant CPC codes. The item count has been taken from patent families rather than applications, where a patent family -i.e., a group of patent applications- represents a unique invention. The data has been plotted against the earliest filing year, which is the known date that is closest to the invention. The plot shows a great patent activity in the years before the commercialisation of MGTs (late 90s) followed by a big drop. In the last few years, MGT patent filings seems to have recovered.

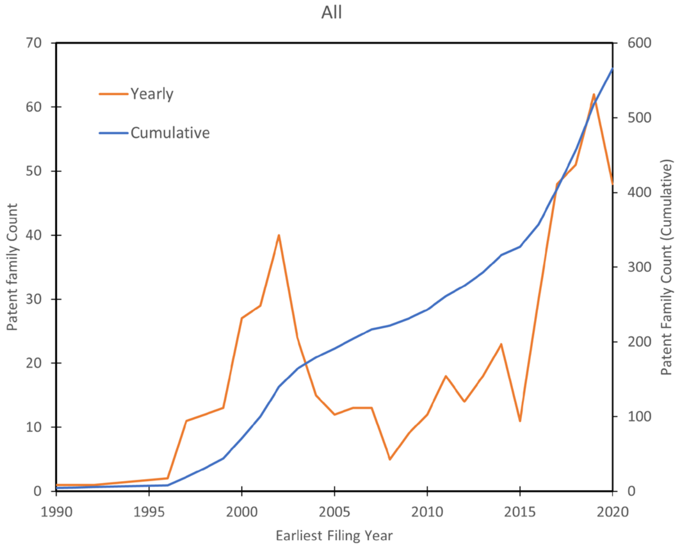

Figure 8: Count of MGT patent families.

This information seems to agree with the historical representation in Figure 7. Effectively, most of the product development concentrated in the 90s and, after initial commercialisation of most products, there was little further development. Only minor improvements in terms of efficiency and rated electrical power are worth noting, the main driver of which was to make the product more competitive; this relationship between power and efficiency was showed in Section 3.1 already, as a result of the fundamental consideration made in Section 3.2. Additionally increasing the power has a positive effect on decreasing the relative cost (e.g., USD/kW), which is the metric used to assess the techno-economic feasibility of on-site power generators. This first phase can be taken as an isolated technological stage, which can be easily explained with the current technological evolution theories, and the subsequent drop in inventions and product development coincided with the lack of market success of MGT and the reduced interest of the market in microgeneration and particularly MGTs, discussed in earlier sections

Lately, the number of inventions appears to have skyrocketed again, to values comparable to the MGT commercialisation. This also appears from Figure 7 where, during the last decade, several companies worked on new products. Some of these products, namely Bladon's and MTT's were recently released.

7. Intellectual Property, innovation and commercialisation related hurdles, and proposed pathway forward

The systematic Root Cause Analysis carried out in WP4 highlights several market-related issues. Very importantly, the **inadequate number of sales** sufficiently reinforces most cost-related issues hindering the successful deployment of micro gas turbines in the market, creating a sort of cycling dependency which is called Negative Reinforcement Loop. As a result, to overcome this issue, the system root causes must be eliminated. This section reports the main issues and high-level causes hindering the deployment of MGT identified in WP4, along with some suggested actions.

7.1 Underdeveloped renewable fuel network and policy framework

The development of renewable systems and renewable fuel networks has been moderately slow due to several challenges. These barriers are the necessity to implement many technologies developing at different paces, the outdated regulations and the substantial required capital investments.

Integrating renewable systems with stable (dispatchable) power generators such as MGT is especially advantageous regarding energy security while complying with the ambitious EU emissions target. MGTs can either be integrated with renewable systems or make direct use of renewable fuels to maximise the benefits of the legal schemes and policies. In many nations, hybrid renewable and alternative energy source systems have been successful due to favouring policies, schemes and acts. However, in order to achieve the mandatory renewable energy targets, there is a need for additional support from the government.

Recent research indicates the need for more technological awareness in policymaking and increased collaboration in the industry to effectively communicate the necessary government support to facilitate the deployment of renewable energy systems. Consequently, the renewable fuel network needs extra attention from policymakers and the many other actors that want to hasten the spread of renewable energy systems. In this framework, ESR15 of WP4 is actively working to provide guidelines to help policymakers make informed decisions to promote green technology based on MGTs in favour of local communities.

7.2 Market-driven innovation

Micro gas turbines entered the market without a clear competitive advantage over the established technology (ICEs) in the targeted market segments. After almost 20 years, the situation remains unchanged from a product standpoint. The sporadic and inconsistent journey to innovation did not enhance MGTs features and performances at the same pace as the competition, nor did it address the actual market necessities.

Amongst the considered scenarios, MGTs are more competitive for selected niche applications. This report recommends a more thorough evaluation of MGT innovation and Product Development paths, balancing costs, performance and product features. The optimal combination of these is application dependent.

7.3 Commercialisation strategies and business models

Wrong commercialisation strategies were a noteworthy constraint, especially in the early stages of MGT commercialisation. The commercialisation approach was general and dispersive instead of driven by the current technology strengths, weaknesses, threats and opportunities. MGTs are competitive only in selected market niches. As per the innovations path, general strategy cannot be considered a compelling option for commercialisation.

7.4 Availability of data and market perception

This report highlighted the role of MGT as an emerging technology in a stage of technological/market niche. Evolutionary market theories recognise policy alignment towards the established technology and market perception and acceptance as solid barriers. The perception of the emerging technology benefits for specific applications often mismatches the actual state of the art. For example, the perceived reliability of emerging technologies like MGTs is crucial to enter some conservative market niches. The poor availability of data, proving the alleged superior performance in terms of reliability and availability, does not favour the commercialisation of micro gas turbines in such segments. Indeed, when assessing the competitiveness in applications where reliability plays an essential role, data availability can cause ambiguity in the results [8].

WP4 encourages wider and joint dissemination of operational data from academia and industry.

7.5 Impact and contribution of WP4

This whole report, in particular this section, highlights the importance of the work of WP4. Micro gas turbines proved to be very promising indeed from a technological perspective. However, the work of WP4 identified several barriers hindering the deployment of MGTs. These factors are related to the economy, technology, policy, regulations and innovation pathways. The work of ESR14 and ESR15 is crucial in qualifying and quantifying these aspects. ESR13, on the other hand, has to process this information to draw a roadmap of the innovation and commercialisation strategies; such a roadmap is necessary to make this technology successful in the market and actively contribute to a low carbon economy.

8. Conclusions

This report analysed the technology, market and innovation history and state of the art of Micro Gas Turbines. The technology has some intrinsic limitations due to the reduced size that negatively affects performance, even if some of these size-related performance barriers are also partially shared by competing technologies. Overall, MGTs present higher capital costs and lower electrical performance than reciprocating Internal Combustion Engines. Nevertheless, thanks to their long maintenance intervals, fuel flexibility and higher heat grade, MGTs managed to be competitive in specific market niches.

Another major observation is that the innovation of microturbine has been discontinuous and dictated by market trends. This conclusion is based on data tracking all the major IP and market-related events in the history of MGTs.

Finally, Section 7 highlighted the major IP and commercialisation-related barriers; the report proposed some general corrective actions that can potentially benefit the MGT industry. In this regard, the work of WP4 is recognised to be of primary importance for the NextMGT project and to holistically draw a roadmap for Micro Gas Turbine development and commercialisation.

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